

The UK Engineering Test Infrastructure

An investigation into the sustainability of the experimental test facility infrastructure in the United Kingdom.

Simon A. Prince,
Secretary, Association of Aerospace Universities

Craig Handford & Dominic Johnson
School of Engineering
City University London

6 February 2011

Executive Summary

The current provision of engineering test facilities in the United Kingdom has been established and the trends appear unsustainable.

Despite common perceptions the UK is very dependent on its engineering industry (£200-250 billion of annual export income compared with only about £50 billion from financial services). Engineering industry depends upon cost effective access to experimental testing facilities for the research, development and through life support of its products, as well as for quality training of the engineering graduates that it recruits.

As documented, the past 50 years has seen a major decommissioning of the UK engineering test infrastructure. The cost driven retreat by the British government from the state provision of experimental engineering support services has been on a much greater scale than seen in our European partner nations, or the US. Appreciating what will affect their future ability to win global engineering projects, China and India are investing in their own modern engineering test facilities. Wind tunnels are a specific example of this general trend where a reduction in UK high speed facilities has caused multinational companies, such as Airbus and Rolls Royce, to outsource work overseas. This retreat from engineering testing work in the UK is accelerating.

The reduction in UK university based engineering test facilities is of particular concern because academia has increasingly become a much more important source of experimental research and development services to UK based engineering business. This reduction has been driven by the financial practice of capital space charging. Using this approach, educating two hundred arts or humanities students in a lecture theatre appears to be much more profitable than training twenty engineering students in an expensive laboratory. It has therefore become economically expedient to scrap engineering laboratory facilities to drive down costs. However graduate recruiters know that practical experience is vital in selecting effective science and engineering employees.

In short, this study, shows that unless action is taken, the ongoing trends that are eroding the UK capabilities in experimental engineering science, resulting in the irremediable destruction of expensive research / development and educational facilities, and the skills and expertise that go with them, will severely impact the UK's ability to win major engineering projects in the future, and will lead to the steady relocation overseas of those multinational businesses which Britain relies upon for the bulk of the £200-250 billion export income that engineering industry currently generates.

In order to address these problems, the Association of Aerospace Universities offers four recommendations in this report:

1. In order to stop the ongoing steady decline in the provision of experimental test facilities and a further serious erosion of sovereign capabilities in engineering science, a government sponsored *national strategy for engineering facilities* is now essential. This should aim to identify those “strategic” UK located test facilities, as well as those overseas where necessary, that are critical to the continuance of sovereign capabilities in engineering science. Public funding streams for experimental research or developmental testing in engineering science should then be focussed only on those strategic facilities, as outlined in chapter 7.
2. A review of the Capital Space Charging system at UK universities should be undertaken in order to identify a better way of funding institutional properties and facilities spend that does not disadvantage space intensive STEM disciplines and will reduce the significant pressures on these disciplines to decommission expensive laboratory facilities.
3. The various public funding streams that currently support the development and maintenance of university laboratory equipment should be opened up to fund those “strategic” facilities located outside of the academic sector, such as those in the ARA and MIRA industry associations, where these can be developed for use in educational programmes, or for final year dissertation studies.

4. The merits of establishing a new grant to fund the living expenses of a selected number of the best UK undergraduate engineering students to undertake their final year dissertation project at a major strategic industrial facility, should be investigated as a tool to promote improved collaboration between industry and academia, while improving the experience and, thereby, capabilities of the very best UK engineering graduates.

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1. Introduction

This section explains the background and motivations behind this study and presents the basic issues surrounding the future of engineering test facilities in the UK. The study comprises five main elements, each presented in its own chapter, which together cover the main issues which need to be considered in developing a national strategy for the management of UK science and technology facilities, which itself is presented in the final chapter.

History shows that the most successful nations are those that embrace broad and balanced economies, with strong “value adding” industries, encompassing resource extraction, processing, manufacturing, trading, financial services, agriculture etc. The science of archaeology is based entirely on the fact that the great ancient civilisations extracted, manufactured and traded. On a purely national level, therefore, a country’s ability to grow or extract raw produce, to add value by processing and to manufacture products to use or sell, is the key to a healthy economy.

On a global societal level, therefore, engineering is an essential discipline that feeds into every other field of human endeavour, continually improving the standard of human life, and without which civilised life would instantly come to a stop. It can therefore be said that everyone is a stakeholder in the sustainability of engineering industry and in the quality of engineering education.

In his introduction for a recent Royal Academy of Engineering (RAE) sponsored conference entitled “Innovation in Engineering Education” the then UK Science Minister, Lord Sainsbury wrote: *“In the global market place of the 21st Century, the UK will only be able to sustain and develop economic growth by maintaining its creative lead in innovative technology and by successfully exploiting it in the face of increasingly intense overseas competition. It is essential that UK engineering graduates are equipped with all the necessary skills to excel in a rapidly changing technological and business environment.”* Clearly, therefore, national governments have a strong interest in the quality of engineering education.

Engineering science, in common with most other science and technology disciplines, is very practical and “hands on”, requiring students to be able to design, construct, test and experiment. The view has prevailed, supported by industry and business as well as by the academic sector itself, that in addition to learning the theories of the natural world, students of science and technology should also learn how to undertake practical tests of these theories in a laboratory. Such practical experience, which relates closely to the kind of work done in industry, for which the students are ultimately being trained, has been seen as essential. Indeed, laboratory training has been a mandatory curriculum requirement for academic accreditation by many professional engineering bodies such as the UK Engineering Council.

The advent of modern computing technology and numerical algorithms for the computer simulation of complex engineering systems has modified this view, somewhat over the last decade. Computer simulation of engineering problems, using Computational Fluid Dynamics (CFD) or Finite Element Analysis (FEA) for instance, has now become routine, relatively accurate and relatively low cost. As a result there is a view that experimental facilities such as wind tunnels, engine test cells and structural test cells, which can be very large and costly to maintain, can be replaced by computer simulation in the engineering design process. Certainly there is some truth in this, and computer simulations can now significantly reduce the amount of time, and associated monetary cost of physical experimental testing.

In the last decade, therefore, there has been a trend, seen in the industrial, governmental and academic sectors, to scrap scientific and engineering test facilities that are seen as too costly to maintain, given the reduced requirements for such physical testing. In the UK in particular, over the last 20 years or so, both industry and academia have been allowed, through pure indifference and lack of a coherent policy or management mechanism, to scrap strategically important national facilities as a means to cut costs and down size – all to the severe detriment of UK Plc. The last two or three years has seen the beginning of what may well become a “mass extinction” event of experimental science and technology in the UK. Unfortunately, what is not understood by many senior managers is that scientific research and engineering design and innovation cannot take place in the virtual world, entirely on a computer, and requires the “real world” data, validation and testing that can only come from robust experimental facilities.

The case of University laboratories is of particular interest in this study, as these are currently under pressure due to the way that Universities charge their schools/faculties for the floor space that they occupy and use – so called “space charging”. As Hargreaves (2009) discusses, this certainly disadvantages STEM (science technology, engineering and mathematics) disciplines compared with less space intensive disciplines, such as the arts or humanities. Any short term measure to cut the properties and facilities spend, by cutting space used by science and technology departments, will result in the irremediable destruction of expensive teaching and research facilities, equipment and experience which will be vital to the country when investment in science and technology will, again, have to be embraced by the UK government.

Compounding this problem there has also been a trend against traditional “hands-on” science experiments being undertaken in UK schools, reported by McCormack (2010), Paton (2010) and by BBC News Online, due in part to costs, the impact of health and safety rules and class sizes.

Given the implications of the global credit crunch of 2008/09, the resulting structural deficit in the UK requiring significant cuts in public spending, a full study of this problem, with the aim of understanding the conflicting issues and of developing strategies to ensure that UK capabilities in science and technology are protected, is now timely and of critical importance to the national economic recovery.

This report documents a study of the various elements of this problem, focussing on the issues surrounding the use, both for education and research, and maintenance of University and non-academic science and technology laboratories, and how they can be better managed to help maintain national capabilities in the STEM disciplines.

First, it is not assumed that the old “hands-on” practices of educating scientists and engineers in the laboratory are still valid in the age of modern computing and the internet. Is it still necessary for practical engineers, trained to be competitive in the global engineering industry, to have “hands-on” practical instruction in a laboratory, or can modern engineering students learn all of the skills they need to know to safely research, design and manufacture engineering systems, such as aircraft, using computer simulation tools instead? Chapter 2 therefore presents a review of the past literature concerning learning theories and the pedagogical pros and cons of “hands-

on” laboratory education to help answer the question “do we need University laboratories for teaching and learning in Engineering science any more?”.

Chapter 3 goes on to assess whether the manufacturing and the higher education sectors, which most rely upon access to the engineering test infrastructure, and have the greatest stake in its sustainability, have any significant value to the UK economy, such that government intervention to help sustain that infrastructure would be worth the effort, or is even necessary. The chapter also investigates the common perception, even in engineering circles, that engineering design can be more cost effectively undertaken, and with acceptable accuracy, using computational methods, such that the physical testing can be significantly or wholly replaced in the design and development of engineering products or systems.

Chapter 4 goes on to present some of the evidence of the decline of the UK engineering experimental infrastructure by focussing on the example of the trends in the provision of wind tunnel facilities across the country, and how the academic sector fits in.

Chapter 5 studies the relatively un-investigated issue of whether students “expect” Universities to offer the provision of “hands-on” laboratory experience, whether they actually desire to gain that experience, and therefore whether test facilities have value in attracting students to a University. This has been tested in a questionnaire survey and in a number of interviews with students at a London university. In addition Chapter 5 also investigates whether there is similar value in good experimental facilities attracting the best academic and research staff.

Chapter 6 then presents the current practices involved in funding science and technology laboratories in British universities, namely through the Higher Education Funding Councils for the education and general research aspects, through the Research Councils for directed research projects, and via industry and charitable funding agencies, and how these practices will affect the future of these labs.

With the information provided in these prior studies, Chapter 7 presents a model for a national strategy, integrating not just University laboratories but external labs and facilities deemed to be of strategic importance to the United Kingdom, to maintain core capabilities and associated experimental facilities, while better employing them in the education of undergraduate and graduate students and in collaborative research efforts. Finally, the conclusions derived from the study are then summarized in Chapter 8.

2. Practical Instruction in Engineering Science: The Pedagogical Evidence

This section presents a review of the most successful models of how students learn, what this tells us about the best learning environment for achieving successful learning outcomes, and what the body of literature on the need for, and the changing role of, engineering laboratory activities in the modern engineering curriculum tells us.

In order to answer the question “do we need University laboratories for teaching and learning in Engineering science any more?”, and to gauge the true value of practical laboratory activities using engineering test facilities, it is important to assess how engineers “learn” the knowledge and the skills necessary for their profession, and what educational / psychological theory tells us about what kind of environment, and what kind of teaching practices best support this learning.

2.1 The Theory of Learning: A Review of the Relevant Models

Much literature has been written, linked with psychological theory, of the attitudes and approaches to student learning which work best, and how the teaching practices can best match these “*learning styles*”. It has been long agreed that natural goal of higher education is to promote a “*Deep*” learning approach, as opposed to a “*Surface*” learning approach. Reece & Walker (2003) listed the characteristics of these conflicting approaches as:

- Characteristics of Surface Learning:
 - 1) Intention to recall/reproduce lecture notes
 - 2) Sole aim to pass assessments
 - 3) Passively accepting teachers ideas/notes
 - 4) No reflection
 - 5) No concept of overall patterns or themes – focus on elements only
 - 6) Treating assignments and reading as a burden.

- Characteristics of Deep Learning:

- 1) Relating concepts to existing knowledge and understanding, and to everyday life.
- 2) Organising and structuring new information.
- 3) An interest in understanding new materials
- 4) Challenging new concepts and reading widely
- 5) Examining the logic of development
- 6) Determining what is significant.

The roll of the university lecturer is then to develop course material, activities and assessments specifically designed to lead the student learner towards deep learning practices. For over half a decade much effort has been made to define recognised learning styles by which individual students will have their own preferred way of learning or processing information. These theoretical models were developed in order to lead educators to adopt approaches to teaching that thereby enable students who use different learning styles to learn effectively.

According to Kolb's experiential learning theory (1984) learning takes place in a cycle of four generic adaptive processes, as shown in figure 1, and students will tend to be strong in some but not generally all of these processes.

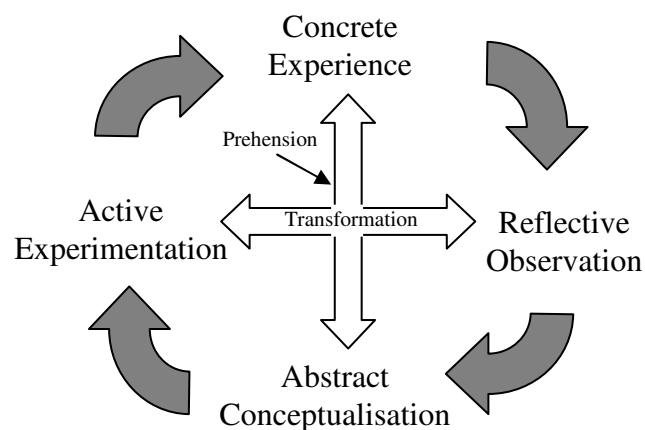


Figure 1: Kolb's Experiential Learning Model - Four stages of learning construction.

The cycle starts with the student's "*concrete experience*" on which he or she undertakes "*reflective observation*". Following this period of observation, the student will then perform "*abstract conceptualization*" whereby they formulate their own theories based on their observations, and then the student undertakes "*active experimentation*" to test his or her theory with their observations, thereby reinforcing their "*concrete experience*". The vertical axis represents the dimension for gaining knowledge new (*prehension*) via apprehension (concrete experience) or comprehension (abstract conceptualisation) or a mix of the two. The horizontal axis is the dimension for *transforming* existing knowledge via active experimentation and/or reflective observation.

Kolb went further, introducing his learning style inventory of four basic types of learners. The "*converger*" learns best in situations where there are correct answers, and excel in practical situations. Their dominant learning processes are abstract conceptualization and active experimentation. Kolb identifies these people as ideal engineers. The "*assimilator*" learns best in analysing and creating theoretical models, with dominant learning processes being abstract conceptualization and reflective observation. Assimilators, according to Kolb, prefer work in science and mathematics. The other two basic types of learner – the "*diverger*" and the "*accommodator*" are much less suited to practical learning, favour ideas and abstract thinking, and are much less suited to science and technology.

Honey and Mumford (1992) published a pioneering study of learning styles, on a similar model to that of Kolb, and proposed a model for the typology of learners as shown in figure 2.

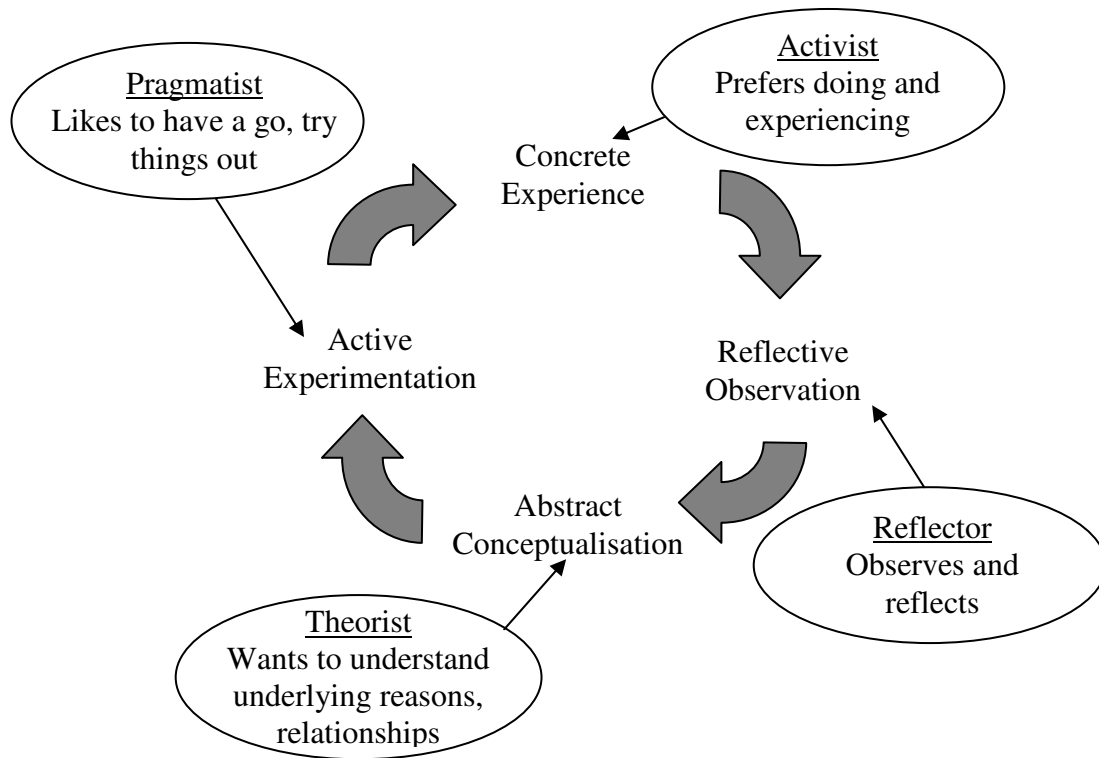


Figure 1: Honey & Mumford's Learning Model – Learner Typology.

Based on results of a questionnaire of 80 topics, Honey and Mumford identified four basic types of learners, linked to Kolb's learning construction model. "Activists" were those they characterized by openness to new experiences, and welcomed challenge and problem solving. Engineers fit well into this category of learner, whose other traits tended to be a sociable nature, but also rather impulsive. "Reflectors" tended to be those who prefer to explore things carefully before coming to a decision, work in a detailed manner preferring time to observe, reflect and think. These people tend to learn as observers rather than participants. "Theorists" learn best by studying in a logical, structured way and tend to like theories and systems but are unhappy with subjective impressions and ambiguity, preferring clear answers and methodical exploration. Some engineers will prefer to learn in this manner, and this learning style is easy to incorporate into any teaching strategy aimed at active learning – especially where problem solving is involved. Finally, "Pragmatists" like to apply things in practice and to experiment with new ideas and prefer learning activities which allow scope for practice and using theory. Again, this style of learning is not

widely different from the activist approach, and a suitable teaching strategy can incorporate activities suitable for both learning styles.

More recently researchers have investigated the relationship between learning styles and presentation styles. An interesting theory presented in Reece & Walker (2003, pg 143-4), based on the work of Felder (2003), identifies four basic learning styles. The *Visual/Verbal* Learning style is one where the learner learns best when information is presented visually and in a written format. These students learn best using course notes and text books and like studying on their own in a quiet room. The *Visual/Non-Verbal* Learning style is used by those who learn best when information is presented visually in a picture or graph rather than in text. The *Tactile/Kinaesthetic* Learning Style, meanwhile, is employed by those who learn best when physically engaged in a hands on activity, and enjoy design projects and laboratory sessions. These students, the theory goes, learn best when they are physically involved in their learning activity. Finally the *Auditory/Verbal* Learning Style is one where the learner learns best when information is presented orally and concepts can be tested orally in a group discussion environment.

Perhaps one of the most important concepts that has come from Teaching and Learning studies of recent years is that of “*Active Learning*” practice, as discussed by Denicolo, Entwistle & Hounsell, (1992), which aims to provide the key to the goal of fostering a deep learning ethos, by giving the student an active, ongoing involvement in their own learning process – which infers student self motivation. Denicolo et al. list their four distinctive features of active learning as:

- A search for meaning and understanding,
- Greater student responsibility for learning,
- A concern for skills as well as knowledge,
- An approach which looks beyond graduation to wider career and social settings.

While these learning style models are certainly very useful, it is important to remember that the preferred learning style of any individuals will include elements of two or more of these categories, whether one uses Kolb or Honey’s or Felder’s models. It is also important to remember that for different learning situations, different learners will use different styles that best suit them, so an engineer might well decide to use a “Divergent” or a “Reflective” approach to a particular topic.

With all of this information on learning styles at hand, what does it tell us about the academic merits of hands-on laboratory classes as a learning approach? First of all, it tells us that it meets many of the learning needs which are not met by the traditional large class lecture, where there is no practical hands-on aspect, little opportunity for team working. Group laboratory work, where students gain hands-on experience in testing something, making something or obtaining and analysing their own data to reinforce class learning meets the learning needs of the *converger-assimilator's* of Kolb's experiential learning model, *activist-pragmatist* of the Honey and Mumford model. Similarly lab experimentation meets the needs of the *Tactile/Kinaesthetic* learner but also the *Visual/verbal* and *Visual/Non-verbal* learning styles of the Felder model, and provides all of the elements of the Denicolo et al *Active Learning* model if the students are not simply passive observers of a lab activity, but actually get to do the experiment/test themselves. This is the key point – Learning theory tells us that to be effective, the learner must gain hands-on experience with the laboratory equipment, and there must be a clear link with theory and definite learning outcomes to which the exercise is designed. All of this is important for the student engineer to gain a better insight into the physical world, and to understand the theory, but there is a much deeper need for hands-on engineering laboratory education.

The skill of “problem solving” - the art of conceptualizing a technical problem, and tackling it with known scientific principles, is so important in the engineering profession that it is a core learning outcome in itself. Similarly the ability to design and undertake a programme of physical testing of an engineering design in order to accurately test its capabilities and limitations, aid in improving efficiency, and ultimately proving its safety is also a core learning outcome. All engineering systems have to be rigorously tested for safety reasons before they will be allowed into the market. Computer simulations cannot ultimately prove that an engineering system will perform efficiently or indeed that it will perform at all, and so prototypes will always need to be manufactured and tested. While computer simulation can certainly help in developing these skills, these learning outcomes simply cannot be met without developing significant experience with real world systems.

2.2 The Learning Group and the effect of Class Size

It has long been known that the traditional vehicle for student learning in University, particularly in 1st year, the large class lecture, is just about the worst learning environment there is. In large class lecturing, the educator has no chance of being able to sense whether the cohort understand what he or she is presenting, cannot realistically engage with the students and cannot cater for every learning style, particularly those who prefer the activist, hands-on mode of learning. For the engineering student, where practical application and problem solving is so central to the engineering profession, this is particularly problematic.

While recognising that learning is individual, adults do naturally learn from others, individually, or in groups. The formation of a “learning group” is therefore a valuable mechanism to support student learning. It is also the norm in industry that complicated engineering projects, such as design and development of a new aircraft system, are only ever done in teams (groups). A group centred approach in engineering student support is therefore desirable to promote group working skills for future employment. The dynamics of group processes (such as the ways in which isolates emerge, status hierarchy develops, and interpersonal competition is apparent) can both enhance and be inimical to the learning process. One of the most critical variables identified in group dynamics is group size and it is important to get this right if peer support groups are to work effectively.

Naturally occurring groups of adults with high levels of interaction between members have been observed to contain between three to five people [Brookfield, S. (2001)]. The study of Slater et al (1958) showed that an individual’s satisfaction with the group decreases as the group gets larger and that the greatest level of individual satisfaction were with a group size of about 5 – 6, and beyond this disruption within the group from competition increased. Bales et al (1951) showed, in his findings, that large group sizes corresponded with greater disparities in individuals’ contributions and that groups of ~5 were ones where individual contributions were more uniform. A study by Kerr (1983) found that larger groups were characterised by reduced levels of individual motivation to perform the tasks, and identified the ‘sucker effect’ whereby individuals contribute less because they see others not working as hard as themselves and they do not want to be seen as the sucker doing all the work.

Studies of group dynamics clearly supports the proposition that large class lectures are not good vehicles for student learning, and need to be supported by small group study exercises of about five members, where peer support can become effective. Such findings support the view that the kind of practices associated with hands-on laboratory classes, where groups tend to be around five or six students, lend themselves very well to an effective learning environment. This is in addition to the strong suggestion, inferred from learning theory in the previous section, that practical engineering laboratory classes, particularly with a problem solving element, have an extremely important place to promote deep learning of engineering principles. The next section presents a review of previous studies of the role and importance (or otherwise) of practical laboratory experimentation in engineering education.

2.3 Hands-On Learning in the Engineering Laboratory: A Review

The in addition to the review of some of the key learning theories and models, provided in the last section, this section provides a chronological review of some of the key studies that have been undertaken in the last three decades on the question of the pedagogical merits of hands-on experimental instruction in science and engineering. The review, while not comprehensive, helps provides a clear answer to the question of whether we need University laboratories for teaching and learning in Engineering science any more, and also provides guidelines as to how these facilities should be employed in future to enhance the learning outcomes of modern engineering students.

In the 1980's, with the advent of modern computing, the prevailing philosophy in engineering education, led by the United States, swung to the ascendancy of theoretical methods which promised major advancements in scientific discovery, revolutions in the engineering design process and significant reductions in costs. The threats posed to experimental science and engineering were not quickly perceived and, as such relatively little attention was given to the importance of maintaining quality hands-on experimental educational faculties. Two studies do stand out, however.

Ainley (1981) presented a very early study on the importance of hands-on experimental experience in science education, focussing mainly on secondary school science teaching. Ainley reviewed much of the scholarly work on the influence of facilities on science teaching up to 1980. This body of work revealed that practical laboratory exercises “*will help to foster science teaching practices which involve students in a variety of stimulating activities*” which he linked with improvements in student motivation and deep learning practice. He concluded that “*In terms of educational policy it would seem important to pay attention to the provision of good teaching facilities in schools if active forms of learning are to be encouraged*”.

Ernst (1983) provided a very important study of the role of undergraduate engineering laboratory classes, identifying three main objectives. Firstly he stated that the student should learn how to be an experimenter – putting the experimental method as a learning outcome in itself. Secondly, the laboratory should aim to provide an environment whereby the student learns something new and can develop the subject matter, and thirdly that the laboratory should help the student gain insight and understanding of the real world – clearly demonstrating the differences between theory and what one actually sees in the natural world.

In the 1990’s, the rapid decline in experimental facilities in industry and universities was no longer being driven just by the advance of computational engineering methods, it was accentuated by the end of the cold war, and the rapid reduction in defence spending that was the main source of funding for the maintenance of large engineering test facilities. In this period much more attention was building on the issue of defending experimentally based engineering education. In addition this was the period when educationalists were beginning to drive the refocusing of higher education away from “what” was being taught, to “how” it was being taught, based on pedagogical research. This also helped to focus attention on active, hands-on, methods of teaching.

In 1991 Dorato and Abdallah (1993) surveyed the curriculum and teaching styles of university engineering programmes in fourteen countries around the world, covering Africa, the Americas, Asia, Australasia and Europe, to identify the issues encountered in delivering engineering education, and how each country addresses them. The items surveyed included, amongst other things, the number of years required to obtain an engineering degree, pre-university preparation / education, cost

of education, completion rates for engineering degrees, entrance requirements, mathematical requirements, and support for laboratory work.

Of most relevance to this study were the results of the survey associated with engineering laboratory support, which the authors acknowledged were difficult to quantify. They summarized that *“respondents complained of poor support for instructional laboratories across the board. University budget problems were cited as the main reason for this poor support. A notable exception was Switzerland, where laboratory support was strong in all areas. Like many universities in the United States, it appears that support for laboratory experiences in engineering programs throughout the world is not what it should be. Many countries are now following the American model of a very theoretically oriented undergraduate education in engineering”*. The strategy for the future of US Engineering programmes that resulted from this study, recommended investment in university engineering laboratories and the national academic test infrastructure to keep American industry and graduates competitive in the global market.

Edder (1994) attempted to develop a learning theory of engineering design, linking the theory of experiential learning with the process of problem solving, which underpins engineering product design. He reviewed both design theory and learning theory, showing that active experimentation in its broadest sense is a key component of both the learning and problem solving cycles.

Aglan and Ali (1996) showed how the introduction of “hands-on” dissection and re-assembly exercises in the engineering laboratory, on systems such as a reciprocating internal combustion engine or a centrifugal pump, delivered significant positive improvements in the student motivation to mechanical design courses at an American University.

Demetry and Groccia (1997) reported on a similar pilot study involving a major redesign of the curriculum of an “Introduction to Materials Science” course in an American university. Educational outcomes were measured for cohorts taking the original curriculum, where the majority of contact hours were in the form of traditional large class lectures, as well as for the cohorts taking the revised curriculum which emphasised active, hands-on (such as product dissection) and group exercises. The results showed that the students taking the modified course retained more knowledge than students on the traditional course, demonstrated significantly greater

improvements in teamworking abilities and communication and social skills, and more evidence of deep learning practice.

Kresta (1998) introduced a number of 50 minute hands-on seminar sessions incorporating simple demonstrations in fluid mechanics principles aiding student learning in subsequent laboratory classes, and providing students with visual, active learning opportunities. Kresta reported that the introduction of these seminars resulted in a significant improvement in assessment grades (based on 10 year of data for the fluid mechanics module – the first seven of which were taught without the additional seminars), better feedback responses and an improved attendance at the course tutorials from 30% to over 80%.

By the turn of the new millennium, internet technology had developed to such a level that online, remotely operated, laboratory equipment became feasible, and there was significant move towards developing such technology for enhancing the educational outcomes of engineering students, and for further reducing costs of laboratory experimental provision. In addition, online technology could also deliver ever more sophisticated virtual reality simulations of laboratory experiments which, it was argued by many (principally the accountants), could make physical experimental rigs for educational support largely obsolete.

Gillet et al. (2001) developed and tested a prototype online computer environment for remotely operating large scale experimental facilities in real time, and presenting the results via webcam link and by graphical means. This tool was demonstrated as a live in-class demonstration. The authors suggested that such an approach could lead to economy of space, by allowing multiple institution access to a facility, freeing up other institutions to rationalise their own facilities and reducing costs, and maximising accessibility to the experiment over large periods of time.

From my own experience, the type of facility suitable for such a demonstration, however, would be the small desktop, less space intensive, type which is not used for research and development. Small scale experimental rigs tend to be set up for a single specific experiment, and can therefore be left for prolonged periods of time for students to work on as they please during term. Large scale facilities typically used for major research projects would not be suitable for this type of activity since they need to accommodate many experimental activities with models and instrumentation being added and removed all the time. It is suggested that the

economy of space would therefore see only minor cost savings in an experimental research intensive university.

Burnitsas (2002) presented a paper on the strategic review undertaken in an Marine Engineering department at an American university, aiming to solve the challenge of simultaneously delivering quality education whilst also delivering quality research outputs. While this work covers issues far beyond those of the use of engineering test facilities for the promotion of student learning, the author dealt with the issue of whether large scale facilities are still required in the educational context. Burnitsas pointed out that *“In our field, both research and education require daily use of experimental facilities that are large and expensive to upgrade and maintain.”* and the resulting strategy recognised that *“It is important to maintain and continuously upgrade facilities that are unique to engineering for the marine environment.”*

Ogot et al. (2003) undertook an important study in 2001 at an American University Mechanical Engineering department, comparing the educational outcomes between a hands-on jet thrust laboratory and its remotely operated equivalent. The laboratory was performed by a set of 15 or so students (in six separate groups) as a hands-on activity, and also by a different but similarly organised set of students who undertook the lab over the internet as a remotely operated exercise. The results indicated no significant difference in the educational outcomes, in terms of quality of assessed laboratory reports and student feedback, between students who performed the hands-on or the remote experiment. An important finding was that there was improvement in the grades of those students who undertook the remote lab, who had had supervision during the exercise compared with those who only had the benefit of online instructions. This would indicate that there is learning benefit of active human supervision, and therefore there is little manpower cost savings to be had from remotely operated labs.

These are important result since they indicate that hands-on experimentation, for some topics at least, can be eliminated from a curriculum without adversely affecting learning outcomes. It must be noted, however, that the learning outcomes assessed in this study are very narrow, and care must be taken in extrapolating this evidence with other important learning outcomes that a hands-on laboratory exercise provides. Another important point to make regarding this study and the many other similar studies in the literature, is that a remote lab does not infer that the test facility can be scrapped to reduces costs – it is still there, takes up space and requires

maintenance, and the same arguments can be made in relation to this study as mentioned for that of Gillet et al. (2001). While there are certainly benefits to be had with this approach, the findings do not support the conclusion that hands-on experimentation can be disposed of in science or engineering programmes.

Jensen et al. (2003) used learning theory to revise the type of learning activities and teaching delivery methods in mechanical engineering courses at the US Air Force Academy and the University of Texas. In particular, much more hands-on group design projects, designed to stimulate group working skills, were implemented and coupled with innovative computer simulation exercises. The authors reported significant improvements in levels of student interest and motivation to deep learning practices.

Wiesner and Lan (2004) undertook a class study whereby the impact of computer-simulated experiments upon student learning was evaluated in a senior unit operations laboratory. The authors obtained data on control and test groups, which included examination results, a questionnaire and oral presentations. The authors concluded that “tactile” laboratory classes should remain an integral aspect of the engineering curriculum but that introducing computer based experiments to support hands-on laboratory learning does not adversely affect student learning.

The National Endowment for Science, Technology and the Arts (NESTA) presented a study, edited by Kestenbaum (2005) advocating what it called “Science Enquiry Learning” as an effective means to enthuse secondary school students in Science and to promote better learning, as well as more youngsters into scientific careers. Science enquiry involves one or more of the following: raising questions and hypotheses; testing these hypotheses through practical investigations; revising the hypotheses based on observations and the interpretation of data; and presenting the findings to others. The report presented some of the growing evidence that suggests that increasing the amount of practical, investigative work can have a marked positive effect on learners’ enjoyment of science, and thereby improve the learning process.

Feisel & Rosa (2005) studied the history (primarily American) of how engineering laboratories have been used in higher education for supporting the learning in engineering programmes, how these have changed over the years and explored a few of the major factors they see influencing laboratory use today. The authors suggested that there is a lack of coherent learning objectives associated with modern engineering laboratory practices and that this lack has limited their

effectiveness. They claimed that there has been little meaningful research in this area, and as such, they presented a list of fundamental objectives for future research into how hands-on laboratory education needs to be more effectively focused.

Feisel et al. made the important point that engineering is a “*practicing profession*” and the goal of engineering education is therefore to prepare students to practice engineering and, in particular, to deal with the forces and materials of nature. They identified three basic roles of the engineering laboratory: i) development, ii) research, and iii) educational, and suggested that these different roles must be understood if there is to be agreement on the educational objectives that the instructional laboratory is expected to meet.

In the research role, a laboratory is used to generate broad knowledge that can be “*generalized and systematized, often without any specific use in mind*”. The development role of a laboratory involves its use in answering specific questions associated with an immediate design or development activity, such as testing, or the development of important design data. Both of these activities involve the finding out of something that is not known. In its educational role, the laboratory, Feisel and Rosa seem to contend, does not generally include these aims, but is more focused on learning something that practicing engineers should know – a principle or knowledge that is already known. The authors suggest that this “something” needs to be “*better defined through carefully designed learning objectives*”.

While clearly the learning objectives of the laboratory exercise are of prime importance, and do need careful treatment for the activity to be of benefit to the student learning experience, it would be wrong, in my view, to suggest that the ability to design a programme for development and/or engineering research should not also be a core learning outcome as well. These elements are core “practices” in the engineering profession – out in industry as well as in academia – and as such modern engineering graduates need to be able to design new experiments to generate previously unknown data or findings.

The advent of modern computing and distance learning, Feisel and Rosa point out, has opened new possibilities for laboratory education, which has brought the issue of the fundamental objectives of laboratory instruction to the fore, but despite this, little attention has been given to it over recent years.

The important observation is made that the rapid growth of electronic, computer controlled, instrumentation in the 1980’s and 90’s, means that modern

computers with specialised electronic instrumentation can acquire data from an experimental environment, analyze it and present it graphically in the time that it used to take to measure and record manually just one data point – and can do this to a more accurate level. This provides the student engineer with the ability to acquire and analyze data for much more complex systems than in the past.

Computers can now be used to provide simulated virtual outcomes of experiments, incorporating some elements of design and development, as well as control real instruments remotely, and Feisel and Rosa also charted the emergence of remotely operated, computer controlled laboratory experiments in the American university sector.

Summarizing their historical analysis, Feisel and Rosa presented their “*The Fundamental Objectives of Engineering Instructional Laboratories*” as a tool for designing suitable experimentally based exercises for student learning. These are reproduced in full below:

Objective 1: Instrumentation. Apply appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities.

Objective 2: Models. Identify the strengths and limitations of theoretical models as predictors of real-world behaviours. This may include evaluating whether a theory adequately describes a physical event and establishing or validating a relationship between measured data and underlying physical principles.

Objective 3: Experiment. Devise an experimental approach, specify appropriate equipment and procedures, implement these procedures, and interpret the resulting data to characterize an engineering material, component, or system.

Objective 4: Data Analysis. Demonstrate the ability to collect, analyze, and interpret data, and to form and support conclusions. Make order of magnitude judgments and use measurement unit systems and conversions.

Objective 5: Design. Design, build, or assemble a part, product, or system, including using specific methodologies, equipment, or materials; meeting client requirements; developing system specifications from requirements; and testing and debugging a prototype, system, or process using appropriate tools to satisfy requirements.

Objective 6: Learn from Failure. Identify unsuccessful outcomes due to faulty equipment, parts, code, construction, process, or design, and then re-engineer effective solutions.

Objective 7: Creativity. Demonstrate appropriate levels of independent thought, creativity, and capability in real-world problem solving.

Objective 8: Psychomotor. Demonstrate competence in selection, modification, and operation of appropriate engineering tools and resources.

Objective 9: Safety. Identify health, safety, and environmental issues related to technological processes and activities, and deal with them responsibly.

Objective 10: Communication. Communicate effectively about laboratory work with a specific audience, both orally and in writing, at levels ranging from executive summaries to comprehensive technical reports.

Objective 11: Teamwork. Work effectively in teams, including structure individual and joint accountability; assign roles, responsibilities, and tasks; monitor progress; meet deadlines; and integrate individual contributions into a final deliverable.

Objective 12: Ethics in the Laboratory. Behave with highest ethical standards, including reporting information objectively and interacting with integrity.

Objective 13: Sensory Awareness. Use the human senses to gather information and to make sound engineering judgments in formulating conclusions about real-world problems.

I suggest that this list of learning outcomes represents a very good model on which to base University engineering laboratory courses. A particular laboratory exercise should aim to meet a number of these learning outcomes, but an engineering student should be able to meet all of these learning outcomes by the end of their undergraduate course.

Interestingly, if one looks at these objectives with a view to identifying those that can be met either remotely over the internet, or via a purely simulated exercise, then we see that objectives 1, 3, 5, 6, 9 and 13, to varying degrees, would be difficult to achieve with only these methods. Clearly, if this list of objectives is a good model for the core learning outcomes of a practical engineer, then a hands-on approach would need to be a part of the learning programme. In these circumstances, access to a well maintained and instrumented engineering laboratory would still be essential.

Heise (2006) examined the benefits of a hands-on laboratory approach compared with similar activities using computer simulations, with reference to his

experiences teaching a university Computer Architecture course. In particular, he investigated, through a review of the existing literature, the inherent benefits of a physical laboratory by drawing from findings in the fields of learning science, cognitive science, and educational research.

Heise compared the assessed learning outcomes of students who had undertaken a digital logic experiment, building a circuit from components and testing it, with a similar group of students who did the same exercise on a computer simulation. Heise found that the physical laboratory more successful at enhanced the learning of the students. In particular, test scores were better and student interest levels higher amongst the cohort who undertook the physical hands-on exercise.

The authors' review of learning and cognitive science revealed that chief among the factors influencing knowledge and skills "*transfer*" - the ability to extend what has been learned in one context to new contexts - are i) time committed to learning, ii) motivation for learning, iii) how closely function is related to structure, and iv) how much problem solving skills are developed in multiple contexts. Heise argued that on each of these factors, the physical laboratory is superior to a computer simulation.

Troina and Klahr (2007) investigated the use of virtual computer based laboratory teaching against equivalent hands-on practical laboratory sessions. They demonstrated in two activities undertaken at secondary school level, that virtual teaching materials can be as effective as physical materials when teaching with explicit instruction and, to a lesser degree, by student led enquiry. Troina et al, however pointed out that their evidence shows that hands-on activities "*tend to increase student motivation and engagement*", and that "*there might be particular domains (eg: life sciences) that require experience with authentic, physical objects rather than their virtual equivalents*".

Meanwhile, Burley (2007) presented a study of virtual reality computer technology for a distance learning DVD whereby students could use online computer models to simulate environmental engineering problems, producing and analysing relevant data. The study showed that computer simulation, in this case, was popular and could be employed to "*take*" students to remote or dangerous environments where visits are not practicable.

Read et al. (2008) reported on the work done on a project called RELOAD (Real labs operated from a distance) which investigated the merits of using computer

internet technology to allow real laboratory facilities and instrumentation to be used remotely over the internet. The “Weblabs” developed in this project were principally intended to support school level science teaching, but could equally be employed in the education and training at Higher Education level. The authors pointed out quite specifically that the aim of Weblabs was to “*to reinforce an experiment, as opposed to replacing the experiment*”, recognising that the ability to design and undertake physically realistic and accurate experiments is a core engineering skill in itself.

This project is still ongoing, but the authors reported that the pilot study, undertaken in 2007, involved the comparison of grades obtained by a group of students who performed an experiment hands-on in the laboratory as well as using Weblabs, with those obtained by a similar group who had undertaken the same experiment only using Weblabs. The grades suggested that the online learners performed as well as those students who also had the face to face version of the laboratory, although this needs further investigation.

Care needs to be taken when assessing these results, however, since the paper does not give any indication of the nature of the two different groups – was sufficient care taken to take into account factors such as the average ability, cultural issues etc. of each group. Also no details are given about the nature of the learning outcomes assessed. The nature of the Weblabs described in the paper indicated that the exercise was simply one of undertaking an experiment – changing parameters or conditions to see how this affected the final result, and comparing with theory. What the Weblabs did not allow was the freedom of the students to design the experiment themselves. This in general is a weakness of this approach. While excellent for learning tools which allow students to test their knowledge against theoretical models, and even undertaking physical experiments remotely, an internet / online exercise can be a poor medium to simulate the real engineering design environment.

Abdulwahed, et al. (2008) also argued that it is very important that engineering be taught in its genuine context rather than the current more theory oriented model, based mainly in the lecture theatre. Their solution, led by constructivist pedagogy, is through remote operation of the laboratory rig during the lecture itself. One benefit of this approach, they propose, is that good online experiments can be shared between universities. Abdulwahed et al. provide a good review of many examples of where remotely operated labs, usually internet based, have been developed and operated.

The paper also gives an account of the authors own study using a Weblab in a classroom demonstration, “blending” classical theory with real experimentation. In particular they wanted to identify whether this “blended” lecture approach improved the students conceptual understanding, enjoyment, and motivation for further theory, and towards an engineering career. The authors used an electronic voting system device in an MSc Chemical Engineering lecture to evaluate the students perceptions using multiple choice questions at the end of the lecture. The results showed that, in general, they enjoyed this style of lecture more than the traditional style, they felt they has gained a better conceptual understanding (though this is perceived, not actual), and felt more motivated to study more theory, and to become a professional engineer.

In my view, this work is certainly interesting, but of limited value. An MSc engineering student would hardly be un-motivated to becoming a professional engineer. Enjoyment, of course, is important as this is a very important factor in a students motivation and ability to learn, but what matters is not so much whether the students feel that they understand better by this method of teaching, but whether they actually have learned better, measured by a suitable assessment method to test the learning outcomes.

Chan and Fok (2009) investigated the effectiveness of virtual laboratories in the teaching of Electrical and Electronic Engineering in the University of Hong Kong. A virtual online experiment was compared with the equivalent physical electrical experiment by a cohort of 50 engineering students. The feedback showed that the virtual experiment, while useful and provided a stimulating learning environment, the students marginally preferred the physical experiment and many suggested that the hands-on lab could not be replaced. From their experience, Chan and Fok listed many of the advantages of virtual laboratories, such as enabling laboratory experience at any time and anywhere, allowing students more opportunities to practice experiments, particularly for those that may not be easily replicated due to resources, time and safety issues, and that it is significantly more cost effective than real laboratory experience. On the negative side, they listed that it discouraged students from learning the physical instruments and real devices, that remote access discourages direct collaboration and interaction amongst students and tutors, and that physical, practical skills that are expected of an engineer are not honed.

Abdulwahed et al. (2009) presented important work on the structure of laboratory class learning, based on Kolb’s experiential learning model, and tested it

using a combination of remote virtual, and hands-on laboratory experiments in the Chemical Engineering Department at Loughborough University. In particular the authors suggested that poor learning in laboratory classes is due to insufficient activation of the prehension (vertical) dimension of Kolb's learning cycle, and tested this by assessing the learning of two laboratory groups. Their control group undertook the hands-on experiment without any pre-preparation, while the test group undertook pre-preparation aimed at gaining new knowledge prior to the hands-on experiment, using a virtual laboratory exercise. The quantitative analysis showed significant enhancement of the learning outcomes of the experimental group compared with the control group, both in terms of knowledge gained, and motivation for further study (deep learning). The authors went further, proposing a model based on Kolb's cycle to facilitate constructivist learning involving additional activities including pre- and post-lab tests.

In this paper Abdulwahed et al. (2009) also reviewed a number of studies of how virtual computer based laboratories and/or remotely activated labs have been used as complementary or alternative tools of the physical hands-on laboratory. Most of the studies reviewed revealed that significant improvements in the learning outcomes have resulted from the combined use of the virtual lab exercise, or remotely operated lab, and hands-on laboratory class. The general conclusion from these studies, and that stated by the authors, is that in order to gain the pedagogical benefits of virtual or remotely operated labs, they need to be used as preparatory aids to a physical hands-on laboratory exercise.

Poay et al. (2010) reported on a study that aimed to develop a "*student evaluation of module*" (SEM) questionnaire suitable for modern university engineering courses. The questionnaire, recognising the shift in emphasis over recent years from what is being *taught* to what is being *learned*, the authors approach was to focus their questionnaire on identifying prior understanding of learning outcomes, and whether learning outcomes had been met as well as the more traditional issues of "student satisfaction".

The questionnaire was piloted at the University of Nottingham Malaysia Campus, whose engineering courses are modelled on the British model. In this study the feedback specific to laboratory classes and facilities showed that less than half of all students found laboratory facilities to be sufficient, and a third indicated inadequacy in software and engineering equipment.

Finally of interest to this study is the recent trend in the field of Astronomy towards the provision of remotely operated telescopes to support the teaching of astronomical science. The Bradford Robotic Telescope Project, Project Slooh and Project Galileo are some of the many projects that currently offer state of the art computer controlled telescope facilities to school and universities alike for education in astronomy. In fact experimental (observational) astronomy seems to be undergoing a renaissance at the moment, and there is much evidence of a popular resurgence of astronomy projects in UK schools.

2.4 Summary

The conclusions derived from the reviews provided in this section seem very clear:

- Engineering science needs to be taught with a view to nurturing the development of both the theoretical knowledge and practical skills required of a modern engineer in a diverse way, catering for the many styles by which people gain those knowledge and skills and then transform them. The goal must be to utilize every vehicle by which this knowledge and the skills can be experienced, conceptualized, actively tested and reflected upon, and to widen the opportunity that the learner has to do this.
- The innovation of web based remotely operated laboratory experiments, and virtual laboratory simulations are therefore important new tools for the engineering educator to use to enrich the learning cycle, and should be incorporated where possible into the engineering curriculum.
- However, the hands-on engineering laboratory class, undertaken in groups of 3 – 6 students, remains a powerful and empowering tool for the effective learning of a whole group of learning outcomes in engineering science and practice, which cannot be provided by web based tools alone.

- The question “*do we need University laboratories for teaching and learning in Engineering science any more?*” has a clear and resounding answer – Yes, but in partnership with the new internet based tools in the manner first outlined by Abdulwahed et al. (2009).

3. Engineering Test Facilities and their Importance to the Wider Economy

Having clearly identified the need for experimental test facilities in the education of modern highly skilled engineering graduates for the global engineering industry, as well as their role in the learning cycle, the next question to answer is “do such experimental facilities also have any role in developing new knowledge and innovation through research and development, and thereby value for national economies? In the context of the recent revolution in computer simulation methods and technology, this section aims to answer this question.

The viability of engineering test facilities, in the final analysis, comes down to their ability to generate enough revenue to pay for their continued operation and maintenance. With the advent of modern global markets – for engineering products, services as well as education, there is clearly much scope for British companies to reduce costs by outsourcing expensive physical testing, and with it, also elements of the design process.

Experimental test facilities are employed as much to test and optimise commercial products, from pins to golf clubs and internal combustion engines, as they are to generate new scientific knowledge. Experimental testing is an essential component of the design process, and is a legal requirement for products where safety is important, such as buildings, bridges, cars, ships and aircraft.

Any engineering company in the UK that is involved in the design and development and/or manufacture of a commercial product will probably require access to experimental test facilities. These facilities could be owned, operated and maintained by that company, or they could be made available by another organisation, such as another manufacturing company, a commercial service, or by the state. With governments pulling out, to some degree, of the provision of scientific laboratory services, this has meant that University laboratories have become much more

important for the continuation of testing and development of commercial products, especially for small to medium enterprises (SME).

In order to develop a strategy for the better management, and the long term sustainability of the UK's engineering test facilities, it is necessary to assess their importance to the British economy as a whole. If the vision of the British government is for the UK to become a "Knowledge Economy" with "Innovation" at the heart of economic growth, then how important is it to have sovereign capability in experimental science and technology, when British public and private sector organisations can source such services overseas?

3.1 Recent Trends in the British Manufacturing

The value of the engineering test infrastructure is predominantly of importance to two economic sectors – manufacturing and education. As mentioned, timely access to test facilities is of prime importance in the development of an engineering product, and manufacturing companies will need to physically test their products, not just during the design and development stage, but also at other stages of a product life cycle as well. Innovation, in itself, does not require the use of test facilities, as much conceptual study can be undertaken using theoretical methods, nowadays done on computers, but later in the design process physical testing will become necessary.

While manufacturing companies can, in principle, source their testing requirements to overseas service companies or state run laboratories, as many now do, there is some strong evidence that skills, and ultimately product design and manufacture, will tend to cluster around world-class facilities. A high-tech metals research industry has grown up around Sheffield because of the world class Steel industry located around the city. Toulouse in France has attracted a cluster of engineering companies that make use of the significant infrastructure that has developed around the Airbus plant in the City, and similar situations have been seen in Derby and Bristol in the UK. This suggests that global engineering companies such as Airbus and Rolls Royce, will tend to locate their activities where world class facilities are available, especially where these are operated by government laboratory services which can also provide consultancy expertise as well. Since the UK government has already closed down or privatised much of its experimental test infrastructure and associated consultancy services, the prospect of important

engineering companies relocating abroad is a very real threat to the UK economy. This is especially so given that two thirds of the big engineering firms located in the UK are actually foreign owned, which means that key decisions on supply chains, research and development and investment will be made overseas.

How bad this would be to the UK economy, given the widely held perception that we do not have much manufacturing industry left[†], and that we make our way in the world by providing services, needs to be assessed in order to gauge the value of having engineering test facilities.

Figure 3.1 presents, for the period 1986 to 2009, the growth in export revenue from the sale of British manufactured goods compared with that from the sale of financial services. Clearly Britain still gains considerably more export revenue by the sale of manufactured goods than it does from financial services – nearly five times as much. If many British based manufacturing companies did, in the longer term, decide to relocate their activities abroad to cluster in areas with the provision of world class test facilities, much of this revenue would no longer pass into the British economy.

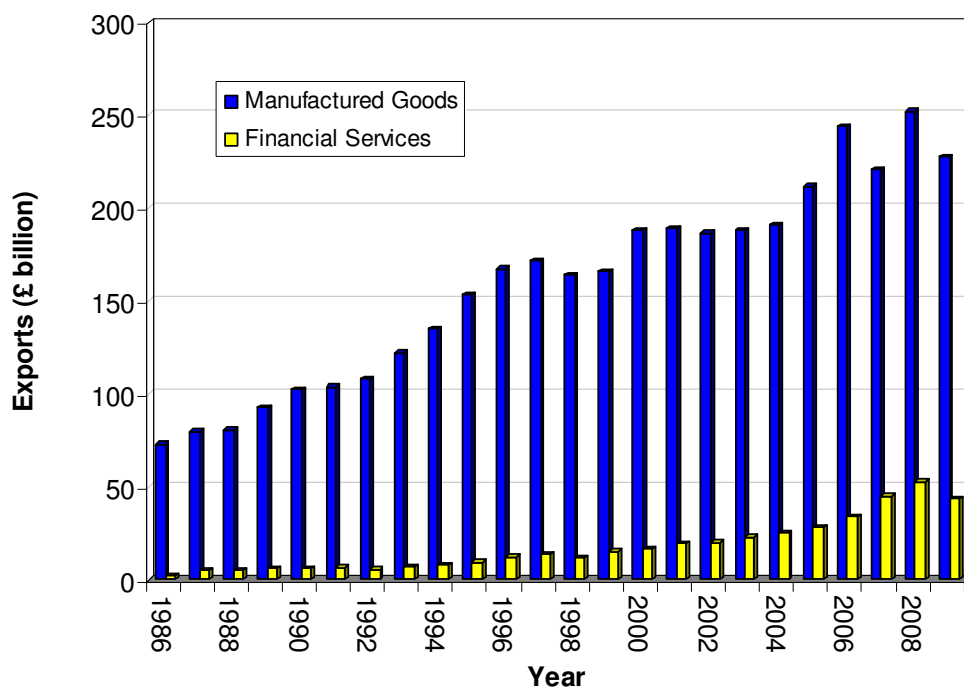
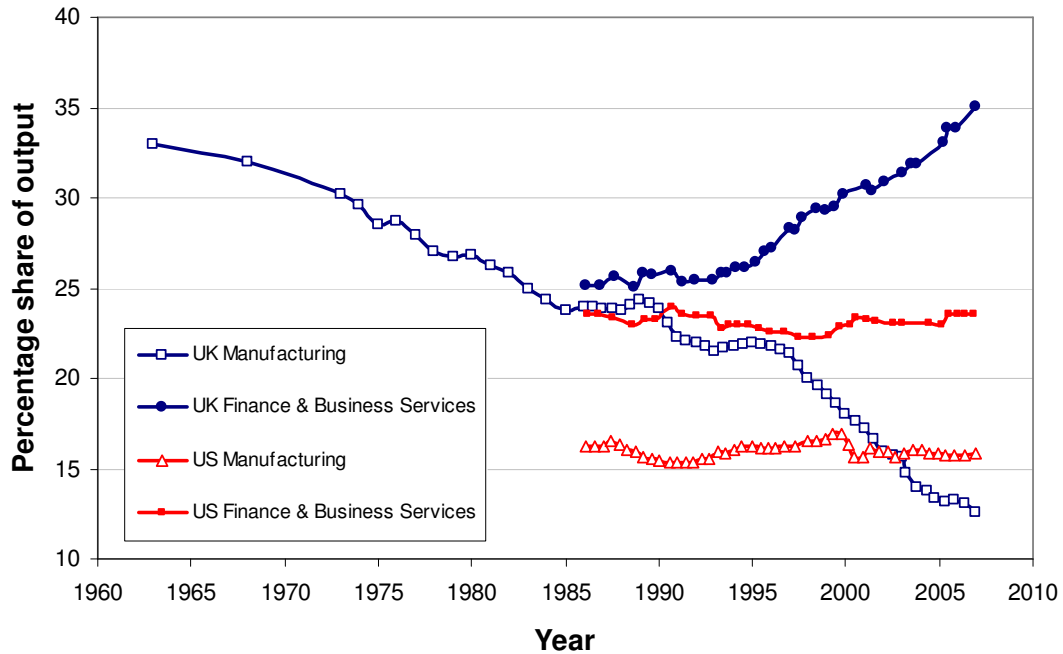


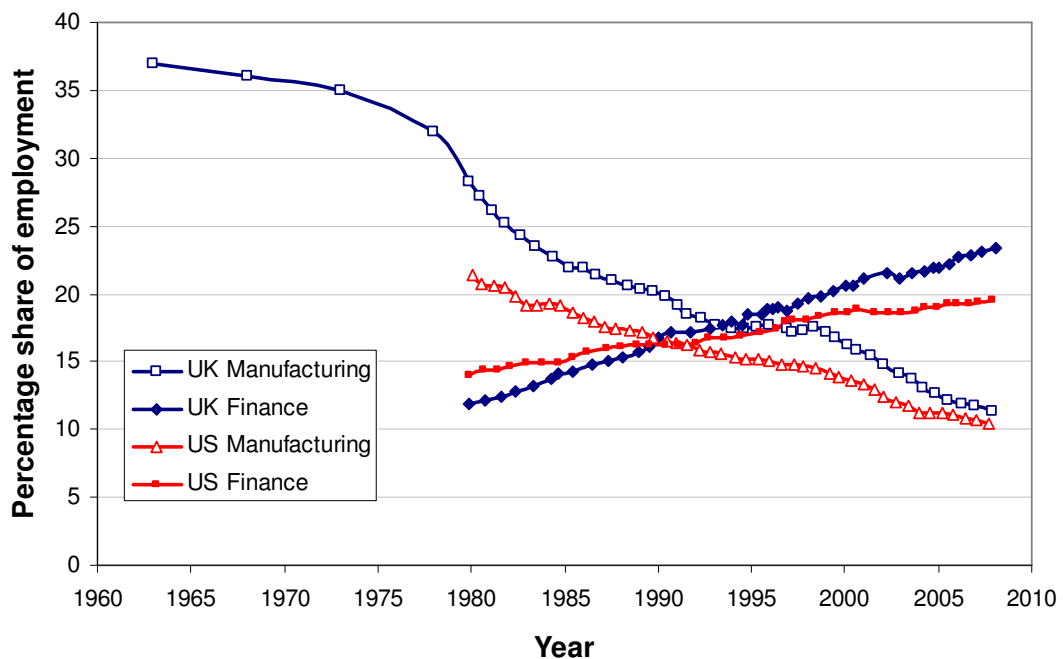
Figure 3.1: Comparison of income from exports of manufactured goods and of financial services, 1986 – 2009 (ONS).

[†] The Engineering Employers Federation has shown that there are 1,800 industrial firms employing more than 250 people in the UK, representing 1.2% of the total. This compares with 4,000 in Germany (2.1%), and almost 13,000 in the US (2.9%).

Figure 3.2 compares the recent trends in economic output from, and employment in, the manufacturing and service sectors in the UK and the US. It needs to be noted that the data for service sectors in these charts include all business related services, and not just the financial services.



a) Share of contribution to GDP



b) Employment

Figure 3.2: Comparison of trends in output and employment in the manufacturing and financial services sectors of the UK and US Economies, 1960 – 2009.

This data clearly shows the decline in manufacturing in both the US and the UK in the period 1980 – 2009. Both countries have seen a rapid, and continuing, reduction in the number of people employed in the manufacturing sector, while simultaneously there has been a corresponding rise in the number of those employed in business services. The economic output from manufacturing, as a share of the total output, has remained fairly constant for both manufacturing and financial services in the US, implying that there has been a major improvement in productivity in US manufacturing. In the UK, meanwhile, manufacturing has seen a significant drop in the percentage share that it contributes to the UK Gross Domestic Product, while business services has seen a corresponding rise.

Analysis of the productivity (economic output per individual employed) of the manufacturing sectors of the UK, US, Germany and France, and corresponding employment in the period 1960-2000 is plotted in figure 3.3.

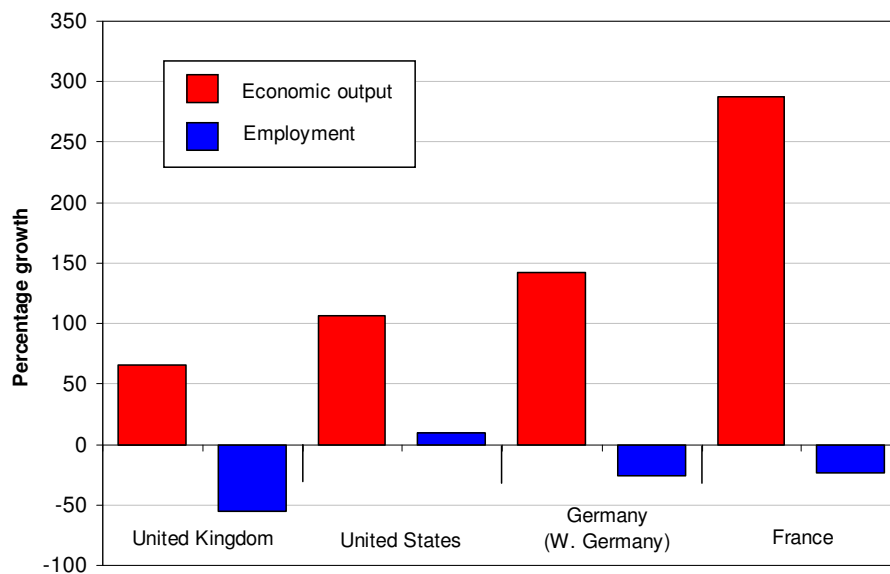


Figure 3.3: Comparison of productivity and employment changes in national manufacturing industries, 1960-2000 (OECD).

While manufacturing productivity has certainly risen considerably in the UK, faster than that of most other sectors in fact, it has grown considerably less than that in the other three competing nations. The number of jobs in manufacturing in the UK has more than halved, while in France and Germany the decline has seen only a quarter of manufacturing jobs lost. In the United States, meanwhile, the number of manufacturing jobs has actually risen by 10% since 1960.

Clearly from this data there has been a much more severe retreat from manufacturing in the United Kingdom since 1960 than in other western countries. Whether this is important to the long term sustainability of the UK economy can be gauged by analysis of the trends in the balance of trade, which is a much more important indicator of the economic health of a nation. The Gross Domestic Product (GDP) is a measure of all economic activity within a nation, and counts all of the transactions that take place within the nation, and which do not make money for the country. The Balance of Trade compares the amount of income a country makes from trade in various commodities and services, with its expenditure in importing commodities and services. A nation which exports more than it imports, effectively profits from trade abroad and is in a healthy position. A nation which imports more than it exports will need to finance its spending by i) selling its assets, such as its state businesses or territory and/or by ii) borrowing foreign money. Such a nation can continue to operate at a deficit in its balance of trade for a certain time, continuing to pay interest on its growing level of debt, but eventually it will run out of assets to sell, and will have to pay back its loans.

Figure 3.4 presents the balance of trade in goods and services for the UK between 1946 and 2009. The data is normalised to 2009 values. Up until 1986 the UK manufacturing sector generally sold about as much goods abroad as the nation imported. Annual deficits, when they occurred, were relatively small. Since 1986 the deficit in manufactured goods has become more significant, particularly since 1997, when the deficit started to grow year by year from ~£12 billion in 1997 to over £90 billion in 2008.

In comparison the services sector overall has seen a considerable rise in the trade surplus that it makes for the UK economy. However, it can clearly be seen that the income generated by the services sector has not kept pace with the loss of trade in manufactured goods. The result, as shown in figure 3.5, is that the UK balance of trade has been in deficit for 22 out of the last 24 years, and has grown to over £30 billion a year, which must be financed by further borrowing, sale of public assets, or by radical cuts in public expenditure. Here, then, is the cause of the debt crisis which Britain faced in 2009, and which has resulted in heavy cuts in public spending.

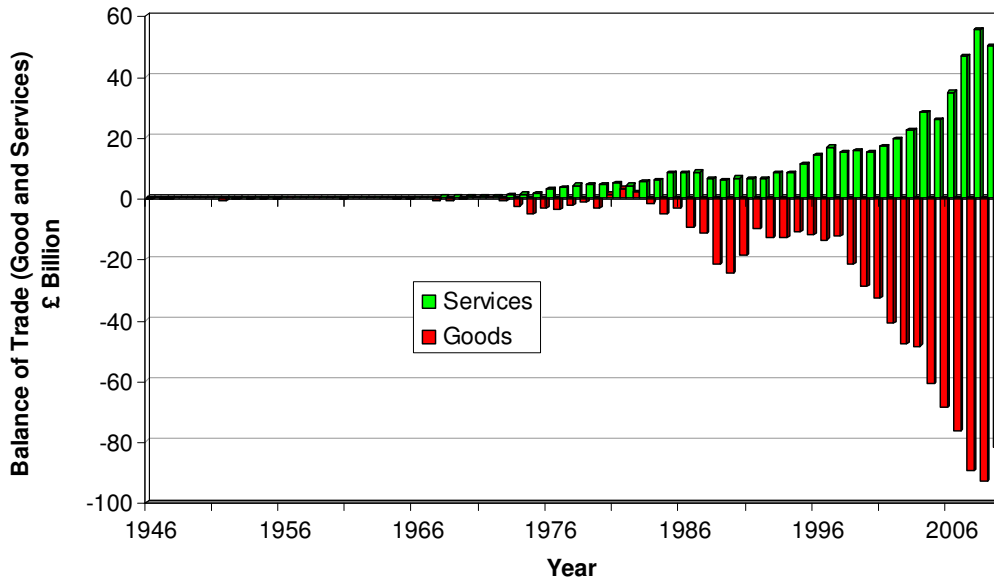


Figure 3.4: Contribution to the UK balance of trade of manufactured goods and of services (ONS)

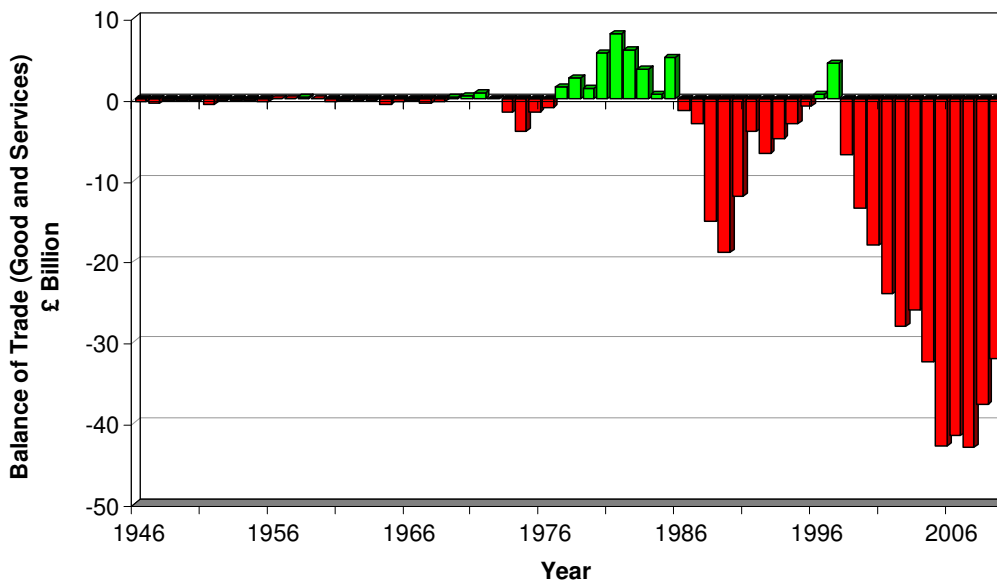


Figure 3.5: UK Balance of trade 1946-2009 (ONS)

Let us now focus on those UK manufacturing sectors which most require the use of engineering test facilities, and which will be most affected by a rationalisation of the available UK test infrastructure – car manufacture, aerospace vehicle and ship building.

3.2 Trends in the UK Automotive Sector.

Figure 3.6 present the export and import sales of motor cars in the UK over the period 1999 – 2009. Clearly it can be seen that the UK based car manufacturers generated well over £10 billion of income into the UK economy each year. The problem is that the nation pays for the import of over £15 billion worth of foreign manufactured motor cars. The result, as shown in figure 3.7, has been a significant deficit in the trade of motor cars in the UK economy.

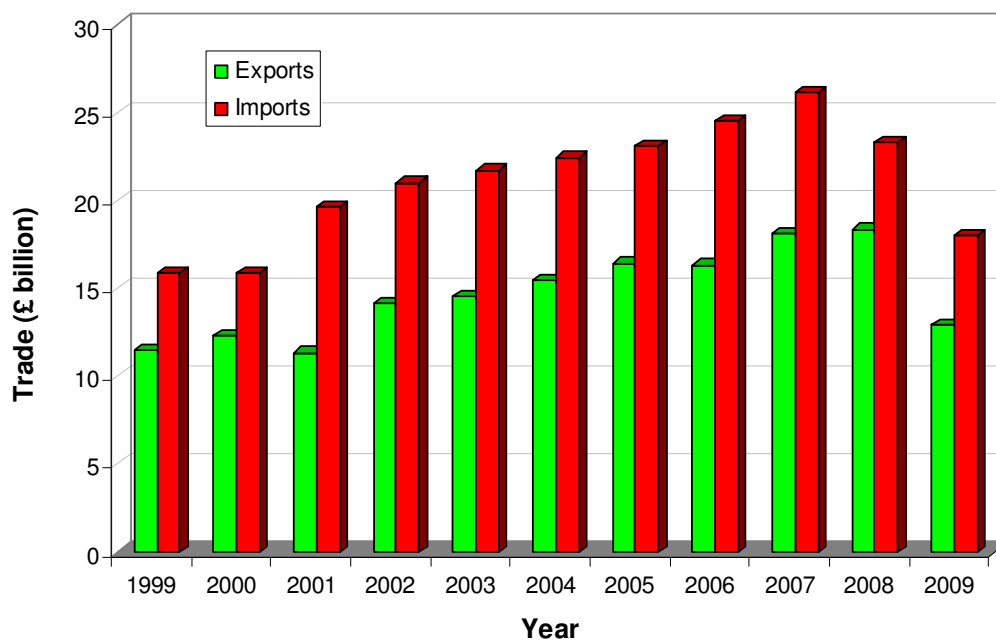


Figure 3.6: Export and Import revenues for motor cars and associated components, 1987-2009 (ONS).

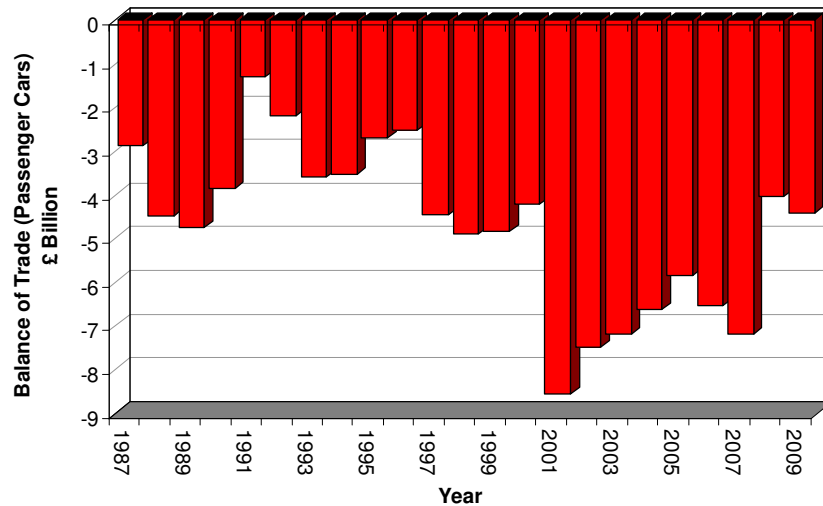


Figure 3.7: Balance of trade in passenger motor cars and associated components, 1987-2009 (ONS).

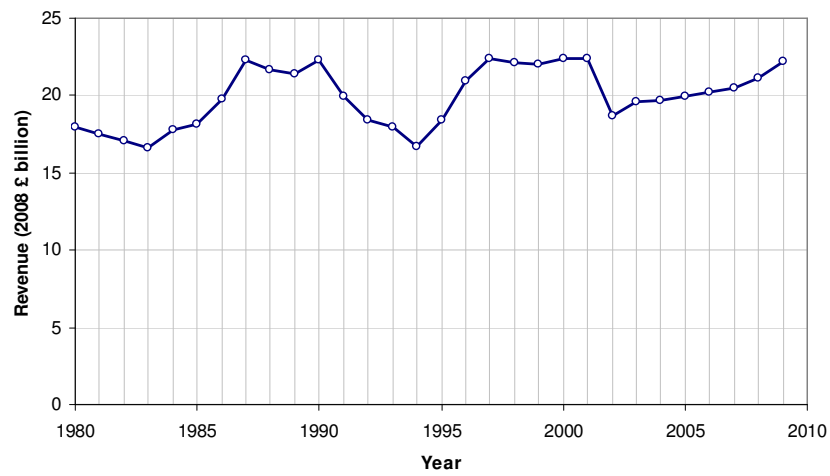
3.3 Trends in the UK Aerospace and Ship Building Sector

Figure 3.8 shows the data, supplied by ADS, on the economic output of the UK aerospace sector, and the corresponding trend in employment. The UK aerospace sector has consistently contributed around £20 billion worth of income annually into the UK economy, and is expected to do at least this well for the next decade. There has also been a net surplus of trade revenue in aerospace vehicles since at least 1997, though more probably well into the 1960s. At the same time, however, the number of people employed by the UK aerospace sector has declined from over 300,000 in 1957, to only about 100,000 in 2009, and this workforce is continuing to decline.

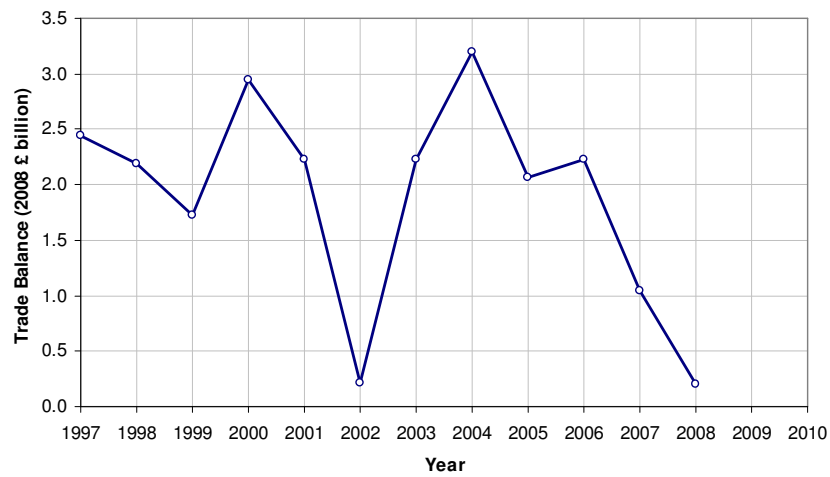
Data for the British ship building sector is not easily obtained, since the Office for National Statistics publishes trade data for both the aircraft and ship building industries together. This data includes sales of aircraft and associated components, but not other aerospace vehicles such as missiles, unmanned air vehicles, satellite technology etc. Figure 3.9 presents the ONS data for the period 1970 – 2009, which are not seasonally adjusted.

The net worth to the UK economy of the exports of ships and aircraft is currently of the order of £10 billion a year. Up until the year 2000 the combined trade in aircraft and ships managed to contribute either a significant surplus in trade

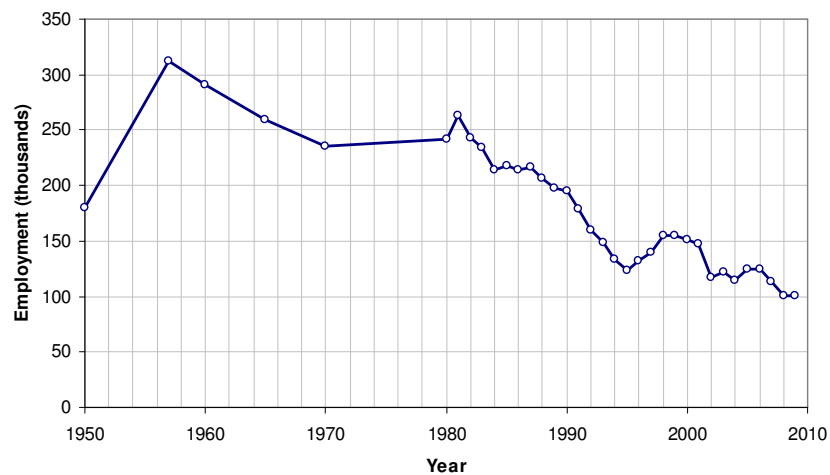
revenue to the UK economy (over £2 billion in 1991) or small deficits. From 2001 on, however, significant deficits have been seen in the trade of ships and aircraft.



a) Contribution of the aerospace industry to UK GDP, 1980-2009 [2009 prices]

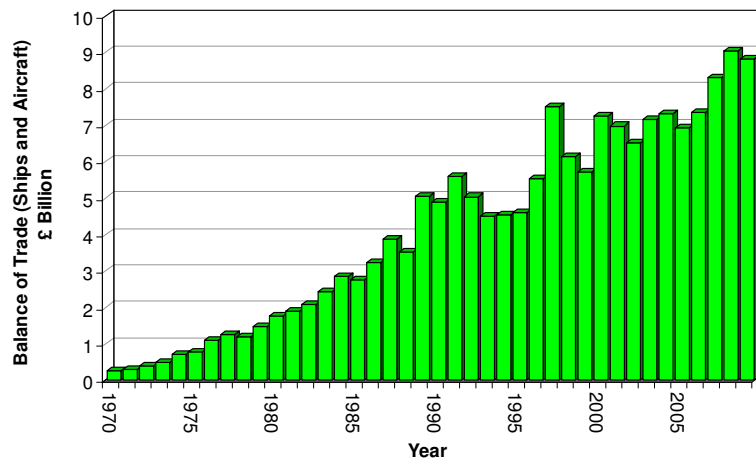


b) Balance of trade in aircraft and associated components, 1997-2008 [2008 prices].

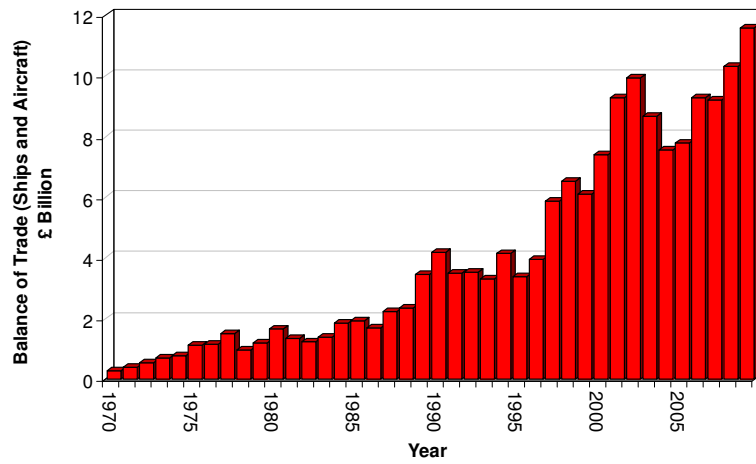


c) Employment trends in the UK aerospace industry,

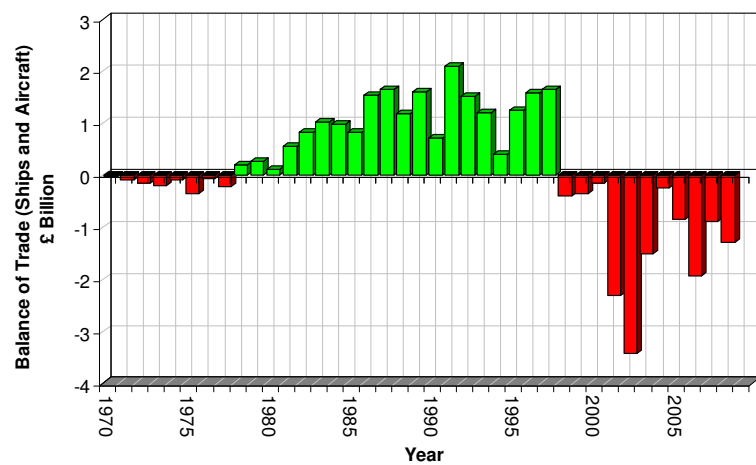
Figure 3.8: The recent economic performance of the UK aerospace sector (ADS).



a) Export trade by the British aircraft and ship industry.



b) Imports of aircraft and ships and associated manufactured components into the UK.



c) Overall balance of trade in aircraft, ships and associated components.

Figure 3.9: Balance of trade – Ships and Aircraft, 1970-200 (ONS).

3.4 Trends in the UK Higher Education Sector.

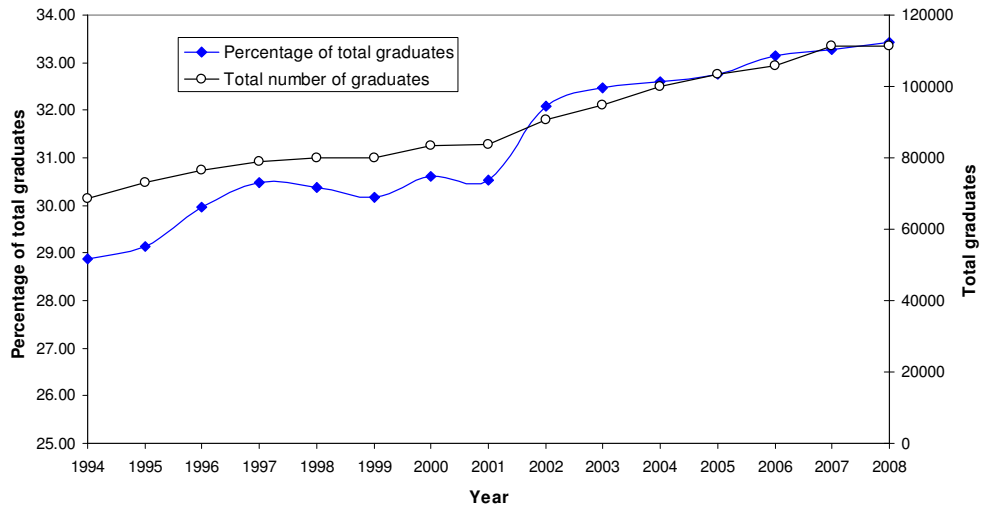
Any assessment of the economic value of the national engineering test infrastructure must also take into account the value that this has for the UK higher education sector, as this sector in its own right contributes considerable export revenue, in terms of the revenue generated in student fees from international students (non EU) and research income from overseas companies and governments.

Kelly et al. (2009) undertook a study for Universities UK, which assessed the economic impact of the British Higher Education sector – the fourth such exercise that this body has sponsored since 1999. The study has estimated that in the academic year 1999/2000 the gross export earnings of the UK Higher Education sector amounted to £1.3 billion. With the rapid growth in the number of overseas (Non-EU) students to UK Universities, this was estimated to have risen to £3.6 billion in 2003/04 and to £5.3 billion in 2007/08. With the growth in social mobility in China, India and other rapidly developing countries, the higher education sector represents a significant potential for national income.

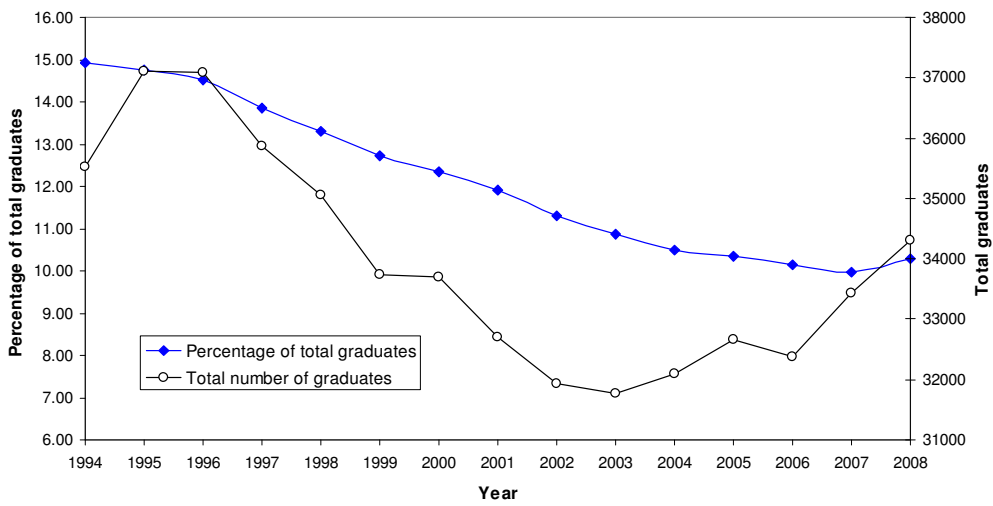
The question, then, is whether this will convert into an increased demand for the UK engineering test infrastructure, with corresponding increases in revenue for maintenance and upgrade of experimental facilities in University laboratories. Data obtained from the UK Higher Education Statistics Agency (HESA) showing the trends, in the period 1994-2008, in the number of students graduating in science and technology, engineering and mathematics (STEM) subjects[†] from UK Universities is presented in figure 3.10.

The total number of STEM first degree graduations rose from about 69,000 in 1994/5 (29% of all HE undergraduate degree awards) to over 111,000 in 2008/9 (nearly 33% of all undergraduate degree awards). This clearly shows a considerable rise in demand for STEM degrees. Focussing on the physical sciences, which include physics, chemistry and engineering sciences, one finds that there has been a decline in the number of graduations from just over 37,000 in 1995/6 to just over 31,700 in 2003/04, but that since then there has followed a modest rise to nearly 34,500 in 2008/9. Viewed as a percentage of the total number of graduations, however, the physical sciences have seen a year on year decline from 15% in 1994/5 to just over 10% in 2008/9.

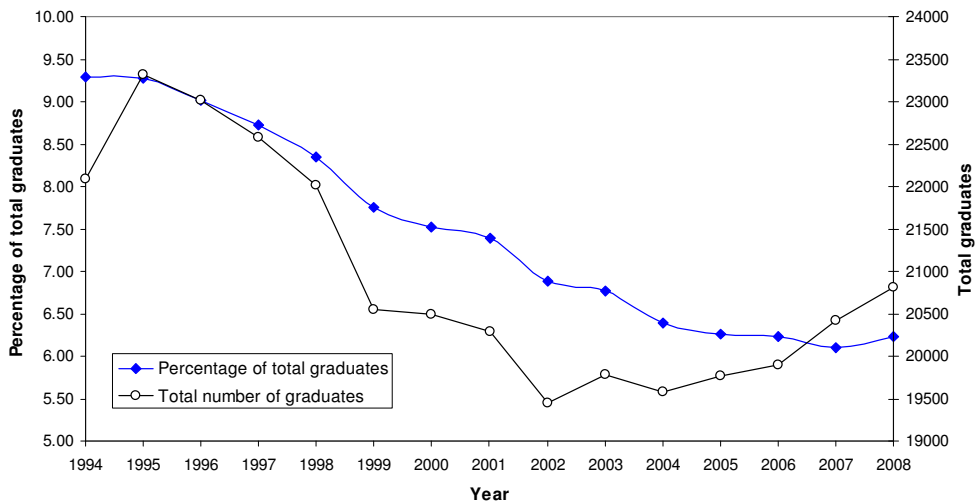
[†] In this analysis computer science is not classified as a STEM subject.



a) All STEM subjects.



b) Physical Sciences



c) Engineering sciences

Figure 3.10: Trends in undergraduate (first) degree graduations in STEM subjects from UK Universities, 1994-2008 (HESA).

For engineering science the picture is similar. There was a general decline in the total number of first degree graduations in engineering between 1995/6, when there were just under 23,500 graduations, and 2002/3 when the figure had dropped to about 19,500, but then a modest rise to nearly 21,000 in 2008/9. Seen as a percentage of total first degree graduations, however, engineering science has declined steadily from 9.3% in 1994/5 to only 6.2% in 2008/9.

What is important in this analysis is the total number of students graduating, not so much the percentage of the total cohort that this represents. A growth in the number of students studying the STEM subjects represents a potential increase in demand for laboratory provision, and an increase in funds available to support experimental laboratories. With the total number of first degree graduations in STEM subjects overall, and in the physical sciences and engineering, it can be argued that the demand for laboratory provision is now steadily increasing, and more funds should be proportionately available to invest in University laboratories.

3.5: Comparing the Costs of an Experimental versus Computer Simulation Program.

Part of the economic decision of whether to manage the decline of the UK engineering test infrastructure, or whether to invest in new infrastructure, is whether it really is more cost efficient to undertake modern engineering design analysis using computational methods instead of large scale experimental tests. If UK based companies were able to significantly reduce their product design costs by undertaking cheap computer based studies, thereby reducing the need for physical testing, which could be done by contracting this work overseas, then this would represent a significant reduction in overall business costs. This has certainly been the general view of how computational engineering methods can change engineering design practice, but the question has to be asked – has this happened in reality?

A good example that will help to answer this question is this case study involving the generation of the aerodynamic data required in the development of a supersonic air to air missile research dataset in 1999, and which clearly highlights the dangers involved in assuming that modern computer simulation methods can be used to replace physical testing of engineering systems.

For an aircraft or missile system the aerodynamic behaviour of the vehicle design needs to be verified for a whole series of conditions – altitude, speed, orientation (pitch, yaw, roll) and so on. The generation of aerodynamic data for a typical missile configuration, in a collaboration between the UK Defence Research Agency (DRA) and NASA in the USA, some 300,000 points of aerodynamic data were required[†]. A wind tunnel model and was tested in supersonic wind tunnels at both the DRA and at NASA at a cost, including the model design, manufacture, shipping, manpower and wind tunnel operation, of approximately £1 million in 1999.

At the same time a series of computer simulations were performed to obtain the same data, but at only a few selected data points of the 300,000 that were required, and were obtained in the experiments. The cost of these simulations were evaluated in terms of manpower and computer running costs (charge out rates for computer time), but not including software licences.

Table 3.1 presents the detailed comparison of the experimental set-up time, run time, costs and associated accuracy relative to the real flight conditions, with those obtained for two computer simulation methods.

Method	Data points	Set-up time	Run time	Cost	Accuracy
Experiment (Wind tunnel)	300,000	4 Months	2 Weeks	~£ 1 million	< 1%
Computer (Navier-Stokes)	24	5 Weeks	1440 hours	£ 2600	< 3%
Computer (Euler)	24	4 Weeks	580 hours	£ 1800	< 20%

Table 3.1: Comparison of details of typical experimental and computer simulation programs

Clearly, from this table, it can be seen that the computer simulation studies were significantly cheaper, in pure monetary cost terms, than the experimental study. While the Euler simulation, with an accuracy of only ~20% relative to what would be expected in real flight, would be good enough in most cases for a reasonable design

[†] For an operational aircraft or missile project, it would be expected that the number of force and moment data points required would actually be in the millions.

assessment, the more accurate Navier-Stokes method would need to be employed for many flight conditions.

The key factor in this analysis, however, is that the costs quoted for the computer simulation studies are for 24 data points only. The experimental study, however, obtained all of the 300,000 data points needed. If one were to extrapolate the data for the computer simulations to see what the real run times and costs would be to obtain the same 300,000 data points, one can quickly see that experimental testing becomes much more cost effective.

For approximately £1 million one could obtain 300,000 data points, accurate to within 1% of real flight data, in 6 months by experimental testing. With the most modern (in 1999) computer simulation codes and super-computing facilities (assuming 50 processors), one could have obtained the same 300,000 data points, with three times less accuracy, in twice the time (nearly a year) for a cost of approximately £2.5 million[†].

From this analysis one can quickly see the true value of maintaining an experimental capability. The more data required in a particular engineering program, the quicker and more cost effective experimental testing will be over computer simulation. Even with the yearly improvement in computer technology and associated reducing costs, it will be many decades before computer simulation can compete in purely cost terms, with experimental testing.

3.6 Summary

The various economic data presented in this section highlights the perilous state of the UK economy which still relies very much on its manufacturing industry, despite the widely held view that “Britain does not make anything any more”. With an unsustainably large balance of trade deficit, due largely to the misguided policy of a managed decline of manufacturing industry and associated laissez-faire economic attitude, coupled with the inability of the services industry to generate enough growth to compensate for the loss in goods exports. Clearly, one cannot reduce imports through policies which actively favour British companies, and thereby stifle free trade. Therefore, the policy should now be to stimulate the development of new

[†] Note that if the computer simulation had been performed on only one processor, instead of the more typical 50 available to major industrial companies, one would get 300,000 data points for a marginally higher cost (taking into account inflation), but taking 50 years to complete !!!

wealth creating industries, while introducing measures to revitalise the traditional industries, giving them a business environment that supports enterprise and provides good state sponsored support facilities on the model still seen in France, Germany and the US. One of the keys to this is in ensuring that British schools provide the best educated youngsters in science and mathematics, and British Universities become the best equipped in the world for the training of the very best scientists and engineers with excellent business and entrepreneurial skills. The higher education sector is an area of investment that would provide significant resources and support to British industry and businesses without contravening any international free trade regulations. Education is a significant “market distorter” that every nation is happy to ignore, and it is one in which Britain excels.

Such a strategy, coupled with the continuing support of the traditional and emerging services industries, would act to drive up manufacturing productivity much further, and retain the global engineering companies that still operate in Britain (that are currently actively looking to relocate more activities overseas) and attract more such companies to the UK, which would become a world centre of excellence in high technology engineering.

Much talk has been heard over the years, along just these lines. In 1979, for instance, Sir Monty Finniston reported to the British government on the then shortage of qualified engineers, the relatively low status of the engineering profession in British society, and the broad economic retreat from manufacturing industry. While some of the recommendations that were made were later implemented, the problems described then are still very much the problems of today. What is now needed is the return of a progressive industrial policy, with British universities at the heart of an engineering renewal.

Part of this policy must be for the state provision of a world class science and technology infrastructure. As outlined in section 3.5, the scrapping of experimental facilities in preference for cheaper and less space intensive computer simulation tools is a false economy. Experimental facilities remain a necessary resource for the design and development of quality products that are safe to employ, and the evidence shows that where these are available, high technology business will be attracted.

If this is the case then well equipped university science and technology laboratories are of central importance in providing both the best educated scientists

and engineers in the world, as well as the best provision of science and technology support, via research and development services, for UK located industries.

UK Universities have already proven to be net contributors to the balance of trade, and contrary to the popular view that science and technology has been a declining field in British universities, the evidence given in the data of section 3.4 proves that this is not now the case. Graduations in STEM subjects, including physics, chemistry and engineering sciences, are all showing year on year growth. UK Universities are therefore well placed to lead the engineering and manufacturing revival that the nation so badly needs.

4. Trends in UK Engineering Test Infrastructure

This section presents a history of the trends in the UK provision of engineering test facilities for education and for public and private research and development. A survey focussing on the recent trends in the UK wind tunnel infrastructure is presented as a case study to highlight the ongoing trends affecting all of the UK's engineering test infrastructure.

There has been no significant study, to the authors knowledge, that has documented and analysed the changing provision of engineering test facilities in the United Kingdom over the last forty to fifty years. In this period it is quite clear that there has been many test facilities, particularly large scale industrial facilities maintained by private industry and by government service agencies, that have closed down and been scrapped, while others have been constructed in Universities and in private industry. If the general view, that the United Kingdom engineering test infrastructure, and associated capabilities, have been significantly eroded despite the investment, in some areas, on new facilities, then this has serious implications for the sustainability of the British manufacturing sector and on the academic STEM community. A clear picture of the current distribution of operational facilities would be the first step in identifying threatened areas of experimental capabilities, and then in developing a strategy for protecting these areas from further erosion. This section provides a background history of the global rise and decline of large industrial test facilities, and describes the general situation in the UK today in comparison to that in other countries.

4.1 The Decline of Post War Engineering Test Infrastructures

In the 1930's most western countries began to build up large infrastructures for scientific and technical experimental capability, in response to the international tensions of the time. The Second World War, and the subsequent advent of the Cold War accelerated this trend. In the United States this led to the emergence of a

powerful “military-industrial complex” with a network of national laboratories which served the nations industries, from the nuclear energy industry to the aircraft and space industries. A similar process occurred in the United Kingdom and in the other western European countries, but on a much more modest scale.

The result of this was that after the end of the Cold War, the massive state expenditure on maintaining these previously strategically important laboratories was deemed to have become no longer necessary. Funding to support these government run laboratories was steadily reduced, and a planned rationalisation began. In the US this was undertaken with very much a view to its own national capabilities, and what its own internal markets, as well its export markets require. The US Government seems to have been very careful, so far, not to allow this rationalisation process to allow sovereign capabilities to be completely abandoned. Also, there appears to have been a very strong move towards linking the academic sector, and its facilities, with those of the state run laboratories.

A good example of this is the *National Institute of Aerospace* (NIA), which is located next door to, and is a strategic partner with, the *NASA Langley Research Center*. The NIA was formed by NASA and the eastern US universities close to the Langley Center, including *Georgia Tech, Hampton University, North Carolina A&T State University, North Carolina State University, the University of Maryland, the University of Virginia, Virginia Tech, Old Dominion University, the College of William & Mary* and the *AIAA Foundation*. Students from these Universities can undertake projects, as part of their education, making use of some of the largest industrial test facilities in the world, thereby being trained to undertake full scale testing as a learning outcome. The cost for the maintenance of the facilities are shared between the government laboratory and the Universities (via the NIA), and they are therefore operated at very high levels of utilization.

This pragmatic approach has also been exercised in France for many years where leading universities have built campuses alongside major national laboratories, with both institutions integrated closely together on both education and scientific research and development. An example is the French laboratory of the *Office National d'Études et de Recherches Aérospatiales* (ONERA) in Toulouse, which is located on the same site as the *Institut Supérieur de l'Aéronautique et de l'Espace* (SUPAERO) which is a postgraduate higher education institute providing graduates for the aerospace industry particularly, but also for the engineering industry generally.

Students enrolled with SUPAERO work closely with ONERA, getting access to industrial scale facilities in their education, and staff in both institutions work together on collaborative research programmes. Similar systems, to the authors' knowledge, are also in place in Sweden and Holland.

The United Kingdom does not have a similar system. Here there is a much more fragmented and laissez faire situation. For a start most of the government laboratories have already been privatised, and have become commercial companies. Many of the big science and technology companies based in the UK are now foreign owned or have much of their "centre of gravity" based overseas. This has resulted in a drift away from the national provision of experimental test facilities and associated capabilities, to a much greater reliance on the remaining facilities in the private sector, on foreign experimental test facilities and on those within the British academic sector. This means that the academic sector has, and continues to, become a much more important provider of experimental science and technology services to British industry, especially at the small to medium enterprise (SME) level.

Focussing on the aerospace sector, as a good example of the recent trends in this area, we can see that the British aircraft industry has been through a major consolidation process, with 27 aircraft companies and several engine companies in Britain in 1945 going down to three aircraft manufacturers today – *Airbus* (owned by EADS of France and Germany), *BAE Systems* (British), *Augusta-Westland* (Italian-British) and *Bombardier* (Canadian), and one engine manufacturer – *Rolls Royce* (British). The various government laboratories that served both the defence and commercial sectors through to the late twentieth centuries were also consolidated during the period 1980-2003. The *Admiralty Research Establishment* (ARE), *Royal Aircraft Establishment* (RAE), *Royal Armament Research and Development Establishment* (RARDE), and the *Royal Signals and Radar Establishment* (RSRE) were all merged to form the *Defence Research Agency* (DRA) in 1991. Then in 1995 the DRA combined with five other MOD establishments to form the *Defence Evaluation and Research Agency* (DERA). This executive agency of the UK MOD was involved as much with the support of commercial, civilian companies, such as *Airbus* and motor sports companies, as it was with military customers. In 2001 it was split into QinetiQ Ltd., which was quickly privatised, and the *Defence Science and Technology Laboratory* (DSTL) which remains within the government sector.

The DSTL focuses solely on the delivery of a defence consultancy service for the Ministry of Defence, and has not taken on the experimental test service element, or the consultancy and test service to private industry that the old DRA provided. These vitally important services were passed into the commercial sector with the new QinetiQ Ltd., and have now been progressively wound down, having proven to be generally too costly to be economically run in the commercial world, where profit margins need to be large enough to satisfy shareholder demand for dividends. This has resulted in the large teams of scientists and engineers in areas with little commercial demand, being made redundant and much skills, experience and capability being lost to UK industry. Now, therefore, British industry is increasingly partnering overseas state provided national laboratories, and also with British and overseas universities, to undertake work that used to be done in UK government laboratories.

The question, therefore, is – given the retreat of the state from the provision of many large scale science and engineering laboratory services, what models for this provision can still be relied upon to support British industry, and British scientific education and research?.

There are also still a few privately run British industry associations which provide experimental test services for British and overseas industry that still maintain large world class industrial facilities in the UK. Two good examples of these are the *Motor Industry Research Association* (MIRA) and the *Aircraft Research Association* (ARA).

The ARA is an independent non-profit distributing research and development organisation, jointly owned (subscribed to) by the major British aerospace industrial companies (*Airbus UK, BAE Systems, Dowty Rotol, Rolls-Royce and Augusta-Westland*) as a wind tunnel test centre for the UK aircraft industry. While the ARA principally serves its subscribing companies, its business model also allows it to win work from overseas companies in order to support the maintenance of its facilities.

The MIRA is an independent industry association providing services for product engineering, testing, consultancy, certification, and research primarily for the motor industry. It maintains a large inventory of automotive related testing facilities and provides various technical services to UK and global manufacturing industries.

The continued success of both of these independent companies, both with similar business models which reinvest profits in maintaining a first class, highly

trained and skilled workforce, and modern up to date facilities, shows that businesses based on the provision of engineering testing and associated design services can flourish. The same is true of university laboratories, whose aim is not to generate profits in order to deliver dividends to shareholders, but to facilitate student learning in the pure and applied sciences, as well as to provide a testing / design / research service to the British government and to private industry.

However, the long term viability of both of these models for provision of engineering test facilities will depend on the long term sustainability of the domestic manufacturing base. Given that the evidence strongly suggests that in the long term, industry migrates to locations where the support of major scientific and engineering test infrastructure, and associated services, are clustered (Cambridge and Toulouse are perfect examples), the relationship between industry and technical and scientific support can be regarded as symbiotic.

Given the severe financial constraints restricting UK government expenditure it would be unrealistic to expect that the state should reinvest in providing scientific laboratory support services. In the short to medium term, therefore, the focus of any strategy aimed at securing the provision of science and technology laboratory test facilities, must be in supporting the university laboratories, and the independent industry associations that provide these services.

4.2 Case Study – Trends in the National Resource of Engineering Wind Tunnels

In order to highlight, with real data, the continuing trends in the decline in the provision of scientific and engineering test facilities in the United Kingdom, and the erosion in associated skills and the capabilities required to keep UK based manufacturing companies competitive, this section presents an analysis of one particular type of facility which is vitally important in supporting the cost effective and safe design and development of motor cars, ships, boats and aircraft – the wind tunnel.

The wind tunnel is particularly indispensable in the design, development and operational maintenance of aerospace vehicles, as well as in educational development of future engineers in university and in fundamental research in aerodynamics and fluid dynamics. The *Aerospace and Defence Knowledge Transfer Network* (KTN) of the *Technology Strategy Board*, the government body which is tasked with facilitating

the development and operation of national strategy in science and technology, has designated “Flight Science”, the discipline which includes aerodynamics, flight dynamics and propulsion physics, as being under threat, and has been given a “red” designation in their traffic light system to identify those areas where facilities and capabilities are being seriously eroded. The *UK National Aerospace Strategy (NATS) 2010* explains that:

“Large-scale technology validation is essential in Aerospace, and despite increasing use of simulation, key experimental facilities are needed to mature technologies to acceptably low risk for application to products. Counter-intuitively, sophisticated computer modelling frequently gives rise to more challenging experimental requirements in order to validate models and processes. In principle, assured access to facilities is more critical than location, but there tends to be strong national alignment between facilities and capability. In the medium to long-term, skills and ultimately product design and manufacture, will tend to cluster around world-class facilities. These can be large and costly to maintain; but are, nevertheless, essential to the future success of the aerospace industry. In many countries, such facilities are in government ownership, generally as part of a national research establishment. In the UK they typically operate as independent cost centres owned by private companies or universities, and as such are at risk of under-investment and/or closure due to underutilisation in a business (but not strategic) sense. In individual cases creative approaches have been found to ensure the medium-term survival of facilities, such as the Noise Test Facility at QinetiQ, but a long-term plan for strategic UK facilities is needed.

The UK possesses key capabilities in its universities and Research companies (such as QinetiQ and ARA). However, these are at risk due to the lack of a coordinated and funded approach to the work carried out in support of NATS.”

In order to assess the true extent, if any, of the erosion of UK test facilities and associated capabilities, the national wind tunnel test infrastructure today is compared, in this study, with that that existed over 30 years ago, in 1977. Data was obtained

from a 1977 government survey of the national wind tunnel infrastructure which listed every research capable wind tunnel in the UK and all of the other Commonwealth nations active in the aerospace industry. A similar comprehensive survey of all of the wind tunnels (small scale educational as well as large scale industrial) currently available in the UK, including those currently active and those that could be made active, has been compiled as part of this study, and is presented in detail by Johnson (2010) and Handford (2010).

Every UK university engineering school / faculty was contacted in the summer of 2008 with a request to provide details of all of the wind tunnel or water tunnel facilities that they maintained in their laboratories, completed with all operational details (working section dimensions, speed ranges, turbulence levels etc.) and all associated instrumentation (force & moment balance, pressure measurement, hot wire anemometry, optical flow visualisation etc.) together with an indication as to whether the tunnel is operational or non-operational at that time. A response was received from about 95% of the University engineering departments contacted.

A similar request was sent out to all the major British based motor car manufacturers, auto-sport companies, aircraft and missile manufacturers, ship or boat manufacturers, industry associations, and remaining government laboratories. In particular, the location or fate of every wind tunnel listed in the 1977 survey was exhaustively traced.

The resulting data, compiled over a two year period, is expected to be nearly definitive with regards to facilities in UK universities, and to cover about 90% of the wind tunnels available outside of academia. The data is, therefore, not comprehensive, but is complete enough for the overall trends in with the UK wind tunnel test infrastructure to become obvious. A summary of the data is presented in appendix A.

The analysis of this data is split into four categories relating to the four recognised wind speed ranges in which the physics of the flow are known to be significantly, or subtly different. These are i) the *Subsonic* flow range where the flow Mach number (the ratio of the speed of the wind to the speed at which sound waves propagate) is less than 0.6, ii) the *Transonic* flow range covering speeds above and below but close to the speed of sound and which is most relevant to civil transport aircraft, iii) the *Supersonic* flow range where the Mach number of the wind flow is above 1.0, which relates to the typical flight speed of missiles, fighter aircraft at full speed, and the Concorde aircraft and, iv) the *Hypersonic* flow range where Mach

number are above 5.0, and which is relevant to the flight of rocket boosters into space and the re-entry of spacecraft through the Earth's atmosphere.

Two separate graphs are plotted for each of the four speed ranges described above, the first comparing 1977 and 2010 data on a graph of Mach number against working section cross-sectional area, and the second comparing the same data on a graph of Mach number against the important ratio of physical properties called the Reynolds number. Basically, the larger the cross-sectional area, the bigger the models one can test and the smaller the experimental error compared with full scale real flight data. Also the higher the achievable Reynolds number (in many cases, but by no means all cases) the better the data compares with full scale real flight data.

Figure 4.1 and 4.2 present the data for the subsonic speed range, defined in this study as for Mach numbers up to 0.6. Figure 4.2 also presents the range of wind tunnel conditions that would be required for the effective design of a Cessna 172 type light aircraft, and an unmanned aerial drone of the Watchkeeper type. The data reveals that while there have been a lot of the wind tunnels that were available in 1977, particularly at the higher working section area / Reynolds number end, have been decommissioned, many more new low speed wind tunnels have been constructed. This is because there has been a significant investment within the automotive industry, particularly within the motor sport sector, in the development of new, well equipped, low speed wind tunnels, following a trend to move away from the utilization of university wind tunnels for commercial security reasons. It cannot be said, therefore, that, in general, there is any problem in the provision of low speed wind tunnels for supporting research and development in the UK. The potential problem is that many of the very best low speed facilities are maintained by private motor sport companies and are not, in general, available to other companies or for government or educational use. These facilities tend to be very heavily utilized by their owning companies, and even if an agreement could be obtained to allow outside use, there would not be much time available for such employment. However, there are still enough decent scale low speed wind tunnel facilities available in the University laboratories and in public and industry association institutions for high quality education and research and development to continue into the future, as long as the trend towards decommissioning of wind tunnel facilities, that this data highlights, is not allowed to further reduce the provision of the best facilities currently available.

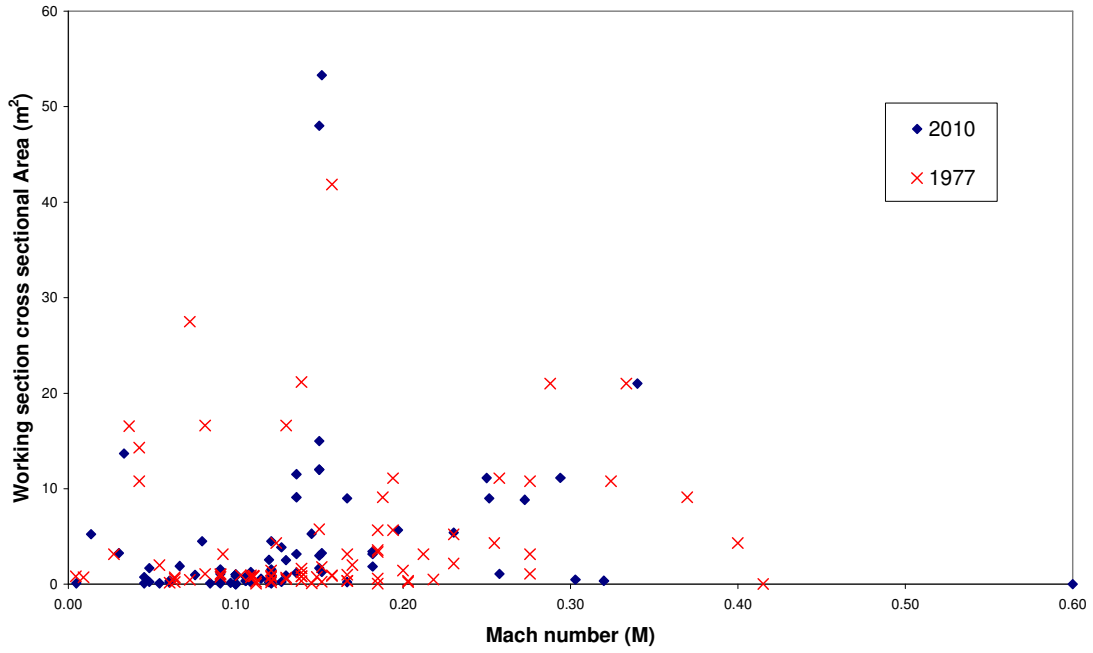


Figure 4.1: Plot of Mach number capability versus working section cross sectional area, comparing data for UK National subsonic wind tunnel facilities - 1977 and 2010.

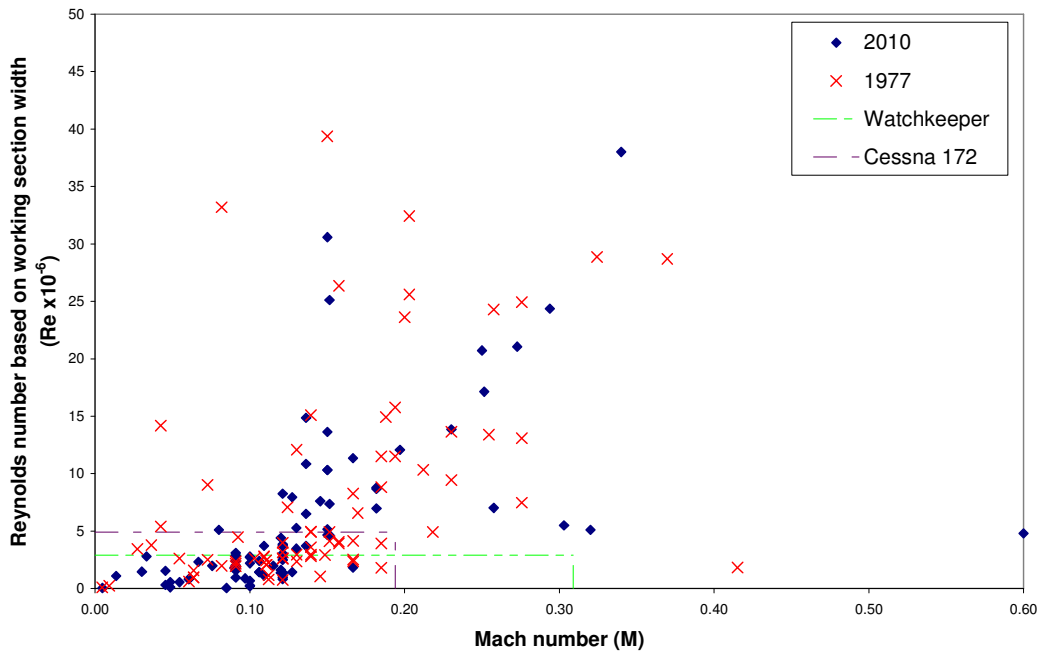


Figure 4.2: Plot of Mach number capability versus Reynolds number based on working section width, comparing data for UK National subsonic wind tunnel facilities - 1977 and 2010. (Typical maximum Mach number and Reynolds number per meter plotted for Watchkeeper and Cessna 172 aircraft).

Figure 4.3 and 4.4 compare the data for the transonic speed range, defined in this study as for Mach numbers in the range 0.6 – 1.6. This class of wind tunnel is very important for the modern aerospace industry, since every modern civil airliner cruises at speeds around 0.8-0.9. Modern combat aircraft also generally cruise in this speed range, though some can achieve higher supersonic speeds with the aid of afterburning thrust augmentation. To reinforce this point, figure 4.4 present the typical range of wind tunnel conditions (Mach number and Reynolds number) required in the development of the most recent Airbus A380 and Boeing 787 airliners.

The data clearly shows that there has been a significant impoverishment in the provision of decent scale transonic wind tunnel facilities. In fact there remains only a single industrial scale transonic wind tunnel in 2010, this maintained by the Aircraft Research Association in Bedford. All of the other large scale transonic facilities available in the UK in 1977 have now been decommissioned. Much of the wind tunnel testing work in support of the new Airbus projects are now undertaken in France and Germany, at the European Transonic Wind Tunnel (ETW) and at ONERA and DLR.

The data shows that there has also been a significant impoverishment in the provision of smaller scale transonic wind tunnels, which were generally found in 1977 in the University laboratories. In 2010 there remains only nine such small facilities, and many of these are actually not in an operational condition.

This is an extremely perilous situation in terms of its implications for UK capabilities in aerospace. The calibration and operation of an industrial scale transonic wind tunnel is much more complicated than that of a small scale university facility, and the correct analysis of data from such large scale facilities is also significantly different to that from small scale facilities. British university graduates, if they get to undertake any transonic experimentation at all, therefore have no exposure to the kind complicated real life practices required of large scale industrial wind tunnel testing typical of modern aircraft development. It is true, that UK university courses in aerodynamics will certainly teach the theory of how large scale transonic test experiments are designed and implemented. It must be remembered, however, that French graduates of SUPAERO in Toulouse, and US graduates of the National Aerospace Institute in Virginia (and there are many other examples in the US and Europe) will gain hands on experience of using facilities at their countries national laboratories and will graduate with the experience to begin work fully trained at

companies like Airbus and Boeing. Of course most French, German and American graduates do not have this excellent experience and are no better than the graduates produced from British universities. However, it is clear that the very best graduates from these countries are superior, in terms of experience and capabilities, than the best British graduates, precisely because the United Kingdom does not have the same model of directly linking universities with national laboratories. The most similar model in the UK is the Cranfield Institute of Technology (now Cranfield University) instituted in 1946 as a postgraduate institution to train engineers and scientists for the British aerospace industry, located close to the Royal Aerospace Establishment, and the Aircraft Research Association research centres being developed in nearby Bedford. No formal integration was ever developed between these institutions, however, to allow students to train using RAE or ARA facilities as part of their education, though doctoral students at Cranfield University were regularly supported and trained at RAE Bedford. With the gradual closure of the RAE / DERA Bedford site in the period 2002-2008, even this educational link has now been severed.

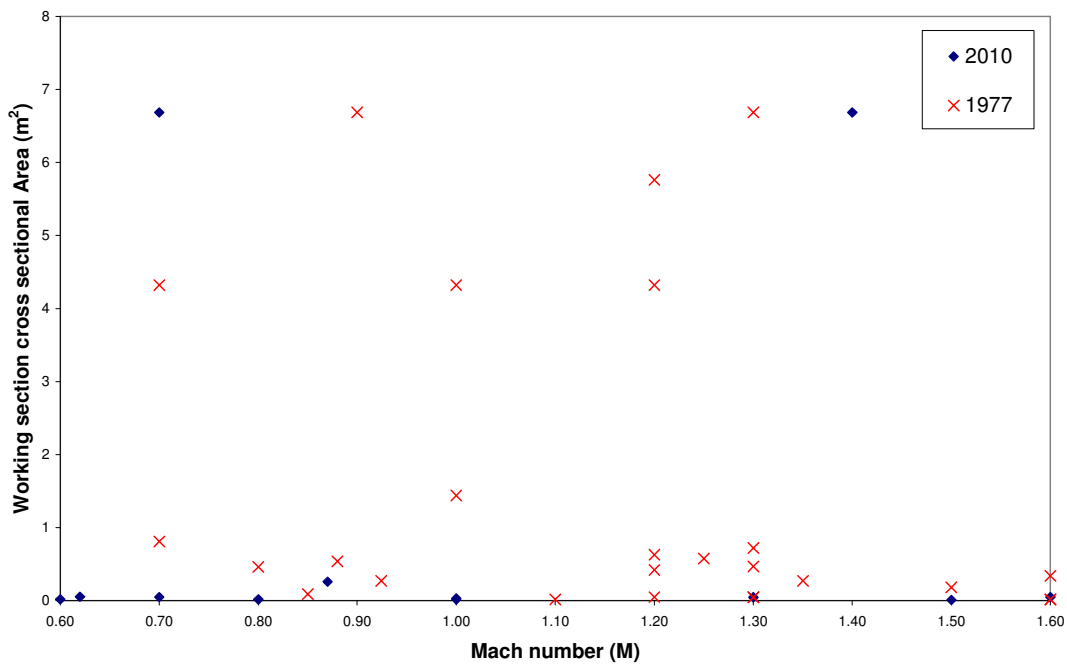


Figure 4.3: Plot of Mach number capability versus working section cross sectional area, comparing data for UK National transonic wind tunnel facilities - 1977 and 2010.

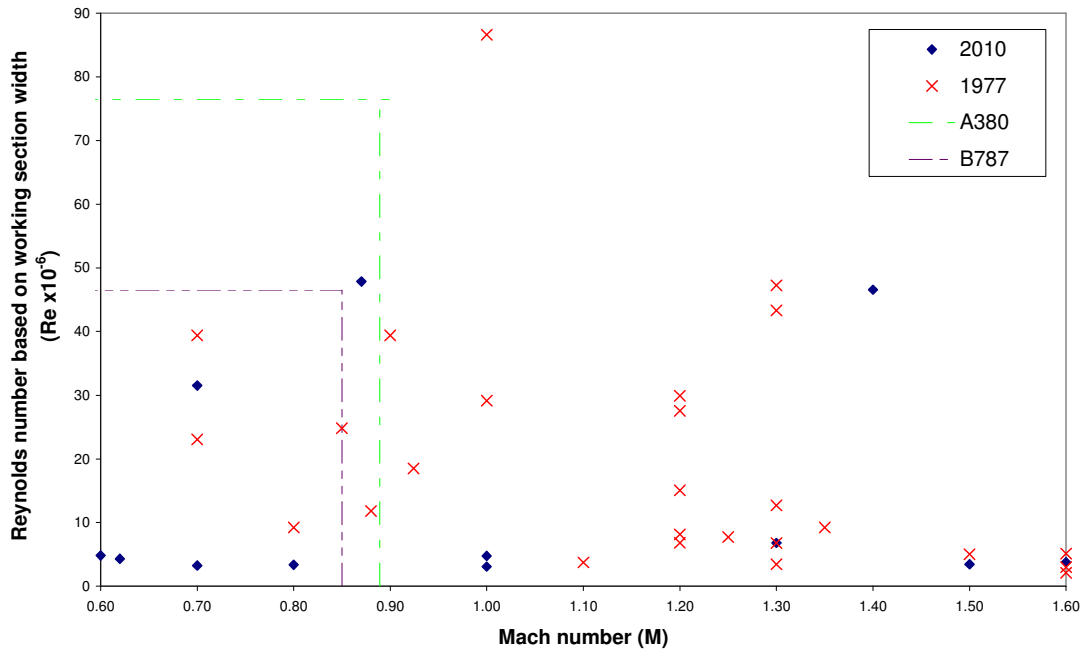


Figure 4.4: Plot of Mach number capability versus Reynolds number based on working section width, comparing data for UK National transonic wind tunnel facilities - 1977 and 2010. (Typical maximum Mach number and Reynolds number per meter plotted for Airbus A380 and Boeing 787 aircraft).

The comparisons for the supersonic speed range, defined in this study as in the Mach number range 1.0 – 5.0, presented in figures 4.5 and 4.6 show that the situation looks even worse for the UK provision of test facilities for this speed range. Supersonic wind tunnels, which are designed to generate a steady uniform stream of air flowing at a constant speed higher than the speed at which sound waves propagate, are indispensable in the design, development and assessment of modern fighter aircraft and missile systems. Air to air missile systems in particular, such as the recent air breathing Meteor missile, require extensive wind tunnel test programmes. Figure 4.6 presents the typical range of wind tunnel conditions (Mach number and Reynolds number) required in the development of the Eurofighter Typhoon and F-16 combat aircraft.

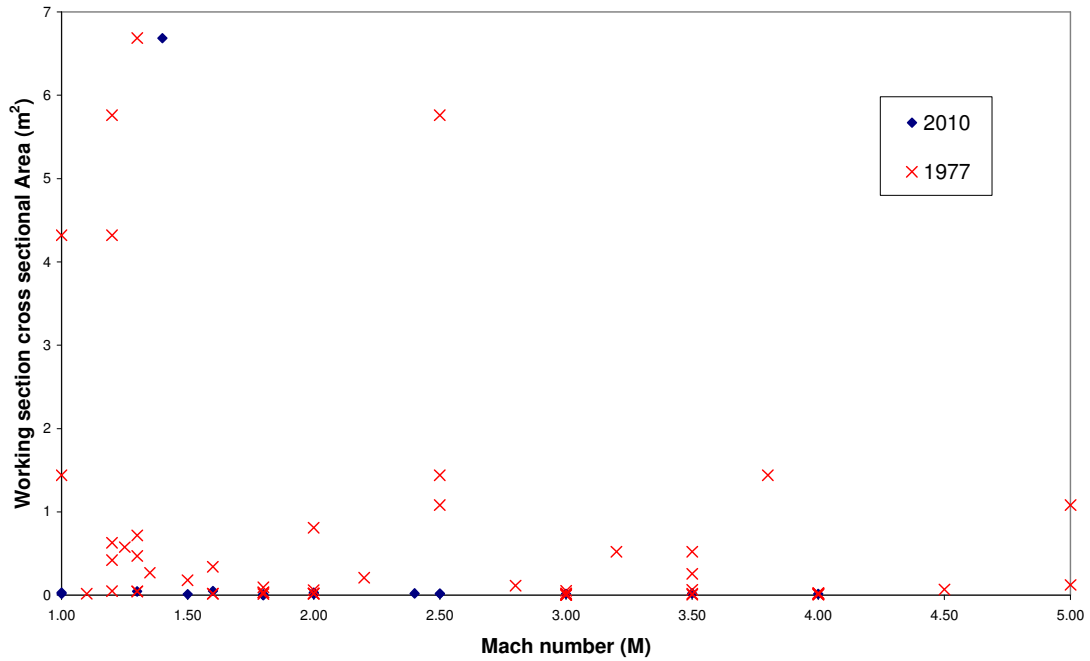


Figure 4.5: Plot of Mach number capability versus working section cross sectional area, comparing data for UK National supersonic wind tunnel facilities - 1977 and 2010.

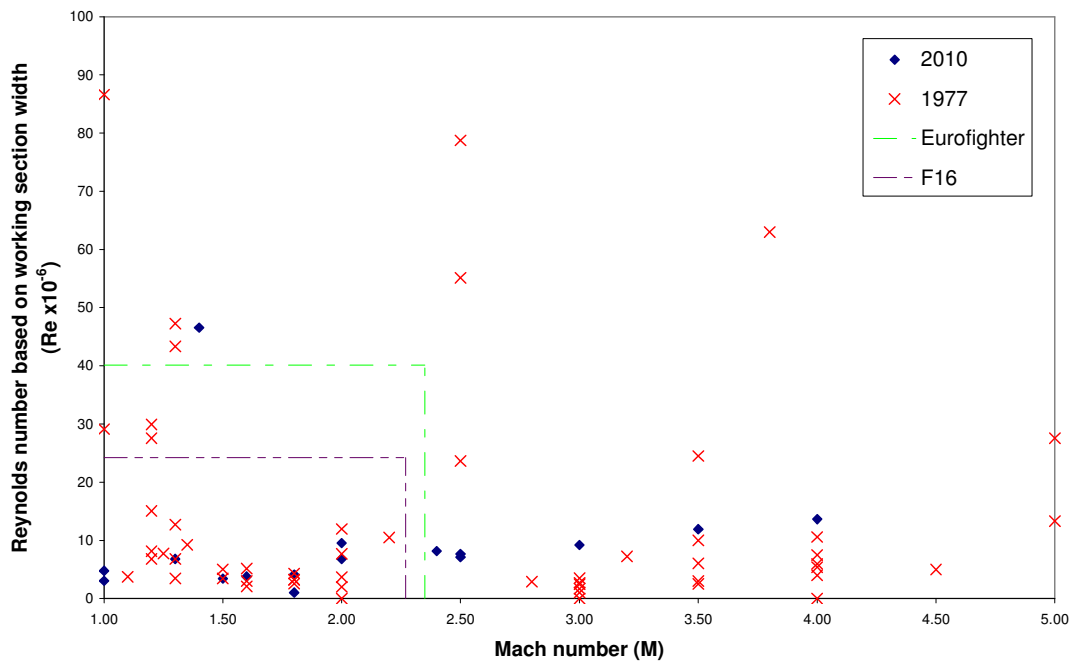


Figure 4.6: Plot of Mach number capability versus Reynolds number based on working section width, comparing data for UK National supersonic wind tunnel facilities - 1977 and 2010. (Typical maximum Mach number and Reynolds number per meter plotted for Eurofighter Typhoon and F16 aircraft).

All but one of the large scale industrial supersonic wind tunnels available in the UK had been decommissioned by 2010. The remaining ARA transonic wind tunnel is capable of testing only up to Mach 1.4, and cannot provide data up to Mach 2.0 and beyond, required for modern fighter jet design and development projects, or up to Mach 5.0 required for missile projects.

Smaller scale facilities that can test up to Mach 4.0 are still available at the ARA and in a few University laboratories, but many are not in an operational condition, and none of them will provide data at the kind of Reynolds numbers required for support of industrial projects such as the Typhoon or the Meteor missile. The small scale UK facilities are therefore useful for education and for basic fluid dynamics research only. The UK government and UK located aerospace companies are therefore entirely dependent on foreign institutions for industrial scale supersonic wind tunnel testing above Mach 1.4. In addition, it is estimated that only half of the aerospace engineers graduating in the UK in 2010 will have gained any experience whatsoever in wind tunnel testing at transonic or supersonic speeds, and the complexities associated with the analysis of data resulting from them. In 1977, however, it is estimated that an overwhelming majority of university students would have graduated with such experience, since almost every university aeronautical or aerospace engineering department then possessed at least a small scale supersonic test facility.

Hypersonic aerodynamics, covering the speed range with Mach number higher than 5.0, has been regarded as a very specialist area which is important only in the design, development and analysis of space vehicles and of nuclear ballistic missiles. As such it has not been a core discipline taught in undergraduate engineering programmes in many US, British or French universities. The discipline has generally been limited to Masters level courses in aerospace engineering aimed at training graduates for jobs in the space sector or in military research and development organisations. The flight physics, at these high Mach numbers, however, is very complicated and computational methods are very poor at predicting physical effects in hypersonic flow, making the wind tunnel even more important for hypersonics research. While the United Kingdom was at the forefront of hypersonics research in the 1960's and early 1970's, due to the development of its own ballistic missile system (the Blue Streak) and civilian space programme (the Black Knight and Black Arrow), rocket engine and booster development work has been all but terminated in

the UK since the early 1980's. The UK work in the space sector is now almost entirely limited to the design and development of satellite technology for Earth observation and for space exploration. Very little hypersonic aerodynamics research is therefore undertaken in the UK any more.

However, if one argues that it is important to maintain a basic sovereign capability in this field then it is important that the subject is taught in at least one or two postgraduate programmes in the UK, and that such postgraduate students have access to hypersonic facilities for their education. In addition, for sovereign capability to be maintained, at least one or two hypersonic facilities would need to be maintained for the provision of a basic research capability.

The data from this study, presented in figures 4.7 and 4.8, shows that in 1977 there were some 21 hypersonic facilities available, covering the Mach number range 5.0 up to 25.0. Today this has diminished considerably, and there are now only four (possibly five[†]) hypersonic facilities that are still operational. The highest Mach number facility available in the UK, can provide short duration airflows up to Mach 12.0. All of these remaining hypersonic facilities, located in university laboratories, are under threat of decommissioning due to their relatively high cost of space, and the lack of research and development work in the hypersonics area.

The evidence from this study clearly highlights the significant impoverishment of the UK infrastructure for aerodynamics testing at high speed (transonic, supersonic and hypersonic speeds). The analysis of Chapter 3 has shown the importance to the UK economy of the aircraft manufacturing industry, which absolutely relies on access to experimental testing at these speed ranges. The UK government acknowledges the significant growth potential of the British space industry, which also requires access to test facilities at the higher Mach number end.

[†] Oxford University is known to have operated a low density hypersonic facility, but this institution declined to provide information for this study, and so no concrete data is available as to the situation of this facility.

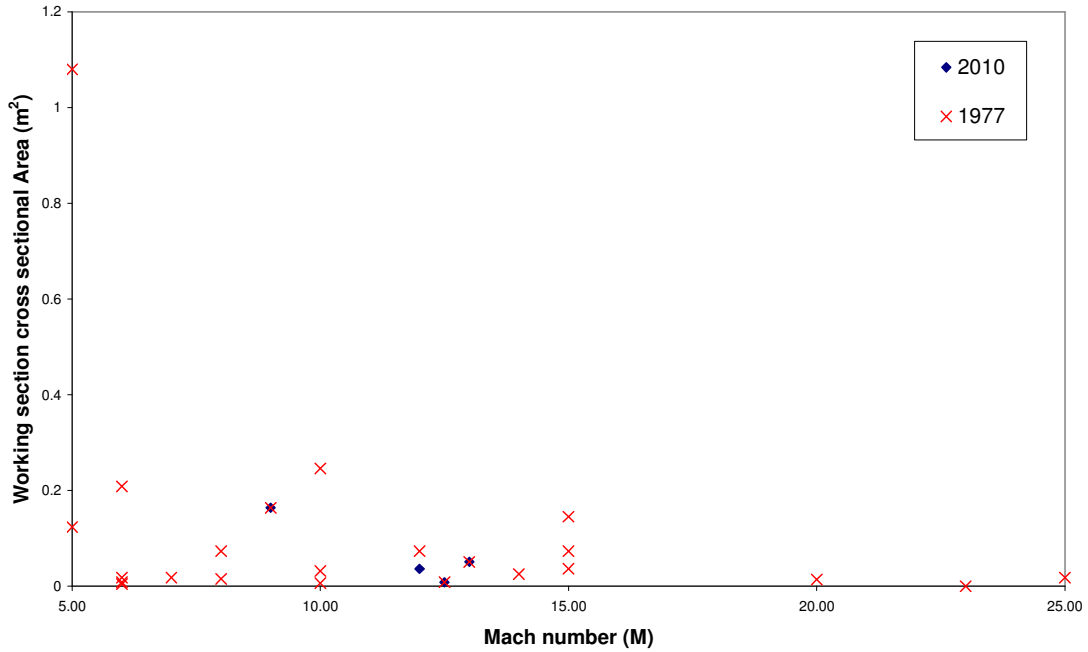


Figure 4.7: Plot of Mach number capability versus working section cross sectional area, comparing data for UK National hypersonic wind tunnel facilities - 1977 and 2010.

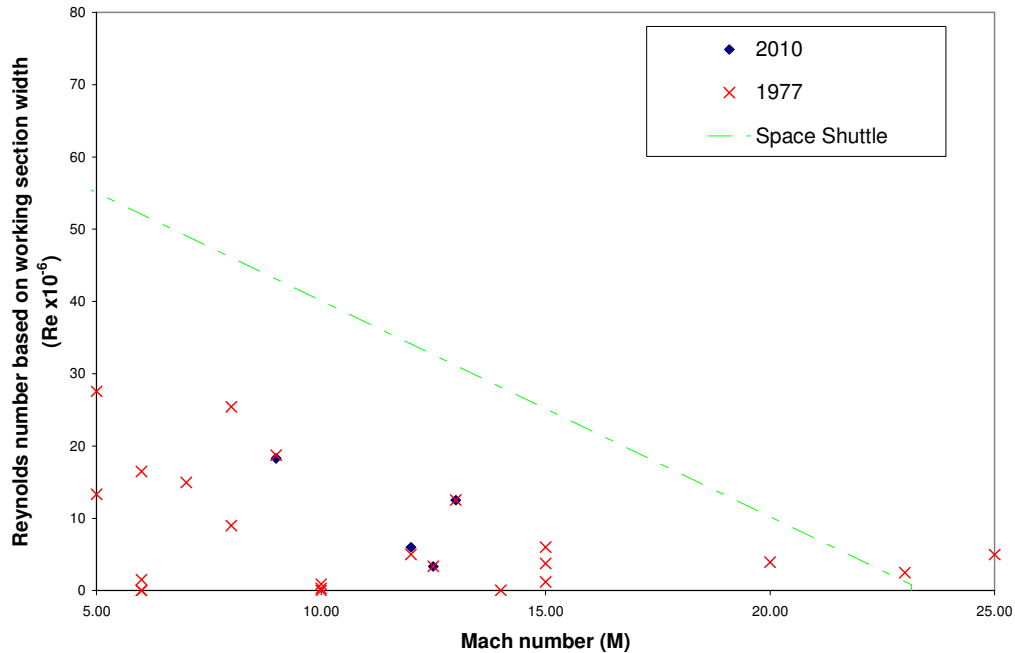


Figure 4.8: Plot of Mach number capability versus Reynolds number based on working section width, comparing data for UK National hypersonic wind tunnel facilities - 1977 and 2010. (Typical maximum Mach number and Reynolds number per meter plotted for the Space Shuttle orbiter).

While this analysis has focussed on highlighting the trends in provision of wind tunnel facilities in the UK, it is known that the same economic forces which have caused this diminution have also acted on all other classes of engineering test facilities, and on science and technology laboratories in general. The authors are aware of many important engine test facilities, structural test facilities and materials testing facilities that have been decommissioned in the academic, governmental and industrial sectors over the past 10 years or so. The issues highlighted in this analysis can therefore be regarded as general, and are effecting the long term provision of all engineering test facilities and associated capabilities in the United Kingdom.

4.3 Summary

Without a national strategy for the funding and maintenance of those engineering test facilities of strategic importance to UK industry and academia, the current trend in the decommissioning of engineering test facilities will soon leave the United Kingdom with very little remaining capabilities, both in terms of physical test infrastructure and human skills and experience, in the field of flight science in particular, and in engineering science in general. Evidence has been already presented that global engineering companies will locate themselves in nations with high levels of technical and scientific skills, and in locations with good provision of experimental test infrastructure and associated research and development services.

The implications are, therefore, that without a national strategy for the preservation of a national experimental test infrastructure, the global companies currently located in the United Kingdom will seek to relocate to economically and scientifically more fertile regions of the world. This will have a knock-on impact on the UK Higher Education sector, which will be left with much reduced private support for engineering degree programmes at just the time when the British government is withdrawing some or all public financial support for such programmes.

5. The Role of Test Facilities in Student and Staff Satisfaction in UK University Engineering Departments

This section reports on the results of a survey, at a UK university engineering school, of student attitudes towards engineering laboratories at university and their perceived value to their education programmes. The aim of the survey was to gauge whether the provision of a well equipped engineering laboratory was a key factor in students choosing their particular engineering course, and whether a reduction in such provision would be viewed by these students, once studying for their degree, as detrimental to their education. In addition this section presents the results of a survey of academic staff at the same institution, to assess attitudes towards rationalisation of engineering test facilities in UK universities.

The value of good scientific laboratory facilities in attracting students to apply and then enrol to study at a particular institution, or their role in the retention of these students, has never been properly assessed. This section presents an attempt to obtain data on the motivations of engineering students at City University London, in their choice to study at that institution, and also their perceptions of how certain possible changes to their course or learning environment might affect their satisfaction with that programme.

The School of Engineering and Mathematical Sciences (SEMS) at City University London educates about 1,500 undergraduate students during a typical year, compared with the total of 14,500 students that are studying at the university. In addition there were also 783 postgraduate students studying for a higher degree in the academic year 2008/9. The School is research intensive and would be regarded as middle ranking in terms of research output and excellence.

The School has about 65 full time equivalent staff involved in teaching and research, and delivers 36 undergraduate and postgraduate degree programmes in the STEM disciplines, broadly split into five streams; Mechanical, Aeronautical, Civil, Biomedical and Electrical Engineering, and Mathematics. The school also has a strong background in experimental engineering, having substantial and well equipped laboratories, with facilities including some of the most advanced engine development and testing facilities in Europe, a wind tunnel laboratory for low speed, transonic and supersonic testing with one of the biggest university transonic wind tunnels left in the UK academic sector, and a geotechnics laboratory with one of the only centrifuges for modelling ground movements and collapse conditions. The school therefore accommodates, and manages extensive engineering test facilities that are typical of a strong engineering department in a UK university.

The school tends to recruit mainly from the London area and from overseas, and the typical engineering student tends to be from lower to middle class families. The demographics of the student body are therefore somewhat different to those of more prestigious institutions such as Oxford, Cambridge or Imperial College London. However, it would not be expected to be too different from the engineering cohort seen in a typical Russell Group institution.

Given that the demographics of the student body at City University London, that the school is both teaching and research intensive and that it manages several laboratories extensively equipped with engineering test facilities, it is expected that the results of this student survey should be representative of the results, given the same survey, of students at most other UK university engineering schools.

The survey questionnaire, which was designed to be submitted anonymously, is reproduced in Appendix B. It was designed to obtain data on a broad range of information, including origin of student (home or overseas), employment details (part-time work or not), parental income etc., in order to mask the purpose of the survey, which was to assess how the students perceive the value of engineering test facilities in their education, whether the provision of such facilities influenced their decision to choose their University, and whether they felt that loss of access to these facilities would be detrimental to their education now that they are studying an engineering degree.

The voluntary survey questionnaire was handed out to all 660 engineering students* from the 2nd, 3rd and 4th years of their programmes. The first year students were excluded from this survey because it was deemed that they would not have had sufficient knowledge about, or experience, to effectively understand the issues surrounding some of the questions (for instance, about accreditation by the Royal Academy of Engineering) until they had completed their first year of professional training at University.

5.1 Survey Results

A total of 93 responses were received, representing just over 14% of the total number of students targeted. A demographic breakdown of the sample is presented in figure 4.1, showing the proportion of males (72) and females (21), age range, origin (home or overseas) and chosen engineering programme, for each cohort.

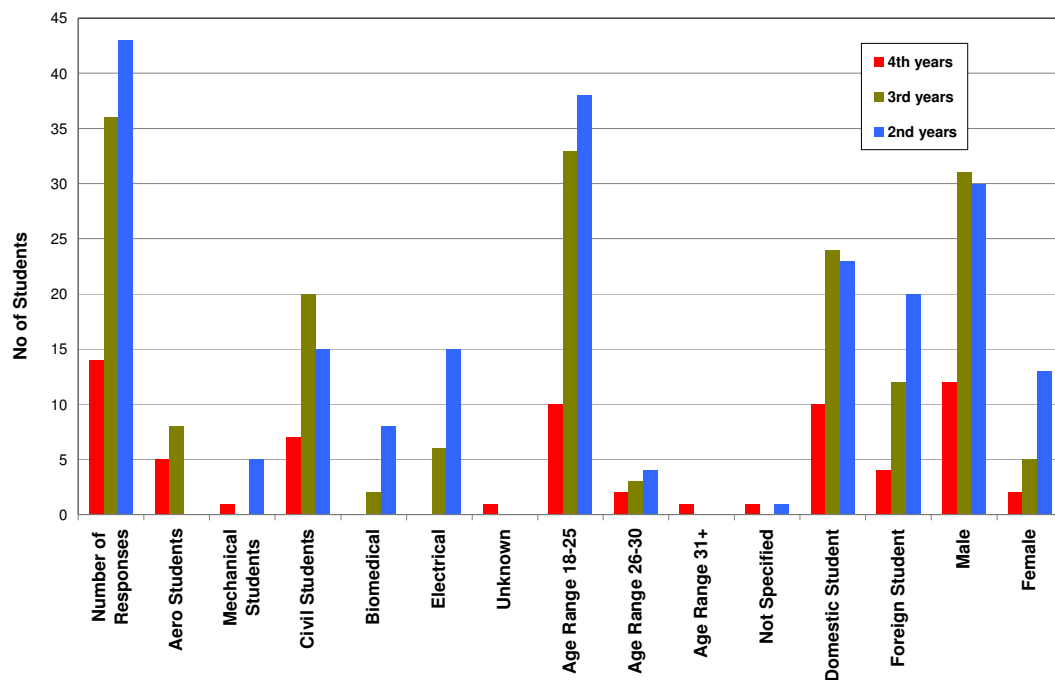


Figure 5.1: Survey Sample Demographics

* Mathematics students were excluded from the survey, as their subject does not require any physical laboratory experience.

The 2nd and 3rd year cohorts comprise the main body of students who are enrolled on the standard three year Bachelors of Engineering degree courses, as well as those (much fewer in number) enrolled on the four year Masters of Engineering courses. This explains why the columns for 4th year students are generally much lower than those of 2nd and 3rd year students – in fact, the total number of 4th year responses represents a return of nearly 74% of those targeted. The sample captured a reasonable cross-section of both domestic and overseas students. The large majority of the respondents were in the age range 18-25, which is a good reflection of the age demographics of the total student body targeted.

Given the sample size and the demographic spread shown in figure 5.1, it is suggested that any strong views indicated by this sample should be representative of the views of the student body targeted, and generally representative of engineering students in most other UK Universities.

The second part of the questionnaire aimed to identify the motivations behind the respondent choosing to go to study at University and to study an engineering discipline. The respondent was asked how they agree or disagree with the statement “*I always knew that I wanted to study engineering at University*”, as well as if they knew a professional engineer in their family or as a friend, and thereby had a professional engineer as a role model. These questions gauged specifically, the motivation of the respondent to join the engineering profession, as opposed to just going to University to get a degree, and thereby better job prospects. The rest of the questions in this section were designed to gauge the respondents’ motivations for going to study at University more generally. Figure 5.2 presents the results of the survey on these questions.

Of the 93 students who took part in the survey, 36 indicated that they had a professional engineer in their family, while 57 indicated that they had not. Just over a half of those taking part indicated that they knew a professional engineer outside of the family that they regarded as a role model.

The Engineering Council gives a figure of 800,000 professional engineers in the UK, with 235,000 of them professionally registered with them. This means that, given a population of 62 million people in 2010, only about 1.3% of the population of the United Kingdom are professional engineers. The fact that 39% of those taking part in this survey have a family member who is a professional engineer demonstrates the enormous positive motivational effect that knowledge of what engineering is, and

what engineers do, has for the engineering profession. This data shows, even if one takes the sceptical view that some students regard their technician brother, for instance, to be a professional engineer, that engineering is profession with the ability to inspire the young.

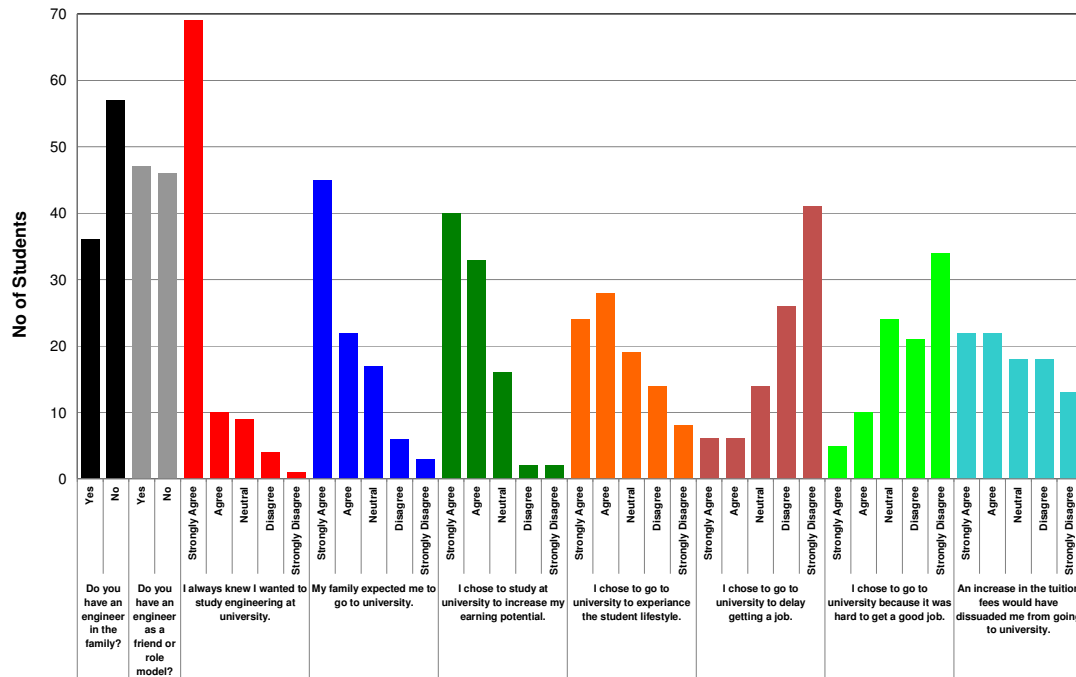


Figure 5.2: Factors in decision to study engineering at University: whole sample of 93 City University engineering students

The results of the next question are more revealing still. Asked to indicate their level of agreement / disagreement to the statement “I always knew that I wanted to study engineering at University”, 69 out of the 93 (74%) who participated indicated that they strongly agreed. Adding those who indicated that they agreed, but not strongly, brings the total up to 79 so that 85% of the participants agreed to some degree that they had planned, for some time, to study at University to become a professional engineer. Those who disagreed or strongly disagreed with the statement totalled five students – only 5% of the participants. This is a strong indication that when an engineering student comes to University they are, in general, highly motivated by the subject that they choose to study.

On the issue of family expectations, 72% of the participants indicated that they believed that their families “expected” them, to some degree, to go to study at

University, while only 10% thought that there were little or no expectations that they would go to University.

Some 78% of the respondents agreed that earning potential was a factor in their choice to go to University and study engineering, while 56% agreed that the student “lifestyle” was a factor. Asked if they agreed that they chose to study engineering at university to delay getting a job, 13% of the participants indicated that they either agreed or agreed strongly, and 44% indicated that they strongly disagreed, while 59% disagreed or strongly disagreed to the statement “*I chose to go to university because it was hard to get a good job*”, with only 16% agreeing or strongly agreeing.

What these results indicate is that the average UK engineering undergraduate is highly motivated by the discipline that they are studying, and are also motivated by the prospect of a career that provides good earning potential, but are less motivated by the idea of experiencing the “student lifestyle”. They also did not, in general, decide to study engineering at University either to delay getting a job, or because they felt that they could not get a good job without a university degree.

The last question of this section dealt with attitudes to the prospect of an increase in student tuition fees. Asked if they agreed or disagreed that “*an increase in the tuition top up fees would have dissuaded me from going to university*” 47% of the participants indicated that they would agree or strongly agree, while 19% were neutral, and 34% disagreed or strongly disagreed. This result really shows that a significant hike in the up front cost to study for an engineering degree would have deterred, to some degree, nearly half of UK undergraduate engineering students from going to university in the first place. This reinforces the view that if, in future, engineers are to pay much more of the cost of their education, and contribute themselves to the maintenance of university engineering test facilities, then it cannot be an up front payment, but a levy that they pay back, when they earn above a certain fair threshold of income.

Figures 5.3 – 5.6 present the same data, but split into the different engineering programme streams that the students are studying. The results show that the same trends observed in the combined data are mirrored in the returns for all four engineering streams, indicating that there is little or no bias from one engineering discipline to another, ie: the findings are generally valid across the engineering disciplines.

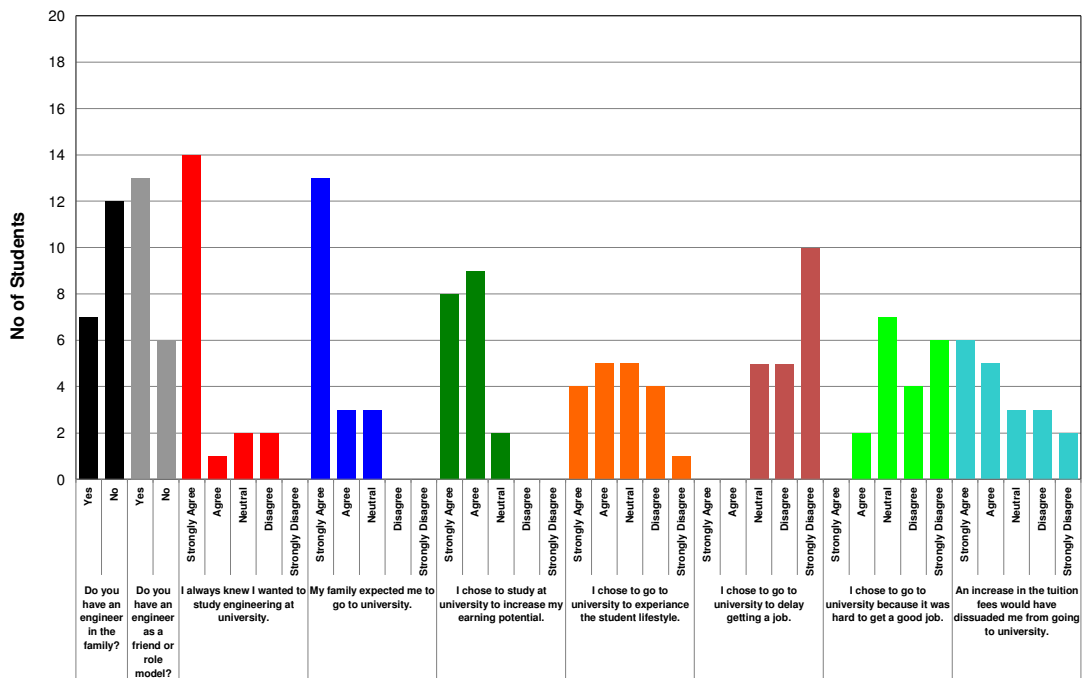


Figure 5.3: Factors in decision to study engineering at University: Mechanical and Aeronautical engineering students

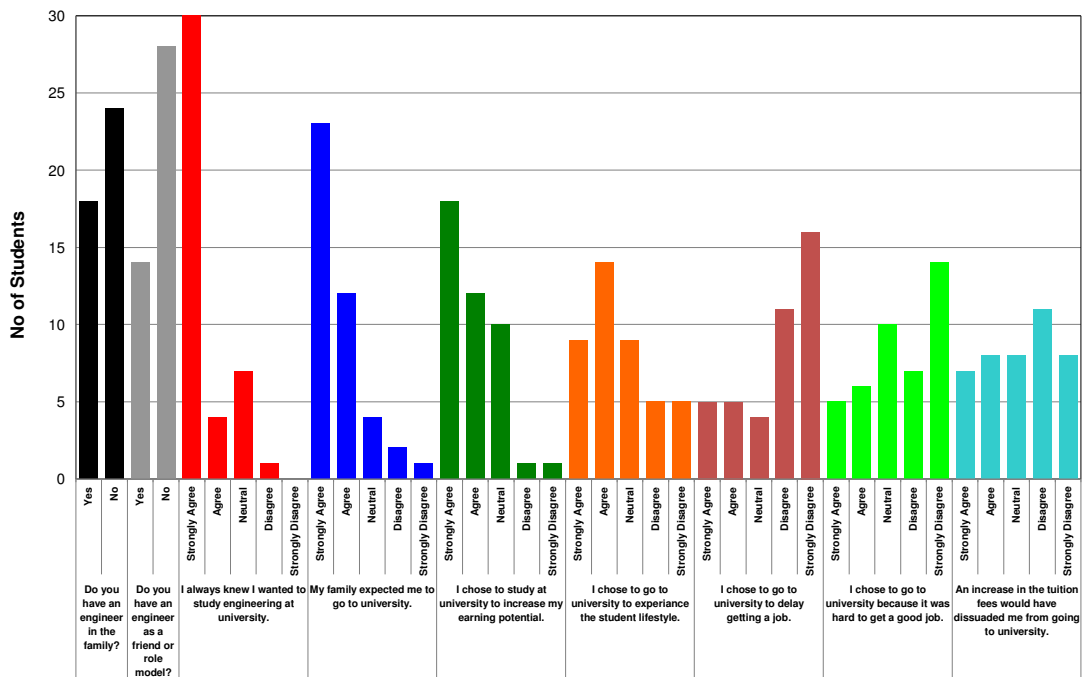


Figure 5.4: Factors in decision to study engineering at University: Civil engineering students

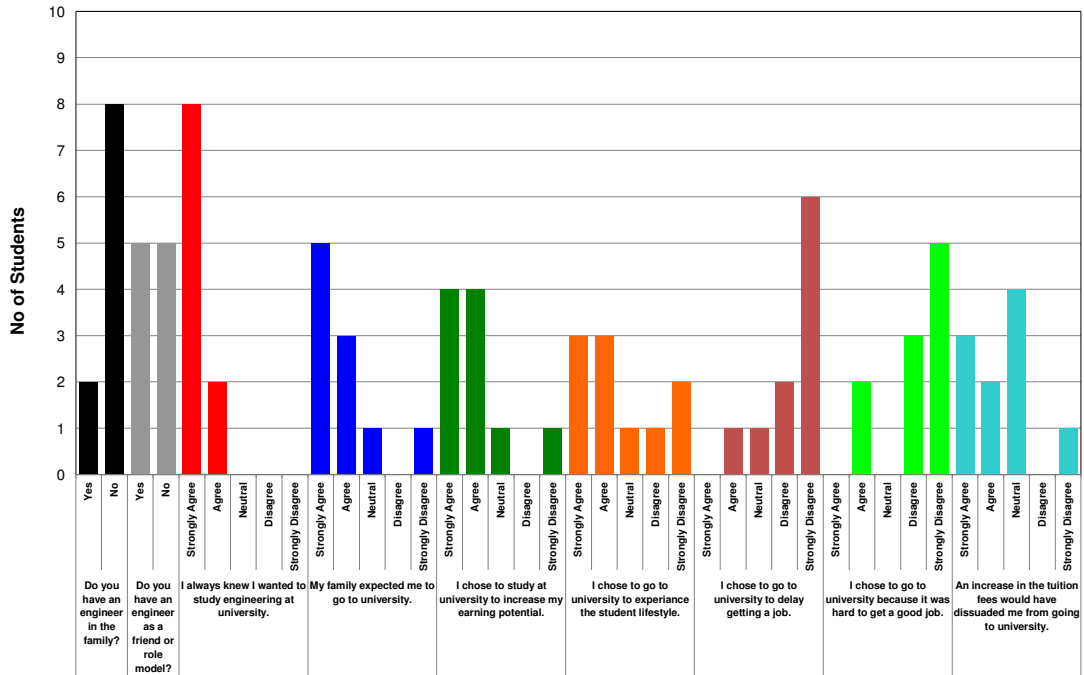


Figure 5.5: Factors in decision to study engineering at University: Biomedical engineering students

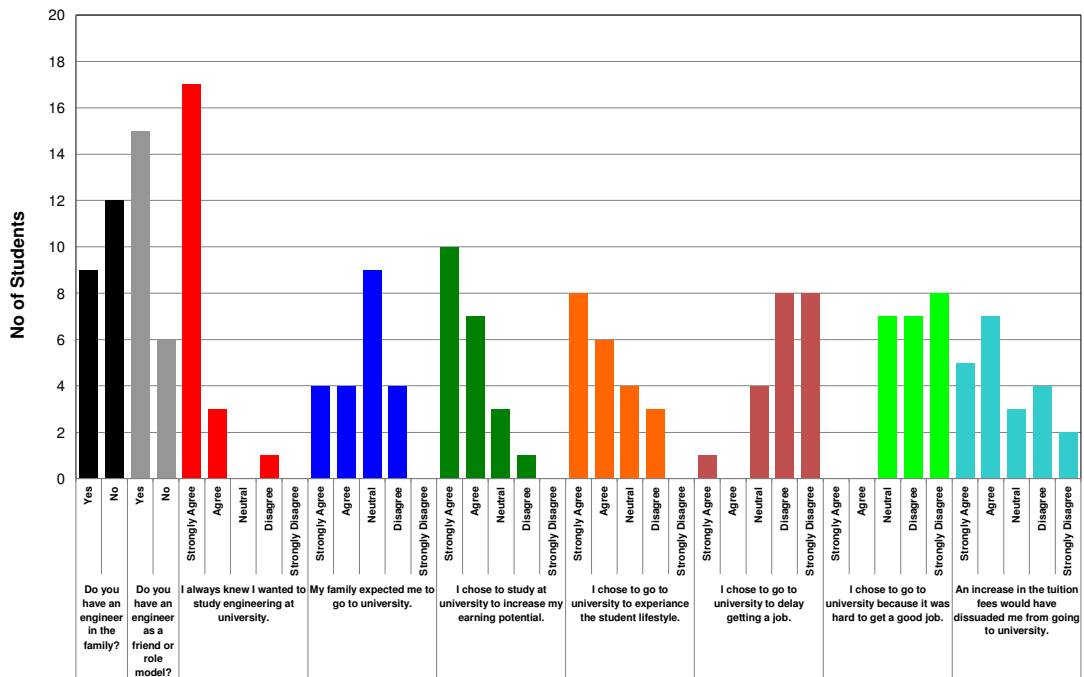


Figure 5.6: Factors in decision to study engineering at University: Electrical engineering students

The next main section of the questionnaire asked the respondent to select, in order of importance, five out of eighteen factors, listed below, influencing why they chose City University at which to study for their engineering degree.

- The reputation of the university.
- The League table position of the university.
- The quality and reputation of the academic staff.
- The entry requirements expected by the university.
- The quality of the laboratory resources that are available for your use.
- The accreditation status of the university.
- The academic atmosphere.
- The social atmosphere.
- The modern feel to the university.
- The traditional feel to the university.
- Because the university is close to family/friends.
- Because the university is far from family/friends.
- A friend was studying at the university.
- The town or city in which the university is situated is desirable.
- The weather associated with the location of university.
- The cost of the tuition fees.
- The availability of scholarships/financial aid.
- Parental opinion.

The data obtained from the returns on this section are presented in tables 5.1 – 5.5, where the reasons for choosing engineering at City University are listed by the number of times a particular reason has been chosen. The order of preference indication has not been taken into account in this analysis, as many respondents simply chose to tick five of the boxes rather than indicate numbers.

. The reputation of the institution, however the individual student interprets that “reputation”, was chosen by 73 out of the 93 participants as being in their top 5 factors. The “quality and reputation” of the staff in the engineering department was chosen by 54 participants, while the accreditation status of the engineering course, and the entry requirements were chosen by 49 and 44 participants respectively.

The quality of the laboratory resources that the university was able to offer was chosen by 40 out of the 93 participants as a top five factor in choosing City University as their institution to study engineering, above factors that might be thought to be more influential like position in the published league tables, location or the availability of scholarships or financial aid.

1	The reputation of the university.	73
2	The quality and reputation of the academic staff.	54
3	The accreditation status of the university.	49
4	The entry requirements expected by the university.	44
5	The quality of the laboratory resources that are available for use.	40
6	The town or city in which the university is situated is desirable.	38
7	The League table position of the university.	35
8	The academic atmosphere.	28
= 9	The cost of the tuition fees.	21
= 9	Because the university is close to family/friends.	21
10	The social atmosphere.	18
11	The availability of scholarships/financial aid.	14
12	The modern feel to the university.	9
= 13	A friend was studying at the university.	5
= 13	Because the university is far from family/friends.	5
= 13	Parental opinion.	5
14	The traditional feel to the university.	4
15	The weather associated with the location of university.	2

Table 5.1: Factors affecting choice of university: whole sample of 93 City University engineering students

Tables 5.2 – 5.5 present the same data, split by programme / discipline stream. Interestingly, for each of the four engineering streams, the students conception of university reputation came number one in the choice of factors they felt most influenced their choice of university.

1	The reputation of the university.	18
2	The accreditation status of the university.	12
3	The quality and reputation of the academic staff.	11
= 4	The quality of the laboratory resources that are available for use.	8
= 4	The entry requirements expected by the university.	8
= 5	The cost of the tuition fees.	7
= 5	The town or city in which the university is situated is desirable.	7
6	Because the university is close to family/friends.	6
= 7	The academic atmosphere.	5
= 7	The availability of scholarships/financial aid.	5
8	The League table position of the university.	4
= 9	The modern feel to the university.	1
= 9	The traditional feel to the university.	1
= 9	Because the university is far from family/friends.	1
= 9	The weather associated with the location of university.	1
= 10	The social atmosphere.	0
= 10	A friend was studying at the university.	0
= 10	Parental opinion.	0

Table 5.2: Factors affecting choice of university: mechanical and aeronautical engineering students

1	The reputation of the university.	32
2	The quality and reputation of the academic staff.	25
3	The accreditation status of the university.	22
4	The entry requirements expected by the university.	21
5	The town or city in which the university is situated is desirable.	20
6	The quality of the laboratory resources that are available for use.	19
7	The League table position of the university.	18
8	The academic atmosphere.	12
9	Because the university is close to family/friends.	9
10	The social atmosphere.	8
= 11	The modern feel to the university.	6
= 11	The cost of the tuition fees.	6
12	The availability of scholarships/financial aid.	5
13	Parental opinion.	3
= 14	A friend was studying at the university.	2
= 14	The traditional feel to the university.	2
= 15	Because the university is far from family/friends.	0
= 15	The weather associated with the location of university.	0

Table 5.3: Factors affecting choice of university: civil engineering students

1	The reputation of the university.	8
= 2	The League table position of the university.	5
= 2	The quality and reputation of the academic staff.	5
= 2	The entry requirements expected by the university.	5
= 2	The accreditation status of the university.	5
= 3	The academic atmosphere.	4
= 3	The town or city in which the university is situated is desirable.	4
= 4	The quality of the laboratory resources that are available for use.	3
= 4	The cost of the tuition fees.	3
= 5	The social atmosphere.	2
= 5	The availability of scholarships/financial aid.	2
= 6	The modern feel to the university.	1
= 6	The traditional feel to the university.	1
= 6	The weather associated with the location of university.	1
= 6	Parental opinion.	1
= 7	Because the university is close to family/friends.	0
= 7	Because the university is far from family/friends.	0
= 7	A friend was studying at the university.	0

Table 5.4: Factors affecting choice of university: biomedical engineering students

1	The reputation of the university.	15
2	The quality and reputation of the academic staff.	13
= 3	The quality of the laboratory resources that are available for use.	10
= 3	The entry requirements expected by the university.	10
4	The accreditation status of the university.	9
= 5	The League table position of the university.	8
= 5	The social atmosphere.	8
6	The academic atmosphere.	7
7	The town or city in which the university is situated is desirable.	6
8	Because the university is close to family/friends.	5
= 9	Because the university is far from family/friends.	4
= 9	The cost of the tuition fees.	4
10	A friend was studying at the university.	3
= 11	The modern feel to the university.	1
= 11	The availability of scholarships/financial aid.	1
= 11	Parental opinion.	1
= 12	The traditional feel to the university.	0
= 12	The weather associated with the location of university.	0

Table 5.5: Factors affecting choice of university: electrical engineering students

Focussing on the issue of how important the students regarded the quality of engineering laboratory facilities, and their access to them, in their decision to choose a particular university to study engineering, table 5.6 lists the ranking of where in the table of the eighteen factors that this issue appeared, together with the percentage of the students who responded that chose this issue as a top five factor.

	Position in table (out of 18)	Percentage of participants choosing laboratories as top 5 factor
All participants	5 th	43
Mech and Aero Eng.	=4 th	42
Civil Eng.	6 th	45
Biomedical Eng.	=4 th	30
Electrical Eng.	=3 rd	56

Table 5.6 Summary of data on engineering laboratory facilities as a factor in the choice made by undergraduates to study at a particular institution.

While the data clearly shows that perceptions of the “reputation” of both the institution and the engineering department itself, are the most important factors in applicants choosing a particular engineering course (though not necessarily from data in the published university league tables), the quality and accessibility of engineering laboratories is still reliably high up the list for all of the four main programmes / streams, with between 30 and 56% of the total participants choosing this as a top five factor. It is suggested, therefore, that good quality engineering laboratories are an important factor, though not the most important, in the recruitment of engineering students, and therefore in the income stream of a UK engineering department. Institutions that choose to rationalise laboratory facilities in favour of non “hands-on” laboratory education may find themselves at a disadvantage to those who choose to maintain and support their labs, when competing for good students in the future, especially if as the Browne report has recommended lifting the cap on tuition fees, and thereby opening up competition in the UK Higher Education sector.

The final section of the questionnaire aimed to assess the relative perception, good or bad, that engineering students would have to a change in the circumstances of their educational environment, including:

- i) Their engineering department loses accreditation status for the course they are studying (effectively putting them at a severe disadvantage on the jobs marked at the end of their studies).
- ii) Their engineering department gains extra accreditation status for the course they are studying.
- iii) Their engineering department closes some of its experimental test facilities.
- iv) Their engineering department invests in additional experimental test facilities.
- v) Their university refurbishes its buildings to look more modern.

Figure 5.7 presents the data on the responses to this set of questions. Out of the 93 participants, 46 (49% of the total) chose City University as their first choice to study engineering when applying via the Universities Central Admissions Service (UCAS), while for 20 students (22% of the total) it was their second choice. Some 62% of the participants regarded their programme losing accreditation as either negative or very negative, while only 15% thought that this would be positive or very positive. Six of the seven respondents who thought such a change would be very positive, and three of the five who thought it would be positive, were electrical engineers. Clearly these students did not understand what programme accreditation is,

and what it would mean to them if their programme lost it. However, the overall majority of participants correctly recognised that such an event would be severely detrimental to their chances of a job at the end of their course.

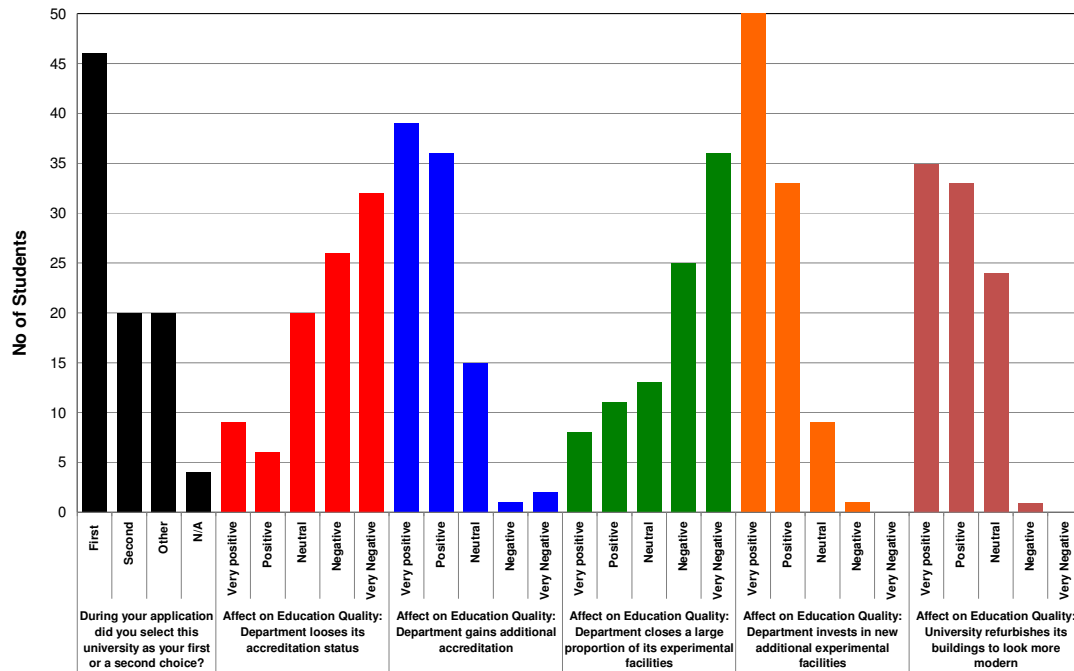


Figure 5.7: Perceptions of the affect of change on education quality: whole sample of 93 City University engineering students

Some 81% of the participants indicated that they perceived that additional accreditation for their course would be very positive or positive, while only 3 students (only 3%) indicated that they thought that this would be negative or very negative. This, again, shows that in general the participants understand the importance of accreditation for their employability following graduation, and leads to the view that engineering students are empowered and generally fully aware of what is important in their own education.

Some 66% of the participant indicated that they viewed any rationalisation of experimental test facilities in their laboratories as being negative or very negative, with only 12% viewing such a move as being positive or very positive. Posed with the scenario of their department investing in additional experimental test facilities 89% of the respondents deemed such a move to be very positive or positive. Not one student thought that this would be negative or very negative.

The small discrepancy between the results of these two questions on facilities would indicate a small level of misunderstanding, but the clear result shows that the student body would generally regard a rationalisation of facilities as detrimental to their own education quality, while an investment in the same would be a positive move for the quality of their own education.

The last of this series of questions surveys the students' attitudes towards improvements in the purely aesthetic environment in which they study. The question asked whether they thought a refurbishment of the university buildings to look more modern would have a positive or negative impact on their education quality. The results show that 73% of the participants thought that a refurbishment of the university buildings would have a positive impact on their education quality, while 26% indicated that it would not have any impact, and only 1% (one student) indicated that they thought it would have a detrimental impact.

This supports the view that students prefer to study in modern, well lit, well provisioned learning environments. In terms of engineering laboratories, one could infer that the student body would be more motivated if the laboratory was maintained with a modern look, with provision of good computers and wireless networks, good lighting and air conditioning etc.

Figures 5.8 – 5.11 present the same data, split by programme / discipline stream. Apart from the bizarre anomaly of 6 electrical engineering students indicating that they believe that their programme losing accreditation, and them thereby subsequently being ineligible for chartership and therefore in a severely difficult position on the jobs market, would have a very positive impact on their education quality, and a few electrical engineers and civil engineers indicating that a closure of a large proportion of engineering test facilities would have a very positive impact on the quality of their studies, the trends in the data are generally consistent across the four engineering streams.

The above discrepancies can only be explained by these particular respondents not understanding the question, for instance a lack of knowledge of what degree accreditation is and what it means for them. It is suggested, however, that these particular anomalies do not distort the overall trends significantly, and can therefore be neglected.

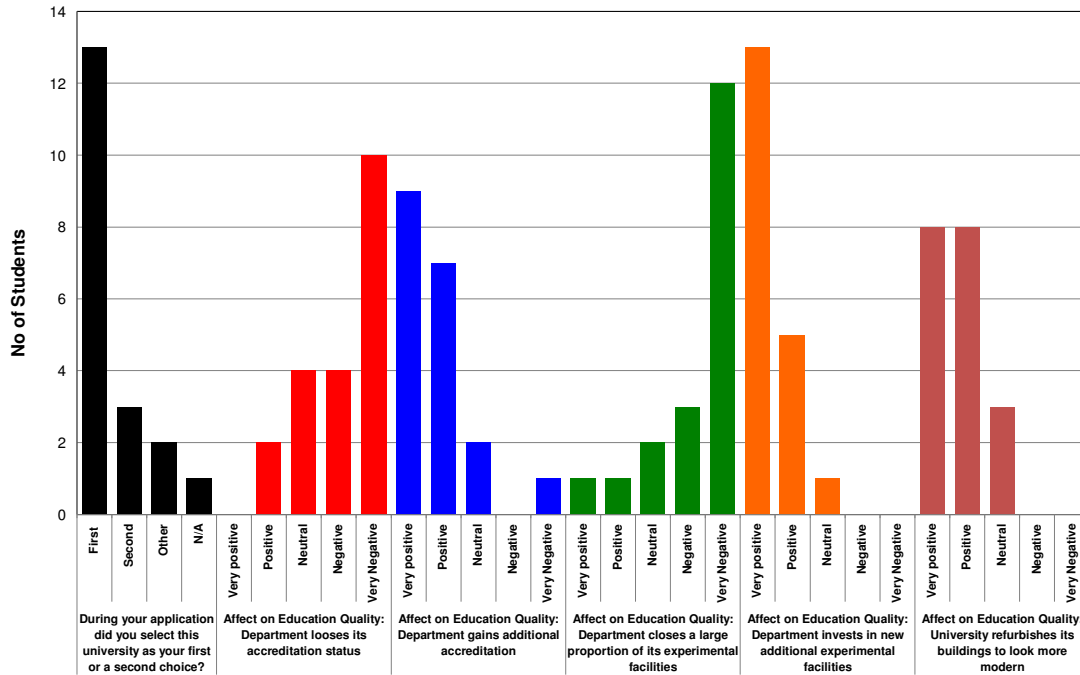


Figure 5.8: Perceptions of the affect of change on education quality: mechanical and aeronautical engineering students

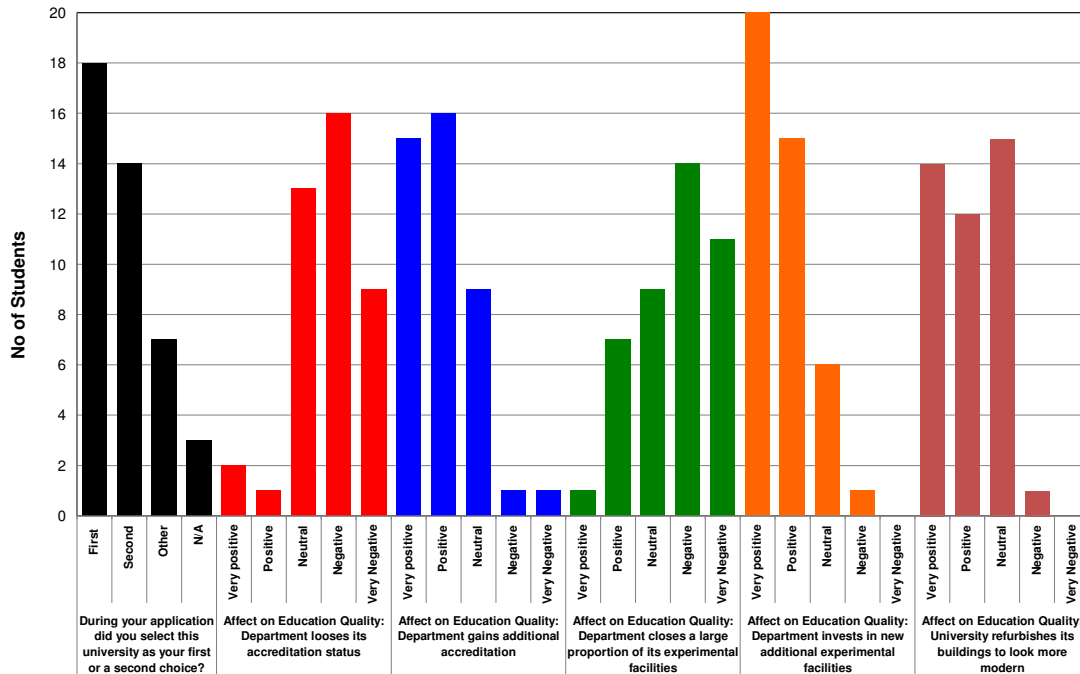


Figure 5.9: Perceptions of the affect of change on education quality: civil engineering students

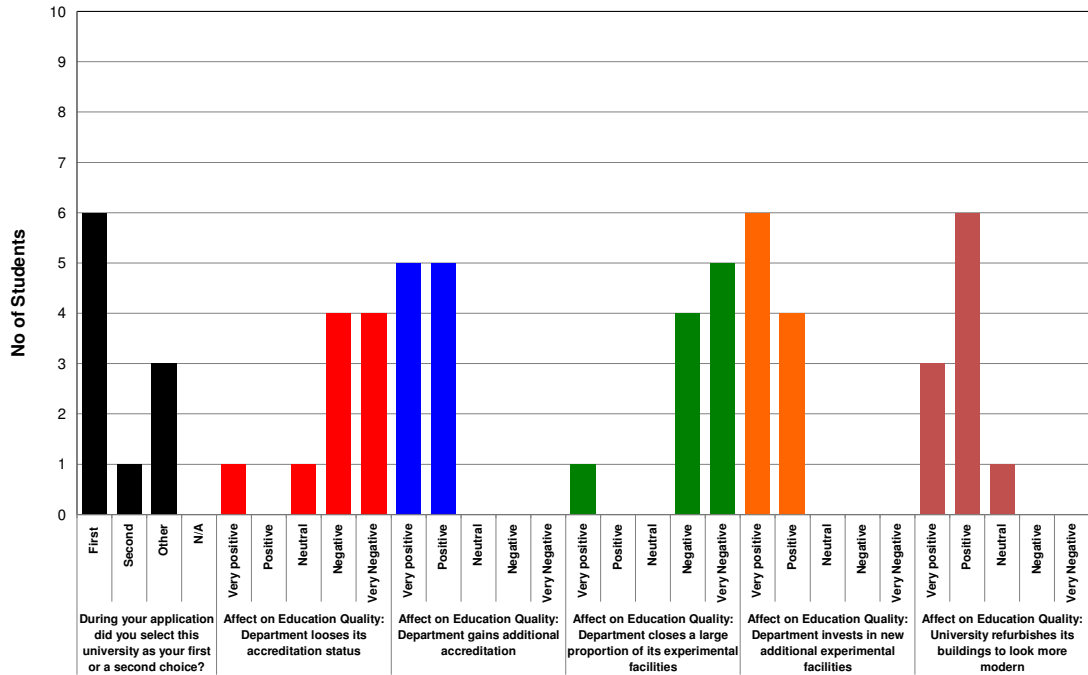


Figure 5.10: Perceptions of the affect of change on education quality: biomedical engineering students

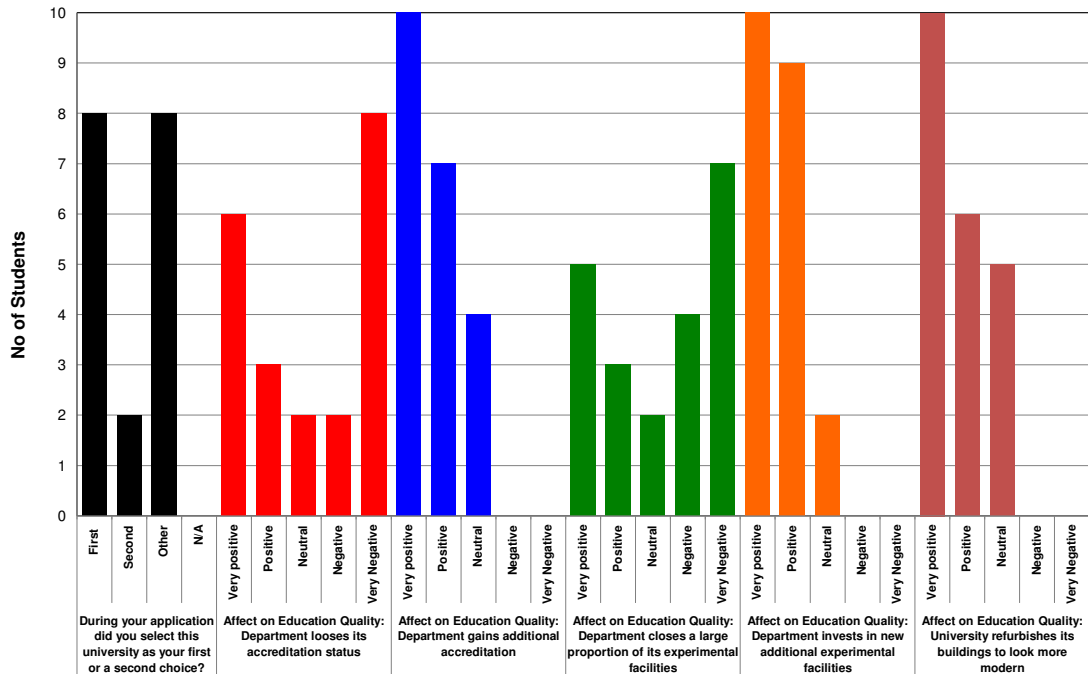


Figure 5.11: Perceptions of the affect of change on education quality: electrical engineering students

The aim of the survey was to identify student perceptions of the value of engineering laboratory facilities associated with their experimental learning activities in their programme of study. The questions specific to engineering laboratories was masked by a whole set of other questions on student attitudes, and motivations which were also designed to gain information on the general levels of motivation amongst the programmes surveyed.

The correlation, between programme streams, in the responses to the questions posed was generally very high. The conclusions are that engineering students are generally highly motivated by the discipline and subjects they are studying, are generally knowledgeable about the issues surrounding the provision of quality education, and about the issues of their profession.

While the provision of good quality engineering laboratory facilities and equipment is not the most important factor in attracting an engineering student to choose a particular university, it is certainly one of the top five out of the 18 factors listed in the survey. The students also indicated that they perceive that the provision of experimental laboratory facilities is an important factor in the quality of their education. This infers that they recognise that the practical learning experience that experimental laboratory work provides is important in their education.

What it does not infer, however, is how they prefer such facilities to be incorporated into their learning experience – whether they prefer the traditional mode of small group hands-on activity running the experiment as a lab-class in the laboratory itself, or as an accessible online laboratory that they can operate remotely from somewhere else. The review of past work on this issue has been discussed in section 1, and has shown that pedagogical benefit is to be gained by a combined approach.

5.2 Staff Perceptions of the Value of Experimental Facilities

In addition to the value that experimental test facilities have in terms of attracting and retaining students, it is intuitive that they also must have some value in attracting and retaining academic and research staff to an institution. To gauge whether this is true, and to what degree this is the case, sixteen of the seventeen academic staff in the Mechanical and Aeronautical Engineering group at City University (the seventeenth is one of the authors) were informally interviewed and

asked two questions relating to their perception of the value, to themselves, of access to a well provisioned engineering laboratory. The results of these interviews are summarized in Appendix C.

Of the sixteen staff asked the question “*Were the test facilities in the laboratories a factor in your decision to accept an academic job in the School of Engineering at City University?*”, ten of them expressed the view that the experimental laboratories were a major factor in their decision to accept an academic job at City University while two of them acknowledged that it was one of the factors which attracted them. Out of the four other staff who said that the provision of experimental facilities had played no part in their decision, two of them were quick to explain that they believed that they were still important to the department for the delivery of quality engineering degree programmes. One made the important point that even though they did not require experimental facilities themselves, they regarded it beneficial to be in a research environment where they could consult with experimentalists.

On the second question - “*If the university decided to consult you on the closure of some of the test facilities you use, what would be your response?*”, nine staff indicated that they would actively oppose such a move and a further five staff who did not indicate that they would actively fight a rationalisation, said that they would regard the move as a mistake that would harm the quality of the engineering degree programmes. One academic member of staff expressed the view that they would not really care, as they were so close to retirement, and only one staff member indicated that they would support a rationalisation if economic survival was at stake.

Seven members of staff indicated that they would then be actively looking around for another job, while another indicated that they would fully expect that such a consultation would prompt a lot of their colleagues to look to leave, and would therefore worry about the security of their own job.

Clearly the future of the engineering laboratories is an emotive subject amongst staff at this particular university in London, when seven of the sixteen staff members of one department would immediately start looking for another job if rationalisation of laboratory facilities were planned. During the process of collating the data for the survey of all of the academic and industrial wind tunnels, presented in the next section, the authors consulted with every UK aerospace engineering department. This second question was posed to all of the academic staff who had assisted with the

survey, and it became quite clear that the strong views expressed by staff at City University London, were mirrored by staff in a large majority of the other institutions.

From this it can be concluded that a continuation of the recent trend towards the managed rationalisation of engineering test facilities in UK universities, and the associated decline in capabilities, has the potential to cause a major decline in morale in the engineering academic community and a large exodus of the most qualified engineers in the country out of the academic sector, and many probably out of the engineering profession completely. The next section presents an analysis of this trend in the UK experimental test facility infrastructure, covering the industrial, governmental and academic sectors where such facilities have historically been provided. The section focuses in detail on the provision of a particular class of test facility – the wind tunnel, as a case study of how the national resource of test facilities, and thereby associated capabilities, have been eroded over the last 40 years.

6. Management and Maintenance of Engineering Laboratories in UK Academia

This section investigates how universities are funded, and how these funding streams currently support university science and engineering laboratories. In addition it explains how the universities levy their various schools / faculties to pay for the institutions' central costs, and how the charging based on floor space used is driving the current trend towards rationalisation of science and engineering experimental test facilities.

Chapter 2 of this study reviewed the available scholarly literature on the pedagogical value of hands on laboratory testing in the education of scientists and engineers and concluded that, while laboratory test facilities can be used in much more innovative and more beneficial ways to promote engineering student learning, they remain a vital element in the education of high quality engineering graduates relevant to the modern global engineering industry.

Chapter 3 has shown how important that the manufacturing sector still is to the wealth creating capabilities of the United Kingdom, and it is upon the continued quality and quantity of engineering graduates that this sector depends. The University engineering departments are therefore a vital factor in the economic wellbeing of the UK.

Chapter 4 has revealed that the UK academic sector has become a much more important provider of experimental research and development services to UK located engineering companies, due to the retreat from this field by the governmental sector via the closure or privatisation of most governmental research laboratories in the engineering sciences. Despite this, the survey of the UK wind tunnel infrastructure has revealed a significant trend towards the decommissioning of university engineering laboratory facilities as well as those in private industry and in government laboratories.

Chapter 5 revealed, through a survey of 93 engineering students at City University London, that engineering laboratories are a significant factor in student perceptions of a university engineering department when deciding which university to apply for to study engineering. The survey also revealed that students understand the value of experimental hands-on laboratory skills and indicated that a diminution of experimental educational opportunities would be seen as highly detrimental to their educational experience. An associated survey of staff revealed that a majority decided to accept employment precisely because of the research opportunities represented by good experimental test facilities, while nearly half indicated that they would look to leave if these test facilities were considered for closure. Clearly, therefore engineering laboratory facilities are of very high value to any university with a strong engineering faculty.

While the decision by national governments to close or privatise their national laboratories can be understood by the desire to reduce public spending at a time when demand for such services have reduced significantly, the question remains why universities should also be closing laboratories and decommissioning important educational and research capable test facilities of national importance when the data of Chapter 3 also shows that over recent years the demand has been increasing for UK engineering degree courses. For an effective national strategy to safeguard the infrastructure of strategically important engineering test facilities, it is therefore necessary to identify the forces which are driving this rationalisation of university experimental facilities.

6.1 Funding Sources for Academic Engineering Laboratories

The way that British universities are funded is currently (the end of the year 2010) in the process of a major overhaul, but the basic funding streams are likely to remain the same. This section presents the funding streams by which money may become available for the funding of university engineering laboratories, depending on the accounting model used by a particular university.

6.1.1 Student tuition fees.

The British government currently estimates that the average cost to educate a university student (averaged over all disciplines) is about £10,000. This predominantly covers personnel costs, but does not include meeting the costs of many overheads such as properties and facilities. However, where students use laboratories as part of their education, then this funding stream can be used to help cover items such as equipment costs.

Since 2004 British universities have charged students home students (those from England and Wales and from the European Union nations) a “*top-up*” tuition fee, currently around £3000 per year. This leaves the Government to subsidise each home student an amount of about £7000. Each university has therefore been allocated a certain number of home students, based on the available budget for higher education. Students from non-EU countries (overseas students) are charged an amount based on the estimated full economic cost of the particular course they are studying, and this can be significantly higher than £10,000. It seems likely that the Coalition Government elected in the 2010 general election will increase the maximum fee for home students (the cap) to £9000. Universities in Scotland and Wales currently do not charge their own domestic students a fee, and the Scottish and Welsh Assemblies therefore subsidise all Scottish and Welsh students for the full tuition costs.

6.1.2 The HEFCE / SHEFCE Grant

The *HEFCE* - *The Higher Education Funding Council for England* (and Wales) or its Scottish counterpart, *SHEFCE*, allocates additional funds to cover costs including funding to cover general research, which can include the maintenance of research laboratories, small scale research equipment and certain research staff costs.

6.1.3 HEFCE / SHEFCE Research Infrastructure Funding

University departments can apply for one-off grants to cover the purchase or construction of major new facilities or upgrades to existing major facilities. Funding from this source is very rarely allocated, and only when a convincing case can be made for investment.

6.1.4 Research Funding Councils

Specific research projects are funded from a different budget to the general HEFCE research budget, and these are managed by the Research Funding Councils including:

- The *Engineering and Physical Sciences Research Council* (EPSRC) provides public funding for research in the engineering and physical science disciplines, except astronomy, particle physics and nuclear physics.
- The *Science and Technology Facilities Council* (STFC) provides public funding for research in astronomy, particle physics and nuclear physics, and funds the operation and maintenance of large UK physics laboratories, such as the Central Laser Facility, the High-End Computing Terascale Resource (HECToR) and the Jodrell Bank radio telescope, as well as the UK involvement in international physics experimental facilities such as CERN, the European Southern Observatory (ESO) and the European Synchrotron Radiation Facility (ESRF).
- *The Biotechnology and Biological Sciences Research Council* (BBSRC)
- *The Medical Research Council* (MRC)
- *The Natural Environment Research Council* (NERC)
- *The Economic and Social Research Council* (ESRC)
- *The Arts and Humanities Research Council* (AHRC)

The funding of academic engineering laboratories obviously falls under the remit of EPSRC, but it is also possible that engineering research projects could also fall under the remit of the NERC, and for multidisciplinary biomedical engineering projects, under the remit of the BBSRC or MRC. This, “directed” research funding can be used to cover the cost of running existing engineering test facilities, upgrading them or, in special circumstances, the purchase of major new equipment. This funding, however, is competitive, and can therefore be quite difficult to obtain.

The UK Research Councils currently employ around 12,000 staff and support around 30,000 researchers in UK universities, managing a total budget of around £2.8 billion.

6.1.5 Government Departmental Research Funding

Various departments of the British Government invite universities to collaborate in research projects with industry. Quite often the funding streams involve funds from the particular government department as well as contributions from the funding councils and from private companies. The Ministry of Defence, for instance, has a number of funding mechanisms to promote defence related research and the collaboration of university academics and the UK defence industry. This represents an important source of research income for UK engineering departments.

6.1.6 International Public Research Funding

In addition to the UK government funding streams there are a number of international bodies who also distribute research grants for specific research projects, most notably the European Union (EU). The EU Research budget is governed according to the *Framework Programmes for Research and Technological Development* (Currently the 7th Framework Programme covering the period 2007-2013). Funding from this budget is based on specific areas deemed to be of strategic importance to the European Union, such as energy diversification or mitigating the environmental impact of powered aviation. The *European Research Council* (ERC) is the European public body which funds the “investigator driven frontier research” element of the EU 7th Programme, in much the same way as the UK EPSRC.

The EU also supports the Regional Development Agencies, which provide research grants to local companies to partner university laboratories to help develop new products in specific strategic areas. An example of this is Renewables East, which as part of the East of England Development Agency, provide research grants to help develop new renewable energy technologies in the East of England area. While these have been useful sources of income in the past, it is likely that the Coalition Government elected in May 2010 are going to abolish the Regional Development Agencies.

6.1.7 Industry Research Funding

Individual engineering companies, or consortia of companies, provide research funding for specific projects relating to their own commercial interests, and these often represent good sources of income to support engineering laboratories. In some cases a major industrial company may sponsor a particular laboratory to support its operation and maintenance.

6.1.8 Charitable Organisations

There are a large number of charitable organisations who offer research grants for specific areas of research, particularly in the medical and biological sciences. There are also a number of not-for-profit companies which are government supported, such as the Carbon Trust, which offer research or commercialisation grants to help bring new innovations to market.

6.1.9 University Spin-Off Enterprise

Universities are increasingly embracing enterprise as a means of generating income, whereby internally developed intellectual property (IP) is exploited either by licensing it to be used by an existing commercial company, or by “spinning-off” a new commercial company to market the IP in some way or form. Where such IP has been developed in a laboratory, it is possible to ensure that a funding stream is set up to support that laboratory.

6.1.10 University Alumni Associations

An important source of financial income for US universities has been through the Alumni Associations, whereby former students commit to contributing to the support of their old university department. Often a university will institute a funding campaign for the development or upgrade of a particular laboratory. British universities are now beginning to recognise the potential of such an income stream and are beginning to develop their Alumni Associations on the US model.

There is, therefore, no shortage of funding sources by which a university engineering laboratory can be financially supported. With the steady rise in students

enrolling onto engineering programmes in UK universities, particularly from overseas, as highlighted in chapter 3, there should be a steadily increasing level of funds available for the support and development of engineering test laboratories. The increasing demand from industry, given the withdrawal of government from the provision of science and technology experimental services highlighted in chapter 5, should also have resulted in improved income to support university experimental facilities. The question, then, is why are so many of the UK engineering departments continuing to rationalise their engineering test infrastructure?. Also can any of these income streams be modified in a way that can further improve the support of academic science and engineering laboratories?

6.2 Costing Models for Academic Engineering Laboratories

Each university has its own buildings and estates, from which the functions of the university – its delivery of education, and its research, are carried out. These buildings must be maintained, heated and powered, and science and technology laboratories form a part of this infrastructure. The university therefore needs to allocate a proportion of its income, brought in by each of its schools or faculties, to cover these Properties and Facilities (PAF) costs.

Properties and Facilities costs generally include buildings maintenance, new building construction (or an element of), rents and rates, utilities costs (water, gas, electricity etc.), cleaning, portering, security and insurance. These costs tend to be levied from the individual schools or faculties based on the space they occupy – the *Space Charge*. The calculation of the space charge levied on an academic school or faculty can take into account the nature of space usage, but quite often does not. For instance, the charge could be reduced for space classified as 'equipment dominated' compared with that for office and teaching space. The details of how the space charge is levied generally comes down to the politics within the particular university.

The result of this space charge is generally that space intensive schools and departments will have to contribute significantly more than the less space intensive. All academic departments will require office space and some degree of storage space. Teaching space, particularly large lecture theatres, will generally be centrally managed and not fall under the remit of any particular school or faculty. Science and

Engineering departments will almost certainly require computer rooms and the provision of costly number crunching computer systems and servers, teaching laboratories of sizeable floor area, as well as research laboratories (sometimes fulfilling both the teaching and research function in one). The disparity between the space charge contribution between, say, a history department, and an engineering department can be enormous.

University central administration departments also charge the schools / faculties for other overheads, such as central services such as the library and information services, computing service, registry and finance departments, human resources etc. Typically those services which are student centred are levied at a rate based upon student numbers, while those services that are staff centred, such as human resources and senior management, are levied according to the number of staff employed. Since science and engineering departments tend to have to employ a sizeable staff of technicians to support the laboratory work, which many humanities departments do not require, this leads to an even higher overhead for science and engineering departments.

At City University, for example the space charge levied by the university for the Handley-Page Aeronautical Laboratory is about £300 per square metre, which results in a cost to its home school of over £300,000 per annum. This cost, does not cover any of the maintenance of its facilities or its equipment, or for any new equipment, but only covers the contribution that it makes to cover the properties and facilities cost of the university as a whole. For this reason the School of Engineering at City University London, which cannot cover the costs of its own space when levied at this current rate, is now down-sizing, relocating the Handley-Page Laboratory and decommissioning four of its eight wind tunnels, in an effort to reduce its space charge burden. Laboratory rationalisation driven by a desire to reduce space charge costs, and thereby “live within means”, is now occurring in most UK engineering departments.

The UK research councils are now funding the “Full Economic Cost” of the research that they support, which include a contribution to space charge of the facilities used, and this has certainly helped to cover the costs of maintaining university engineering laboratories. However, it is clear that this is simply not enough.

What makes this problem worse, is that it does not seem to be understood that unless the rationalisation of laboratory space results in the sale of an entire building, or its renting out by a commercial company, then it is a false economy. If the

relinquished space, which must still be maintained by the university properties and facilities organisation, is left empty and unused by another school or faculty (which is the case in most instances) then the space charge per square metre will have to be increased for every faculty, thereby diminishing the benefit of giving up the space in the first place.

Any short term measure to cut the properties and facilities spend, by cutting space used by science and technology departments, will result in the irremediable destruction of expensive teaching and research facilities, equipment and experience that the data of chapter 3 shows is vital to the national economy, and which chapter 4 has shown has significant value in attracting and retaining both staff and students.

It is certain that the Space Charge model of levying academic schools for the central cost of the university's properties and facilities, is a major cause of the current trend towards the rationalisation of engineering test facilities, and is a major threat to the sustainability of the UK's university engineering departments. A major review should therefore be instituted to investigate alternative models by which university science and technology laboratories are maintained, in relation to the maintenance of university properties and facilities as a whole.

7. A National Integrated Strategy for Engineering Test Facilities

This section summarises the findings of the previous chapters, and makes the recommendation for a national strategy for engineering test facilities, which this study has shown is now essential for the UK to retain its current capabilities in engineering science and technology. A number of specific actions have been recommended that, for minor monetary investment, will significantly improve the environment for the funding and support of world class engineering test facilities for education, research and product development in the UK.

7.1 Overview

This study has reviewed and assessed the main issues affecting the sustained provision of experimental test facilities, such as wind tunnels and engine test facilities, in the UK academic and industrial engineering sectors.

Chapter 2 of this study undertook to assess whether engineering laboratories remain necessary in modern university degree programmes, given the educational flexibility and cost effectiveness of modern computational methods of teaching, and whether there remains some pedagogical value in hands on laboratory testing in the education of scientists and engineers. The consensus proved to be that, while laboratory test facilities can be used in much more innovative and more beneficial ways to promote engineering student learning, they remain a vital element in the education of high quality engineering graduates relevant to the modern global engineering industry.

The value of the UK's remaining manufacturing industries to its economy and the importance of the domestic availability of engineering test facilities was reviewed in Chapter 3. It was shown that manufacturing, despite prevailing perceptions of industrial decline propagated by the media, is still a vitally important to the UK

economy, representing around £200-250 billion or export income annually. It was also shown that manufacturing industry, which relies upon access to physical testing facilities to ensure the functionality and safety of its commercial products, and the other creative industries, must be the growth sectors upon which the United Kingdom can reverse its long term, and ever worsening balance of trade deficit. The chapter also shows that the Higher Education sector itself generates strong and growing export revenues, and that, following a long period of decline, engineering and the broader STEM subject area, are growth disciplines with strong demand from both home and overseas students.

Chapter 3 also showed that the view that modern computational engineering methods such as Computational Fluid Dynamics, or Finite Element Stress Analysis, can replace physical testing in the engineering design process, due to a perception of acceptable accuracy, flexibility, and cost effectiveness, is simply false. The more data required in a particular engineering design program, the quicker and more cost effective experimental testing will be over computer simulation. Even with the yearly improvement in computer technology and associated reducing costs, it will be many decades before computer simulation can compete in purely cost terms, with experimental testing.

The very real decline in the UK national engineering test infrastructure, and the economic forces which have driven it, have been discussed in Chapter 4, where the details of the decline in the provision of high speed wind tunnel facilities are also documented. It has been shown that the UK academic sector has become a much more important provider of experimental research and development services to UK located engineering companies, due to the retreat from this field by the governmental sector via the closure or privatisation of most governmental research laboratories in the engineering sciences. Despite this, the survey of the UK wind tunnel infrastructure has revealed a significant trend towards decommissioning university engineering laboratory facilities as well as those in private industry and in government laboratories.

Chapter 5 studied the value that engineering laboratory facilities have for universities in attracting good students to apply to their engineering departments, and in retaining those students, and the value they have in attracting and retaining good academic staff. The survey, undertaken at one inner city university with a strong track record in engineering education and extensive engineering laboratories for education

and research activity, revealed that the provision of good engineering laboratory facilities had been one of the top 5 (of 18) factors in students choosing their university engineering department, and that an overwhelming majority of students indicated that a diminution in provision of such facilities would be detrimental to effective learning on their degree programme. In addition 75% of the staff interviewed indicated that the engineering test facilities were a factor in their decision to accept employment at their university, while just over 40% indicated that they would immediately start looking for alternative employment if a rationalisation of such facilities was signalled. There is, therefore, strong evidence that engineering laboratories have significant value to any university aiming at the long term delivery of engineering education programmes.

The ways by which UK university schools or faculties generate income, and the methods by which this income is charged to fund university central services, management and properties and facilities costs, is reviewed in Chapter 6. One of the principal causes of the ongoing trend in the decommissioning university engineering test facilities was identified as the charging for central overheads, based on floor space occupied by the income generating schools or faculties. Such a levying system significantly disadvantages science and technology disciplines, over other less space intensive disciplines, and is a major economic force in driving science and technology departments to give up laboratory space and thereby significantly reduce costs.

Given that capability and skills, and therefore eventually product design and manufacture, tend to cluster around world class facilities, the diminution of UK located world class test facilities has serious implications for the sustainability of the UK manufacturing base. Global industrial companies will locate their activities where the local skills are best aligned with corporate needs, and where world class engineering design, test and research services are locally available. If UK graduates are not properly skilled in the area of physical testing of engineering systems, or in the experimental scientific methods, and graduate with little or no experience at all in these disciplines, the United Kingdom cannot compete for major engineering projects. The danger, then, is that the large negative balance of trade figures will be accentuated as UK manufacturing continues to decline, leading inexorably, without spectacular growth in other areas of the economy, to national bankruptcy.

7.2 A National Strategy for Engineering Test Infrastructure.

It seems clear that a national strategy is now needed to ensure that the best engineering test facilities are saved for the nation, and that funding streams are designed to ensure that there are enough funds to allow these to be properly maintained and developed. The following measures, based on the findings of this study, are recommended for inclusion in a national strategy for engineering test infrastructure.

7.2.1 Review of University Capital Space Charging.

This study has shown that, apart from a few world class industry associations, such as ARA and MIRA, most of the engineering test infrastructure is now maintained in the care of the universities, where it is employed in providing practical education experience, and in research as well as in design and development services to industry and government. The policy of capital space charging, which represents a significant tax upon these facilities, must therefore be addressed and revised in a way to stop it being economically detrimental to maintain scientific or engineering laboratories.

7.2.2 Register of Strategic Facilities

The Department for Business Innovation and Skills should coordinate the process, with input from other public and private stakeholders, of establishing a register of nationally important, and thereby strategic, facilities across the broad engineering sector, encompassing mechanical, aerospace and civil engineering sectors. This recognises that there is still scope for further cost reductions, within both public and private sectors, in further rationalisation of old and defunct test infrastructure. However, having such a register would allow the most important facilities to be identified and for funding to be directed to better support their continued utilization, maintenance and development. Such a register would also allow government oversight of this strategically important resource, and would mitigate somewhat the current practice of individual institutions unilaterally decommissioning important facilities on the basis of immediate economic requirements, without reference to any broader national concerns.

A transparent process would need to be defined by which individual test facilities are designated strategic or not. This might involve a temporary committee being set up, under the auspices of the Technology Strategy Board, with subcommittees based on class of facility, tasked with assessing each case. All public and private engineering organisations holding engineering test infrastructure should be expected to submit details of their facilities, recognising that it will be in their financial benefit to do so if they wish to receive public support for such facilities.

7.2.3 Online National Database of Scientific and Engineering Test Facilities

An online, open access, searchable database of the available scientific and engineering test facilities should be established, which will help government, industry and academia to monitor the situation in the future, and, perhaps more importantly, to “*advertise*” UK capabilities to the global marketplace. This will help UK based companies, laboratories and facilities maximise their chances of winning experimental work from overseas, and retaining UK based work.

7.2.4 Focused Funding Streams

Once a register of national strategic test facilities has been identified the funding streams by which engineering test facilities are supported needs to be reviewed and changed in order to favour those facilities designated strategic. This economic advantage will incentivise those institutions which own or have custody of a strategic facility to retain and properly maintain those facilities.

Specifically the rules governing the allocation of public money for engineering research and development should be changed such that funding can only be directed for use in a strategic facility, unless there is a strong overriding case for this rule to be broken. Such a policy would allow public funding to be focused, having the strongest possible power in supporting and sustaining national capabilities in engineering.

For the academic community, this would not result in any diminution of academic freedom to undertake research, as each investigator would have the freedom to apply for funding to employ any strategic facility (either in the public or private sector). This would have the potential added benefits of i) expanding

the scientific infrastructure available to the academic community, by including privately owned and operated facilities, ii) better ensuring world class research as all publicly funded research would be done in the highest quality facility, rather than in sub-standard facilities chosen purely for domestic expediency, iii) better promoting collaborative research, where investigators will have to partner the experienced staff of the host institution providing the strategic facility, iv) provide additional funding for the support of privately owned facilities and promote stronger collaboration between academia and private industry – an area in which the UK has been relatively poor compared with other countries, the US in particular.

7.2.5 Statutory Conditions

New regulations should be imposed upon those public bodies, such as universities, who are custodians of a national strategic test facility. Since all university laboratory facilities are technically public property, this would be both legal and proper. A public body should have to inform the Department of Business, Innovation and Skills (or its successor) of any intention to divest itself of a strategic facility at least six months before any action is taken. In this time the justification for such a move can be investigated, and possible actions taken to keep the facility going, including funding via the HECFE or SHEFCE infrastructure funding stream. In this time, if necessary, new custodians could be found and details of the relocation of the facility worked out. This would prevent instances of facilities – even whole laboratories – being closed and decommissioned without the wider community being aware, and thereby able to make alternative arrangements for suitable relocation.

Any institution, public or private, which contravenes these regulations, should then automatically become ineligible for new public research and development funding for three years.

The professional engineering bodies also have a role to play, particularly the Engineering Council which defines the criteria to be met for accreditation of engineering degrees, and for the Chartered Engineer (*CEng*) qualification. Currently every accredited engineering programme is required to provide a course that meets the learning outcomes on Engineering Applications EA1 –

knowledge and skills associated with metalworking and fabrication using such tools as the lathe, the milling machine and modern digital CNC machines. In a similar way, the Engineering Council should introduce criteria, in the UK specifications for engineering degrees, to formally codify the learning outcomes required from engineering laboratory courses. This could be done to allow flexibility in how this is achieved within a particular three or four year programme. Introducing such criteria for accredited programmes will help to ensure that all UK engineering graduates meet a minimum requirement for knowledge and skills in the design and execution of an experimental test programme, and in the associated data, accuracy and error analysis.

7.2.6 Industry-Academia Collaboration

Stronger collaborative links should be promoted between those private organisations with good world class engineering facilities such as ARA and MIRA and the academic sector, and for these facilities to be, where possible, employed in experimental laboratory activities such as laboratory classes, and project dissertation research. Where these are strategic facilities, and projects are for developing the facility for educational activity, such companies should be made eligible for HECFE / SHEFCE strategic infrastructure grants.

A new funding scheme to cover the travel and subsistence costs for good students to spend up to two weeks at a strategic facility, to undertake experiments as part of their final year dissertation research, should also be investigated. This measure would help the cream of UK engineering graduates gain the same specialised experience in large scale testing (which few currently do) that is gained by many US graduates at institutions such as the National Institute of Aerospace / NASA, and by many French graduates at SUPAERO / ONERA.

8. Conclusions

The following conclusions can be drawn from the findings of this study:

- Manufacturing industry, which relies upon access to physical testing facilities to ensure the functionality and safety of its commercial products, generates around £200-250 billion of export income annually, compared with only about £50 billion from financial services. The UK engineering industry therefore remains of primary importance to the UK economy.
- Modern computational engineering methods such as Computational Fluid Dynamics, or Finite Element Stress Analysis, cannot replace physical testing in the engineering design process. The more data required in a particular engineering design program, the quicker and more cost effective experimental testing will be over computer simulation. Even with the yearly improvement in computer technology and associated reducing costs, it will be many decades before computer simulation can compete in purely cost terms, with experimental testing.
- The Higher Education sector itself generates strong and growing export revenues, and following a long period of decline, engineering and the broader STEM subject areas are now growth disciplines with strong demand from both home and overseas students.
- Engineering laboratory facilities in universities remain essential tools for the education of well trained, relevantly skilled and globally competitive engineering graduates. Modern computer based laboratory simulation tools, while effective in enriching the learning opportunities of the modern UK university engineering student, cannot properly provide many essential learning outcomes which can be gained through practical laboratory instruction.

- The provision of good quality and extensive engineering laboratory facilities is an important factor in attracting good students to a university engineering department. This is particularly important if the UK is to continue to attract engineering students from overseas countries, like China and India, whose universities are now investing in modern facilities themselves. Laboratory facilities are also important factors in attracting and retaining good academic staff in engineering disciplines.
- However, a very real and serious decline in the provision of engineering test facilities in the UK has occurred, and is continuing. It has been shown that the UK academic sector has become a much more important provider of experimental research and development services to UK located engineering companies, due to the retreat from this field by the governmental sector via the closure or privatisation of most governmental research laboratories in the engineering sciences. Despite this, a significant ongoing trend towards decommissioning of university engineering laboratory facilities has been revealed, driven mainly by the imposition of capital space charging which disadvantages science and technology departments considerably more than other less space intensive departments.
- In order to stop the ongoing steady decline in the provision of experimental test facilities and a further serious erosion of sovereign capabilities in engineering science, a government sponsored national strategy for engineering facilities is now essential. This should aim to identify those “strategic” UK located test faculties that are critical to the continuance of sovereign capabilities in engineering science. Public funding streams for experimental research or developmental testing in engineering science should then be focussed only on those strategic facilities, as outlined in chapter 7.
- A review of the Capital Space Charging system at UK universities should be undertaken in order to identify a better way of funding institutional properties and facilities spend that does not disadvantage space intensive STEM

disciplines and will reduce the significant pressures on these disciplines to decommission expensive laboratory facilities.

- The various public funding streams that currently support the development and maintenance of university laboratory equipment should be opened up to fund those “strategic” facilities located outside of the academic sector, such as those in the ARA and MIRA industry associations, where these can be developed for use in educational programmes, or for final year dissertation studies.
- The merits of establishing of a new grant to fund the living expenses of a selected number of the best UK undergraduate engineering students to undertake their final year dissertation project at a major strategic industrial facility, should be investigated as a tool to promote improved collaboration between industry and academia, while improving the experience and, thereby, capabilities of the very best UK engineering graduates.

Acknowledgements

The authors would like to express his gratitude for the support freely given by the Association of Aerospace Universities, the Association of the Defence Sector, the Aerospace and Defence Knowledge Transfer Network, and the Ministry of Defence. Almost every mechanical and aerospace engineering department in the UK has voluntarily provided data for this study, and thanks must go to all those, unmentioned here, who have contributed in this endeavour.

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Appendix A: Summary of UK Wind Tunnel Survey 2010

No	Name of tunnel	Owner / Operator	Reynolds number per metre (m)	Working section dimensions			Maximum Mach number	Tunnel Classification
				Height (m)	Width (m)	Length (m)		
1	Airbus Filton Low Speed Wind Tunnel Facility	Airbus, New Filton House, Bristol	6675562	3.05	3.65	-	0.29	Subsonic
2	Small Transonic Tunnel (Z4T)	Aircraft Research Association	29523876	0.2	0.23	-	1.3	Transonic
3	Transonic Wind Tunnel (1.2bar) (0.8bar)	Aircraft Research Association	17000000	2.44	2.74	-	1.4	Transonic
4	2 dimensional tunnel (2DT)	Aircraft Research Association	11500000	2.44	2.74	-	0.7	Transonic
5	Wind Tunnel 1	AT & T Williams	55000000	0.3	0.87	-	0.87	Subsonic
6	Wind Tunnel 2	AT & T Williams	3785112	3	3	-	0.17	Subsonic
7	Filton 12 * 10 ft Low Speed Wind Tunnel	BAE Systems Air Systems	5712079	3	3	-	0.25	Subsonic
8	Boundary Layer Wind Tunnel	BAE Systems Air Systems	5677669	3.048	3.65	7.62	0.25	Subsonic
9	Low Speed Wind Tunnel	British Maritime Technologies	3096910	2.4	4.8	15	0.14	Subsonic
10	Wind Tunnel 1	British Maritime Technologies	4473315	2.1	2.7	-	0.20	Subsonic
11	Large Low Speed Wind Tunnel	Brawn F1	3303371	2.3	2.3	6	0.15	Subsonic
12	Low Turbulence Wind Tunnel	University of Bristol	4129213	1.5	2.1	-	0.18	Subsonic
13	Open Jet Wind Tunnel	University of Bristol	6882022	0.6	0.8	-	0.30	Subsonic
14	Open Return Low Speed Wind Tunnel 1	University of Bristol	2752809	1.1	1.1	-	0.12	Subsonic
15	Open Return Low Speed Wind Tunnel 2	University of Bristol	2408708	0.6	0.6	-	0.11	Subsonic
16	Armfild	University of Bristol	2408708	0.6	0.6	-	0.11	Subsonic
17	Other	University of Bristol	2752809	0.3	0.3	-	0.12	Subsonic
18	Plint & Partners	Brunel University	1101124	0.5	0.5	-	0.05	Subsonic
19	Plint & Partners Supersonic	Brunel University	2064607	0.457	0.457	-	0.09	Subsonic
20	1A	Brunel University	40879213	0.1	0.025	-	1.80	Supersonic
21	2	Cambridge University	2000000	0.51	1	0.75	0.09	Subsonic
22	Markham	Cambridge University	2500000	0.4	0.4	-	0.12	Subsonic
23	SST1/SST2	Cambridge University	4100000	1.1	1.7	2.5	0.18	Subsonic
24	T1	Cambridge University	40000000	0.114	0.178	0.6	2.5	Supersonic
25	T2	Cambridge University	27000000	0.114	0.178	0.6	0.6	Transonic
26	T3	City University, London	1400000	0.3	1	0.06	20	Subsonic
27	T4	City University, London	3100000	0.81	1.12	1.78	0.13	Subsonic
28	T5	City University, London	3800000	1.12	1.5	0.16	55	Subsonic
29	T6	City University, London	2900000	0.4	0.56	-	0.12	Subsonic
30	T7	City University, London	1.30E+07	0.2	0.25	0.5	0.7	Supersonic
31	T10	City University, London	1.51E+07	0.2	0.25	0.5	1.6	Supersonic
32	Boundary layer wind tunnel	City University, London	1700000	1.5	3	8	0.08	Subsonic
33	Closed section	City University, London	3800000	0.45	0.47	0.92	0.09	Subsonic
34	DS Houghton	Cranfield University	2064607	0.13	0.76	-	0.09	Subsonic
35	Greenwich	Cranfield University	2752809	1.1	1.4	-	0.12	Subsonic
36	Supersonic	Cranfield University	2890449	1.4	2.75	-	0.13	Subsonic
37	Two by Two	Cranfield University	2615169	0.76	0.76	-	0.12	Subsonic
38	Gun tunnel	Cranfield University	54505618	0.15	0.15	-	2.4	Supersonic
39	No. 1	Cranfield University	1376404	0.6	0.6	-	0.06	Subsonic
40	No. 2	Cranfield University	27887140	0.215 (diameter)	0.215	-	12.00	Hypersonic
41	No. 3	Farnborough Air Sciences Trust	3441011	7.3	7.3	-	0.15	Subsonic
42	Gun tunnel	Farnborough Air Sciences Trust	6193820	2.6	3.4	6.1	0.27	Subsonic
43	Icing Wind Tunnel	Farnborough Air Sciences Trust	5849719	0.9	1.2	3.4	0.26	Subsonic
44	Arcyl Wind Tunnel	Gas Dynamics Ltd., Farnborough	32808400	0.102 (diameter)	0.102	-	12.50	Hypersonic
45	Handley Page Wind Tunnel	GKN	14080618	0.178	0.305	1.07	0.62	Subsonic
46	Low Speed Wind Tunnel	Glasgow University	7267416	0.508	0.702	1.07	0.23	Subsonic
47	Cascade	Glasgow University	5230307	2.04	2.65	-	0.23	Subsonic
48	Closed Return	Glasgow University	4129213	1.51	2.13	-	0.18	Subsonic
49	Large Open Return Wind Tunnel	Glasgow University	2064607	0.95	1.15	-	0.09	Subsonic
50	Open Jet-Closed Return Tunnel	University of Hertfordshire	2202247	0.4	0.4	-	0.10	Subsonic
51	Small Supersonic Wind Tunnel	University of Hertfordshire	1720506	0.84	1.145	-	0.08	Subsonic
52	Super Sonic Wind Tunnel	University of Hertfordshire	1514045	1.24	1.54	-	0.07	Subsonic
53	Hypersonic Gun Tunnel	University of Hertfordshire	3785112	0.48	0.48	-	0.17	Subsonic
54	Low Speed Closed Circuit	University of Hertfordshire	40879213	0.025	0.1	-	1.8	Supersonic
55	Supersonic Blow Down Tunnel	Imperial College London	90842697	0.1	0.15	-	4	Supersonic
56	Donald Campbell	Imperial College London	40000000	0.457 (diameter)	0.457	-	9.00	Hypersonic
57	The Honda Low Speed Tunnel	Imperial College London	2408708	0.91	0.91	-	0.1	Subsonic
58	Circular Open Jet	Imperial College London	45421348	0.1	0.15	-	2	Supersonic
59	Closed Cicuit	Imperial College London	3406601	1.22	1.37	-	0.15	Subsonic
60	AAE Wind Tunnel	Imperial College London	2752809	1.5	3	9	0.12	Subsonic
61	Open Jet Low Speed	Kingston University	2752809	1.6	1.6	-	0.12	Subsonic
62	Small Low Turbulence	Kingston University	2752809	1	1	-	0.1	Subsonic
63	Blowdown Wind Tunnel	Loughborough University	2752809	1.32	1.92	3.6	0.13	Subsonic
64	Low Turbulence Wind Tunnel	Loughborough University	2752809	1	1	-	0.1	Subsonic
65	Transonic Wind Tunnel	University of Manchester	3441011	0.95	1.35	-	0.15	Subsonic
66	Gun tunnel	University of Manchester	2752809	0.95	1.35	-	0.12	Subsonic
67	Steady Uniform Flow	University of Manchester	2890449	0.5	0.5	3	0.13	Subsonic
68	Climatic Wind Tunnel	University of Manchester	22710674	0.15	0.21	0.6	1	Transonic
69	Full Scale Wind Tunnel	University of Manchester	45421348	0.15	0.21	0.8	2	Supersonic
70	Model Scale Wind Tunnel	Mclaren Mercedes	45212600	0.254 (diameter)	0.254	-	13.00	Hypersonic
71	Low Speed Wind Tunnel	MIRA	3441011	4	3	-	0.15	Subsonic
72	Low Speed Wind Tunnel	MIRA	3823346	8	8	-	0.15	Subsonic
73	1	MIRA	3441011	5	3	-	0.15	Subsonic
74	2	MIRA	3441011	2	1.5	-	0.15	Subsonic
75	3	MIRA	3441011	2	1.5	-	0.15	Subsonic
76	4	QuintEQ	7600000	4.2	5	8	0.34	Subsonic
77	Blower Tunnel	Queen Mary University London	3096910	1	1.2	4	0.14	Subsonic
78	Low Turbulence Tunnel	Queen Mary University London	2752809	0.77	1	2.3	0.12	Subsonic
79	Smoke Tunnel	Queen Mary University London	2408708	0.77	1	2.3	0.11	Subsonic
80	Sonic tunnel	Queen Mary University London	2752809	0.38	0.5	2.4	0.12	Subsonic
81	Transonic Tunnel	Queen Mary University London	1238764	0.22	0.45	0.8	0.05	Subsonic
82	F1 Wind Tunnel	Queen Mary University London	2752809	0.38	0.5	2.4	0.12	Subsonic
83	Boundary Layer Wind Tunnel	Queen Mary University London	1101124	0.22	0.45	0.8	0.00	Subsonic
84	Environmental Tunnel	Queen Mary University London	22710674	0.127	0.135	-	1.00	Transonic
85	Large Super Sonic Wind Tunnel	Queen Mary University London	56776685	0.127	0.135	-	2.50	Supersonic
86	Low Speed Wind Tunnel	Queen Mary University London	68132022	0.127	0.135	-	3.00	Supersonic
87	LSWT a	Queen Mary University London	18168539	0.089	0.185	-	0.8	Subsonic
88	LSWT b	Queen's University Belfast	2271067	0.1	0.1	-	0.1	Transonic
89	No 1	Renault	3406601	3	4	-	0.15	Subsonic
90	No 2	Salford University	1032303	0.3	0.3	1.1	0.05	Subsonic
91	No 3	Salford University	688202	1.53	2.14	10	0.03	Subsonic
92	Small Super Sonic	Salford University	79487360	0.15	0.15	0	3.5	Supersonic
93	Re-circulation	Salford University	2408708	0.1	0.1	-	0.1	Subsonic
94	Suction	Salford University	2408708	0.1	0.1	0.15	0.1	Subsonic
95	3' x 2'	Salford University	2408708	0.1	0.1	0.15	0.1	Subsonic
96	7' x 5'	Salford University	2477528	0.85	1.5	-	0.11	Subsonic
97	Other	Salford University	2064607	0.85	1.5	-	0.09	Subsonic
98	Other	Salford University	2477528	0.45	0.45	-	0.11	Subsonic
99	Other	Salford University	40879213	0.1	0.1	0.25	1.8	Supersonic
100	Other	Sheffield University	155000	0.3	0.3	-	0.08	Subsonic
101	Other	Sheffield University	9000	1.3	1.3	-	0.05	Subsonic
102	Other	Southampton University	2752809	0.6	0.9	4.5	0.12	Subsonic
103	Other	Southampton University	757022	3.7	3.7	4.6	0.03	Subsonic
104	Other	Southampton University	3096910	1.5	2.1	4.4	0.14	Subsonic
105	Other	Southampton University	3096910	2.6	3.5	10.5	0.14	Subsonic
106	Other	University of Surrey	309691	1.5	3.5	20	0.01	Subsonic
107	Other	University of Surrey	2064607	0.6	0.9	5	0.09	Subsonic
108	Other	University of Surrey	1032303	0.5	1.5	2	0.05	Subsonic
109	Other	University of Surrey	2271067	0.3	0.3	0.3	0.10	Subsonic
110	Other	University of Surrey	1376404	0.3	0.6	2	0.06	Subsonic
111	Other	University of Surrey	2064607	1.1	1.4	9	0.09	Subsonic
112	Other	UWE	3441011	1.53	2.14	-	0.15	Subsonic
113	Other	UWE	2752809	1	0.5	-	0.12	Subsonic
114	Other	UWE	34410112	0.1	0.1	-	1.50	Supersonic

Appendix B – Student Questionnaire

City University Engineering Students Anonymous Survey

University _____

Which course are you on? _____ Part _____

Age _____ Male Female

Are you a domestic or foreign student? Do you have a part time job?

Domestic Foreign Yes No

Parental income

£0 - £30,000 £30,000 – £60,000 £60,000 - £90,000 Over £90,000

Do you have an engineer in the family?

Yes No

Do you have an engineer as a friend or role model?

Yes No

With regards your decision to go to university and study an engineering discipline, how would you agree / disagree with the following statements?

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
I always knew I wanted to study engineering at university.					
My family expected me to go to university.					
I chose to study at university to increase my earning potential.					
I chose to go to university to experience the student lifestyle.					
I chose to go to university to delay getting a job.					
I chose to go to university because it was hard to get a good job.					
An increase in the tuition fees would have dissuaded me from going to university.					

During your application did you select this university as your first or a second choice?

First Second Other

What was the main reason behind your “First choice” selection?

What was the main reason behind your “Second choice” selection?

From this list can you select five the top five reasons for selecting a university in order of importance.

- The reputation of the university.
- The League table position of the university.
- The quality and reputation of the academic staff.
- The entry requirements expected by the university.
- The quality of the laboratory resources that are available for your use.
- The accreditation status of the university.
- The academic atmosphere.
- The social atmosphere.
- The modern feel to the university.
- The traditional feel to the university.
- Because the university is close to family/friends.
- Because the university is far from family/friends.
- A friend was studying at the university.
- The town or city in which the university is situated is desirable.
- The weather associated with the location of university.
- The cost of the tuition fees.
- The availability of scholarships/financial aid.
- Parental opinion.

If the following events were to occur, indicate the degree to which you think that it would be a positive (good) or negative (bad) change to the quality of your university education.

	Very positive	Positive	Neutral	Negative	Very Negative
Department loses its accreditation status					
Department gained additional accreditation					
Department closes a large proportion of its experimental facilities					
Department invests in new additional experimental facilities					
University refurbishes its buildings to look more modern					

Appendix C – Results of Staff Survey on Attitudes to Laboratory Provision

	<i>Q1: Were the test facilities in the laboratories a factor in your decision to accept an academic job in the School of Engineering at City University?</i>	<i>Q2: If the university decided to consult you on the closure of some of the test facilities you use, what would be your response?</i>
Academic A	Yes	I would fight it. I can still contract my research out elsewhere, but I would still oppose such a move. How could we teach our students to be good engineers?
Academic B	Yes, but back then the facilities were more extensive.	I would simply look to take my work elsewhere. There are plenty of other institutions that would accommodate my laboratory work.
Academic C	It was a factor, even though I don't need to use them.	I would resist it, as they provide significant value to our courses.
Academic D	Yes, most definitely	I would argue against it. It would be disastrous for the students, and I would have to consider looking to move elsewhere.
Academic E	Yes, though I brought some of my own equipment	They would not listen to me.
Academic F	Absolutely, I cannot do my research without them	Protest, and I would immediately start looking for another job.
Academic G	No, I don't really use labs, my work is computer based	I would feel it a great pity, a further impoverishment for our programmes
Academic H	Certainly yes, I have my own lab and need it for my research.	I would object, for what it is worth. I would then have to partner some other institution.
Academic I	Absolutely, I was impressed that City still had big laboratories.	I would object strongly, and would have to consider my options if it happened.
Academic J	Yes, at the time I enrolled, but I'm about to retire and they don't affect me now.	I would not oppose it, one has to survive financially and if they are too costly to keep. Engineering courses need to evolve with the times.
Academic K	Definitely, yes. While the facilities are not the best, there is an impressive array of capability.	I would look for another job.
Academic L	Not really, but I can see that they are important for delivery of the engineering degrees.	I don't need them and am too close to retirement to want to get involved.
Academic M	Indeed. I was impressed with the facilities.	I would protest to the Vice Chancellor, and write to my MP.
Academic N	Yes, to a degree, but I don't need them personally.	I would support any objection, but it would not do any good.
Academic O	Not really, my area is more operations and management, but I recognise that they are important in the delivery of our programmes	If asked I would express my opinion that it would be a mistake - we would not attract good students.
Academic P	I don't use them, but I was still impressed when I saw them, and it is good to have practical people as colleagues in the school.	It would be a great shame, but I don't need them to do my research. It would make me think if my position was safe if my colleagues started to leave for other institutions.