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THE EFFECT OF TECHNOLOGY ON THE SUPPORTABILITY AND COST OF AVIONICS EQUIPMENT

Daniel B. Levine
Stanley A. Horowitz
Joseph W. Stahl

August 1988

INSTITUTE FOR DEFENSE ANALYSES
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PREFACE

This paper examines the question whether the advance from solid state to micro-miniaturized devices has made avionics equipment more costly and less supportable. It reports the results of an analysis that relates electronic technology and its maturation to the reliability, maintainability, and cost of some thirty items of avionics equipment.

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CONTENTS

I. INTRODUCTION AND CONCLUSIONS

A. INTRODUCTION

In keeping pace with recent advances in electronics, the military services have shifted from solid state devices (transistors) to micro-miniaturized devices (chips) in the design of avionics. By employing micro-miniaturized electronics, those who design military aircraft have sought to take advantage of the intrinsically higher reliability of chips. At the same time, designers have taken advantage of micro-miniaturized components to build more performance into avionics systems. However, in the views of some, the means used to increase performance have had negative effects on supportability, which counters the positive intrinsic effect.

The relationship between micro-miniaturization and supportability has an important bearing on military planning. To the extent that modern avionics systems are unreliable and difficult to maintain, the military services will suffer from lower aircraft sortie rates, lower combat performance for a given force of aircraft, and lower performance from a given total budget spent on tactical aircraft. If pushing hard on the forefront of technology does, in fact, exact a high premium in reduced reliability and maintainability, policy planners may wish to consider this tradeoff in deciding how much performance to design into future aircraft.

The principal question for this study is whether the net effect of micro-miniaturization on reliability has been positive or negative. Has the intrinsically high reliability been outweighed by lower reliability and higher cost from the push to higher performance? Has maturation of the new technology increased reliability and decreased cost enough to counteract these effects, if they exist?

To determine the net effect, we will relate reliability to technology and maturity without holding constant the intervening variable of cost. The net effect will be the combined result of the "intrinsic" and "performance" effects.

We will then relate technology to cost, and cost to supportability. We will also estimate the extent to which the relationship between cost and reliability depends on technology and maturation.

B. CONCLUSIONS

We find no evidence that the transition from solid state to micro-miniaturized devices lowered the supportability of avionics equipment. The picture was mixed when the new technology was first introduced: reliability rose but maintainability fell even more, which yielded an unfavorable net effect on repair time per operating hour. But as the new technology matured, reliability improved, and maintainability, though still lower than before the transition, improved as well, which gave a favorable effect on repair time per operating hour.

When cost is included in the analysis, the evidence points to the conclusion that, at least in the case studied, as technology matures, the Services may be able to achieve both greater reliability and higher performance in avionics equipment without paying a higher price for them.

II. DATA

The data on 33 items of avionics equipment are listed in Table 1, and the variables in the table are defined in the remainder of this section. For some of the electronic items, we obtained the reliability and maintenance data from the Air Force Logistic Command's D056 Log Reports for August 1979 through January 1980 and the cost data from a proprietary data base. For the remaining items, we obtained the reliability and maintenance data from the Navy VAMOSC-Air Reports for October 1985 through September 1986 and the cost data from a data base prepared by Information Spectrum, Inc. The variables are defined as follows:

Number (No.). Some of the data are proprietary, so we have omitted the detailed designations (AN/ numbers) of the items and simply numbered them for convenience.

Reliability (REL). Reliability was calculated by dividing total operating hours by the total number of failures. "Total" means summed over all the aircraft in which the item was installed, and for the entire period of data collection.

Maintainability (REP). Maintainability was calculated by dividing repair time by the number of failures. Repair time is measured in man-hours, and includes the time spent on unscheduled maintenance at the organizational level plus the time spent on all maintenance at the intermediate level, both scheduled and unscheduled. Although repair time for scheduled maintenance at the organizational level is not included, it only amounts to less than 1 percent of the total, according to detailed data we were able to obtain for 8 of the 33 items of equipment.

Procurement Cost (COST). Cost is the estimated cost of the 100th unit procured, measured in thousands of FY 1978 dollars.

Technology (TECH). TECH is a dummy variable used to discriminate between the items built with solid state technology and those built with micro-miniaturization: TECH = 0 for solid state technology; TECH = 1 for micro-miniaturization.

Experience (EXP). EXP is a dummy variable used to capture the effect of maturation on supportability: EXP = 0 for those items whose data were obtained from the

1979-80 reports and which were built with solid-state technology and earlier micro-miniaturization; EXP = 1 for the remaining items, whose data were obtained from the 1985-86 reports and which were built with later micro-miniaturization technology. We will be able to use this variab'e to make a judgment about the reliability of the F-18, since all the 1985-86 data are for this aircraft, and this aircraft alone.

Type of Equipment (TYPE). The last seven columns are dummy variables used to describe the type of equipment as defined by the second letter (the Equipment Designator) in the item's AN/ designation: T1 = electro-mechanical, T2 = countermeasure, T3 = radar, T4 = radio, T5 = special types, T6 = visible light, and T7 = data processing. For example, an AN/APG-65 is a radar ("P" stands for radar in the AN/ code) and is represented by setting T3 equal to 1 and all the other T's equal to zero. A few items lacking an AN/ designation were represented by setting all seven T's to zero.

Table 1. Data on Avionics Equipment

No.	REL	REP	COST	TECH	EXP	T1	T2	T3	T4	T5	T6	T7
1	805.4	9.9	1.8	0	0	0	0	0	1	0	0	0
2	69.6	13.0	7.4	0	0	0	0	1	0	0	0	0
3	32.3	12.5	14.4	0	0	0	0	0	1	0	0	0
4	49.6	20.6	18.1	0	0	0	0	1	0	0	0	0
5	52.2	19.3	21.5	0	0	0	0	1	0	0	0	0
6	55.5	8.9	23.8	0	0	0	0	0	0	1	0	0
7	70.9	16.7	47.9	0	0	0	0	0	0	1	0	0
8	59.3	34.8	97.6	0	0	0	0	0	1	0	0	0
9	29.6	13.6	140.8	0	0	0	0	0	0	1	0	0
10	57.3	30.9	152.0	0	0	0	0	1	0	0	0	0
11	35.0	25.8	156.4	0	0	0	0	1	0	0	0	0
12	6.5	14.3	338.6	0	0	0	0	1	0	0	0	0
13	13.8	27.3	350.7	0	0	0	0	1	0	0	0	0
14	13.8	34.2	498.2	0	0	1	0	0	0	0	0	0
15	202.7	44.4	30.0	1	0	0	0	0	0	0	0	0
16	341.9	29.6	40.9	1	0	0	0	0	0	0	0	0
17	244.4	24.9	42.2	1	0	0	0	0	0	1	0	0
18	697.5	66.0	53.0	1	0	0	1	0	0	0	0	0
19	379.1	32.2	53.7	1	0	0	0	0	0	0	0	0
20	80.1	40.1	87.3	1	0	0	0	0	0	0	1	0
21	81.6	41.0	164.6	1	0	0	0	0	0	1	0	0
22	63.4	28.2	219.8	1	0	0	0	1	0	0	0	0
23	86.3	36.0	235.0	1	0	0	1	0	0	0	0	0
24	156.6	46.7	490.0	1	0	0	1	0	0	0	0	0
25	20.8	48.9	1015.9	1	0	0	0	1	0	0	0	0
26	20.7	23.2	534.9	1	1	0	0	1	0	0	0	0
27	75.7	16.0	97.8	1	1	0	0	0	0	0	0	1
28	59.6	23.4	128.7	1	1	0	0	0	0	1	0	0
29	132.3	15.7	77.8	1	1	0	0	0	0	0	1	0
30	758.8	22.3	10.6	1	1	0	0	1	0	0	0	0
31	2608.4	36.3	6.6	1	1	0	0	1	0	0	0	0
32	2455.0	33.4	14.2	1	1	0	1	0	0	0	0	0
33	878.6	74.6	205.9	1	1	0	1	0	0	0	0	0

III. SUPPORTABILITY

In this section we estimate the net effects of technology and experience (maturation) on supportability. First we estimate the effects of micro-miniaturization and maturation on reliability. Then we estimate their effects on maintainability. Finally, we examine their combined effect on a measure of supportability in which our measures of reliability and maintainability are combined.

A. RELIABILITY

The dependence of reliability on technology is shown in Table 2. The dependent variable is the (natural) logarithm of reliability. We found that using the log form of reliability and maintainability (and cost in later regressions) yielded closer fits with the data.

Table 2. Net Effect of Micro-Miniaturization on Reliability

(Dependent variable: log REL)

Independent Variable	Coefficient	t-statistic	Significance (%)
Constant	5.14	5.40	<1
TECH	0.56	0.86	40
EXP	1.34	2.14	4
T1	-2.51	-1.64	11
T2	-0.10	-0.11	91
T3	-1.63	-1.79	9
T4	-0.39	-0.33	75
T5	-1.36	-1.46	16
T6	-1.73	-1.52	14
T7	-2.71	-1.79	9
$R^2 = .53$			

The fact that the coefficient of TECH is positive bears on the central question of the study. It indicates that, holding the other variables constant, the shift from solid state to micro-miniaturized devices probably led to an improvement in reliability, not the reverse. The size of the coefficient indicates that the improvement was an increase of 75 percent. (Reliability improved by a multiplicative factor of $e^{.56} = 1.75$, a rise of 75 percent.)

The coefficient of TECH has fairly low statistical significance, however. The t-statistic of .86 corresponds to a 40-percent level of significance, meaning that the true coefficient of technology could have been zero and there would still have been a 40-percent chance of obtaining data yielding a coefficient as large, in absolute value, as the one actually estimated. This percentage fails to meet the criterion of 10 percent often used in empirical studies.

Significance levels notwithstanding, the coefficient of TECH must be regarded as the best estimate that can be made with the data and specification of the regression equation. Taking everything together, we can certainly say that the analysis offers no support whatever for a judgment that replacing transistors with chips lowered reliability.

The positive (and statistically significant) coefficient of EXP suggests that reliability improved even further, by a factor of 3.8 as the micro-miniaturization technology matured. Taken together, the coefficients of TECH and EXP thus imply that, in the long run, shifting from solid state to mature micro-miniaturization led to a huge rise in reliability, by a factor of almost 6.7.

B. MAINTAINABILITY

Although items with micro-miniaturization technology seem to fail less often, Table 3 implies that they take longer to fix: the coefficient of TECH is positive (higher technology leads to longer repair time) and the estimate is highly significant. The numerical value of 0.70 implies that, holding the other variables constant, the shift from solid state to micro-miniaturized technology has led to an approximately 100 percent increase in repair time per failure.

As before, added experience seems to have had a beneficial (though not highly statistically significant) effect, tending, in this case, to lower repair time per failure. It did not, however, completely counteract the negative effect of technology: taking the two changes together, the time spent on repair rose by 46 percent.

Table 3. Net Effect of Micro-Miniaturization on Maintainability
(Dependent variable: log REP)

Independent Variable	Coefficient	t-statistic	Significance (%)
Constant	2.85	9.58	<1
TECH	0.70	3.39	<1
EXP	-0.32	-1.60	12
T1	0.68	1.41	17
T2	0.46	1.63	12
T3	0.12	0.43	67
T4	-0.07	-0.18	86
T5	-0.20	-0.69	50
T6	-0.17	-0.47	64
T7	-0.46	-0.97	34
$R^2 = .63$			

Note also that some of the "T" variables in Tables 2 and 3 have sizable coefficients and t-statistics, which shows that it was important to control for the type of equipment.[1] The coefficients of T1, for example, confirm the suspicion that electro-mechanical items have poorer reliability and higher repair time.

C. TOTAL REPAIR TIME

Our results, so far, indicate that, regarding the ability of the military services to support its avionics equipment, the transition from solid-state to micro-miniaturization technology was a mixed blessing: Micro-miniaturized equipment fails less frequently but takes longer to fix when it does fail. Experience (maturation), however, improves both reliability and maintainability.

We need to tie these threads together and consider the joint effect of micro-miniaturization technology and maturity on reliability and maintainability. First of all, we

[1] We re-ran the regressions without the type dummies that had poor t-statistics. Most of the changes were negligible and in no case did the coefficient of the important variables–technology, experience, and cost–change sign or general magnitude.

can combine reliability and maintainability into repair time per operating hour: repair time per operating hour equals failures per operating hour multiplied by repair time per failure, which equals (1/REL) x REP. Next, we can calculate the effect of technology on this composite measure by combining the changes in 1/REL and REP obtained from the regression coefficients in Tables 2 and 3 (we are referring to *multiplicative* changes in this section): change in repair time per operating hour equals change in failures per operating hour multiplied by change in repair time per failure, which equals $(1/e^{.56}) \times e^{.70} = .57 \times 2.01 = 1.15$. Thus, the transition to micro-miniaturization seems to have had an adverse, but rather small, effect on repair time per hour, increasing it by 15 percent. The failure rate was cut almost in half (the .57 factor), but the doubling of repair time per failure was more than enough to counteract it. However, factoring in the effects of experience from Tables 2 and 3 changes the picture: change in repair time per operating hour = $(1/(e^{.56} \times e^{1.34})) \times (e^{.70} \times e^{-.32}) = .15 \times 1.46 = .22$.

Thus, once the micro-miniaturization technology had matured, it required 78 percent less repair time per operating hour than did solid state items. Repair time was still higher than before the transition to micro-miniaturization (although now only 46 percent as opposed to 100 percent before maturation had taken place), but the failure rate was now lower by a huge factor of seven (1/.15).

IV. COST

Up to now, we have focussed attention on the net effect of technology on supportability, neglecting the individual contributing factors mentioned earlier (the intrinsic reliability of chips and the move toward building more performance into electronic systems).

In the remainder of this report, we present three additional analyses that are designed to cast light on these contributing factors. We estimate the effect of micro-miniaturization and maturation on cost, the effect of cost on supportability, and the extent to which the cost-reliability relationship depends on technology and maturation.

A. MICRO-MINIATURIZATION

Has micro-miniaturization been accompanied by higher cost, as many believe? The figures in Table 4 suggest "yes, but only initially": The coefficient of TECH is positive, but it is outweighed by the negative coefficient of EXP. The coefficient of TECH (implying that cost initially rose by a sizable factor of 2.8) is consistent with the hypothesis that the military services took advantage of the size and weight savings of micro-miniaturization to incorporate greater performance into their electronic equipment, which drove up the cost. (There might also have been an intrinsic effect in either direction, due to a difference in cost of constructing a given component with micro-miniaturized or solid state technology.)

The fact that the coefficient of EXP is higher and opposite in sign to the coefficient of TECH suggests that as the new technology matured, it became possible to achieve the higher performance without paying a higher price. Engineering changes, improved production techniques, and market forces may have been factors leading to a reduction in cost.

Table 4. Effect of Micro-Miniaturization on Cost
(Dependent variable: log COST)

Independent Variable	Coefficient	t-statistic	Significance (%)
Constant	2.66	2.29	3
TECH	1.03	1.30	21
EXP	-1.23	-1.60	12
T1	3.55	1.90	7
T2	1.51	1.36	19
T3	1.59	1.44	16
T4	-0.05	-0.04	97
T5	1.30	1.15	26
T6	1.33	0.96	35
T7	2.11	1.14	27
$R^2 = .29$			

B. SUPPORTABILITY

For a given technology, does higher cost lead to lower supportability? The negative sign and highly significant coefficient of log COST in Table 5 confirm the suspicion that costly, high-performance equipment is indeed less reliable. Technology is included in the regression and thus held constant, and so the coefficient of cost measures the extent to which reliability depends on changes in cost that were not brought about by changes in technology. We therefore assume that the cost variable in Table 5 is primarily performance related. Because reliability and cost are both in the log form, the coefficient of log COST implies that a 10-percent increase in cost leads to a 6.8-percent reduction in reliability, for items with a given technology.[2]

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2 Although we assume that two independent variables–cost and technology–are systematically related, we have reported the results of ordinary least squares regression in Table 5 because we obtained nearly identical results when we estimated the log COST and log REL equations simultaneously with two stage least squares regression.

Table 5. Effect of Cost on Reliability
(Dependent variable: log REL)

Independent Variable	Coefficient	t-statistic	Significance (%)
Constant	6.95	11.57	<1
Log COST	-0.68	-6.99	<1
TECH	1.26	3.27	<1
EXP	0.51	1.35	19
T1	-0.10	-0.10	92
T2	0.93	1.72	10
T3	-0.55	-1.01	32
T4	-0.42	-0.63	53
T5	-0.48	-0.87	39
T6	-0.83	-1.26	22
T7	-1.28	-1.43	17
$R^2 = .85$			

Higher cost is associated with worse maintainability as well (Table 6). The coefficient of log COST implies that a 10-percent increase in cost led to approximately a 1-percent increase in repair time per failure.

C. RELIABILITY VERSUS COST AND THE CASE OF THE F-18

It is interesting to view the figures in Table 5 from a different perspective: how the relationship between cost and reliability has been affected by technology and experience. This is shown in Figure 1, which depicts the original data points and the relationships between reliability and cost implied by the regression equations in Table 5. In Figure 1, "Solid State" corresponds to setting both TECH and EXP to zero in Table 5; "Micro-Min. (Earlier)," to setting TECH to 1 and EXP to zero; and "Micro-Min. (Later)," to setting both TECH and EXP to 1. In generating the regression curves in the figure, the dummy variables for type of equipment were set at their mean values, which is why the curves are not the best fits to the reliability and cost data points.

Table 6. Effect of Cost on Maintainability

(Dependent variable: log REP)

Independent Variable	Coefficient	t-statistic	Significance (%)
Constant	2.61	8.27	<1
Log COST	0.09	1.81	8
TECH	0.60	2.96	1
EXP	-0.20	-1.02	32
T1	0.35	0.71	49
T2	0.32	1.14	27
T3	-0.02	-0.08	93
T4	-0.06	-0.17	87
T5	-0.32	-1.13	27
T6	-0.29	-0.84	41
T7	-0.66	-1.41	17
$R^2 = .68$			

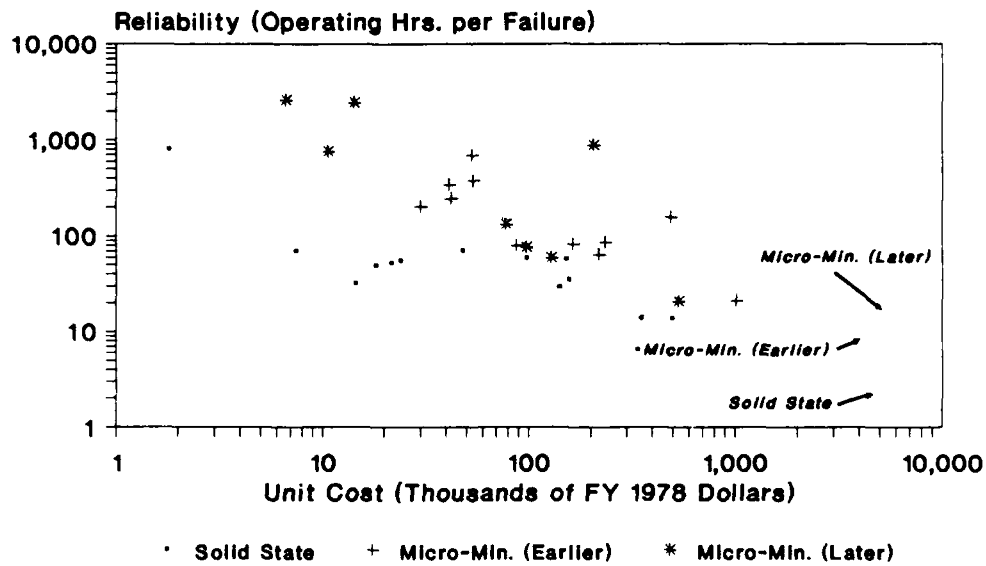

Figure 1. The Effect of Micro-Miniaturization on the Reliability-Cost Curve

The positive and sizable coefficient of TECH in Table 5 implies that the initial move from solid state to micro-miniaturized technology shifted the reliability-cost curve upward by a substantial amount. In other words, the services were able to achieve higher reliability for a given cost.

The coefficient of EXP, while positive, is much smaller than that of TECH. The reliability-cost curve thus continued to rise as the new technology matured, but by a smaller extent than that resulting from the initial move to micro-miniaturization. The maturation effect is substantial, especially given the fact that the plot is logarithmic. However, the t-statistic of the coefficient of EXP indicates that we cannot be as confident of the maturation effect as of the initial shift.

The information in Figure 1 bears on two issues regarding the F-18's reliability. (The F-18 items were all constructed with mature, "later" micro-miniaturization technology represented by the top curve.) The first question is, to what extent does the F-18's electronics use an improved technology relative to previous aircraft? The results we have just discussed indicate that the use of mature micro-miniaturization did seem to offer the aircraft's designers a somewhat better reliability-cost tradeoff to work with. The evidence is mixed because the coefficient of EXP is substantial but the statistical significance is not high.

The second question concerns the area of the reliability-cost curve that the F-18's designers chose to work at. During the development of the F-18, the Navy made a deliberate effort, costing approximately $100 million, to achieve a high level of reliability for the aircraft's avionics through improved design and restraint in pushing for higher performance.

Were the Navy's efforts successful? The fact that the data points for the F-18 (indicated by stars) generally lie higher than the points for the earlier micro-miniaturized items (indicated by plus signs) suggests "yes": The items installed in the F-18 are somewhat more reliable than those used in the other aircraft.[3] Moreover, the fact that the F-18 items lie generally to the left–lower in cost–supports the notion that the Navy achieved the simplicity and restraint it sought in the design effort.

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[3] It's difficult to pick out the two collections of points in Figure 1 and compare the values of reliability by eye, especially because it is a log-log plot. However, we tested the hypothesis that the two distributions have the same mean and obtained a fairly high t-statistic of 2.01 (17 degrees of freedom). This means that we can reject the hypothesis that the two means are the same with 6-percent statistical significance.

In summary, the higher reliability of the F-18 items is due to two causes: the more mature micro-miniaturization afforded the Navy a better reliability-cost (i.e., reliability-performance) tradeoff, and the Navy chose to seek the upper-left side of the tradeoff by investing in greater simplicity and using some restraint in seeking higher performance.