# DEFENCE ECONOMIC RESEARCH PAPER

# INTERGENERATIONAL EQUIPMENT COST ESCALATION

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## Summary

David Kirkpatrick and Philip Pugh made several observations, beginning in 1983, on the increasing cost of UK defence equipment, suggesting that a high rate in cost growth between generations of defence platforms was a feature common to most defence platforms. In 1983, Norman Augustine noted that the cost of fighter aircraft was increasing exponentially and he famously predicted that by 2054 the US defence budget would permit only the purchase of one aircraft to the exclusion of all other defence equipment. Others, for example Malcolm Chalmers, suggest that intergenerational cost growth is lower than earlier estimates had suggested as a result of the end of the Cold War.

Economic theory suggests that defence equipment is a tournament good, and that to maintain military superiority the equipment needs to be at the cutting edge of what is technologically possible and superior to that of potential opponents. National security may dictate limited reliance on supply of electronic control equipment from outside countries driving up costs which incorporate research and development into the final price. Sometimes limited export markets reduce the opportunities to recover research costs. Limited competition between suppliers of defence equipment may lead to monopolistic inefficiency in pricing of defence contracts, while short production runs, the need to maintain employment and skills bases leads to the potential for an element of social and political pressure by defence industries and may also be factors. There is also the perception of run-away cost growth due to “bad choices”, or poor procurement processes. All of these conditions, to the extent that they do exist, would lead to economic inefficiency and potential for higher costs. Another explanation for each generation to cost more is simply that it reflects the technological, dimensional or capacity change between one generation and the next.

In this paper, the first of a series of MoD economic research papers, we estimate the broad category and individual category estimates for the intergenerational real cost growth of UK platforms[1]. We find these are generally lower rates in absolute percentage than those found by Pugh and Kirkpatrick. Our figures are in line with the Arena et al work, in the US, and the Chalmers work, in the UK, on more recent data. However, due to the limited number of strictly new generations of equipment since the 1990s[2] and lack of sufficiently detailed accounts of earlier data used by Pugh and Kirkpatrick, it has not been possible to conclude that the rate of intergenerational cost growth has been markedly different since the Cold War although there is tentative, if largely anecdotal, evidence for this.

We have analysed overall trends in intergenerational cost growth of defence equipment platforms and suggest that much of the cost escalation reflects the choice of characteristics e.g. a shift from smaller to larger ships, or the choice for larger engines in main battle tanks. This appears widespread across defence equipment platforms and is illustrated in terms of the explained increases in costs associated with destroyers, frigates, combat aircraft, and aircraft carriers and main battle tanks. For all of these, most, if not all of the cost growth can be explained by the change in the specified characteristics of each generational platform.

However, this does not mean that intergenerational cost growth is, or has been, largely discretionary. There may have been no real choice about the size of the engine, for example, when the new generation of tank was being considered if it was to match the military requirement at the time.

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[1] Data work for this paper was completed in November 2011; all figures are based on the information available then.

[2] The time frame between development and in-service delivery of relatively large or complex platforms, such ships or aircraft, is generally longer than one or two decades. This suggests that since the end of the Cold War, a period of 20 years, there have been relatively few examples of new generations of UK equipment entirely developed post the end of the Cold War (1989-91).

## Introduction

1. It would be difficult to identify one single item of everyday technology that has not become better, with more features, smaller, larger, faster and relatively cheaper…even over a relatively short period such as the last few years. Cars, washing machines, mobile phones and cameras over the last decade are more efficient and do more than previous editions. Much of this technological and capability development has been possible because of the exponential development in computing hardware, a trend identified by Gordon Moore, the co-founder of *Intel*, and described in a paper in 1965[3]. Moore noted that between 1958 and 1965 the number of relatively inexpensive integrated components had doubled each year and as more transistors are put on a chip, the cost to make each transistor decreases.

2. In 1983, Norman Augustine, a CEO of US defence contractor Lockheed Martin, observed that the characteristic of falling real prices associated with the electronics industry did not carry over into the defence equipment market. The cost of defence equipment, in the field of fighter aircraft, was not falling but increasing exponentially and he famously predicted that by 2054 the US defence budget would permit only the purchase of one aircraft to the exclusion of all other defence equipment.

3. David Kirkpatrick and Philip Pugh made several observations, beginning in 1983, on the increasing cost of UK defence equipment, suggesting that a high rate in cost growth between generations of defence platforms was a feature common to most defence platforms. Others, for example Malcolm Chalmers, have suggested that more recently intergenerational cost growth was significantly lower than earlier estimates had suggested, as a result of the end of the Cold War.

4. Economic theory would suggest that there are several differences between the defence industry and civilian electronics industry which would tend to militate against the unit cost of defence equipment falling as it has tended to in the economy more generally. There is the argument that defence equipment is a tournament good. This postulates that to maintain military superiority the equipment needs to be at the cutting edge of what is technologically possible and superior to that of potential opponents. Kirkpatrick argues that relative capability remains approximately constant as rivals soon acquire similar technology so tactical advantage is short lived, however, the need to be at the forefront of technological progress comes at a high cost. Kirkpatrick suggests that a new technology inflates combat equipment real cost growth by 7.5% per annum. There is an argument that national security dictates limited reliance on the supply of electronic control equipment from outside countries. This implies incorporating research and development costs into the final price and sometimes limited export markets to recover the research costs. Limited competition between suppliers of defence equipment leads to monopolistic inefficiency in pricing of defence contracts and leads to higher cost. Short production runs, the need to maintain employment and skills bases leads to the potential for an element of social and political pressure by defence industries. In the past there has been the perception of run-away cost growth due to "bad choices", or poor procurement processes[4]. All of these conditions, to the extent that they do exist, would lead to economic inefficiency and potential for higher costs. Another explanation for each generation to cost more is simply that it reflects the technological, dimensional or capacity change between one generation and the next.

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[3] "Cramming more components onto integrated circuits", *Electronics Magazine* April 1965: Previously, Alan Turing, in 1950, had predicted the growth in the computer storage capacity and Douglas Engelbart, in 1960, had spoken of the trend towards minimization of circuit boards.

[4] Bernard Gray (2009) and National Audit Office (1999-2010).

5. With the real cost of defence equipment increasing and UK defence budget reducing as a proportion of UK GDP there is an increasing need for the UK Government to make a trade off between the quality, capability and quantity of its military equipment. The recent Strategic Defence and Security Review (2010) set out the UK government plans for the future structure and aims of a military force capability for the next 10-20 years. The review set out the choices it had made on large equipment purchases, the future structure of the forces in terms of skills and personnel and the need for future technology of communications and command management. Central to decision making on future equipment choices is the need to understand historic cost growth and anticipate future equipment cost pressure.

6. This paper, however, is not attempting to explain the working of the procurement relationship or impact of defence industry structure on costs but to establish as far as is possible the extent of historic intergenerational cost growth for the various defence equipment platforms for which data can be obtained and to establish to what extent the increase in intergenerational cost is explained by the change in the characteristics of the equipment provided.

7. The paper is arranged as follows. Section 1 provides the background context of UK defence expenditure compared with some NATO neighbours and selected countries and illustrates the trend of declining proportion of UK defence spending to GDP from post WW2 to present day. Section 2 describes a new database and provides a review of the literature on equipment cost escalation, Section 3 provides the empirical results of rates of cost escalation derived from our database, showing key trends, models and analysis and examines evidence for any pre-and post Cold War changes. Section 4 concludes.

## Section 1, Background context to UK defence expenditure

### *Background context to UK Defence expenditure*

8. Although the US spends about ten times as much as the UK on defence, globally the UK ranks about third in terms of defence spending, behind the US and China, while Japan, France, Germany, Russia, India, Brazil and Saudi Arabia spend slightly less. As a percentage of GDP the UK currently spends about 2.5% while the US spends around 4.8% of its GDP and China over 2.2% of its GDP ( based on IMF estimates of individual countries GDP[5] this suggests US defence expenditure in 2010 of some US$ 690 billion, some US$ 130 billion in China and US$ 60 billion in the UK).

9. The proposed UK defence budget for each of the next four years will be around £34 billion[6] in cash terms, about 2% of UK GDP.

10. Since the mid 1950's the ratio of UK defence spending to GDP has generally fallen. The 1955/56 percentage was 7% which then fell steadily (with a few exceptions, namely during the Falklands War(1983/84), the first Gulf War (1991/92) and Afghanistan and Iraq (2000-2010) when the proportion of GDP devoted to defence expenditure increased slightly) to some 2.5% in 2010.

### *The UK defence expenditure on equipment*

11. The UK currently spends around a third of its defence budget on new military equipment, a third is spent on personnel (civilian and military wages) and a third is spent on other goods and services.

12. Historically, between 1980 and 2000, the largest share of the equipment spending was on air equipment (40%), followed by spending on sea equipment (30%) and the smallest share on land equipment (20%).

13. However, while the UK is allocating an increasingly smaller proportion of its resources to defence the cost of the components of defence expenditure (personnel, equipment and services) have been increasing, often faster than the growth in the UK economy.

14. A measure of "defence inflation" has recently been developed and is published annually by the MoD. This measures yearly change in the cost of defence (goods and services, pay etc) with quality and quantity held constant, however, the measure excludes the increased cost associated with the purchase of equipment with changed capability. This increased cost as a consequence of moving from one generation of equipment to the next, termed "intergenerational cost growth or cost escalation" is the focus of this paper.

15. We examine the growth in costs of military equipment and in particular how the cost increases with the each new generation of technology and improved capability of equipment platform.

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[5] Nominal GDP in local currency, converted at yearly average market exchange rates.

[6] The Total Departmental Expenditure Limit (excluding depreciation) for Defence over the Spending Review period will be £33.8bn in 2011-12, £34.4bn in 2012-13, £34.1bn in 2013-14 and £33.5bn in 2014-15. This settlement does not provide for the Net Additional Cost of Military Operations: these costs will continue to be met from the Treasury Reserve.

## Section 2, Review of the literature

### *Equipment Cost Growth*

16. Various analysts have suggested that the cost of equipment rises with each new generation of technology faster than economic growth and the failure of the equipment budget to keep pace with UK economic growth presents significant strain on the defence budget and the UK's ability to replace equipment at the necessary rate to maintain overall defence capability.

17. We review the literature on the equipment cost growth assumption and find considerable variability in published estimates. The published estimates of cost growth are often based on data of varying quality or data that is exclusively held by the author.

18. This paper presents a comprehensive re-analysis of equipment cost growth based on the construction of a UK defence equipment dataset and the application of a range of estimation methodologies. The estimated rates of cost escalation are compared, where possible, with published estimates of equipment cost growth from the literature with the aim of providing a better understanding of the impact of equipment cost growth.

### *Intergenerational cost escalation*

19. Definitions in the literature differ. We define "intergenerational cost growth" as being the change in cost between one platform of military equipment and the next generation of a similar platform of military equipment. The next generation is likely to be more technologically advanced or with improved capacity or capability, however, the contribution of changed capability, weight or capacity upon the increase in unit cost may not be easily identifiable. The cost is measured as the in-service unit real cost at 2009 prices and represents the price paid in that financial year. Delivery into service of a particular generation of equipment may be spread over a number of years as for example in the delivery of very large ships. The in-service date is defined as the year in which the individual platform is delivered "in-service" and the date of the start of a new generation is the in-service date of the first example of that generation. The average generational unit cost is the average cost of all platforms of that generation.

20. Literature on the analysis of UK intergenerational cost escalation, since the 1980's has been dominated by two authors Prof David Kirkpatrick and the late Philip G Pugh and more recently by Malcolm Chalmers. Both Kirkpatrick and Pugh had distinguished careers including analysis of air defence systems and procurement of defence systems which has provided them with access to data that is not generally available. Malcolm Chalmers holds various professorships in defence, international politics, and foreign policy.

21. Published rates of intergenerational cost growth vary widely dependent on individual definitions, time series and varying quality of data.

22. An early paper by Kirkpatrick and Pugh (1983) drew attention to intergenerational escalation in unit costs of combat aircraft using UK cost data. Kirkpatrick and Pugh (1983) proposed that since the end of the Second World War, the real rate of growth (of combat aircraft) had been some 8.3% per annum. The aircraft data used for their calculations is unavailable to other analysts.

23. Later Kirkpatrick (1995) updated the data for fighter aircraft and calculated a rate of 11.5% per annum.

24. Pugh (1986) focused on British naval raw cost data for a selected number of platforms. No detailed commentary is provided on the data itself, or the resulting escalation rates. Pugh (1986) provided a chart from which some annual rates of cost increase may be inferred. In real

terms, his figures are approximately 3% for escort carriers, 5% for aircraft carriers, 9% for submarines, 11% for frigates and 9% for destroyers. However, the time periods used in the derivation of each estimate appear to vary in each category.

25. Pugh (1986) estimates cost escalation of around 8% and 9% for helicopters and fighter aircraft, respectively. The fighter aircraft estimate is similar to that given in Kirkpatrick and Pugh (1983), which can be explained by the similarities in the data period employed[7].

26. More recently, Kirkpatrick (2008) reported Pugh calculations in the order of 5-10% per annum for general combat equipment cost escalation. Assuming a median value of annual cost inflation rate of 7.5%, this is similar to the earlier estimates of Kirkpatrick and Pugh (1983) for combat aircraft. Kirkpatrick (2008) considers the intergenerational costs of all types of military equipment rather than general categories of platform (e.g. aircraft). Kirkpatrick (2008) argues that platforms incorporating mature technologies will typically lie at the lower end of the 5-10% range, whereas less mature technologies will appear around the 10% per annum mark. This implies a new generation of equipment based on new or less mature technologies carries a premium in cost terms compared with its predecessor. Kirkpatrick (2008) suggests the desire to procure next generation technology is a key driver of cost escalation.

27. Kirkpatrick (2008) discusses incorporating the measurement of capability (although his estimates do not include this) into cost growth estimates. Kirkpatrick suggests a capability measure would consider the relative capability of a unit of military equipment against a threat, an area which was first considered in work by Pugh (2007a) and Pugh (2007b). However, Kirkpatrick (2008) then argues that new combat equipment provides the same military capability against an enhanced threat where a potential adversary develops a more capable piece of equipment, one attempts to follow suit thus relative capability between nations remains constant over the time, supporting the theory that defence products are classic ‘tournament goods’.

28. In the two papers Pugh (2007a) and Pugh (2007b), Pugh estimates cost escalation for a wide range of equipment platforms and Pugh (2007a) is arguably the most substantial piece of work that has been produced on this topic. The Pugh analysis, however, has used an international cross-section of data across a range of equipment which limits the value of these estimates in providing UK comparisons. It is likely that countries with large production runs or more competitive defence industries may experience lower cost escalation. Pugh analysis is based on cost escalation rates per unit kilogram or tonnage as a proxy for capacity arguing that increased size and weight of platform provide more capacity to support larger and more capable sub-systems which enhance capability.

29. Using international cross section data and adjusting rates by weight Pugh (2007a) reports figures for unit per ton cost growth averaging 3% per annum across all equipment types. This represents a lower rate than Pugh had previously estimated for UK equipment, possibly reflecting economies of scale available in countries outside the UK. Pugh (2007a) also provides estimates for equipment classes and equipment systems for land, air and sea domains, for example, the estimate for unit cost growth is for bomber aircraft at 10%, then 4% for Infantry, fighter/strike aircraft, then 3% for aircraft carriers and nuclear submarines, 2% for armoured personnel carriers and 1% for main battle tanks.

30. Pugh (2007a) estimate of 4% for fighter/strike aircraft (international cross sample) is about half that of earlier estimates of around 8-9% (largely UK data) in Kirkpatrick and Pugh (1983) and Kirkpatrick (1995).

31. In sharp contrast to the analysis by Pugh and Kirkpatrick, Chalmers (2009) is sceptical about the scale of cost escalation and suggests that, at least in the most recent period, cost

[7] The period 1952-76 was used in Pugh (1986). Although Kirkpatrick and Pugh (1983) do not provide details of the data, the fact that the paper was authored in 1983 implies that it will have been very similar to that used in Pugh (1986).

escalation may not be that high. Chalmers (2009) compares the unit cost of Typhoon with the Tornado F3, Astute-Class submarines the Trafalgar and finally the Type 45 destroyers with the Type 42 providing annual real cost growth estimates of 3.4%, 2.2% and 2.8%, respectively. Chalmers (2009) proposes that if these are the rates obtained when considering known high cost and troubled platform examples there is only weak evidence of cost escalation in other platforms which by assertion have not experienced higher cost growth rates. This extrapolation received short shrift from Kirkpatrick (2009), in which he suggested that a longer time series, containing more than just two data observations, may have provided a different estimate. Kirkpatrick (2009) was also concerned that some observations were forecasts which may rise during procurement.

32. Possibly, the underlying trend in equipment cost growth may vary over time. This was argued by Kirkpatrick, whereas Pugh suggested it was a constant driven by institutional factors. What Chalmers (2009) has observed reflects similar observations of a RAND study illustrating anecdotal data of recent equipment platforms (see below).

33. The RAND study by Arena et al (2006) is a paper resulting from a commissioned study into intergenerational unit production cost increases of US Navy equipment. The RAND study noted that over the past 50 years the annual cost escalation rates for amphibious ships, surface combatants, attack submarines and nuclear aircraft carriers had ranged from a nominal 7% to 11%. Arena et al (2006) sought to identify the component factors contributing to ship cost growth which it had grouped as being either economy driven (labour cost, material and equipment cost) or customer driven (complexity, standards and requirement and procurement) and found that each of these two groups accounted for approximately half the overall rate of increase in cost. Comparing the cost escalation for surface combatants over the period 1961 to 2002 it found a rate of 9% but between two programmes between 1990 and 2004 an average rate of just 3.4% concluding that much of the more recent change in costs were due to customer driven factors. A similar conclusion reported in the rather limited study in Chalmers (2009). For the period 1950-2000 Arena et al (2006) report nominal annual cost escalation rates of 10.8% for amphibious ships, 10.7% for surface combatants, 9.8% for attack submarines and 7.4% for nuclear aircraft carriers. Adjusting these nominal figures an index for average US GDP deflator over the period of 4.5%[8], we derive rates in real terms of 6.3% for amphibious ships, 6.2% for surface combatants, 5.3% for attack submarines and 2.9% for nuclear aircraft carriers. This implies that the cost of US naval platforms typically escalates at a rate of 5.2% per annum, which is higher than the 2.9% implied by Pugh (2007a) and Chalmers' 2.2%, though lower than Kirkpatrick's (2008) estimate of 7.5% for overall combat equipment.

34. The conclusion to be drawn from existing literature is that real terms defence equipment cost escalation is evident in both historical UK and US data although the estimates vary widely over time and type of platform. The differing estimates observed reflect some key differences in approaches, rigor, reliability of data and differing periods over which cost escalation has been measured. There is also some evidence, though not developed in UK studies that cost escalation rates are variable over time and will reflect changes in defence industry consolidation, and the state of international conditions.

## Section 3, Empirical results, key trends, models and analysis.

### *Equipment Cost database*

35. In the next section we describe the sources of information from which a new equipment cost database has been compiled and highlight some limitations of the data.

36. Information has been drawn from a number of different sources to construct a comprehensive single source database of historic UK military equipment expenditure for the period 1955 to

[8] Implied by Arena *et al* (2006).

2011. A difficulty in this approach has been in ensuring consistency across all types of equipment and within categories and ensuring consistency of definitions of observations, for example, a unit cost figure for naval platforms might be a flat class average (i.e. total programme production cost, divided by the number of units), or the average of the costs attributed in the financial year of each individual vessel adjusted for general price inflation. Information by financial year also provides transparency to the possible benefits of learning and scale.

37. Individual data sources include Hansard Parliamentary Questions, providing unit cost figures quoted by defence secretaries and ministers, Defence Estimates providing official estimates of programme production costs prior to the 1980's. The Fixed Asset Register (FAR), which lists individual pieces of equipment under ownership by the ministry, its initial purchase cost and its re-valued current cost[9] provides a valuable source of information, although cost of any asset prior to 1997 has been subject to asset re-valuation. Other useful sources of information have included figures presented in published copies Jane's publications[10] such as "Armour and Artillery", "Fighting Ships" and "World's Aircraft". The National Audit Office reports annually on Major Defence Projects and this has provided useful information on causes and costs of delay in recent equipment procurement.

38. Detailed data was obtained for Destroyers (1962-2011), Aircraft Carrier (1955-2011), Diesel Electric Hunter-Killer submarines (1964-1990), Nuclear Power Hunter-Killer submarines (1963-1983), Nuclear Ballistic Missile submarines (1967-1999) and Frigates (1956-2000).

39. For Air equipment, platform data was established for Combat Aircraft[11] (1955-2008), Transport Aircraft (1966-1984) and Trainer Aircraft (1976-2008). Reconnaissance aircraft and Maritime Patrol aircraft data was not considered sufficiently reliable and was excluded.

40. For Land platforms, data was limited to Main Battle Tanks (1963-1994) where sufficiently robust data was available from a range of sources including Hansard, Defence Estimates and various Jane's publications. Although data on Armoured Personnel Carrier (1965-2009) and Infantry Fighting Vehicles (1971-1988) was available from Fixed Asset Register, data prior to 1997 had been re valued and was considered not suitable for this purpose.

41. The data was then re-based into 2009 prices using the appropriate GDP deflators, and grouped into pre-defined equipment categories for sea, air and land systems. Consideration was given to identification of each new generation of equipment within each platform category based on whether it performed a similar role to that of its predecessor. Sea equipment appears to provide useable examples of where one generation is replaced by a more contemporary version, for example, the Swiftsure Class of Nuclear Power Hunter-Killer submarine was replaced by the Trafalgar Class, and the Type 22 Frigate was replaced by the Type 23. For Air equipment, although platforms can be loosely identified by generation based on technology, function and other factors distinct generations were more difficult to identify. In this case the analysis was based on categories for example, all combat aircraft are grouped together and the type (i.e. fighter, strike etc) ignored. Annual cost growth rates were based on observed cost changes between each observation within category rather than by defined generation. Within land equipment the only category where the intergenerational effect could be clearly observed was Main Battle Tanks.

### *Equipment Characteristics*

42. It has been possible from a range of sources, to include within the equipment cost database some indicative equipment characteristics of platforms. For example for aircraft, the

[9] The Fixed Asset Register also lists other useful equipment features such as its in-service date.

[10] Jane's publications such as "Armour and Artillery", "Fighting Ships" and "World's Aircraft".

[11] This refers to Fighter/Strike Aircraft.

characteristics for each aircraft class, such as empty weight, maximum speed, height, length, range were obtained from the Jane's publications which provide a detailed breakdown of specifications by platform across the period 1955-2009 in various editions. The inclusion of equipment characteristics to the cost data base has allowed some exploration of the contribution made to cost escalation rates by changes in platform characteristics. This has been achieved using principal component regression analysis and the results are shown later in the paper.

43. Meeting the required sample size for a regression analysis constrained this exercise and it was necessary to aggregate some date to provide workable data sets. The data set for Frigates contained some 84 observations, indicating its suitability for estimation, while data on destroyers, aircraft carriers and each type of submarine contained far fewer cost observations, which constrained our ability to estimate equations for these platforms individually and it was necessary to aggregate the sample of naval vessels. For RAF platforms only data on combat aircraft was available with sufficient data points to attempt regression analysis, whilst for the Army platforms, the sample obtainable was not large enough even for tank platforms as a whole.

44. Table 1 illustrates summary cost and characteristic data on Frigates providing unit cost £ million in 2009 prices and details of displacement, length and beam etc. of each Type illustrated.

**Table 1 Summary cost and characteristic data on Frigates**

| earliest isd | Frigate | Unit Cost (£m, 2009 Prices) | Displacement (Tons) | Length (Metres) | Beam (Metres) | Draught (Metres) | Speed (Knots) | Range (Nautical Miles) | Propulsion |
|---|---|---|---|---|---|---|---|---|---|
| 1956 | Type 14 | 33 | 1456 | 94 | 10 | 5 | 27 | 5,200 | COSAG |
| 1957 | Type 12 | 62 | 2150 | 113 | 13 | 5 | 30 | 4,200 | COSAG |
| 1957 | Type 12M | 71 | 2150 | 113 | 12 | 5 | 30 | 5,200 | COSAG |
| 1959 | Type 81 | 94 | 2300 | 110 | 13 | 5 | 28 | 5,300 | COSAG |
| 1961 | Leander | 81 | 2500 | 113 | 13 | 5 | 27 | 3,997 | COSAG |
| 1972 | Type 21 | 192 | 2750 | 117 | 42 | 7 | 32 | 4,000 | COGOG |
| 1976 | Type 22 | 413 | 4400 | 131 | 15 | 6 | 30 | 4,500 | COGAG |
| 1989 | Type 23 | 183 | 4800 | 133 | 16 | 5 | 34 | 7,821 | CODLAG |

## *Equipment Cost Escalation Rates Estimated*

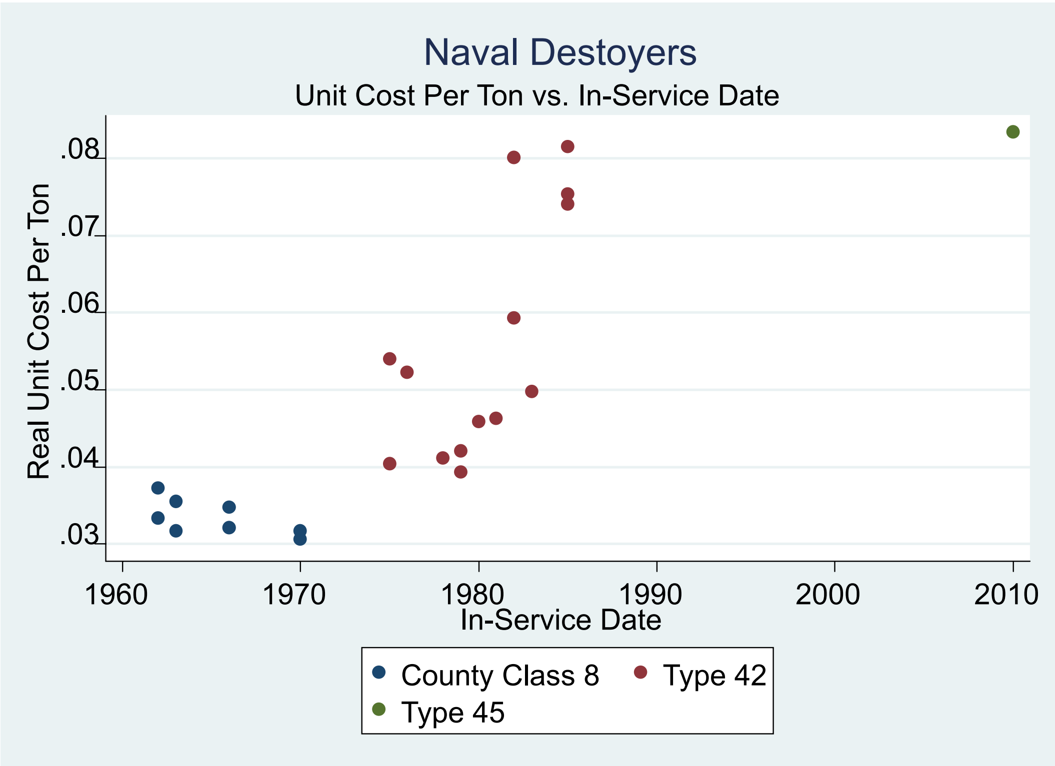
45. In this paper we apply several approaches to estimating the intergenerational cost escalation. This has the advantage that it enables an update of the cost escalation previously published in the literature where our dataset may be closely aligned with the data of, for example by Pugh and Kirkpatrick, and may allow us to establish the consistency of their earlier estimates. Also, by employing alternative estimation approaches it is possible to establish the robustness of the estimates over various samples and sample periods. The detailed algorithms of cost escalation are provided in Annex A.

46. Although Kirkpatrick (2009) questioned the validity of producing estimates from two data observations this is essentially the traditional approach to measurement of a rate of cost escalation and is based on observing cost increases between time intervals. As in Arena et al (2006), a compound cost growth function is derived. This approach uses the first and last generation of a given platform sample, the normalised cost growth to a common baseline (in our case to 2009 prices), to derive the annual escalation rate. The validity of approach relies on sufficient regard to the shape of the trend over the sample time period. A good fit suggests the approach is a reasonable approximation.

47. Estimation of cost growth between successive generations of platform dynamically over a sample series of data provides useful information on successive generational cost growth which may be attributable to identifiable changes in characteristics, for example a large increase in size or weight of ship.

48. Over the whole sample period 1956-2010 the unit cost escalation between the 1956 Pallister (Type 14) frigate and the 2000 St Albans (Type 23) suggests an average compound real rate of cost escalation of 3% per annum for frigate category. However, this masks significant changes in costs associated with different generations (or classes of frigate). For example, the intergenerational annual rate between the Type 21 (cost £192m, 1972) and Type 22 (£413m,1976) is 21% per annum, whereas between the Type 22 and the Type 23 (£183m,1989) it is - 6%. The Type 21 is a smaller ship at 2750 tons; the Type 22 is 4400 tons and the Type 23 is 4800 tons. Pugh 2007a introduces weight as a proxy for capability estimating annual growth per ton at 2%[12]. Applying this approach suggests a rate of cost growth of 8% per annum between Type 21 and 22 and a rate of -6% per annum between Type 22 and 23. That is, the Type 23 is less expensive than the previous generation per ton. However, although the Type 23 is slightly wider than the Type 22, it is also lighter, shorter, with reduced draught and is 14% faster and with 74% more range (nautical miles). It may be that we have a new type of ship may with radically different technology or capability rather than simply a new generation of ship with a change in size.

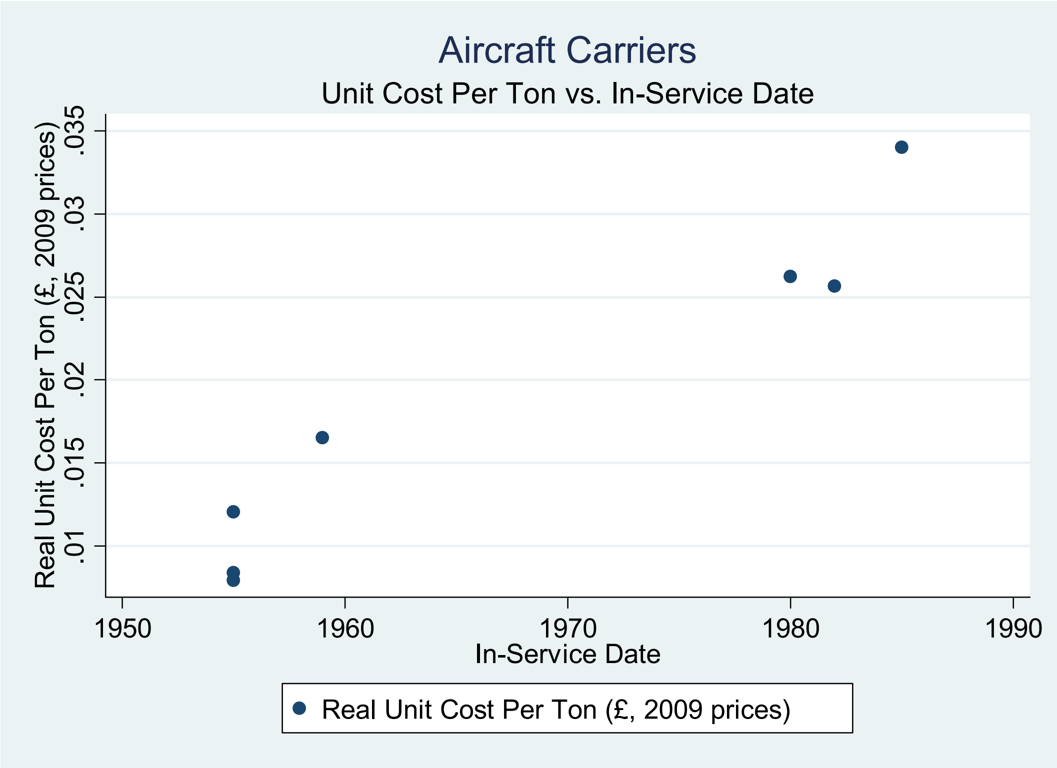
**Figure 1 Naval Destroyers cost per unit ton verses in-service year**




49. These examples demonstrate the complexities of suggesting that there is any single average rate of cost escalation that is appropriate across any category of platform and that using weight as a proxy for capability, as Pugh has done, has limited application. Figure 1 provides an illustration of individual cost per ton for Navy destroyer category, by destroyer class. Considerable variation is illustrated within Type 42 destroyer class with individual costs ranging from under £40,000 per ton to over £80,000 per ton (in 2009 prices).

[12] Based on Pugh (2007a) “anti-submarine warfare vessel of around 2500 tons.

**Figure 2 Illustrates the cost per ton of aircraft carriers**




50. Table 2 presents a summary of the results for Destroyers, Frigates, Aircraft Carriers and Submarines Naval Platforms illustrating average and individual intergeneration growth rates based on costs per ton and cost only.

**Table 2 Destroyers, Frigates, Aircraft Carriers and Submarines Naval Platforms illustrating average and individual intergeneration growth rates**

| In-service year | Individual intergenerational rate of cost escalation | cost (per ton) growth per yr | cost growth per yr |
|---|---|---|---|
| **Destroyers** | | | |
| btwn 1962 and 1966 | btwn County Class 8 / Batch 1 and County Class 8 / Batch 2 | -3.4% | -3.4% |
| btwn 1966 and 1975 | btwn County Class 8 / Batch 2 and Type 42 / Batch 1 | 2.9% | -3.0% |
| btwn 1975 and 1980 | btwn Type 42 / Batch 1 and Type 42 / Batch 2 | 2.7% | 5.9% |
| btwn 1980 and 1982 | btwn Type 42 / Batch 2 and Type 42 / Batch 3 | 37.3% | 26.7% |
| btwn 1982 and 2010 | btwn Type 42 / Batch 3 and Type 45 / .. | 0.1% | 4.2% |
| Average intergenerational rate Destroyers | | 7.9% | 6.1% |
| Average annual growth (1) | 1% | | |
| **Frigates** | | | |
| btwn 1957 1956 | btwn Type 12 and Type 14 | 29.0% | 90.5% |
| btwn 1957 1957 | btwn Type 12M and Type 12 | 13.6% | 13.6% |
| btwn 1959 1957 | btwn Type 81 and Type 12M | 12.2% | 16.6% |
| btwn 1961 1959 | btwn Leander and Type 81 | -10.5% | -7.1% |
| btwn 1972 1961 | btwn Type 21 and Leander | 10.6% | 12.5% |
| btwn 1976 1972 | btwn Type 22 and Type 21 | 8.6% | 28.7% |
| btwn 1989 1976 | btwn Type 23 and Type 22 | -4.6% | -4.3% |
| Average intergenerational rate Frigates | | 8.4% | 21.5% |
| Average annual growth (1) | 3% | | |
| **Submarines** | | | |
| **Nuclear Power Hunter Killer** | | | |
| btwn 1966 and 1963 | btwn Valient Class and Dreadnaught Class | -1.5% | -28.1% |
| btwn 1973 and 1966 | btwn Swiftsure Class and Valient Class | -5.9% | -0.3% |
| btwn 1983 and 1973 | btwn Trafalgar Class and Swiftsure Class | 6.0% | 0.2% |
| btwn 2009 and 1983 | btwn Astute Class and Trafalgar Class | 1.8% | 20.3% |
| Average intergenerational rate Nuclear Power Hunter Killer | | 0.1% | -2.0% |
| **Diesel Electric Hunter Killer** | | | |
| btwn 1990 and 1964 | btwn Upholder Class and Oberon Class | 17.6% | 0.2% |
| **Nuclear Ballistic Missile** | | | |
| btwn 1993 and 1967 | btwn Vanguard Class and Resolution Class | 4.4% | 25.8% |
| **Aircraft Carriers** | | | |
| btwn 1955 and 1955 | btwn Bulwark and Ark Royal (1955) | -10.9% | -35.0% |
| btwn 1985 and 1955 | btwn Ark Royal (1985) and Ark Royal (1955) | 6.1% | 2.3% |
| btwn 1985 and 1955 | btwn Ark Royal (1985) and Bulwark | 11.8% | 11.8% |
| cost gwth invincible class | | | |
| btwn 1985 and 1980 | btwn Ark Royal (1985) and Invincible | 5.9% | 5.9% |
| Average annual growth (1) | 6% | | |
| Average annual growth (1) | compound annual rate between first and last in-service of time series | | |

## *Cost escalation rates of Combat Aircraft*

51. A plot of individual unit costs (in 2009 prices) is illustrated in Figure 3 for the sample period 1950 -2010. Cost escalation appears low between mid 1950 to mid 1970, then increasing steeply between 1980 and 2010. However, there are considerable differences in specification and capability of combat aircraft over this period. Figure 3 also illustrates the particular aircraft introduced into service over the sample period. The broad characteristics of the main aircraft are illustrated in Table 3. The approach adopted in the literature to intergenerational cost growth generally ignores intra-generational variation and represents the generational cost as the average cost over a particular generation. This is illustrated for combat aircraft in Figure 4.

52. Average costs are illustrated in Table 3 for some illustrative classes of combat aircraft. Rates of cost growth between these classes of combat aircraft are shown in Table 4.

**Figure 3 Unit cost of combat aircraft by aircraft type**

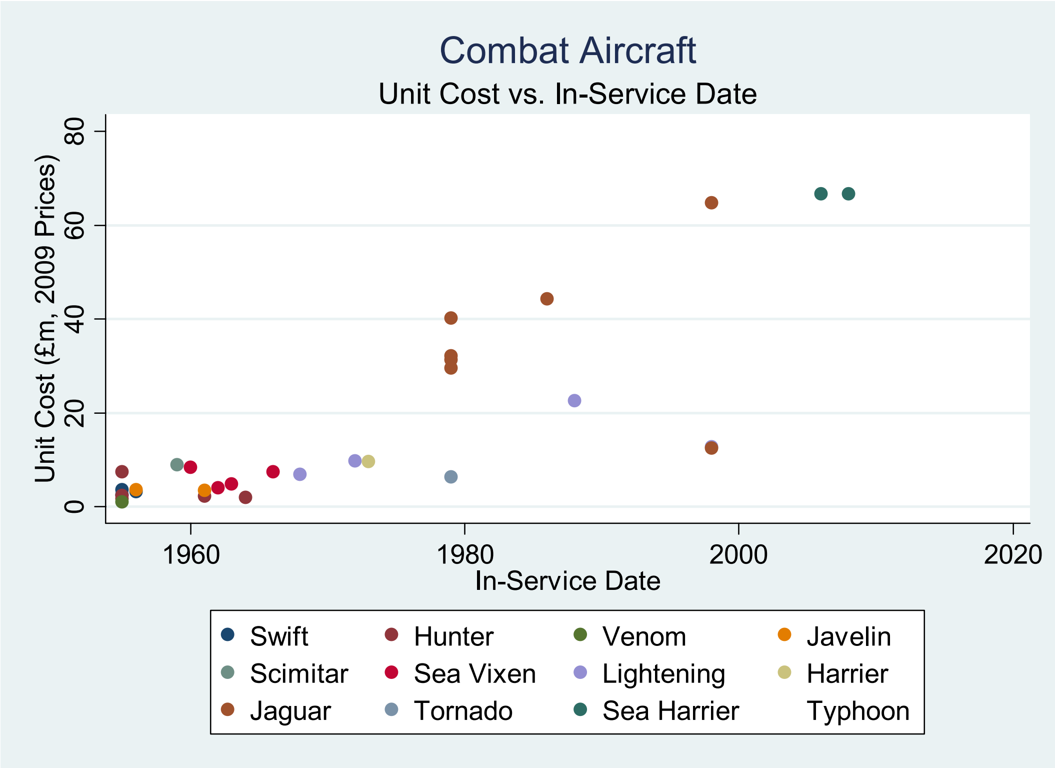



**Table 3 Average cost and characteristics of combat aircraft 1950-2010**

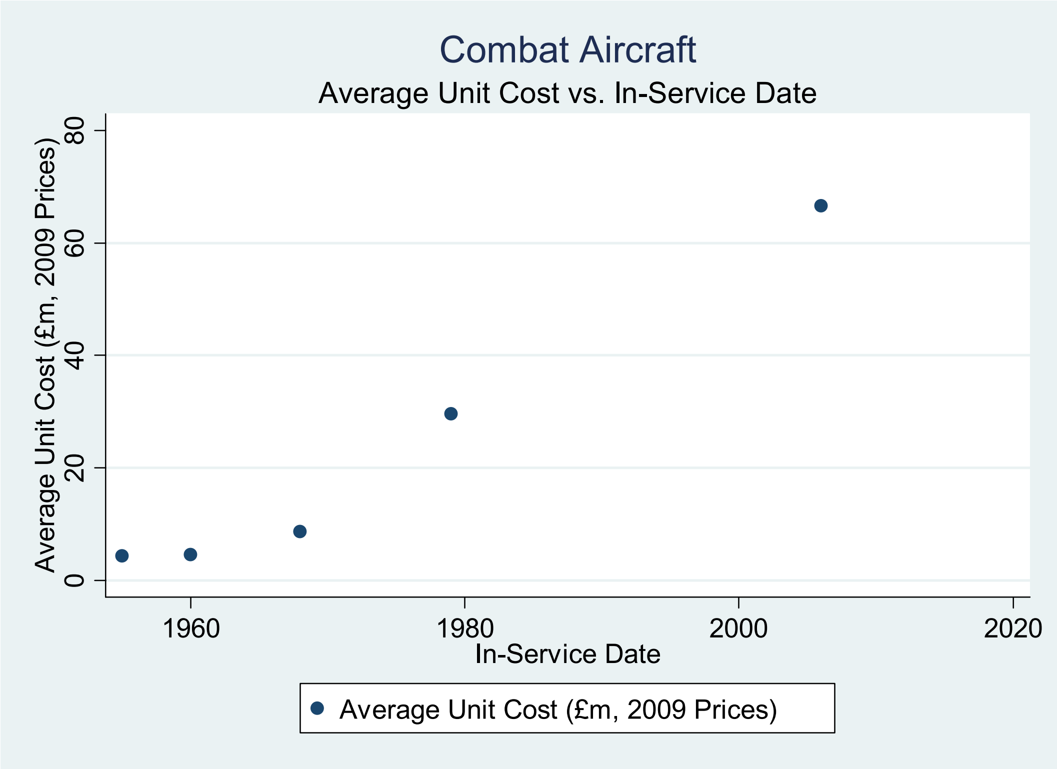
| combat aircraft typified by | in-service yr | Unit Cost of combat aircraft (£m, 2009 Prices) | Displacement (Kg) | Length (Metres) | Speed (mph) | Range (KM) | Height (Metres) |
|---|---|---|---|---|---|---|---|
| Hunter | 1955 | 4.29 | 6,509 | 14 | 715 | 1,819 | 4 |
| Lightening | 1960 | 4.55 | 9,851 | 16 | 1,049 | 1,849 | 5 |
| Harrier | 1968 | 8.66 | 6,670 | 14 | 843 | 3,337 | 4 |
| Tornado | 1979 | 29.59 | 11,487 | 16 | 854 | 1,943 | 5 |
| Typhoon | 2006 | 66.64 | 11,150 | 16 | 1,550 | 2,900 | 5 |

**Table 4 Intergeneration cost growth based on average cost**

| Combat Aircraft | in-service yrs | cost growth per annum |
|---|---|---|
| Hunter-Lightning | 1955-1960 | 1.2% |
| Lightning-Harrier | 1960-1968 | 11.3% |
| Harrier-Tornado | 1968-1979 | 22.0% |
| Tornado-Typhoon | 1979-2006 | 4.6% |
| Average p.a. | | 6% |

53. Cost growth between subsequent generations is based on difference in price between the first in-service dates.

**Figure 4 Average unit cost of combat aircraft**

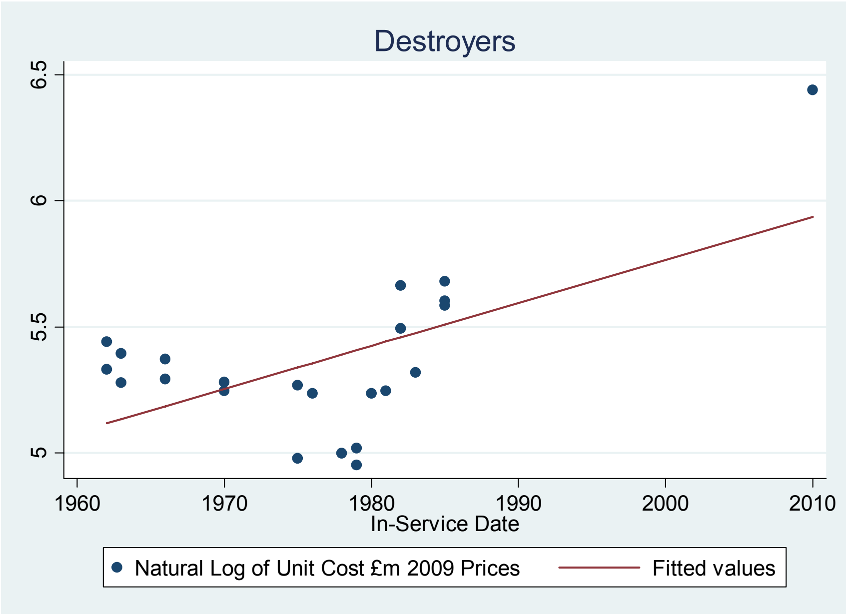



*Key Trends in Equipment Costs based on average cost data*

54. Key trends in Equipment cost escalation are derived using average generational (or class) cost data and based on fitting a suitable trend.

55. The trend in unit cost of UK Naval destroyer ships based on unit costs is illustrated in Figure 5. The data spans across three generations, namely County Class, the Type 42 and the Type 45. The average cost of the Type 45 increased by around 200% on the average cost of the Type 42. The intervening gap between the in-service dates is some 25 years, implying an annual rate of 3.8%. This cost increase, was greater than that between the County Class and the Type 42, which remained approximately constant (0.04% growth) in real terms. The generational characteristics suggest that the weight of Type 45 was almost twice that of the Type 42, whereas the Type 42 was lighter than the County Class. The technology embodied within the Type 45 is more advanced than that of the Type 42 and the time gap between production of Type 42 and Type 45 was larger than between County Class and Type 42. The Type 45 has in-service dates post the end of the Cold War (see section on End of Cold War Effect, paragraphs 80 to 89). An alternative approach estimating unit cost growth rates is based on equipment count data. The unit real cost growth of destroyers, by this alternative approach, is estimated to be 1.23% per annum based on a sample period 1967 to 2009. Annex B explains this alternative approach and provides illustrative estimates of unit cost growth for sea and air equipment.

**Figure 5 Trends in Unit Costs of Destroyers**



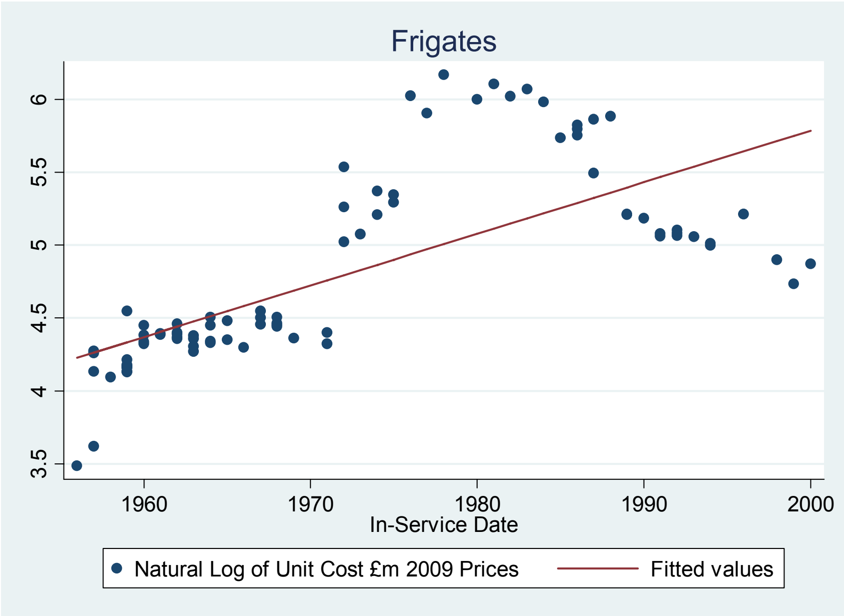

Source: Hansard Parliamentary Questions

56. Figure 6 illustrates the unit cost trends for frigates. The cost between Type 14 and Type 12 grew at a rate of 77.85% across just one year. The displacement of the Type 12 was 47% heavier than its predecessor and the procured units produced fell from 15 to 6, possibly leading to reduced economies of learning scale.

57. The average unit cost of the Type 21 was £195.4 million, compared with the approximate £82 million Leander Class. Most of this jump appears to reflect the difference in specification, a significantly shorter production run, and that the Royal Navy had been looking to enhance the capability of frigates to serve a multi-purpose role. The cost of the Type 22 was yet 90% higher than the Type 21. Type 22 Batch 3 represented the largest frigates ever built for the Navy. Although the production run had increased between these classes there may have been other reasons for this significant cost increase.

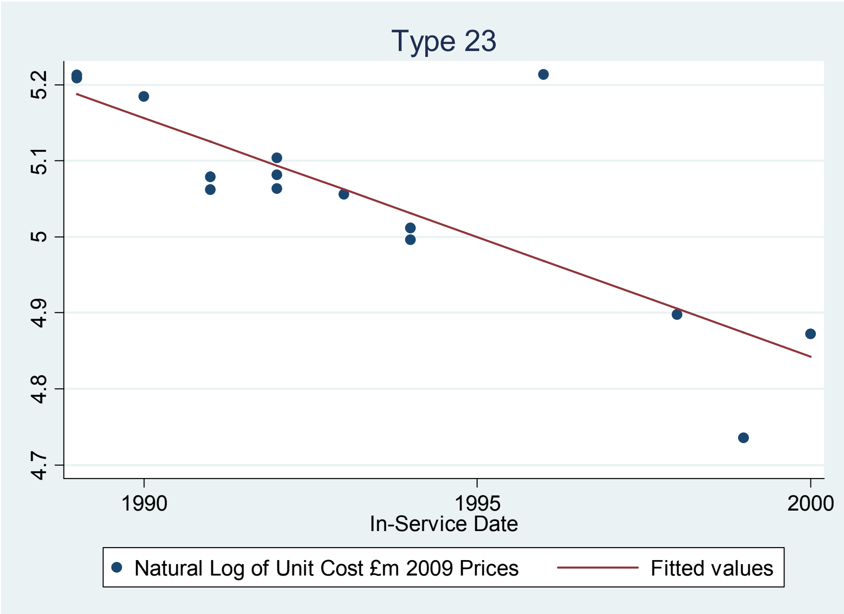
58. The unit cost of Type 23 reduced by some 8.04% per annum on the Type 22 possibly suggesting a cross-generation learning effect. The within class learning effect due to production run length is illustrated in Figure 7. This will have helped offset the generational cost growth of the Type 23.

**Figure 6 Trends in Unit Costs of Frigates**




Source: Hansard Parliamentary Questions

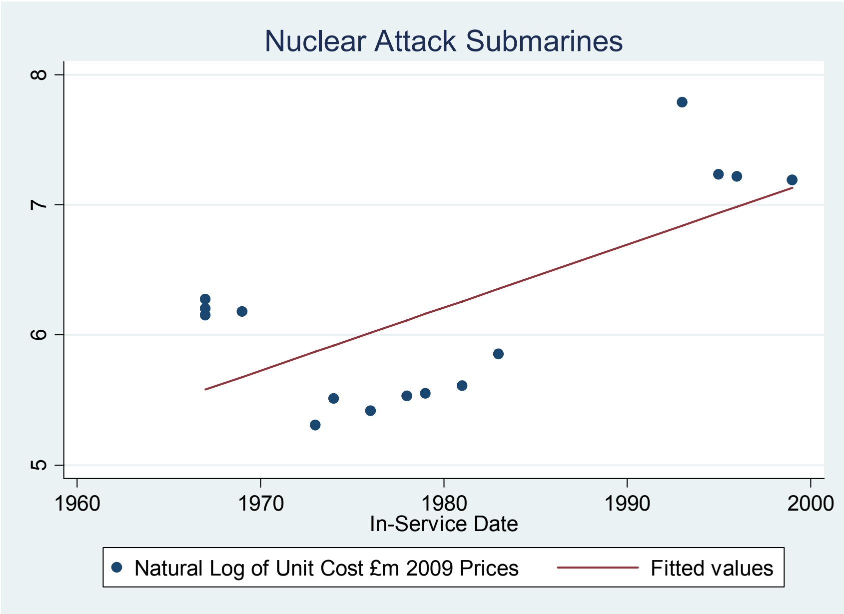
**Figure 7 Learning and Sales Economies in Type 23 Frigates**




Source: Hansard Parliamentary Questions

59. Figure 8 presents unit costs for nuclear powered hunter-killer submarines, which include the Dreadnaught, Valiant, Swiftsure, Trafalgar and Astute Classes. The increased cost following the introduction of the Astute class is some 130% on its predecessor some years before, however this represents an average annual escalation rate of 3.3%. As outlined by the NAO (2009), despite Astute being among the most troubled defence procurement programme in recent years, this was lower than the annual rise between the Swiftsure and Trafalgar classes, which amounted to 6%.

**Figure 8 Trends in Unit Costs of Nuclear Power Hunter-Killer Submarines**

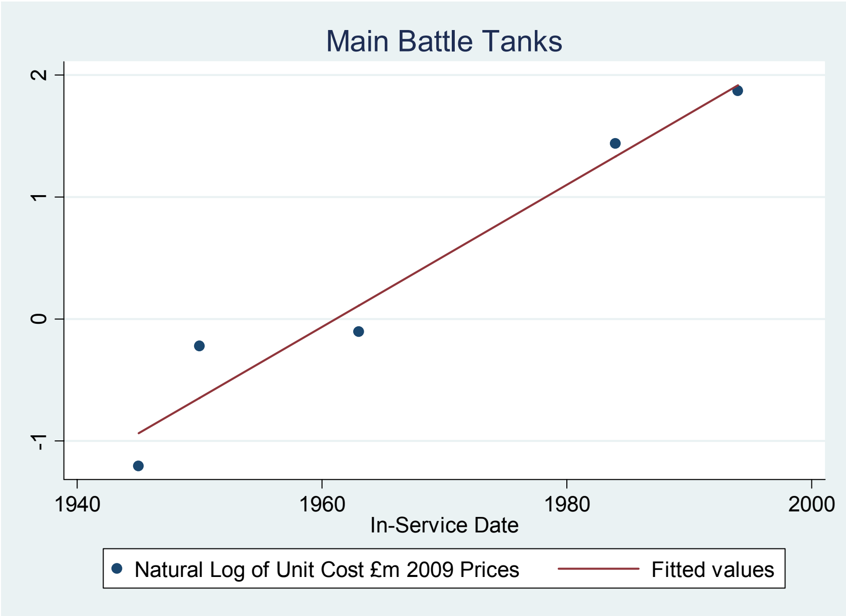



Source: MOD Defence Estimates, Hansard Parliamentary Questions and Jane's Fighting Ships

60. Figure 10, shows unit costs of combat aircraft exhibit a positive exponential trend, representing aircraft systems including Hunter (F1, F4 and F6), Swift (F1/F2, F5, F7), Lightening (F1, F2, F3, F6), Tornado (F2, F3) and the Euro-fighter Typhoon. The Typhoon, which entered service in 2006, cost nearly 3000% more than the Hunter, which came into service in 1955. However, between the two aircraft, the weight and speed has enhanced two-fold, and there was a strong enhancement in complexity and capability.

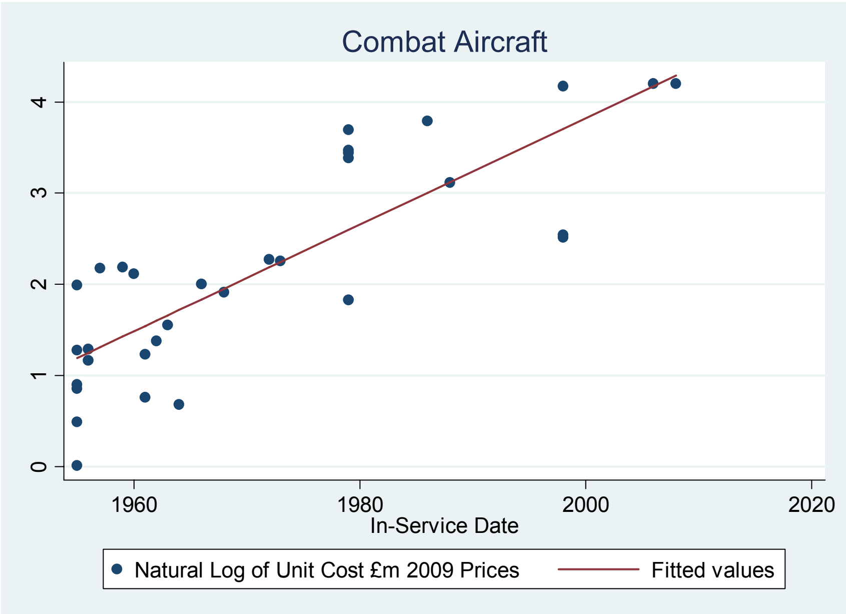
61. Land platforms data has been limited to Main Battle Tanks (MBT). The observations provided within Figure 9 reflect the Cromwell, Centurion, Chieftain, Challenger 1 and Challenger 2 MBT systems. As with combat aircraft, it is apparent from Figure 9 that the cost of tanks has grown exponentially with time. The largest annual cost increase appears to be between the Cromwell and Centurion tanks, which amounted to 24%. More recently, although the Challenger 2 remained the same weight and size as the Challenger 1, the unit cost increased by 4.3%. It is known that Challenger 2 improved on the poor rates of fire and armour associated with its predecessor.

**Figure 9 Trends in Unit Costs of Main Battle Tanks**




Source: Pugh Private Communications (1993), MOD Defence Estimates (1981) and Jane's Armour and Artillery (1994).

**Figure 10 Trends in Unit Costs of Combat Aircraft**




Source: Pugh Private Communications (1993) and MOD Fixed Asset Register (2009)

*Models of Equipment Cost Escalation*

62. The key trends in the cost data are explored further through the construction of empirical time trend models based on multiple regression analysis. To date this has been the standard approach to measuring intergenerational cost escalation in the UK literature.

63. The model we use is given in equation (1)

$$\ln(U) = \alpha + \beta T_{it} + \varepsilon_{it} \tag{1}$$

Where:

ln*(U)* = natural log of averaged unit cost of a given equipment platform
*T* = mid-generation in-service date of equipment platform
*ε* = error term
*α, β* = coefficients to be estimated

64. In (1), β may be interpreted as the average annual ratio of cost change. The percentage rate of cost escalation is given by 100%x β.

65. The coefficient of trend identified in this simple model represents all change over time, including enhanced capability, size and technology and should be considered as representing the overall cost growth. Developing this model to include identified characteristics is considered below.

66. The empirical results of the simple unit time trend model given in (1) are shown in the Table 5 below. These rates may be considered the estimates of overall intergenerational cost growth.

**Table 5 Simple unit time trend model of overall intergenerational cost growth**

| | % annual cost growth (simple time trend model ) |
|---|---|
| Generic Naval platforms | 3.4% |
| Destroyers | 2.6% |
| Frigates | 4.3% |
| Generic submarines | 2.9% |
| Aircraft carriers | 3.8% |
| Combat aircraft | 5.8% |
| Main battle tanks | 5.9% |

67. As identified above, the standard trend model provides a cost growth estimate unadjusted for changes due to enhanced capability, size and technology. Unfortunately our data set is limited in the characteristic data available, however, it may be possible to provide an analysis of the extent to which costs grows over time over and above changes in characteristics of platforms. To explore the effect of characteristic changes on the overall cost growth rate, the standard model framework may be extended to equation (2).

$$\ln(U) = \alpha + \gamma_1 T_{it} + \gamma_2 q_{it} + \varepsilon_{it} \tag{2}$$

68. Where *q* denotes a vector of physical equipment characteristics and $\gamma$ represents the vector of coefficients to be estimated. The coefficient $\gamma_1$ represents the annual average rate of increase in cost due to factors not explained by the explanatory variables in vector *q*

69. However, the physical equipment characteristics by platform are likely to be highly correlated. For example, a generation of ships that are longer than the previous generation is also likely to be wider, broader in the beam, deeper in the water etc. A high degree of multicollinearity present in the explanatory variables of the vector q will impair the accuracy and stability of the parameter estimates $\gamma_1$.

70. Analysis of pair wise correlation of the naval platform data suggest there is a correlation of 0.86 between displacement and length, and 0.94 between beam and draught in our submarine data sample. In the destroyer data sample there is a correlation of 0.93 between displacement and length and a correlation of 0.81 between beam and draught. In Frigates, the correlation between displacement and length is 0.96 and between beam and draught of 0.64. It is clear that these very high degrees of correlation between the equipment characteristic variables may render the standard multiple regression estimation of the coefficients in model (2) inaccurate and unstable and the effects of the characteristics on costs cannot be sensibly investigated this way.

71. However, the method of principal components, a special case of the more general method of Factor Analysis, may provide a solution. The aim of the method of principal components is to construct out of the non-orthogonal variables a new set of variables (the principal components) say *P* which have the property that they are linear combinations of the original variables and constructed such that they are orthogonal. Regressions performed on the orthogonal variables are therefore valid, reliable, precise and stable. The methodology is described in Annex C. The characteristic variables identified by the principal component approach are then used to estimate the coefficients of the model (2) by exogenously selecting the variables which contribute most on the basis of principal component analysis rather than a regression based selection of variables which may have been compromised by multicollinearity.

72. The principal component methodology has two advantages which relate to the estimation of the model in (2) as applied to our cost and characteristic data available on equipment platforms. The first is that the methodology has been suggested as appropriate where a high degree of multicollinearity is present (whether the methodology is appropriate depends on whether there is a meaningful interpretation of the artificial principal component variables) and secondly where the number of explanatory variables, on a priori grounds, to be included is large relative to the sample size of the data[13]. In our case the artificial variable is a linear combination of dimension metrics and if these are standardised, a linear combination represents standardised proxy for generalised size or capability.

73. The exogenous variables available for naval platforms would include displacement weight, length, beam, draught, speed and range whilst an aircraft equation would feature weight, length, speed, range and height. The model specification in (2) develops Pugh's (2007a; 2007b) approach to using weight as a proxy for capability and complexity, while empirically judging each variable's contribution.

74. The principal component methodology requires a number of observations which has limited this application to the naval platforms Destroyers, Frigates and to the RAF combat aircraft.

75. The characteristics identified by principal component analysis suggest that beam, range and draught contribute more to the change in cost than the in-service delivery date for destroyers and for frigates displacement (weight) and range are more significant determinants of cost than in-service delivery date. In the combat aircraft category displacement (weight) is the characteristic variable identified by principal component analysis.

[13] Theory of Econometrics. Koutsoyiannis A, p251& p425

76. Estimation of the model in (2) on the basis of the equipment characteristic (s) identified suggests that the remaining or residual rate of cost escalation for destroyers is 1% per annum; for frigates is 2.2% and for combat aircraft is 5.7%.

77. The residual rate of cost escalation using principal component analysis of 1% is considerably lower than the rate implied by Pugh (2007a) of 2.9%.

78. The underlying rate of cost escalation of RAF combat aircraft of 5.6% using principal component analysis is lower than the rate estimated by the simple model approach of 5.8% but higher than the estimated cost growth of Pugh (2007a) of 4% for fighter/strike aircraft based on international data.

### *Main Battle Tanks*

79. Main Battle Tank data did not lend itself to principal component analysis. The estimated cost growth of Main Battle Tank category of 5.9% per annum shown in Table 5 has been examined further using regression analysis of a basic model of regressing cost against each variable of equipment characteristic, namely weight, width, volume, height, range speed and engine size. It was found that except for engine size, none of the equipment characteristic variables were individually statistically significant. Engine size regressed on cost however was statistically significant and could completely replaced trend in the relationship on cost. This suggests that cost growth is accounted for by changes over time of main battle tank engine size and consequently unexplained residual cost growth is negligible.

### *The End of the Cold War Effect*

80. The implications for international relations since the end of the Cold War and the disintegration of the Soviet Block between 1989 and 1991 are now well known. The removal of the Soviet Threat, it was argued, would allow the US and its allies to moderate their defence spending.

81. There had been rapid expansion of US military expenditure throughout the 1980's as the Cold War was seen increasingly as a global struggle between the United States and the Soviet Union. The Soviet Union too, fighting an increasingly frustrating war in Afghanistan, was facing escalating costs of the Cold War arms race with the US during the 1980s. Therefore, the "peace dividend", it was argued, would follow the end of the Cold War and allow the US and its allies to significantly reduce defence spending. This did happen particularly among the US's European allies, but absolute US defence expenditure began to increase as the US became involved in Iraq and Afghanistan from the early 2000's.

82. It has also been suggested that the end of the Cold War would impact on equipment cost growth. There is currently little UK empirical evidence on which to provide any robust analysis. As the procurement time scale from development to in-service delivery of military platforms, which can be several decades, currently exceeds the time that has elapsed since the end of the cold war the data that is available is limited to equipment with post cold war in-service delivery dates but with development programme origins that are during the cold war period. The perception that with the end of the arms race the necessity of ever more high cost technology and increased capability equipment (the arms race), which is assumed to have driven up cost assumes that the tournament feature of military equipment is somehow lessened since the end of the cold war. There is no evidence that this is the case in the UK as the Typhoon aircraft introduced since the cold war is considered at the cutting edge of current technology. The potential for reduced cost since the end of the cold war is more likely to lie in the degree to which countries are able to co-operate in production of equipment and achieve more economic defence industries.

83. The time frame between development and in-service delivery of relatively large platforms, such as a ship, is generally longer than one or two decades. This suggests that since the end of the Cold War, a period of 20 years, there have been relatively few examples of new generations of UK equipment. However, Arena et al (2006)[14] found in their study of post Cold War US naval data, for the three naval categories "surface combatant, "attack submarine" and "aircraft carriers" that the unit cost escalation rates were lower for the 10-15 year period (post Cold War) than for the 40 -50 year period (pre- & post-Cold War period). The analysis suggests that the customer-driven factors (due to characteristic complexity, standards etc) and the economy-driven factors (wages, labour productivity, material costs etc) were roughly equal in magnitude for both periods. Arena et al offered no explanation for the difference in unit cost growth rates or whether the differences were statistically significant. Also, the data included in the post Cold War period in the Arena et al study included costs of equipment that had been ordered and developed prior to the end of the Cold War[15].

84. In terms of UK equipment platforms, defining a period as post Cold War since 1990 would include the Type 23 Frigate, introduced in 1989 replacing the Type 22 Batch 3 Frigate introduced in 1986. The Type 23 Frigate was developed prior to the end of Cold War. A purely statistical analysis, however, of the sample periods (1956 to 1989) and (1990 to 2000) would indicate that unit cost growth is lower per annum for the more recent sample (3.7% compared with 4.4% and statistically significant). However, as shown in Figure 6, the unit cost of Frigates had begun to decline in the 1980s and continued until 2000, which suggests that factors other than the end of the Cold War were influencing unit cost.

85. The Type 45 destroyer class could be defined as a new generation of ship within the end of the cold war period and replaces the Type 42 destroyer class which will be withdrawn from service by 2013. The first Type 45 destroyer entered service in 2009 and subsequent vessels will be delivered in service by 2015. The Type 45 ship is a highly versatile and technological advanced class of ship, equipped with the world leading Principal Anti-Air Missile System (PAAMS). Currently cost data for this class of destroyer is limited or projected.

86. A pre- and post cold war analysis for combat aircraft suggests that unit cost escalation between 1990 – 2008 was some 4.8%, and for 1955 – 1988 was 5.8% although this difference was not statistically significant. The aircraft in the post cold war sample included the Tornado GR4 Interdictor and the Tornado GR4A Interdictor which are based on pre – cold war Tornado models. The Euro fighter Typhoon, two of which were introduced into service in the UK in 2006 and 2008 were the result of a collaborative Anglo, French and German development, with UK origins dating back to 1979 and the RAF Harrier 2 and the AST 403 programmes and the concurrent French ACT-88 and German TKF-90 programmes.

87. Analysis of Main Battle Tanks unit cost data for the pre and post cold war periods provided no statistical difference in cost growth rates.

88. The Astute class of submarine was commissioned in 2010. The approval to define the batch 2 Trafalgar class (which later became Astute) was granted in 1991.

89. The empirical evidence for a statistically significant difference between intergenerational cost growth pre and post the end of the cold war is therefore currently unavailable and evidence based on analysis of unit cost pre-and post end of cold war sample periods suggests that this is anecdotal at best.

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[14] Annex D "Cost escalation over the past 15 years"

[15] For example, the *Los Angeles* class submarine delivered in 1988 and the *Virginia* class submarine in 2002.

## Section 4, Conclusion

### *Conclusion*

90. We have established a defence equipment platform data base for the United Kingdom and estimated the broad category and individual category estimates for the intergenerational cost growth. These are generally lower rates in absolute percentage than those found by Pugh and Kirkpatrick. It is difficult to assess, but it may be because the rate of increase in intergenerational cost has slowed since the estimates provided by Pugh and Kirkpatrick. Our figures are in line with the Athena et al and the Chalmers work on more recent data. However, due to limited data on new generations of equipment since the 1990s and lack of sufficiently detailed accounts of earlier data used by Pugh and Kirkpatrick, it has not been possible to conclude that the rate of intergenerational cost growth has been markedly different since the Cold War although there is tentative, if largely anecdotal, evidence for this.

91. We have looked at the overall trends in intergenerational cost growth for defence equipment platforms and suggest that much of the cost escalation reflects the choice of characteristics e.g. a shift from large to smaller ships, or the choice for larger engines in main battle tanks. This appears widespread across defence equipment platforms and is illustrated in terms of the explained increases in costs associated with destroyers, frigates, combat aircraft, and aircraft carriers and main battle tanks. For all of these, most, if not all of the cost growth can be explained by the change in the specified characteristics of each generational platform.

92. However, this does not mean that intergenerational cost growth is, or has been, largely discretionary. There may have been no real choice about the size of the engine, for example, when the new generation of tank was being considered if it was to match the military requirement at the time.

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## Annex A Cost Escalation Algorithms

93. A general cost growth estimation approach calculates a compounded real rate over the whole data series of n observations using the first and last observation of the real unit cost of an equipment platform. The average annual real rate of cost growth is obtained by solving for r in equation (A1). Where unit cost are expressed to common base year (i.e. in 2009 prices)

$$\text{Unit cost } (t_n)=\text{unit cost}(t_0)*(1+r)(t_n- t_0) \qquad \text{(A1)}$$

94. Where $t_n$ is the latest year of the sample period and t0 the first year of the sample period, unit cost ($t_n$) is the unit cost of equipment delivered for service in year $t_n$ and unit cost ($t_0$) is the unit cost of equipment delivered for service in year $t_0$. The rate derived in (A1) is average real cost growth per annum.

95. Intergenerational cost escalation is the rate of growth per year measured between two successive generations, say G1 and G2 are defined as two successive generations of platform. The rate is calculated based on in-service date and the associated unit cost at in-service date (G1) and in-service date and the associated unit cost at in-service date (G2). Where specified, average unit costs of generations may be used.

96. Where intergenerational cost growth is measured over several generations of platform as in Arena et al (2006), we derive a compound cost growth function over the whole sample period. This approach takes the first and last generation of a given platform and solves (A2), which normalises cost growth to a common baseline, to derive the annual escalation rate.

$$r = [(P_n-P_0) \surd \text{Cost}_n/\text{Cost}_0] - 1 \qquad \text{(A2)}$$

97. where (p) is the period interval reflecting the in-service date of a specified generation of equipment, ($\text{Cost}_n$) is the real cost of a unit of equipment in the most recent time period observed ($\text{Cost}_0$) is real cost in the oldest time period observed.

98. Kirkpatrick (2009) questioned the validity of producing estimates from two data observations, since both could be affected by special circumstances so the outturn results from (A2) are compared using an OLS time trend approach which incorporates more of the data into the calculation. The functional form being determined by which best fits the data. In most cases, we estimate a simple OLS linear time trend, as represented by (A3),

$$\text{Ln}(\text{Cost}_t) = \alpha + \beta t + \varepsilon_t \qquad \text{(A3)}$$

## Annex B Equipment Count Approach

99. Assuming that defence budget constraints operating under increasing equipment unit cost reduces the number of units of equipment, there is an alternative approach to estimating cost escalation based on the reduction in the numbers of equipment. This approach requires information on equipment quantities that are in-service at a given point in time and corresponding budget information.

100. The International Institute of Strategic Studies (IISS) provided published information on some UK naval systems, the remainder from internal MOD sources, providing annual in-service quantities of Aircraft Carriers, Cruisers, Destroyers, Frigates and Submarines as a major platforms sub-group (1967-2009), including data on Frigates which was sufficient for individual category analysis (1967-2009). A further series was constructed of all ships (1967-2009), which included minor platforms such as Mine Counter Measures (MCM) vessels, Offshore Patrol, Patrol and Ice Patrol vessels. For each series assembled, the total number of units in-service in each year, under the specified category, was available.

101. Obtaining numbers for air equipment was problematic, necessitating a number of assumptions to derive consistent time series of the Royal Air Force (RAF) in-service fleet. Some quantity data on older systems, was available from IISS publications, for more recent aircraft, figures produced by the UK Defence Statistics (UKDS) for the Forward Available Fleet (FAF)16 were available, although this excluded aircraft undergoing major services and routine maintenance. Sufficient data provided the grouping of equipment by Combat aircraft, Transport aircraft, Patrol aircraft and Trainer aircraft which was mapped against time with gaps in the time series filled using an assumed rate of attrition17.

102. Land equipment in-service data was limited although an equipment count series for main battle tanks was established.

### *Methodology and caveats*

103. This equipment count approach is based on the assumption that under a constrained defence budget and escalating unit costs fewer platforms are supplied. This approach constructs a model which frames equipment numbers with time and infers the cost escalation rate from the reducing platform quantities. The model assumes that equipment quantities drop by a constant proportion each year as unit costs increase by a fixed percentage each year deriving a geometric series model. Analysing the quantity of equipment in service across a long-run time period we are able to observe the intergenerational alterations in the structure of a given system of equipment. Taking the total number of platforms in the initial year, At, in Force Y and Category X, then modelling implies that the number of platforms in At+n is

$$A_{t+n}(Y,X) = A_t / (1+r)^n \qquad \text{(B1)}$$

104. where r is the ratio of relative unit costs from one generation to the next and n is the number of years.

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[16] The FAF is a new way of managing aircraft resources with the aim to enable the optimal level of availability to the Royal Navy. FAF is defined as the number of aircraft required to undertake the mandated task.

[17] By attrition, we refer to the annual rate of reduction in the quantity of equipment in-service. Pugh (1986) has suggested a figure of 4.1% per annum for naval aircraft, although we have sought to solve for the rate which minimises the error between the first and last data points, and their estimated values.

105. It is apparent that this modelling approach is similar to discounting, whereby number of platforms is 'discounted' by a corresponding constant annual unit cost escalation rate. The value of r can be solved in either of two ways. Either, for the given equipment quantity in Force Y and Category X in (B1) can be re-arranged to derive (B2).

$$r = (At - At+n)1/n -1 \qquad \text{(B2)}$$

106. Alternatively, r can be solved electronically using a solver function within software packages such as Microsoft Excel. Such an approach derives values for A and r by solving for those values that minimise the square of the distance between the modelled points from the actual quantities of equipment platforms. This approach has been used to provide estimated cost escalation in Tables B1 and B2

107. The equipment count data approach requires a number of other generalised assumptions. For a given unit of equipment it is assumed that the only factors that matter are the annual rate of unit cost escalation and the level of defence expenditure. This in turn suggests that demand for specific equipment platforms is subject only to a budget constraint. There is an assumption that the unit costs of a given platform will adjust at a constant rate for each generation and therefore each year. Headline expenditure on equipment is assumed constant in real terms over time. This is plausible since the overall defence budget has remained roughly constant in real terms in the long run and the proportion of defence equipment expenditure has remained relatively constant. Finally, the assumption is made that the different classes of equipment are homogenous so that characteristics of size, role and useful life are assumed equal. This enables us to adopt aggregate numbers throughout out analysis. Assuming homogeneity also implicitly removes the effect of factors such as size and speed on unit cost.

*Estimated Cost Escalation*

108. The estimated real unit cost escalation rates for the platforms listed are shown in Table B1 for naval platforms and in Table B2 for air equipment, together with the attrition rates assumed where necessary.

Table B1: Annual Real Unit Cost Escalation Rates for Sea Equipment

| Platform | Sample period | Cost growth |
|---|---|---|
| All major and MCMs | 1967-2009 | 3.10% |
| All major platforms | 1967-2009 | 2.90% |
| Destroyers | 1967-2009 | 1.23% |
| Frigates | 1967-2009 | 3.70% |
| Aircraft Carriers | 1967-2009 | 0.77% |
| Submarines | 1967-2009 | 2.63% |
| MCMs | 1967-2009 | 3.50% |

Table B2: Annual Real Unit Cost Escalation Growth for Air Platforms

| Platform | Sample period | Attrition Assumed | Cost growth |
|---|---|---|---|
| Combat aircraft | 1964-2009 | 5.0% | 4.7% |
| Transport aircraft | 1964-2009 | 2.3% | 5.4% |
| Patrol aircraft | 1964-2009 | 2.0% | 3.5% |
| Trainer aircraft | 1964-2009 | 2.0% | 4.0% |

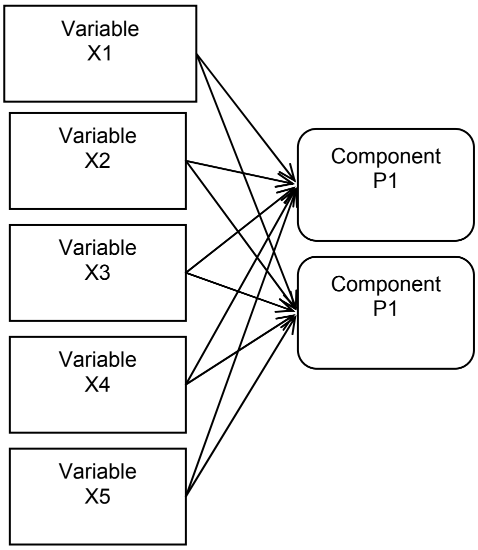
## Annex C Method of Principal Components

Method of Principal Component Analysis (PCA)[18]

109. Given the model

$$Y = \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \quad \text{(C1)}$$

110. The aim of the method of *principal components* is to construct out of the set of variables $x_j \ (j = 1,2\ldots k)$, not necessarily uncorrelated, a new set of orthogonal (uncorrelated) *principal components,* $P_r \ (r = 1,2\ldots n)$, $r < k$ . This is depicted in figure 1 where the direction of influence is indicated by the arrow.




111.

*112. Figure 1 – The model for PCA*

*113.* The linear combination of the variables can be constructed such that they are orthogonal and ordered so that the first *principal component* absorbs the most variability of the original variables, the second the next highest variability and so on yielding the maximum *k principal component* explaining all the variation:

$$\begin{aligned} P_1 &= \alpha_{11}x_1 + \alpha_{12}x_2 + \ldots + \alpha_{1k}x_k \\ P_2 &= \alpha_{21}x_1 + \alpha_{22}x_2 + \ldots + \alpha_{2k}x_k \\ \vdots \quad & \vdots \qquad \vdots \qquad\qquad \vdots \\ P_k &= \alpha_{k1}x_1 + \alpha_{k12}x_2 + \ldots + \alpha_{kk}x_k \end{aligned}$$

114. By estimating the values of $\alpha$ (the loadings) and the *score* of $P_r$ , the values of $\beta$ in equation (C1) may be constructed.

115. The method used in this paper uses the standardized variables defined as

$$z_i = \frac{x_i - \bar{x}_i}{\sigma_x}$$

116. Where $\bar{x}_i$ and $\sigma_x$ are the mean and standard deviation of $x_i$ respectively. This transformation standardises the original variables and computes *principal components* and subsequently the $\beta^*$ in equation (C1a) allowing interpretation of variables irrespective of their original measurement.

$$Y = \beta^*{}_1 Z_1 + \beta^*{}_2 Z_2 + \ldots + \beta^*{}_k Z_k + \varepsilon \quad \text{(C1a)}$$

The computation proceeds as follows:

117. Given the model in equation (1), and standardised $z_i$, estimate the loadings $\hat{\alpha}_i$ which provide the *principal components* $P_i \ (i = 1,2\ldots k)$[19].

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[18] The method is based on Koutsoyiannis, A. *Theory of Econometrics 2nd Ed.*1977, Macmillan pp424-426

[19] The methodology for estimating the loadings is beyond the scope of this annex

118. A decision criterion is used to decide how many of the *k* principal components to retain. The computation yields an eigenvalue $\lambda_i \ \forall \ P_i$. The eigenvalues (or latent roots) are equal to the sum of the squares of the loadings of $P_i$, and is related to the amount of variance in the $z$'s explained by $P_i$. In this paper we retain all $P_i$ for which the corresponding eigenvalue $\lambda_i$ is 'close to' or greater than one. This enables us to retain sufficient explanatory power from the *principal components* while not including *principal components* which are heavily affected by factors not common to all the original variables.

119. To illustrate the methodology assume the original model contained 3 variables (standardised) $z_j \ \ (j = 1,2,3)$ and the process described above has resulted in $P_r \ \ (r = 1,2)$ retained (i.e. $P_3$ has been discarded). This yields:

$$P_1 = \hat{\alpha}_{11} z_1 + \hat{\alpha}_{12} z_2 + \hat{\alpha}_{13} z_3 \qquad \text{(C2)}$$
$$P_2 = \hat{\alpha}_{21} z_1 + \hat{\alpha}_{22} z_2 + \hat{\alpha}_{23} z_3 \qquad \text{(C3)}$$

120. Only the loadings $\alpha$ which are deemed statistically significant are retained for further analysis. The loading can be considered to be similar to correlation coefficients. On this basis, one can reject the null that $\alpha = 0$ if the value of $\alpha$ is greater than the critical value given for the test of significance for the Pearson correlation coefficient.[20]

121. We proceed by regressing the dependent $Y$ variable from the model on the principal components scores to estimate the principal component model:

$$Y = \hat{\gamma}_1 P_1 + \hat{\gamma}_2 P_2 + \upsilon \qquad \text{(C4)}$$

122. Substituting (2) and (3) into (4) allows the values of the estimated value of structural parameters $\hat{\beta}$ from the original model to be recovered.

$$\hat{\beta}_1 = \hat{\gamma}_1 \hat{\alpha}_{11} + \hat{\gamma}_2 \hat{\alpha}_{21}$$
$$\hat{\beta}_2 = \hat{\gamma}_1 \hat{\alpha}_{12} + \hat{\gamma}_2 \hat{\alpha}_{22}$$
$$\hat{\beta}_3 = \hat{\gamma}_1 \hat{\alpha}_{13} + \hat{\gamma}_2 \hat{\alpha}_{23}$$

123. This is shown by recognising that:

$$Y = \hat{\gamma}_1 (\hat{\alpha}_{11} z_1 + \hat{\alpha}_{12} z_2 + \hat{\alpha}_{13} z_3) + \hat{\gamma}_2 (\hat{\alpha}_{21} z_1 + \hat{\alpha}_{22} z_2 + \hat{\alpha}_{23} z_3) + \upsilon$$
$$Y = (\hat{\gamma}_1 \hat{\alpha}_{11} + \hat{\gamma}_2 \hat{\alpha}_{21}) z_1 + (\hat{\gamma}_1 \hat{\alpha}_{12} + \hat{\gamma}_2 \hat{\alpha}_{22}) z_2 + (\hat{\gamma}_1 \hat{\alpha}_{13} + \hat{\gamma}_2 \hat{\alpha}_{23}) z_3 + \upsilon$$
$$Y = \hat{\beta}_1 z_1 + \hat{\beta}_2 z_2 + \hat{\beta}_3 z_3 + \upsilon$$

124. Or in the more general case for *j* retained principal components and *k* variables

124.1. $\hat{\beta}_k = \sum_{i=1}^{j} \hat{\gamma}_i \hat{\alpha}_{ik}$

The relative contribution each variable makes to the dependent variable is then represented by the coefficients in the standardised equation (C1a) and is not influenced by the units of measurement of that variable.

[20] For ease of exposition all loadings are retained for this example