A Part Total Cost of Ownership Model for Long Life Cycle Electronic Systems

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Dedicated part selection and management groups within large OEMs are responsible for various tasks involved with managing parts or components used in electronic systems. The tasks range from part adoption to obsolescence management and include numerous assembly and support activities that are performed on a regular basis. Long life cycle electronic systems typically utilize commercial "off-the shelf" (COTS) parts, which subject them to the same supply chain constraints imposed by a market that is oriented towards short-term, high-volume products. Relevant issues involve a high frequency of part procurement obsolescence, reliability concerns, and the risk of long-term supply-chain disruptions. Unfortunately, initial part selection decisions are often driven by procurement management processes with little or no insight into the total cost of ownership (TCO) of the part's adoption and use within the organization. The part total cost of ownership model proposed in this paper enables better informed part selection and management decisions. The paper discusses and demonstrates the model's use in Lifetime Buy (LTB) and Design Reuse case studies for an example surface-mount electronic part. Additionally, the model proposed in this paper is well suited for addressing the impacts of part number reduction, retirement of parts from databases, organizational adoption of new parts, sourcing strategies and part-specific long-term supply chain disruptions by influencing initial component selection and providing guidance on what actions taken at the component management level provide the maximum payback (or maximum future cost avoidance).

Keywords: total cost of ownership; through-life cost; long life cycle; electronic systems; part management; product platform design

Introduction

In today's market, materials and goods flow through complex networks of organizations called "supply chains" on their way to becoming a final finished product. Original Equipment Manufacturers (OEMs) are product manufacturers that purchase lower-level parts or components and integrate them into products that bear the organization's name. Few of the OEMs that make complex electronic end-products, fabricate the individual electronic parts themselves leaving the majority of the electronic systems' hardware content, consisting of "chips" and other electronic components, to be procured from elsewhere. Whether the individual electronic parts are fabricated in-house or procured through a supply chain, there are significant life cycle costs associated with an electronic part besides its manufacturing cost or purchase price.

Large OEMs such as Ericsson and Honeywell, have dedicated part selection and management groups whose primary focus is identifying, selecting, qualifying and purchasing parts for specific products, as well as qualifying the manufacturers and distributors of those parts. Part selection and management groups are responsible for part management activities performed on a regular basis such as determining the procurement status of parts, managing purchase orders, and part database maintenance. In addition, part-specific concerns such as reliability issues and long-term availability problems are the responsibility of these groups if and when they occur. Each part that exists as a unique part number in an organization's database requires support activities and dedicated resources, which incur life cycle costs that can, in many cases, be significantly

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higher than the part's procurement price. To complicate the role of the part selection and management group, actual product manufacturing may be performed by other organizations (e.g., contract manufacturers) that may be outside the control or influence of the part selection and management groups.

Unfortunately, part selection for products is often driven or significantly influenced by procurement management processes that have little or no view into the effective cost of ownership or through-life cost ramifications of the part. Procurement organizations are often motivated by minimizing procurement cost or selecting suppliers that offer parts at lower prices, and may not take into account many of the part selection and management group's activities listed above (or more importantly, how the cost of these activities may vary from part-to-part). Price has long been considered a driving factor in purchases (Evans 1981, Lehmann and O'Shaughnessy 1974) but more recent studies have shown that price has declined in relative importance as a selection criterion (Jackson 1985, Wilson 1994). A survey study by Bharadwaj (2004) found that, out of four key supplier selection criteria – delivery, price, quality, and post-sale service – price was indeed the penultimate decision criteria used by electronic component procurement organizations followed by post-sales service. The study by Bharadwaj also suggests that differences do not exist within the buying criteria across an array of electronic components. However, the implications of such policies and the impact of these decision criteria are yet to be explored.

Existing models used to address the issues stated above tend to be either: a) primarily focused on manufacturing (containing little or no view into the post-manufacturing life cycle), b) product specific, and/or c) lack an understanding of the unique attributes of electronic part management. For example, the methodology presented by Boothroyd *et al.* (1994) presents an assembly (DFA) and manufacturing (DFM) approach to product cost modeling that does not capture activities beyond the manufacturing of the system. In another example, Wang *et al*. (2007) establishes a decision-support model in order to enable part changes from a life cycle cost perspective, however, the cost model estimates static and dynamic costs from a product perspective as opposed to a part perspective.

Ellram and Siferd (1998) describe the shortcomings of traditional cost analysis methods as a focus on price, a de-emphasis of suppliers' performance, and a disregard for internal costs; in addition, traditional cost analysis methods often tend to focus on aspects of an organization that lack efficiency rather than modeling all processes. Ellram and Siferd support the emergence of the total cost of ownership (TCO) approaches to promote strategic decision-making and express that the true benefits of a total cost of ownership is the marriage between strategic cost management concepts (focus on financial and accounting perspectives) and the fundamental approach of total cost of ownership as a holistic costing approach.

This paper describes the formulation and use of an electronic part total cost of ownership model that allows part selection and management organizations to predict the total cost of ownership of a part in order to enable better informed fundamental part selection decisions. The model presented in this paper focuses on optimal part management from a part selection and management organization's viewpoint as opposed to the optimum part management from a product group's perspective. These perspectives differ because the part selection and management group has a more holistic view of a part's cost of ownership than a product group, and a part (especially an electronic part) may be concurrently used in many different products within the same organization. This approach requires a cost model that comprehends long-term supply chain constraints that are associated with specific parts and their effects downstream at the product level, therefore the cost that we wish to predict and minimize is the effective total cost of ownership (TCO) of the part as used across multiple products. Assessing the total cost incurred over the life cycle of the part as an effective total cost of ownership will allow part management organizations to quantify the cost spent (inclusive of procurement) per part.

In the next section, the part total cost of ownership model will be described followed by example results for the effective cost per part site of different part usage scenarios. The paper will also discuss applications of the part total cost of ownership model to minimize the life cycle cost associated with part design reuse across multiple products and part obsolescence management using lifetime buys.

Part total cost of ownership model

Total cost of ownership modeling requires an understanding of the product's life cycle costs.[1] Life cycle cost represents the total cost of acquisition and ownership of a product over its full life, including the cost of planning, development, acquisition, operation, support, and disposal. General life cycle cost analysis of products has been treated by many authors, e.g., (Fabrycky and Blanchard 1991, Asiedu and Gu 1998). The context of this paper is electronic parts for which life cycle costs (besides procurement) include the assessment of part manufactures and distributors (Jackson *et al.* 1999), qualifying and screening parts (e.g., Kim 1998), the impacts of part reliability (e.g., Alcoe *et al.* 2003), warranty, sparing and availability, obsolescence management (Sandborn 2008), and support.

The proposed part total cost of ownership model is composed of the following three sub-models: part support model, assembly model, and a field failure model. This model contains both assembly costs (including procurement) and life cycle costs associated with using the part in products.

Part Support Model

The part support model captures all non-recurring costs associated with selecting, qualifying, purchasing, and sustaining the part (these costs may recur annually, but do not recur for each part instance). The total support cost in year *i* (in year 1 dollars) is given by,

[1] In this paper the effective total cost of ownership (TCO) refers to the life cycle cost of the part from the part customer's point of view, which should not be confused with Cost of Ownership (COO), which is a manufacturing cost modeling methodology that focuses on the fraction of the life cycle cost of a facility that is consumed by an instance of a product.

$$C_{support_i} = \frac{\left(C_{ia_i} + C_{pa_i} + C_{as_i} + C_{ps_i} + C_{ap_i} + C_{or_i} + C_{nonPSL_i} + C_{design_i}\right)}{(1+d)^i} \quad (1)$$

where

C_{ia_i} = initial part approval and adoption cost. All costs associated with qualifying and approving a part for use (i.e., setting up the initial part approval). This could include reliability and quality analyses, supplier qualification, database registration, added NRE for part approval, etc. The approval cost occurs only in year 1 (i = 1) for each new part.

C_{pa_i} = product-specific approval and adoption. All costs associated with qualifying and approving a part for use in a particular product. This approval cost would occur exactly one time for each product that the part is used in and is a function of the type of part and the approval level of the part within the organization when the product is selecting the part. This cost depends on the number of products introduced in year i that use the part.

C_{as_i} = annual cost of supporting the part within the organization. All costs associated with part support activities that occur for every year that the part must be maintained in the organization's part database such as database management, PCN (Product Change Notice) management, reclassification of parts, and services provided to the product sustainment organization. This cost depends on the part's qualification level, which can change over time.

C_{ps_i} = all costs associated with production support and part management activities that occur every year that the part is in a manufacturing (assembly) process for one or more products such as volume purchase agreements, services provided to the manufacturing organization, reliability and quality monitoring, and availability (supplier addition or subtraction).

C_{ap_i} = purchase order generation cost, which depends on the number of purchase orders in year i.

C_{or_i} = obsolescence case resolution costs – only charged in the year that a part becomes obsolete.

C_{nonPSL_i} = setup and support for all non-PSL (Preferred Supplier List) part suppliers – depends on the number of non-PSL sources used.

C_{design_i} = non-recurring design-in costs associated with the part – only charged in years of new product introduction using the part; includes: cost of new CAD footprint and symbol generation if needed.

d = after tax discount rate on money.

i = year (starting at year 1).

C_{ia_i} , C_{pa_i} , C_{as_i} , and C_{ps_i} are determined from an activity based cost model in which cost activity rates can be entered or calculated by part type.[2]

Assembly Model

The assembly model captures all the recurring costs associated with the part: purchase price, system assembly cost (part assembly into the system), and recurring functional test/diagnosis/rework costs. The total assembly cost (for all products) in year *i* assuming exactly one part site per product is given by,

$$C_{assembly_i} = \frac{N_i C_{out_i}}{(1+d)^i} \tag{2}$$

where

N_i = total number of products assembled in year *i*

C_{out_i} = output cost/part from the model shown in Figure 1. C_{out} is a function of C_{in} as shown in Figure 1

C_{in_i} = incoming cost/part $= P_i + C_{a_i}$

P_i = purchase price of one instance of the part in year *i*

C_{a_i} = assembly cost of one instance of the part in year *i*

This model uses the previously developed test/diagnosis/rework (TDR) model for the assembly process of electronic systems described in Figure 1 and Table 1, (Trichy *et al.* 2001).[3] The approach includes a model of functional test operations characterized by fault coverage, false positives, and defects introduced in test, in addition to rework and diagnosis (diagnostic test) operations that have variable success rates and their own defect introduction mechanisms. The model accommodates multiple rework attempts on any given product instance and enables optimization of the fault coverage and rework investment during assembly tradeoff analyses.

[2] Part type definitions are: Type 1 – resistors, capacitors, inductors, and mechanical parts; Type 2 – integrated circuits, oscillators, filters, board connectors; Type 3 – ASICs, RF connectors, RF integrated circuits, DC/DC, synthesizers, optical transceivers (TRX); and Type 4 – RF transistors, circulators, isolators.

[3] Note, several typographical errors should be corrected in (Trichy *et al.* 2001): In (2) and (3) in Trichy, the maximum of the summation should be *n-1* instead of *n*, and (4a) can be used for either definition of f_p with $N_{d_{n+1}}$ changed to N_{d1_n} . In (13) in Trichy *et al.*, the subscript of N_r should be *i-1* instead of *i* when $i > 0$.

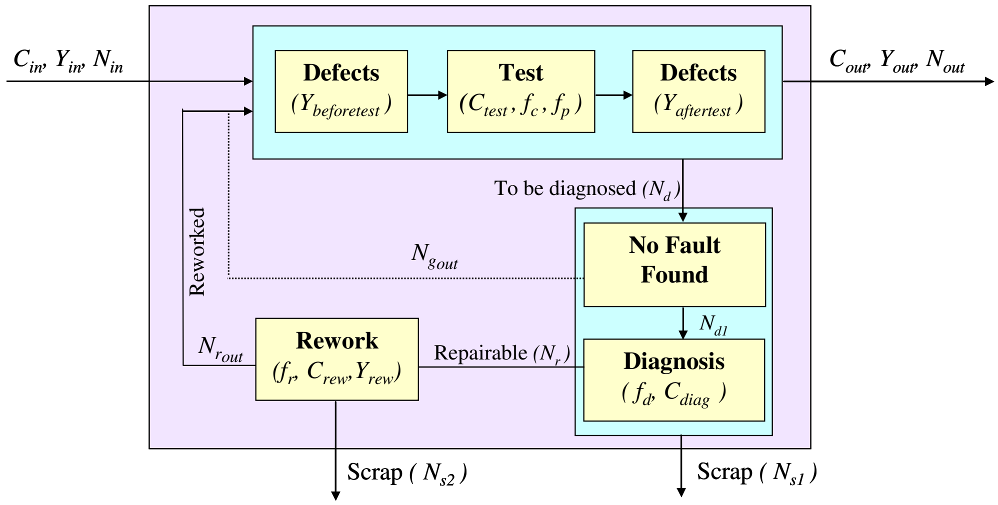


Figure 1. Test/diagnosis/rework (TDR) model from Trichy *et al.* (2001). Table 1 describes the notation appearing in this figure.

The model discussed in this paper contains inputs to the test/diagnosis/rework model that are specific to the part type and how the part is assembled (automatic, semi-automatic, manual, pre-mount, lead finish[4], extra visual inspection, special electro static discharge (ESD) handling – see (Prasad 1997)). The output of the model is the effective procurement and assembly cost per part site. For simplicity, the application of the test/diagnosis/rework model in this paper assumes that all functional and assembly introduced part-level defects are resolved in a single rework attempt, i.e., $Y_{rew} = 1$, that there are no defects introduced by the testing process, i.e., $Y_{beforetest} = Y_{aftertest} = 1$, and that there are no false positives in testing, i.e., $f_p = 0$. These yield assumptions guarantee that Y_{out} will always be 1.

[4] Lead finishes are very relevant for electronic parts since traditional tin-lead solder finishes were banned for many electronic product sectors in 2003 by the RoHS directive (Ganesan and Pecht, 2006).

Table 1. Nomenclature used in Figure 1

C_{in}	= Cost of a product entering the test, diagnosis and rework process	N_{in}	= Number of products entering the test, diagnosis and rework process
C_{test}	= Cost of test per product	N_d	= Total number of products to be diagnosed
C_{diag}	= Cost of diagnosis per product	N_{gout}	= Number of no fault found products
C_{rew}	= Cost of rework per product	N_{d1}	$= N_d - N_{gout}$
C_{out}	= Effective cost of a product exiting the test, diagnosis and rework process	N_{out}	= Number of a products exiting the test, diagnosis and rework process, includes good products and test escapes
f_c	= Fault coverage	N_r	= Number of products to be reworked
f_p	= False positives fraction, the probability of testing a good product as bad	N_{rout}	= Number of products actually reworked
f_d	= Fraction of products determined to be reworkable	N_{s1}	= Number of products scrapped by diagnosis process
f_r	= Fraction of products actually reworked	N_{s2}	= Number of products scrapped during rework
$Y_{beforetest}$	= Yield of processes that occur entering the test	$Y_{aftertest}$	= Yield of processes that occur exiting the test
Y_{in}	= Yield of a product entering the test, diagnosis and rework process	Y_{out}	= Effective yield of a product exiting the test, diagnosis and rework process
Y_{rew}	= Yield of the rework process		

Field Failure Model

The field failure model captures the costs of warranty repair and replacement due to product failures caused by the part. Equation (3) gives the field failure cost in year *i*.

$$C_{field\ use_i} = \frac{N_{f_i}(1-f)C_{repair} + N_{f_i} f\, C_{replace} + N_{f_i} C_{proc_i}}{(1+d)^i} \tag{3}$$

where

N_{f_i} = number of failures under warranty in year *i*. This is calculated using 0-6, 6-18 and > 18 month FIT rates[5] for the part, the warranty period length (an ordinary free replacement warranty is assumed with the assumption that no single product instance fails more than one time during the warranty period), and the number of parts sites that exist during the year.

f = fraction of failures requiring replacement (as opposed to repair) of the product

C_{repair} = cost of repair per product instance

$C_{replace}$ = cost of replacing the product per product instance

C_{proc_i} = cost of processing the warranty returns in year *i*

Total Cost of Ownership

Traditionally, the term "part" is used to describe one or more items with a common part number from a part management perspective. Several items with a common part number may be used in multiple products as an artifact of design reuse (Meyer and Lehnerd 1997). 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. The reason part sites are counted (instead of just parts) is that each part site could be occupied by one or more parts during its lifetime (e.g., if the original part fails and is replaced, then two or more parts occupy the part site during the part site's life). For consistency, all cost calculations are presented in terms of either annual or cumulative cost per part site.

The total cost of ownership expressed as an effective cumulative cost per part site is given in (4) up to year *i*,

$$C_i = \frac{\sum_{j=1}^{i}\left(C_{support_j} + C_{assembly_j} + C_{field\ use_j}\right)}{\sum_{j=1}^{i} N_j} \tag{4}$$

where N_j = number of part sites assembled in a particular year *j*

In this paper we focus on the effective cost per part site, rather than the cost per part because when product repair and replacement are considered there is effectively more than one part consumed per part site. All computed costs in the model are indexed to year 1 for reference where year 1 refers to the period between time 0 and the end of 1 year.

[5] FIT (Failures in time) rate – Number of part failures in 10^9 device-hours of operation.

Example Analyses

This section includes example analyses performed using the model described in the previous section. The model was populated with data from Ericsson AB for a generic surface-mount capacitor (Type 1 component). Figure 2 shows a summary of inputs to the model that correspond to all of the example analyses presented in this section. A part site usage profile indicating the number of part sites used for each product annually is provided as an input to the model. The profile in Figure 2 also describes the number of unique products using the part in each year and the total quantity of part sites assembled each year (N_i). In all cases, inflation or deflation in cost input parameters can be defined (electronic part prices generally decrease as a function of time).

PART-SPECIFIC INPUTS:

Parameter	Value
Part name	SMT Capacitor
Existing part or new part?	New
Type	Type 1
Approval/Support Level	PPL
Procurement Life (*YTO* at beginning of year 1)	16.7 years
Number of suppliers of part	7
How many of the suppliers are not PSL but approved?	5
How many of the suppliers are not PSL AND not approved?	0
Part-specific NRE costs	0
Product-specific NRE costs (design-in cost)	0
Number of I/O	2
Item part price (in base year money)	$0.015
Are order handling, storage and incoming inspection included in the part price?	Yes
Handling, storage and incoming inspection (% of part price)	10.00%
Defect rate per part (pre electrical test)	5 ppm
Surface mounting details	Automatic
Odd shape?	No
Part FIT rate in months 0-6 (failures/billion hours)	0.05
Part FIT rate in months 7-18 (failures/billion hours)	0.04
Part FIT rate after month 18 (failures/billion hours)	0.03

GENERAL NON-PART-SPECIFIC INPUTS:

Parameter	Value
Part price change profile (change with time)	Monotonic
Part price change per year	-2.0% per year
Part price change inflection point (year)	5
Manuf. (assembly) cost change per year	-3.00%
Manuf. (test, diagnosis, rework) cost change per year	-3.00%
Admin. cost change per year	0.00%
Effective after-tax discount rate (%)	10.00%
Base year for money	1
Additional material burden (% of price)	0.00%
% of part price for LTB storage/inventory cost (per part per year)	66.67%
LTB overbuy size (buffer)	10%
Expected obsolescence resolution	LTB
Fielded product retirement rate (%/year)	5.00%
Operational hours per year	8760 hours
Product warranty length	18 months
% of supplier setup cost charged to non-PSL, approved suppliers	0.00%

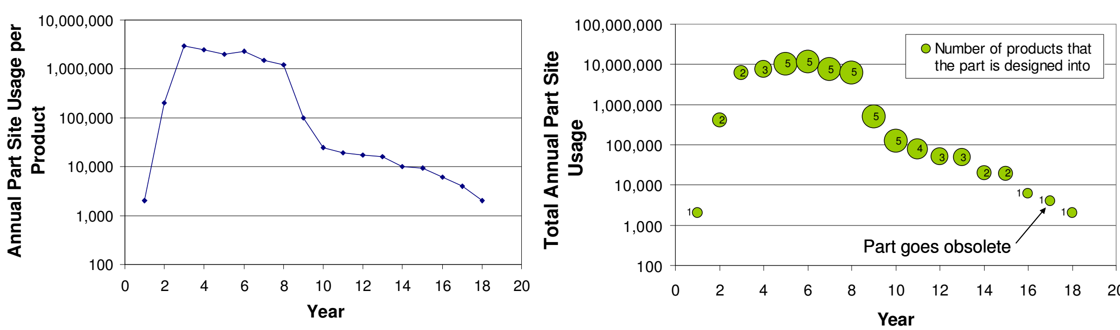


Figure 2. Inputs used in the part total cost of ownership cost model for the examples provided in this paper.

Evaluating Part Total Cost of Ownership

As an example of the part total cost of ownership model, consider the part data shown in Figure 2. For this part used in the products given in Figure 2 (for which a resultant total annual part site usage is also shown), the results in Figure 3 are obtained. The plots on the left side of Figure 3 show that initially, all the costs for the part are support costs, i.e., initial selection and approval of the part. Manufacturing and procurement costs approximately follow the production schedule shown in Figure 2. This example part becomes obsolete in year 17 (*YTO* is 16.7 years at year 0) and a lifetime buy of 4,000 parts is made at that time indicated by the small increase in procurement and inventory costs in year 17. Year 18 is the last year of manufacturing after which field use costs dominate.

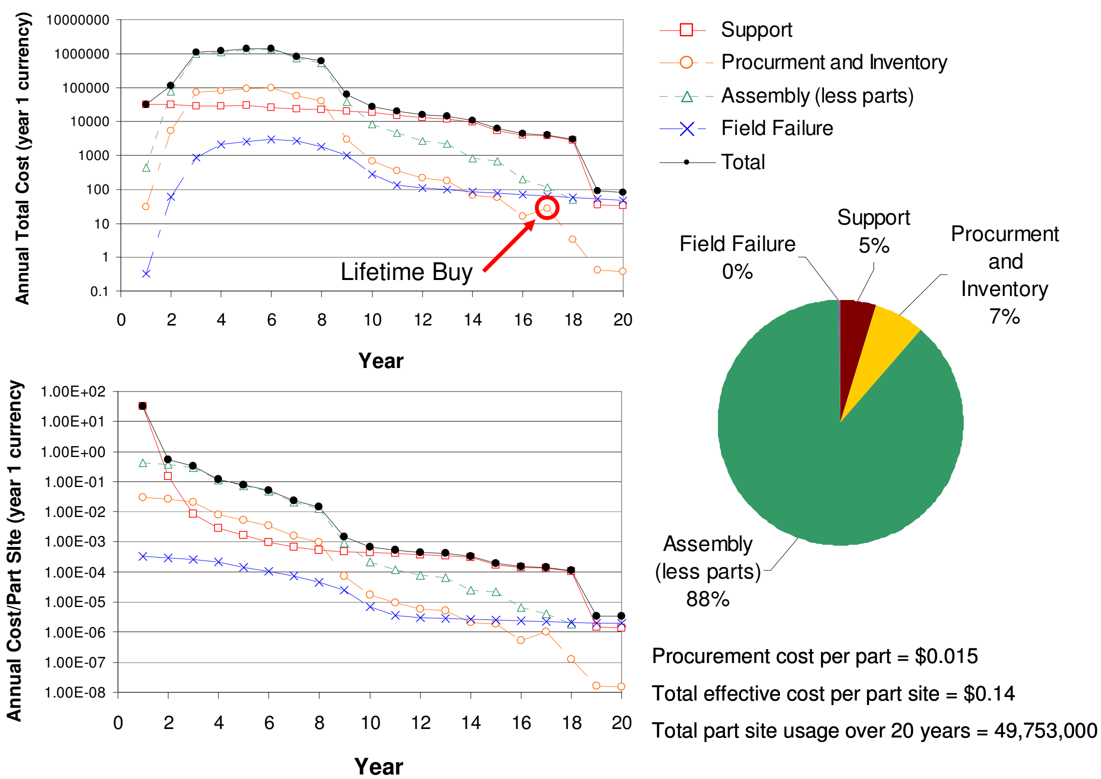
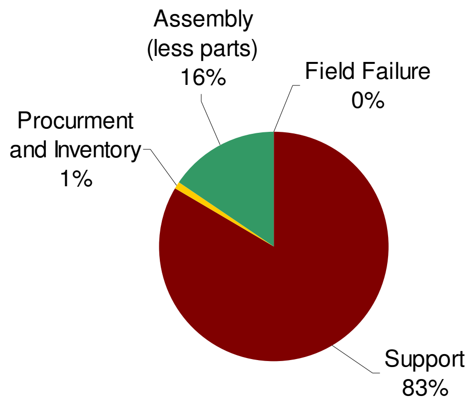
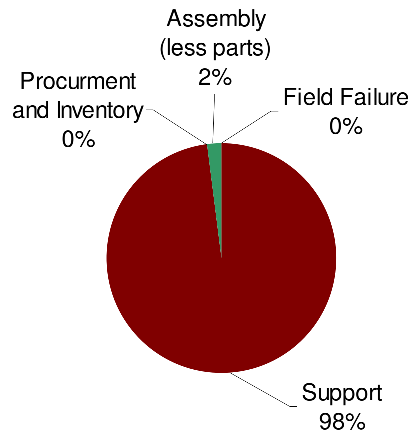


Figure 3. Example part total cost of ownership modeling results (high-volume case).

For the case shown in Figure 3, the initial procurement price per part ($0.015/part) is only 11% of the cumulative effective cost per part site ($0.14/part site) during a 20 year usage life. The results in Figure 3 show that, at high volumes, the procurement and inventory cost after 20 years is 7% of the total effective cost per part site. Assembly and support costs contribute to a combined share of the total cost of ownership of 93% (88% and 5% of the total effective cost per part site respectively). The organization dedicates an annual average of $1.85 per operational hour of support cost over 20 years for all 49,753,000 part sites in this high-volume case.





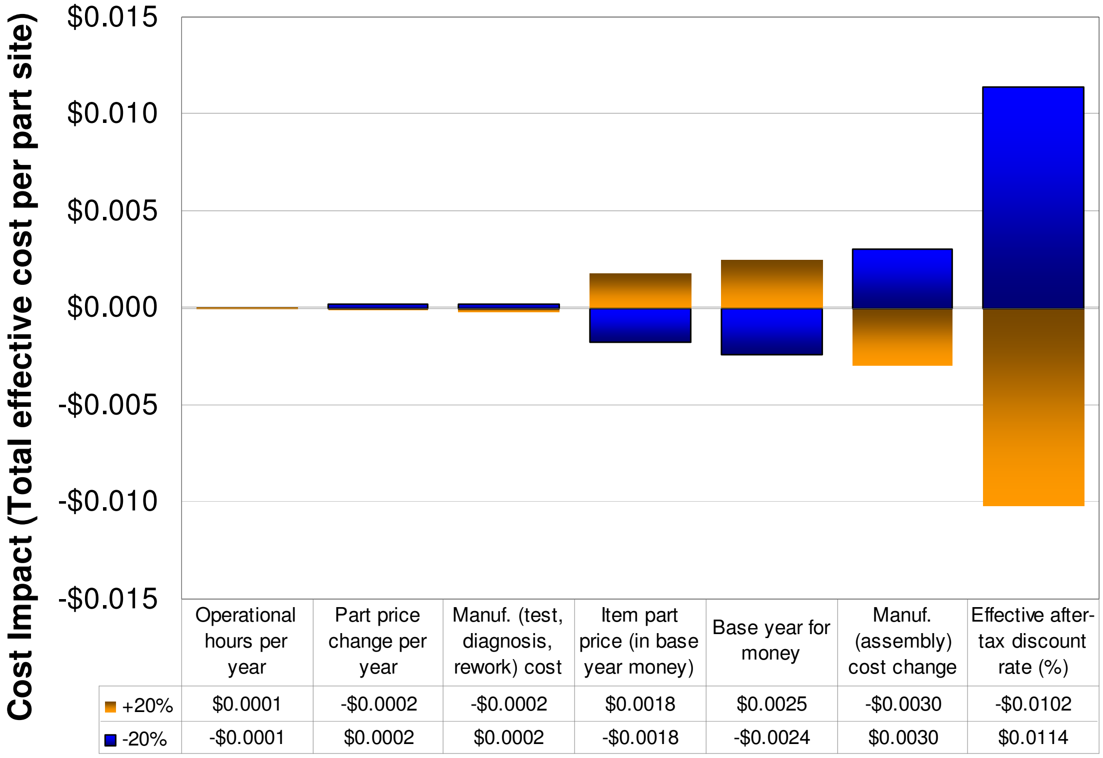
Procurement cost per part = $0.015
Total effective cost per part site = $0.78
Total part site usage over 20 years = 497,530

Procurement cost per part = $0.015
Total effective cost per part site = $6.63
Total part site usage over 20 years = 49,752

Figure 4. Part total cost of ownership results for different part volumes (lower-volume cases).

At lower volumes, support costs dominate with significant contributions from fixed and variable costs that may be a hundred times larger (for example, in the case of production support costs) than costs incurred by field failures, procurement and inventory. The effect of "economy of scale", a benefit of high-volume production, is demonstrated in Figure 4, which compares two lower-volume cases as variations of the SMT capacitor considered in Figure 3. Support costs make up 83% of the $0.78 spent per part site (shown on the left side of Figure 4) when a total of 497,530 parts are consumed over 20 years. When the volume consumed is further reduced to 49,752 parts over 20 years (shown on the right side of Figure 4), support costs contribute to 98% of the $6.63 spent per part site.

A sensitivity analysis was conducted to determine the effects of the input parameters on the total effective cost per part site for the example case considered in this section. In Figure 5, a variability of ±20% for each input parameter was introduced to study the response of the model results. Effective after-tax discount rate was found to contribute significantly to changes in total effective cost per part site. The relative value of currency in a particular year is affected by the after-tax discount rate, *d*. The variation observed is a common effect in long life cycle products and is a source of uncertainty in the TCO estimation. Considering the case study results, a 20% saving on the procurement price of the part saves a negligible amount in effective cost per part site. If the procurement price per part is doubled to $0.03 per part then the procurement cost per part site increases by only $0.01 or 6.6% of total effective cost per part site in the high volume base case (1.2% in the low volume case of 497,530 parts). Savings at the procurement stages lead to minimal savings in total effective cost per part site due to the limited contribution from the procurement and inventory level when compared to costs incurred due to support (at low volumes) and assembly (at high volumes) activities.



	Operational hours per year	Part price change per year	Manuf. (test, diagnosis, rework) cost	Item part price (in base year money)	Base year for money	Manuf. (assembly) cost change	Effective after-tax discount rate (%)
+20%	$0.0001	-$0.0002	-$0.0002	$0.0018	$0.0025	-$0.0030	-$0.0102
-20%	-$0.0001	$0.0002	$0.0002	-$0.0018	-$0.0024	$0.0030	$0.0114

Figure 5. Tornado Chart of cost impact as change in total effective cost per part site due to ±20% variability in input values.

The assembly cost is dependent on the quantity of parts consumed every year, which, in turn, is dependent on the number of products the part is "designed into". The capacitor considered in Figure 3 is designed into a maximum of 5 concurrently produced products (between year 5 and 10). When the part is used in no more than one product, the total effective cost per part site increases to $0.17. The assembly cost increase is approximately proportional to the number of parts consumed by assembly processes. Despite lower product design-in costs C_{design} (since fewer products need to be qualified) and annual purchasing costs C_{ap} (fewer purchase orders made), support costs begin to take over with a share of 12% of the total cost per part site since the largest contributor, production support costs C_{ps}, remains.

The negligible contribution from field failures (in Figures 3 and 4) is a characteristic of the part's reliability and the product warranty policy employed. The products using the part considered in this case – a SMT capacitor were assumed to follow an 18 month warranty repair policy. Field failure costs tend to be significantly larger if the part is used in sustainment-dominated systems[6] where the product is expected to function for 10 year or more (as long at 30+ years for many systems). Field failure costs for parts used in sustainment-dominated systems may be driven by repair processes (similar to the test,

[6] Products for which the cost sustainment (operating and supporting) is significantly larger than the cost of procurement, e.g., airplanes, military systems, infrastructure communications systems, and power plant controls (Sandborn and Myers 2008).

design, and rework model used in the assembly cost model). Many sustainment-dominated electronic systems, such as rack-mounted servers used by banks or insurance companies, employ maintenance strategies that must adhere to stringent availability[7] policies or contracts (Ng *et al*. 2009). Field failures of these systems require immediate attention, and repairs that cannot be resolved quickly decrease the system's availability for which significant availability cost penalties may be incurred. Such penalties may be attributed to the failure of a particular part and contribute to the part's field failure cost. The example case presented here accounts for the cost of site visits, down time, transportation, and handling in the event of system failures; however, specific financial penalties associated with reduced availability are assumed to be zero.

Part Lifetime Buy Tradeoffs

Part decisions are often trumped by uncertainty in the market. Supply chain changes during the life of a part, both expected and unexpected, require a reaction or resolution. Electronic parts are subject to high-frequency involuntary procurement obsolescence, (Sandborn 2008). Part obsolescence becomes a problem when a product must be manufactured and/or supported for longer than its constituent parts are available for procurement. Because short manufacturing and support life products such as cell phones and laptop computers dominate the demand for electronic parts, many electronic parts are only procurable from their original manufacturer for a few years and are then discontinued in favor of newer, higher performing parts. For long field life electronic products, such the avionics in airplanes, medical applications, and military systems, it is not uncommon for the majority of the electronic parts to be obsolete and non-procurable before the first instance of the product is fielded, and then the system has be manufactured and supported for significant amounts of time beyond that. When parts become obsolete and are still required by the system, considerable resources may have to be expended to resolve the problem.

When an electronic part becomes obsolete a range of possible mitigation approaches are possible (Stogdil 1999), but there are usually two viable resolution actions considered if more than a few thousand parts are needed: 1) replace the part with a newer part, or 2) buy enough parts to satisfy your anticipated future needs and store them until they are needed (i.e., lifetime buy), (Feng *et al.* 2007). Replacement of the existing part with a new part carries with it potentially significant costs associated with finding the new part, approving the part for use, possibly qualifying the supplier of the part, and product-specific qualification tests – depending on the product and the role the part plays in the product. Due to prohibitive costs, replacement of an obsolete part with a new part may or may not be viable. In this example, we will only consider lifetime buys.

The following is a very simple lifetime buy analysis that demonstrates the quantification of the value associated with the selection of parts with different years to obsolescence.

[7] Operational availability is the probability that a system will be able to function when called upon to do so. Availability depends on the system's reliability (how often it fails) and its maintainability (how quickly it can be repaired or restored to operation when it does fail).

This analysis does not address prediction or optimization of lifetime buy quantities, which are out the scope of this analysis.

In order to include the costs of lifetime buys, the number of years to obsolescence (*YTO*) of the part must be determined,

$$YTO = \left(1 - \frac{L}{6}\right) T_{PL} \tag{5}$$

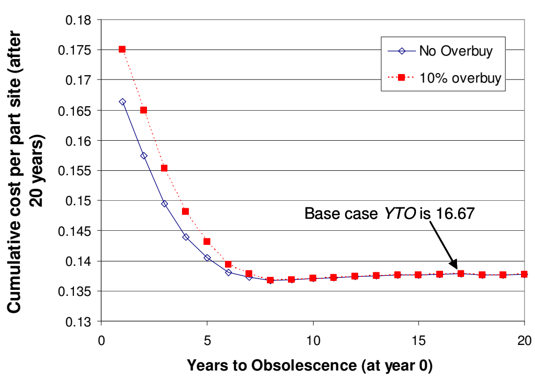
where,

L = lifecode for the part in year 0, L =1 (introduction), 2 (growth), 3 (maturity), 4 (decline), 5 (phase out), and 6 (obsolete), (ANSI/EIA 1997, Sherwood 2000). Commercially available databases provide lifecodes for electronic parts.

T_{PL} = total procurement lifespan (Sandborn et al. 2010) of a particular part type in years. Length of time the part was or will be procurable from its original source.

When the year of obsolescence occurs, a procurement of the remaining parts needed to manufacture and support all the products (plus an overbuy quantity called a "buffer" that represents the purchase of more parts than the demand forecast) happens prior to the supplier's discontinuance of the part at that year's part price. In subsequent years the cost of procuring parts becomes zero, but the cost of inventory for the lifetime buy of parts must be included.

In the case of a lifetime buy, the organization incurs an additional cost in the event of part obsolescence that is included in the support cost model as an obsolescence resolution cost C_{or}. An increase in procurement cost is seen during the year of obsolescence as a result of the lifetime buy purchase followed by annual inventory costs for every subsequent year until the stored parts are either completely consumed or disposed of. During the year of obsolescence, a lower support cost is incurred since only a single purchase order is placed



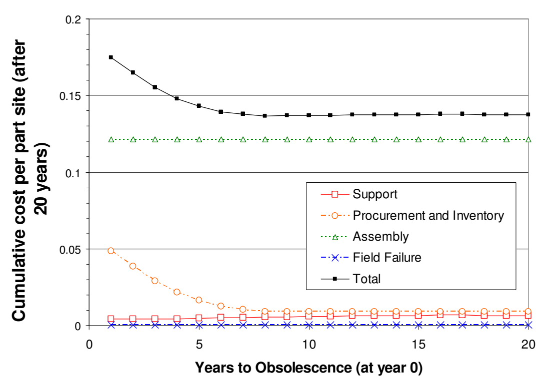


Figure 6. Cumulative cost per part site as a function of part procurement life (*YTO*) for (left) 0% and 10% overbuy on lifetime buys, and (right) 10% overbuy with respect to cost category.

when a lifetime buy is made. In Figure 6, we see that parts with shorter *YTO*s (parts that start closer to their obsolescence date) tend to incur higher procurement cost (larger life time buy quantities with larger overbuys must be bought) and inventory cost (parts remain in inventory/storage for longer).[8] This conclusion assumes that the total inventory quantity is not limited due to constraints imposed by the warehouse or storage facility (or budget). Figure 6 clearly shows the magnitude of the value of choosing parts that have longer *YTO*s over shorter *YTO*s. Consider a part that is identical to the Figure 2 case example in all aspects except with a procurement price that is 20% less ($0.012 per part) and *YTO* of 3 years (instead of 16.7 years) at introduction. This alternative part incurs a total effective cost per part site of $0.15; that is $0.012 more than the base case result after 20 years due to its earlier obsolescence.

Feng *et al*. (2007) suggests that a lifetime buy made for many years is likely to suffer from large uncertainty in forecasted part consumption. Variations in storage quantities may also occur as a result of part pilfering (stored parts being misplaced, lost or used by unassigned products) and inventory mismanagement. The additional overbuy parts (as a percentage of the required lifetime buy quantity) are stored to reduce the risk of unexpectedly depleting the inventory, a scenario that would incur high penalty costs. The case shown in this paper assumes that the predicted lifetime buy quantity is sufficient to sustain all products using the part and any inventory cost incurred is due to residual parts (unused parts from lifetime buy including the overbuy) remaining in storage. This model does not account for penalties incurred by prematurely depleting the inventory as described earlier. Models that estimate the lifetime buy quantity and cost (inclusive of penalties) can be found in Bradley and Guerrero (2009) and Feng *et al*. (2007).

A Product Change Notice (PCN) issued with sufficient warning prior to an obsolescence event enables a lifetime buy to be made. But this is not always the case, some obsolescence events occur as unexpected long-term supply chain disruptions for which no warning is provided. The next example discusses long-term supply chain disruptions in the context of design reuse.

Design Reuse of Electronic Components Subject to Long-Term Supply Chain Disruptions

In order to support existing products and facilitate the development of new products, electronic systems OEMs maintain databases that consist of hundreds of thousands of electronic parts, (Pecht 2004). Conventional wisdom dictates that the design reuse of components across a family of products generally leads to cost reductions and should be encouraged. If possible, using an existing part that is readily available in a new product design is far more cost effective than pursuing new components. Platform design (design reuse) means that a common platform is reused across a product family, where a platform is a set of common components, modules, or parts, which are shared within a product family, (Meyer and Lehnerd 1997). The concept of platforms is commonly used in the

[8] Note, the higher procurement cost for smaller *YTO* is also due to cost of money, i.e., even without considering deflation in the part costs, one would rather buy the parts in the future than today due to a non-zero discount rate.

automotive, computer, aircraft and other industries. The potential advantages of multiple products using a common platform include reductions in (Nelson *et al.* 1999): inventory, part proliferation, design lead-time, and the number of different manufacturing (assembly) processes required. The commonality shared across a product platform, class or market segment is referred to as "leveraging" (de Weck *et al.* 2003). Platforms are in essence a policy of component reuse that attempts to take advantage of the economies of scale across a family of products, (de Weck *et al.* 2003). For example, design reuse reduces the number of Product Changes Notices (PCNs) that must be managed.[9] In addition, there are several other advantages of leveraging (or commonizing) electronic parts that include: reductions in part-specific qualification testing, and consolidation of obsolescence resolution and in some cases subsequent lifetime buys.

Although many aspects of platform design have been addressed in the literature, few studies address supply chain issues, and there is little or no treatment of life cycles beyond manufacturing. In addressing design reuse, the model proposed by Huang *et al.* (2005) quantifies platform design benefits by comparing supply chain cost at varying levels of product platform commonality. This is done by assessing the supply chain in its entirety; a supply chain cost and inventory level is calculated at each stage of the supply chain to obtain a total supply chain cost. Su *et al.* (2005) propose a method for calculating the total supply chain cost and customer waiting times to study the performance of mass customization postponement structures (time postponement and form postponement). Huang *et al.* and Su *et al.* provide a complete view of the supply chain from a manufacturing organization's viewpoint, however, these models are insufficient for assessing long-term disruptions during the part's life cycle since they do not account for field failures, support, and manufacturing defects that play a role in warranty returns and product reliability decisions (post-manufacturing challenges).

A potential drawback of reusing the same component in multiple products that has been articulated by electronics system manufactures is described by the following scenario: All of your products use (depend on) a common part. An unexpected problem develops with the part. Instead of fighting a fire for one product, you are simultaneously in trouble on every product, i.e., you may have effectively created a "single point of failure" scenario by reusing the part. This situation occurs, for example, when the part becomes obsolete and an acceptable resolution must be found for each of the products that use the part – note, a resolution that is acceptable for one product may not always be acceptable to another. This scenario becomes an issue when there are a specific finite set of resources available to resolve problems across all products, which is often the case after a product enters manufacturing. Those resources cannot address every product simultaneously and as a result manufacturing or support delays occur. It is not the fact that problems with parts occur – they always will, it is not that there are insufficient resources to solve all the problems, it is the timing of the problems – there are insufficient

[9] An electronic manufacturer announces that their part or the process of fabrication has changed by issuing a PCN. In 2006, over 340,000 PCNs were issued for active and passive electronic parts (Baca 2007) where the changes ranged from modifications to the part marking and delivery packaging, to parametric changes and lead finishes. Over 18% of all the procurable electronic parts will have PCNs issued on them in any given year, (Baca 2007). The change indicated by a PCN on a part used in a particular product may or may not be relevant, but every PCN should be evaluated to determine if action is needed.

resources to solve all the problems simultaneously. Finite resources (people, equipment, etc.) to address problems becomes an issue when multiple problems or the same problem in multiple products occur concurrently and the resolution to one or more problems or products has to be delayed due to a lack of resources.

A finite resource model has been developed to allow the assessment of cost impacts of a part-specific problem occurring at a future point in time (at a user defined date). The effective finite resource limited cost of resolving a problem *j* quarters after the problem is introduced at date *D* is,

$$C_{FRM_j} = \frac{\left(N_{R_j} C_{res} + \left(N_{RT} - \sum_{k=1}^{j} N_{R_k} \right) C_{unres} \right)}{(1+d)^{D+j/4}} \qquad (6)$$

where

N_{R_j} = number of problems (products) resolved in quarter *j* (determined from the resolution rate dictated by the available resources)
C_{res} = cost of resolving the problem for one product
N_{RT} = effective total number of full resolutions that have to be done = 1 + (1 - *Co*) (N_c - 1)
Co = commonality in resolutions (0 = no commonality, 1 = all activities common)
N_c = number of products using the part on the problem date
C_{unres} = cost of unresolved problems/product/quarter
D = problem date
d = after tax discount rate

The cost in (6) is included until the problem has been resolved in all products. The model uses the commonality to determine the effective number of full resolutions that have to be done and then performs them as quickly as the finite resources will allow, charging for the resolutions and penalties for unresolved problems as it goes. The model assumes that the problem resolution resources are busy 100% of the time doing something, i.e., no idle time is paid for.

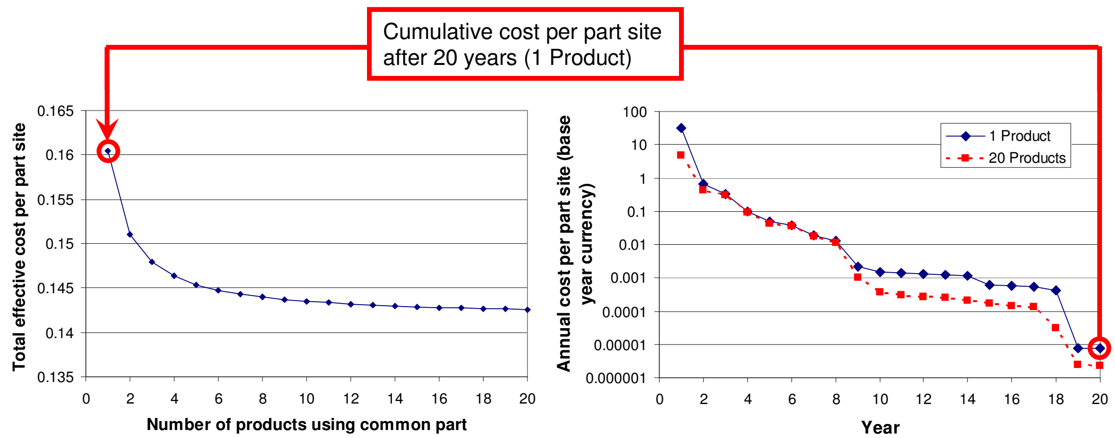


Figure 7. (left) 1 to 20 products concurrently using the example part described in Figure 2. No finite resource limited problems. (right) annual cost per part site of design reuse in 1 product and 20 products.

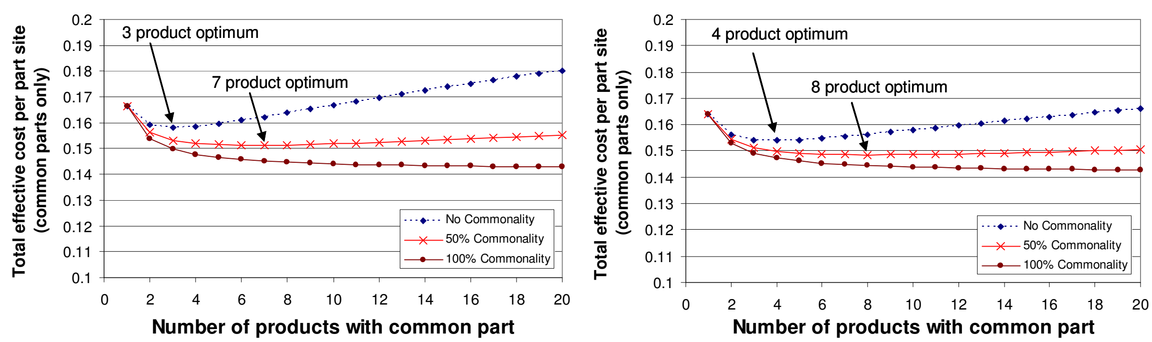


Figure 8. 1 to 20 products concurrently using the example part described in Figure 2. Problem introduced in year 5 (left) and year 10 (right).

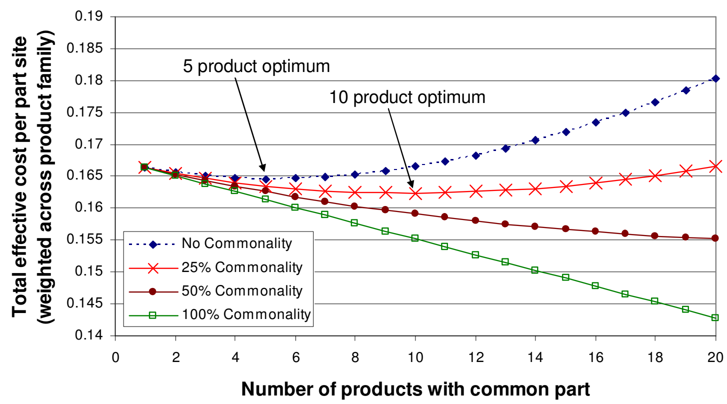


Figure 9. Weighted total effective cost per part site of a fixed pool of 20 products. Problem introduced in year 5.

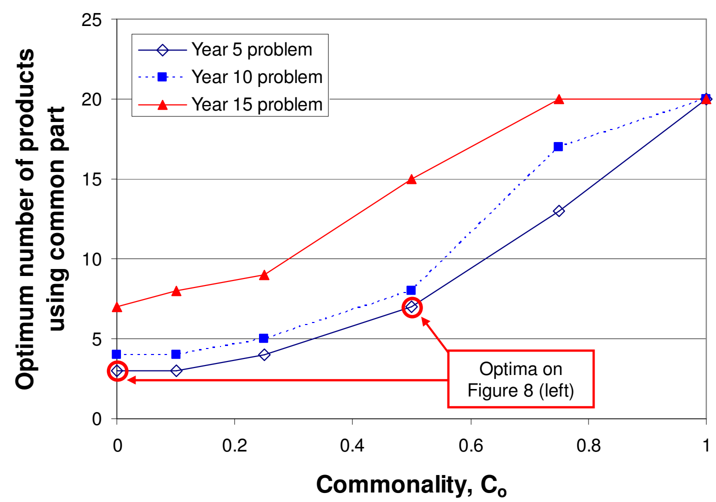


Figure 10. Optimum number of products using a common part with respect to problem resolution commonality. Total quantity of each part = 12,910,500.

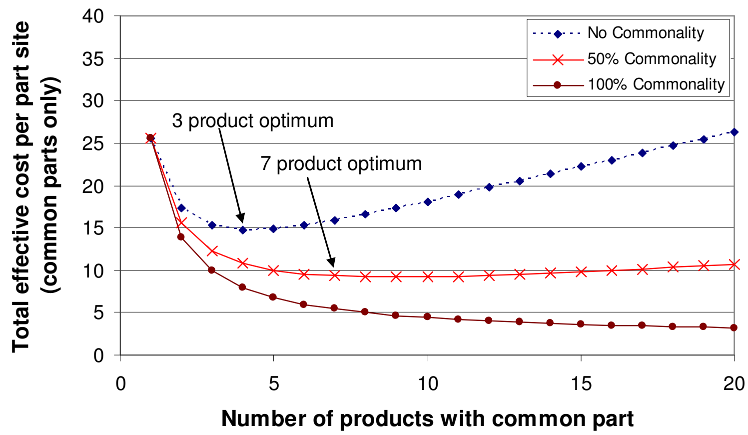


Figure 11. 1 to 20 products concurrently using the example part described in Figure 2. Problem introduced in year 5, total quantity of each product = 12,910.

We now explore potential design reuse strategies across multiple products of the example part described in Figure 2. For simplicity, we have assumed that all the products have the same production schedule i.e., every product in the product family has the same annual part (site) usage per product shown in Figure 2. Therefore, the total number of part sites in a product family (i.e., total number of common parts) is calculated by multiplying the annual part site usage per product by the desired level of design reuse. The design reuse examples in this section also assume that the number of products that the part is designed into remains the same throughout the 20 period. If we first consider the case where no problems (that would be finite resource limited) are introduced, the results in Figure 7 are obtained. As shown on the left side of Figure 7, as the number of products that use the part increases, the effective cost per part site drops. The effects of "economy of scale" are observed as a greater degree of design reuse helps distribute costs across a larger number of part sites. The right side of Figure 7 shows a comparison of the annual cost per part site for the 1 and 20 product cases. Nearly all of the difference between the annual costs is support cost (economies of scale are taking effect). Note that Figure 7 is consistent with a traditional platform design analysis that only considers manufacturing costs.

Now consider the introduction of a disruptive problem whose solution could be limited by finite resources. In this case, we will assume that the problem is not an obsolescence problem since the example part we are considering is forecasted to become obsolete in year 17 and a lifetime buy at that time is already figured into the base model. If a problem is introduced in year 5,[10] the costs as a function of the number of products the part is in are given in Figure 8 for a range of solution Commonality (*Co*). For one product, the cost is slightly higher (because the year 5 problem has to be resolved) than

[10] For the analysis results given here, we have assumed that the cost of the problem resolution in a single product is C_{res} = \$100,000, that we have resources to perform a maximum of one full resolution every 6 months (resolution rate = 0.5 resolutions/quarter), and the cost of unresolved problems is C_{unres} = \$50,000/product/quarter.

the results in Figure 7. If there is no commonality between products in the solutions to the problem, Figure 8 indicates that for this example, there is a 3 product optimum usage. As the commonality of problem solutions increases, the size of the optimum product usage increases until 100% commonality results in approximately the solution in Figure 7.

In Figure 9, a fixed pool of 20 products exists from which a design reuse strategy for a single part must be implemented. For example, if 5 products use a common part, the remaining 15 products (out of the pool of 20 products) have unique parts of similar characteristics. Contrary to the belief that consolidating common parts in a family of products minimizes cost, a threshold for commonality exists below which an optimum number of products minimizes the total cost of ownership of a predetermined family of products.

The date of the introduced problem and the sensitivity of the results to total volume of part site usage have been explored. Figure 8 and Figure 10 show that the optimum number of products to use the part in increases as the date of the problem moves further into the future. For the results in Figures 7-10, the total volume of parts is 12,910,500 parts per product. If this volume is decreased by a factor of 1,000 to 12,910 parts per product, the effective cost per part site increases substantially (the various non-recurring support costs and the cost of problem resolution at year 5 increase it dramatically), but the optimum number of products to use the part in is the same as the high-volume case, Figure 11. In finite resource limited problems, it appears that the optimum design reuse strategy is independent of the volume of parts used since problem resolutions are performed at the product level. Note, in the example case used here (a capacitor), the price variation due to volume above a few thousand parts is negligible, but the relationship may be important in more expensive parts.

Conclusion

The part total cost of ownership model presented in this paper enables fundamental part management decisions by assessing the life cycle cost incurred when introducing, assembling, and supporting a part. The approach involves the estimation of a part's life cycle cost that begins when a part is first adopted into a product design and may continue until (or even beyond) the part's obsolescence. The model takes a part-specific (rather than a product-specific) approach since supply-chain constraints and disruptions are part-specific. The application of the model has been demonstrated in a total cost of ownership estimation of a surface-mount capacitor as well as lifetime buy and a design reuse case studies.

The model demonstrates that for electronic parts, savings at the procurement level may only translate into minimal savings over the life cycle since costs due to procurement and inventory may be much smaller than costs due to manufacturing and support. Significant effort is dedicated to negotiating lower procurement prices but it becomes apparent that, for low-volume part site usage over long-term production, the benefit is low compared to the potential for cost avoidance through better management of the part over a long life cycle.

The lifetime buy case study confirms that the total cost of ownership of a part increases when parts with early obsolescence dates are chosen when the obsolescence event is resolved using a lifetime buy purchase. Choosing higher procurement price parts that have obsolescence dates that are further in the future is preferable to choosing less expensive parts that will be obsolete sooner.

The design reuse case study results indicate an increasing benefit to greater degrees of design reuse in cases where no long-term supply chain disruptions occur. For finite resource limited problems, an optimum design reuse strategy exists and it is not to reuse the part in as many products as possible. The case study results indicate dependencies between part commonality and timing of a disruption event in determining the optimum design reuse strategy (number of products using a particular part). The optimum is independent of part volume since problem resolutions are performed on the product level.

Future work involves utilizing the part total cost of ownership model to quantify the through life cost of sourcing strategies against the benefit of lower supply chain disruption risk and competitive part pricing. The total cost of ownership model can be coupled with existing decision-making techniques, such as real-options and decision-tree analyses, to enable quantitative supplier selection decisions. Other applications of the proposed part total cost of ownership model include quantifying savings associated with part number reduction, retirement of parts from databases, and organizational adoption of new parts by influencing initial component selection and providing guidance on what actions taken at the component management level provide the maximum payback (or maximum future cost avoidance).

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