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Defence investment cost escalation
– A refinement of concepts and revised estimates

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English summary

This report explores the topic of investment cost escalation (ICE) – the increase in unit costs beyond inflation between generations of a weapon system. One aim of this report is to clarify important concepts. We make a distinction between cost *escalation* and cost *growth*. Where cost escalation refers to long run increase in cost, for example from F-16A/B to F-22A, cost growth is a project specific term, indicating cost increases within a specific project. Cost escalation is the sum of *intragenerational* and *intergenerational* cost escalation. Examples of these two types of cost escalation are cost increases from F-16A/B to F-16E/F (intragenerational) and from F-16E/F to F-22A (intergenerational).

There are several sound reasons as to why cost escalation exists. The concept of *relative effect* says that to counter the weapons of an adversary, we must upgrade our weapons to at least their level. As this requires sophisticated *technology*, the result is an increase in costs relative to general inflation. Advanced technology also carry risks of further cost increases if new technology is more difficult to develop than originally thought. The power of suppliers and buyers are also of significance – as there are few suppliers and few buyers of military equipment, the relative negotiating strength can influence cost growth. If a string of mergers and acquisitions increase supplier power, cost escalation could be a persistent phenomenon.

Previous studies all confirm investment cost escalation as a phenomenon, and generally find higher rates on more advanced systems with low rates of production. We conduct a similar study and find similar results. We then isolate the part of the price that can be explained by characteristics such as development in range, weight, displacement, speed, total production quantity and other variables. Controlling for these variables, we find a lower investment cost escalation. The table below summarizes our main results. The table shows annual unit cost escalation for various types of weapon systems using only time as an explanatory variable and using characteristics and total production quantity as explanatory variables.

Weapon system \ Explanatory variables	Only time	Characteristics
Transport aircraft	7,4 %	3,1 %
Fighter aircraft	7,0 %	3,9 %
Infantry fighting vehicle	5,2 %	2,1 %
Artillery vehicles	4,5 %	
Submarines	4,5 %	1,7 %
Fast attack craft	3,6 %	0,5 %
Helicopter	2,5 %	0,6 %
Frigates	2,4 %	0,8 %
Main battle tank	2,1 %	1,1 %
Small arms	1,2 %	

Sammendrag

Denne rapporten tar for seg konseptet enhetskostnadsvekst på forsvarsinvesteringer (EKV-I). EKV-I er kostnadsøkningen utover generell inflasjon mellom generasjoner av et våpensystem. Et mål med denne rapporten er å klargjøre viktige begreper. Vi skiller mellom ulike typer kostnadsvekst – den langsiktige mellom generasjoner (som er tema for denne rapporten), og den mer kortsiktige som skjer underveis i utviklingen av et prosjekt. Den langsiktige enhetskostnadsveksten, for eksempel mellom F-16A/B og F-22A, kan dekomponeres i en intragenerasjonell del (fra F-16A/B til F-16E/F) og en intergenerasjonell del (F-16E/F to F-22A).

Det er flere årsaker til at enhetskostnadsvekst er et naturlig fenomen. Konseptet *relativ effekt* sier at for å svare på nye våpen hos en potensiell motstander, må vi oppgradere våre våpen til å være minst like gode. Dette krever avansert teknologi, hvilket er kostnadsdrivende sammenlignet med den generelle kostnadsutviklingen. Avansert teknologi innebærer også at risiko for fremtidig kostnadsvekst øker, siden ny teknologi kan bli betydelig mer vanskelig å utvikle enn forutsatt. Kjøper- og tilbydermakt har også betydning – ettersom det bare eksisterer et fåtall kjøpere og et fåtall tilbydere av militære investeringer, vil den relative styrken mellom de to kunne komme til å spille en viktig rolle. Dersom en rekke oppkjøp og fusjoner reduserer antallet tilbydere, kan det føre til økte priser.

Tidligere studier bekrefter EKV-I som fenomen og finner ofte høye kostnadsvekstrater for mer avanserte systemer med lavt produksjonsantall. Vi gjør en lignende studie og finner tilsvarende resultater. Vi isolerer så de deler av prisen som kan forklares ved utvikling i egenskaper som rekkevidde, tyngde og lengde, samt totalt produksjonsvolum. Vi sitter da igjen med en lavere uforklart EKV-I. Tabellen under oppsummerer de empiriske resultatene. Tabellen viser årlig enhetskostnadsvekst for ulike typer våpensystemer hvor vi har brukt tid som forklaringsvariabel, samt der hvor vi også har brukt egenskaper (vekt, rekkevidde, total produksjon) som forklaringsvariabler.

Våpensystem \ Forklaringsvariabler	Bare tid	Egenskap
Transportfly	7,4 %	3,1 %
Kampfly	7,0 %	3,9 %
Stormpanservogn	5,2 %	2,1 %
Tauet artilleri	4,5 %	
Undervannsbåter	4,5 %	1,7 %
Korvetter m.m.	3,6 %	0,5 %
Helikopter	2,5 %	0,6 %
Fregatt	2,4 %	0,8 %
Stridsvogn	2,1 %	1,1 %
Håndvåpen	1,2 %	

Contents

Preface

This report is written as a part of the ROS project, exploring cost growth in the public sector. We would like to thank the authors of Kvalvik and Johansen (2008) for providing their dataset, and our summer student Mikael Modum Bilet for valuable input for the report.

Data available upon request.

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. This report considers some possible causes as to why we observe these large increases in costs, as well as providing estimates for different military systems.

The objective of any defence procurement strategy must be to maximize the utility one can obtain from the entire range of equipment, subject to the restraint that funds are limited. Furthermore, 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. These insights form a background for this report, where we discuss concepts and results concerning investment cost escalation (ICE).[1] This reports builds upon a previous body of Norwegian Defence Research Establishment (FFI) reports, especially Nesset and Wessel (1995), Dalseg (2003) and Kvalvik and Johansen (2008).

The purpose of this report is twofold – to refine the ICE concept, and to estimate historical ICE using a wider variety of methods than previously applied. Chapter 2 to 4 contain definitions and previous results, while Chapter 5 to 7 contain our updated ICE estimates. Chapter 2 first makes a distinction between cost *escalation* and cost *growth*. Cost escalation is the cost increase between generations of a weapon system, for example between F-16A/B and F-35A (both early versions). 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* (sometimes known as 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, as mentioned above. 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. The main topic in this report is the long run ICE. In Chapter 3, we provide some possible reasons behind ICE, before Chapter 4 summarizes some previous empirical work.

In the empirical part of the report, Chapter 5 briefly describes and outlines some challenges regarding

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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.

our data. Chapter 6 describes various methods for estimating ICE. We attempt to estimate historical ICE ”as is”, as well as historical ICE net of quality improvement and changes in production quantity. The hypothesis is that ICE net of such changes will be lower than the unadjusted ICE. Chapter 7 contains the results, which do indeed confirm our hypothesis. Chapter 8 summarizes and outlines future research.

2 What is ICE

2.1 Concepts and previous ICE studies

Seemingly ever increasing prices on defence equipment have for a long time been subject of concern and discussion in many countries. Back in 1959, Marshall and Meckling of the RAND Corporation found that early stage cost estimates of new weapons systems in the USA were biased downwards (Marshall and Meckling, 1959). In 1980, the so called Spinney report (Spinney, 1980) was published, where the author claimed that increasing technological complexity and the role of the military industrial congressional complex (MICC) leads to increasing costs. Spinney 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 growth to a more prominent position in the public debate.

In the 1980s and 1990s, attention started turning towards *intergenerational* ICE, which is the main point of attention of this report. Spinney focused on political reasons behind cost growth and the broader consequences for defence capability. The RAND reports of Marshall and Meckling and later studies focused on cost growth from beginning to end of the procurement process of a specific weapon system. The 1980s and 1990s studies by Deitchman (1979), Kirkpatrick and Pugh (1983), Pugh (1986), Pugh (1993), Kirkpatrick (1995) and Pugh (2007), later extended by Davies et al. (2011), discuss cost escalation in the long run – between generations of weapons systems. These studies discuss cost escalation from the Gloster Meteor (in service from 1944) to the Eurofighter Typhoon (2006) and from the Dreadnought class (1963) to the Astute class nuclear submarine (2010).

We summarize the various cost escalation concepts in Figure 2.1. Concentrate on the black curves of Figure 2.1. The lowermost curve shows the development of the consumer price index (CPI), i.e. the growth in the general price level of a representative household (this could also be another price index, such as the gross domestic product (GDP) deflator, the point is only to illustrate a well known baseline price index). The defence sector however, generally faces a somewhat greater inflation in prices than the average household (see for example Jones and Woodhill, 2010), represented by the curve for defence specific inflation (DSI). Both CPI and DSI are price indices for consumption. Investment costs can grow at even higher rates, as is the case in Figure 2.1, where the ICE curve has the greatest slope of all the curves. We can measure ICE as the growth beyond DSI if we aim to measure how much investment costs grow beyond the average defence inflation. Or we can, given that the Ministry of Defence (MoD) receive an annual compensation from the Treasury according

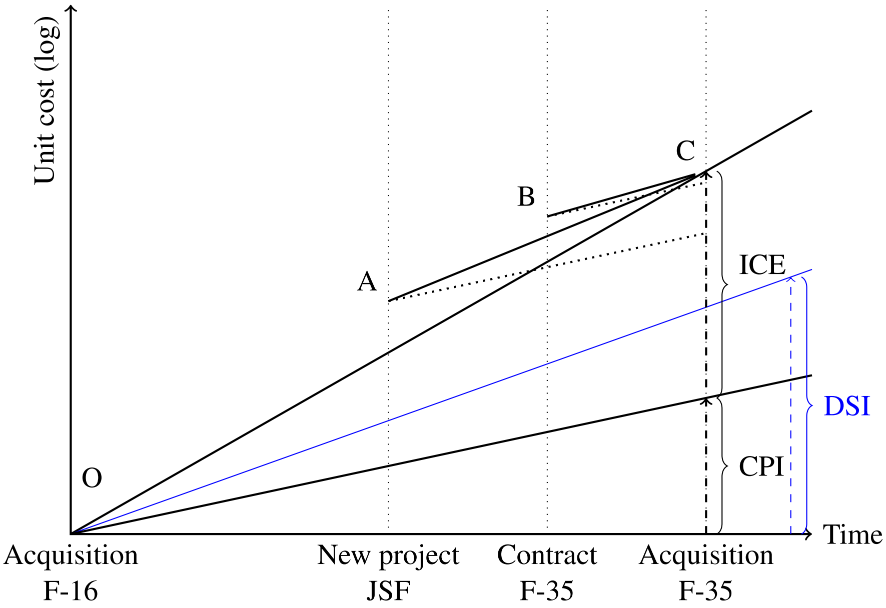

Figure 2.1 Unit cost as a function of time (base year in origo). In this figure, defence specific inflation (DSI) grows at a higher rate than the consumer price index (CPI). Investment cost escalation (ICE) exceeds CPI. Cost growth (during the development phase of a new system), the AC and BC lines, is lower (measured by the slope coefficient) than the long run cost escalation, but higher than CPI. Aggregated nominal ICE measures the entire dashed line from acquisition F-35 to point C. Aggregated ICE equals the difference between the CPI and ICE lines.

to DSI, measure how much of ICE is uncompensated growth, and therefore an annual reduction in purchasing power. However, as indices such as the DSI are generally not well known, and ICE relative to DSI therefore would not make sense to the general public, ICE is often defined as cost growth beyond a well known index, often CPI or the GDP deflator. In this report, we employ the following definition.

Investment cost escalation (ICE)
is defined as the annualized long run increase in *unit costs*
– *over generations* of a weapon system and
– *beyond a base index, here CPI.*

In Figure 2.1, we start our measurement of ICE at the time of an acquisition of a weapon system, say F-16 (point O). After a number of years, we decide to replace the F-16, and embark upon a new project, the JSF project. At the time of project startup, we estimate a future price level of A, which we estimate will rise only with the general price level (the dotted line originating in A has the same slope as the CPI curve). However, when we come to the time where we write up the delivery contract, we have an increased cost estimate of B. When the aircraft are finally delivered, we conclude that the total costs were C, i.e. slightly above what the contract stated. We see from the slopes of Figure 2.1 that 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 investment 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 et al. (2006b), 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), Pugh (1993), Nesset and Wessel (1995), Kirkpatrick (1995), Dalseg (2003), Arena et al. (2006a), 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.

Before we proceed, for simplicity, we deflate all values in Figure 2.1 by CPI (as well as removing DSI from the figure), and end up with Figure 2.2. In this figure, costs are expressed in real terms.

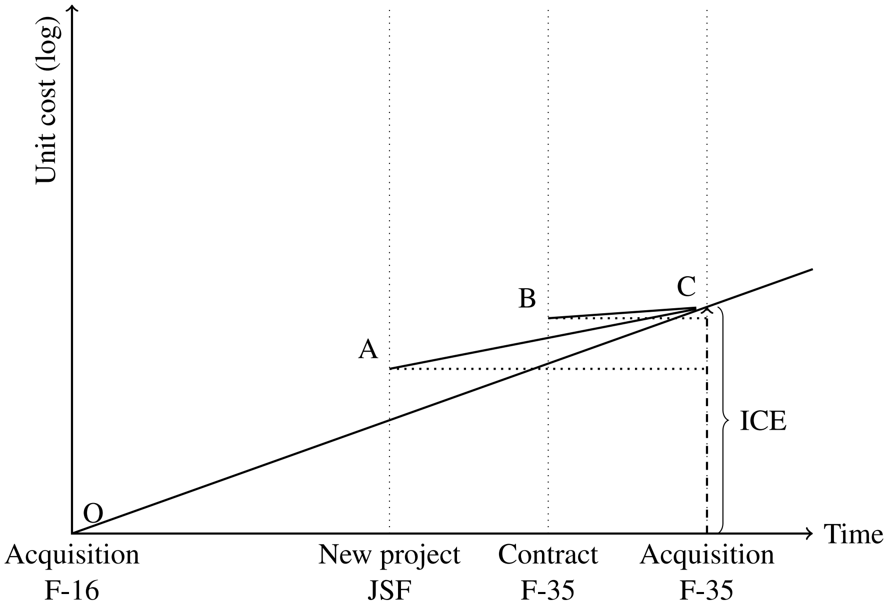

Figure 2.2 Unit cost as a function of time. Real terms. Aggregated ICE measures the entire height of the dashed line from the point Aquisition F-35 *to point C.*

2.2 Intra- and intergenerational ICE

It is useful to make a distinction between intra- and intergenerational ICE. We illustrate this in Figure 2.3, where a new system can utilize all the available technology improvements of the old system (for an example where this is not the case, see Section 2.4). During its lifetime, a system often goes through radical changes in design and capability. For example, the F-16E/F Block 60 is a far superior fighter to the F-16A/B Block 1, in that is has a more powerful engine, all-weather capability, conformal fuel tanks (CFT), beyond-visual-range (BVR) missiles, improved radar and improved avionics. Still, they are both F-16s. Figure 2.3 illustrates a *conceptual* picture of the intragenerational cost escalation of the F-16 (the actual F-16 picture is somewhat different, see Arena et al. (2008, p.

13) for the actual development in prices from 1978 to 2001). After the first aircraft are delivered, prices fall due to economies of scale (there are more units to allocate fixed costs, such as development costs, to), and learning effects (you produce the second aircraft more efficient and using less time than the first one). When an upgraded model is released, the F-16 price increases because the new model is more complex, made of more expensive materials, has incurred new development costs, and because we cannot fully utilize learning from the previous version in the production of the new version. Soon, however, economies of scale and learning effects become visible also for the upgraded F-16. At the time of the F-35 acquisition, buying a new F-16 will be more expensive, although admittedly also more capable, than the F-16 we once bought. Note that intragenerational cost escalation happens at any point on the blue curve, while intergenerational cost escalation can only be measured when we are at point C.

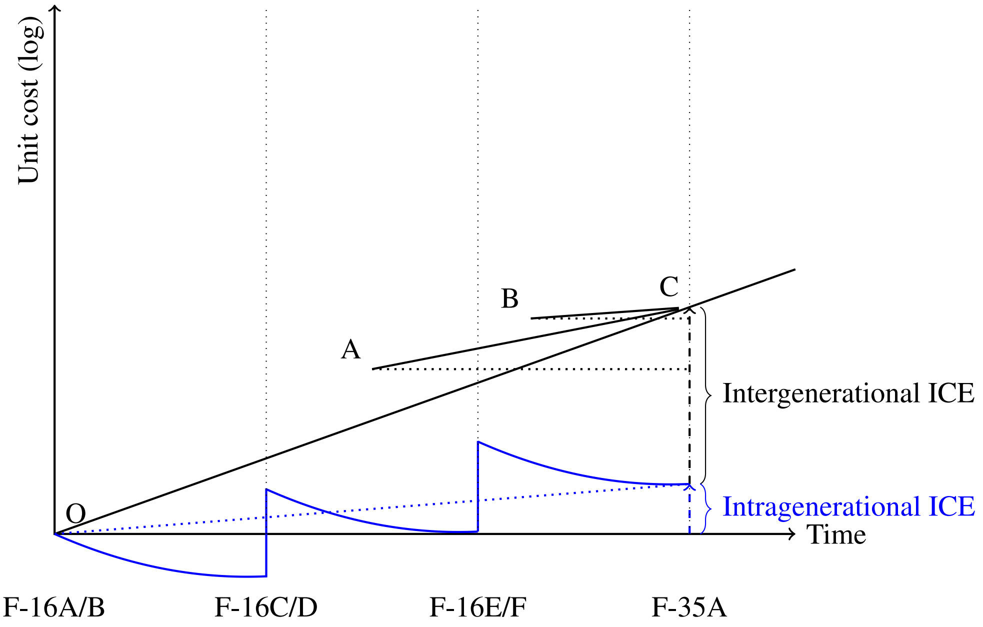

Figure 2.3 Unit cost as a function of time. ICE is split into an intergenerational (black lines) and an intragenerational (blue lines) part, the sum of which constitute total ICE.

Figure 2.4 illustrates this further over multiple generations. The names of the aircraft are given only as illustration, and do not reflect actual prices. In the figure, the unit prices for F-86 falls during its lifetime, perhaps indicating no significant upgrades. However, F-5, which replaces F-86, is a great deal more expensive from the offset. F-5 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. F-16, which replaces F-5, reaps the benefits of the research and development (R&D) work that was conducted during the lifetime of F-5, and the unit costs of this system starts at approximately the same unit cost level as F-2 ended. The long term trend is shown by the thick black curve. The following chapters of this report will mainly focus on this long run ICE.

While intra- and intergenerational ICE are both cost escalation on equipment, the causes and the size of the change might be quite different. The remainder of this section covers intragenerational ICE,

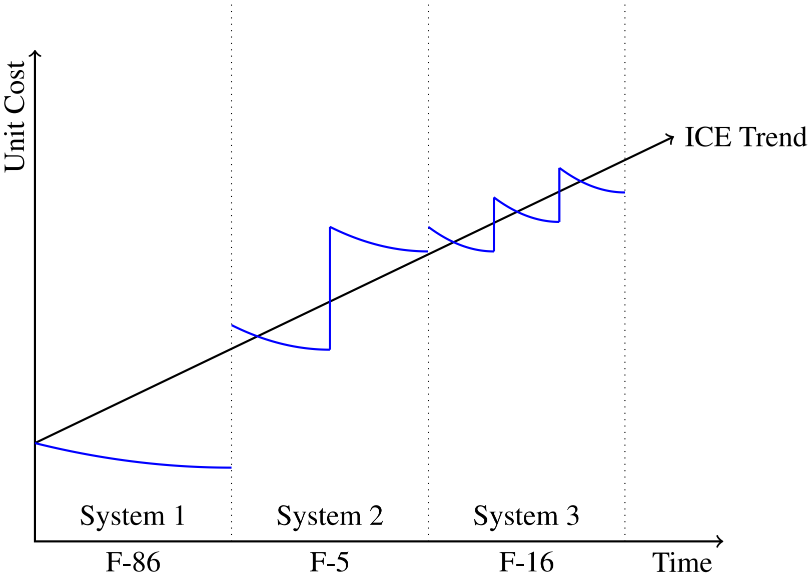

Figure 2.4 The figure shows how total ICE, the thick black line, can differ from the intragenerational ICE, the coloured lines.

while Chapter 3 discusses ICE in the long run. One cause of increasing cost within a generation of a weapon system is ongoing development of the equipment (Arena et al., 2008). An example of this is the F-16 fighter aircraft that had an annual cost increase of about 6 percent from 1978 to 1992 (Pløen, 2005). Another example is the increase in unit cost of the F-15 from $44 million in 1974 to $58.6 million in 2000 measured in constant 2006 dollars (Arena et al., 2008). This price increase is probably caused by the substantial upgrades the aircraft underwent in this period (Arena et al., 2008). Arena et al. (2006a) finds that cost increases within a generation of British war ships primarily are due to capability evolutions, while costs are relatively stable in periods without upgrades. This could indicate that much of the ICE is capability driven. Cost decreases could be expected as the technology used in the system is becoming cheaper and as the production process improves. 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.”

2.3 Cost growth

Cost growth is not the main subject of this report. It can however, in the interest of completeness, be of interest to mention the results of a study in order to illustrate some causes of cost growth. Bolten et al. (2008) track the sources of cost increases in 35 mature US defence procurement programmes. Note that these are results per programme, not per unit, so that a 100 percent average unit cost increase and a 50 percent reduction in the number of items procured results in a 0 percent cost growth. Bolten et al. (2008, p. 73) find that of a weighted average cost growth of 11 percent, 6 percentage points can be attributed to cost estimating errors, 7 percent to changes in requirement decisions, 10 percentage points to changes in schedule and -12 percentage points to changes in quantity. Technical, financial and other external issues were of less importance. Cost growth is 40 percent in the development phase and only 4 percent in the procurement phase, but this is due to large reductions in the number of aircraft in the F-22 and F/A-18E/F-programmes, which constitute a large part of total investments. Cost estimates, requirements and schedule still slip 5, 6 and 10 percent respectively during the procurement phase, but quantity reductions reduces the cost growth by 15 percentage points.

2.4 Summary of the concepts

We can sum up the various ICE concepts as outlined below. An ICE of 6.4 percent is assumed in this example, i.e. the annualized increase in unit cost from an (early) edition of the current generation of a weapon system to an (early) edition of the next generation of the same weapon system is 6.4 percent. Of these 6.4 percent, 2.2 percentage points are intragenerational, i.e. the annualized increase in unit cost from an early edition of the current generation of a weapon system to the latest edition of the current generation of a weapon system. The remaining 4.2 percentage points, i.e. the annualized increase in unit cost from the latest edition of the current generation of a weapon system to an early edition of the next generation of the same weapon system, are intergenerational as long as we can utilize all of the technology developed during the lifespan of the old generation. In this case, the 4.2 percent are the residual of 6.4 and 2.2 percent. If the new generation doesn't reuse any of the improved technology from the current generation, 6.4 percent is the more precise expression of the added cost escalation of the new generation (see the next example). For the time being, we assume that we utilize all available technology.

Of the 4.2 percent of intergenerational ICE, 2.4 percentage points (4.2-1.8) have been taken into account when estimating the costs of the new generation of a weapon system. The 4.2 percent are unknown at this stage, and 2.4 constitutes the best available estimate. Thus, 1.8 percent remain as an underestimation of future, unknown, costs. When the contract is written up, a further 1.2 percent of cost growth is known and taken into account, leaving 0.6 percent in, so far, unknown contract cost growth. Neither the 1.8 or the 0.6 percent of cost growth are known at the time the project is started and the contracts are written, they are only fully known at the time of acquisition, as are the total of 6.4 percent.

Concept	**Annual rate**
Investment cost escalation	6.4 %
└ Intragenerational investment cost escalation	2.2 %
└ Intergenerational investment cost escalation	4.2 %
└ └ Investment cost growth	1.8 %
└ └ └ Investment cost growth - contract	0.6 %

Now, assume that we only utilized half of the new F-16 technology. In this example, intergenerational investment cost escalation has increased by an additional half the intragenerational ICE. Total ICE is still the same, as the technological leap from F-16A/B to F-35A is the same. In other words, intra- and intergenerational ICE is only related as far as intragenerational ICE is inherited between generations. Figure 2.5 is an adaptation of Figure 2.3, which is adapted to this scenario. The part of the intragenerational vertical dashed line overlapped by the intergenerational line is technology not relevant for the development of the F-35.

Concept	**Annual rate**
Investment cost escalation	6.4 %
Intragenerational investment cost escalation	2.2 %
Intergenerational investment cost escalation	5.3 %
Investment cost growth	1.8 %
Investment cost growth - contract	0.6 %

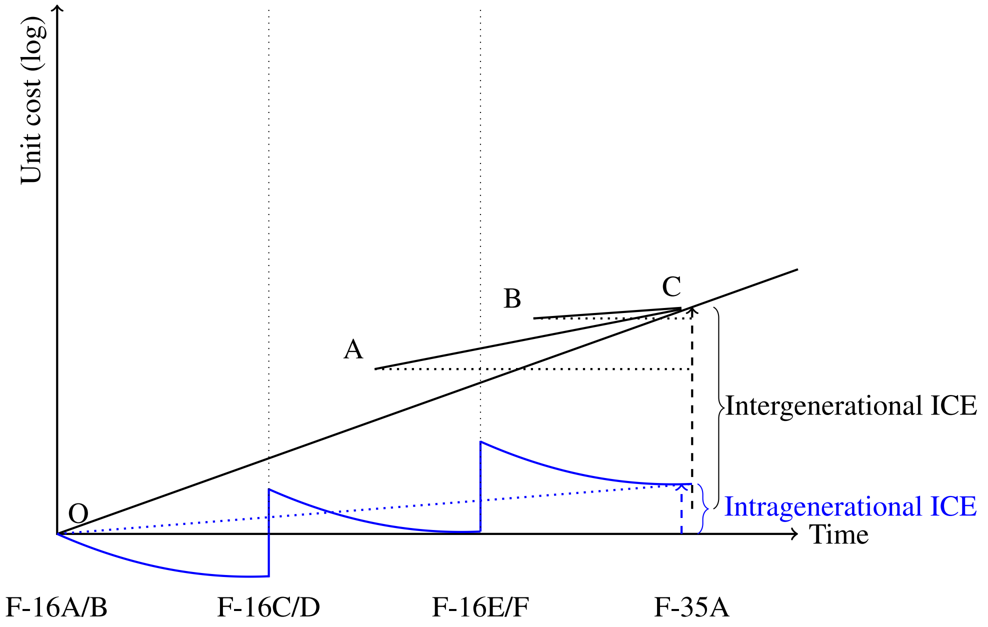

Figure 2.5 *Unit cost as a function of time. ICE is split into an intergenerational (black lines) and an intragenerational (blue lines) part, the sum of which constitutes total ICE.*

3 Reasons behind ICE

3.1 The vicious circles of cost escalation

Kirkpatrick and Pugh (1983) and Kirkpatrick (1995) provide some thoughts as to why at least some of the long run cost escalation is unavoidable. Figure 3.1 summarizes their main reasoning. The figure displays three vicious circles at work. 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 Chapter 3.2. If the Blue nation acquires a new fighter jet, this will increase the threat towards the

Red nation, spurring an advance in new, highly sophisticated, technology in the Red country, and finally to the procurement of more effective Red aircraft. Developing new technology when you are already at (or close to) the technology frontier is hugely expensive (see Chapter 3.3). This higher development cost (the circle at the left hand side) leads to less frequent projects because one cannot afford to upgrade as often as before. As a consequence, this leads to bigger jumps in technology, and more difficult decisions, which again fuel higher development costs. When aircraft are more expensive per unit (though more capable), fewer units are produced, leaving less room for economies of scale and learning in production, both feeding back into higher unit production cost (the circle at the right hand side). Fewer units produced also means there are fewer units to allocate fixed costs (for example research and development costs) between. For technologically advanced equipment, fixed costs are generally high, so fewer units produced does in itself translate into higher unit costs.

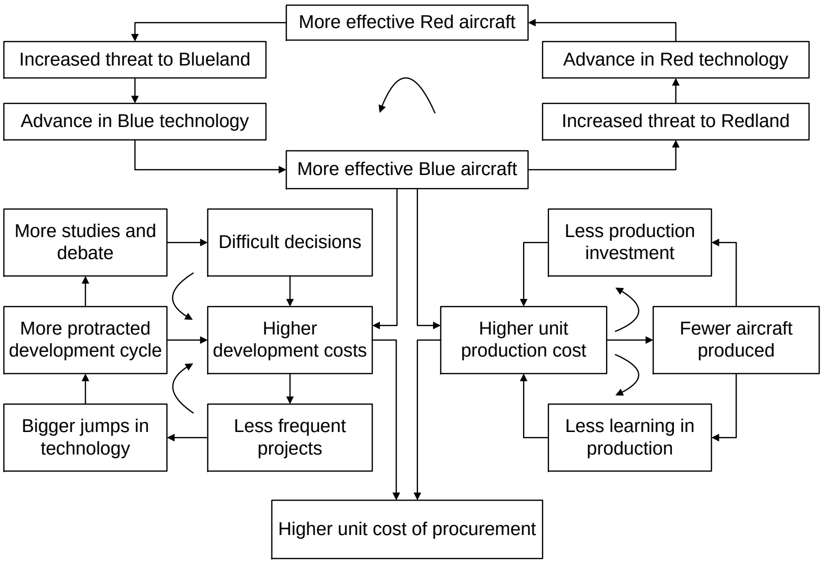

Figure 3.1 The vicious circles of unit cost escalation. Figure from Kirkpatrick and Pugh (1983) and Kirkpatrick (1995).

3.2 Relative effect

As military equipment has little or no intrinsic value (the value of an object in itself), but has a value only when compared to other actors' equipment, many consider an increase in effect per unit to be offset by a similar increase in the effect per unit of competing actors' equipment (Kirkpatrick, 1997; Kirkpatrick, 1995; Kirkpatrick, 2004; Kirkpatrick and Pugh, 1983; Pugh, 1993; Pugh, 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 lead to reduced relative effect.

Kirkpatrick (2004) illustrates this mechanism as in Figure 3.2. Initially we are in situation *A* with a given equipment at a given price. New technology becomes available and we move to situation *B*, where the equipment are more costly, but also more effective. When the same technology becomes available for our 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 we procure additional units, the price of the new equipment may decrease due to learning effects and economies of scale, as in situation *D*. The steps from *A* to *D* will then repeat themselves, as illustrated by the dashed lines. The consequence of this continuous spiral is increasing costs, but no increased relative effect per unit. This mechanism is considered one of the main causes behind ICE. Pugh (1986, p. 141) illustrates this using an example of how the 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 this 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. Still, there is no doubt that the absolute price increases.

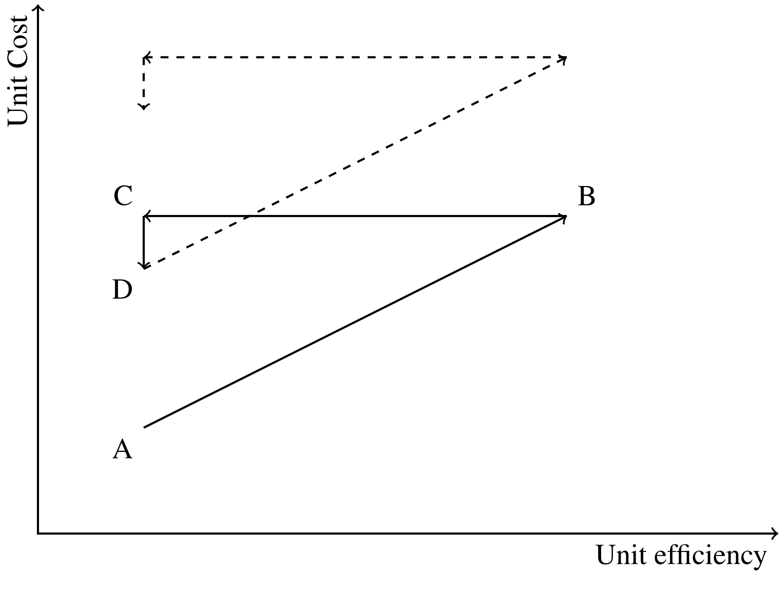

Figure 3.2 Initially in situation A, *new technology is available, moving a nation to* B, *with more efficient, but costly, equipment. The same technology becomes available for the adversary, moving the situation to* C, *where the increase in effect is offset by the new equipment of the adversary. As we procure additional units, the price of the new equipment decreases (*D*). The steps from* A *to* D *then repeat themselves. Figure from Kirkpatrick (2004).*

Pugh (1993, p. 180) writes that "cost escalation is not a feature of defence alone but is to be found wherever cost buys performance but effectiveness is obtained from superiority of performance over that of a rival. In broad terms, just as there is only one fastest racing car or only one most prestigious impressionist painting, so there is, for each role, only one best aircraft design. Wherever there is an element of competition between buyers of retail goods and sometimes [this competition is] fully as fast as for military equipment. Defence is [exceptional] only in the overtness of the processes involved. The advantage sought in the procurement of, say, a new aircraft resides in its higher performance degrading the effectiveness of aircraft employed by potential adversaries. They are thus obliged to respond in kind in order to restore the effectiveness of their forces—so sustaining the spiral of escalating costs."

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. A good example of a tournament good is football players. A football player has, as military equipment, no intrinsic value, but is valued when compared to the opponents players. There seem to be little research done on tournament goods, but some insight into the mechanics of tournament goods can be derived from Lazear and Rosen (1981). They describe the effects of remuneration by performance ranking among employees on employees optimal choice of effort. The same line of thought can be used to describe willingness to invest in military equipment.

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

$$E(U) = P(W_1 - C(\mu)) + (1 - P)(W_2 - C(\mu)) \tag{3.1}$$

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

$$C'(\mu) = \frac{\partial P}{\partial \mu}(W_1 - W_2) \tag{3.2}$$

(3.2) says that the marginal cost of investing (left hand side) should be equal to the marginal expected gain from investing (right hand side). In this case, 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.

In case of military equipment, the difference in gain from winning and loosing could be quite large. For essential equipment like fighter aircraft, the best fighter aircraft will give control of the air, hence the rank is essential. In this case 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.

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 for a moment that at any given time, we can buy a weapon system from along a technology possibility frontier where unit price increases as technology level increases. Technology encompasses such things as better machinery, more research and productivity and learning gains. If we increase the level of technology (or performance) from a low level to a slightly higher level, the price only marginally increases. This is because both technologies have been available for some time, are thoroughly tested and are serially produced. However, if we increase the technology from a high level to a higher level, the price will exhibit a dramatic increase, because the new level of technology is newer, 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 3.3, adapted from Deitchman (1979, p. 240).

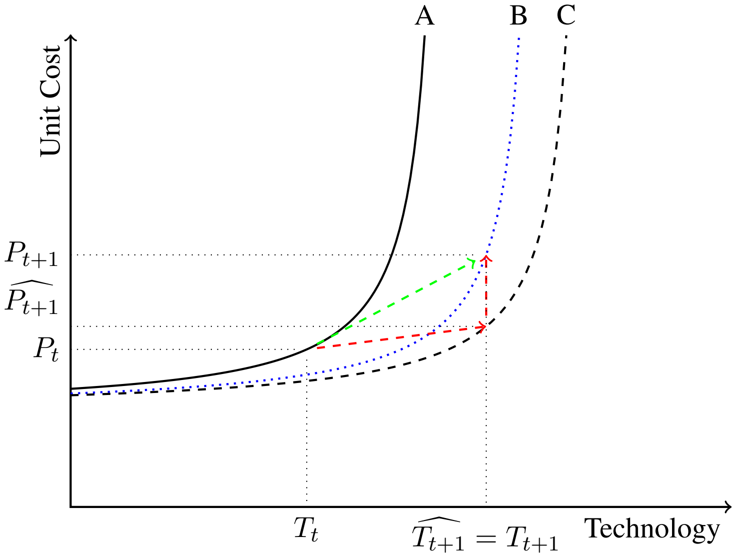

Figure 3.3 *The current weapon system is selected at today's technology frontier (the thick black curve – A), where we have selected a combination of technology, or performance, (T_t) and unit cost (P_t). The higher the performance, the exponentially higher the unit cost. We then estimate a future technological frontier for our next weapon system (the dashed black line – C), and select a combination of vastly improved performance ($\widehat{T_{t+1}}$) and, in this specific case, a slight increase in price ($\widehat{P_{t+1}}$). At the time of acquisition, the technology frontier has only moved to the blue, dotted line – B. 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 green arrow. Figure adapted from Deitchman (1979).*

The technology frontier will shift outwards as research drives technology development forwards. In Figure 3.3, the estimated shift in technology between generations is the shift from the black thick line (A) to the black dashed line (C). In Figure 3.3, we have planned for a modest increase in price, but a great leap in technology (the horizontal red arrow ending in a combination of technology $\widehat{T_{t+1}}$ and price $\widehat{P_{t+1}}$). However, there is always a certain degree of uncertainty with regards to the future technology level. If the technology level only reaches the blue dotted line (B), and we maintain demands for performance, the unit cost will shift upwards dramatically, as illustrated by the vertical red arrow. It will shift more the further up the possibility curves we are. ICE between generations can thus be illustrated by the green arrow. Table 3.1, from Deitchman (1979, p. 239), shows how Deitchman illustrated the link between technology and prices.

Technical features	**Maximum range (nautical miles)**	**Cost of nth unit (1978 dollars)**
Basic radar with mapping and moving target indication, usable for air-to-air and air-to-ground	15	100 000
– with weapon guidance capability, wide angle scan, high range accuracy and resistance to countermeasures	20	225 000
–– with higher power	40	300 000
––– with high resolution mapping and data link to remote ground station	40	450 000
Long range air-to-air, with high range accuracy, high countermeasures resistance, and weapon guidance	100	600 000

Note Deitchman (1979, p. 239): "Mapping" permits observation on a screen of the scene "painted" by the scanning radar beam, and of man-made objects therein. The higher the "resolution", the smaller the natural and man-made objects that can be distinguished in the scene.

Table 3.1 Cost performance relationships for fighter aircraft radars. Table from Deitchman (1979).

In Figure 3.3, prices increased greatly because we did not change requirement specifications as a response to technology not developing the way we predicted. However, a jump in technology need not necessarily increase prices. Figure 3.4 shows an example where we have chosen a constant technology level (prices fall), where we have chosen a technology level that gives an unchanged price and where we have chosen a technology level that gives increased prices. When we upgraded our television set from a 28" cathode ray tube (CRT) to a 40" liquid-crystal display (LCD) set, we did not pay any more for the latter than for the former, i.e. we moved from $T^{*'}_{t+1}$ to $T^{*''}_{t+1}$ in Figure 3.4. Since income (for most) grew at a faster rate than CPI in the meantime, we used a smaller amount of our income to buy the LCD set. A country could in theory do the same for defence equipment, but this would run against the relative effect argument. Remember that the LCD set has value in itself, not relative to the TV sets of neighbours. If television sets were a tournament good and, say, only the 50 per cent largest television sets of any block of apartments were working at any time, the prices of television sets would inevitably increase. If they were also important for your own survival, the price would increase even more, from $P^{*'}_{t+1}$ to $P^{*'''}_{t+1}$ in Figure 3.4.

3.3.1 Complexity and state of the art

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

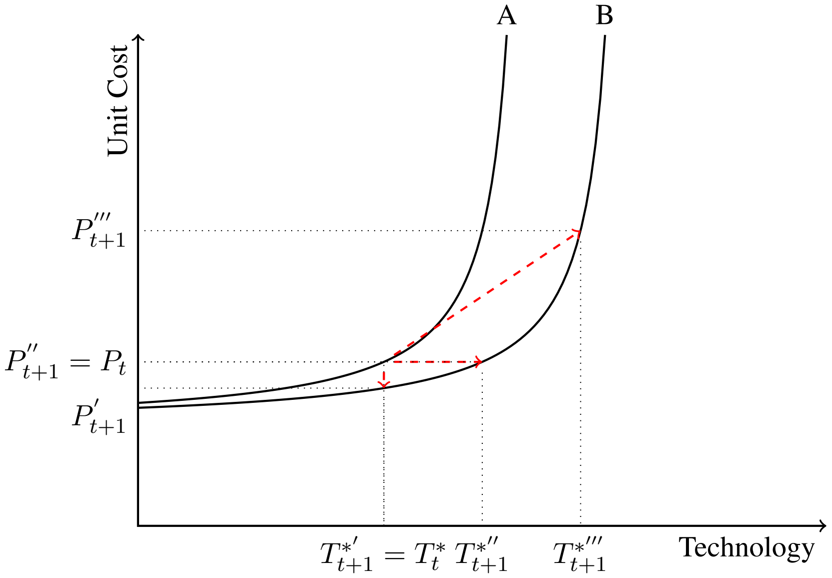

Figure 3.4 The consequences of new technology on cost is ambiguous. When available technology shifts from A to B, we can choose to remain at the same level of technology ($T^{*'}_{t+1} = T^*_t$) and obtain a lower price, we can choose a somewhat higher level of technology ($T^{*''}_{t+1}$) and obtain the same price, or we can choose a more improved level of technology ($T^{*'''}_{t+1}$) and have to pay a greater price. The blue dashed lines indicates the maximum available technology, independent of cost.

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." This leads to one of Augustine's laws (Augustine, 1983, p. 47): "The last 10 percent of the performance sought generates one-third of the cost and two-thirds of the problems."

3.4 Supply and demand

In a perfectly competitive market, prices are set according to supply and demand. In less perfect markets, distortions, such as monopoly power, can increase prices beyond the perfect market equilibrium. If supply and demand are to have any influence on price escalation (beyond what can be expected due to changes in input factor prices), market conditions have to worsen (or perhaps improve, seen from the supplier) over time. In this section, we hypothesize around some supply and demand variables at play. We will use Figure 3.5 to illustrate during this section.

3.4.1 Supply

In a perfectly competitive market, a supplier offers supply (S) until the price equals demand (D), point C in Figure 3.5. However, suppliers of weapon systems have a certain amount of market power. At the top quality level, they provide highly specialized equipment, so competition is limited. Economic theory says that a greater degree of differentiation between suppliers, or fewer suppliers, increases the market power of the remaining suppliers. This lets the suppliers raise prices by reducing

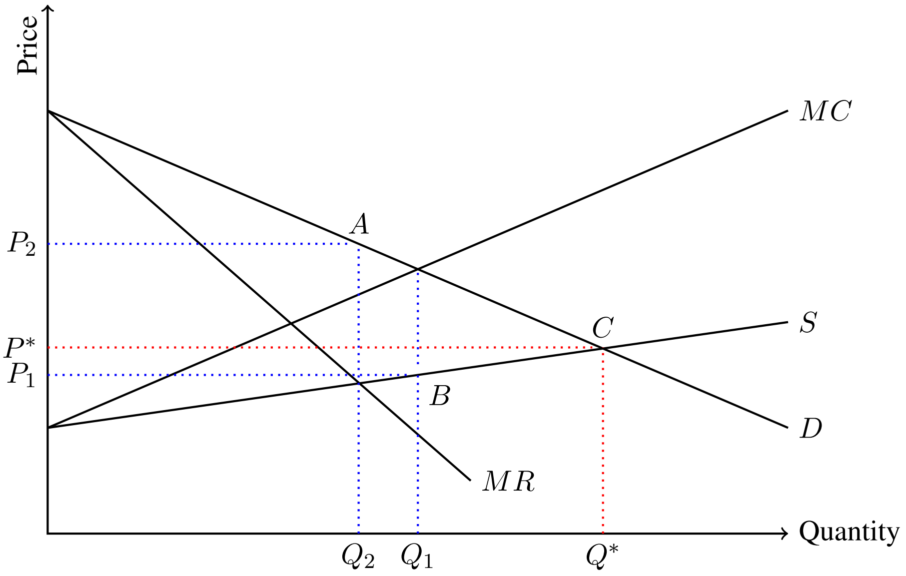

Figure 3.5 Example of a bilateral monopoly in the defence market. In a perfectly competitive market, optimal price P^* and quantity Q^* are set at the intersect between supply S and demand D. In a monopoly, price P_2 and quantity Q_2 are determined where supply is equal to marginal revenue MR. In a monopsony, 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.

the numbers of items supplied (Tirole, 1988). The image is perhaps not as clear in the defence sector, since there are also important demand side variables at play, which we will come to shortly. However, theory is clear in stating that 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 themselves. If a company is the sole provider of a technology, they have monopoly power, and will only supply until marginal revenue $(MR) = S$ in Figure 3.5. 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 the 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 (for example 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 increasing prices. Another aspect is the smaller incentives towards productivity inventions in monopoly like markets. This can lead to greater price increases than in more competitive markets.

3.4.2 Demand

In each country, there is only one consumer of defence goods (or a few, if private military companys (PMCs) exists), so reducing the number of items supplied (as mentioned in Section 3.4.1) does not necessarily benefit the supplier. In the short run it might increase profits, but if it leads to a reduction in the quantity procured by a sole customer, total profits will fall. We do, in other words, also have 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 of P_1 (point B) in Figure 3.5. Since the defence market exhibit both monopoly and monopsony power, the final price will end somewhere between P_1 and P_2, depending on the relative 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:

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

Obviously, both these factors can contribute to an increase in supplier power, since they will know it is more difficult for the defence 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 also mentioned MICC in his famous 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.”[2]

Because of 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 price. If this willingness to pay increases over time, it can contribute not only to a high price level, but to ICE. The competition between countries can lead to a sharper focus on quality than on prices.

As buyers of weapon systems are humans, they are not perfectly rational. 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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[2] `http://coursesa.matrix.msu.edu/~hst306/documents/indust.html`

In defence, there is a challenge of asymmetric information between countries. 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 they exploit this power, we could see increasing prices.

3.4.2.1 Nonfunctional demand

In his classic 1950 article, Leibenstein (1950) makes the distinction between functional and nonfunctional demand. By functional demand, he means the ”part of demand for a commodity which is due to the qualities inherent in the commodity itself.” In other words, we buy cheese because we need food, and cheese is a kind of food we like. Nonfunctional demand is the part of demand which is not due to the quality of the product itself, but for example is due to external effects on utility of purchasing exactly that good. Leibenstein makes a distinction between the bandwagon effect (you buy a product because others buy it), the snob effect (demand falls when more consumers acquire the product) and the Veblen effect, where the demand for a commodity (for example an Aston Martin) increases because of its high price tag. Possible nonfunctional demand elements involved in the defence sector is mostly related to the bandwagon effect, i.e. we buy equipment because our allies buy similar equipment. Some of this is obviously due to ”qualities inherent in the commodity itself”, because buying the same type of equipment enables communication (the network effect), however there is a possibility that some of the demand specifications are influenced by the bandwagon effect, i.e. that we specify a need for something because everyone else has got it. If such a tendency increases over time, it will contribute to ICE.

To sum up, 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 even 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 What can we afford?

Eventually, 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 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).[3] This is not a realistic level of spending for any country, as there is a range of other areas in which to spend money. How large share a country can realistically

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[3] 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`.

spend of GDP depends on an array of variables, including politics, demographics, economic growth, etcetera, and is a complex topic. However, one thing is clear: as a country approaches this limit, it has to decide whether to

- increase spending (and bear the political cost)
- invest in equipment with lower ICE
- reduce the number of units within each weapon system
- 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. 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 certain critical mass. If we follow this logic, the only long term solution is to reduce the number of weapon systems. The period of having a complete set of weapon systems on ones own might be prolonged by 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).

3.6 Chapter summary

In this chapter, we have discussed several concepts that might induce ICE. In Section 3.2, we mentioned the concept of relative effect, where the continuing struggle to obtain state of the art equipment leads to a spiral of increasing costs. The demand for advanced equipment increases faster than productivity improvements can reduce the price. This has been named by several authors as the main underlying reason behind ICE (Kirkpatrick and Pugh, 1983; Pugh, 1986; Kirkpatrick, 1995). Furthermore, we discussed the role of technology, where acquiring technologically advanced equipment is costly in itself, as well as increasing the risks of cost overruns by overestimating the availability of future technology. The demand for sophisticated technology is related to relative effect.

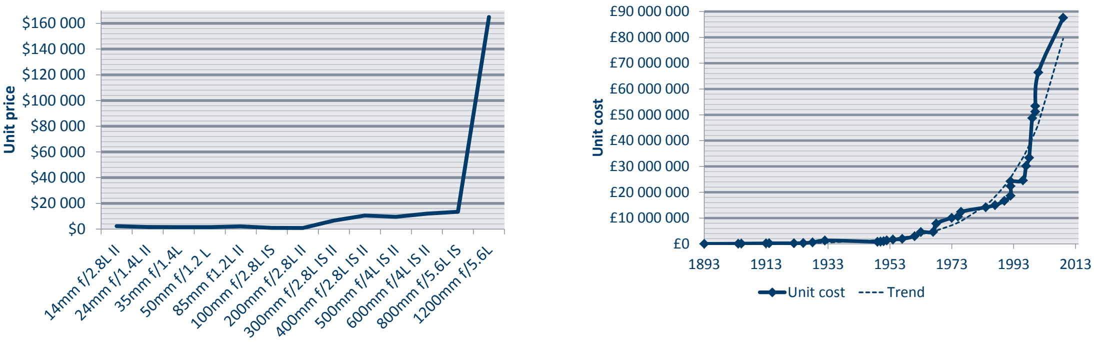
We then discussed some supply and demand variables. There exist both supplier and buyer power in the defence market. A change in the relative strength between suppliers and buyers can increase investment costs. Such an increase can come about due to mergers and acquisitions, asymmetric information or because of political processes. Finally, we also made a point out of what a country can afford. While large countries can continue to procure fewer units to abate increasing unit costs for some time, smaller nations with low inventory levels of each weapon system are facing a problem.

None of the forces mentioned in this section are unique to defence, neither are they completely impossible to deal with. Their effects can be reduced through continually efficient procurement processes, increased international cooperation and so on. However, the underlying forces are still there. We end this chapter by illustrating other industries who experience similar forces.

3.6.1 Lenses and footballers

We can illustrate the concepts of i) complexity, ii) state of the art, iii) relative effect, and the issue of iv) low or no serial production (which is directly related to i) and ii)) using a couple of seemingly unrelated examples. In the left pane of figure 3.6, we show unit prices of Canon's L series lenses. All lenses from 14 mm (wide angle) to 800 mm (super tele) are serially produced. All lenses of 200 mm or below cost a maximum of USD 2 200. The super tele range (300 mm and above) are significantly more complex and expensive than the range below, starting at USD 6 600 for the 300 mm. The largest serially produced range, the 800 mm, cost USD 13 500. The 1200 mm, however, only produced after a sale had been made (well below 100 in total), was virtually hand made and was produced in a quantity of two per year, had a lead time of 18 months and was very complex in that it took ”nearly a year to grow fluorite crystals large enough to be ground and polished for use in this lens” (Carnathan, 2009). The point of this example was to illustrate that the mechanism of extremely high prices at a frontier is not unique to defence. For lenses, we observe the same effect for high end, hand made lenses.

In football, we see it where a Championship (tier 2) striker can cost £1 million, a bottom half Premier League (tier 1) striker can cost £3 million, an average Premier League striker can cost £7 million, and a top three club Premier League striker can cost £35 million. The price at the very top end of the league is far greater in magnitude than at levels just below the top end. The right pane of Figure 3.6 illustrates the unit cost escalation of footballers by plotting the world record fees over time.[4] The average unit cost escalation at the frontier is 6.7 per cent for the entire sample (36 observations).



Prices of Canon L lenses measured in September 2014.

Illustration of unit cost escalation for footballers at the frontier. Prices in Pound Sterling, deflated by RPI. Annual cost escalation: 6.7 percent.

Figure 3.6 Prices of Canon L lenses (left) and footballers (right).

For lenses, the high price is a consequence of complexity, and the fact there is no serial production (both because of a limited market, and because of complexity). In football, the fierce competition to

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[4] The source is the Wikipedia article *World football transfer record* (2014), which again quotes one or more sources per observation. We have deflated all observations by UK retail price index (RPI) to obtain real values.

finish at the top leads clubs to spend vast amounts of money on state of the art players in the chase of maximum relative effect (Section 3.2). Other markets also exhibit some of the same traits, for example the health market, where increasingly expensive treatment and equipment is available.

In the defence market, all these four forces are at play, as shown earlier in this chapter. As illustrated by the examples in this section, all four forces contribute to high prices. Complexity leads to high price levels (even for serially produced items), state of the art equipment increases exponentially in price as we approach the technology frontier, relative effect leads to continually increasing prices, and low or no serial production leads to high prices.

4 Some previous empirical work

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. This chapter summarizes some of these previous studies.

Table 4.1 summarizes several previous studies. Pugh (1993) finds very high rates of cost escalation – between 9 and 11 per cent annually for destroyers, submarines, helicopters, frigates, guided missiles and fighter aircraft (costs are corrected for inflation, thus comparable over years). However, in 2007, Pugh find rates of 4 per cent for fighter aircraft, 3 per cent for submarines and 5 per cent for helicopters when adjusting price by weight, as a proxy for quality(Pugh, 2007). 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 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. Table 4.1 summarizes studies where prices are adjusted and not adjusted for weight. 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. Figure 4.2 summarizes some studies graphically.

Arena et al. (2008) and Arena et al. (2006a) 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 4.1 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 et al., 2006a).

	Kvalvik and Johansen (2008)			Nordlund et al. (2011)		
Weapon system	Cost[a]	Weight	Period	Cost	Weight	Period
Fighter aircraft	6.7 %	5.8 %	1940–2010	7.1 %	6.4 %	1953–2001
Helicopter, light	4.7 %	3.2 %	1950–2010	3.8 %	4.1 %	1963–2006
Helicopter, medium[b]				6.9 %	5.9 %	1969–2006
Corvette	7.8 %		1960–2010	7.0 %	4.2 %	1963–2006
Submarine	6.0 %		1907–1991	4.4 %	2.5 %	1960–1995
MBT	2.2 %	1.2 %	1960–2006	0.7 %	0.3 %	1963–1996
IFV	6.0 %	4.6 %	1960–2006	7.6 %	5.1 %	1965–2004
Artillery vehicles				4.5 %	3.1 %	1943–2010
Small arms	1.3 %		1868–2008	2.8 %		1950–2010
Transport aircraft	7.6 %	3.7 %	1940–2010			
Ammunition				1.2 %		1983–2010
Uniforms				-1.0 %		1990–2010
Destroyers						
Frigates	3.8 %		1963–2011			
Guided missiles						
Escort carriers						
Trainer aircraft						
Aircraft carriers						

	Pugh (2007)		Pugh (1993)	Pugh (1986, p. 144)		K&P (1983)[c]
Weapon system	Weight	Period	Cost	Cost	Period	Cost
Fighter aircraft	4 %	1955–2005	11.0 %	10 %	1952–1976	8 %
Helicopter, light	4 %	1958–2006	9.5 %	8 %	1961–1975	
Helicopter, medium	6 %	1958–2006				
Corvette	1 %	1958–2004				
Submarine	3 %	1950–2010	9.0 %	9 %	1900–1972	
MBT	1 %	1950–2002				11 %
IFV	4 %	1960–2010				
Artillery vehicles	2 %	1960–2010				
Small arms	2 %	1935–2008				
Transport aircraft						
Ammunition						
Uniforms						
Destroyers			9.0 %	9 %	1960–1980	9 %
Frigates			10.5 %	11 %	1966–1978	
Guided missiles	8 %	1954–1992	11.0 %	11 %	1964–1977	
Escort carriers				3 %	1945–1972	
Trainer aircraft	4 %	1959–2006		3 %	1961–1974	
Aircraft carriers	3 %	1943–2007		5 %	1944–1975	6 %

[a] ”Cost” is unit cost regressed on time, ”Weight” is unit cost divided by weight regressed on time.

[b] Where no split is made between light and medium helicopters, the helicopter estimates are reported as helicopter, light.

[c] K&P: Kirkpatrick and Pugh (1983).

Table 4.1 Results from previous ICE studies.

	Davies et al. (2011)			Dalseg (2003)[b]	
Weapon system	Cost	Character[a]	Period	Cost	Period
Fighter aircraft	5.8 %	5.7 %	1955–2006	4.9 – 7.1 %	1980–2010
Helicopter, light					
Helicopter, medium					
Corvette				8.0 – 11.6 %	1967–2002
Submarine	2.9 %		1963–2009		
MBT	5.9 %		1945–1994	2.5%	2070–2002
IFV					
Artillery vehicles					
Small arms					
Transport aircraft				3.6 – 4.8 %	1952–2010
Ammunition					
Uniforms					
Destroyers	2.6 %	1.0 %	1962–2010		
Frigates	4.3 %	2.2 %	1956–1989	6.0 %	1964–2005
Guided missiles					
Escort carriers					
Trainer aircraft					
Aircraft carriers	3.8 %		1955–1985		

[a] ”Character” is the result of regressions with explanatory variables related to characteristics, much in the same way we do in later chapters.

[b] The Dalseg (2003) study is based on only a couple of observations, many of whom are estimates of future costs.

Table 4.1 Results from previous ICE studies (continued).

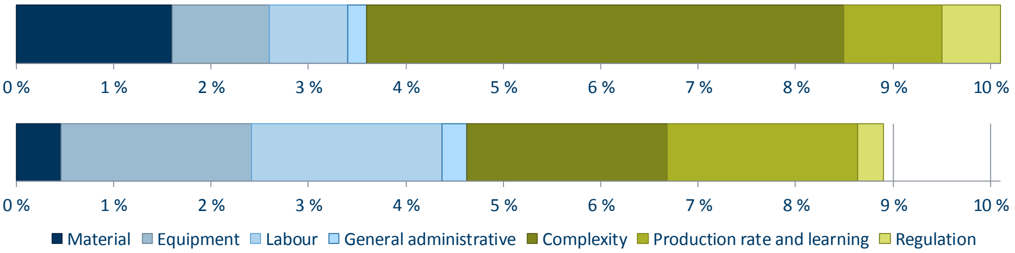
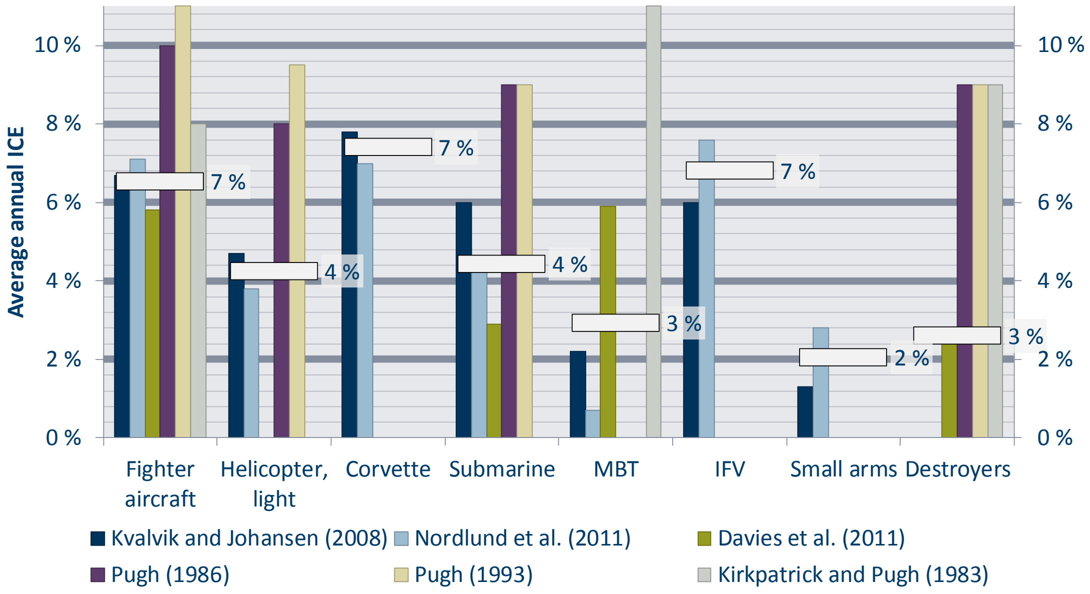


Figure 4.1 Top: Breakdown of causes of average annual cost increase from the F-15A (1975) to the F-22A (2005) in economy driven factors (blue areas) and customer driven factors (green areas). Data from Arena et al. (2008). Bottom: Breakdown of causes of average annual cost increase from DDG-2 (1961) to DDG-51 (2002) in economy driven factors (blue areas) and customer driven factors (green areas). Data from Arena et al. (2006a).



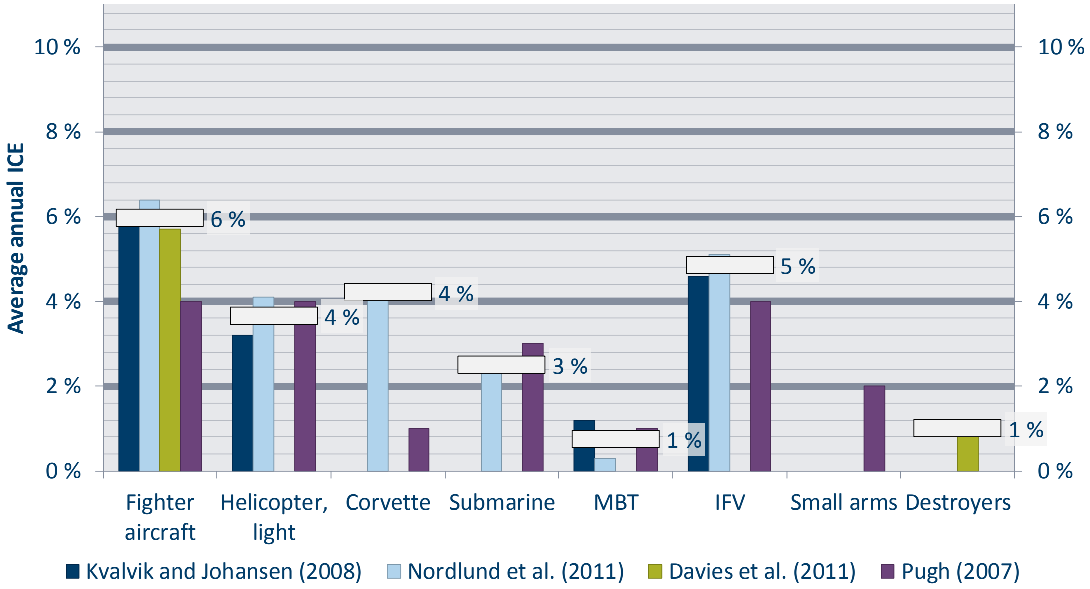


Figure 4.2 Unit cost escalation rates from various studies. Unit cost (top) and unit cost per tonne (bottom). Grey bars are averages based upon Kvalvik and Johansen (2008), Nordlund et al. (2011) and Davies et al. (2011).

Arena et al. (2008, p. xvi-xvii) provide the following 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.
  - 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.
    - 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
    - Lower weight
- Regulation, such as environmental, health related and those designed to protect American industries, are also cited as drivers behind ICE.

Arena et al. (2006a) and Arena et al. (2008) also study ICE, but do not deflate by a price index, i.e. their ICE is nominal. Table 4.2 summarizes their findings.

Arena et al. (2006a, 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 4.2 Results from the Arena et al. (2006a) and Arena et al. (2008) studies on cost escalation of navy ships and fixed wing aircraft. Growth rates are in nominal dollars.

Based results of their own study, Kvalvik and Johansen (2008) plotted their results in the matrix shown in Table 4.3. They classified their results according to the relative importance of having state of the art equipment, the scale in production and the risk of loss. 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. Based on their estimates they also constructed a matrix with ICE estimates recommended for use in long term 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

		Recommended ICE in long term planning		
	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 4.3 Matrix from Kvalvik and Johansen (2008), based on Dalseg (2003), displaying a classification of their results based on relative importance of having state of the art equipment, scale in production as well as the risk of loss of equipment. 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. "Importance for military capability" was the original title of what is here called "Relative importance of state of the art". The name was changed to the latter in Kvalvik et al. (2009). The following abbreviations are used elsewhere in the report: main battle tank (MBT), infantry fighting vehicle (IFV), fast attack craft (FAC).

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. This is because, as we will return to in Chapter 5.1, the definitions of what constitute a proper unit costs differ significantly. However, as national defences do not readily share data with foreign researchers, we would have had to use Norwegian data. There are several reasons why this is not possible. First, the Norwegian Defence does not buy a great variety within each weapon system. Collecting such data would have been difficult anyway, since according to Espenes et al. (2001),”The Norwegian Armed Forces has had a remarkable ability to shred their historical sources”, meaning that there are not much good quality cost data available.

We have therefore resorted to open sources, as Kvalvik and Johansen (2008) did, and we have extended their data set. Our data consist of some 280 observations of prices and characteristics of submarines, transport aircraft, artillery vehicles, MBTs, IFVs, FACs (among other things encompassing motor torpedo boats (MTBs) and corvettes), fighter aircraft, small arms, helicopters and frigates. Table 5.1 summarizes our data. In the following sections, we discuss some challenges in our dataset.

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 5.1 Description of the dataset used in this paper.

5.1 What is the cost of a weapon?

If we want to measure unit cost escalation, we must define what a unit cost is. Unfortunately, there exist a whole range of definitions. Figure 5.1 and the following list show an example of such definitions, though varying definitions exist.[5]

Recurring flyaway cost covers the ”basic” equipment of a system, such as the airframe, engines

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[5] Our definition is similar to that of Defense Acquisition University (DAU) at their Defense Acquisition Portal (DAP) (`https://dap.dau.mil/acquipedia/Pages/ArticleDetails.aspx?aid=419dcd24-0e78-4279-a50a-9c122c4f0630`), though our illustration differ significantly.

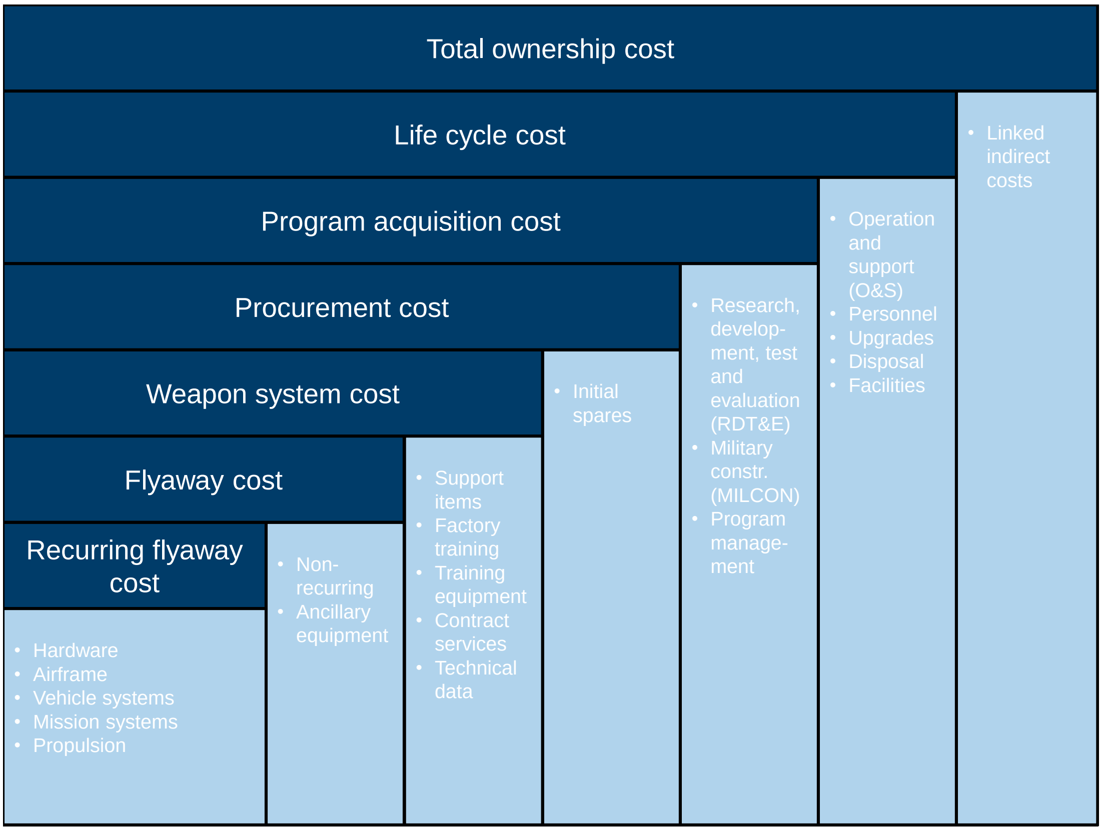

Figure 5.1   Illustration of various definitions of cost. See associated list for more details.

and avionics in a fighter. The recurring flyaway cost per unit is often denoted unit recurring flyaway (URF).

Flyaway cost (FAC) (or Rollaway/Sailaway for such systems) includes the recurring flyaway cost, as well as *non-recurring* flyaway costs, such as ”startup” costs (which are often apportioned over the entire production series) and customer specific tailoring. An example of such tailoring is Norway and Canada having brake chutes fitted to their F-35s. FAC is an often quoted cost.

Weapon system cost (confusingly also known as *total flyaway cost*), is composed of FAC as well as support items, factory training, training equipment, contract services, technical data packages and various contract services related to initial support. These costs are generally amortized over the entire purchase.

Procurement cost includes the weapon system costs as well as initial spares. The cost per unit is known as average procurement unit cost (APUC) and is, together with FAC an often quoted cost.

Program acquisition cost adds research, development, test and evaluation (RDT&E) and military construction (MILCON), such as test facilities, to the procurement cost. These costs are often fixed, i.e. they do not vary with the number of units produced. The unit cost, known as program acquisition unit cost (PAUC), can therefore be much higher than APUC if production quantities are small (and/or if RDT&E or MILCON are very high).

Life cycle cost (LCC) adds all the building of facilities, as well as the lifetime operational and upgrade costs of a system to the program acquisition cost. These costs include fuel, spares, replenishment, depot maintenance, system support, modifications, disposal, as well as hiring, training, supporting, and paying the personnel. There is no one life cycle cost (LCC) method, therefore one should be wary of assuming that all LCC analyses contain the same cost elements.

Total ownership costs also includes the indirect effects of a purchase, though these costs are not borne by the customer. Such indirect costs can include the building of a new bridge to an island of an enlarged defence base, since the current bridge can no longer sustain the increased traffic. As for LCC, this is more of a concept than an established methodology, so estimates are difficult to compare.

Even without examples, we understand that an URF quote and a LCC per unit quote will differ significantly, as will an URF and a PAUC quote. Table 5.2 illustrates an example of the different unit costs one can obtain. The rightmost column does not reflect R&D and production costs, whereas the mid column does. Consider for example the F-22, where including R&D and production costs almost doubles the unit cost.

Aircraft Type	Unit Total Cost[1,2]	Unit Production Cost[1]
Combat aircraft		
Eurofighter Typhoon[3]	170	110
Saab JAS 39 Gripen	86	78
Dassault Rafale	153	70–91[4]
Boeing F-15E Strike Eagle[5]	NA[6]	122
Boeing F/A-18E/F Super Hornet	107	67–88[4]
Lockheed Martin F-22 Raptor	381	200
Lockheed Martin F-35 Lightning II	162	137[7]
Transport aircraft		
Airbus A400M Atlas	216	118
Boeing C-17 Globemaster II	328	245
Lockheed Martin C-130J Super Hercules	NA[6]	73

[1] Million US dollars at 2011 prices and exchange rates.
[2] Includes R&D costs and production costs.
[3] According to Hartley (2012), "no capital charges [are] included in the price."
[4] Sources differ.
[5] McDonnell Douglas until their merger with Boeing in 1997.
[6] Not available.
[7] Alternative estimates range from $197mn (F-35A) to $238mn (F-35C). Costs are estimated prior to large-scale production and are averages for F-35A/B/C.

Table 5.2 Examples of unit prices with different types of costs included. Table from Hartley (2012).

Ideally, we would like to include only one type of cost for our entire sample, and that type of cost would depend on what we wanted to study. I.e. we would like URF or FAC if we want to study what the aircraft frame itself cost, but PAUC if we also want to include development costs. If we hypothesize that development costs per unit increase with time, we will find a greater ICE using

PAUC than using URF or FAC. However, 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. Arena et al. (2008, p. 13) obtain very similar estimates when estimating cost escalation using APUC and using FAC, but in the F-22 case of Table 5.2 we clearly see that R&D costs are of significant importance.

5.2 What is a weapon system?

5.2.1 Classification

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 do you draw the distinction between a motor torpedo boat, a fast attack craft, a corvette and a frigate? As corvettes grow larger, when is a new generation classified as a frigate? If we combine the categories, the characteristics and prices between vessels will fluctuate significantly. If we do not, 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. We therefore expect to see significant variation in prices for such systems.

5.2.2 Effect

The question of effect is also important. Unit costs are obviously not dependent only on time as if by magic. Characteristics of the weapon system will also influence prices. An aircraft with 10 percent added range will be more expensive than without the added range. The same goes for maximum altitude, the number of weapons that can be carried, stealth technology and so on. The number of units produced is also of importance, as a fall in numbers will reduce the benefits of learning effects and economies of scale. In our estimation in the following chapters, we will correct for certain observable characteristics, but there remain unobservable characteristics we cannot correct for. These include the quality of stealth technology, the *importance* of having greater range, maximum altitude and so on, as well as actual effect measures. For example the Lockheed SR-71 Blackbird operated at such high speeds (Mach 3.3) and altitudes (80,000 ft) that it essentially could accelerate away from missiles.[6] Does this mean that the aircraft is some 30 percent better than an aircraft capable of 60,000 ft and Mach 2.5, or is it even better because of its ability to outfly missiles? This is a question we cannot answer, but we still expect the observable characteristics to account for some of this effect. We will include effect variables on logarithmic form, thus we postulate that a one percentage increase in effect leads to a constant percentage increase in unit cost.

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[6] `http://en.wikipedia.org/wiki/Lockheed_SR-71_Blackbird`. It is interesting to note that of 32 SR-71s built, 12 were lost due to accidents, none due to enemy action. Compare this to the complexity of the Andretti car of Chapter 3.3.1.

6 Method for ICE estimation

We conduct our analyses using ordinary least squares (OLS) regression, followed by more advanced methods outlined in section 6.1. For an introduction to OLS regression, see for example Gujarati (2003).

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 (and the error term u_t)

$$log(p_t) = \alpha + \beta t + u_t \tag{6.1}$$

A one year increase in time increases the price by $\beta * 100$ percent. For the ICE that is not due to improvements in technology or production rates, we employ the regression

$$log(p_t) = \tilde{\alpha} + \tilde{\beta} t + \bar{\gamma} X_t + \epsilon_t \tag{6.2}$$

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 aim is to remove the effects of these variables when we estimate $\tilde{\beta}$. If prices are more positively than negatively related to characteristics, β will be higher in (6.1) than in (6.2). We use the logarithmic form of X_t, i.e. we assume that a one percent increase in for example weight (w), leads to a $\gamma_w * 100$ percent increase in price.

In addition to the consistency challenges in the dataset discussed in Chapter 5, the dataset has a few structural weaknesses. First, the dataset is a time series dataset, but it has large gaps (called a *gappy* time series) and has years with multiple observations. Different approaches are used when dealing with gappy timeseries (interpolating or estimating the missing values), but as the gaps are fairly large in our dataset, neither of the methods are suitable. Second, since most of our variables share a common trend, growing over time, we have *multicollinearity*. The consequence of multicollinearity is that the correlated regression coefficients will be unstable, but remain unbiased (Gujarati, 2003). Third, our sample size within each weapon system is not large, together with the multicollinearity, resulting in a possible problem of so called *micronumerosity*, which reduces precision of our estimates (Gujarati, 2003). Fourth, since both the price and time are non-stationary, we can also expect *autocorrelation*. The consequence of autocorrelation is that the standard deviations from OLS will be biased, but the coefficients will remain unbiased (Gujarati, 2003). Due to the weaknesses in our dataset it is difficult to test for autocorrelation. These weaknesses make ordinary time series methods difficult to apply. However, since we aim to estimate a growth rate for use in long term planning, we are only interested in the β coefficient, not the standard errors or significance levels. When we present the results in Chapter 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.

6.1 Shrinkage methods and derived input methods

OLS estimates are, given certain assumptions, unbiased, but can have a high variance. *Shrinkage* and *derived input methods* are advanced econometric subjects aiming to reduce this variance. This section does not try to explain the various methods in detail, only provide a short overview of them.

Chatterjee and Hadi (2012) recommends using alternative methods in addition to OLS when collinearity is suspected. The methods recommended are ridge regression (RR), partial least squares (PLS) or principal component regression (PCR). For a more thorough introduction to PCR, PLS, and RR than we provide here, see for example Hastie et al. (2009) or Chatterjee and Hadi (2012)

Shrinkage methods are regression methods that shrinks the coefficients towards zero (Hastie et al., 2009). This introduces a bias, but the variance of the predictions are often reduced by more than the increase in the bias, which leads to reduced prediction error. Shrinkage methods also address some of the multicollinearity issues previously mentioned (Gujarati, 2003). Ridge regression shrinks by penalizing the coefficients' size. The solution is achieved by minimizing the residual sum of squares (RSS) plus the penalty from the coefficients (Hastie et al., 2009). If increasing the coefficient increases the penalty more than the added prediction power, then the coefficient should not be increased (and vice versa). According to Vinod (1978), ridge regression is a useful alternative to OLS when we are interested in robust and stable coefficients.

With *derived input methods*, as PLS and PCR, instead of shrinking the coefficients directly, new variables are constructed on the basis of the original variables. The new variables are constructed to capture maximal variation from the original variables. A subset of these new variables are then used in the regression.

For both shrinkage methods and derived input methods, a tuning or smoothing parameter has to be selected. This tuning parameter determines how much the coefficient should be shrunk. Since the tuning parameter cannot be selected on the basis of the same dataset as the model is regressed, some other method has to be applied. In this report these parameters are selected by tenfold cross validation (CV_{10}). This means we partition the sample into 10 equal size subsamples. Nine of these are used to estimate the model (training data), while the last sample is used for testing the model (validation data). This procedure is completed 10 times, using a different subsample as validation data each time.

The types of methods mentioned in this section don't fit the data as well as OLS, but can have more precision in the estimated coefficients and often has a smaller prediction error when tested on a test set. In other words, the $\hat{\beta}$ from shrinkage methods can be expected to be closer to the true β than β^{OLS} (Chatterjee and Hadi, 2012).

6.2 Omitted variables

When adjusting for improvements, there might be other variables that better describes the quality of the equipment than the ones we have included in the regressions. Variables that not are easy to quantify, that are difficult to observe or interactions between multiple variables might be candidates. For example, we have no variables that directly capture relative effect (Section 3.2), position in relation to the technology frontier (Section 3.3), supply and demand factors (Section 3.4) directly. Variables for weight, ceiling, range etc. are a proxy for effect and technology, while total production is a proxy for some supply and demand factors. Neither of these are of course perfect, so we have an issue of omitted variables.

If some omitted quality parameter that affects price is correlated with time, the coefficient on time will be biased upwards (Hansen, 2014; Angrist and Pischke, 2008). In the first estimation, (6.1), without quality variables, a bias resulting from omitted variables is not critical as we are interested in total ICE. In the second estimation, (6.2), with quality variables, this bias is critical. Omitted variables correlated with time, particularly if more correlated with time than with the included quality variables, will result in a biased coefficient on time. Since we are interested in the ICE not resulting from quality or production changes, this is critical. Formally, if the true relationship is the one in (6.3), but x_2 is omitted from the regression, such that the estimated equation is (6.4), it is fairly straight forward to show that a bias is introduced, the last term in (6.6). Step one is to insert for the true equation (6.3) in (6.5) (the OLS solution). Clean up and use that, by construction, the residuals are uncorrelated with its regressors.

$$Y = X_1\beta_1 + X_2\beta_2 + u \tag{6.3}$$

$$Y = X_1\tilde{\beta} + \tilde{u} \tag{6.4}$$

$$\begin{aligned}\tilde{\beta} &= \left(X_1'X_1\right)^{-1} X_1'Y \qquad (6.5)\\ &= \beta_1 + (X_1'X_1)^{-1}X_1'X_2\beta_2 + (X_1'X_1)^{-1}X_1'u\\ &= \beta_1 + (X_1'X_1)^{-1}X_1'X_2\beta_2 \qquad (6.6)\end{aligned}$$

From (6.6) it is apparent that the higher the covariance between the included and the omitted variable the larger the bias. The quality variables tend to be more correlated with each other than with time, meaning that the quality variables can be expected to be biased. If this holds also for the omitted variables, then the bias can be expected to be small.

6.3 Difference equations

In addition to OLS, PCR, PLS and RR, we estimate a set of differenced equations. Assume that the price P_t is a result of the price at $t = 0$ (P_0) growing continuously at rate r and by some quality variable $\bar{X}_t$ at rate $\bar{\beta}$.

$$P_t = P_0 e^{rt} e^{\bar{\beta} X_t} \tag{6.7}$$

The standard first difference is given by

$$\begin{aligned}\frac{P_t}{P_{t-1}} &= \frac{P_0 e^{rt} e^{\bar{\beta} X_t}}{P_0 e^{r(t-1)} e^{\bar{\beta} X_{t-1}}} \\ \frac{P_t}{P_{t-1}} &= e^r e^{\bar{\beta}\Delta X_t} \\ \ln\left(\frac{P_t}{P_{t-1}}\right) &= r + \bar{\beta}\Delta X_t \qquad (6.8)\end{aligned}$$

where r is ICE. However, our data are gappy, i.e. where we have an observation of P_t, we often do not have an observation of P_{t-1}. In other words, we cannot take first differences. In response, we construct a matrix of k-differences, where we find the cost escalation between all combinations of equipment (for example between F-16 and F-18, between F-16 and F-22, and between F-18 and F-22) and run regressions on the form shown in (6.9).

$$\begin{aligned}\frac{P_t}{P_k} &= \frac{P_0 e^{rt} e^{\bar{\beta} X_t}}{P_0 e^{rk} e^{\bar{\beta} X_k}} \\ \frac{P_t}{P_k} &= e^{r(t-k)} e^{\bar{\beta}(X_t - X_k)} \\ \ln\left(\frac{P_t}{P_k}\right) &= r(t-k) + \bar{\beta}(X_t - X_k) \qquad (6.9) \\ \forall k &\in K | k < t\end{aligned}$$

6.4 Methods: Summary

In this chapter, we have presented five estimation techniques, OLS, PCR, PLS, RR and a k-difference approach. Due to the weaknesses of the dataset, the results from the set of regression methods should be viewed as complimentary. As the standard deviations from the regressions on this dataset cannot be trusted, they will not be reported. There are various biases, both inherent in the methods (Section 6.1) and due to omitted variables (Section 6.2). One should therefore be careful in interpreting the results – some of the statistical assumptions are violated, but for use in long term planning as an indication of long run cost escalation, the results will be useful.

7 Results

7.1 Total ICE

Table 7.1 and Figure 7.1 summarizes the simple OLS regressions on the form

$$log(p_t) = \alpha + \beta t + u_t \qquad (7.1)$$

Note that the coefficients in Figure 7.1 are somewhat different than in Table 7.1. This is because the coefficients are converted from log percent to actual percent. For transport aircraft, this gives $\exp(0.072) - 1 \approx 7.4\%$

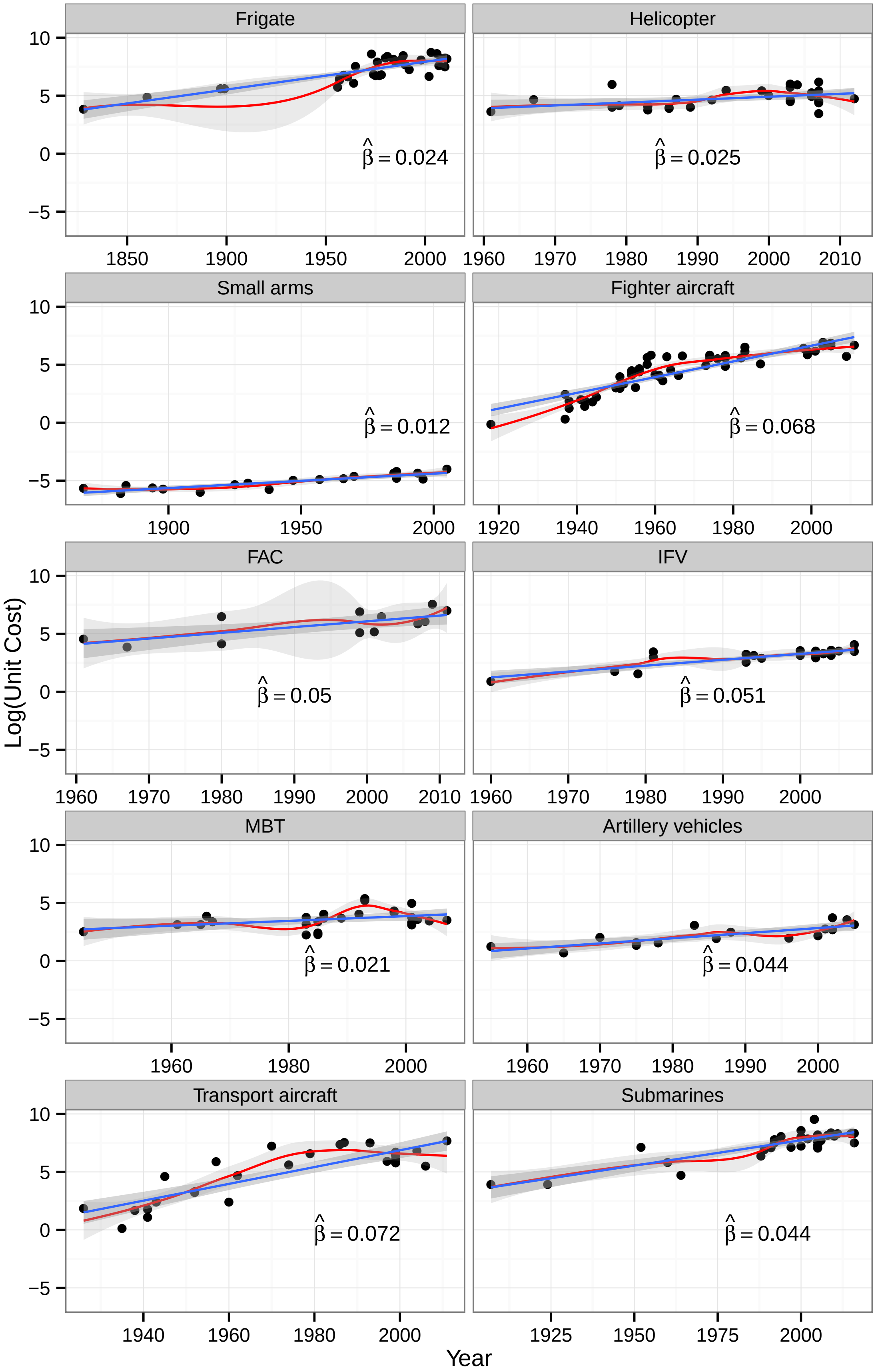

Figure 7.1 OLS regressions (blue line) and local linear regression (red line) of price versus time.

System	ICE estimate
Transport aircraft	7.4 %
Fighter aircraft	7.0 %
IFV	5.2 %
Artillery vehicles	4.5 %
Submarines	4.5 %
FAC	3.6 %
Helicopter	2.5 %
Frigate	2.4 %
MBT	2.1 %
Small arms	1.2 %

Table 7.1 OLS results, total ICE.

As well as the linear fit, Figure 7.1 illustrates a local linear regression with a confidence interval. 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 it in our estimates in Section 7.3. 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 7.1 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 7.1, 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 7.1, we saw 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 in east–west relations, with the signing of the Strategic Arms Limitation Talks (SALT) agreements and the Helsinki Accords. There were other types of conflict, such as wars by proxy (such as the Vietnam war), but less threath of a direct war between the US and the Soviet Union. By the 1990s, the US was the lone world power, and the last ten years have seen more focus 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.

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 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 Chapter 1, 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 7.2 summarizes the estimates. The OLS estimates are based on a regression of (6.2). PCR (a) is a PCR regression on the same variables. PCR (b) is also a PCR regression, but where the time variable is not included among the principal components, but included as a separate variable. The difference between the two results is therefore that the time variable is shrunk in (a) but not in (b). The PLS, ridge and k-diff estimates outlined in Chapter 6 are also reported. The included quality variables for each system can be found in Appendix A.

Not much previous research has been conducted controlling for variables other than weight. Of the

System — Method	OLS	PCR (a)	PCR (b)	PLS	RR	k-diff
Transport aircraft	4.2 %	3.1 %	3.7 %	3.5 %	2.7 %	4.6 %
Fighter aircraft	4.1 %	3.9 %	4.4 %	4.0 %	3.7 %	4.5 %
IFV	2.1 %	2.1 %	2.3 %	2.1 %	2.0 %	2.1 %
Submarines	2.2 %	1.7 %	2.0 %	1.9 %	1.9 %	2.2 %
FAC	4.9 %	0.5 %	4.8 %	1.0 %	0.9 %	4.9 %
Helicopter	2.7 %	0.6 %	1.5 %	1.5 %	1.2 %	2.1 %
Frigate	0.2 %	0.8 %	0.9 %	0.7 %	0.6 %	0.1 %
MBT	-1.5 %	1.1 %	2.1 %	0.5 %	0.2 %	-1.7 %

Table 7.2 Estimated ICE for different types of military equipment. Quality variables vary with availability between weapon systems, but not between regression methods.

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 7.2 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, particularly for MBT, there are clearly differences. For MBT, the OLS methods (OLS and k-diff) find negative ICE rates, while PCR (a), PLS and RR find rates of about zero. This is could be because of very high variance within the data, hence a large shrinkage on the coefficients.

8 Summary and recommendations

8.1 Summary

In this report, we first clarified the ICE concept in Chapter 2. ICE is defined as the annualized per unit cost escalation over generations of a weapon system, beyond an inflation index. We can split this cost escalation into intergenerational and intragenerational cost escalation. In Chapter 3 we moved on to reasons behind ICE. In particular, we mentioned the concept of relative effect, where we have to invest in more advanced (and thus more expensive) equipment in order to answer to new investments by our adversaries. In relation to this, we mentioned the role of technology. 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. In Chapter 4 we compared some previous empirical work, and found different rates of ICE, though they pointed in the same direction.

In Chapter 5 and 6, we outlined our data, their challenges and our methods for estimating ICE. We used a range of different estimating techniques to estimate ICE. Most estimates are robust across techniques, but not all. We find that once we control for characteristics and production quantity, ICE tends to fall, but stay positive. In other words, our control variables cannot explain all the variation, because we have a problem of omitted variables (unless we believe that time itself *actually* explains some of the cost escalation). Table 8.1 summarizes the results of previous studies and of these studies. The last column contain our PCR (a) 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 %	
Submarines		9 %	9 %	6 %	4 %	3 %	5 %	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.

Table 8.1 Summary of previous studies and of this study.

8.2 Recommendations

As mentioned in Chapter 1, ICE can have a significant impact on future costs, thus playing an important role in long term planning. Dalseg (2003) suggested a matrix, later extended by Kvalvik and Johansen (2008), of ICE values as guidelines for use in long term planning. The matrix from Kvalvik and Johansen (2008) were shown in table 4.3. While the matrix can provide a good rule of thumb, we do recommend to always determine ICE based on reasoning rather on only relying on a matrix of values (Kvalvik and Johansen also recommends using the matrix only as a rule of thumb). For example, the importance of relative effect is an important determinant of future ICE. Historic ICE is influenced by World War II and the Cold War, whereas future ICE is influenced by other factors (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 values at the lower end of their intervals as the rule of thumb.

When considering for example a new investment in transport aircraft several elements must be considered. First: is the new aircraft larger and more advanced? If it is not, we should perhaps be leaning more towards the ICE estimate in the last column of table 8.1 than the second to last. If we have received an estimate of the future price, we should consider the cost growth literature while also considering the ICE estimate in the last column of table 8.1.

8.3 Future research

In this report, we have adjusted for observable quality and production parameters. An obvious improvement of this study would be to improve the dataset. However, such data could be classified and not available through open sources. 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 one can follow. First, one can conduct more case studies, in the same manner as Arena et al. (2006a) and Arena et al. (2008), and try to decompose 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. Our reasoning in Chapter 3 is based mainly on verbal arguments. Such models can quickly become very complex and only explain elements of what we are interested in, but they can still provide value.

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Abbreviations

APUC	Average procurement unit cost
BVR	Beyond-visual-range
CFT	Conformal fuel tanks
CPI	Consumer price index
CRT	Cathode ray tube
CV_{10}	Tenfold cross validation
D	Demand
DAP	Defense Acquisition Portal
DAU	Defense Acquisition University
DSI	Defence specific inflation
FAC	Flyaway cost
FAC	Fast attack craft
FFI	Norwegian Defence Research Establishment
GDP	Gross domestic product
ICE	Investment cost escalation
IFV	Infantry fighting vehicle
JSF	Joint Strike Fighter
LCC	Life cycle cost
LCD	Liquid-crystal display
MBT	Main battle tank
MC	Marginal cost
MICC	Military industrial congressional complex
MILCON	Military construction
MoD	Ministry of Defence
MR	Marginal revenue
MTB	Motor torpedo boat
OLS	Ordinary least squares
PAUC	Program acquisition unit cost
PCR	Principal component regression
PLS	Partial least squares

PMC	Private military company
R&D	Research and development
RDT&E	Research, development, test and evaluation
RPI	Retail price index
RR	Ridge regression
RSS	Residual sum of squares
S	Supply
SALT	Strategic Arms Limitation Talks
URF	Unit recurring flyaway

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.1 The included quality variables for each system.