
A model for comparing sourcing strategies for parts in long life cycle products subject to long-term supply chain disruptions

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Abstract: Long life cycle products, commonly found in aviation, medical and critical infrastructure applications, are often fielded and supported for long periods of time (20 years or more). The manufacture and support of long life cycle products rely on the availability of suitable parts, which over long periods of time, leaves the parts susceptible to a number of possible supply chain disruptions such as suppliers exiting the market, counterfeit part risks, and part obsolescence. Strategic sourcing offers one way of avoiding the risk of part unavailability (and its associated penalties) but at the expense of qualification and support costs for multiple suppliers. Existing methods used to study part sourcing decisions are procurement-centric where cost tradeoffs focus on part pricing, negotiation practices and purchase volumes. These studies are commonplace in strategic part management for short life cycle, high-volume products; however, procurement-driven decision-making provides little or no insight into the accumulation of life cycle cost (attributed to the adoption and use of the part), which can be significantly larger than procurement costs for long life cycle, low-volume products.

This paper presents a methodology to perform tradeoff analyses and identify the conditions under which sourcing strategies (with a predetermined number of suppliers) will be cost effective based on the organization's capability to streamline qualification and support activities. The method utilizes a part total cost of ownership (TCO) approach to identify the life cycle cost tradeoffs between extending a part's procurement life through multi-sourcing versus the additional cost of qualifying and supporting the alternative sources for long life cycle product applications. The method is demonstrated for electronic parts in an example case study of linear regulators subject to obsolescence and shows that the cost of qualifying and supporting a second source determines if the organization is likely to benefit from extending the part's effective procurement life when procurement and inventory costs are small contributions to the part's TCO. The model presented offers a means to determine the "break-even" learning index necessary to make a second sourcing strategy viable.

Keywords: learning curve; obsolescence; part management; procurement life; supplier qualification; sustainment

1 Introduction

Products can be categorized into long life cycle and short life cycle products. Popular consumer electronics, such as personal computers, mobile phones, GPS (global positioning systems), etc., have relatively short procurement lives and are replaced with newer products within a few years of their market introduction (usually 5 years or less). Long life cycle products, such as those used in aerospace, military, communications infrastructure, power plants, and

medical applications, remain in use significantly longer (often 20 years or more). Long life cycle products, because of their relatively low-volume requirements, often do not control their own supply chains and must draw their parts from the same supply chain as high-volume products. Electronic parts are an example where all products, regardless of their market, must draw parts from the same supply chain; the outcome is a relatively high frequency of involuntary part obsolescence (Sandborn, 2008). As a result, the assessment and management of parts used in long life cycle electronic products differs significantly from their short life cycle counterparts.

Two types of supply-chain disruptions can occur for products:

- 1) *Short-term disruptions* - temporary problems that usually only affect a limited number of products that share the part for a short period of time, e.g., you receive a defective batch or lot of parts, or this week's delivery of parts is going to be two days late, etc. Short-term disruptions usually impact manufacturing processes.
- 2) *Long-term disruptions* - problems that make it impossible for an organization to continue using the part, e.g., reliability issues, changes made to the part by the part manufacturer, or the part becomes unprocurable (obsolete). Long-term problems affect all products that share the part and require that a permanent solution (often a different replacement part) must be found. Examples of long-term problems are discontinuance of the part (obsolescence), supplier unavailability, functional design error in the part, counterfeit part issues, and reliability problems with the part. Long-term disruptions may impact manufacturing, but more often impact the ability to support a long life cycle product over a long period of time, e.g. maintenance and sparing.

Short-term supply chain disruptions have been extensively studied and are an important aspect of supply-chain research for both short life cycle and long life cycle products (Wilson, 2007; Tomlin, 2006; Yu *et al.*, 2009; Christopher and Lee, 2004; Tang, 2006). This paper will focus on assessing and mitigating long-term supply chain disruptions which are especially relevant to long life cycle products where resolutions are often complex and expensive to implement.

Sourcing strategies (e.g., sole-, single-, second-, dual-, and multi- sourcing) are often adopted to mitigate supply chain disruptions as well as reduce procurement cost by promoting competition between suppliers. Although, supply chain risk subject to sourcing-related uncertainties has been extensively studied for high-volume, short life cycle products (e.g., Li and Debo, 2009; Gurnani and Ray, 2003; Gaonkar and Viswanadham, 2004; Ruiz-Torres and Tyworth, 2000, and others), the applicability of the existing work to long life cycle products is unknown. Existing methods used to study part sourcing decisions, especially for high-volume consumer oriented applications, are procurement-centric where cost tradeoffs at the part level focus on part pricing, negotiation practices and purchase volumes (Lyon, 2006; Anton and Yao, 1990; Riordan and Sappington, 1989; Laffont and Tirole, 1993). These studies are commonplace in strategic part management for short life cycle products; however, conventional procurement-centric approaches offer only a limited view of the assessment of parts used in long life cycle products providing little to no insight into the accumulation of life cycle cost (attributed to the adoption and use of the part over a long period of time), which can be significantly larger than procurement costs in long life cycle products (Prabhakar and Sandborn, 2012). Previous research shows that procurement price of an electronic part has almost no correlation to life cycle cost for small part volumes in products that are supported for long periods of time (Prabhakar and Sandborn, 2012). In addition, like short life cycle products, the impact of supply chain failure has been recognized as a major concern in the manufacturing and sustainment of long life cycle products. The impact of the risk and the cost of mitigating supply chain disruptions for long life cycle products in particular have not been quantified yet. For example, obsolescence status and forecasts for electronic parts are available through commercial databases, however, the interpretation and application of the forecasted obsolescence characteristics to optimize sourcing and inventory management has only been qualitatively implied and no quantitative treatments have appeared.

This paper presents a life cycle modeling approach to compare sourcing strategies for parts used in long life cycle products and systems wherein qualifying and supporting alternative part sources offers a means to reduce the risk of long-term supply chain disruptions. The methodology presented in this paper can be used to: 1) quantify the part total cost of ownership (TCO) for a multi-sourcing strategy, 2) set targets for "stream-lining" qualification and support activities for multiple sources represented by learning curves, and 3) develop a business case for utilizing a particular multi-sourcing strategy based on a part's effective TCO. The comparison of various sourcing strategies for

use in long life cycle systems provides application-specific insight into the cost benefits of each strategy as a proactive approach to mitigate supply chain disruptions. The analyses presented in Prabhakar and Sandborn (2012) indicate that the money spent on qualification and approval (categorized as “support costs”) are the largest contributors to the part’s TCO in low-volume, long life cycle products; in high-volume products, these support costs would be distributed over higher volumes and thus have a much smaller impact on a “per part” basis. The problem is exacerbated when these support costs are effectively multiplied with the addition of extra part sources or suppliers. For example, some portion of the supplier qualification process must be repeated before a second supplier can be used if dual or second sourcing strategies are implemented. In addition, parts from multiple sources may need to be qualified for use in many (if not all) of the products that the part is designed into resulting in a duplication of product-related support costs. Using a part in multiple products could also potentially lead to expensive design changes following a supply chain disruption if the alternative part is not a direct “drop-in” replacement. The next section describes a modification to TCO models to address alternative sourcing strategies.

2 Total Cost of Ownership (TCO) of Sourcing

The part TCO is a function of the timing of a supply chain disruption event and the impact the event has on the characteristic usage of the part within the original equipment manufacturer (OEM). This section presents a part TCO model to assess the life cycle cost impacts of different sourcing strategies as a function of the date of supply chain disruptions.

The part total cost of ownership (TCO) is the total cost spent at various stages of the part’s life cycle: procurement (C_{PROC}), inventory (C_{INV}), support (C_{SUP}), assembly (C_{ASY}), and field failure repairs (C_{FF}). Let C_{TCO} be the part TCO as a function of the disruption date, D , and sourcing strategy, s . The general form, shown in (1), is the basis for part TCO models.

$$C_{TCO}(s, D) = C_{PROC}(s, D) + C_{INV}(D) + C_{SUP}(s, D) + C_{ASY} + C_{FF} \quad (1)$$

There are various implementations of TCO models, all include some combination of the terms in (1), (e.g., Prabhakar and Sandborn, 2012; Ellram and Siferd, 1998). This paper focuses on estimating the support cost, C_{SUP} , to support multi-sourcing.

Let C_i^x be the annual contributions to the support cost from a support activity x during the i th year of being used in the organization. Let n be the number of support activities in vector x . Let N_s^{SUP} be the number of suppliers in sourcing strategy s and p be a supplier’s index. Then $C_{SUP}(D, B^x, N_s^{SUP})$ is the total support cost after j years when a disruption occurs in year D and subject to an annual discount rate r , assuming that the cost of support activity x (part and product qualification, annual data management, production support, annual purchasing, etc.), is subject to a learning index, B^x .

$$C_{SUP}(D, B^x, N_s^{SUP}) = \sum_{i=1}^j \frac{\sum_{x=1}^n \sum_{p=1}^{N_s^{SUP}} C_i^x(D) p^{B_i^x}}{(1+r)^i} \quad (2)$$

An implementation of the Crawford or Boeing model (Crawford, 1944; Swamidass, 2000) for supplier-related support cost is shown in (2). In (2), learning curves are applied to support cost components in the “bottom-up” costing approach. Incorporating learning curves into the total cost of ownership offers a means to capture the decrease in cost to support multiple suppliers wherein information gathered on prior attempts reduces the time, effort, or other resources needed for subsequent attempts of the same activity.¹

¹ Lyon (2006) applies learning curves to represent learning effects responsible for promoting collusion between suppliers in dual sourcing. Conditions for estimating learning curves using price data are discussed in Lieberman (1984).

In (2), if $B_i^x = 0$, then no learning occurs and all support activities are completely repeated for each subsequent supplier (e.g., the cost of supporting two suppliers is exactly double the cost of supporting one supplier). If $B < 0$ then support activities (and thereby, support cost) decreases for subsequent suppliers (e.g., the cost of supporting two suppliers is less than double the cost of supporting one supplier). For example, when $B = -\infty$, then the addition of subsequent suppliers requires no additional support activities and therefore adds no support cost. Similarly, if $B > 0$ then support cost increases for subsequent suppliers (e.g., the cost of supporting two suppliers is more than double the cost of supporting one supplier).

The number of suppliers, N_s^{SUP} , is dependent on the sourcing strategy used, s . For example, $N_s^{SUP}=1$ for single sourcing and $N_s^{SUP} = 2$ for second sourcing. However, the number of suppliers that actually require a particular support activity may be unique to the type of sourcing strategy and may vary annually. In practice, the activities performed for different sourcing strategies may differ despite using the same number of suppliers. For instance, second sourcing and dual sourcing both use two suppliers; however, parts are procured from the two suppliers interchangeably when second sourcing is used. When dual sourcing, parts are procured from both suppliers simultaneously (i.e., purchase orders are separated effectively doubling the resources needed for generating purchase orders). In order to distinguish between two sourcing strategies, an array of N_s^{SUP} is used to define the characteristics of the sourcing strategy to model support cost (where $N_{sx}^{SUP} \leq N_s^{SUP}$). Some example (sourcing-specific) arrays of the variable N_s^{SUP} with respect to various support activities, x is shown in Table 1.

Table 1 – Example matrix for the number of suppliers (N_{sx}^{SUP}) for which support cost components (x) are applicable with respect to various sourcing strategies.

Support cost components (x)	Number of suppliers (N_{sx}^{SUP})		
	Single	Second	Dual
Initial Approval	1	2	2
Part NRE Cost	1	2	2
Product-Specific Approval	1	2	2
Supplier Qualification	1	2	2
Annual Part Data Management	1	2	2
Annual Production Support	1	1	2
Annual Purchasing	1	1	2
Obsolescence Case Resolution	1	1	2

Section 3 presents the problem statement, discusses the solution strategy used in this paper, and discusses the implementation of a part TCO model to assess cost tradeoffs between two sourcing strategies² subject to a supply chain disruption (when the number of sources is predetermined and the corresponding effective disruption dates are known).

3 Model Formulation

This paper provides a means to perform tradeoff analyses and identify the conditions under which a set of sourcing strategies with N_s^{SUP} suppliers will be cost-effective based on the organization's capability to streamline qualification and support activities.

² This paper considers only supply chain disruptions associated with the of COTS (Commercial off the shelf) parts. The formulation of a sourcing strategy refers to the selection and qualification of a finite number of suppliers from which the COTS parts can be procured. The word "sources" refers to the part's "suppliers".

The maximum allowable cost and resources to support a second source in order for a second sourcing strategy to be viable can be determined mathematically. This paper extends a part TCO model to estimate the life cycle cost impact of long-term part sourcing based on assumptions specific to part sourcing in long life cycle electronic products and systems.

This section applies the part TCO model to sourcing tradeoff analyses for long life cycle product applications. The part TCO can be represented as $C_{TCO}(D_s, B_s, N_s^{SUP})$. Let D_s be the effective disruption date and let B_s be the learning index of all support activities when sourcing strategy s is adopted. The sourcing strategy s is defined by the number of suppliers/sources used, N_s^{SUP} .

The difference in C_{TCO} between two strategies that use different sourcing strategies (strategies “ a ” and “ b ”) is given by (3),

$$[\Delta C_{TCO}]_{a,b} = [C_{TCO}(D_a, B_a, N_a^{SUP})]_a - [C_{TCO}(D_b, B_b, N_b^{SUP})]_b \quad (3)$$

Let D_a and D_b be the effective part supply chain disruption dates associated with the two sourcing strategies (i.e., two combinations of suppliers), a and b . As an example of a quantifiable disruption with known uncertainties, we will use part obsolescence for our example analysis in Section 5 (see Appendix A for a detailed description of this disruption).

The objective of this solution is to identify the “break-even” learning index between two potential part sourcing strategies. In the context of this paper, learning indices for multi-sourcing support cost, B , are said to be at “break-even” when the resulting TCO of the two sourcing strategies being compared, strategy a and strategy b , (subject to independent disruption dates) are equal; i.e., $[\Delta C_{TCO}]_{a,b}$ becomes zero. If a learning index below the break-even learning index is possible then a benefit from a multi-sourcing strategy is possible.

The analysis incorporates sourcing-related disruption dates to determine the “break-even” learning index, B_{BE} , relative to a threshold learning index, B_{TH} , which defines the minimum achievable learning index imposed on the part support process. This method is demonstrated in an example case study (Section 5) of linear regulators with a focus on the comparison of single and second sourcing.

In order to evaluate the analytical C_{TCO} , the following assumptions are made:

1. The cumulative part assembly cost, C_{ASY} is constant for a given part demand profile and is not affected by the sourcing strategy used. It is assumed that supplier-specific part quality (defect rates) are the same for all suppliers, therefore there is no change in the effective yield across the entire population of parts. The assembly cost is then independent of the number and selection of suppliers from which the part is procured. Subsequent calculations include assembly cost in order to maintain proportionality in part TCO and can be calculated as a function of annual part demand, N_i^{VOL} . Note: part procurement price will be considered independent of the assembly cost henceforth.
2. The product warranty period is shorter than the part’s earliest possible wear-out failure under the expected operating conditions (most electronic parts, even in long field life applications, rarely reach wear-out). Failures due to infant mortality and random failures during the useful life are assumed to be negligible. Therefore, $C_{FF} \approx 0$. Note, based on this assumption, the number of parts (procured) are equal (i.e., no replacement parts are needed).
3. Non-recurring support activities (such as qualification and validation) are all performed in year 1.
4. Learning indices, B_i^x are assumed to be constant for all organization-specific support activities, x , and do not change over time. For example, $B_i^{as} = B_i^{op} = \dots = B_i^n = B$ and $B_1^x = B_2^x = \dots = B_j^x = B$

5. TCO over the product usage life cycle of the part is an accumulation of spending up to year j ; cost saved or recovered (e.g., part salvaging) is not considered in the TCO model, i.e., $C_{PROC} \geq 0$, $C_{INV} \geq 0$, $C_{SUP} \geq 0$, $C_{ASY} \geq 0$, $C_{FF} \geq 0$.
6. The number of suppliers, N_{sxi}^{SUP} , for a sourcing strategy s in year i does not change throughout the part's procurement life cycle unless the part is no longer procurable from a particular supplier involved in the sourcing strategy (i.e., supplier-specific part obsolescence). For example, $N_{sx1}^{SUP} = N_{sx2}^{SUP} = \dots = N_{sxj}^{SUP} = N_{sx}^{SUP}$. Also, for a sourcing strategy, s , all suppliers require the same set of support activities x . Let the size of vector x (consisting of support activities) be n . Therefore, $N_{s,as}^{SUP} = N_{s,ap}^{SUP} = \dots = N_{sn}^{SUP} = N_s^{SUP}$.
7. The part price, P_{pi}^{SUP} is the same for all suppliers that parts are procured from (where supplier index, p goes from 1 to N_s^{SUP}) and all the parts are subject to the same annual price change, i.e., $P_{1i}^{SUP} = P_{2i}^{SUP} = \dots = P_{N_s^{SUP}i}^{SUP} = P_i^{SUP}$. For low-volume part procurement, second or multiple sources are usually not selected based on part price. The case studies presented in Prabhakar and Sandborn (2012) indicate that procurement price is a small contribution to the life cycle cost for low volume, long life products.

The following presents the formulation of the part TCO model based on the seven assumptions stated above.

Based on assumption 7, the total part procurement cost when multi-sourcing can be simplified to the form shown in (4), which assumes the same part price, P^{SUP} , across all suppliers subject to the same annual price change d .

$$C_{PROC}(D_s) = \sum_{i=1}^j \frac{P^{SUP} N_i^{PROC}(D_s)}{(1+d)^{i-1} (1+r)^i} \quad (4)$$

The total part quantity procured from all suppliers in year i is, N_i^{PROC} , which is a function of effective disruption date D_s when sourcing strategy s is adopted, and annual part demand volume, N_i^{VOL} . If the disruption is the discontinuance of the part by a manufacturer (part obsolescence) then N_i^{PROC} is given by,

$$N_i^{PROC}(D_s) = \begin{cases} N_k^{VOL} & \rightarrow \text{if } i < D_s \\ (1 + F_{overbuy}) \sum_{k=D_s}^j N_k^{VOL} & \rightarrow \text{if } i = D_s \\ 0 & \rightarrow \text{if } i > D_s \end{cases} \quad (5)$$

The equation for N_i^{PROC} in (5) when $i = D_s$ assumes that a lifetime buy³ is made (the quantity of which is the sum of the demand volume in all years from D_s to the end of the support life for the part) including a buffer/overbuy, $F_{overbuy}$ as a fraction of the lifetime buy quantity. The effective obsolescence date depends on the sourcing strategy used.⁴ Other forms of N_i^{PROC} can be created for other types of disruptions.

³ A lifetime buy means that when the discontinuance date for a part is announced (i.e., the obsolescence date), the total future demand for a part is estimated, procured and stored in inventory to support future production and sparing needs. Usually the forecasted demand is increased by a buffer (expressed as a fraction of the actual demand quantity) to account for unforeseen demand.

⁴ The "effective" obsolescence date of a part associated with a particular sourcing strategy is the observed obsolescence date as a result of N_s^{SUP} suppliers. For example, the effective obsolescence date of a second sourcing strategy is the later of the obsolescence dates of the two suppliers' parts, see Appendix A (specifically Figure A.2) for an example.

Let $C_{TCO}(D_s, B_s, N_s^{SUP})$ be the part TCO for a sourcing strategy s after j years. The part TCO depends on procurement, inventory, support, assembly and field failure costs, and can be rewritten, based on the assumptions above, in terms of disruption date, D_s , learning index for support cost, B_s , and the number of suppliers from which parts are procured, N_s^{SUP} , as shown in (6).

$$C_{TCO}(D_s, B_s, N_s^{SUP}) = C_{PROC}(D_s) + C_{INV}(D_s) + \left(\sum_{p=1}^{N_s^{SUP}} C_{SUP}(D_s) p^{B_s} \right) + C_{ASY} \quad (6)$$

Section 4 applies the part TCO model discussed in this section to tradeoff analyses between various part sourcing strategies. The part TCO model is also used to solve for break-even learning indices that indicate the conditions under which a sourcing strategy will be cost-effective.

4 Comparison of Sourcing Strategies

This section discusses a method to utilize a part TCO model to estimate the difference in TCO between two sourcing strategies based on sourcing-specific disruption dates. This section also discusses a method to estimate a “break-even” learning index for a second sourcing strategy (implemented to extend the procurement life of a part) that would result in a TCO equal to that of a single sourcing strategy. This section also presents a general form for calculating the break-even learning index to assess multi-sourcing against single sourcing strategies.

4.1 Comparing TCO of single sourcing strategies

This section quantifies the TCO difference between two single sourcing strategies as a function of the disruption dates of the single sourced parts. For single sourcing, learning index, B , is not required (and meaningless) since $N_a^{SUP} = N_b^{SUP} = 1$. Learning indices only apply to sourcing strategies with two or more suppliers. Therefore, the equation for ΔC_{TCO} at year j comparing two single sourcing strategies (strategy “ a ” vs. strategy “ b ”) under the assumptions stated in Section 3 is,

$$[\Delta C_{TCO}]_{a,b} = [C_{TCO}(D_a)]_a - [C_{TCO}(D_b)]_b \quad (7)$$

where D_a and D_b are obsolescence dates for two single sourcing strategies. Therefore, the difference in TCO after j years between two single sourcing strategies can be written as follows,

$$\Delta C_{TCO_j} = [C_{PROC}(D_a) + C_{INV}(D_a) + C_{SUP}(D_a)] - [C_{PROC}(D_b) + C_{INV}(D_b) + C_{SUP}(D_b)] \quad (8)$$

Note, as stated in the assumptions, C_{ASY} is the same for both sourcing strategies (“ a ” and “ b ”) and is independent of disruption date. Therefore, for single sourcing, the difference in TCO for two single sourcing strategies after j years is given in (9),

$$\Delta C_{TCO} = \Delta C_{PROC} + \Delta C_{INV} + \Delta C_{SUP} \quad (9)$$

where,

$$\Delta C_{PROC} = C_{PROC}(D_a) - C_{PROC}(D_b) \quad (10)$$

$$\Delta C_{INV} = C_{INV}(D_a) - C_{INV}(D_b) \quad (11)$$

$$\Delta C_{SUP} = C_{SUP}(D_a) - C_{SUP}(D_b) \quad (12)$$

4.2 Part sourcing TCO tradeoffs (single sourcing vs. second sourcing)

This section compares the TCO of single sourcing (strategy “a”) versus second sourcing (strategy “b”) a part. The learning index for strategy “a”, B_a may be omitted from (6) since the learning index for a single sourcing strategy does not apply. Therefore, the learning index of strategy “b”, B_b constitutes the break-even learning index that is of interest in this tradeoff analysis. The part sourcing tradeoff can be represented by,

$$[\Delta C_{TCO}]_{a,b} = [C_{TCO}(D_a)]_a - [C_{TCO}(D_b, B_b, N_b^{SUP})]_b \quad (13)$$

Substituting $N_a^{SUP} = 1$ for single sourcing and $N_b^{SUP} = 2$ for second sourcing into (13), we get the resulting equation for ΔC_{TCO} after j years for the two sourcing strategies of interest (single vs. second sourcing) under the assumptions stated in Section 3 and derived from (6) to be,

$$\Delta C_{TCO} = [C_{PROC}(D_a) + C_{INV}(D_a) + C_{SUP}(D_a)] - \left[C_{PROC}(D_b) + C_{INV}(D_b) + \sum_{p=1}^2 C_{SUP}(D_b) p^{B_b} \right] \quad (14)$$

where D_a and D_b are disruption dates when single sourcing and second sourcing respectively. Second sourcing offers a redundancy in the supply of parts which means that D_b is effectively the later of the two supplier-specific disruption dates.

$$\Delta C_{TCO} = [C_{PROC}(D_a) - C_{PROC}(D_b)] + [C_{INV}(D_a) - C_{INV}(D_b)] + [C_{SUP}(D_a) - C_{SUP}(D_b)] - C_{SUP}(D_b) 2^{B_b} \quad (15)$$

To identify the learning index, B_b , for which ΔC_{TCO} for the two sourcing strategies is zero (“break-even” point for the two sourcing strategies), the following equation must be solved for B_b ,

$$\Delta C_{PROC} + \Delta C_{INV} + \Delta C_{SUP} - C_{SUP}(D_b) (2^{B_b}) = 0 \quad (16)$$

$$(2)^{B_b} = \frac{\Delta C_{PROC} + \Delta C_{INV} + \Delta C_{SUP}}{C_{SUP}(D_b)} \quad (17)$$

$$B_b = \log_2 \left[\frac{\Delta C_{TCO}}{C_{SUP}(D_b)} \right] \quad (18)$$

Equation (18) allows the learning index at break-even to be calculated based on known effective supply chain disruption dates and single sourcing costs modeled via the part TCO model.

4.3 General form: single sourcing vs. multi-sourcing (“N” suppliers)

To compare a single sourcing case (strategy “a” where $N_a^{SUP} = 1$) against a sourcing strategy with N_b^{SUP} suppliers (strategy “b” where $N_b^{SUP} > 1$), (3) can be rewritten as,

$$\Delta C_{TCO} = [C_{PROC}(D_a) + C_{INV}(D_a) + C_{SUP}(D_a)] - \left[C_{PROC}(D_b) + C_{INV}(D_b) + \sum_{p=1}^{N_b^{SUP}} C_{SUP}(D_b) p^{B_b} \right] \quad (19)$$

$$\Delta C_{TCO} = [C_{PROC}(D_a) - C_{PROC}(D_b)] + [C_{INV}(D_a) - C_{INV}(D_b)] + [C_{SUP}(D_a) - C_{SUP}(D_b)] - C_{SUP}(D_b) \sum_{p=2}^{N_b^{SUP}} (p)^{B_b} \quad (20)$$

To obtain the break-even learning index, the learning index for sourcing strategy b (B_b) must satisfy the following equation where ΔC_{TCO} for the two sourcing strategies is zero.

$$\Delta C_{PROC} + \Delta C_{INV} + \Delta C_{SUP} - C_{SUP}(D_b) \sum_{p=2}^{N_b^{SUP}} (p)^{B_b} = 0 \quad (21)$$

Equation (9) can be represented in terms of the unknown variable, B_{BE} .

$$\sum_{p=2}^{N_b^{SUP}} (p)^{B_{BE}} = \frac{\Delta C_{PROC} + \Delta C_{INV} + \Delta C_{SUP}}{C_{SUP}(D_b)} = K_{(1, N_b^{SUP})} \quad (22)$$

where B_{BE} is the break-even learning index for sourcing strategy b . Substituting ΔC_{TCO} into (18), we get,

$$K_{(1, N_b^{SUP})} = \left[\frac{\Delta C_{TCO}}{C_{SUP}(D_b)} \right] \quad (23)$$

Equation (22) can be solved to find the value of B at “break-even”, B_{BE} , corresponding to ratio⁵, K , as shown in Figure 1. Therefore, the cost tradeoffs between two sourcing strategies (irrespective of the number of suppliers) can be represented by costs from equivalent single sourcing cases as functions of learning indices and obsolescence dates. When solving (22), the introduction of a logarithm function results in there being real and imaginary solutions for break-even learning index, B_{BE} . For the relationship in (18) and (22) to provide a real solution, K must be greater

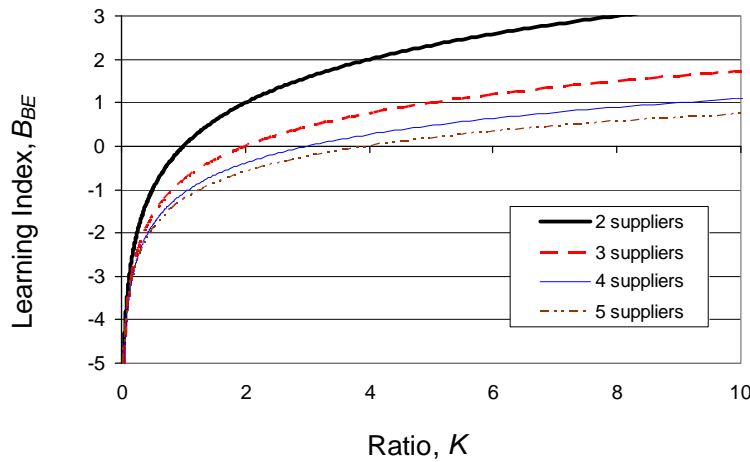


Figure 1 – Plot of break-even learning index, B_{BE} , with respect to the ratio, $K = \Delta C_{TCO}/C_{SUP}$, at break-even (where TCO of a sourcing strategy with N_b^{SUP} number of suppliers is equal to the TCO of single sourcing).

⁵ Subscripts of ratio, K , denote the number of sources being used by the two sourcing strategies being compared.

than 0. This condition implies that ΔC_{TCO} must be greater than 0. The correlation between learning index, B_{BE} and the bounding limits for support cost, C_{SUP} are given by,

$$\begin{aligned} \text{Case 1: } C_{SUP}(D_b) &\rightarrow 0^+ \\ \lim_{C_{SUP} \rightarrow 0^+} B_{BE}(C_{SUP}(D_b)) &= \infty \end{aligned} \quad (24)$$

$$\begin{aligned} \text{Case 2: } C_{SUP}(D_b) &\rightarrow \infty \\ \lim_{C_{SUP} \rightarrow \infty} B_{BE}(C_{SUP}(D_b)) &= -\infty \end{aligned} \quad (25)$$

Section 4.4 provides a summary of the methodology used to evaluate sourcing strategies based on the calculations developed in this section.

4.4 Methodology for evaluating sourcing strategies

The following summarizes the steps in the methodology used to evaluate sourcing strategies based on ratio K and “break-even” learning index, B_{BE} :

1. Populate and calibrate the part total cost of ownership model with key variables/inputs: procurement and inventory costs, support costs, annual demand volumes, annual discount rate, and so on
2. Generate disruption dates for each of the two sourcing strategies that are to be assessed (e.g., obsolescence dates via data-mining): D_a and D_b
3. Estimate single-sourcing total cost of ownership associated with each disruption date and cost difference, ΔC_{TCO} , using (20)
4. Use (23) to calculate ratio K and learning index at the “break-even” condition; these variables can be used as targets to determine the maximum resources (support cost) that can be dedicated to qualifying and supporting a given number of part sources

Steps 3 and 4 can be repeated for a sample size n to perform a Monte Carlo simulation based on supplier-specific disruption distributions (e.g., obsolescence dates sampled from procurement life distributions). The methodology to evaluate sourcing strategies based on ratio K and “break-even” learning index, B_{BE} are demonstrated in the case study presented in Section 5.

5 Estimation of Ratio K and Break-Even Learning Index – A Case Study

The analysis to compare sourcing strategies presented in this section is useful when parts management organizations are aware of limitations in their capabilities and their ability to streamline support activities. For example, the analysis provides the organization with a means to identify a viable multi-sourcing strategy so that support cost learning indices, B^x , are within achievable limits.

This section discusses the comparison of two sourcing strategies in terms of TCO and disruption risk. The example cases will also estimate a break-even learning index subject to a learning index threshold, B_{TH} imposed by the capabilities of the part management organization.

The example problem addressed in this section can be stated as follows:

1. Determine the break-even learning index, B_{BE} for second sourcing linear regulators from two possible suppliers: “X” and “Y”. The inputs for this example are shown in Figure 2. The part demand profile assumed for this case is shown in Figure 3. Additional inputs used to calculate support cost for this example case study are provided in (Prabhakar and Sandborn, 2012).
2. For a particular learning index, what is the maximum allowable inventory cost (per part) that makes a second sourcing strategy viable?

Price (all suppliers), P^{SUP}	\$1.0
Price change (per year), d	0.02
Lifetime overbuy, $F_{overbuy}$	0.10
Discount rate, r	0.10

Strategy	L_P (years)	D_I (year)
Single Sourcing (X)	5	0
Single Sourcing (Y)	10	0
Second Sourcing (X + Y)	10	0

Figure 2 – Inputs for the example case study (L_P is the part’s effective procurement life and D_I is the part’s introduction date).

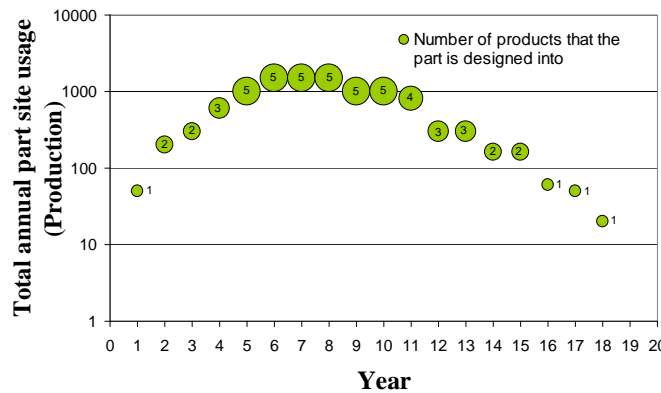


Figure 3 – Part demand volume, N^{VOL} , and number of products using the part for the example case study (total production volume = 10,500 part sites).

This case study demonstrates the methodology to estimate the break-even learning index for second sourcing using the part TCO model. The results are presented as the part TCO (per part site⁶) with respect to the year of support starting at year 1 (e.g., part TCO at year 1 is the cost incurred between year 0 and year 1). The part TCO (per part site) decreases over time since high initial qualification and verifications costs, a characteristic of long life cycle products, are apportioned as parts are consumed by assembly activities. The results show the cost impact of disruptions and are a function of the lifetime buy size and inventory cost. The example case varies inventory cost for the part presented in Figure 2 and Figure 3. For an inventory cost of \$0.1 per part (per year), second sourcing is viable when learning index is $B < -4.22$ as shown in Figure 4. Similarly, when inventory cost is \$10 per part (per year), the required learning index for second sourcing to be cost effective is $B < 1.35$ as shown in Figure 5.

⁶ A “part site” is defined as the location of a single instance of a part in a single instance of a product. For example, if the product uses two instances of a particular part (two part sites), and 1 million instances of the product are manufactured, then a total of 2 million part sites for the particular part exist. In this paper, based on assumption 2 in Section 3, the number of parts required for repairs and replacements is zero (i.e., the number of part sites over the part’s demand life cycle is equal to the total part demand).

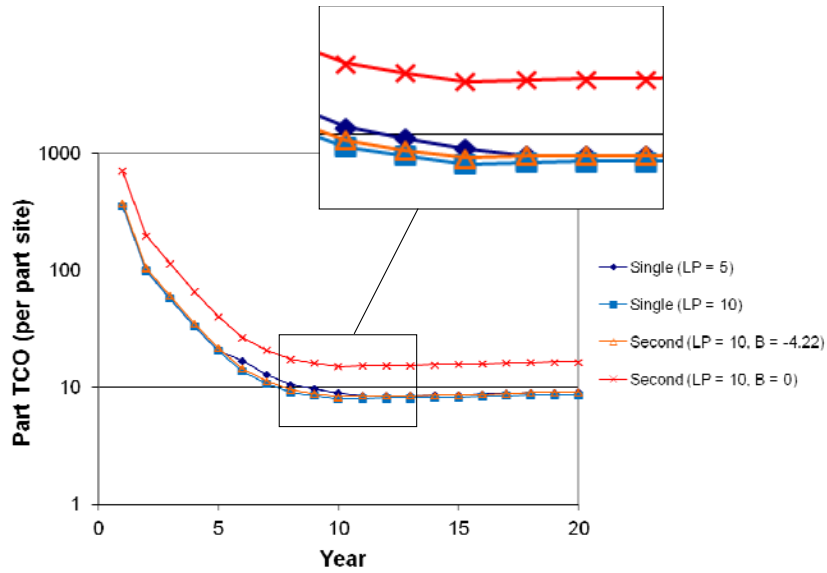


Figure 4 – Part TCO (per part site) versus year of support for the example case where inventory cost is \$0.1 per part. The plot includes an inset figure showing a break-even cost for single sourcing ($L_p = 5$) and second sourcing ($L_p = 10, B = -4.22$) cases after 11 years.

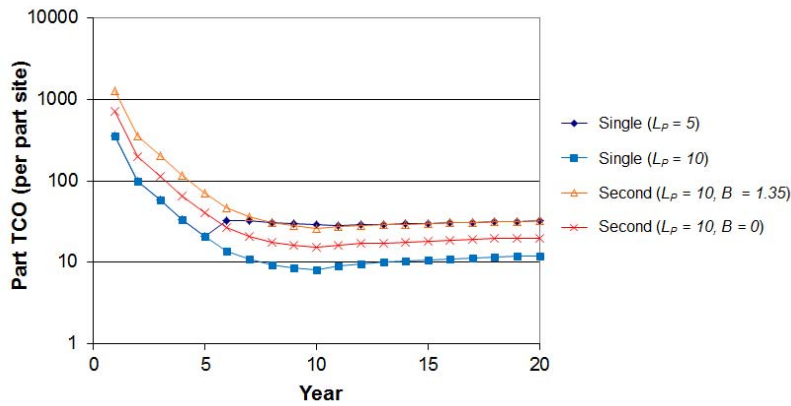


Figure 5 – Part TCO (per part site) versus year of support for the example case where inventory cost is \$10 per part.

Consider a learning index threshold, B_{TH} imposed on the part management organization⁷. The learning index threshold, B_{TH} yields the ratio, K_{TH} (derived from (22)) and vice versa, is given by,

⁷ In order to minimize repeated support activities (reduce the ratio K and subsequently total support cost) in multi-sourcing strategies, the part management’s goal is to minimize learning index value (where $-\infty < B < \infty$). The learning index may be determined by the level of qualification needed (either based on product regulations or organizational policy) or practical capabilities (i.e., the cost of resources used).

$$K_{TH} = \sum_{p=2}^{N_b^{SUP}} (p)^{B_{TH}} \quad (26)$$

where $0 \leq K_{TH} < \infty$ are the feasible boundary conditions for ratio K

K_{TH} = ratio (threshold) of support cost for repeated support activities in sourcing strategy b with respect to support cost in single sourcing strategy a

N_b^{SUP} = number of suppliers in multi-sourcing strategy b

B_{TH} = learning index threshold

p = supplier index

In practice, $B_{TH} = 0$ ($K_{TH} = 1$ for second sourcing) defines the realistic “worst-case” for learning index since adding suppliers under these conditions requires the complete duplication of support activities when no learning occurs. The following example cases comparing second sourcing to single sourcing assumes $B_{TH} = 0$ ($K_{TH} = 1$). When break-even learning index is $B_{BE} > 0$, second sourcing is always a cost effective option. Figure 6 shows the second sourcing part TCO (per part site) when $B = 0$. For $B = 0$, the maximum allowable inventory cost was estimated by iteration to be \$3.84 per part (per year) for single sourcing and second sourcing strategies to “break-even.” Note that the same result can be found graphically using Figure 8 and is discussed later in this section.

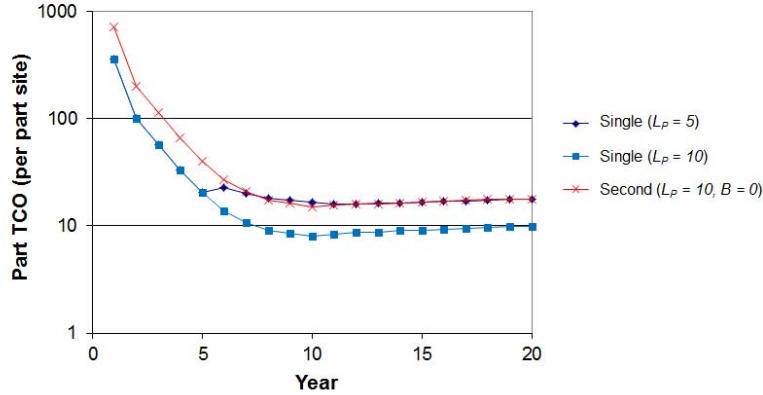


Figure 6 – Part TCO (per part site) versus year of support for the example case where learning index, B is 0 (maximum allowable inventory cost is \$3.84 per part).

If $K_{TH} = 1$, then from (22) as applied to second sourcing, we get,

$$\frac{\Delta C_{PROC} + \Delta C_{INV} + \Delta C_{SUP}}{C_{SUP}(D_b)} \geq 1 \quad (27)$$

$$\Delta C_{PROC} + \Delta C_{INV} \geq C_{SUP}(D_b) - C_{SUP}(D_b) + C_{SUP}(D_a) \quad (28)$$

$$\Delta C_{PROC} + \Delta C_{INV} \geq C_{SUP}(D_a) \quad (29)$$

From (29), the key costs that drive the decision to single source or second source the part under the “worst-case” conditions discussed above are the difference in cumulative procurement cost (after j years), ΔC_{PROC} , difference in cumulative inventory cost (after j years), ΔC_{INV} , and the cumulative cost to support the part (after j years), C_{SUP} , subject to disruption date, D_a .

Figure 7 shows a plot of break-even learning index, B_{BE} versus inventory cost for a linear regulator part with a procurement price of \$1. Figure 8 shows a plot of break-even learning index, B_{BE} versus inventory cost with contours for part price at varying orders of magnitude. As inventory cost increases, the decrease in TCO is larger due to extending the effective procurement life from 5 years (single sourcing strategy a) to 10 years (second sourcing strategy b) thereby increasing the break-even learning index, B_{BE} . For the example case, $B_{BE} > 0$ when inventory cost exceeds \$3.83 (per part per year) where second sourcing is the preferred sourcing strategy. Similarly, Figure 9 shows the relationship between K_{BE} (fraction of support cost repeated for the second supplier with respect to single sourcing support cost at break-even) vs. inventory cost. Figure 8 and Figure 9 show that, when part price is high, the cost of money increases the benefit of extending the part’s procurement life. When part price is approximately \$100 (per part), second sourcing is preferred for all values of inventory cost. The given information allows the calculation of an exact break-even learning index that determines the feasibility of a multi-sourcing strategy.

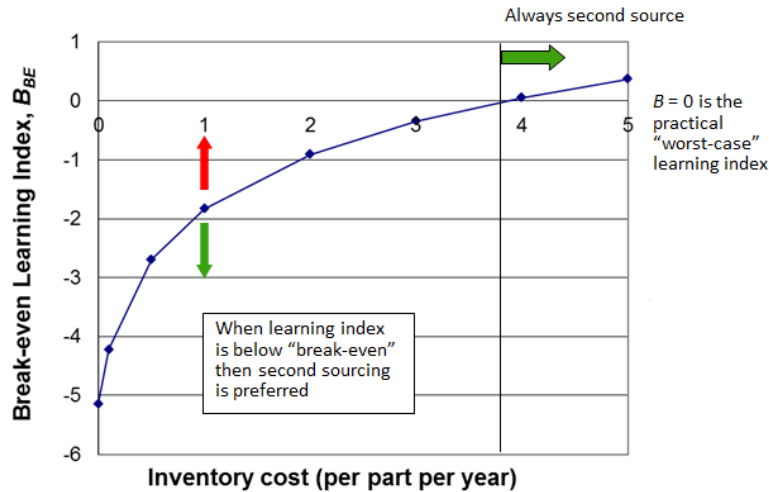


Figure 7 – Break-even learning index, B_{BE} versus inventory cost (per part per year) for the low volume example case defined in Figure 2 and Figure 3.

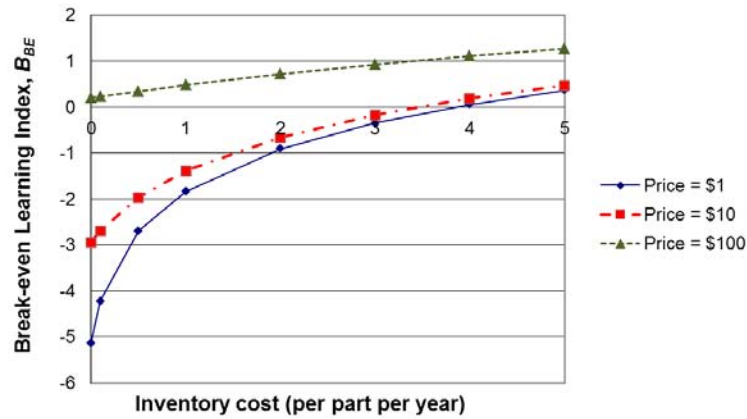


Figure 8 – Break-even learning index, B_{BE} versus inventory cost (per part per year) with contour lines of varying procurement price for the low volume example case defined in Figure 2 and Figure 3.

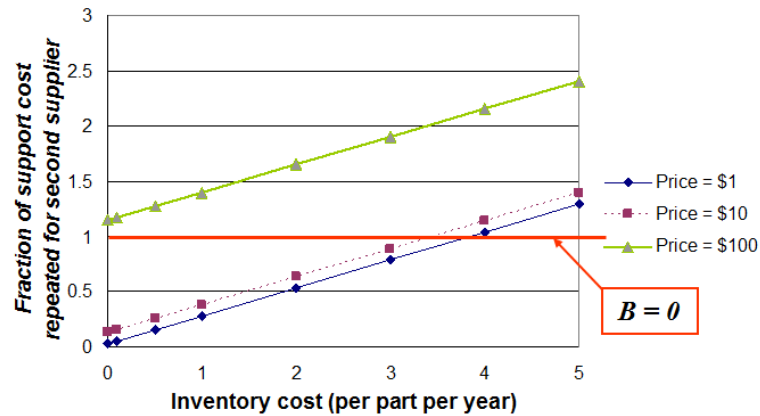


Figure 9 – Fraction of support cost repeated for second supplier (with respect to single sourcing support cost) at break-even, K_{BE} vs. inventory cost (per part per year) with contour lines of varying procurement price for the low volume example case defined in Figure 2 and Figure 3.

6 Discussion and Conclusions

The methodology presented in this paper addresses the tradeoff between the cost of qualifying, procuring and supporting parts from multiple suppliers or sources versus the benefit of reducing the risk of long-term supply chain disruptions. This paper presents an example case study for linear regulators and compares the life cycle cost tradeoffs between single sourcing and second sourcing part over long periods of time (20+ years). The case study shows that the benefit of using a second sourcing strategy is dependent on the value of K , the ratio $\Delta C_{TCO}:C_{SUP}$ where ΔC_{TCO} is the difference in total cost of ownership and C_{SUP} is the cost to support a source. Ratio K can be interpreted from two perspectives: 1) as a threshold, K_{TH} (calculated from the “break-even” learning index, B_{BE}) serves as an indicator for the organization’s capability to stream-line qualification and support activities for additional suppliers and 2) as a target, K_{BE} can be used to estimate the maximum fraction of support cost that can be duplicated for the second source and still make second sourcing viable.

The results of the case study indicate that when the combined cost of procurement and inventory are high, second sourcing offers greater cost avoidance by extending the part's effective procurement life. Under conditions of high procurement and/or inventory cost, higher values for K_{BE} (lower values for B_{BE}) increase the likelihood that K_{BE} will be greater than the threshold, K_{TH} . As a corollary to this principle, parts with a lower combined cost of procurement and inventory benefit less from extending the effective procurement life and should be single sourced instead.

Possible extensions of this work include the study of short-term disruptions and their effects on sourcing decision. For example, a current issue in the management of long life cycle (low volume) electronics caused, in part, by single sourcing policies is the emergence of excessively long delivery lead-times causing disruptions that are albeit temporary yet recurring throughout the part's life cycle. These so called "allocation" problems hit the low-volume manufacturers the hardest because when part suppliers cannot satisfy demand, the low-volume customers go to the "end of the line" for parts and can experience lead times of 12-18 months or more for parts that are not obsolete (Jorgensen, 2011). For example, parts purchased by large high-volume OEMs exhaust available commodities causing a back-order for lower-volume purchasers, i.e., low-volume purchasers are effectively pushed to the "end of line" to get parts. Procured parts may take many months to be delivered to product manufacturers and system sustainers. Therefore, inventory management may be critical to protect against short-term supply chain disruptions for selected parts. This problem is compounded when organizations have chosen to follow "lean inventory" and "just-in-time delivery" management strategies that aim to minimize excess inventory. The trend toward "lean" has been traditionally driven by high inventory cost and limited storage space but variability in lead-times leave organizations susceptible to part unavailability. Future work involves assessing the effects of sourcing and inventory management strategies on the TCO of parts used in long life cycle products to determine when multiple sources should be used and when (and how much) inventory should be held to avoid lead-time problems.

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Appendix A - DMSMS Type Part Obsolescence and Supplier-Specific Procurement Life

Many technologies and parts have procurement life cycles that are shorter than the production and support life of the product or system they are in. Life cycle mismatches caused by obsolescence can result in large life cycle costs for long field life or long life cycle systems. This appendix describes DMSMS (Diminishing Manufacturing Sources and Materials Shortages) type obsolescence, which is defined as the loss of the ability to procure a technology or part from its original manufacturer (Sandborn, 2008).⁸ Obsolescence is a significant supply chain disruption for long field life systems. Obsolescence is particularly disruptive for safety, mission and infrastructure system that have significant qualification and certification requirements that effectively discourage changes to the system, i.e., systems have to be supported with the same parts that the original system was built and qualified with (they may not be able to use newer parts without expensive system requalification). This problem is particularly pervasive for low-volume, long field life systems with large electronics content (e.g., military systems, avionics, rail, industrial and power plant control system) since they have no control over the electronic part supply chain that they depend on.

To predict the supply chain disruption risk associated with electronic part obsolescence we must be able to forecast when specific parts will become unavailable (non-procurable). Sandborn *et al.* (2011) describes a quantity called procurement life, L_p , determined from a database of past obsolescence data using,

$$L_p = D_o - D_i \quad (\text{A.1})$$

where,

L_p = Procurement life, amount of time the part was (or will be) available for procurement from its original manufacturer

D_o = Obsolescence date, the date that the original manufacturer discontinued or will discontinue the part

D_i = Introduction date, the date that the original manufacturer introduced the part

⁸ Inventory or sudden obsolescence, which is more prevalent in the operations research literature, refers to the opposite problem to DMSMS obsolescence. Inventory obsolescence occurs when the product design or system component specifications changes such that the existing inventories of components are no longer required.

The distribution of procurement lives (L_P) observed for parts introduced in the past can be fit with a Weibull (2-parameter) using Maximum Likelihood Estimation (MLE). The shape (β) and scale (η) parameters obtained through MLE provide a Weibull distribution representative of the part's procurement life. The method has been demonstrated on a range of different electronic parts and for the trending of specific part attributes (Sandborn *et al.*, 2011). This method can also be applied to address the likelihoods of supplier-specific part obsolescence events.

In Figure A.1, PDFs and CDFs for procurement life (L_P) are generated from supplier-specific data for linear regulators from three different suppliers. Note, the Weibull distribution, like most parametric fits, evolves over time as more data is accumulated. The method presented by Sandborn *et al.* (2011) generates censored Weibull distributions to account for the fact that the data is right-censored, i.e., the data set used in this study contains introduction dates for all parts, but only a subset of parts have obsolescence dates because some of the parts in the data set are not obsolete yet.

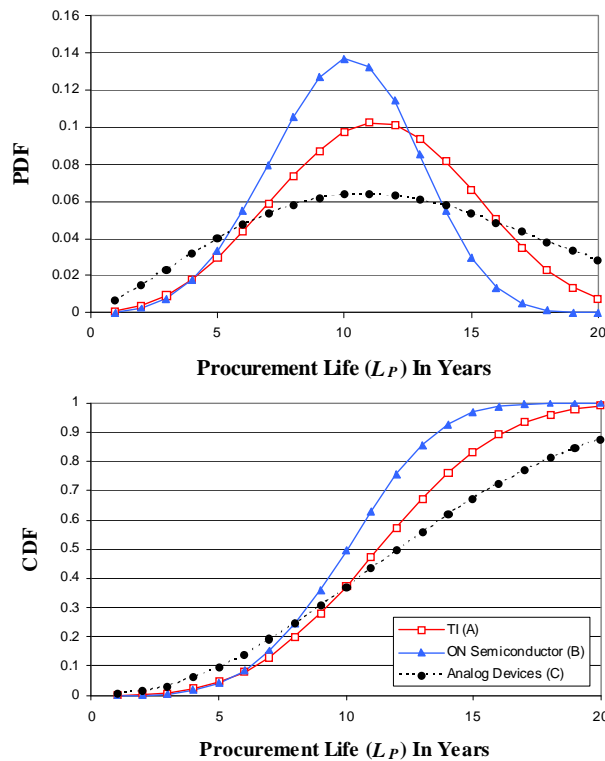


Figure A.1 – Supplier-specific obsolescence likelihoods for linear regulators as (top) PDF and (bottom) CDF determined from historical data provided by SiliconExpert. The resulting Weibull fits are given in Table A.1.

Table A.1. Supplier-specific censored Weibull distribution parameters, β and η , for linear regulator parts. $-LKV$ is the negative log-likelihood function (larger negative values indicate a better fit).

Weibull Parameters	Texas Instruments	ON Semiconductor	Analog Devices
β (shape) units – n/a	3.3299	3.9668	2.1858
η (scale) units – years	12.5831	11.0008	14.2503
$-LKV$	-69.917	-113.246	-39.424

The PDF of L_p is the likelihood that a part will become obsolete during specific intervals of time after it is introduced. The censored CDF of L_p (bottom of Figure A.1) can be interpreted as the likelihood that a part will be obsolete L_p number of years after it is introduced. The supplier-specific CDFs can be used to construct effective CDFs for second sourcing strategies. The PDF of L_p is the likelihood that a part will become obsolete during specific intervals of time after it is introduced.

Prabhakar and Sandborn (2011) demonstrate that the CDFs corresponding to different suppliers can be combined to generate the likelihood as a function of time that a second sourced part will encounter an obsolescence supply chain disruption. Figure A.2 shows an example of combining the CDFs for linear regulators of different combinations of suppliers.

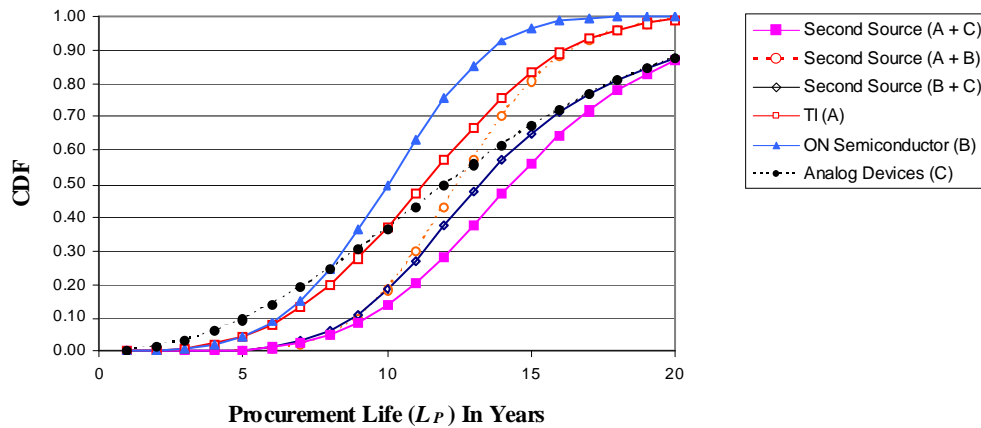


Figure A.2 – CDF of obsolescence likelihood over time by sourcing strategy.

The case study in Section 5 of this paper uses procurement life (L_p) as an input that can be sampled from single and second sourcing distributions discussed in this appendix.