Second Source Manufacturing: Lessons from the Second World War

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Abstract: Manufacturing defense systems at different sites is increasingly common due to foreign coproduction and international cooperative ventures. These situations challenge estimators, posing questions about the transfer of learning and relative efficiency of multiple production sites. This paper examines cost history from World War II, when U.S. bomber production lines were shared across multiple companies. The conclusions are tested against modern experience and guidance provided to estimators seeking help. .

Introduction

Estimators are sometimes confronted with situations where production on an already existing program begins at a second manufacturing site. Building the same product at multiple sites poses a challenge to conventional learning curve theory. How much, if any, learning can be transferred from the lead manufacturing site to the secondary site? How much learning curve improvement can be expected at the secondary site? Is it possible for the second source producer to become as productive as the lead site?

There are four common situations in the aircraft and missile industries where manufacturing of an item may occur at two or more sites simultaneously. These include:

- **Production at different facilities owned by the same firm.** A recent example is the commercial Boeing 787 manufactured simultaneously at its Everett, Washington and Charleston, South Carolina plants from 2011 until 2021 when final assembly was consolidated at Charleston. (Podsada, 2021)
- **Foreign coproduction.** A variety of U.S. military systems – fighters, helicopters, missiles, trainers, and anti-submarine warfare aircraft – have been coproduced simultaneously in the U.S. and foreign countries. The first military aircraft to do so was the F-86 in 1949. A list of U.S. military aircraft with foreign coproduced components or aircraft includes the F-86, T-33, T-34, S-2, P-2H, F-104, F-5, F-4, P-3C, F-16, AV-8B and F-35. (Rich, 1981)
- **International cooperative ventures.** Popular among European countries, these feature joint development projects with production and design authority split among the industries of different countries. A typical setup might have countries assigned to build specific aircraft components with some final assembly and flight test performed in each country. Examples include Jaguar, Tornado, Eurofighter Typhoon, and the Airbus family of commercial aircraft. (Svartman, 2018)
- **Competing companies producing the same end item.** This is more common in the missile industry where a second-source manufacturer competes with the developing company for a variable share of overall production. Examples include the AMRAMM, Hellfire, Maverick, Phoenix, Sidewinder, Sparrow, Standard, Stinger and Tomahawk missiles. (Lyon, 2006) The terminated Navy A-12 program would have required a price competition between General Dynamics and McDonnell-Douglas for a variable share of production after several production lots. (GAO, 1990)

Note that these situations are different from a true workshare, where two or more companies work together on the same end-product but each having build responsibilities which do not overlap.

Examples include Boeing and Northrop Grumman's split of the F/A-18E/F or Lockheed Martin and Boeing's split of the F-22 program. In these cases, there is not a question of learning transfer between firms. For instance, Boeing built F-22 aft fuselages and wings – neither Lockheed Martin nor any other company simultaneously built those components.

Learning Curve Theory – What Might We Expect?

In cases where two or more manufacturing sites build the same end-product, it is reasonable to expect learning can be transferred from the lead manufacturing site to the second source. In a typical contractual arrangement, both parties have a strong incentive for transfer to occur. If the lead company failed to provide manufacturing know-how to the second source, the second source will likely fail to make on-time deliveries, creating legal, contractual, manufacturing, and financial problems for the lead. Likewise, the second source is incentivized to accept technical assistance to bring its production up to speed and make it profitable as quickly as possible.

Technology transfer can cross multiple functions – engineering, planning, tooling, management – and come in many forms: data, training, on-site management, and assistance teams, furnishing start -up parts, et al. Success of the technology transfer program also depends on the capability of the second source. All else equal, the more capable the second source the more learning can be transferred to it.

On the other hand, it is unrealistic to expect that 100% of a firm's learning can be transferred. There are some things that only be learned by "hands-on" effort. If we think of Anderlohr's five elements of learning – shop personnel, supervision, continuity of production, tooling, and methods – it is apparent that no amount of formal or informal training can completely prepare a worker asked to work on a part he has never built before. (Anderlohr, 1969) Some things can only be learned by experience.

So how much learning should the estimator assume can be achieved by technology transfer, and how much left to experience? Let us construct a quick example to illustrate the complexities.

We begin with a company which is the original manufacturer of an item (the lead site). After several years, a second firm joins it in building the same product (the second source). Assume:

- The lead site builds 150 units with a first unit cost of 20,000 hours on an 80% learning curve slope before the second source builds its first unit.
- The second source retains 80% of the learning that the lead site accumulated up to that point (or equivalently, the second source will experience 20% learning loss).
- The second source also experiences an 80% learning curve slope beginning from the equivalent point on the lead site's learning curve after learning loss is applied.
- Both sites build an additional 350 units each.

Units Built by Lead Site Before Break-In	150
Hours per Unit (HPU) (Lead Site) at T-1	20,000
Unit Factor (UF) (Lead Site) at T-150	0.1993 [calculated as 150 ^ (ln (0.80) / ln (2))]
HPU (Lead Site) at T-150	3,986 [calculated as 20,000 x 0.1993]
Learned to Date	0.8007 [calculated as 1 - 0.1993)
Learning Lost	0.1601 [calculated as 0.8007 x 0.20 learning loss]
UF for Second Source's 1st Unit on Lead Site's Learning Curve	0.3594 [calculated as 0.1993 + 0.1601)
Second Source's HPU for its 1st Unit	7,188 [calculated as 20,000 x 0.3594]
Equivalent Unit for Second Source's 1st Unit on Lead's Learning Curve	24 [calculated as 2 ^ [(ln (0.3594) / ln (0.80)]
Unit Setback on Lead's Learning Curve	-84% [calculated as (24-150) / 150]

Example 1.

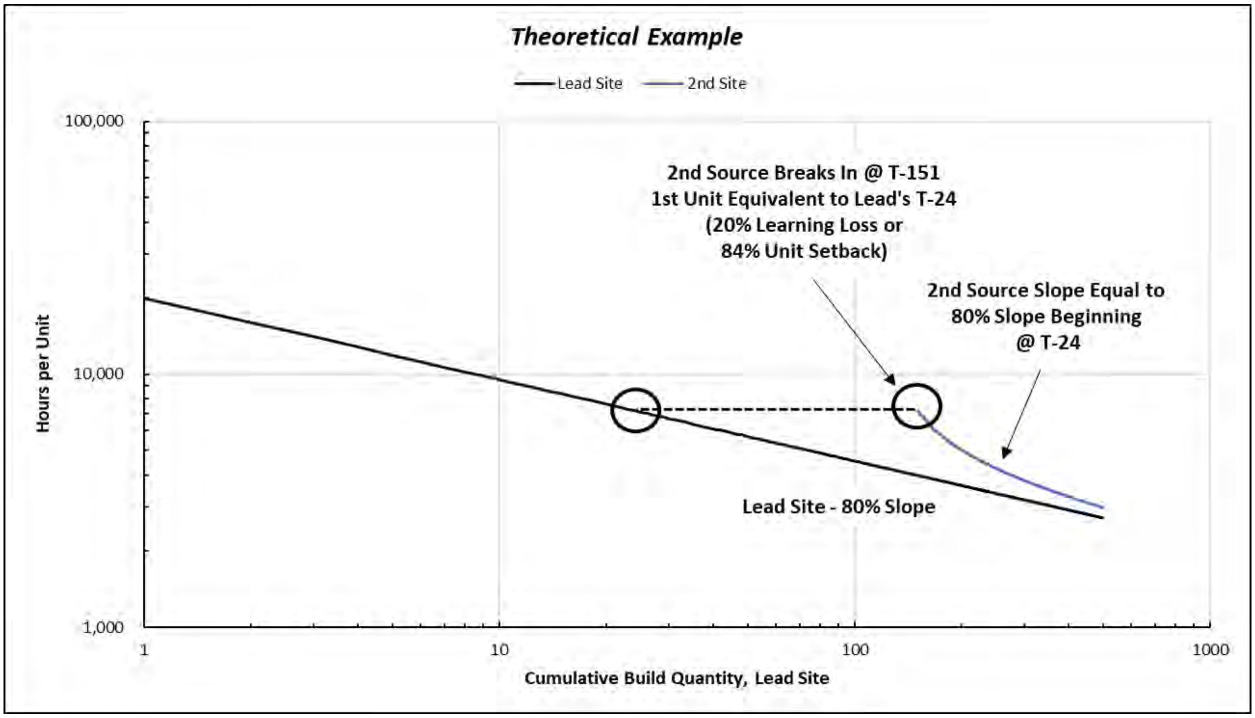

Figure 1. Theoretical Example – Hours per Pound Performance (I)

In this example, we have measured learning loss (or its inverse, learning gain) in two ways. The first is the percent of learning lost from the lead site's cumulative experience. The second is percent unit setback – that is, from the lead site's position on its learning curve, how far will the second source be set back on the learning curve when it builds its first unit? As we see, these two (learning loss/gain, unit setback) are not the same.

Figure 1 shows this case graphically. At the point of break-in, the lead site is building units at slightly under 4,000 hours per unit. The second source's first unit is 7,188 hours, which is equivalent to T-24 on the lead site's learning curve. This represents a 20% learning loss (or an 84% unit setback). As the second source continues to build, its HPU declines over time to its final unit at 2,973 hours. That is equivalent to T-373 on the lead site's learning curve. Meanwhile, the lead site's costs continue down the learning curve as well. Its final unit – the 500th – will cost 2,705 HPU.

Two things are apparent from the graph. First, the second source will asymptotically approach – but never intersect with – the lead site's cost performance. At no point will there be convergence, which will we define as the point the second source equals or exceeds the lead site's *historical* performance at some point on the curve. (It does not matter if the lead is currently producing the product at a lower cost, only that the second source matches where the lead formerly performed.) If there is no convergence to the lead site's learning curve, then it is also impossible for the second source to meet a second, stricter test: whether it can perform better than the lead's *current* performance.

Figure 2 shows the same information but uses a different method to plot the data. In it, the first unit of the second source's build is plotted as T-1. This method emphasizes the lower first unit cost for the second source because of learning gain. It also shows the second source's asymptotic cost performance as it approaches, but does not reach, the lead site's hours per unit. (Due to the peculiarities of the logarithmic scale, it may appear that the second source achieves the same cost as lead site. It does not – the plotted data is the same as that portrayed in Figure 1, where the gap is more visually apparent.) By treating the second source's first build as T-1, this would give an equivalent 86% learning curve for the second source.

Asymptotic non-convergence results from our assumption the second source will achieve the same learning slope as the lead site. If we assumed a flatter slope by the second source, the gap widens further. Only if the second source achieves a steeper rate of learning is it possible for the two slopes to achieve convergence.

In Figure 3 we have given the second source a steeper slope (76%) than the lead site beginning at the same break-in HPU. This allows the second source to achieve convergence with the lead – its cost performance intersects the learning curve of the lead site. Moreover, by the end of production it is actively producing units at a lower cost than the lead site can. When each site finishes its last unit – T-500 for the lead, T-350 for the second source – the second source's last unit costs is 2,426 hours versus 2,705 hours for the lead site. Under different learning curve assumptions, a second source could converge to the lead site's learning curve performance but at the same time does not produce the aircraft at a lower cost than the lead.

Nevertheless, theory cannot tell us whether the estimator should assume the second source's learning curve slope is shallower, steeper or the same as the lead site. A theoretical case could be made for any of these outcomes:

1. *The second source's learning curve slope will be the same as the lead site*. After the initial transfer of learning, the second manufacturing site will experience the same sources of future learning as the lead company – worker proficiency, supervisor familiarity with his crews, improvements in production layouts and improved part availability as the supply chain gears up. The second source experiences a "rerun" of the lessons the lead site learned

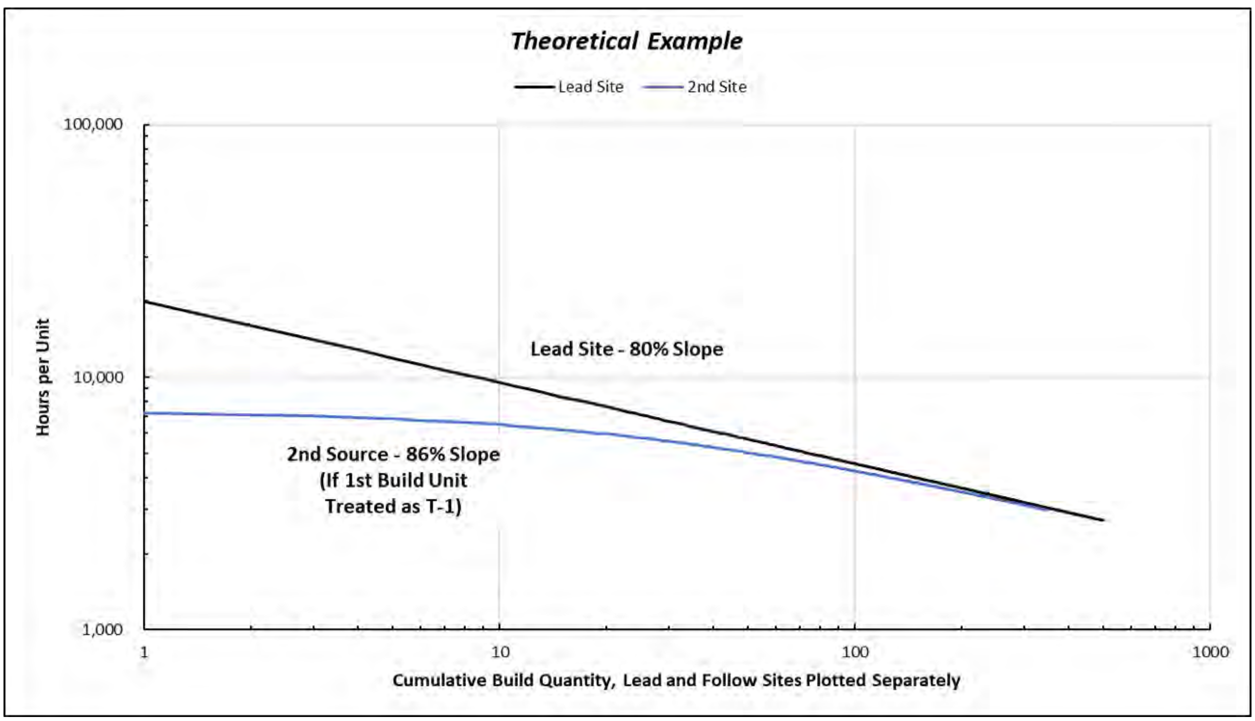

Figure 2. Theoretical Example – Hours per Pound Performance (II)

(but could not transfer to the second source). In such a case, the second source will improve its performance at the same rate of learning as the lead site at an equivalent point on the curve. This is the standard assumption in production gap literature, which also deals with the subject of lost and retained learning. (Anderlohr, 1969; DCAA, 1996)

2. *The second source's learning curve slope will be flatter than the lead site*. This argument looks at build rates and the phenomena of learning and forgetting. The longer the period between build units, the harder it is for the mechanic to retain what he has learned since the last time he completed a task. If the second source's production rates are lower than the lead, its shop floor mechanics will go longer between builds, potentially losing learning and creating a flatter learning curve slope relative to the lead site.

3. *The second source's learning curve slope will be steeper than the lead site*. Learning curve analyst E. B. Cochran wrote of the "time compression penalty," which encompasses many of the issues surrounding aircraft development and early production: late engineering releases, tooling errors, part shortages, manpower disruption, and high levels of scrap and rework, all of which conspire to force the learning curve to be flatter in its early phases. (Cochran, 1968) If technology transfer is successful, however, much of this early disruption endured by the lead site can be avoided by the second source. It too will have its growing pains, but they need not be as severe. That suggests the second source might be able to start its phase of rapid cost improvement sooner, rather than later, resulting in an overall steeper slope.

But which of these scenarios is the most likely to unfold?

The answer to that question lies in historical experience – after all, this is not a new situation in the aircraft business. However, such historical experiences are typically locked away in company vaults as proprietary information and not available for wider distribution. What can we do?

Fortunately, there is a public domain, nonproprietary database we can use to develop answers, and which has been used in several influential learning curve studies over the years. (Stanford Research Institute, 1949; Asher, 1956; Alchian, 1963) The database is the *Source Book of World War II Basic Data*. (*Source Book*, undated) This data, collected from Aeronautical Monthly Progress Reports (AMPR) provided by contractors during the war, provides manufacturing hours per month by model and facility as well as hours per pound against cumulative plane number. Moreover, this database contains several examples of the same aircraft model being produced at different facilities.

The obvious objection is that this data is 80 years old, and aircraft manufacturing processes have changed substantially over eight decades. That is entirely true; but the data can still provide important insights into the transfer of learning between manufacturing sites. We will use this data to test four propositions. After drawing conclusions from the wartime data, we will compare it (at a high level, to protect proprietary information) with modern-day data to determine if these conclusions still appear valid in today's environment.

The four propositions to be tested are as follows:

1. The second source will show some degree of learning transfer – that is, it will not begin back at the lead's T-1 cost – but it will not completely transfer all the lead's learning, either.

2. A concerted effort by the lead site to foster technology transfer should improve the learning gain achieved by the second source, resulting in a lower-cost break-in.

3. The second source will not fully converge to the lead company's learning curve – that is, the two lines will not intersect.
4. The second source will not be able to produce at a lower cost than the lead company – that is, the coproducer's best hours per pound performance will always be greater than the lead company's best hours per pound performance.

Approach of the Second World War

As war in Europe approached, the United States began preparing itself for possible conflict. The American aircraft industry was poorly prepared for a substantial expansion of deliveries. The industry had numerous manufacturers, each making aircraft in small quantities in an artesian "job-shop" environment. Most manufacturers did not build aircraft on an assembly line, but in one spot on the factory floor in their entirety. (Stoff, 1993) In 1938 the United States produced 900 military aircraft. The entire industry employed only 36,000 people – slightly less than the knit-hosiery industry. (Harr, 1965)

An executive for Consolidated-Vultee Aircraft described the aircraft manufacturing process in the prewar years:

> Under the pre-war production system, if an order for say 60 planes (a big order in those days) was received, groups of workers would concentrate on the various parts needed for the components and produce 60 units. As fast as these components were made they were stored in a central stockroom, there to remain until all the parts for certain subassemblies had been completed. Then they would be withdrawn and the 60 subassemblies fabricated. And as the 60 subassemblies were finished they, in turn, would be assembled into the completed unit until the 60 had been constructed, tested, and delivered. (Laddon, 1943)

This system worked fine for small orders, minimizing setup time and parts fabrication costs. (Laddon, 1943) However, production quantities started increasing as Europe grew closer to war. In June 1938 Lockheed received an order for 200 Hudson bombers for Great Britain, at the time the largest aircraft order received by a U.S. firm between the world wars. (Harr, 1965) But the watershed moment did not come until May 1940, when President Franklin Roosevelt declared before Congress:

> Our immediate problem is to superimpose on this [military aircraft] production capacity a greatly increased additional production capacity. I should like to see this nation geared up to the ability to turn out at least 50,000 planes a year. (*The New York Times*, 1940)

In response to Roosevelt's demand, the War Department began developing plans for a rapid expansion of aircraft production. Bomber production was a high priority of the United States Army Air Force. However, there was insufficient capacity to provide the needed quantities of any given aircraft model. In addition, there was a high concentration of aircraft manufacturers on the West Coast, which was considered vulnerable to enemy attack. The need was two-fold: (1) to increase production capacity by bringing on more suppliers and (2) build more aircraft production facilities in the interior of the United States – "behind the mountain chains" -- where they would be safe from enemy attack. (Holley, 1964)

The answer was to pool bomber production across multiple companies, each producing the same aircraft and sharing production knowledge. Douglas and Lockheed-Vega would build B-17s under license from the designer and lead producer Boeing. Similarly, Douglas, North

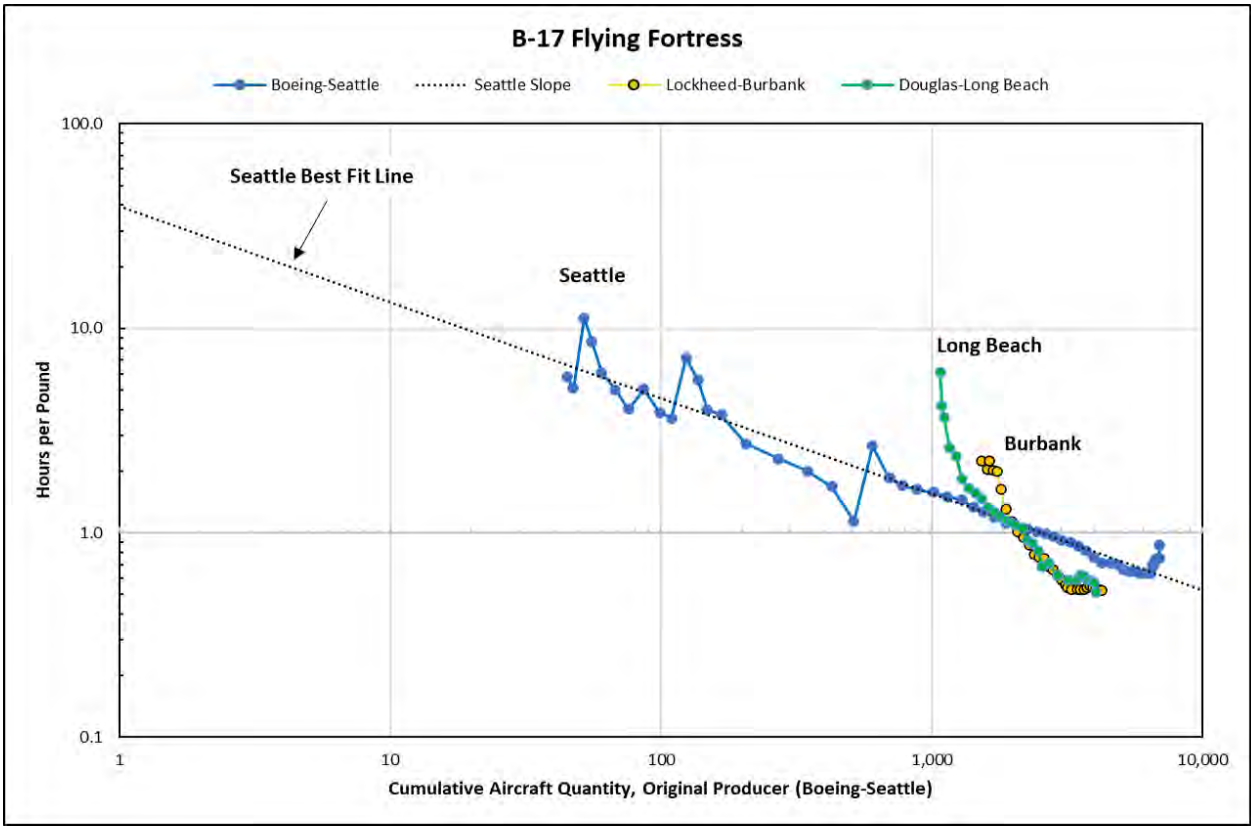

Figure 4. B-17 Flying Fortress Hours per Pound (I)

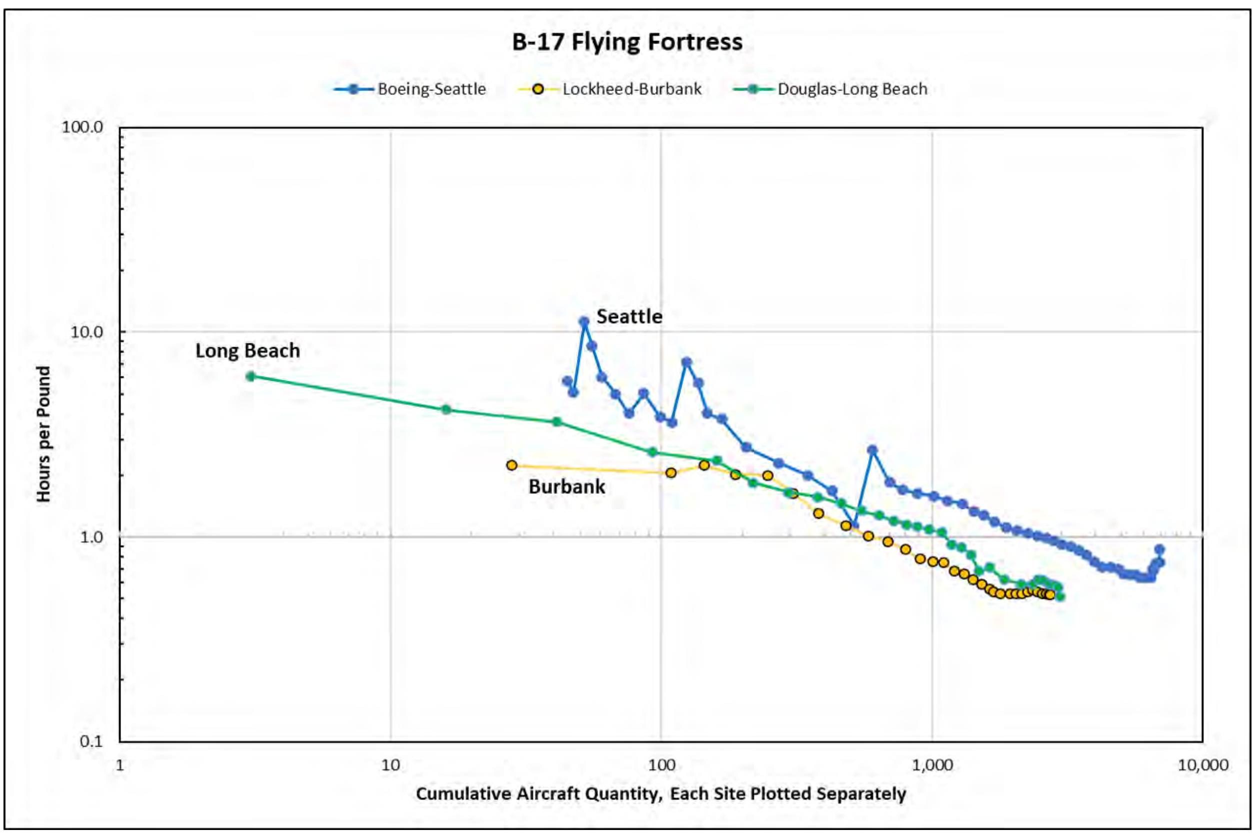

Figure 5. B-17 Flying Fortress Hours per Pound (II)

American and the automaker Ford would join Consolidated-Vultee to build B-24s. Finally, for the B-29 Superfortress, the Air Force's largest bomber, Bell and Martin would enter a licensing agreement with Boeing. As part of the capacity expansion, new aircraft facilities would be opened in Dallas (North American), Fort Worth (Consolidated-Vultee), Long Beach (Douglas), Marietta (Bell), Omaha (Martin), Tulsa (Douglas), Wichita (Boeing) and Willow Run, Michigan (Ford).

The sudden explosion in order sizes forced dramatic changes on the shop floor. Consolidated-Vultee soon discovered that its central warehouse could not stock millions of finished parts. Consequently, it eliminated the warehouse and installed smaller stock bins along the assembly line, working to a just-in-time inventory system. Building an entire aircraft in place was replaced by a moving line that transported the aircraft as it was built through successive stations manned by dedicated crews. Planes were stationed in final assembly at 45-degree angles, allowing 50% more aircraft to be worked in the same floor space. Complicated assemblies previously worked by highly skilled craftsmen were broken into simpler and more accessible subassemblies that could be more easily worked by inexperienced mechanics. Better, more precise tooling was introduced to simplify drilling and machining operations. (Laddon, 1943). These lessons learned by Consolidated were repeated across the aircraft industry.

This program was enormously successful. In the end, these eight companies delivered almost 35,000 bombers before the end of the war. Overall, the entire American aircraft industry not only met the President's goal of 50,000 aircraft per year, but almost doubled it, producing over 96,000 aircraft in 1944 alone. (Holley, 1964)

We will examine the cost performance of each of these bomber models in turn.

B-17 Flying Fortress

The B-17 had been in production at Boeing's Seattle plant as early as 1938, but at very low production rates. Only 53 aircraft were delivered in 1940. In addition to rapidly expanding Boeing production at Plant 2, Douglas Aircraft and Vega Aircraft (a wholly owned subsidiary of Lockheed) were brought on-line in 1942 and 1943 respectively. By 1944, the three facilities were delivering almost 5,400 bombers a year. In total, more than 12,600 B-17s were delivered. (Holley, 1964)

Figure 4 shows the cost performance of the three facilities. (*Source Book*, undated) The first units of the Long Beach and Burbank facilities are plotted beginning at the cumulative number of aircraft produced to date at the lead site in Seattle.

Figure 5. shows the same information except that the cumulative production of the Long Beach and Burbank facilities is plotted independent of the number of units produced at Seattle.

Table 1 summarizes the performance of the three sites in terms of learning curve slopes, percent learning loss and percent unit setback. It also answers if the coproducing sites were able to achieve convergence with the lead site's learning curve, and if they were able to produce at an eventual lower cost than the lead.

Figure 4 shows that the Long Beach and Burbank were not only able to converge to Seattle's learning curve but eventually produce the B-17 at a lower cost than Seattle, despite producing half as many aircraft as the Seattle plant. One reason the B-17 coproducers were so successful was the robust level of cross-company cooperation between the three contractors. In May 1941 a committee of company and government representatives was established, the so-called BDV (Boeing-Douglas-Vega) committee. The committee coordinated material purchases, master production schedules, release

B-17 Flying Fortress		*Lead*	*Coproducer*	*Coproducer*
		Boeing Seattle	**Douglas Long Beach**	**Lockheed Burbank**
Initial Build Plotted as T-1	Actual 1st Lot (Hrs/Lb)	5.79	6.12	2.24
	Theoretical First Unit (TFU) (Hrs/Lb)	39.57	13.79	16.31
	Unit Curve Coefficient	(0.4689)	(0.3886)	(0.4406)
	Unit Curve Slope	72.3%	76.4%	73.7%
	R-Square (R^2)	94.2%	95.4%	92.3%
	Minimum Hrs/Lb	0.63	0.51	0.52
Initial Build Plotted at Setback Unit #	Setback Unit on Lead's Learning Curve	N/A	54	457
	% Learning Loss	N/A	12.1%	2.5%
	% Unit Setback	N/A	95.0%	69.5%
	Unit Curve Slope	N/A	67.9%	55.1%
Additional Data	1st Delivery	1938	Oct-42	Jan-43
	Prior Units Produced by Lead	N/A	1,073	1,495
	Total Aircraft Built	6,981	3,000	2,750
	Achieve Convergence to Lead's Learning Curve?	N/A	Yes	Yes
	Achieve Lower Cost Than Lead?	N/A	Yes	Yes

Table 1. B-17 Flying Fortress Cost Performance by Manufacturing Site

of engineering drawings, inspection criteria and production lessons learned between the three companies. Ideas for improvement did not just flow from the lead to the second sources. If the second source or one of their lower-tier suppliers simplified a design, reduced the use of expensive materials, or improved performance, the committee recommended the revised design as the standard for all companies. The BDV committee became the template for other aircraft programs with multiple contractors, including the B-29. (Holley, 1964) It is not surprising, then, that learning loss was minimized (12% for Long Beach, 2% for Lockheed-Vega) – by far, the least amount of learning loss among all the bomber producers.

B-24 Liberator

While the B-17 is probably the most iconic World War II bomber, the Army Air Force purchased more B-24 Liberators than any other bomber model – over 18,000 aircraft. (Holley, 1964) Given such large procurement quantities, production was eventually split over five sites: San Diego, Fort Worth, Willow Run, Tulsa and Dallas. Consolidated-Vultee was the lead, beginning B-24 production in 1940 at its San Diego facility.

Figure 6 shows the cost performance of the five facilities. (*Source Book*, undated) The first units of the Fort Worth, Willow Run, Tulsa, and Dallas facilities are plotted beginning at the cumulative number of aircraft produced to date at the lead site in San Diego.

Figure 7 shows the same information except that the cumulative production of the Fort Worth, Willow Run, Tulsa, and Dallas facilities is plotted independent of the number of units produced at San Diego.

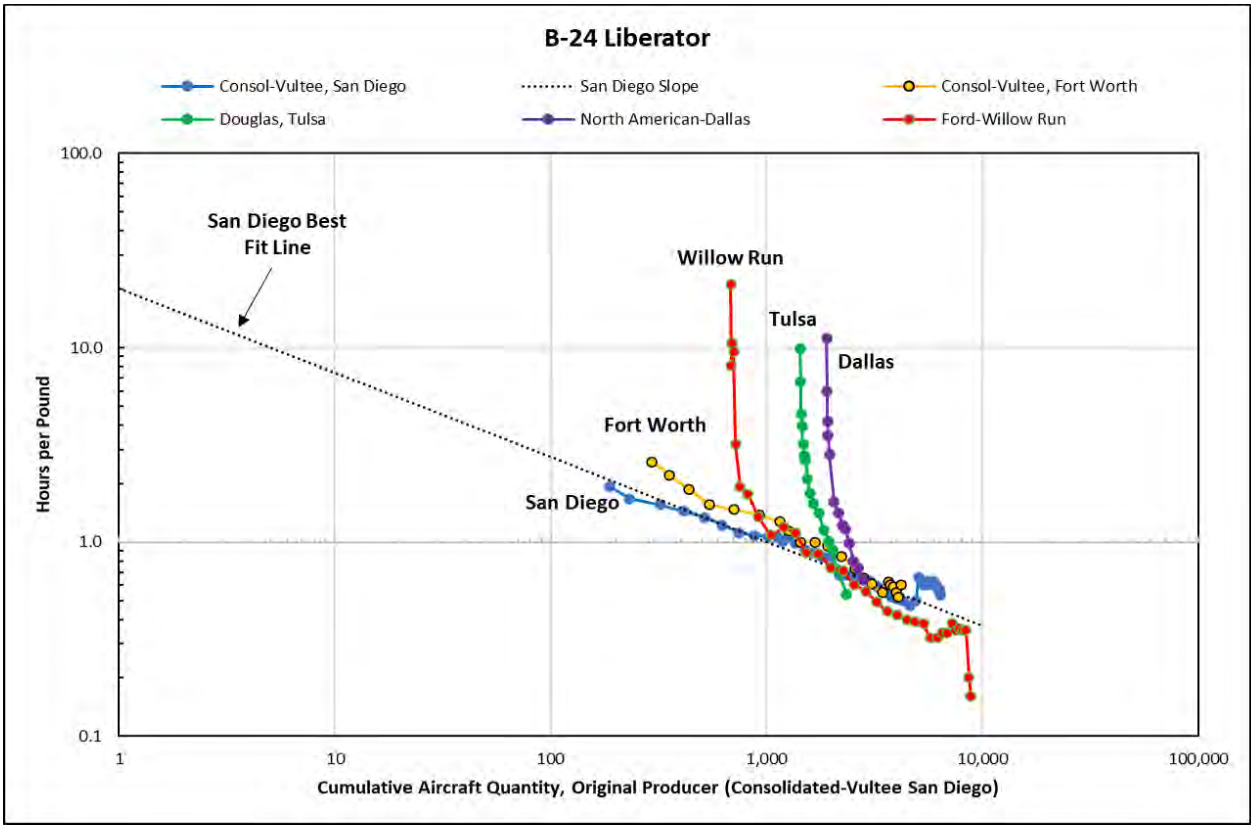

Figure 6. B-24 Liberator Hours per Pound (I)

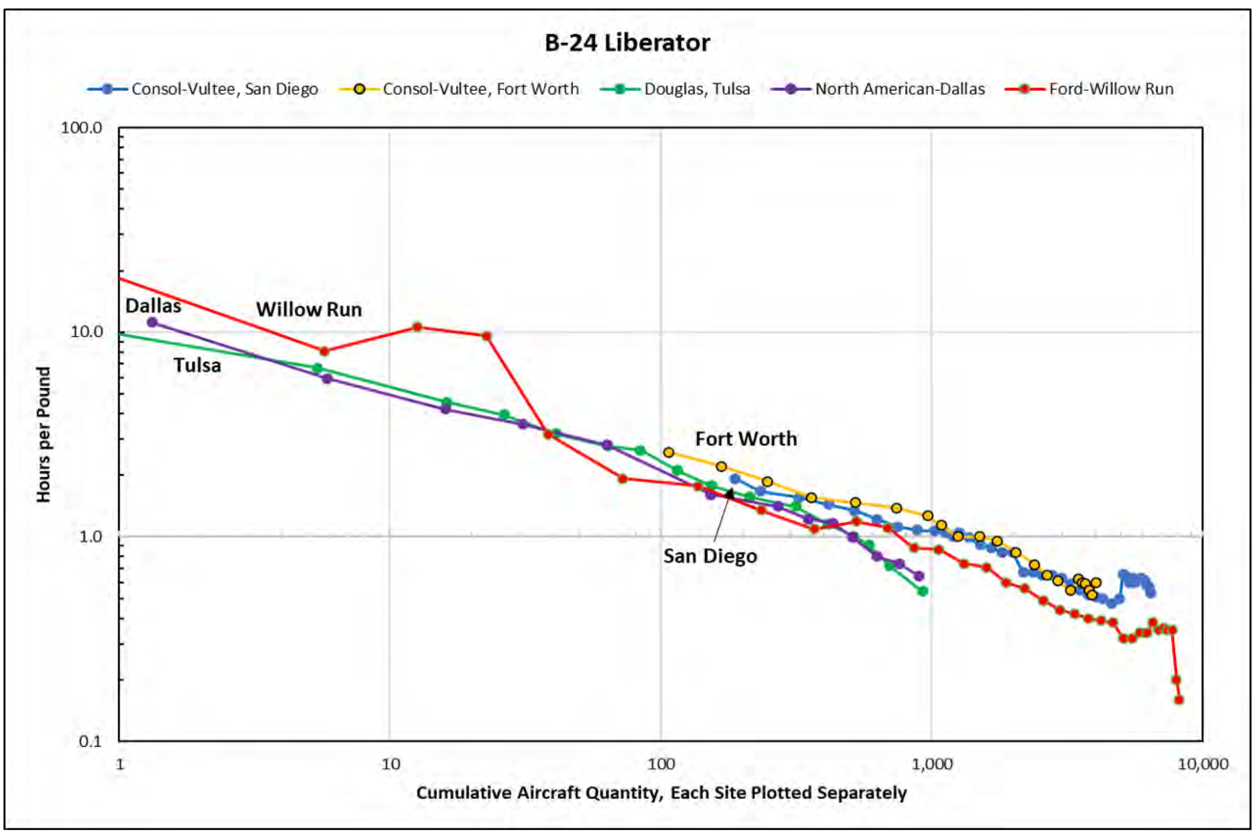

Figure 7. B-24 Liberator Hours per Pound (II)

Table 2 summarizes the performance of the five sites in terms of learning curve slopes, percent learning loss and percent unit setback. It also answers if the coproducing sites were able to achieve convergence with the lead site's learning curve, and if they were able to produce at an eventual lower cost than the lead.

The B-24 shows a wide variance in the degree of learning loss experienced by the coproducing companies. Consolidated-Vultee's Fort Worth facility experienced 3% learning loss while Ford experienced greater than 100% learning loss. All four coproducing sites were able to reach convergence with San Diego's cost performance. Only one – Ford's plant in Willow Run – was able to produce the B-24 at an eventual lower cost than Consolidated's San Diego plant.

Several factors explain the wide variance in learning loss. Unlike the B-17, there was no coordinating committee for B-24 production. At the low end, the minimal loss of learning from San Diego to Fort Worth is best explained that both facilities operated under the same company, and the new Fort Worth plant was operated by a cadre of management and engineers transferred from San Diego. At the high end, Willow Run decided to adopt a completely different manufacturing approach from the other sites. In 1940 Henry Ford's leading manufacturing expert, Charles Sorensen, was sent to the San Diego B-24 line, only to be dismayed by Consolidated's assembly approach:

> Inside the [Consolidated] plant I watched men putting together wing sections and portions of the fuselage…. [W]hat I saw reminded me of nearly thirty-five years previously when we were making Model N Fords…before we achieved the orderly sequence of the assembly line and mass production.
>
> The nearer a B-24 came to its final assembly the fewer principles of mass production there were as we at Ford had developed and applied over the years. Here was a custom-made plane, put together as a tailor would cut and fit a suit of clothes.
>
> The B-24's final assembly was made out of doors under the bright California sun and on a structural

B-24 Liberator		*Lead* **Consol-V San Diego**	*Coproducer* **Consol-V Fort Worth**	*Coproducer* **Ford Willow Run**	*Coproducer* **Douglas Tulsa**	*Coproducer* **N. American Dallas**
Initial Build Plotted as T-1	Actual 1st Lot (Hrs/Lb)	1.93	2.59	21.25	9.91	11.21
	Theoretical First Unit (TFU) (Hrs/Lb)	20.10	22.18	22.95	13.53	13.74
	Unit Curve Coefficient	(0.3641)	(0.4393)	(0.4882)	(0.4146)	(0.4249)
	Unit Curve Slope	77.7%	73.7%	71.3%	75.0%	74.5%
	R-Square (R^2)	91.8%	96.7%	96.4%	95.5%	98.5%
	Minimum Hrs/Lb	0.47	0.52	0.16	0.54	0.64
Initial Build Plotted at Setback Unit #	Setback Unit on Lead's Learning Curve	N/A	113	1	5	4
	% Learning Loss	N/A	2.8%	106.1%	47.0%	54.0%
	% Unit Setback	N/A	39.9%	99.9%	99.6%	99.8%
	Unit Curve Slope	N/A	72.6%	71.0%	70.2%	71.3%
Additional Data	1st Delivery	Early 1940	Apr-42	Sep-42	Apr-43	Jul-43
	Prior Units Produced by Lead	N/A	188	680	1,433	1,897
	Total Aircraft Built	6,435	4,105	8,233	1,052	1,000
	Achieve Convergence to Lead's Learning Curve?	N/A	Yes	Yes	Yes	Yes
	Achieve Lower Cost Than Lead?	N/A	No	Yes	No	No

Table 2. B-24 Liberator Cost Performance by Manufacturing Site

> steel fixture. The heat and temperature changes so distorted this fixture that it was impossible to turn out two planes alike without further adjustment….[I]t was obvious that if the wing sections had uniform measurements, the way we made parts for automobiles, they would not fit properly under out-of-doors assembly conditions.
>
> All this was pretty discouraging, and I said so. Naturally, and quite properly, the reply was "How would you do it?" I had to put up or shut up. "I'll have something for you tomorrow morning," I said.

Sorensen retreated to his hotel room and overnight produced a plan for a new manufacturing facility based on automotive build principles. Sorensen's rough sketches became the blueprint for Ford's massive Willow Run facility, designed to roll out a B-24 every hour at maximum capacity. (Sorensen, 1956)

Realizing Sorensen's dream was more difficult than he or the other Ford executives imagined. Ford was forced to re-do 30,000 drawings it received from Consolidated because it could not resolve discrepancies between loft boards and detailed part designs, discrepancies which Consolidated simply left to their skilled production workers to reconcile on the shop floor. Likewise, Ford built 21,000 jigs and fixtures, but eventually only used 11,000 of them – the rest scrapped due to errors in the source drawings or rendered obsolete by the stream of engineering design changes flowing from the Air Force and Consolidated. (Holley, 1964) Willow Run struggled to accelerate initial production – a commonly asked question by journalists of the day was: "Will It Run?" (Baime, 2015) By March 1944, though, Willow Run had wrung out its production inefficiencies and was producing over 400 bombers per month – short of Ford's stated goal of a B-24 every hour, but still more than the Air Force could absorb in the field. (Holley, 1964) In the end, Ford's automotive-based process was able to produce the B-24 at a lower cost per pound than Consolidated-San Diego or the other sites.

The Tulsa and Dallas plants represent learning loss in between the extremes of Fort Worth and Willow Run, losing 47% and 54% of learning respectively in their first build. The reason for North American's higher loss of learning was, ironically, poor liaison between the Dallas plant and Ford. Ford was slow to notify North American of engineering design changes, thus creating downstream tooling and production problems; and the drawings Ford provided were inadequate. Eventually North American redrew all the engineering drawings Willow Run provided. (Holley, 1964)

These widely varying experiences on the B-24 confirm that the ability of the lead contractor to successfully transfer its technology and lessons learned is the predominant factor on the degree of learning loss.

B-29 Superfortress

The Air Force's heaviest bomber, the long-range B-29 Superfortress, began production in 1943 at Boeing's new Wichita facility. In short order, production lines at Marietta (Bell), Renton (Boeing) and Omaha (Martin) were opened. Almost 3,900 Superfortresses were eventually delivered, over half at the two Boeing facilities.

Figure 8 shows the cost performance of the four facilities. (*Source Book*, undated) The first units of the Marietta, Renton, and Omaha facilities are plotted beginning at the cumulative number of aircraft produced to date at the lead site in Wichita.

Figure 9 shows the same information except that the cumulative production of Marietta, Renton and Omaha is plotted independent of the number of units produced at Wichita

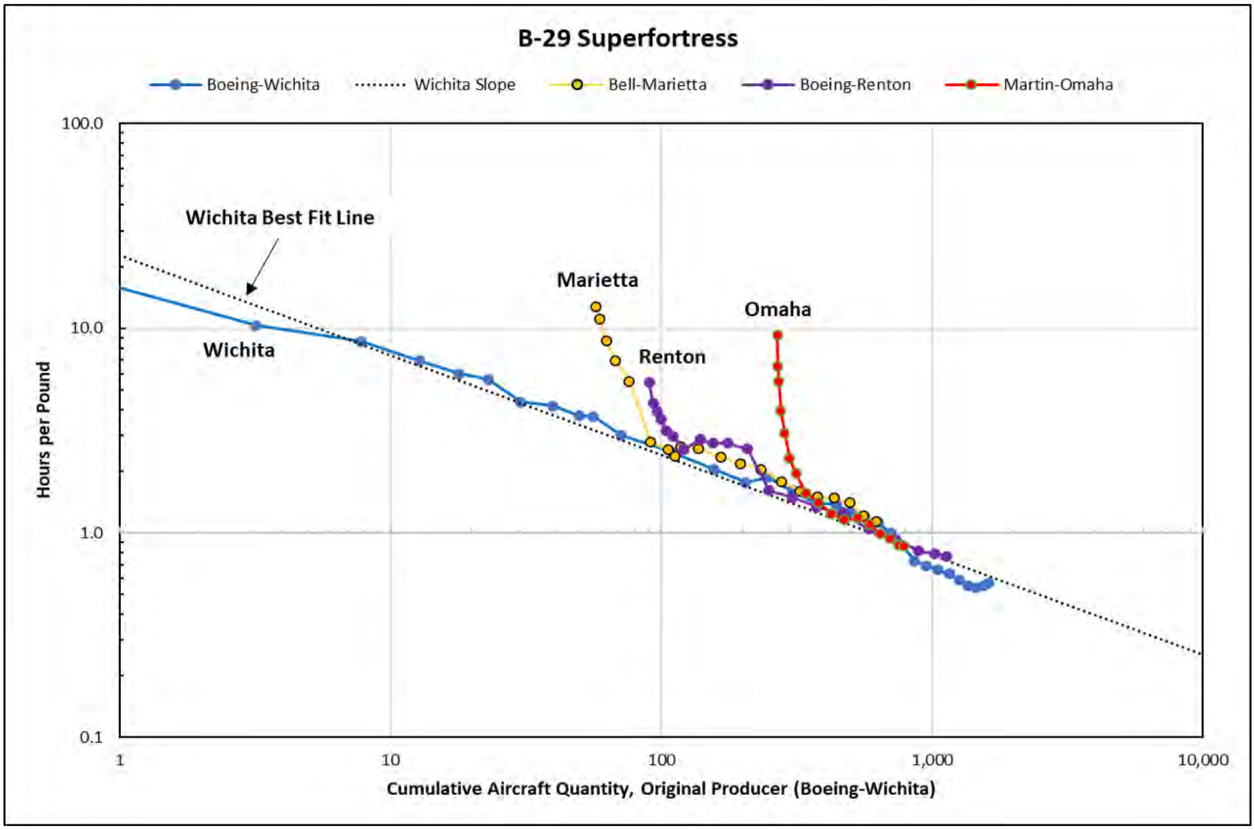

Figure 8. B-29 Superfortress Hours per Pound (I)

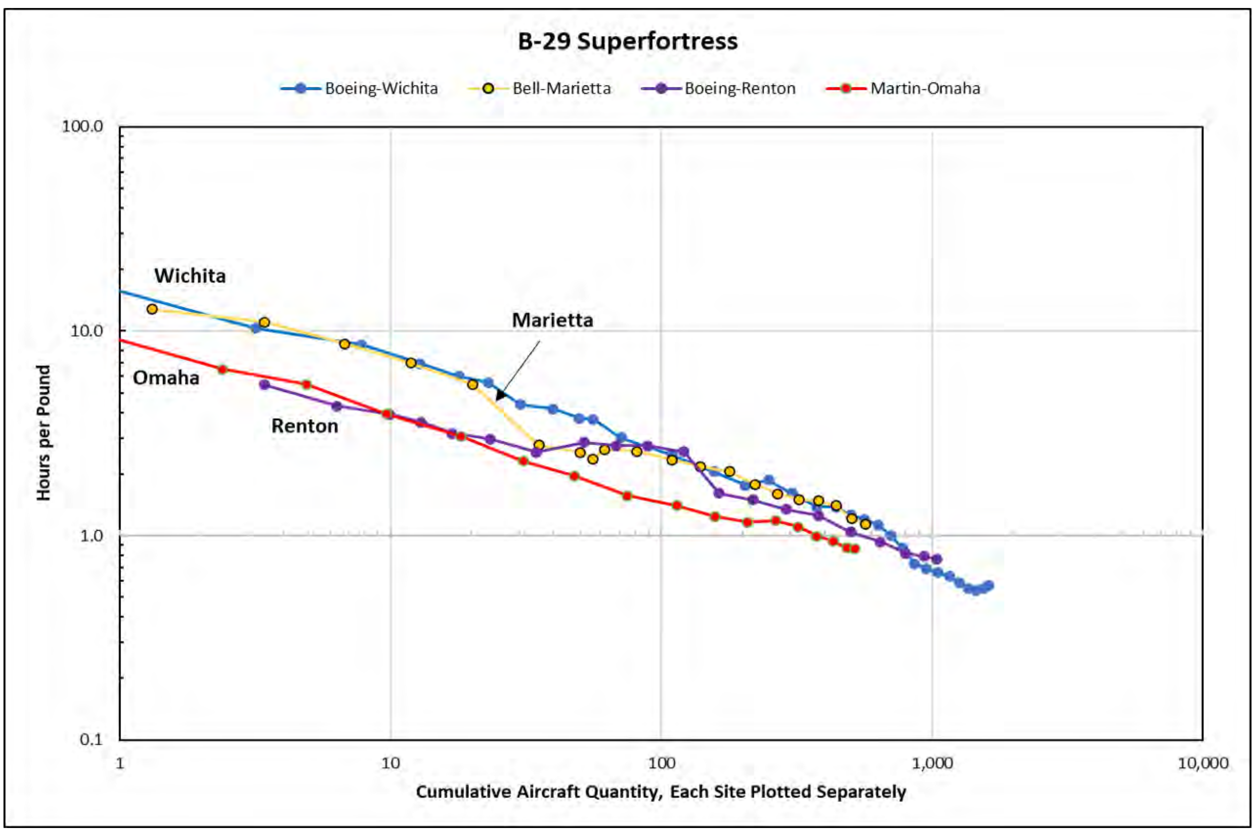

Figure 9. B-29 Superfortress Hours per Pound (II

Table 3 summarizes the performance of the four sites in terms of learning curve slopes, percent learning loss and percent unit setback. It also asks if the coproducing sites were able to achieve convergence with the lead site's learning curve, and if they were able to produce at an eventual lower cost than the lead.

Like the B-17, the B-29 program had a coordinating committee among the build companies. However, several factors kept the B-29 committee from performing as successfully as its B-17 predecessor. First, the B-29 program was originally intended to pair Boeing with North American and the Fisher Body Division of General Motors. However, these companies eventually dropped as prime contractors and were replaced by Martin and a second Boeing plant in Renton. In addition, the B-29's design was highly experimental, resulting in a high degree of engineering changes. Finally, five other companies –Chrysler, Hudson, Goodyear, McDonnell, and Republic – provided major components and assemblies to the prime contractors. These factors significantly complicated production coordination and the sharing of knowledge. Historian Irving Holley writes, "The B-29 program was the most complex joint production undertaking of the war." (Holley, 1964)

The B-29's prime coproducers experienced between 14% to 49% learning loss. Boeing's Renton plant showed the lowest degree of learning loss. Like Consolidated's San Diego and Fort Worth B-24 plants, the Renton plant was initially staffed with a management and engineering cadre from Seattle and Wichita. (Mishina, 1999) For the other two coproducers, Omaha achieved 36% learning loss while Marietta experienced 49% loss. Only two coproducers (Renton, Omaha) reached convergence with Boeing-Wichita's learning curve, and none of the coproduction sites achieved a lower hours per pound than the lead Wichita site.

B-29 Superfortress		*Lead*	*Coproducer*	*Coproducer*	*Coproducer*
		Boeing Wichita	**Bell Marietta**	**Boeing Renton**	**Martin Omaha**
Initial Build Plotted as T-1	Actual 1st Lot (Hrs/Lb)	16.15	12.77	5.45	9.25
	Theoretical First Unit (TFU) (Hrs/Lb)	22.81	16.30	9.09	9.05
	Unit Curve Coefficient	(0.4883)	(0.4168)	(0.3382)	(0.3793)
	Unit Curve Slope	71.3%	74.9%	79.1%	76.9%
	R-Square (R^2)	97.8%	96.6%	94.0%	99.4%
	Minimum Hrs/Lb	0.54	1.14	0.77	0.86
Initial Build Plotted at Setback Unit #	Setback Unit on Lead's Learning Curve	N/A	3	19	6
	% Learning Loss	N/A	48.8%	14.2%	36.4%
	% Unit Setback	N/A	94.1%	78.4%	97.6%
	Unit Curve Slope	N/A	72.2%	73.4%	71.7%
Additional Data	1st Delivery	Feb-43	Dec-43	Feb-44	May-44
	Prior Units Produced by Lead	N/A	56	87	267
	Total Aircraft Built	1,642	636	1,096	531
	Achieve Convergence to Lead's Learning Curve?	N/A	No	Yes	Yes
	Achieve Lower Cost Than Lead?	N/A	No	No	No

Table 3. B-29 Superfortress Cost Performance by Manufacturing Site

Like the B-17, the B-29 program had a coordinating committee among the build companies. However, several factors kept the B-29 committee from performing as successfully as its B-17 predecessor. First, the B-29 program was originally intended to pair Boeing with North American and the Fisher Body Division of General Motors. However, these companies eventually dropped as prime contractors and were replaced by Martin and a second Boeing plant in Renton. In addition, the B-29's design was highly experimental, resulting in a high degree of engineering changes. Finally, five other companies –Chrysler, Hudson, Goodyear, McDonnell, and Republic – provided major components and assemblies to the prime contractors. These factors significantly complicated production coordination and the sharing of knowledge. Historian Irving Holley writes, "The B-29 program was the most complex joint production undertaking of the war." (Holley, 1964)

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Summary of World War II Experience

Table 4 summarizes the experience of the B-17, B -24, and B-29 coproducers.

We can summarize our conclusions from the World War II data as follows:

- Some degree of learning transfer from the lead to the coproducer occurred in eight of nine cases. Learning loss shows a wide variation from as little to 2% to as much as 106%. The reasons for these extremes have

Aircraft	Coproducer Company/Site	% Learn Loss	Setback Unit	% Setback	Converge to Lead's Cost at Equiv Position?	Best Cost Lower Than Lead's Best?
B-17	Douglas-L. Beach	12%	53.6	95.0%	Yes	Yes
	Lockheed-Burbank	2%	456.7	69.5%	Yes	Yes
B-24	Consolidated-Ft. Worth	3%	113.1	39.9%	Yes	No
	Ford-Willow Run	106%	0.9	99.9%	Yes	Yes
	Douglas-Tulsa	47%	5.1	99.6%	Yes	No
	N. American-Dallas	54%	3.8	99.8%	Yes	No
B-29	Bell-Marietta	49%	3.3	94.1%	No	No
	Boeing-Renton	14%	18.8	78.4%	Yes	No
	Martin-Omaha	36%	6.3	97.6%	Yes	No
Statistics	Mean	36%	73.5	86.0%	N/A	N/A
	Median	36%	6.3	95.0%	N/A	N/A
	Minimum	2%	0.9	39.9%	N/A	N/A
	Maximum	106%	456.7	99.9%	N/A	N/A

Table 4. Summary of Bomber Coproducer Experience

already been discussed, but in general the more successful the lead company's technology transfer, the lower the learning loss. On average, 36% learning loss (or alternatively, a 64% learning gain) was achieved during World War II coproduction.

- Percent setback varies from a minimum of 40% to a maximum of 100% with an average of 86% (mean) and 95% (median)
- In eight of nine cases, the coproducer converged to the lead company's learning curve.
- In three of nine cases, the coproducer eventually produced at a lower cost than the lead company.

Comparison to Current Experience

Fast forward 80 years. Military aircraft today are manufactured using advanced materials (titanium and composites) unknown to World War II designers. Fighters and bombers perform at supersonic speed with jet engines, not in the subsonic environment with turboprops. Aircraft are stuffed with electronic computers which can fly and maneuver the aircraft, operate its weapons systems, and allow a fighter pilot to engage his target far beyond visual range. Parts and assemblies are manufactured to previously unachievable tolerances to appear nearly invisible on enemy radar screens. So, are these conclusions – drawn from a war our grandparents and great -grandparents fought – still valid?

Ideally, we could test this hypothesis by looking at postwar data with smaller production runs. However, there is limited data for military aircraft to be built in two locations inside the United States. There are only three such cases, all of them from the 1950s, the North American F-86 and F-100 and the Boeing B-52. However, the published data provides little insight into the questions we are considering. (Rich, 1981, Cook, 2002)

However, if we look not at the total aircraft level, but at individual components and consider either foreign coproduction or cases where work was incrementally transferred from one site to another, the available dataset begins to expand.

Due to the proprietary nature of this data, it can only be discussed at a high level without any program identification. All these cases, however, represent components with a lead manufacturing site and a coproducing second source brought in later during the program life cycle. All have occurred within the past 30 years. In addition, all had robust technology transfer programs to reduce program risk and enable the second source to come up to speed as quickly as possible by sharing production and tooling lessons learned.

	% Learn Loss	% Setback	Converge to Lead's Cost at Equiv Position?	Best Cost Lower Than Lead's Best?
Component A	28%	64%	Yes	Yes
Component B	23%	71%	Yes	Yes
Component C	40%	82%	Yes	Yes
Component D	31%	94%	Yes	No
Component E	44%	88%	No	No
Component F	56%	95%	No	No
Mean	37%	82%	N/A	N/A
Median	35%	85%	N/A	N/A
Minimum	23%	64%	N/A	N/A
Maximum	56%	95%	N/A	N/A

Table 5. Modern-Day Manufacturing Coproduction.

Table 5 shows the mean learning loss in our modern sample is almost identical to the World War II experience – 37% versus 36%. The range of learning loss in the modern sample is substantially narrower. This percentage is not surprising since in all these cases the lead site pushed hard to make a successful learning transfer. There is no modern-day equivalent of Ford's Willow Run experience.

As a secondary data point, in its 2002 analysis of F-35 final assembly alternatives RAND assumed that learning transfer in a work split was analogous to a production gap. The analogy assumes that after a production gap learning gains attributable to shop personnel would be lost but gains attributable to methods improvements could be retained. The retained learning is the same kind of knowledge which could be transferred from a lead to a second manufacturing site. Based on prior research, RAND calculated learning retention of 30-88%, with an average of 64% retained learning after a production gap. (Said alternately, RAND observed 36% lost learning). (Cook, 2002). Coincidentally, that 36% learning loss assumption exactly matches the observed World War II learning loss in Table 4.

Like the World War II experience, in four of the six modern-day cases in Table 5, the second source was able to converge to the lead site's learning curve. Less often, the second source was able to produce at lower hours per unit than the lead site. A discussion of why that occurred might potentially disclose sensitive information: therefore, we only note that it happened and leave the "How?" and "Why?" to a different forum.

Conclusions

How might this data assist an estimator dealing with a second-source manufacturing situation? Let us revisit our four propositions:

Proposition 1: The second source will show some degree of learning transfer – that is, it will not begin back at the lead's T-1 cost – but it will not completely transfer all the lead's learning, either.

True. In all but one of the World War II cases, there was learning gain from the lead site. In the only case where there was not – Ford's B-24 Willow Run plant – Ford explicitly rejected Consolidated's manufacturing and tooling philosophy in lieu of its automotive-based approach. This rejection was an unusual situation unlikely to be repeated in a modern second-source case study. Exactly how much learning transfer should be assumed by the estimator depends however on the strength of the technology transfer program, leading us to our second proposition.

Proposition 2: A concerted effort by the lead site to foster technology transfer should improve the learning gain achieved by the second source, resulting in a lower-cost break-in.

True. The World War II data shows a wide variation in learning loss experience. For the B-17, B-24 and B-29, successful technology transfer depended on the lead's ability to communicate engineering and production knowledge to the second sources. Learning loss was minimized in cases where there was successful cross-company coordination (the B-17's BDV committee) or the second source happened to be a sister plant which absorbed a cadre of engineers and management from the lead site (B-24 Fort Worth, B-17 Renton). Learning loss was greater when there were difficulties in the engineering handoff (B-24 Willow Run, B-24 North American), when the lead site was poorly prepared for the transfer (B-24 San Diego) or the second source rejected the lead company's manufacturing approach and instead struck out on their own (Willow Run, again).

In a world of Computer Aided Three-Dimensional Interactive Application (CATIA) and other 3-D modeling tools, the engineering handoff should be much easier compared to the primitive design tools of 80 years ago. But even in a modern era, the handoff can pose difficulties. In the shipbuilding industry, where production at multiple shipyards is more common, the use of incompatible design and analysis tools for CAD/CAM at different sites has posed significant problems. (Cook, 2002)

Other factors can influence the transmission of manufacturing and tooling lessons learned. Amicable business relationships between the two companies were cited as another significant factor in Navy shipyard learning transfers. (Cook, 2002) Contractual arrangements can weigh heavily – for instance, if the two companies are direct competitors fighting over a share of production, there may be a strong *disincentive* to cooperate.

It is tempting for the estimator to use 36% as a default assumption. In the end, the estimator must make a careful analysis of the technology transfer program and the experience and capabilities of the companies involved to determine how successful he believes the learning transfer will be – a decision difficult to quantify, and largely judgmental.

Proposition 3: The second source will not fully converge to the lead company's learning curve – that is, the two lines will not intersect.

Frequently untrue. The World War II data suggests our theoretical construct of second source learning is partially incorrect. Theory suggests a coproducer can only asymptotically approach the lead's cost performance. The World War II data shows under the right circumstances, the second source can intersect the lead company's learning curve. This occurred primarily because the second source's learning curve slope was slightly steeper than the lead site's. However, it is important to note that all the second source bomber manufacturers had large production runs (ranging from 500 to 8,000 aircraft) which gave them an opportunity for convergence. If those production runs had been smaller -- say, only 50 or 100 units – such performance would probably have been impossible.

Choosing a learning curve slope for projection is always treacherous and adding a second source does not make it any less so. Without a better appreciation for why the slopes were steeper – difficult to ascertain after eight decades – it is difficult to provide guidance. The estimator's tolerance for risk also comes into play. Assuming the second source will perform at the same learning curve slope as the lead company is a conservative choice, but it may serve where a more risk-adverse estimate is desired.

Proposition 4: The second source will not be able to produce at a lower cost than the lead company – that is, the coproducer's best hours per pound performance will always be greater than the lead company's best hours per pound performance.

Usually, but not always true. In most cases, the second source will not perform at a lower hours per pound than the lead site. Yet successful instances appear in the World War II data if the degree of learning loss is low (B-17 assembly lines at Long Beach and Burbank) or if the second source's manufacturing and tooling approach proves superior (Willow Run). Either instance would require an extended production run by the second source to play out, however. Another possible scenario where a second source might provide lower costs could arise from an aircraft with multiple models. If the second source is permitted to concentrate on a single model while the lead site must build more than one variant – and experience the attending loss of learning and disruption – it is conceivable the second source could demonstrate better cost performance. That scenario did not appear in the World War II data, however, so it remains untested.

This proposition provides a lower bound for learning curve slopes. If the second source's learning curve slope creates projections where the coproducer has a lower cost than the lead site, the estimator should recognize this for a lesser probability scenario and possibly alter his choice.

Caution:

A final word. It is important to note what we have *not* attempted to prove here: that the use of a second-site manufacturing facility is cost-effective in terms of the total program cost. That would require an analysis of relative labor rates, overhead impacts, production capacity, additional overseas sales generated by the inclusion of foreign industry, domestic industrial base considerations, etc. and is far beyond the scope of this paper. The analysis of second-site manufacturing is only one piece of a much larger puzzle.

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