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Estimates of Unit Cost Reductions of the F-16 Fighter as a Result of U.S. Arms Export Production

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Arms exports have increasingly become an attractive option for reducing escalating unit costs of new weapon systems to the United States Department of Defense. However, while there is no lack of conjecture, there is little data that show weapon system costs to the United States actually decrease when the same weapon is sold to a foreign buyer. The authors use the sale of the F-16 multi-role fighter aircraft to foreign nations as a case study to quantify the financial gains realized through learning and economies of scale attributed to export production. Using a rate-adjustment cost improvement analysis, the authors' case study shows the unit costs the United States Department of Defense would have incurred without the concurrent export production of F-16s. Estimates suggest that the production savings resulting from export production were in excess of the research, development, test, and evaluation costs of the F-16 for the period 1975 to 1991. The potential benefits associated with keeping the F-16 production line "warm" through export production and the limits of applying the findings to other weapon systems are discussed.

Introduction

Arms exports have been a critical lever of U.S. foreign policy for the past 60 years and remain so today (Bajusz & Louscher, 1988; Agmon et al. 1996; DISAM, 2010). Arms trade scholars argue that exports have numerous financial benefits including reducing per-unit procurement costs and preserving production lines (Bajusz & Louscher, 1988; Sandler & Hartley 1995; Agmon et al. 1996). However, there is a lack of research that actually shows weapon system unit costs to the U.S. Department of Defense (DoD) have actually been lowered as a result of increased sales to foreign buyers.

As the costs of new weapon systems escalate, arms exports have become increasingly attractive as an option for reducing the unit cost of a system to DoD. Consideration of financial factors arising from proposed arms transfers is an important aspect of U.S. foreign and domestic industrial policy. In this work, we identify three sources of potential savings associated with export production: reducing fixed and nonrecurring per-unit costs, reducing costs through achieving economies of scale and learning, and preserving production lines. We use the sale of the F-16 multi-role fighter aircraft program as a case study to quantify the financial gains realized through learning and economies of scale attributed to export production. Using a rate-adjustment cost improvement analysis, our case study shows the

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per-unit costs that DoD would have incurred without the concurrent export production of F-16s. We discuss potential benefits associated with keeping the F-16 production line “warm” through export production that could accrue to the U.S. Finally, we offer some remarks on the significance of the cost improvement analysis and discuss the limits of applying our findings to other weapon systems.

Affordability is a top priority in the acquisition of any weapon system. A popular conjecture is that U.S. arms exports financially benefit DoD, the U.S. defense industrial base, and the nation as a whole. Arms-trade scholars argue that arms exports theoretically provide financial benefits to DoD by (1) reducing nonrecurring and fixed per-unit costs, such as those for production and research and development (R&D), (2) reducing per-unit costs through achieving economies of scale and learning, and (3) preserving production lines (Bajusz & Louscher, 1988; Sandler & Hartley, 1995; Agmon et al., 1996).

Reducing Unit Costs by Allocating Nonrecurring Fixed Costs to Greater Volume

A larger production volume enables total fixed costs to be spread over a larger allocation base; therefore, the fixed cost per unit component of total unit cost should decrease as production increases. However, the U.S. experiences a reduction in such costs (to include R&D and production) if, and only if, a portion of these nonrecurring costs are allocated to the customer-nation. If DoD incurs the fixed R&D cost, applies it only to domestic orders, and waives the R&D cost for export orders, then DoD is essentially subsidizing foreign weapon sales rather than realizing the full economic benefit. The Arms Export Control Act (AECA) Section 21(e)(2)(A) [22 USC Sec. 2761] stipulates that the DoD must charge the customer-nation its proportional share of the nonrecurring costs in the Foreign Military Sales (FMS) deal. However, nonrecurring costs for particular sales to NATO and other eligible countries may be waived if the sale significantly advances U.S. interests (DISAM, 2010). Note that the nonrecurring cost waiver only applies to FMS cases administrated by DoD. Direct sales by the contractor are not required to charge the customer-nation its proportional share of recurring cost. DoD’s waiving or failing to recoup these costs enables the defense contractor to remain competitive on price.

By waiving nonrecurring costs and not charging customer-nations their proportional share of such costs, direct sales greatly benefit the profit-maximizing defense contractor. The defense contractor can then export the military goods at a price determined by the average variable costs to produce the weapon system and thereby increase its competitiveness in the global arms market. In other words, placing the nonrecurring cost burden on DoD amounts to the *U.S. taxpayers subsidizing foreign arms sales*.

In 1998, the Government Accountability Office (GAO) reported that DoD had not recovered $183 million in nonrecurring costs from delivered sales—some of which dated back to 1989 (GAO, 1998). Though the GAO admonished DoD for poor financial management practices, this example highlights the fact that bureaucratic inconsistencies and a lack of coordination can result in not only the failure of the U.S. public to realize cost savings through arms exports, but also in the public subsidization of foreign arms transfers.

Reducing Unit Costs through Economies of Scale and Learning

A second source of cost savings is in the scale of production. Large production runs can lower costs through economies of scale and learning. “Economies of scale” refers to the relationship between a firm’s cost and output. A firm enjoys economies of scale when it doubles its output for less than twice the cost, where marginal cost is less than average

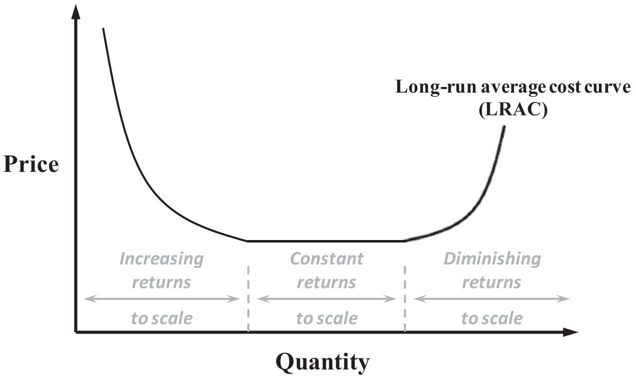

FIGURE 1 Long run average cost curve (from Waterson, 2010).

cost (Pindyck & Rubinfeld, 1998). Theoretically, DoD benefits from economies of scale if it can augment the lower levels of weapon system production for domestic consumption with foreign orders. Assuming that augmenting domestic production with foreign orders occurs while the defense contractor experiences increasing returns to scale, increasing production will result in a lower per-unit cost than without foreign orders. Further, not all cost reductions are the same. As illustrated in Figure 1, movement along the long run average cost curve in the downward, negative-sloped region reveals that marginal cost reductions decrease at a slower rate until reaching constant returns to scale where increases in total cost are proportional to output.

This equates to additive foreign orders theoretically having a greater impact in reducing per-unit cost early when the level of production is low. However, augmenting domestic production with foreign orders will not always provide a lower per-unit cost; if the additive foreign orders occur during diminishing returns to scale, the addition of foreign orders would actually provide a higher per-unit cost.

Similar to economies of scale, learning may reduce per-unit costs. Learning curve theory introduces an estimate of the incremental per-unit cost reduction in the production process as the number of units produced increases from zero. It follows that if learning occurs in the production process, each time the volume of production doubles, the per-unit cost decreases at a predictable rate (FAA, 1999). Put differently, the cost of the doubled unit equals the cost of the un-doubled unit multiplied by the slope of the learning curve (Nussbaum, 2010). Therefore, the equation defining the learning curve is exponential and negatively sloped. Figure 2 illustrates a general learning curve model that is consistent with the early observations of aircraft production by Wright (1936) and is discussed very clearly by Argote and Epple (1990) and Nussbaum (2010) showing unit costs decreasing as the quantity produced increases. The shape of the learning curve makes it evident that more learning and consequently greater per-unit cost reductions occur early in the production process.

Both economies of scale and learning curve theory posit per-unit cost reductions. However, the basis for economies of scale is the scale of production, while learning curve cost reductions rely on cumulative production. Therefore, arms exports theoretically provide the largest cost reductions if they are incorporated at the beginning of production. Conversely, dedicating units of production for export toward the end of U.S. procurement will have a significantly lesser effect on cost reduction. Making the case for arms exports, unit cost savings depends greatly on both the scale of production and learning

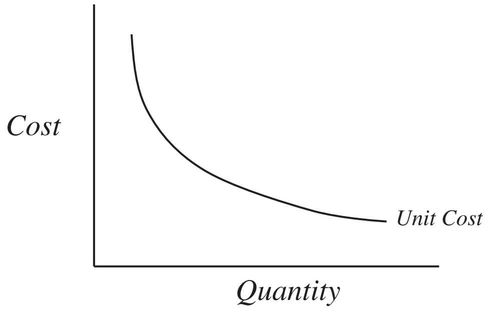

FIGURE 2 General learning curve model.

TABLE 1 Estimated savings through minimum to optimal production for selected weapon systems (from Hartley, 2006)

Weapon System Type	Cost Savings
Warships	<10%
Tanks	<10 %
Combat Aircraft	20%
Conventional Munitions	20–30%
Missiles	25–40%

already achieved. Empirical research has shown that it is difficult to differentiate cost savings between economies of scale and learning (Hartley, 2007). However, Hartley (2006) found that median, per-unit cost savings were 10 to 20% as a result of increasing the scale of production from minimum efficiency to what might be called ideal or efficient conditions. Table 1 shows the cost savings associated with different weapon systems as the scale of production moves toward most efficient conditions (Hartley, 2006).

Further, Sandler and Hartley (1995) suggest that the production and learning curves associated with aircraft production range from 75 to 80%. The production and learning curves associated with other weapon system production, to include aircraft engines, avionics, electronics, missiles, main battle tanks, and warships, range from 70 to 96% (Sandler and Hartley, 1995). While labor learning is important, Hartley (2007) points out that cost reductions associated with learning have been affected by technology and process improvements, such as new materials, computer-aided design, computer-aided manufacturing, lean, six sigma and supply chain management.

Cost Analysis of the F-16 Multi-Role Fighter

It is difficult to accurately isolate the financial benefits enjoyed by the U.S. from foreign arms production. Theoretically, per-unit cost reductions occur through increases in production volume due to economies of scale and gains in efficiency through learning. Foreign arms sales present an opportunity to increase production volume and allocate nonrecurring and fixed costs to non-U.S. customers. The Lockheed Martin (formerly General Dynamics) F-16 fighter aircraft is one of the most prolific arms exports to date, flying under 21 separate flagged air forces and is also the most produced fourth-generation western fighter, with 4,519 copies to date (Janes Information Group, 2010). Although this program began during

TABLE 2 F-16 data table

Delivery Year	U.S. Delivery (Production Rate)	Cum U.S. Delivery	Foreign Delivery	Cum Foreign Delivery	Total Delivery	Cum Total Delivery	LMP	Actual U.S. AUC At Procurement (CY09$M)	LN (LMP) X_1	LN (Total Delivery) X_2	LN (AUC - 2 yrs) Y	Reconstructed LMP (U.S.)
1978	5	5		–	5	5	2.5000	37.43	0.9163	1.6094		
1979	60	65	20	20	80	85	34.0416	25.08	3.5276	4.3820		
1980	125	190	97	117	222	307	179.4935	21.32	5.1901	5.4027	3.6225	
1981	161	351	108	225	269	576	431.5991	21.77	6.0675	5.5947	3.2220	
1982	170	521	111	336	281	857	710.0996	34.54	6.5654	5.6384	3.0596	
1983	152	673	99	435	251	1,108	979.0100	30.20	6.8865	5.5255	3.0806	
1984	123	796	71	506	194	1,302	1,203.5657	27.45	7.0930	5.2679	3.5422	733.7322
1985	125	921	37	543	162	1,464	1,382.3280	28.97	7.2315	5.0876	3.4079	857.8798
1986	152	1,073	66	609	218	1,682	1,571.6274	25.67	7.3599	5.3845	3.3123	996.0693
1987	174	1,247	100	709	274	1,956	1,816.9363	24.86	7.5049	5.6131	3.3661	1,158.8859
1988	178	1,425	83	792	261	2,217	2,084.9736	22.15	7.6425	5.5645	3.2453	1,335.0333
1989	158	1,583	76	868	234	2,451	2,333.0457	25.17	7.7549	5.4553	3.2131	1,503.4753
1990	200	1,783	95	963	295	2,746	2,596.9197	28.65	7.8621	5.6870	3.0978	1,682.0285
1991	141	1,924	80	1,043	221	2,967	2,855.9408	25.42	7.9572	5.3982	3.2255	1,853.3390
1992	57	1,981	65	1,108	122	3,089	3,028.1978	32.34	8.0157	4.8040	3.3553	
1993	116	2,097	51	1,159	167	3,256	3,172.4571	37.34	8.0623	5.1180	3.2355	
1994	61	2,158	137	1,296	198	3,454	3,354.7770	47.41	8.1181	5.2883	3.4762	

the Cold War era, the merits of using the F-16 as a case study for analysis lie in the fact that the F-16 Multinational Fighter Program involved the European Participating Governments (EPG) of Belgium, Denmark, the Netherlands, and Norway in the early development and later in the co-production of the aircraft. This multinational effort resembles the F-35 joint strike fighter program in that several allied nations entered into an agreement to purchase a common aircraft that could be purchased affordably due to the large numbers of orders. The F-16 program began in 1975, with the U.S. receiving its first five aircraft in 1978; within a decade, close to 2,200 aircraft had been delivered, with foreign customers accounting for 35% of the total deliveries.

Beginning in 1981, a host of other nations entered into agreements with the U.S. to purchase the F-16 aircraft for their own air forces. As of 2010, 50.1% of all F-16 deliveries were to foreign customers. Of those foreign deliveries, 22.8% were to the EPG (Janes Information Group, 2010). The F-16 production for this analysis can be partitioned into two model generations, the A/B and the C/D. The A and the C models are single-seat aircraft, while the B and D are double-seat variants primarily used for training. This case study will focus on cost reductions that result through larger production quantities as a result of increasing the market of the weapon system through foreign sales.

Methodology

Although the F-16 is one of the most prevalent fighter aircraft programs in modern history, there is a lack of detailed foreign sales and unit production cost data. DoD's Selected Acquisition Reports (SAR) provide annual data on U.S. procurement cost, U.S. procurement quantity, foreign procurement quantity, and U.S. aircraft delivery. The SARs do not contain data regarding foreign deliveries. Foreign delivery data were obtained through F-16 archivist Björn Claes (2010), who compiled a database of F-16 delivery schedules and quantities from Foreign Military Sales documents, official Lockheed Martin datasets, and contacts from within foreign air forces.

The SARs provide production and delivery data, covering the years 1975 through 1994. By the end of 1994, the F-16 program reached 90% of its expected production delivery and SAR reporting concluded. In fact, after 1991, U.S. deliveries significantly tapered off, thereby making that year a reasonable upper bound for the analysis. To identify cost reductions with cost improvement analysis, production for the U.S. and foreign customer-nations must be concurrent. Cost and quantity data from 1984 coincide with deliveries of C/D models and the preponderance of foreign sales (excluding EPG). For these reasons and others discussed in the following section, the scope of this case study focuses on F-16 deliveries between 1984 and 1991.

Using cost improvement analysis, this case study takes a counterfactual approach to estimate per-unit cost if export production *did not* occur. Two main types of cost improvement analysis exist: ordinary cost improvement curves (CIC) and a rate-adjustment cost improvement curve (RACIC) model that includes a rate term. Ordinary CICs are synonymous with learning curves and postulate that in production involving repetitive tasks, the per-unit variable costs will decrease by a certain factor with each doubling of cumulative production. Moses (1990) notes that production rates can lead to greater specialization of labor, quantity discounts in raw material purchases, and greater utilization of facilities thereby increasing the production quantity against which fixed overhead costs are allocated. Bemis (1981), Boger, Greer, and Liao (1990), Large, Hoffmayer, and Kontrovich (1974), and Linder and Wilbourn (1973) suggest that together these effects can increase efficiency and reduce production cost. However, Moses (1990) argues that increasing the production rate does not always reduce costs. In fact, increased production rates can actually increase per-unit costs due to factors, such as over-time pay, lack of skilled labor, or additional fixed chunk investments, to increase capacity, such as constructing more production facilities. Production rates may therefore lead to either economies or diseconomies of scale.

Moses (1991) found that ordinary CICs engendered bias due to the existence of fixed costs in total cost and tended to understate the actual costs. While the rate-adjustment CIC (RACIC) eliminates bias, there is a tradeoff between bias and accuracy. Moses (1991) notes that in some cases ordinary CICs can be more accurate but the high fixed costs associated with F-16 production warrants the use of the rate-adjustment model. The equations for the CIC and RACIC are expressed by Equations (1) and (2), respectively:

$$\text{Ordinary CIC: } C = aQ^b, \tag{1}$$

where

C = Unit cost of a F-16 at quantity Q;
Q = Cumulative quantity of F-16 production;
a = Theoretical first unit cost; and
b = Cost improvement curve exponent.

$$\text{Rate-adjustment CIC: } C_R = aQ^bR^c, \tag{2}$$

where

C_R = Unit cost of a F-16 at quantity Q and production per period R;
Q = Cumulative quantity of F-16 production;
R = Annual F-16 production rate;
a = Theoretical first unit cost;
b = Cost improvement curve exponent; and
c = Production rate exponent.

Given that the unit cost is a function of cumulative production volume and rate, a large production volume will theoretically decrease the unit cost. We define cumulative production as the sum of production for U.S. and foreign customer-nations. By considering the unit cost as a function of total cumulative production, we may estimate the unit cost had the U.S. decided *not* to produce F-16 fighters for export.

Given the lack of detailed data, assumptions were made regarding the nature of production and delivery. A fundamental tenet of cost improvement analysis is that the units produced are homogeneous. By the end of 1984, 99.2% of the F-16 A/B models were delivered into the U.S. Air Force inventory. Save the remaining six undelivered A/B models, the follow-on F-16 deliveries to the U.S. were all C/D models. The main differences between the A/B and C/D include improved cockpit avionics and radar. These distinguishing qualities imply heterogeneity and the existence of different cost curves. Within each model generation, additional variation exists between block numbers that denote upgrades. However, the data to which we had access do not permit disaggregation, so block variation is held constant in the model. As illustrated in Figure 3, a delivery usually occurred two years after procurement. This two-year lag is also assumed to remain constant through the period analyzed.

Further, deliveries were assumed to follow the same pattern as procurement; that is, a delivery lot of size 150 succeeds a procurement lot of size 150. Figure 4 shows actual cost overlaid on U.S. delivery quantity. The figure shows that peaks and troughs in average

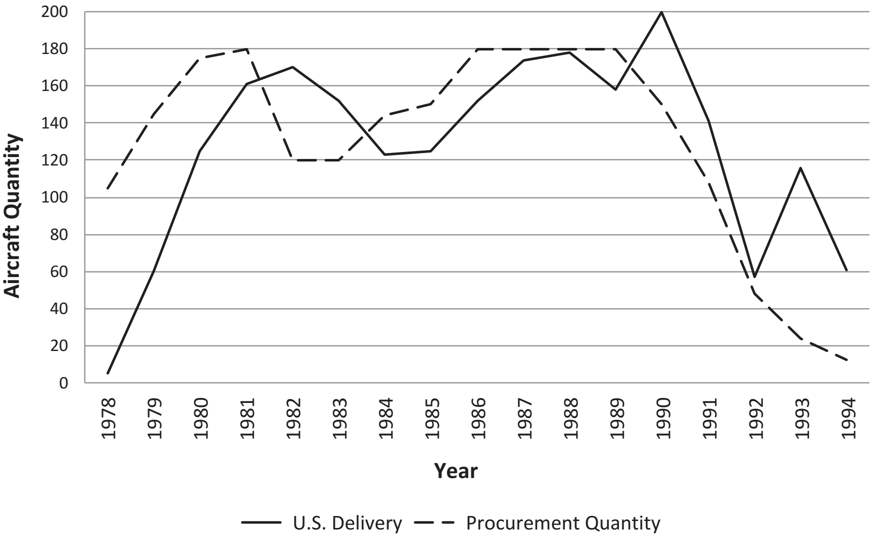

FIGURE 3 F-16 procurement quantity vs. F-16 delivery quantity.

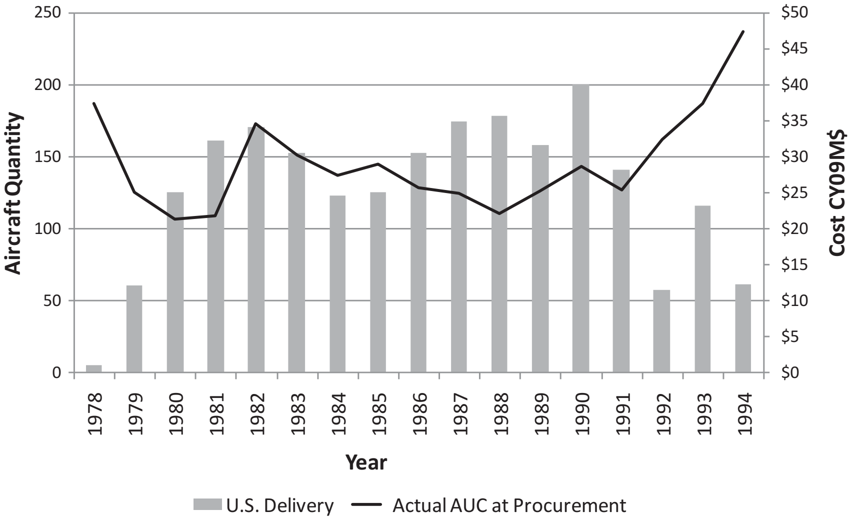

FIGURE 4 U.S. F-16 average unit cost vs. U.S. F-16 delivery quantity.

unit cost occur about two years before increases and decreases in delivery, respectively. Therefore, the analysis will attach cost reductions to the year of delivery. A second tenet of cost improvement analysis is the reduction in unit cost. The SARs publish procurement annual cost and quantity that permits a unit cost for the U.S. to be calculated for each production year, which in effect becomes an annual average unit cost (*AUC*). This analysis draws the annual cost from costs published under the Aircraft Procurement, Air Force appropriation, since these costs directly pertain to the variable costs of production. This analysis assumes a fair playing field in which the price the U.S. government pays on average in any one year is indicative of what all purchasers paid in the same year if they had bought the same equipment with the same profile. Therefore, the model will use the annual U.S. *AUC* as the unit cost for all annual production. After 1991, the U.S. tapered off its deliveries. Consequently, the high fixed costs and reduced production base contributed to the increase in *AUC* after 1991. Due to this cost structure, post-1991 delivery data is omitted from the analysis.

Application of the Ordinary and Rate-Adjustment Cost Improvement Curves

The cost improvement curve analysis utilizes the equations introduced in the aforementioned methodology section. Table 2 contains actual F-16 cost and quantity data and can be used to replicate this analysis. To construct the ordinary CIC, the theoretical first unit cost term, a, and the cost improvement curve exponent, b, must first be solved by employing the linear regression technique to the log transformation of the lot midpoint (*LMP*), LN(*LMP*) or x_1, and the log transformation of the average unit cost from two years prior, LN(*AUC*-2yrs) or y. To compute the lot midpoint for each year, the cumulative U.S. delivery and cumulative foreign delivery data must be aggregated in order to determine the total annual cumulative deliveries.

Since we do not know the actual slope of the learning curve, we calculate the *LMP* associated with each year using a parameter–free approximation method from Nussbaum (1994). We calculate the *LMP* using the total cumulative deliveries such that:

$$LMP = \frac{F + L + 2\sqrt{FL}}{4}, \tag{3}$$

where F is the first unit number in a lot which is the previous year's cumulative production plus one unit and L is the last unit number in a lot. Nussbaum (1994) points out that Equation (3) is not a good estimator for the first lot so a "rule-of-thumb" is used to estimate the lot midpoint, *RLMP*, for lot 1 such that:

$$RLMP = \begin{cases} L/2 \text{ if } L < 10; \\ L/3 \text{ otherwise.} \end{cases} \tag{4}$$

With the independent and dependent variables identified, the regression can then be calculated for the range 1984 through 1991. The regression yields coefficients for the intercept and independent variable (x_1). The intercept coefficient is the logarithm of a. Therefore, to get the theoretical first unit cost term, the antilogarithm of a is applied by raising the constant e (base of the natural logarithm) to the power of a, so the expression becomes e^a or approximately 2.71828^a. The x_1 coefficient simply becomes b. Similarly, the rate-adjustment CIC requires the addition of the log transformed total delivery independent variable, LN(Delivery) x_2, into the regression model. The x_2 coefficient from the regression output becomes the production rate exponent or c. With the CIC terms solved, the ordinary and rate-adjustment CICs can now be constructed. Using the assumptions stated earlier, the cost improvement curves are expressed by Equations (5) and (6):

$$\text{Ordinary CIC: } C = 567.9886Q^{-0.4027}, \tag{5}$$

$$\text{Rate-adjustment CIC: } C_R = 721.5729Q^{-0.3618}R^{-0.1009}. \tag{6}$$

The ordinary cost improvement curve model expresses the relationship between per-unit F-16 cost and cumulative production whereas the rate-adjustment cost improvement curve model expresses the relationship between per-unit F-16 cost, cumulative production, and production rate.

Both cost improvement models enable the estimation of F-16 AUC, had the U.S. decided not to produce the aircraft for export between 1984 and 1991, by using the reconstructed LMP for the U.S. as the quantity term and annual U.S. delivery for the rate term in the rate-adjustment model. Table 3 and Figures 5 and 6 illustrate the estimated average annual per-unit cost savings. The actual AUC at delivery in Table 3 is based on the actual AUC at procurement lagged by two years from Table 2. Comparing the calculated cost savings (or costs avoided) using the estimated average unit costs for ordinary and rate adjustment CICs, the rate-adjustment CIC estimates savings in excess of 12% higher than the ordinary CIC, with savings estimated at an average of 20 and 23%, respectively, from 1984 to 1991.

A second method of estimating cost savings is through the use of annual lot costs using the derived Equations (5) and (6). As discussed earlier, this analysis relies on attaching the procurement average unit cost to delivery lots. First, the lot costs need to be reconstructed using U.S.-only delivery quantities to determine notional costs incurred for the scenario where the U.S. does not incorporate export production. Second, the lot costs need to be reconstructed based on the U.S. delivery lot quantities and where these lots occurred with respect to total cumulative production (U.S. and foreign). In order to make these estimates, a critical assumption is made: within each production lot (year), all U.S. deliveries are produced first and foreign deliveries second. Without this assumption, it becomes increasingly difficult to make these types of estimates. Further, it seems logical that the U.S. would want to take delivery of its fighters before satisfying the needs of foreign buyers. The ramifications of this assumption are obvious in that any estimated savings will be minimized since U.S. deliveries within each lot will be more costly per unit than the foreign deliveries within the same lot because they were all produced earlier. Thus, all estimated savings are very conservative, given our assumption that the U.S. takes its deliveries first.

The cost of a specific lot using the ordinary cost improvement curve (CIC) is determined by taking the integral of the CIC, that is

$$CIC_{F,L} = a\left[\sum_{Q=1}^{L} Q^b - \sum_{Q=1}^{F-1} Q^b\right], \tag{7}$$

which may be approximated by

$$CIC_{F,L} \cong \frac{aL^{b+1}}{b+1} - \frac{a(F-1)^{b+1}}{b+1}. \tag{8}$$

The cost of a specific lot using the rate-adjustment cost improvement curve (RACIC) is

$$RACIC_{F,L} = a\left[\sum_{Q=1}^{L} Q^b R^c - \sum_{Q=1}^{F-1} Q^b R^c\right], \tag{9}$$

which may be approximated by

$$RACIC_{F,L} \cong \frac{aL^{b+1}R^c}{b+1} - \frac{a(F-1)^{b+1}R^c}{b+1}. \tag{10}$$

TABLE 3 Estimated F-16 export production U.S. average unit cost savings

Delivery Year	Actual AUC* At Delivery	Quantity	Ordinary CIC Estimated AUC	Estimated Ordinary CIC Savings**	Estimated Ordinary CIC Per-Unit Savings %**	Rate-Adjustment CIC Estimated AUC	Estimated Rate-Adjustment CIC Savings**	Estimated Rate-Adjustment CIC Avg Per-Unit Savings %**
1984	$34.54	123	$39.85	$653.13	15%	$40.80	$769.98	18%
1985	$30.20	125	$37.42	$902.50	24%	$38.49	$1,036.25	27%
1986	$27.45	152	$35.23	$1,182.56	28%	$35.76	$1,263.12	30%
1987	$28.97	174	$33.15	$727.32	14%	$33.39	$769.08	15%
1988	$25.67	178	$31.31	$1,003.92	22%	$31.65	$1,064.44	23%
1989	$24.86	158	$29.85	$788.42	20%	$30.69	$921.14	23%
1990	$22.15	200	$28.53	$1,276.00	29%	$28.77	$1,324.00	30%
1991	$25.17	141	$27.44	$320.07	9%	$28.78	$509.01	14%
Totals (CY09$M)				$6,854.03			$7,659.80	

*Actual AUC is from two years prior, due to delivery lag.
**Savings based on average unit costs.

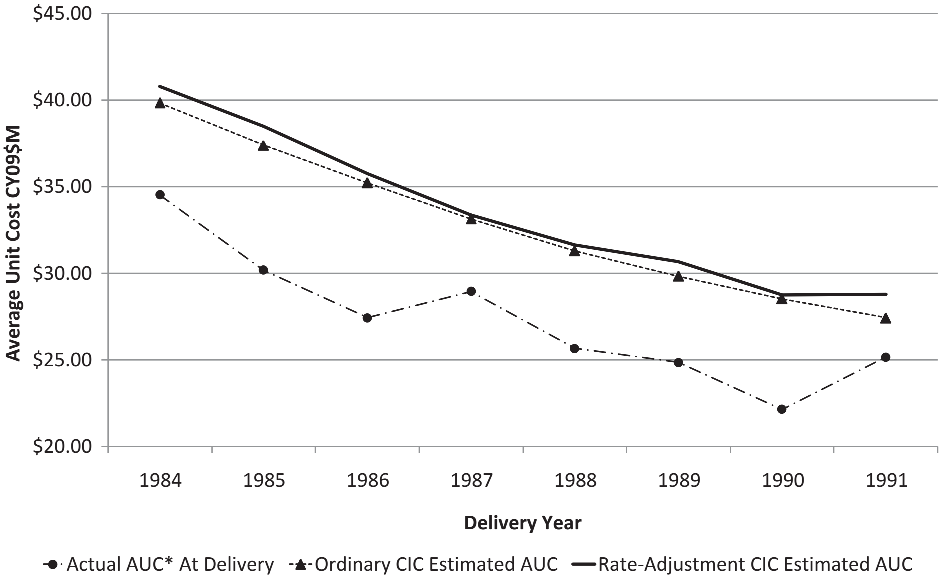

FIGURE 5 F-16 estimated average unit costs.

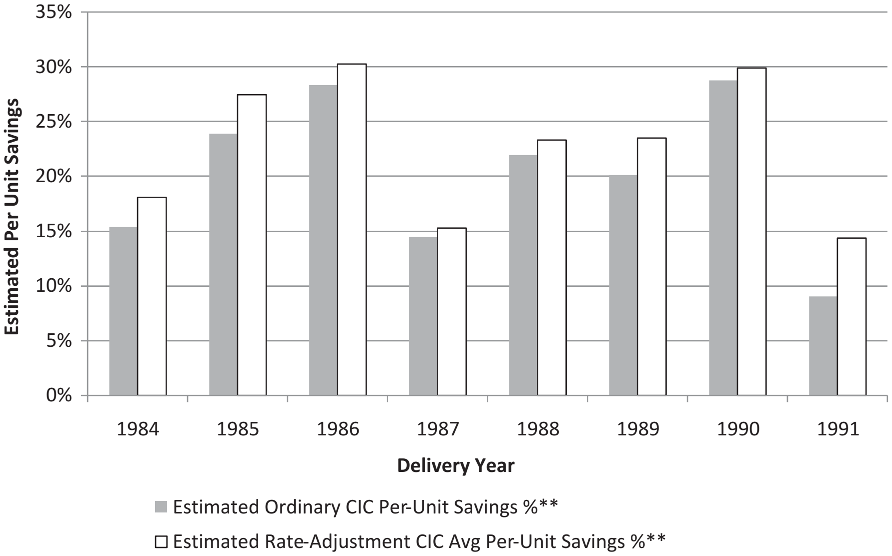

FIGURE 6 F-16 estimated per-unit cost savings.

The values of a, b, and c are expressed in Equations (5) and (6).

Using Equation (8), we may use the ordinary CIC to estimate the lot cost in the year 1984 that is associated *without* export production, so that

$$CIC_{F,L} \cong \frac{567.9886 \cdot 796^{-0.4027+1}}{-0.4027+1} - \frac{567.9886 \cdot 673^{-0.4027+1}}{-0.4027+1} = \$4,902.2698,$$

TABLE 4 Estimated F-16 export production U.S. lot cost savings using ordinary cost improvement curve model

Delivery Year	Reconstructed U.S. Lot Costs Without Export Production*	Estimated U.S. Lot Costs With Export Production	Estimated Lot Savings	Estimated Lot Savings %
1984	$4,902.2698	$4,063.2563	$839.0135	17%
1985	$4,677.8849	$3,880.4459	$797.4390	17%
1986	$5,356.0763	$4,494.3644	$861.7119	16%
1987	$5,768.4893	$4,865.5042	$902.9851	16%
1988	$5,574.1557	$4,694.8413	$879.3144	16%
1989	$4,716.6312	$3,977.2396	$739.3916	16%
1990	$5,706.5033	$4,825.5873	$880.9160	15%
1991	$3,868.9873	$3,268.7841	$600.2032	16%
Totals (CY09$M)	$40,570.9978	$34,070.0231	$6,500.9747	

*Reconstructed lot costs for U.S. aircraft if no export production occurred.
Estimates assume all U.S.-delivered aircraft produced first in each lot (year).

where 796 (or L) is the last U.S. unit delivered in the year 1984, which is the cumulative U.S. delivery of F-16s in the year 1983 plus the production rate of 123 in the year 1984, and 673 is the cumulative U.S. delivery of F-16s in the year 1983 (see Table 2). The estimated lot cost without export production is $4,902.2698M, which corresponds with the first row in Table 4. Using Equation (8) we may use the ordinary CIC to estimate the lot cost in the year 1984 that is associated *with* export production, so that

$$CIC_{F,L} \cong \frac{567.9886 \cdot 1{,}231^{-0.4027+1}}{-0.4027+1} - \frac{567.9886 \cdot 1{,}108^{-0.4027+1}}{-0.4027+1} = \$4{,}063.2563,$$

where 1,231 (or L) is the last U.S. unit delivered in the year 1984, which is the cumulative delivery of F-16s in the year 1983 (both U.S. and foreign deliveries) plus the production rate of 123 in the year 1984, and 1,108 (or F-1) is the cumulative delivery of F-16s in the year 1983 (see Table 2). The estimated lot cost with export production is $4,063.2563M, which corresponds with the first row in Table 4.

Using Equation 10 we may use the rate-adjustment CIC to estimate the lost cost in 1984 that is associated *without* export production, so that

$$RACIC_{F,L} \cong \frac{721.5729 \cdot 796^{-0.3618+1} \cdot 123^{-0.1009}}{-0.3618+1} - \frac{721.5729 \cdot 673^{-0.3618+1} \cdot 123^{-0.1009}}{-0.3618+1} = \$5{,}019.3643,$$

where 796 (or L) is the last U.S. unit delivered in the year 1984, which is the cumulative U.S. delivery of F-16s in the year 1983 plus the production rate of 123 in the year 1984. The production rate, R, for the year 1984 is 123, and 673(or F-1) is the cumulative U.S. delivery of F-16s in the year 1983 (see Table 2). The estimated lot cost without export production is $5,019.3643M, which corresponds with the first row in Table 5. Using Equation (10) we

TABLE 5 Estimated F-16 export production U.S. lot cost savings using the rate-adjustment cost improvement curve model

Delivery Year	Reconstructed U.S. Lot Costs Without Export Production*	Estimated U.S. Lot Costs With Export Production	Estimated Lot Savings	Estimated Lot Savings %
1984	$5,019.3643	$4,240.4323	$778.9320	16%
1985	$4,812.5376	$4,068.6793	$743.8583	15%
1986	$5,435.7007	$4,643.2035	$792.4972	15%
1987	$5,810.8297	$4,986.7368	$824.0929	14%
1988	$5,634.7490	$4,829.3824	$805.3666	14%
1989	$4,849.1211	$4,160.4031	$688.7180	14%
1990	$5,755.2622	$4,950.4340	$804.8282	14%
1991	$4,058.2147	$3,487.8715	$570.3432	14%
Totals (CY09$M)	$41,375.7793	$35,367.1429	$6,008.6364	

*Reconstructed lot costs for U.S. aircraft if no export production occurred.
Estimates assume all U.S.-delivered aircraft produced first in each lot (year).

may use the rate-adjustment CIC to estimate the lot cost in the year 1984 that is associated *with* export production, so that

$$
\begin{aligned}
RACIC_{F,L} \cong\ & \frac{721.5729 \cdot 1{,}231^{-0.3618+1} \cdot 123^{-0.1009}}{-0.3618+1} \\
& - \frac{721.5729 \cdot 1{,}108^{-0.3618+1} \cdot 123^{-0.1009}}{-0.3618+1} = \$4{,}240.4323,
\end{aligned}
$$

where 1,231 (or L) is the last unit produced in the year 1984, which is the cumulative delivery of F-16s in the year 1983 plus the production rate of 123 in the year 1984. The production rate, R, for the year 1984 is 123, and 1,108 (or F-1) is the cumulative delivery of F-16s in the year 1983 (see Table 2). The estimated lot cost with export production is $4,063.2563M, which corresponds with the first row in Table 5.

Table 4 displays the estimated U.S. lot cost savings using the ordinary cost improvement curve model. Table 5 displays the estimated U.S. lot cost savings using the rate-adjustment cost improvement curve model. The results in Tables 4 and 5 suggest that for the years 1984–1991, the cost savings due to export production are (in CY09$) $6.5B (16.0%) and $6.0B (14.5%), based on the ordinary and rate-adjustment CICs, respectively. Figures 7 and 8 display the estimated U.S. lot cost savings using both the ordinary and rate-adjustment cost improvement curve models. Since the ordinary CIC does not control for production rate, the savings are slightly more robust.

Both attempts at estimating cost savings take different approaches. The first cost savings method using *AUC* is potentially less refined because it does not incorporate the effects of learning within that production lot. Further, the *AUC* method aggregates both U.S. and foreign deliveries and makes no assumption as to when U.S. and foreign-bound production occurred within the lot. Finally, this method relies on comparing the calculated *AUC* to the actual *AUC* based on procurement costs and quantity. This method most closely compares estimated costs with actual costs. The second method utilizes lot costs to estimate savings assuming the U.S. decided not to export F-16s to foreign customers. All costs utilizing this

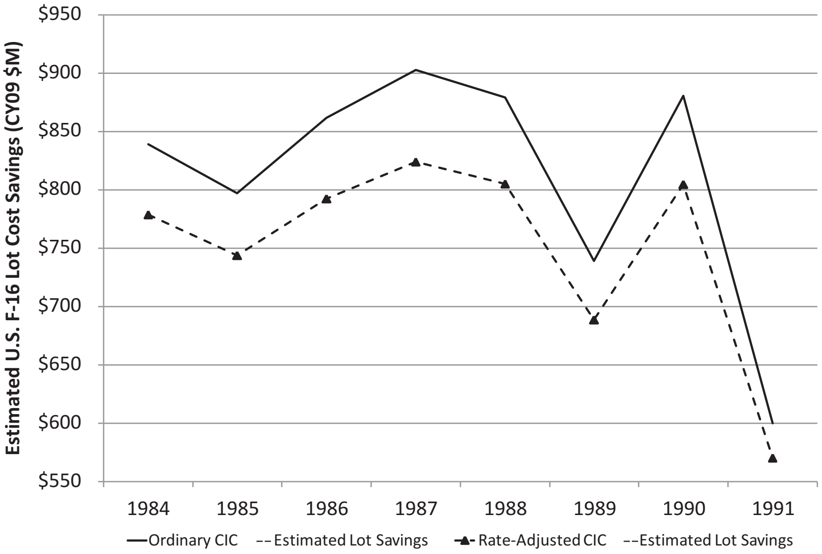

FIGURE 7 Estimated U.S. F-16 lot cost savings.

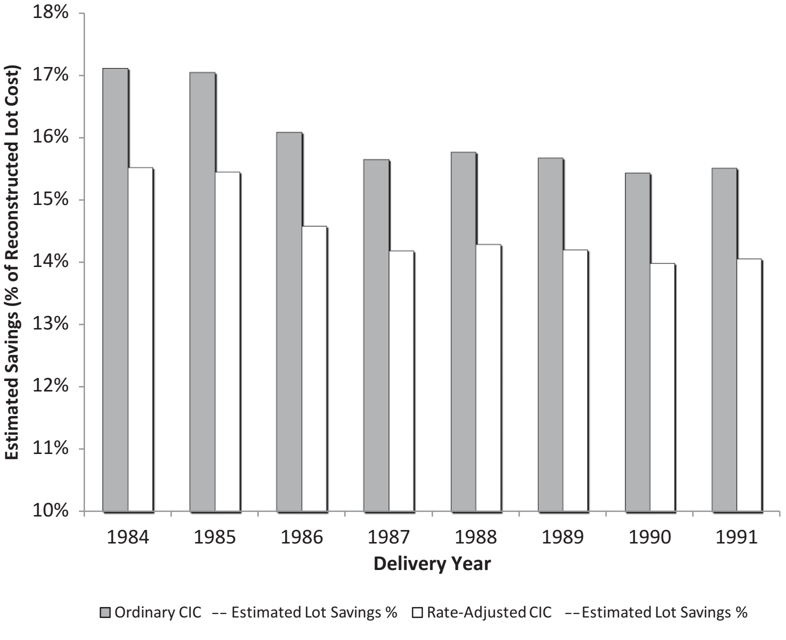

FIGURE 8 Estimated U.S. F-16 lot cost savings.

second method are reconstructed. Further, the assumption regarding the production of U.S. deliveries prior to foreign deliveries within each lot results in conservative estimated cost savings to the United States.

As with any analysis, results are only as valid as the underlying assumptions. We have assumed that the U.S. would have followed the same production rate had there been no sales to foreign countries. Unfortunately, there are no data available to determine whether or not this assumption is sound or whether the U.S. would have produced aircraft at a different rate in the absence of foreign sales. Given the fixed costs and potential excess capacity, the U.S. may have decided to speed up the procurement schedule, and thus conclude production earlier. Regardless of the model used, we estimate that the U.S. saved at least $6 billion by incorporating export production over the year period between 1984 and 1991. Further, according to the selected acquisition reports (SARs), from 1975 to 1991, the research, development, test, and evaluation (RDT&E) costs for the F-16 were approximately $3.5 billion in current year 2009 dollars, which suggests that the estimated savings accrued as a result of export production more than covered the development costs of the aircraft.

Preservation of Production Lines as a Measure to Reduce Life Cycle Costs of Weapons

Generally, the decision to keep a production line open is a balance between cost and schedule (or response time). An open production line serves as an insurance policy of sorts in that it provides the U.S. with quick, cost-effective surge capacity in times of war, and the open production line prevents the cessation of production capabilities and the erosion of employee skill sets that are needed for production in the near term. Reconstituting a stagnant production line can incur high restart costs in addition to significant increases in lead times (Gold, 1999).

Gaps in production lines occur due to misalignment of U.S. weapon system procurement or conversion. There are three options to address gaps in production. First, a production line could go “cold,” whereby it will be reconstituted later. Birkler, Large, Smith, and Timson (1993) suggest that reconstituting a cold production line can sometimes be the most cost-effective solution, since restarted programs take less time from program start to first delivery and are less expensive and risky than the original program. However, when reconstituting a cold production line is deemed more costly, other options exist. An alternative to letting a production grow “cold” is to keep it “warm” through sustained low-rate production. This is often the desired option when the system is a critical national asset with one supplier and no commercial market because if production ceases, the supplier might go out of business (Birkler et al., 1993). While keeping the production line “warm” might be a lower cost alternative, the costs may still be extraordinarily high due to the fact that the existing fixed-cost structures were designed for high-rate production. The third option is maintaining high-rate production and storing any excess or unneeded equipment for later use or contingencies. In this case, it could also mean selling the excess to foreign buyers. Regardless of the option, significant costs are associated with maintaining production capacity in reserve for the future. However, these costs can be reduced if the capacity is allocated for export production because the U.S. will incur neither production costs when there is no actual demand nor the holding costs associated with keeping non-operational systems in the inventory.

Agmon et al. (1996) identified export production as a cost-saving solution to preserving production lines during gaps in U.S. production noting that a period of two to three years elapsed between the end and resumption of production for both the M1 main battle tank and AH-64 attack helicopter programs. During these periods, only export units remained in production. In the case of the M1 production ending in 1993, maintaining the production base and employment levels through export enabled a one-third cost reduction for the U.S. M1 tank conversion program that commenced in 1995 (OUSD A&T, 1994). Similarly, export production of the AH-64 kept the production line “warm” after U.S. production ended in 1993 and recommenced in 1996 with production of the upgraded

AH-64D (OUSD A&T, 1994). Overall, export production provides a convenient lever for maintaining production lines, and more broadly, industrial base "warmth."

The U.S. F-16 program reached its 90% completion in 1994. After 1994, delivery quantity dropped to a squadron (24 aircraft) or less per year. In fact, the F-16 delivery quantities to DoD dropped to single digits from 1997–2002. The last originally programmed U.S. F-16 delivery was for 1999, yet production continued at Lockheed's Fort Worth plant. Between 1995 and 2007, U.S. F-16 deliveries constituted roughly 10% of U.S. production and 7% of all F-16s produced worldwide (Claes, 2010; Aerospace Industries Association, n.d.). Further, the U.S. produced an average of 55 aircraft annually between 1995 and 2007 with F-16 production occurring in overseas plants averaging 21 aircraft per year during this same period (Claes, 2010). From an operations and maintenance standpoint, DoD stands to benefit from a "warm" F-16 production line with the availability and reduced cost of spare parts. Clearly, by continuing lower rate production beyond the U.S. planned requirement, this "warm" production line retained valuable skill sets. Whether those skill sets can be applied to the production of future, fifth-generation fighter aircraft, such as the F-35 Joint Strike Fighter, is a topic that warrants future research.

Even after the U.S. ceased procurement of the F-16, Lockheed Martin continued to develop the F-16 for its foreign customers. The F-16 E/Fs delivered to the United Arab Emirates in mid-2005 are considered "half of a generation" ahead of the U.S. F-16 inventory (Defense Industry Daily, 2010). These F-16s are equipped with the Northrop Grumman AN/APG-80 AESA radar that allows an aircraft to simultaneously perform air-to-air search-and-track, air-to-ground targeting, and aircraft terrain-following, making the UAE the first foreign military (other than the U.S. Air Force) to possess this revolutionary technology. Indeed, the avionics and electronics of the F-16 have dramatically progressed. In fact, the current F-16s produced for export have a core computer suite that has 2,000 times as much memory and over 260 times as much throughput as the original F-16s (Defense Industry Daily, 2010). Undoubtedly, the F-16s currently rolling off the Lockheed Martin's Fort Worth plant are much more capable than the USAF's own F-16 inventory. Should future fifth-generation combat aircraft, such as the F-35, become too costly, the new production F-16s may be a cost effective solution to supplement the U.S.'s air forces. This solution would be financially beneficial to DoD since export production kept the F-16 line and DoD would not incur the substantial costs of restarting a production line. Further, the evolution of the F-16 was supported through export production. If DoD did decide to procure new late-model F-16s, the costs associated with technology upgrades would have been subsidized through foreign sales, reducing DoD's aircraft upgrade cost burden. In sum, the F-16 production line kept "warm" and evolving through foreign demand provides a potentially cost-effective solution for supplementing U.S. combat aircraft inventory.

Conclusions

Brzoska (2004) points out that, despite numerous analyses, books, and research articles on the global arms trade, very little is known about the financial aspects of arms exports. Further, conjecture acknowledging savings through arms exports is commonplace, though the magnitude of savings is rarely, if ever, *quantified*. This research suggests that such conjectured savings do exist and are potentially substantial. From a financial standpoint, decision-makers must be wary in assuming that export production is universally beneficial to DoD. As discussed, if additive export production enables total production to achieve economies of scale, certainly export production is easier to justify in financial terms. Conversely, if the additive export production necessitates substantial overtime labor charges or significant investments for chunk capacity, the export production may actually create diseconomies of scale.

However, as indicated in the conventional arms transfer (CAT) policy, financial factors are one aspect that must be considered in any proposed arms transfer. Therefore, the quantification of financial benefits realized through export must be weighed against any potentially negative security externalities. While this research does not attempt to explicate the tradeoff between financial benefits and negative security implications arising from the transfer of arms, this research does provide an understanding of the financial gains through export production and insight into comprehending the holistic financial gains associated with such proposed arms transfers.

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