Accepted for publication in *Defence and Peace Economics*

Manufacturing Scale, Lot Sizes and Product Complexity in Defense and Commercial Manufacturing

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ABSTRACT

Almost no systematic empirical analyses exist directly comparing defense and commercial manufacturing processes. A unique survey of nearly 1000 US manufacturing establishments allow comparing similar manufacturing processes in the machining intensive durable goods industries, which account for more than half of all defense purchases of durable goods. Organizations with and without defense contracts do not differ statistically in several measures of scale. Neither are production volumes or lot sizes different on average in machining operations, though defense production does tend more to concentrate where flexible manufacturing technologies are well suited. However, defense related machining products in this sector are more complex to manufacture.

JEL Classifications: H57 (Procurement);
L11 (Production, Pricing, Market Structure; Size Distribution of Firms);
L61 (Industry Studies, Manufacturing: Metals & Metal Products).

Keywords: Defense Industry, Manufacturing, Scale, Product Specifications, Survey Data, United States.

INTRODUCTION

This brief note presents unique data comparing manufacturing processes on products made for defense purposes to those for commercial uses. Despite large-scale policy attention in the US to improving defense manufacturing efficiency and to acquisition reform, remarkably little independent, empirical data is available about the actual manufacturing practices employed. Even less is actually known beyond case studies about how those practices compare with commercial practices in similar industries. Theories and assumptions abound and sometimes significantly drive policies (e.g. "full and open competition"). Yet, there is generally a lack of solid data on the nature of defense manufacturing and performance efficiencies, and almost no systematic empirical comparative analyses directly comparing process details across the defense and non-defense sectors. A richer empirical understanding would have important implications both for policy and for defense economic theory.

In explaining the long history of unit cost inflation in defense systems, for example, significant theoretic divides exist in modeling efficiency incentives in defense procurement. More managerial economic and structural approaches such as Peck and Scherer's classic (1962) focus on the differences in organization, cost, contracting, risk and competitive conditions between weapons markets and competitive markets. By contrast, political economic views such as Rogerson (1991) point to strategic positioning between Congress and the military and/or the defense industries. Similarly, Kirkpatrick (1995) and Alic (1998) focus explanations on arms-race induced demand for increasing performance and system complexity rather than emphasizing different structural conditions.

Moreover, the empirical details about manufacturing processes matter theoretically. For just one high profile illustration, perhaps the most influential formal models of arms races, Richardson (1960), leads to very different arms race behavior under different assumptions about returns to scale in Brito and Intriligator (1999).

On the policy side, despite divergent theories, nearly all the emphasis during many decades of US acquisition reform has been on issues surrounding industry structure and managerial incentives:

concern over the lack of competition in defense industries leading to inefficient processes, overly bureaucratic contracting procedures, deeply entrenched assumptions about how different the defense industry practices and scale are from commercial ones, and periodically flaring Congressional emphasis on waste fraud and abuse. So too, the current wave of acquisition reform under DOD procurement guru and defense industry author Jacques Gansler emphasizes adoption of commercial contracting practices and increased integration of defense and commercial manufacturing at the process level (for example, see Gansler, 1989 and 2000, or General Services Administration, 1998). Nonetheless, despite decades of effort and attention, unit costs continue to escalate. The evidence is no farther than the most recent huge procurement program, the F-22.

There is little sign in the data below that the problem has been at the level of the organization or manufacturing processes, if commercial practices are the benchmark. On the other hand, there is evidence from machining operations that defense manufacturing on average is more complex and more flexible, though not less efficient. This suggests that the overwhelming policy emphasis has been misplaced, and implies that the payoff might be higher from significantly increased policy attention to reducing political economic pressures for system complexity.

METHODOLOGY

Empirical comparison of defense manufacturing to commercial manufacturing is problematic in part because of the vast diversity in products, technologies, manufacturing processes, organizational practices and market structures. Though the data used here were originally collected for other purposes, they provide a unique opportunity for apples to apples evaluation because they focus on a single very broadly used manufacturing process, metal machining. Metal-cutting machine tools are central to nearly all manufactured products, for making components or molds or the manufacturing equipment itself, and are therefore used in a wide variety of manufacturing facilities and industries.

The sample, described in detail in Kelley (1995), was selected from the sector Kelley and Watkins (1995) define as machining-intensive durable goods (MDG). The manufacture of high-tech military equipment, including aircraft, ordnance, navigational equipment, satellites and missiles is concentrated in this sector. It includes 21 industries (at the 3-digit level of the US Standard Industrial Classification system) that each account for at least one percent of machining employment and in which machining occupations account for at least ten percent of production employment.[1] Overall, the MDG sector accounted for more than half (51.3%) of all durable goods purchased for defense in 1990 and about ¼ of all US manufacturing output.[2]

The survey encompassed a size-stratified, random sample of manufacturing establishments from the Dun and Bradstreet manufacturing plant universe, with oversampling from large plant sizes. From 1177 selected establishments still in business, 973 of the production managers contacted between January and April 1991 completed the survey, a response rate of 83 percent.

Of these, 523 reported either direct (prime) shipments to federal defense agencies or subcontracts to defense prime contractors. For the analysis below these plants are classified as defense contractors and the remaining 450 as solely commercial plants. The sample n for each organizational variable below varies slightly due to response rates. On a weighted basis, this represents an estimate that 50.3 ($\pm$3.1) percent of the plants in the MDG sector are defense prime or subcontractors. As a check on the validity of the sampling, this corresponds well with the 49.7 percent estimate in these same industries from data from the 1988 Census of Manufacturers.[3]

In addition to overall organizational variables, each plant also reported details of specific products manufactured on metal-cutting machine tools in the plant. Each plant could report up to two products, resulting in records on 1637 products, 391 of which were identified as produced for federal defense agencies or for defense prime contractors and are classified below as defense products. Other products are classified as commercial. Again, sample n varies slightly by product variable due to response rates.

MANUFACTURING SCALE

Limited scale compared to commercial manufacturing is one of the most ubiquitous assumptions in discussions of defense manufacturing. Yet the implicit comparison to mass manufactured consumer products ignores a vast lower-volume array of strictly commercial products, from jumbo jet aircraft to elevator fail-safe brakes to parcel sorting systems to fast food restaurant french-frying equipment. It also overlooks the large and deeply tiered subcontracting systems relied on by the producers of both defense and commercial final products. Through random sampling by establishment, the data here represent a cross-section of where manufacturing is done in the MDG sector.

Table 1 compares various metrics indicative of the scale of defense and commercial manufacturing plants at the organizational level. Remarkably, considering the consistency of assumptions to the contrary, there is no statistical difference on average between plants with and without defense contracts in the overall scale of their manufacturing plants (measured by total employment or annual sales or production employment). Since plants could be part of larger multi-plant companies, corporate-level variables are also reported. Again, there is no statistical evidence that defense contractors are different on average in terms of the scale of employment, annual revenues, likelihood of multi-plant operations or number of plants in the company.

More narrowly, looking only at the scale of machining operations in these plants, measured by machining employment, number of machine tools in the plant, value of machining output or spending on metal materials inputs, there is again no statistical evidence that defense contractors differ on average. Nor--as metrics related to manufacturing practices used--do they differ either in the capital intensity of machining operations as measured by the number of machine tools employed per machining employee or in the relative importance of machining occupations in their overall employment. In the MDG sector at least, defense contracting is not done in facilities or companies notably different on average in scale or machining capital intensity than solely commercial ones.

Interestingly, the only statistically significant difference in Table 1 is that defense contractors on average have fewer production employees as a fraction of total plant employment (69.7% vs. 73.3%). This amounts to more than 13 percent more non-production employees on average. Though only loosely indicative, this difference is at least consistent with concern with overemphasis on bureaucracy in defense contracting.

While Table 1 reports averages, more detailed looks are also possible at the frequency distributions. Though the overall conclusion of few organizational scale differences does not change, more subtle differences are evident. Figures 1 and 2 show the sample weighted frequency log distributions of plant employment and plant sales for plants with and without defense contracts. Chi-squared goodness of fit tests find no significant distributional differences at the 0.05 level for either figure (p=.060 & p=.369). Though the distributions differ hardly at all for medium and larger scale plants, where most of the policy and theoretic concern centers, defense contractors in this sample are less likely to be from the very smallest establishments, the mom-and-pop shops. A likely explanation is that the very smallest organizations either cannot or will not enter the defense-contracting system.

Figure 1.
Number of Employees in US Manufacturing Plants With and Without Defense Contracts

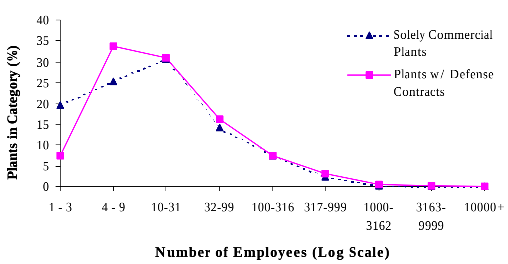
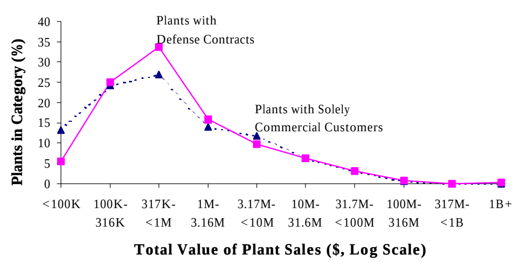


Figure 2.
Total Value of Plant Sales For Plants With and Without Defense Contracts



In Figures 3 and 4, the frequency log distributions of the scale of machining operations specifically and their capital intensity are similarly, broadly overlapping. Though not statistically different (chi2 p=.125), if anything, in Figure 3 the distribution of defense contractors lies on the larger rather than smaller-scale side. Moreover, if Figure 4 is any indication (chi2 p=.872), rhetoric about the gulf between the operational practices of defense contractors compared with their commercial brethren is, at best, significantly overstated. However, we will see in the next section, that operations do differ in some important measurable ways, particularly related to product complexity and manufacturing flexibility.

Figure 3.
Value of Annual Machining Output
from Plants With and Without Defense Contracts

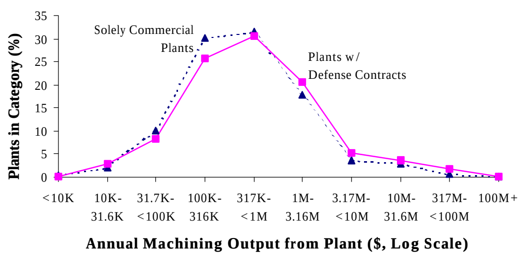
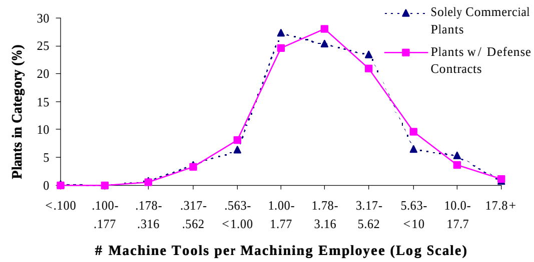


Figure 4.
Machining Capital Intensity
in Plants With and Without Defense Contracts



PRODUCTION VOLUMES AND PRODUCT COMPLEXITY

If measures of the overall organizational scale do not notably differ, perhaps metrics at the level of specific products and processes will confirm the received assumptions about limited scale? The data also enable comparison of details related to product complexity. Table 2 compares specific products made in machining operations. Interviewed production managers identified whether or not the specific product was being produced for the federal defense agencies or their prime contractors. Because all the products were produced using similar process technologies, the data present a unique opportunity for directly comparing the manufacturing practices employed for defense contracts with those employed for commercial products in the same industries.

As Table 2 shows, metrics of manufacturing scale for specific products, such as lot (batch) size, annual batch repetition and annual production volume, show no statistically significant differences on average. We will see below, however, that there are interpretable differences in how these scale variables are distributed.

Table 2 also moves on to metrics representative of how complex the products being manufactured are. There are again no statistical differences in the means of cost of materials used per unit, maximum part dimension, volumetric part size, or surprisingly, in the closest machining tolerances held. Were the statistical tests uniformly negative, one might begin to wonder about the discriminatory power of this data set.

But Table 2 gets interesting largely because the variables that do demonstrate significant differences are all seemingly related. Though defense related products are neither bigger nor more costly in materials nor have closer tolerances, they do appear to be more complex and difficult to machine than solely commercial products. Defense related machining jobs take more than 40 percent longer for the machinists to set up on average, and well over twice as long to run per batch, both indicative of more involved processes. Defense related jobs also use one third more cutting tools per item, meaning that the tool bits need to be changed in mid batch more often to complete all the processing steps. By this measure, defense related parts tend to have more complicated features or shapes.

Despite this additional process and product complexity, the average production time per unit (including setup, programming, if any, and run time) of defense products is not statistically different than for solely commercial products. One reason for this apparent contradiction might be that defense products in Table 2 are more than 20 percent more likely to be produced using the more advanced process technology of programmable automated machine tools (PA) rather than conventional machines. Note in Table 2 that the average unit production time for products done on programmable tools is significantly lower than the overall averages, both for defense and commercial products.

The cost, performance and flexibility advantages of information technology in manufacturing, including PA, are broadly understood and well rehearsed in the literature (see for example Kaplinsky (1984), Ayres et al. (1992), Kelley (1994)). On programmable machine tools, the tool positions, cutting speeds and feed rates are controlled not by a human operator but by a pre-preprogrammed sequence, often alterable at the machines. This permits far more flexible and/or complex machining control. Both complexity and flexibility advantages appear correlated to the process choices made by managers for defense products, as can be seen by looking beyond the variable means to their distributions. A general comment before proceeding is to note is the large fraction of overlap of all of the distributions between commercial and defense machining products. Rather than vastly different manufacturing worlds, the differences found indicate more subtle differences at the margins. The vast bulk of machining jobs are similar by these metrics in both sectors in MDG industries.

Related to product complexity, Figure 5 shows the frequency log distributions of set up time. Reinforcing the difference in means, the distribution of defense products is significantly (chi2 p=.000) shifted toward higher set up times compared with strictly commercial products. So too, in Figures 6 and 7, run time and number of cutting tool distributions of defense products are significantly (chi2 p=.000 & p=.001) right shifted, the direction consistent with more complexity. By contrast, Figure 8 shows no significant (chi2 p=.078) general tendency of defense products to have stricter tolerances overall, though a higher proportion do appear to concentrate at the relatively tight tolerance of $\pm$0.0001 inches.

Figure 5.
Time to Set Up Machining Jobs for Defense and Commercial Products

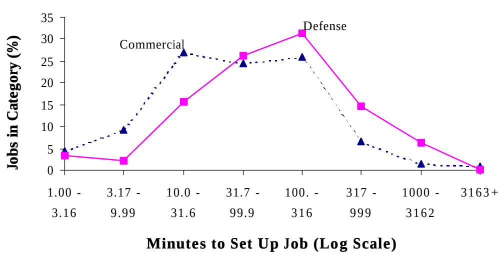


Figure 6.
Time to Run Machining Jobs for Defense and Commercial Products

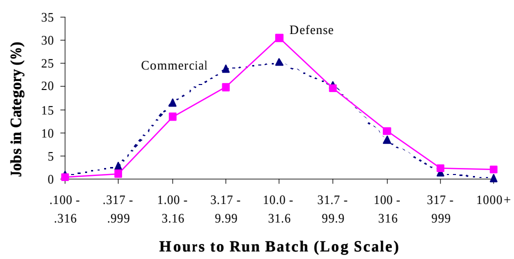


Figure 7.
Number of Cutting Tools Used Per Item for Defense and Commercial Machining Jobs

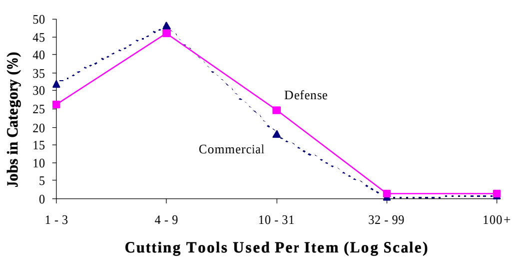
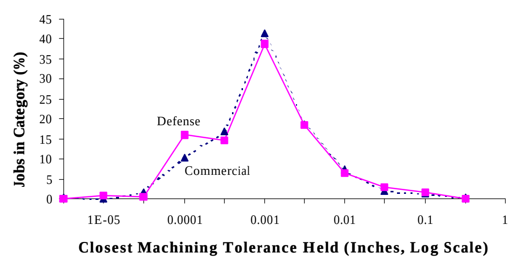


Figure 8.
Closest Machining Tolerance Held for Defense and Commercial Products



Related to manufacturing scale, though the means are not statistically different and there remains broad overlap, as Figures 9 and 10 show, defense products are less likely to me made in the very smallest lot sizes and annual volumes, and also less likely to be made in the very largest. The differences in the distributions are statistically significant in both (chi2 p=.001 & p=.001). The rightmost tails of the distributions are consistent with the received assumptions of the limited scale of defense manufacturing to the extent that few defense products are mass manufactured above 100,000 units per year. Indeed, on an un-weighted basis, the 10 highest annual product volumes reported in the data set are for non-defense products, including six above one million units per year. (Note though, that two of those ten highest volume non-defense products were reported by plants that also do defense work.) But so too, the leftmost tails indicate that commercial products are also more likely to be highly customized, in lots smaller than 10 units. Thus, defense products in the MDG sector tend to concentrate more in the middle range lot sizes and annual volumes. This is also the range most suitable for flexible programmable manufacturing technologies like PA compared with conventional dedicated machinery (see Gebhart and Hatzold, 1974, Ayres and Miller, 1983, Wright and Bourne, 1988).

Figure 9.
Machining Lot Size
for Defense and Commercial Products

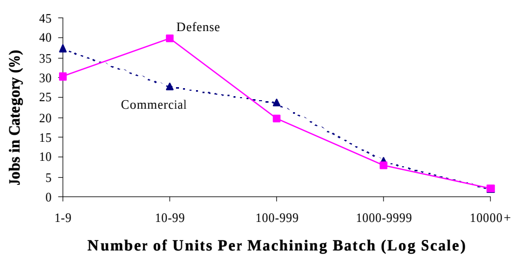
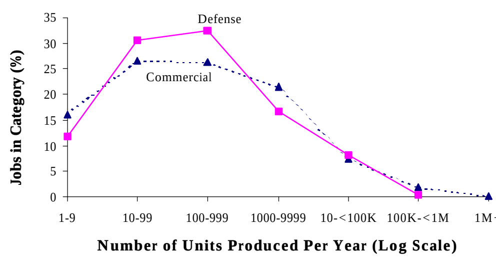


Figure 10.
Annual Output Volume
for Defense and Commercial Machining Products



OPERATIONAL FLEXIBILITY

This flexibility at the product level is also reflected in variables collected at the organizational level. Table 3 shows that plants with defense contracts report a broader scope of machining products, more than two and a half times more on average, as measured by the number of different products produced. Figure 11 confirms the statistically significant difference (chi2 p=.000) in the frequency log distributions of product scope, with commercial plants much more likely to specialize in a small number of products. Additionally, some plants have no specific product lines, but rather perform machining services on contract, so-called machining jobshops. In Table 3, defense contracting plants are nearly 45 percent more likely to be such jobshops. Presumably these plants have higher flexibility needs for their machining operations than plants making specific products.

Figure 11.
Scope of Products Made Using Machine Tools in Plants With and Without Defense Contracts

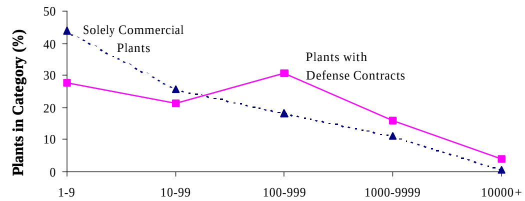


Table 3 also indicates that the average plant with defense contracts is one third more likely to have adopted programmable machine tools than their solely commercial counterparts. Moreover, they have a higher percentage of programmable tools in their total machine tool stock. As another check on the reliability of this sample data, this higher incidence of these flexible manufacturing technologies is consistent with the findings of the 1988 Census of Manufacturers, which found PA use in 61 percent of defense contracting establishments in industries in the manufacturing SIC codes (34-38) compared with 41 percent among non-defense plants (Bureau of the Census, 1988).

CONCLUSIONS

So in summary, the survey data here allow comparing similar manufacturing processes across manufacturing plants with and without defense prime or subcontracts in the same industries. These industries, the machining intensive durable goods sector, account for more than half of all defense purchases of durable goods and a quarter of US manufacturing output. The organizations in the defense and strictly commercial sectors do not differ statistically in organizational scale or in the scale of their production operations. Neither are production volumes or lot sizes different on average in machining operations, though their distributions indicate defense production does tend to concentrate where flexible manufacturing technologies are well suited. On the other hand, even though done in similar organizations, defense related machining products in the MDG sector are more complex to manufacture.

Except in unit production time and unit materials cost, this note does not address or model the, perhaps, more fundamental question of how the efficiencies of defense manufacturing compare to commercial practice, controlling for relevant explanatory variables. Given the similarities in scale found here coupled with the more advanced manufacturing technologies employed in defense contractors, it would be instructive to develop models and data to test the received assumptions about the inefficiencies of defense procurement, and to better understand why defense contractors are more technically advanced. Flexibility needs is the hypothesis suggested by the descriptive statistics here. Neither do the data here allow examination of issues beyond the shop floor, such as bureaucracy and overhead in defense procurement. It does however suggest the importance in any such comparative effort of including the diverse range of commercial practice, rather than focusing exclusively on the idealized mass manufacturer. Finally, (except programmable machine tools) the surveyed industries do not include the other, increasingly important half of defense procurement, namely computers and electronics. Findings from that sector might differ.

Nevertheless, at least in the large and industrially fundamental machining-intensive durable goods sector, the findings are more consistent with political economic explanations of increasing costs that center on system complexity than with structural and managerial economic approaches that focus on organization and scale. Defense manufacturing practices in machining operations were in 1991--even before the latest restructuring wave in US defense industries--already very significantly overlapping and consistent with commercial practice, yet the products more complex. The policy implication is increased effort to address the incentives for system complexity rather than nearly exclusive attention to structure and the integration of defense and commercial manufacturing at the product and process levels.

[1] The industries are: nonferrous foundries, cutlery, hand tools and hardware, heating equipment and plumbing fixtures, screw machine products, metal forgings and stampings, ordnance and accessories—nec, miscellaneous fabricated metal products, engines and turbines, farm and garden machinery and equipment, construction and related machinery, metalworking machinery and equipment, miscellaneous machinery—excluding electrical, electrical industrial apparatus, motor vehicles and equipment, aircraft and parts, guided missiles and space vehicles, engineering and scientific instruments, measuring and controlling instruments, jewelry silverware and plateware.

[2] Based on Census input-output matrix estimates from the Office of Policy Analysis, Economics and Statistics Administration, US Department of Commerce (1991).

[3] Authors' estimates based on data from Bureau of the Census (1988).