INVESTMENT COST ESCALATION – AN OVERVIEW OF THE LITERATURE AND REVISED ESTIMATES

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Abstract

This article presents an overview of literature and previous estimates of defence specific investment cost escalation (ICE). ICE, the cost increase between two generations of a weapon system, can place a heavy strain on defence budgets if not properly accounted for. Previous literature specifically pinpoints the competition element as the main driver behind ICE. This article also discusses the role of technology and of supply and demand. Finally, we provide more recent estimates of ICE, using more sophisticated methods than those previously used. Results indicate that ICE estimates are reduced when changes in weapon system characteristics are accounted for.

Keywords: Investment cost escalation; Intergenerational cost escalation; Defence; Military capabilities

1 Introduction

> In the year 2054, the entire defense budget will purchase just one tactical aircraft. This aircraft will have to be shared by the Air Force and Navy 3 1/2 days per week except for leap year, when it will be made available to the Marines for the extra day.
>
> *Norman Augustine (1983, p. 55)*

With his First Law of Impending Doom, or the Final Law of Economic Disarmament, Norman Augustine (1983) claims that if the current rate of cost increases in weapon systems continues, it will soon consume the entire defence budget. In this article, we review the literature

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on investment cost escalation (ICE)[1] as well as provide revised estimates for the magnitude of ICE. Such estimates, and the understanding of driving forces, are crucial in long term defence planning.

Cost escalation occurs between generations (intergenerational) and within generations (intragenerational). An example of the former is the increase in cost from F-16E/F to F-35A, an example of the latter is the increase in price between F-16A/B and F-16E/F. Cost *growth* (a part of defence inflation) is the rise in costs from the time a project is started to the time of acquisition, i.e. from Joint Strike Fighter (JSF) estimates to actual F-35 acquisition unit cost. We believe the most important reason behind cost escalation is the continuing struggle to obtain the very best equipment. There are no silver medals in war, thus high quality equipment is of vital importance. Important drivers behind cost growth include overoptimistic forecasting (deliberate or not) and changes in requirement specifications.

Two insights form a background for this article. First, the objective of any defence procurement strategy must be to maximize the utility from available equipment, subject to the restraint that funds are limited. Second, the utility of a defence good is not derived from the good itself, but from its effect relative to the equipment of potential adversaries. It is therefore of great importance to have equipment that is state of the art.

The remainder of this article is organized as follows. Sections 2 to 4 discuss definitions and previous estimates, while Sections 5 to 7 contain our updated ICE estimates. Section 2 makes a distinction between cost *escalation* and cost *growth*. Section 3 discuss potential causes of ICE, while 4 discuss previous empirics. Section 5 and 6 describe the data and various methods for estimating ICE. In Section 7, we to estimate historical ICE ”as is”, as well as historical ICE net of quality improvement and changes in production quantity. The hypothesis that ICE net of such changes will be lower than the unadjusted ICE is confirmed.

2 The ICE concept

2.1 Concepts and previous ICE studies

Increasing defence equipment unit costs have long been a source of concern in many countries. Back in 1959, Marshall and Meckling of the RAND Corporation found a downward bias in early stage cost estimates of new weapons systems in the USA (Marshall and Meckling 1959). Later, the so called Spinney report (Spinney 1980) claimed that increasing technological complexity and the military industrial congressional complex (MICC) were significant contributors to increasing costs. The Spinney report concludes that ’our strategy of pursuing ever increasing technical complexity and sophistication has made high technology solutions and combat readiness mutually exclusive.’ The report propelled Spinney to the front page of TIME, and the issue of defence specific cost increases to a more prominent position in the public debate.

In the 1980s and 1990s, attention turned towards *intergenerational* ICE, which will be our main focus. Studies by Deitchman (1979), Kirkpatrick and Pugh (1983), Pugh (1986, 1993), Kirkpatrick (1995), Pugh (2007), and Davies et al. (2011) discuss cost escalation between generations of weapons systems – from the Gloster Meteor (in service from 1944) to the Eurofighter Typhoon (2006) and from the Dreadnought class (1963) to the Astute class nuclear

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[1] This concept is sometimes called intergenerational cost escalation, but such a name hides the fact that there is also *intragenerational* cost escalation, as we will see later.

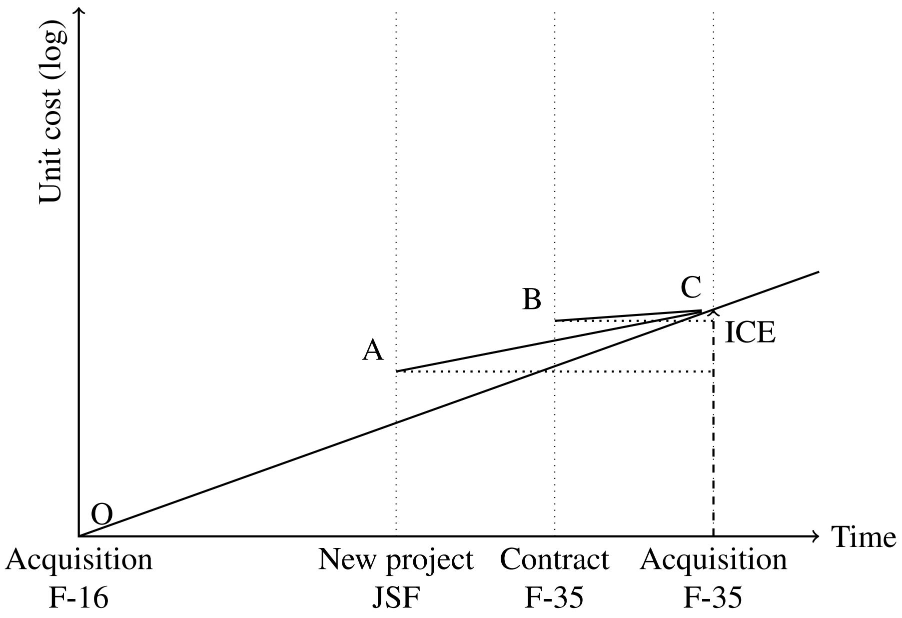

Figure 1: Unit cost as a function of time. Real terms. Aggregated ICE measures the entire dashed line from the point *Aquisition F-35* to point C.

submarine (2010). In this article, we define ICE as the annualized long run increase in unit costs over generations of a weapon system beyond a base cost index (i.e. in real terms).

We summarize some cost escalation concepts in Figure 1. Measurement of ICE starts at the time of acquisition, say F-16 (point O). After a number of years, a decision is made to replace the F-16. At the start of the replacement project JSF, a future price level of A is estimated, which will rise only by the general price level (hence the flat dotted line originating in A, i.e. no real cost growth). However, when the delivery contract is written up, cost estimates have increased to a future price level of B. When the aircraft are finally delivered, final costs were C, i.e. slightly above what the contract stated. The slope of the curve OC is much steeper than that of AC, which in turn is steeper than that of BC. Thus, the new project and the contract have taken into account some of the (at this point unknown) intergenerational cost escalation, but not all of it. Arena et al. (2008) denote the line OC cost escalation, while the AC and BC lines are denoted cost growth. The focus of Marshall and Meckling (1959), Calcutt (1993), Drezner et al. (1993), Arena, Leonard, et al. (2006), Younossi et al. (2007), Bolten et al. (2008), and Smirnoff and Hicks (2008), are on the AC or BC lines, i.e. underestimation of costs, while Crocker and Reynolds (1993) and Bajari and Tadelis (2001) are examples of studies of cost growth only during the contract phase, BC. The focus of Deitchman (1979), Kirkpatrick and Pugh (1983), Pugh (1986, 1993), Nesset and Wessel (1995), Kirkpatrick (1995), Dalseg (2003), Arena, Blickstein, et al. (2006), Pugh (2007), Kvalvik and Johansen (2008), Arena et al. (2008), Nordlund et al. (2011), and Davies et al. (2011) are on the OC line, i.e. long run cost escalation between generations.

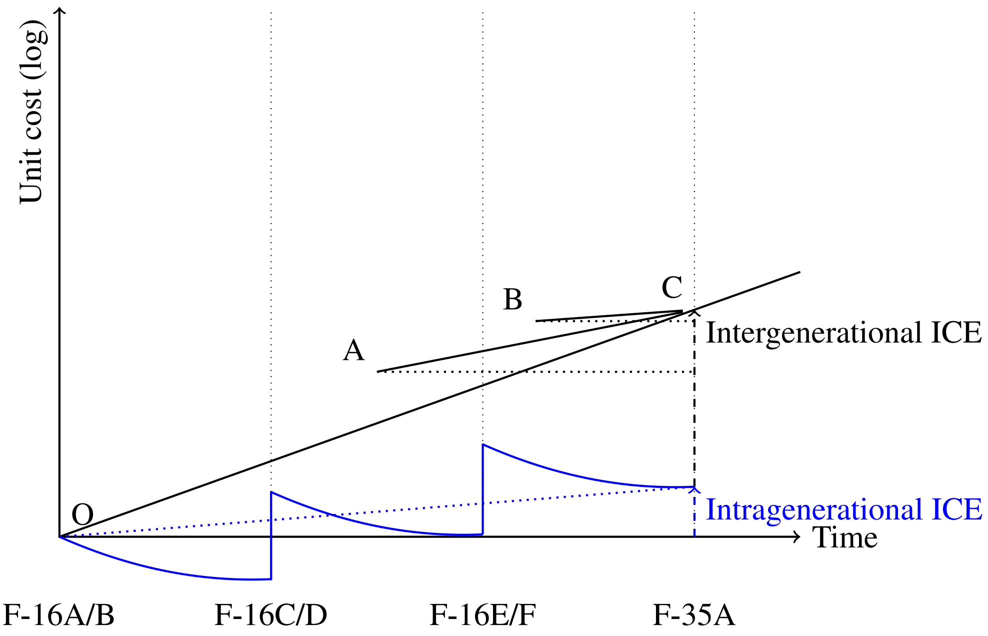

Figure 2: Intergenerational and intragenerational ICE, the sum of which constitute total ICE.

2.2 Intra- and intergenerational ICE

It can be useful to make a distinction between intra- and intergenerational ICE, as illustrated in Figure 2.[2] During its lifetime, a system can go through radical changes in design and capability. The F-16E/F Block 60 is a far superior fighter to the F-16A/B Block 1, though they are both F-16s. Figure 2 illustrates a conceptual picture of the intragenerational cost escalation of the F-16.[3] Soon after the first aircraft are delivered, prices fall due to economies of scale and because of learning effects. When an upgraded version becomes available, the F-16 unit cost increases because the new model is more complex, made of more expensive materials, has incurred new development costs, and learning from the previous version cannot be fully utilized. Economies of scale and learning effects gradually come into effect also for the upgraded F-16. Note that intragenerational cost escalation can be measured at any point on the intagenerational ICE curve, while intergenerational cost escalation is only known when we are at point C. In Figure 2, F-35 can utilize all improvements made during the F-16 lifetime and total ICE equals intragenerational ICE plus intergenerational ICE. If it cannot, utilize all improvements, intragenerational ICE plus intergenerational ICE will be higher than total ICE.

Figure 3 illustrates this further over multiple generations. Note that this is only an illustration of different cost developments, and not reflect actual development. Unit prices for system 1 falls during its lifetime, perhaps indicating no significant upgrades. System 2, which replaces system 1, is far more expensive from the offset due to large research and development (R&D) costs. System 2 enjoys economies of scale and learning effects in the beginning, but undergoes heavy upgrades and improvements at the middle of its lifetime, pushing unit prices up. System 3, which replaces system 2, reaps the benefits of the R&D work that was conducted during the

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[2] In Figure 2, the new system can utilize all the available technology improvements of the old system. To the degree this is not possible, the blue and black dashed lines will overlap.

[3] the actual F-16 picture is slightly different, see Arena et al. (2008, p. 13) for the actual development in prices from 1978 to 2001.

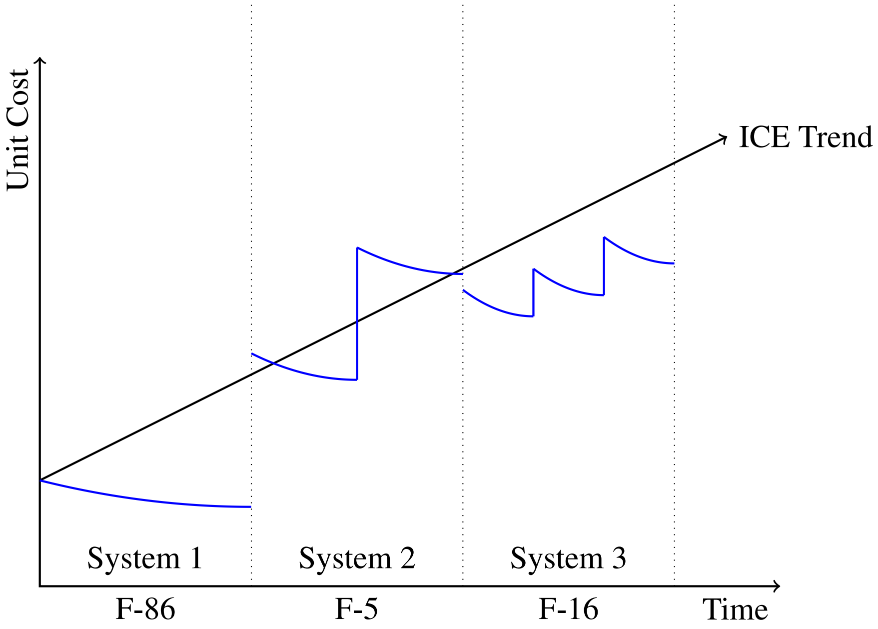

Figure 3: Intergenerational ICE trend and intragenerational ICE for three generations.

lifetime of system 2, and the unit costs of this system starts at approximately the same unit cost level as system 2 ended. The long term trend is shown by the continuously upwards sloping curve.

While intra- and intergenerational ICE are both types of cost escalation, the causes and the size of the change might be quite different. Increasing cost within a generation of a weapon system can be caused by on-going development (Arena et al. 2008). F-16 saw an annual cost increase of about 6 percent from 1978 to 1992 (Pløen 2005) and the F-15 from \$44 million in 1974 to \$58.6 million in 2000, probably caused by the substantial upgrades the aircraft underwent in this period (Arena et al. 2008). Arena, Blickstein, et al. (2006) found that cost increases within a generation of British war ships to primarily be caused by capability evolutions, while costs were relatively stable in periods without upgrades. This could indicate that much of the ICE is capability driven. As the technology used in the system becomes cheaper and as the production process improves, cost decreases could be expected. As shown by Arena et al. (2008), the net result of production improvements and capability improvements on intragenerational ICE can be both positive and negative.

Deitchman (1979, pp. 252–253) studies cost progression through generations and cost progression through improvements in a single generation, and concludes that the 'average difference in slope [...] is about a factor of 2.5. That is, over a given period of time it is less than half as expensive to improve the capabilities of major systems by continually improving their subsystems than it is to buy wholly new systems incorporating new technology in all their parts.'

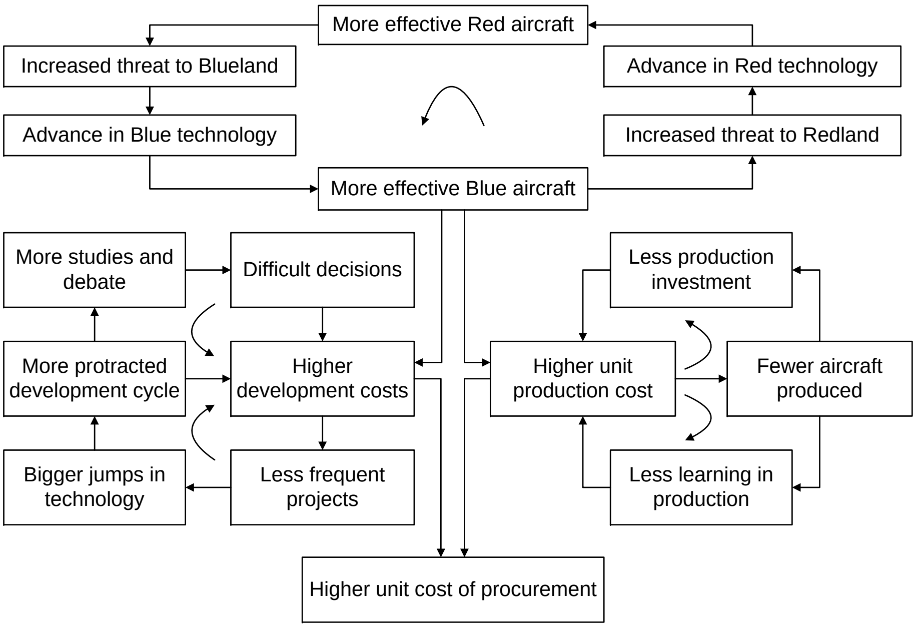

Figure 4: The vicious circles of unit cost escalation. Figure from Kirkpatrick and Pugh (1983) and Kirkpatrick (1995).

3 The causes of ICE

3.1 The vicious circles of cost escalation

Kirkpatrick and Pugh (1983) and Kirkpatrick (1995) identify three vicious circles to explain why at least some of ICE is a natural phenomenon. Figure 4 summarizes their reasoning. The top ”circle” relates to the concept of *relative effect* (corresponding to the concept of *effectiveness* in Kirkpatrick 1995), which we will return to in Section 3.2. In the top circle, the Blue nation acquires a new fighter jet. This increases the threat towards the Red nation, spurring development of new, highly sophisticated, technology in the Red country or its allies. In turn, the Red country can procure more effective aircraft. Developing new technology when you are already close to the technology frontier, is hugely expensive (cf. Section 3.3). Higher development cost (the circle at the left hand side) leads to less frequent projects, because a country cannot afford to upgrade as often as before. As a consequence, bigger jumps in technology and more difficult decisions occur, fuelling increased development costs. Higher unit costs mean fewer units produced, leaving less room for economies of scale and learning effects. Both effects feed back into higher unit production cost (the circle at the right hand side). Fewer units produced means there are fewer units to allocate fixed costs between. For technologically advanced equipment, fixed costs are often high, so fewer units produced does in itself translate into higher unit costs.

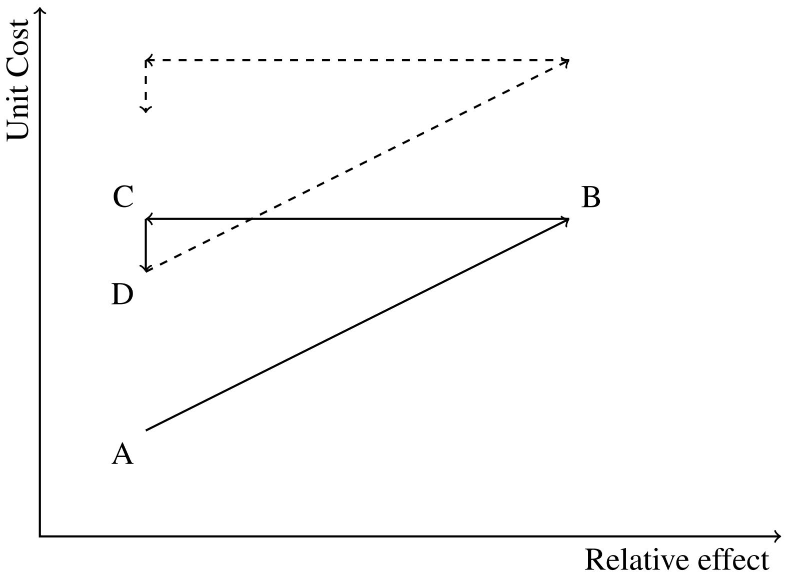

Figure 5: Relative effect. Figure from Kirkpatrick (2004).

3.2 Relative effect

Military equipment has little or no intrinsic value. It has a value only when compared to equipment of adversaries. Many consider an increase in effect per unit to be offset by a similar increase in the effect per unit of equipment of potential enemies (Kirkpatrick 1997, 1995, 2004; Kirkpatrick and Pugh 1983; Pugh 1993, 1986). As Pugh (1986, p. 140) writes, equipment 'is good or bad only in relation to what possessed by a potential (or actual) adversary. The benefits of improved armament are largely those of devaluing existing equipment, especially that of the adversary.' While the absolute *performance* of a new generation of a weapon system might increase, the *effectiveness* relative to the weapons of the adversary might be unchanged. Investing in unchanged performance would thus lead to reduced relative effect.

Kirkpatrick (2004) illustrates relative effect as in Figure 5. Initially in situation *A* with a given equipment at a given price, new technology becomes available and we move to point *B*. In *B*, equipment are more costly, but also more effective. When the same technology becomes available for the adversary, we move to situation *C*, where we have the same expensive equipment, but the increase in effect is offset by the new equipment of the adversary. As additional units are produced and economies of scale and learning improve, the price of the new equipment can decrease, as in situation *D*. The steps from *A* to *D* repeat themselves, as illustrated by the dashed lines. This continuous spiral increases costs, but not relative effect per unit. Pugh (1986, p. 141) illustrates the concept using an example of how penetrative capacity of battleship guns and the resistance capacity of battleship armour follow each other closely. Over the time period studied, the performance of both increases by a factor of four, leaving relative effect unchanged. While Kirkpatrick (1997) argues that relative effect causes ICE, Chalmers (2009) argues that if ICE exists, the increase in prices will affect the adversary as well, and therefore will have an ambiguous effect on relative effect of the equipment. There is no doubt, however, that the absolute price increases.

3.2.1 Rank order tournaments

We consider military equipment as a form of *tournament good.* Tournament goods are goods that only have value when compared to the goods of other actors. An example of a tournament good is football players. A football player has, as military equipment, no intrinsic value, but is valuable when compared to the opponents players. No previous research has been done on defence equipment as tournament goods, but some insight into the mechanics of tournament goods can be derived from Lazear and Rosen (1981). They describe effects of remuneration by performance ranking among employees on employees optimal choice of effort. A similar reasoning can be used to describe willingness to invest in military equipment.

A nation would like to maximize expected utility ($E(U)$):

$$E(U) = P(W_1 - C(\mu)) + (1 - P)(W_2 - C(\mu)) \tag{1}$$

Where P is the probability of winning, and depends on investment in equipment, μ. W_1 and W_2 respectively are payoffs from winning and losing. $C(\mu)$ is the cost of investing, and depends on the amount invested. Maximizing with respect to μ gives the solution:

$$C'(\mu) = \frac{\partial P}{\partial \mu}(W_1 - W_2) \tag{2}$$

I.e., the marginal cost of investing should be equal to the marginal expected gain from investing. Here, the marginal gain from investing is equal to the difference between W_1 and W_2 times the marginal increase in probability of winning from investing.

For military equipment, the difference in gain from winning and losing could be quite large. For essential equipment like fighter aircraft, the best fighter aircraft will provide air superiority, and hence rank is essential. In such circumstances, we could expect quite high willingness to invest. A class of goods where we could expect the opposite to be true is trucks. The gain from having better trucks than the opponent could be expected to be quite small, and hence the willingness to invest can also be expected to be quite small.[4]

3.3 The role of technology

The most expensive and well known pieces of defence equipment are items we think of as being state of the art. Imagine we can buy a weapon system along a technology (or performance) possibility frontier, where unit price increases with technology level. Technology encompasses such things as better machinery, R&D and productivity and learning effects. Increasing the level of technology from a low level to a slightly higher level only marginally increases price. This is because both technologies have been available for some time, are thoroughly tested and serially produced. However, increasing the technology from a high level to a very high level, prices will exhibit a dramatic increase. This increase occurs because the new level of technology has to be developed, have not previously been tested to the same extent (and therefore has a greater risk of errors), and must perhaps be custom made. The possibility curves will therefore slope upwards and at an increasing rate, as in Figure 6, adapted from Deitchman (1979, p. 240).

The technology frontier shifts outwards as research drives technology development. In Figure 6, the current weapon system is selected at today's technology frontier (the solid curve),

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[4] This is also an explanation why quite old trucks still is in use by the armed forces.

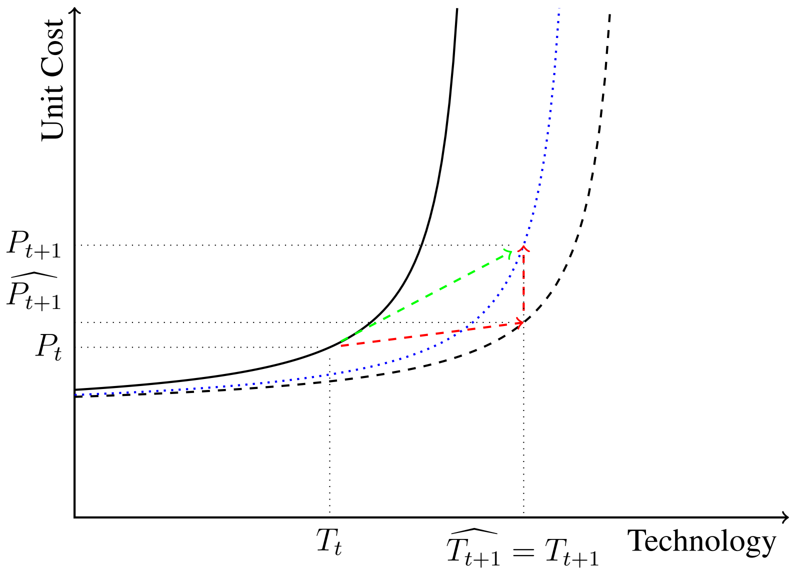

Figure 6: The role of technology. Figure adapted from Deitchman (1979).

where we have selected a combination of technology, or performance, (T_t) and unit cost (P_t). The higher the performance, the exponentially higher the unit cost. We then estimate a future technological frontier for our next weapon system (the dashed line), and select a combination of vastly improved performance ($\widehat{T_{t+1}}$) and, in this specific case, a slight increase in price ($\widehat{P_{t+1}}$). However, there is always a certain degree of uncertainty with regards to the future level of technology. At the time of acquisition, the technology frontier has only moved to the dotted line. At this point, the chosen level of performance, still equal to the previously estimated level, ($T_{t+1} = \widehat{T_{t+1}}$) costs significantly more (P_{t+1}). The higher the performance requirements, the greater the difference between the points at the dashed and the dotted line will be. Total ICE is illustrated by the upward sloping arrow.

Spinney (1980) pointed at the role increasing complexity has for increasing prices. Augustine (1983, pp. 44–45) points out that not only ”does operation near the edge of the state of the art often greatly increase cost and risk, but in addition it can have a seriously deleterious effect on reliability” and illustrates this by listing Mario Andretti’s 17 Indianapolis 500 starts, of whom he only finished three, but each time at the podium. He continues: ”Even when dealing with *available* technology, the best is often inordinately expensive. Sometimes, this cost is, of course, very worthwhile in that it provides the winning margin – that narrow edge between victory and defeat. But other times, particularly in times of fixed overall budgets, the practice of seeking that last little bit of capability can be not only very costly but also very counterproductive.”

3.4 Supply and demand

Distortions, such as monopoly power, can increase prices beyond the perfect market equilibrium. Supply and demand can influence on price escalation beyond what can be expected due to changes in input factor prices if market conditions worsen over time. In this section, we hypothesize around some supply and demand variables at play. We will use Figure 7 as an il-

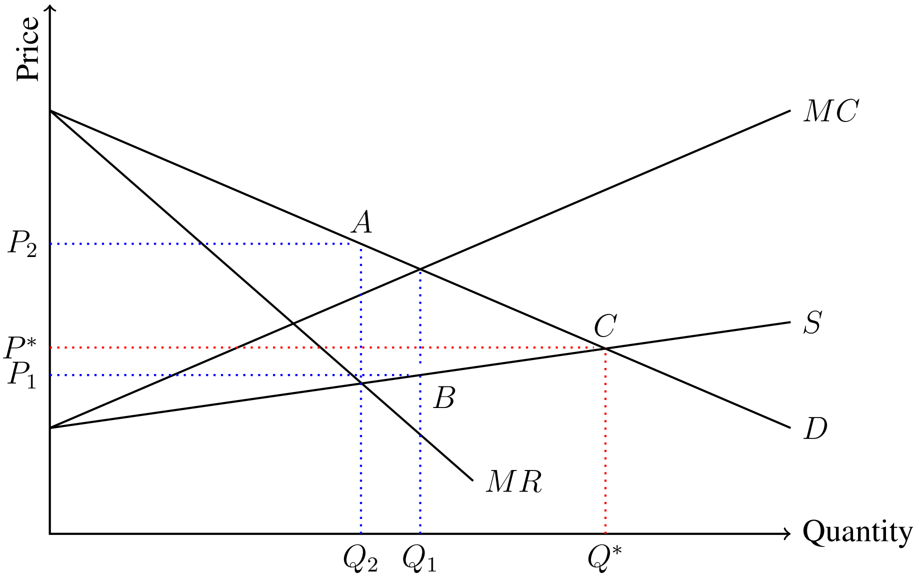

Figure 7: Example of a bilateral monopoly.

lustration throughout the section. Figure 7 is an example of a bilateral monopoly in the defence market. In a perfectly competitive market, optimal price P^* and quantity Q^* are set at the intersect between supply S and demand D. In a monopoly, price P_2 and quantity Q_2 are determined where supply is equal to marginal revenue MR. In a monopsony, price P_1 and quantity Q_1 are determined where the marginal cost MC is equal to demand. In a situation where we have both monopoly and monopsony effects, prices will be in the range of $[P_1, P_2]$ and quantity in the range of $[Q_1, Q_2]$, i.e. between points A and B.

3.4.1 Supply

In a perfectly competitive market, supply (S) occurs until the price equals demand (D), point C in Figure 7. However, suppliers of weapon systems can exercise a certain amount of market power. At the top quality level, they provide highly specialized equipment and competition is limited, at times bordering on monopoly. A greater degree of differentiation between suppliers, or fewer suppliers, increases the market power of the remaining suppliers. This lets suppliers raise prices by reducing the number of items supplied (Tirole 1988). The is perhaps not as clear in the defence sector, since there are also important demand side variables at play, which we come to shortly. However, prices would be lower if there were a large number of similar defence firms offering similar products in a competitive market. Since willingness to pay for high levels of performance is high, suppliers can to a certain extent determine prices. A company with monopoly power will only supply until marginal revenue (MR) $= S$ in Figure 7. The corresponding price is P_2 (point A).

The previous paragraph can help explain high prices. The effect on ICE, i.e. are prices merely high, or are they increasing, relates to change in supplier power over time. Over a long period of time, the number of defence firms was in decline due to mergers and takeovers (Northrop Corporation buying Grumman Aerospace Corporation in 1994, Lockheed Corporation merging with Martin Marietta in 1995 and Boeing and McDonnell Douglas merging in 1997). Reducing the number of suppliers can obviously increase market power (although one can also claim the mergers were necessary in order to meet new technology demands), thus increase prices.

3.4.2 Demand

In each country, there is only one (or a few, if private military companys (PMCs) exists) consumer of defence goods. Reducing the number of items supplied (as mentioned in section 3.4.1) does therefore not necessarily benefit the supplier. In the short run profits might increase, but if it leads to a reduction in the quantity procured by a sole customer, total profits will fall. In other words, there is also a certain degree of demander power (monopsony in the case of only one buyer). A monopsony buyer will demand until marginal cost (MC) equals demand (D), resulting in a price P_1 (point B) in Figure 7. Since the defence market exhibits both monopoly and monopsony power, the final price will be somewhere between P_1 and P_2, depending on the relative supplier and buyer power and the relative slope of the demand and the supply curves. If supplier power increases over time, prices tend to be pushed upwards over time, resulting in ICE.

The procurement of defence goods is also a highly political process. In the American case, Spinney (1980) mention two mechanisms at work:

1. *Front loading*, which is the concept of overstating capabilities and understating future problems in order to get a project adopted.

2. *Political engineering*, which is the spreading of dollars, jobs and profits to as many congressional districts as possible, in order to avoid cancellation of a programme.

Both factors contribute to an increase in supplier power, since suppliers will know it is more difficult to cancel contracts even when costs spiral. The military industrial congressional complex (MICC) mentioned by Spinney (1980) can therefore increase supplier power and hinder cancellation of projects. US president Dwight D. Eisenhower famously mentioned MICC in his 1960 speech, where he said that 'we must guard against the acquisition of unwarranted influence, whether sought or unsought, by the military industrial complex. The potential for the disastrous rise of misplaced power exists and will persist.'[5]

Due to the importance of having state of the art weapons, the extra utility of a marginal increase in weapon system output can be quite large, translating into a high willingness to pay an increased unit price. If this willingness to pay increases over time, it can contribute not only to a high price level, but to ICE. Competition between countries can lead to a sharper focus on quality than on prices.

Spinney (1980, p. 75) claims that there is a bias towards investing in high complexity weapons and that the 'interaction of the short-term bias towards investment in high complexity weapons with the long-term budget uncertainty is a central feature' to his discussion of cost increases, and that 'complexity decreases the predictability of future costs [and increased] complexity has a cost because it decreases our ability to understand, and consequently, makes it more difficult for us to adjust to, or shape, internal or external change. Put in another way, increasing complexity increases our rigidity in a game where survival of the fittest makes flexibility a paramount virtue' (Spinney 1980, pp. 8–14).

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[5] `http://coursesa.matrix.msu.edu/~hst306/documents/indust.html`

Asymmetric information between countries can also influence prices. We do not know the full capability of the weapons of our adversaries, so we cannot work out the full threat at any given time. This might induce a country to increase their demand for quality beyond what is needed based on relative effect, because the downside risk by underestimating the weapons of the adversary is so great. Thus, risk aversion leads to high, and perhaps increasing, unit costs (Feinerman and Lipow 2001). There is also asymmetric information between suppliers and buyers. As a product becomes more technologically advanced, there is a possibility that this asymmetric information worsens in the favour of the supplier. If suppliers exploit this power, we could see increasing prices.

As in any market, there is a symbiosis between suppliers and buyers. If the buyer has a non-negotiable list of specifications and there is only one or two possible suppliers, the suppliers has considerable market power in terms of setting prices. Suppliers cannot set prices completely independently, though, as they depend heavily on their very few (or only one) buyer in order to ensure their survival. If the power of balance changes, ICE can go up or down, though the net effect seems impossible to quantify.

3.5 Limits to what can be afforded

Finally, the question regarding what we can afford must surface. Of course, one could put forward the argument that a country could increase its military spending to a share of gross domestic product (GDP) which equals that of North Korea, where it is estimated that 25 percent of GDP is used for defence purposes (Marine Corps Intelligence Activity 1997).[6] This is not an approachable level of spending for any country, as there is a range of other areas in which to spend money. The political cost of increasing defence spending when insufficient funds are allocated towards health care and education can be high. How large share a country can realistically spend of GDP depends on an array of variables, including politics, demographics, economic growth, and is a complex topic. However, as a country approaches this limit, it has to decide whether to

1. increase spending (and bear the political cost)
2. invest in equipment with lower ICE
3. reduce the number of units within each weapon system
4. reduce the number of weapon systems

For example, Denmark disbanded its entire submarine capacity as a part of its 2005–2009 defence agreement (*Forsvarsforlig 2005–2009*) in order to channel available funds into other parts of its defence. The relative effect argument makes it difficult to accept substandard equipment, as you would inevitably lose to an adversary with superior equipment. Furthermore, there is a limit to how many units of a weapon system there is a point in having. If you only own one fighter aircraft, you could probably not afford to use it – i.e. there exist a critical mass of units. If we follow this logic, the only long term solution is to reduce the number of weapon systems. The time span of having a complete set of weapon systems on ones own might be prolonged by

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[6] These estimates differ wildly. In 2004, a number of 40 percent was claimed: `http://www.washingtontimes.com/news/2004/aug/3/20040803-122618-7502r/?page=all`.

international cooperation. Small countries have reduced the number of weapon systems before large countries, as large countries can reduce the number of units within each weapon system for a longer period of time. If the USA spends one percent of GDP on a single fighter jet, it could still operate a few jets. No European country would, as the same aircraft would cost Germany five percent of its GDP (though the whole of the European Union could afford it through cooperation).

4 Previous ICE empiry

Many previous studies have attempted to quantify ICE. A major reason behind such studies is their relevance in long term defence planning. A weapon system costing 100 million in year t will cost 321 million in the year $t + 20$ if ICE is 6 percent annually. Table 1 summarizes selected results from several studies. Abbreviations include main battle tanks (MBTs), infantry fighting vehicles (IFVs) and fast attack crafts (FACs) (which encompass equipment such as motor torpedo boats (MTBs) and corvettes).

	K83[a]	P86[b]	P93[c]	K08[d]	N11[e]	D11[f]	P07[g]	K08[h]	N11[i]
Transport aircraft				8 %				4 %	
Fighter aircraft	8 %	10 %	11 %	7 %	7 %	6 %	4 %	6 %	6 %
IFV				6 %	8 %		4 %	5 %	5 %
Artillery vehicles					5 %		2 %		
Submarines		9 %	9 %	6 %	4 %	3 %	3 %		3 %
FAC				8 %	7 %		1 %		4 %
Helicopter		8 %	10 %	5 %	5 %		4 %	3 %	4 %
Frigates				4 %		4 %			
MBT	11 %			2 %	1 %	6 %	1 %	1 %	0 %
Small arms				1 %	3 %		2 %		
Uniforms					-1 %				

[a] Kirkpatrick and Pugh (1983). Dependent variable: Price.
[b] Pugh (1986). Dependent variable: Price.
[c] Pugh (1993). Dependent variable: Price.
[d] Kvalvik and Johansen (2008). Dependent variable: Price.
[e] Nordlund et al. (2011). Dependent variable: Price.
[f] Davies et al. (2011). Dependent variable: Price.
[g] Pugh (2007). Dependent variable: Price divided by weight.
[h] Kvalvik and Johansen (2008). Dependent variable: Price divided by weight.
[i] Nordlund et al. (2011). Dependent variable: Price divided by weight.

Table 1: Summary of previous studies.

Kirkpatrick and Pugh (1983) and Pugh (1986, 1993) find very high rates of cost escalation – between 8 and 11 per cent annually for destroyers, submarines, helicopters, frigates, guided missiles and fighter aircraft. However, in 2007, Pugh find rates of 4 per cent for fighter aircraft, 3 per cent for submarines and 5 per cent for helicopters (Pugh 2007) when prices are adjusted for weight (as a proxy for performance). Davies et al. (2011) also find growth rates far below those of Pugh (1993) – between 2.6 and 5.9 per cent annually. Nordlund et al. (2011), Kvalvik and Johansen (2008), and Davies et al. (2011) conduct analyses using Swedish data (Nordlund

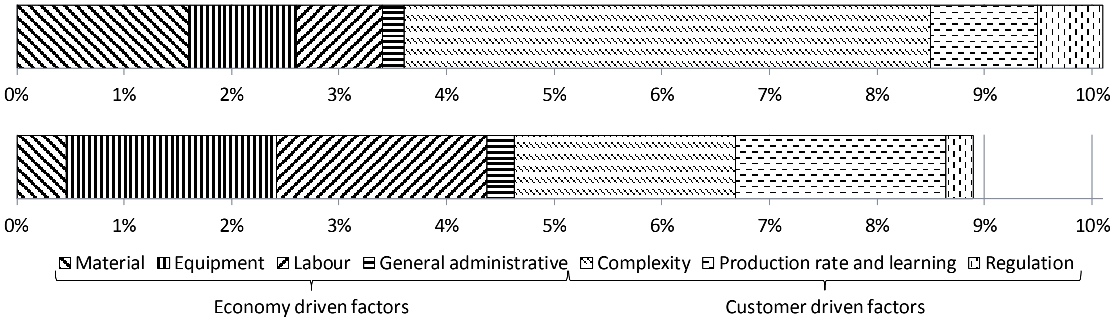


Figure 8: Breakdown of causes of average annual cost increase from the F-15A (1975) to the F-22A (2005) (top) and breakdown of causes of average annual cost increase from DDG-2 (1961) to DDG-51 (2002) (bottom). Data from Arena et al. (2008) and Arena, Blickstein, et al. (2006).

et al.) and international data (Kvalvik and Johansen; Davies et al.). They find rates of approximately 7 per cent for aircraft, 5 per cent for helicopters, 4 per cent for submarines and rates of 1 to 3 per cent on small arms. Nordlund et al. (2011) even find a negative unit cost change, of -1 per cent, on uniforms. The overall picture based on these studies is somewhat scattered, though they often point in the same direction, and they often show higher cost escalation for critical weapon systems that are technology intensive and are produced in small quantities.

Arena et al. (2008) and Arena, Blickstein, et al. (2006) break down the cost escalation between the F-15A (1975) to the F-22A (2005) and the DDG-2 (1961) and DDG-51 (2002) naval vessels into two main categories – economy driven and customer driven factors. Figure 8 shows a further breakdown of the two categories. The sum of the economy driven factors is approximately 3.5 per cent in the F-15–F-22 case, 'which is less than the rate of increase for some inflation indices during the same time' (Arena et al. 2008, p. xvi). Generally, the economy driven factors are somewhat higher for naval vessels (Arena, Blickstein, et al. 2006).

Arena et al. (2008, p. xvi-xvii) provide some key insights behind aircraft cost escalation: With the exception of speciality metals and avionics, metal and equipment have increased in cost at roughly the same rate as other measures of inflation. Labour costs have grown slightly faster than inflation, which is the combined effect of two sub effects – labour costs per hour have grown significantly and labour productivity has increased. The proportion of labour cost has been steadily decreasing as more manufacturing has been outsourced. Higher production rates help reduce unit prices, which they speculate may be due to one or more of at least three hypotheses – the larger economic leverage allows manufacturers to invest in efficiency improvements, the spreading of fixed costs over more units, and higher production rates allow for a more efficient use of labour and tools. Complexity (performance and airframe material) contribute significantly to ICE. In particular, they emphasize the demand for greater aircraft stealth and lower weight. Finally, regulation, such as environmental, health related and those designed to protect American industries, are also cites as drivers behind ICE. Arena, Blickstein, et al. (2006) and Arena et al. (2008) also estimate ICE, but do not deflate by a price index, i.e. their ICE is nominal. Table 2 summarizes their findings.

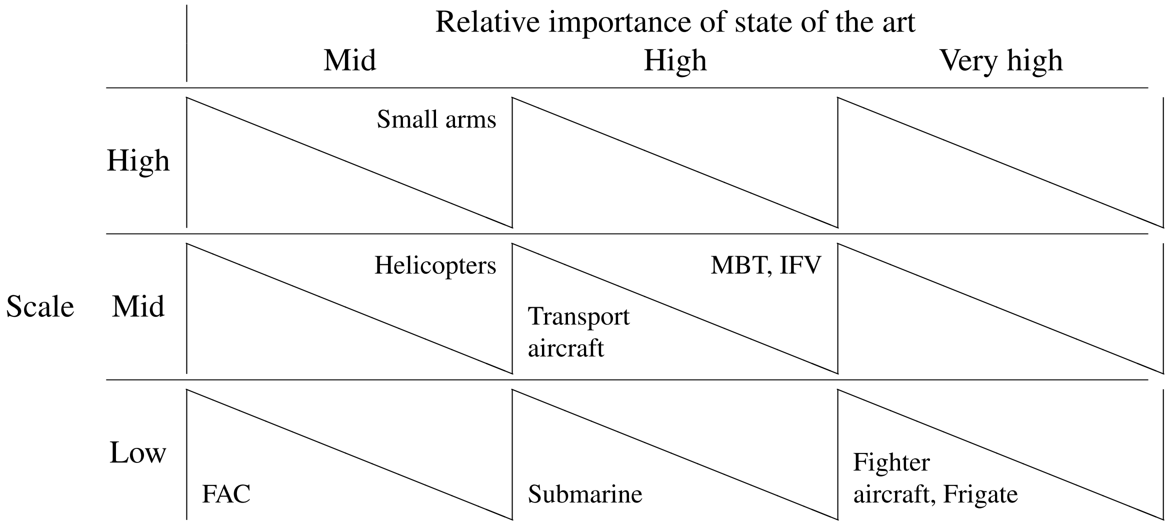
Based on results of a Norwegian study, Kvalvik and Johansen (2008) (based on the original

Arena, Blickstein, et al. (2006, p. 15)		**Arena et al. (2008, p. 11)**	
Ship type	**Annual growth**	**Aircraft type**	**Annual growth**
Amphibious ship	10.8 %	Patrol	11.6 %
Surface combatants	10.7 %	Cargo	10.8 %
Attack submarines	9.8 %	Trainer	9.1 %
Nuclear aircraft carriers	7.4 %	Bomber	8.4 %
		Attack	8.3 %
		Fighter	7.6 %
		Electronic	6.7 %
		Inflation indices	
		CPI	4.3 %
		DoD procurement deflator	3.8 %
		GDP deflator	3.7 %

All prices are in nominal dollars, which is why patrol aircraft tops the aircraft list. The P-3 program ran from 1974 to 1987, a period of high inflation, which increases nominal prices.

Table 2: Results from the Arena, Blickstein, et al. (2006) and Arena et al. (2008) studies on cost escalation of navy ships and fixed wing aircraft. Growth rates in nominal dollars.

matrix of Dalseg 2003) plotted their results in the matrix shown in Table 3 and 4. Kvalvik and Johansen classified their results according to the relative importance of having state of the art equipment, the scale in production and the risk of loss of personnel. The risk of loss increases for equipment involved in front line battle. The risk of loss is shown by the diagonal line within each box – low risk of loss is bottom left, while high risk of loss is top right. The matrix is used in Norwegian long term defence planning.



		Relative importance of state of the art		
		Mid	High	Very high
	High	Small arms		
Scale	Mid	Helicopters	MBT, IFV Transport aircraft	
	Low	FAC	Submarine	Fighter aircraft, Frigate

Table 3: ICE matrix from Kvalvik and Johansen (2008), based on Dalseg (2003).

		Relative importance of state of the art		
		Mid	High	Very high
	High	0–1 % 0 %	1–2 % 0–1 %	2–4 % 1–2 %
Scale	Mid	1–2 % 0–1 %	2–4 % 1–2 %	4–6 % 2–4 %
	Low	2–4 % 1–2 %	4–6 % 2–4 %	6–8 % 4–6 %

Table 4: The Kvalvik and Johansen (2008) matrix displaying recommended ICE rates for use in Norwegian long term defence planning.

5 Data

We now proceed to the estimation part of the report. In this chapter, we briefly outline our data, before we proceed to discuss issues relating to the data set.

When constructing our data set, we would ideally have liked to have as much data as possible from a single source. However, as national defences do not readily share data with foreign researchers, we have resorted to open sources when construction the data set. Our data consist of some 280 observations of prices and characteristics of submarines, transport aircraft, artillery vehicles, MBTs, IFVs, FACs, fighter aircraft, small arms, helicopters and frigates. An overview of our data can be seen in table 5.

System	Observations	Time period
Transport aircraft	28	1926 - 2011
Fighter aircraft	57	1918 - 2011
IFV	22	1960 - 2007
Artillery vehicles	16	1955 - 2005
Submarines	30	1907 - 2016
FAC	12	1961 - 2011
Helicopter	30	1961 - 2012
Frigate	35	1828 - 2011
MBT	26	1945 - 2007
Small arms	19	1868 - 2005

Table 5: Description of the dataset used in this paper.

If we want to measure unit cost escalation, we must have a definition of what a unit cost is. Unfortunately, there exist a whole range of definitions. From recurring flyaway cost, which only covers the ”basic” equipment of a system, such as the airframe, engines and avionics in a fighter, to total ownership costs which includes total life cycle costs and even the indirect effects of a purchase. Such indirect costs can for example be building of a new bridge to an island of an enlarged defence base. Even within definitions, cost estimation techniques varies.

Hartley (2012) finds that the difference between unit production costs and total unit cost may be significant. For example the total unit cost, which incudes R&D, of a F-22 is nearly twice the unit production cost.

Ideally, we would like to include only one type of cost for our entire sample, but unit prices quoted in public sources are seldom specified in more detail, hence our data probably contain several types of costs. If the ratio between the various types of costs had remained constant over time and we had many observations, this wouldn't matter as much as it would if the ratios differed and observations were few.

A second challenge, even when knowing which type of cost we have, is to define what constitute a weapon system. In the case of a fighter aircraft, this is fairly well defined (though one can still argue about the distinction between a fighter and an attack aircraft, but one can combine these categories as they have a lot in common). We are seldom in doubt what constitute a fighter/attack aircraft. However, how can one draw the distinction between a motor torpedo boat, a fast attack craft, a corvette and a frigate differ. As corvettes grow larger a new generation will eventually be classified a frigate. Once a new generation of a corvette changes classification, the average price of the remaining corvettes will experience a fall in average prices given that the version changing category was among the most expensive. If we combine the categories, the characteristics and prices between vessels will fluctuate significantly, thus there will always exist a bias.

6 Method for ICE estimation

Two types of ICE are interesting, the total ICE and the ICE that is not due to improvements in technology or changes in production rates. The part of ICE that is due to equipment improvement and production rates can to some extent be controlled (though at a loss of relative effect), while the remaining ICE can be more of a underlying phenomenon – a part of the price escalation that cannot be influenced. We estimate total ICE as the logarithm of price regressed on time

$$log(p_t) = \alpha + \beta t + u_t \tag{3}$$

For the ICE that is not due to improvements in technology or production rates, we employ the regression

$$log(p_t) = \tilde{\alpha} + \tilde{\beta} t + \tilde{\gamma} X_t + \epsilon_t \tag{4}$$

where X_t is a vector of explanatory variables related to characteristics. These include range, speed, length, width, weight, ceiling, displacement and total numbers of items produced. The characteristics included for each of the systems can be seen in Appendix A. All characteristics are in log form. The aim is to remove the omitted variable bias in β, and hence get the underlying cost escalation. If prices are more positively than negatively related to characteristics, β will be higher than $\tilde{\beta}$.

As most of our variables share a common trend, growing over time, we expect *multicollinearity*. Since the consequence of multicollinearity on a small dataset, is that the correlated regression coefficients will be unstable, but remain unbiased (Gujarati 2003), we have chosen to extend our analysis by applying shrinkage methods. Since shrinkage methods shrinks the coefficients towards zero, the coefficients are biased, but the variance of the predictions are often reduced by more than the increase in the bias, which leads to reduced prediction error (Hastie, Tibshirani, and Friedman 2009). In addition to ordinary least squares (OLS) we will also perform the analyses by partial least squares (PLS), principal component regression (PCR), and ridge regression (RR). We refer to PLS and PCR as shrinkage methods, although they are not in the same sense as ridge regression. These methods are recommended as complements to OLS when collinearity are suspected (Chatterjee and Hadi 2012; Vinod 1978). The variables are standardized in the regressions, but the coefficients reported are unstandardized. All tuning parameter for RR and number of components for PCR and PLS are selected by tenfold cross validation.

Due to expected autocorrelation, the estimated standard errors will probably be biased downward. However, we are primarily interested in the β coefficient, not the standard errors. When we present the results in Section 7, we will therefore only report β, not standard errors, significance levels or any $\bar{\gamma}$ coefficients, since these are highly correlated with one another. Some of the statistical assumptions are violated, and one should therefore be careful in interpreting the results. For use in decision making and long term planning, the results are still highly useful.

7 Estimation results

7.1 Total ICE

Table 6 and Figure 9 summarizes the simple OLS regressions on the form of equation (3). The results are the estimated annual investment cost escalation.

System	ICE estimate
Transport aircraft	0.072
Fighter aircraft	0.068
IFV	0.051
Artillery vehicles	0.044
Submarines	0.044
FAC	0.035
Helicopter	0.025
Frigate	0.024
MBT	0.021
Small arms	0.012

Table 6: OLS results, total ICE.

Our estimates for cost escalation of transport aircraft may seem high, but transport aircraft have seen a massive increase in capacity since the relatively small aircraft of the 1940s. There is also great variation when it comes to capacity. For example, a 1985 C-5 Galaxy has a payload capacity of more than six times a modern C-130J Super Hercules. Obviously, they fill different roles, but this variation in capacity is not accounted for in this section. We will account for

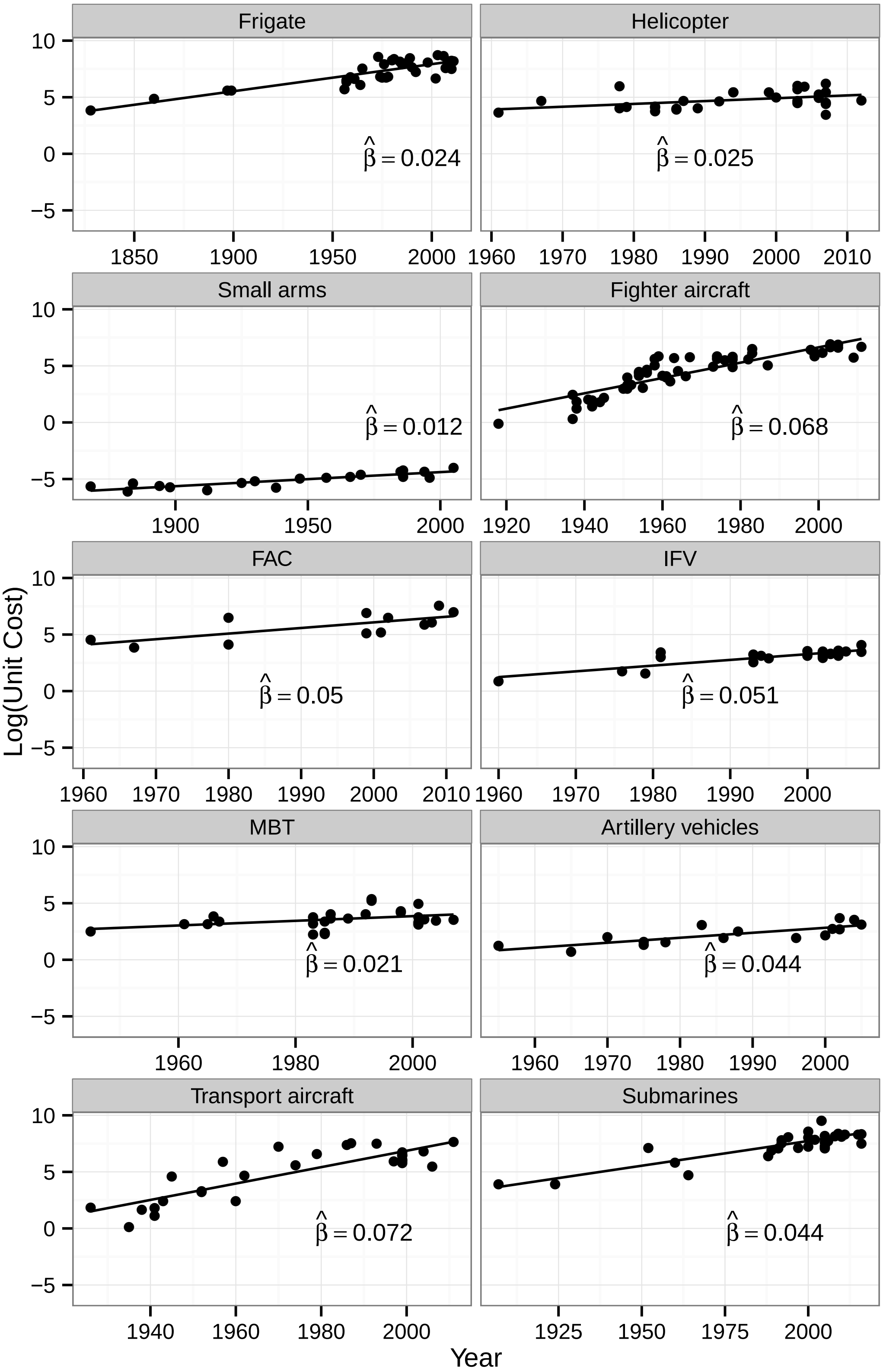


Figure 9: Plot of the dataset with OLS regressions on time.

it in our estimates in section 7.3. Our fighter aircraft estimates are slightly lower than those of Kvalvik and Johansen (2008), Nordlund et al. (2011) and Davies et al. (2011). Again, we see from Figure 9 that unit costs seem to have abated somewhat at the end of our time period. Some of this might be because of recent sales of older designs (for example the F-18), but we clearly see a lower growth rate since 1970.

IFVs have a growth rate that is somewhat lower than Kvalvik and Johansen (2008) and Nordlund et al. (2011) For artillery vehicles, we find the same ICE as Nordlund et al. (2011). Our submarine ICE is similar to that of Nordlund et al. (2011), lower than that of Kvalvik and Johansen (2008), but higher than that of Davies et al. (2011). FACs grow at 3.5 percent annually, significantly lower than Kvalvik and Johansen (2008) and Nordlund et al. (2011). This might be because of varying definitions. Our FAC class includes MTBs as well as corvettes. Kvalvik and Johansen (2008), on the other hand, limit their data to only a few observations. Our helicopter estimates are again lower than both Kvalvik and Johansen (2008) and Nordlund et al. (2011). This could be because there exist a range of different helicopters, and we have more utility helicopters at the end of our time frame than at the start. Utility helicopters are cheaper than attack helicopters, so price escalation will seem lower. Out frigate estimate is somewhat lower than the 3.8 percent of Kvalvik and Johansen (2008) and the 4.3 percent of Davies et al. (2011). Both the Kvalvik and Johansen (2008) and Davies et al. (2011) estimates are based on observations that do not include the latest observations we use. From Figure 9, we see that unit costs seem to escalate at a slower rate after 1990. This could be because the chase for the best relative effect have abated, or it could be because of weaknesses within our dataset. MBTs display a cost escalation of 2 percent annually, higher than Nordlund et al. (2011), but lower than Davies et al. (2011), the latter having very few observations. Small arms estimates are the same as in Kvalvik and Johansen (2008), because we use the same data.

7.2 A further note on variation over time

From Figure 9 we see clear variation over time for certain weapon systems. In Section 7.1 we mentioned the reduced cost escalation of transport aircraft and gave one possible explanation. We see the same effect for fighter aircraft. ICE until 1960 was in the region of ten percent, while it has been around four percent after 1960. Several possible explanations can be offered as to the causes of the reduced cost escalation. For example, fundamental changes to the security environment can affect prices. For example, the period between the Cuban Missile Crisis (1962) and the Soviet invasion into Afghanistan (1979) was a relatively calm period, with the signing of the Strategic Arms Limitation Talks (SALT) agreements and the Helsinki Accords. By the 1990s, the US was the lone world power, and the last ten years have seen more attention directed towards asymmetrical warfare, than warfare against opponents with fighter aircraft. This reduced relative effect could be one contributor behind ICE. For example, the need for massive troop transports is not as high as it once was, perhaps contributing to a lower transport aircraft cost escalation.[7]

A second reason, related to the previous, might be the role of disruptive technologies, meaning that new types of technology or equipment makes technologies or equipment that once was absolutely vital lose some of its importance. For example, battleships lost its importance in the

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[7] One can argue for a split between tactical and strategical transport aircraft, where ICE probably differs between the two.

face of new technologies making it increasingly costly to operate, and many of its capabilities obsolete.

A third, also related, reason for lower ICE can be that a point is reached where only a handful of countries can afford a large enough number of state of the art units for there to be any point in having any at all. For example, no country would buy only the one aircraft Augustine suggested in the introductin, because it would be to risky to use, and probably not provide much of a deterrent anyway. In other words, as many countries approach a critical mass of units, they might discard the entire weapon system (as Denmark did with its submarines) or buy cheaper equipment, both reducing the ICE resulting from relative effect.

7.3 Unexplained ICE

In this section, we present the results from the regressions where we account for variation in quality variables and total production. Table 7 summarizes the estimates. The OLS estimates are based on a regression of equation (4).

Method	OLS	PCR	PLS	RR
Transport aircraft	0.041	0.033	0.037	0.027
Fighter aircraft	0.04	0.038	0.039	0.037
IFV	0.021	0.021	0.02	0.02
Submarine	0.022	0.017	0.019	0.019
FAC	0.048	0.005	0.01	0.009
Helicopter	0.027	0.006	0.015	0.01
Frigate	0.002	0.008	0.007	0.006
MBT	-0.015	0.01	0.005	0.002

Table 7: Estimated ICE for different types of military equipment. Quality variables vary with availability between weapon systems, but not between regression methods.

Not much previous research has been conducted controlling for variables other than weight. Of the few studies conducted, Davies et al. (2011) find an unexplained cost escalation of 2.2 percent for frigates, and 5.7 percent for combat aircraft using PCR. Initial estimation was respectively 4.3 and 5.8 percent. Eskew (2000) found a cost escalation of fighter aircraft of 5 percent when estimating price only on time. When quality variables were introduced, the coefficient on time was reduced to 3.3 percent (still using OLS). Our fighter aircraft results are in line with those of Eskew (2000), while our frigate estimates are lower than those of Davies et al. (2011).

The general picture from Table 7 is that ICE is lower when we control for quality variables and total production. The estimates for fighter aircraft, frigates, IFVs, transport aircraft and submarines are also broadly similar across estimation techniques. However, for FAC, there are clearly differences. For FAC, the OLS estimate is about 5 per cent, while the result from the shrinkage methods are close to zero. This could be because of very high variance within the data, hence a large shrinkage on the coefficients. FAC is also the only system where the ICE increases notably when including quality variables. This reinforces the suspicion that the usable variation in the data for FAC is quite low.

When controlling for quality variables and total production the ICE of FAC, helicopter, frigate, and MBT comes out as quite close to zero. In particular when using shrinkage methods this is true. Although the dataset is too small to draw any strong conclusions, some insight can be derived from the results. As the estimates remains positive, but are reduced, when taking improvements into account, there seems to be some evidence for an underlying ICE.

8 Summary and discussion

In this article, we first clarified the ICE concept in Section 2. We define ICE as the annualized per unit cost escalation over generations of a weapon system, beyond an inflation index. ICE can be split into intergenerational and intragenerational cost escalation. In Section 3 we moved on to reasons behind ICE. In particular, we mentioned the concept of relative effect, where investment in more advanced equipment is required in order to answer new investments by adversaries. Acquiring technologically advanced equipment is both expensive and risky, because the new equipment might be harder to develop than previously thought. We also mentioned the role of supply and demand, and how changes in supplier and buyer power can influence cost escalation. Section 4 compared some previous empirics and found different rates of ICE, though rates pointed in the same direction.

We used a range of different estimating techniques to quantify ICE. Most estimates are robust across techniques, but not all. Once we control for characteristics and production quantity, ICE tends to fall, but stay positive. Table 8 summarizes the results of previous studies and of these studies. The last column contain our PCR estimates, while all previous columns show price regressed only on time.

	K1983[a]	P1986[b]	P1993[c]	K2008[d]	N2011[e]	D2011[f]	H2014[g]	H2014[h]
Transport aircraft				8 %			7 %	3 %
Fighter aircraft	8 %	10 %	11 %	7 %	7 %	6 %	7 %	4 %
IFV				6 %	8 %		5 %	2 %
Artillery vehicles					5 %		5 %[i]	
Submarines		9 %	9 %	6 %	4 %	3 %	5 %[i]	2 %
FAC				8 %	7 %		4 %	1 %
Helicopter		8 %	10 %	5 %	5 %		3 %	1 %
Frigates				4 %		4 %	2 %	1 %
MBT	11 %			2 %	1 %	6 %	2 %	1 %
Small arms				1 %	3 %		1 %	

[a] Kirkpatrick and Pugh (1983)
[b] Pugh (1986)
[c] Pugh (1993)
[d] Kvalvik and Johansen (2008)
[e] Nordlund et al. (2011)
[f] Davies et al. (2011)
[g] This study.
[h] This study. Adjusted for characteristics and production quantity using principal component regression.
[i] The coefficient in table 6 was 0.044. $\exp(0.044) - 1 \approx 4.5\%$.

Table 8: Summary of previous studies and of this study.

As mentioned in the introduction, ICE can have a significant impact on future costs, thus playing an important role in long term planning. Historic ICE is influenced by World War II and the Cold War, whereas future ICE is influenced by the rise of China and Russia, terrorist groups, etc. Thus, the importance of relative effect might change over time. Since our results generally are somewhat lower than those of Kvalvik and Johansen (2008), we would use the matrix values at the lower end of their intervals as the rule of thumb in long term defence planning. When considering for example a new investment in transport aircraft several questions must be adressed. First: is the new aircraft larger and more advanced? If it is not, we should perhaps lean more towards the ICE estimate in the last column of Table 8 than the second to last.

In this paper, we adjusted for observable quality and production parameters. An obvious improvement of this study would be to improve the dataset. Researchers with access to data from classified sources can hopefully provide more precise estimates than those we have found. There are also a couple of less direct future routes research can follow. First, more case studies can be conducted, in the same manner as Arena, Blickstein, et al. (2006) and Arena et al. (2008), and try to separate the cost growth from one generation to the next into subcategories. It is also possible to explore the possibility of developing theoretical models to explain why we have ICE.

9 Acknowledgements

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Abbreviations

D	demand
FAC	fast attack craft
GDP	gross domestic product
ICE	investment cost escalation
IFV	infantry fighting vehicle
JSF	Joint Strike Fighter
MBT	main battle tank
MC	marginal cost
MICC	military industrial congressional complex
MR	marginal revenue
MTB	motor torpedo boat
OLS	ordinary least squares
PCR	principal component regression
PLS	partial least squares
PMC	private military company
R&D	research and development
RR	ridge regression
S	supply
SALT	Strategic Arms Limitation Talks

Appendix A Quality variables

System	Quality variable	System	Quality variable
Transport aircraft	Total production Length Empty weight Speed Wingspan Height Ceiling Range	Fighter aircraft	Total production Length Height Wingspan Ceiling Empty weight Range Speed
IFV	Length Empty weight Width Speed Height	Frigate	Total production Length Empty weight Width Speed
Submarine	Total Production Length Speed Depth Displacement Draft Width	FAC	Total production Length Empty weight Speed Displacement Draft Width
Helicopter	Total production Length Empty weight Speed Height Range Rotor diameter	MBT	Total production Length Empty weight Width Speed Height

Table A.9: The included quality variables for each system.