CANNIBALIZATION: HOW TO MEASURE AND ITS EFFECT IN THE INVENTORY COST

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Abstract

Even though it is usually avoided in civil aviation, cannibalization can be of paramount importance in spare-parts shortages situations. Establishing a straightforward approach to cannibalizing and quantifying for the first time the potential a component has to be cannibalized allows maintenance providers to make an informed decision when selecting the most suitable maintenance procedure. In addition, it is desirable to know the impact of commonality and cannibalization in the total inventory cost.

1 Introduction

Cannibalization is often used as a maintenance alternative due to the high acquisition and holding costs of spare parts inventories and the need for reduced maintenance delays. For example, a recent study cited in [1], documented 850 000 cannibalization actions performed on U.S. Air Force and U.S. Navy aircraft over a five-year period that consumed 5.5 million maintenance man-hours. According to [2], as cannibalization actions can consume more labor than standard part removal and spare part installation, the workload on maintenance personnel can be increased significantly. A resulting decrease in maintenance personnel morale and the potential for maintenance induced damage are often stated as criticisms of cannibalization. However, there is a clear benefit from using cannibalization.

Interchanging parts in the absence of spares can reduce the maintenance turnaround time for a failed unit of equipment. However, increasing spare parts inventories can provide similar benefits at an additional inventory cost.

During research one thing was clear: there is virtually no information about implementation of cannibalization in civil aviation. After acquaintance with a renowned maintenance provider philosophy, this became even clearer as cannibalization is poorly understood and relegated to second plan.

Given this, the first approach relied strongly on information gathered from military aviation, the only sector where cannibalization is assumedly enforced. After several conversations and research on the field, it was possible to get a clearer view of what is cannibalization is practice and its advantages and disadvantages.

Any delay in maintenance works (*i.e.*, maintenance works that surpass the given period of time established by contract) will have severe consequences for the airline which has submitted the equipment to repair, as well as for other airlines and the maintenance provider itself since resources will be being used and not available for other MRO processes (scheduled or not).

According to [1], when two similar machines are inoperative because of a different failed component in each, a common maintenance practice is to cannibalize the required part from one machine to restore the other. Thus, cannibalization is often used in the absence of available spare parts to enable maintenance managers to satisfy performance constraints such as the readiness required by contracts.

It had been implicit that cannibalization can only occur between *identical* devices composed by identical sub-parts, within an identical fleet. However, in a broader sense, it is also possible the interchangeability of *similar* parts, *i.e.*, parts that are not equal but that are certificated to perform the same function. This is especially noticeable between aircrafts of different manufacturers. This interchangeability of similar components reflects the commonality property of these devices.

Commonality between two assemblies appears when these two assemblies share parts that can be interchanged between both of them. Although this sounds always desirable, according to [3], determining the extent to which to use component commonality can be difficult: "Solving the commonality problem optimally requires an assessment of the total production, inventory holding, setup and complexity cost associated with different configurations of components". Given this, it is important to easily measure commonality with the available data.

2 Commonality

The importance of higher component part standardization has been recognized as an important area of empirical investigation since it has been hypothesized to reduce inventory levels by reducing safety requirements, to reduce planned load through larger lot sizes and to reduce planning complexity through reducing number of items to be planned. Therefore, component part standardization offers considerable promise for managers wishing to improve their production capabilities.

It is important to define some concepts. *End-item* refers to a finished product or major subassembly subject to a customer order or sales forecast; *piece*, *spare* or *component part* is any inventory item (other than an end item) that goes into higher level items; and a *parent item* is any inventory item that has component parts.

To assess commonality, it is very important that the bill of material (BOM) of an end-item is available. The BOM is a diagram or record that shows all the components of an end-item or major subassembly, the parent-component relationships and used quantities. It is a listing of all components (subassemblies and materials) that go into an assembled item which includes the part numbers and quantity required per assembly.

2.1 Commonality index

There are several methods to assess commonality. These methods pretend to measure the extent of commonality between different end-items and also inside a single one. However, in this particular project, commonality was assessed using only one of these methods. The chosen method was the Total Constant Commonality Index (*TCCI*), proposed in [4]:

$$TCCI = 1 - \frac{d-1}{\sum_{j=i+1}^{i+d} \Phi_j - 1} \tag{1}$$

$$0 \leq TCCI \leq 1 \tag{2}$$

In Equation (1), i stands for the total number of end-items or the total number of highest level parent items for the product structure level(s); d is the number of distinct piece parts in the set of end items or product structures; and Φ_j is the number of immediate parents of component j.

When $TCCI$ = 0, there is no commonality as no item is being used more than once in any product. When $TCCI$ = 1, there is complete commonality. The $TCCI$ can be interpreted as the ratio between the number of common parts in a product family and the total number of parts in the family.

An illustrative example can be seen in Figure 1 [4]:

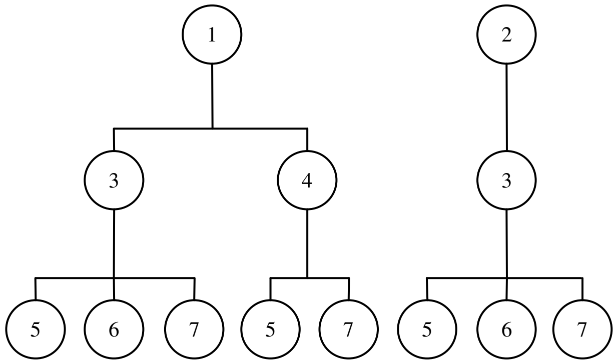

Fig. 1 – BOM of two distinct components

In this case, $i = 2$ (two distinct components, 1 and 2), $d = 5$ (there are three distinct piece parts, 3 to 7) and $\Phi_3 = 2$, $\Phi_4 = 1$, $\Phi_5 = 3$, $\Phi_6 = 2$ and $\Phi_7 = 3$. This results in:

$$TCCI = 1 - \frac{5-1}{2+1+3+2+3-1} = 0.6 \qquad (3)$$

The main advantages of the *TCCI* are its ease of computation and its fixed boundaries; conversely, its main limitation is the information considered (*i.e.*, only the number of common parts in the family; no associated cost, for example, is included): this index gives a quick but rough estimate of how good the commonality is within a product family.

3 Cannibalization

Much has been said about cannibalization but a definition is yet to be presented. The classical definition of cannibalization states that it is a maintenance procedure that consists in the removal of serviceable parts from an aircraft/component for use in the repair of other equipment of the same kind. In other words, it consists in removing a serviceable piece part from an unserviceable component to replace an identical unserviceable piece part in another unserviceable component. This is done when said piece part is not available in the maintenance provider stock and it is very hard to get it either from the manufacturer, the market or second-hand market.

According to [2], there are several discouraging and encouraging factors to cannibalize components:

<u>Discouraging factors</u>

1) *Increased maintenance workloads*

Cannibalizations increase the workload of aircraft maintenance personnel because, typically in the aircraft community, actions to repair cannibalized items take at least twice as long as normal repairs. Thus, a direct cost of cannibalizations is the additional personnel hours required to remove and replace a part. In the process, personnel must also check or repair other parts removed to gain access to the cannibalized part. For a typical assembly repair, the inoperative part is removed and a new part is installed. For a typical assembly cannibalization, the workload is doubled: the inoperative part is removed, a working part is removed from the cannibalized assembly, the working part is installed on the recipient assembly and a new part is installed on the cannibalized assembly.

2) *Potential effects on morale*

Evidence suggests that cannibalizations have a negative effect on morale because they are seen as routinely making unrealistic demands on maintenance personnel. It has been reported that cannibalization is counterproductive and has a “huge” impact on morale. Cannibalizations are performed at any time, day or night, and often very quickly to meet operational requirements. In these cases, maintenance personnel must continue working until the job is done, without additional pay. Cannibalizations increase maintenance personnel hours required for specific repairs, thus increasing the overall workload.

3) *Expensive assets unusable*

Cannibalized assemblies are not available for operations, thus denying the commercial use of expensive assets.

4) *Potential for mechanical side effects*

To remove a component, maintenance personnel often must remove other components to gain access. This increases the risk of maintenance induced damage to the aircraft. Additionally, cannibalizations do not replace a broken part with a new one, but with a used one. Therefore, cannibalizations do not restore a component to its full projected life expectancy, but rather increase the chance that the component will break down prematurely and decrease the fidelity of end item wear-out estimates.

Encouraging factors

1) *Spare parts shortages*

Spare parts shortages are the main reason for cannibalizations, and it is claimed that cannibalization shall be enforced if parts are not available. Reasons for such shortages include unexpectedly high demand, insufficient funding, production or repair delays, and higher than expected component failure rates.

2) *High operational tempo*

Readiness and operational demands put heavy pressure on the supply system to provide parts in the right place at the right time. Maintenance personnel will do whatever is necessary to keep readiness ratings high, even if it means routinely cannibalizing and working overtime.

3) *Aging aircraft*

As aircrafts become old, they tend to break down more often, take longer to inspect and maintain, and are, therefore, less available for operations. With aging aircraft, obsolescence can be a particularly serious problem. The age of these aircraft increases parts consumption and makes cannibalization necessary.

As already said, in civil aviation cannibalization has been considered only as a last resort and there is still no understanding of its full capacities and opportunities. Therefore, instead of relegating cannibalization for second plan, one has to be able to tell if this procedure is more indicated than any other one from the very beginning of the maintenance process. In order to decide when it is more viable to perform cannibalization, a method to assess the cannibalization potential of any component was developed.

3.1 Potential to be cannibalized (Λ)

This method assesses the potential a component has to be cannibalized and is denoted by Λ.

Since cannibalization deals greatly with lead-time, this was the basis for the construction of Λ. The first assumption is that the highest of any component's Λ, the hardest it is to meet lead-times (*i.e.*, the hardest it is to find a replacement via 'normal' channels – stock, supplier, second-hand market, etc.), hence, the most likely that component should be considered to be cannibalized.

The method used to assess the difficulty of finding a replacement is intrinsically related with historical data provided by a renowned maintenance provider. In the end, it was possible to define a cut-off value against which any component can be analyzed. This cut-off value is in fact a function that gives, for each one of all the recent past repairs, the correspondent percentage of awaiting piece parts period (*%APP*). *%APP* is given by the quotient of time that in the past a given component was waiting to be repaired due to lack of piece parts (awaiting piece parts period, *APP*) and the total time it took for it to be repaired (the total lead time, *LT*):

$$\%APP = 100 \times \frac{APP}{LT} \tag{4}$$

The equation that describes the cut-off line is:

$$y = \begin{cases} 0, & 0 \le x \le 0{,}3 \\ (e^{6x} - e^{1.8}) \times \frac{100}{(e^{6} - e^{1.8})}, & 0{,}3 \le x \le 1 \end{cases} \tag{5}$$

In this equation, *y* may be seen as standing for *%APP* while *x* stands for the occurrence number divided by the number of occurrences.

Equation (5), when plotted, gives the chart represented in Figure 2. The horizontal axis is not represented in Figure 2 because it is meant only to be representative of the shape of the line; in fact, the occurrence number is not important for a reason that will be explained shortly.

Given the cut-off line and the *%APP* line for any component, these two can be compared. The *%APP* line for a given component is gotten by calculating the *%APP* for every single occurrence present in the historical repair performance database and ordering these in ascending order (this is why it is not important to represent the horizontal axis, as the order in which each *%APP* occurred is lost when ordering). When this line is obtained, then it can be finally compared to the cut-off line.

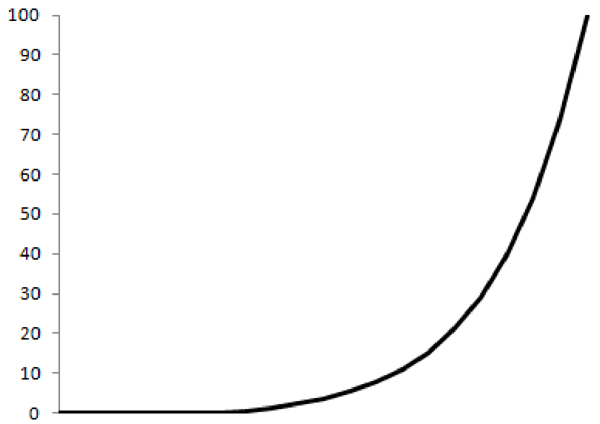

Fig. 2 – Chart of the cut-off line

The obtained result is a chart with two lines – the component's *%APP* line and the cut-off line. The goal here is to compare these two lines and tell when a component shall be considered for cannibalization. Whenever a component's *%APP* line is above the cut-off line, the component must be cannibalized and otherwise when it is below.

However, the resulting chart can be difficult to read and to extract a conclusion from because in some segments the *%APP* line may be above and in others below the cut-off line. To avoid this, Λ was defined as the sum of the differences between *%APP* and the cut-off line calculated in some very specific points:

$$\Lambda = \sum (\%APP - y) \qquad (6)$$

The domain was discretized in 20 sub-domains and the differences were calculated in the end of each one of these sub-domains (21 points in total):

	Cut-off line	
#	***x***	***y***
1	0.00	0
2	0.05	0
3	0.10	0
4	0.15	0
5	0.20	0
6	0.25	0
7	0.30	0
8	0.35	0.532620413
9	0.40	1.251582768
10	0.45	2.222080436
11	0.50	3.53211526
12	0.55	5.300477307
13	0.60	7.687516389
14	0.65	10.90968212
15	0.70	15.25915091
16	0.75	21.13031966
17	0.80	29.05556852
18	0.85	39.75353549
19	0.90	54.19428042
20	0.95	73.68724716
21	1.00	100

Table 1 – Discretization of the cut-off line

With this discretization it is possible to infer that the limits for Λ are:

$$-3.65 \leq \Lambda \leq 16.35 \qquad (7)$$

When Λ is equal to -3.65, it means that this component should not be considered to be cannibalized because its historical *%APP* line says that it is extremely easy to find any required replacement in the market. Conversely, when some component's Λ is equal to 16,35, this component should be considered to be cannibalized because its historical *%APP* line says that it is extremely hard to find any required replacement in the market. When Λ is equal to zero, the component is on the limit and other aspects shall be taken into consideration, such as obsolescence or costs.

4 Impact of commonality and cannibalization in the total inventory cost

In order to assess the impact of the extent commonality and cannibalization in an effective reduction in terms of inventory costs, total inventory costs were calculated before (Total Inventory Cost, TIC) and after integrating the weight of these two variables (Total Inventory Cost Integrated, TICI) using five different Inventory Control methods. The chosen methods were the Wagner-Whitin Algorithm (WWA), the Silver-Meal Heuristic 2 method (SMH2), the Part-Period Balancing method (PPB), the Silver-Meal Modified 1 method (SMM1) and the Least Unit Cost method (LUC) because for the current set of data it was verified that they gave the best results (lowest costs).

4.1 TIC

First, the inventory cost without considering commonality and cannibalization was calculated according to all of the five methods. For these, an existent model was used [5, 6, 7].The inputs for this calculation were:

1) Demand related:
    a. Average inter-demand interval (ADI);
    b. Square coefficient of variation in demand (CV2).

2) Component related:
    a. Item cost (IC);
    b. Ordering cost (OC);
    c. Carrying cost (CC).

These last three variables were condensed in a single variable called Economic Part-Period (EPP):

$$\mathrm{EPP} = \frac{\mathrm{OC}}{\mathrm{CC} \times \mathrm{IC}} \quad (8)$$

In this study, it was considered that both the OC and the CC to be constant and equal to €125 and 2% respectively. Therefore, EPP was further simplified to the variable that was finally used, the Inventory Carry Cost (ICC):

$$\mathrm{ICC} = 0.02 \times \mathrm{IC} \quad (9)$$

ADI is the average inter-demand interval of a given component's demand. It considers the demand pattern, which can be intermittent (with many time periods having no demand) or having a demand for almost every time period. The ADI is defined as the average number of time periods between two successive demands. So a small value for the ADI means a not very intermittent demand and a high value for the ADI an intermittent demand. By definition, ADI is greater than or equal to 1.

The square coefficient of variation in demand (CV2) considers the size of the demand when it occurs. CV2 is defined as the standard deviation of period requirements divided by the average period requirements. So a high value for CV2 means that there is a high variation in the size of demand every order. By definition, CV2 is greater than or equal to 0.

Using statistical software, it was possible to apply a linear regression (General Linear Model, GLM) to the set of data and the results are presented in Tables 2 and 3. The set of data included the three inputs referred to above (ADI, CV2 and ln(ICC)[1]) as covariates and ln(TIC)[2] as response. This was performed five times, one per each Inventory Control method and allowed to derive a linear equation to calculate ln(TIC) instead of using the definition or the complex model already existent.

4.1.1 Analysis of the results

Table 4 shows the R-squared adjusted values for each one of the linear regressions. This value indicates the variability in the response which is explained by the variables and must be higher than 60% to assure a good prediction of results. Given the fact that for all the five methods the R-Squared adjusted value is higher than 60%, the models are good and the predictions are accurate enough.

[1,2] A natural logarithm transformation of the dependent variable/response was used to overcome the problem of inconstancy of error variance in linear models (see [8]).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
(a) Analysis of variance for ln(WWA), using adjusted SS for tests (p-values)						
ln(ICC)	1	909.78	2.19	2.19	16.97	0.000[1]
ADI	1	4.71	5.60	5.60	43.42	0.000[1]
CV2	1	5.14	7.12	7.12	55.15	0.000[1]
ln(ICC)*ADI	1	2.68	2.90	2.90	22.45	0.000[1]
ln(ICC)*CV2	1	0.43	3.07	3.07	23.77	0.000[1]
ADI*CV2	1	4.72	6.83	6.83	52.93	0.000[1]
ln(ICC)*ADI*CV2	1	3.14	3.14	3.14	24.32	0.000[1]
Error	750	96.76	96.76	0.13		
Total	757	1027.35				
(b) Analysis of variance for ln(SMH2), using adjusted SS for tests (p-values)						
ln(ICC)	1	938.73	2.33	2.33	18.03	0.000[1]
ADI	1	3.39	6.68	6.68	51.65	0.000[1]
CV2	1	4.36	7.43	7.43	57.51	0.000[1]
ln(ICC)*ADI	1	2.39	3.14	3.14	24.30	0.000[1]
ln(ICC)*CV2	1	1.40	3.16	3.16	24.43	0.000[1]
ADI*CV2	1	5.61	7.44	7.44	57.61	0.000[1]
ln(ICC)*ADI*CV2	1	3.28	3.28	3.28	25.41	0.000[1]
Error	750	96.93	96.93	0.13		
Total	757	1056.10				
(c) Analysis of variance for ln(PPB), using adjusted SS for tests (p-values)						
ln(ICC)	1	1052.57	4.07	4.07	23.90	0.000[1]
ADI	1	3.64	7.66	7.66	44.95	0.000[1]
CV2	1	4.69	9.13	9.13	53.59	0.000[1]
ln(ICC)*ADI	1	1.33	5.19	5.19	30.47	0.000[1]
ln(ICC)*CV2	1	1.46	5.09	5.09	29.91	0.000[1]
ADI*CV2	1	5.68	8.85	8.85	51.97	0.000[1]
ln(ICC)*ADI*CV2	1	5.26	5.26	5.26	30.88	0.000[1]
Error	750	127.74	127.74	0.17		
Total	757	1202.37				
(d) Analysis of variance for ln(SMM1), using adjusted SS for tests (p-values)						
ln(ICC)	1	878.41	1.49	1.49	13.83	0.000[1]
ADI	1	1.46	7.31	7.31	68.03	0.000[1]
CV2	1	3.52	8.48	8.48	78.95	0.000[1]
ln(ICC)*ADI	1	2.73	2.12	2.12	19.69	0.000[1]
ln(ICC)*CV2	1	1.20	2.16	2.16	20.12	0.000[1]
ADI*CV2	1	6.41	8.26	8.26	76.84	0.000[1]
ln(ICC)*ADI*CV2	1	2.26	2.26	2.26	21.03	0.000[1]
Error	750	80.60	80.60	0.11		
Total	757	976.59				
(e) Analysis of variance for ln(LUC), using adjusted SS for tests (p-values)						
ln(ICC)	1	984.48	3.08	3.08	22.74	0.000[1]
ADI	1	4.15	6.41	6.41	47.34	0.000[1]
CV2	1	4.40	7.81	7.81	57.69	0.000[1]
ln(ICC)*ADI	1	1.52	4.01	4.01	29.62	0.000[1]
ln(ICC)*CV2	1	1.15	3.99	3.99	29.45	0.000[1]
ADI*CV2	1	4.98	7.56	7.56	55.82	0.000[1]
ln(ICC)*ADI*CV2	1	4.12	4.12	4.12	30.41	0.000[1]
Error	750	101.55	101.55	0.14		
Total	757	1106.34				

[1]Indicates significance at the 0.01 level

Table 2 – Summary of unbalanced ANOVA (GLM) results

Term	Coef	SE Coef	T	P
(a) ln(WWA)				
Constant	-6.793	1.995	-3.40	0.000
ln(ICC)	-2.4158	0.5864	-4.12	0.000
ADI	8.599	1.305	6.59	0.000
CV2	51.938	6.994	7.43	0.000
ln(ICC)*ADI	1.8172	0.3835	4.74	0.000
ln(ICC)*CV2	10.047	2.061	4.88	0.000
ADI*CV2	-33.161	4.558	-7.28	0.000
ln(ICC)*ADI*CV2	-6.622	1.343	-4.93	0.000
(b) ln(SMH2)				
Constant	-7.938	1.997	-3.97	0.000
ln(ICC)	-2.4919	0.5869	-4.25	0.000
ADI	9.452	1.306	7.24	0.000
CV2	55.639	7.000	7.95	0.000
ln(ICC)*ADI	1.8919	0.3838	4.93	0.000
ln(ICC)*CV2	10.194	2.063	4.94	0.000
ADI*CV2	-35.700	4.562	-7.83	0.000
ln(ICC)*ADI*CV2	-6.775	1.344	-5.04	0.000
(c) ln(PPB)				
Constant	-8.826	2.293	-3.85	0.000
ln(ICC)	-3.2938	0.6738	-4.89	0.000
ADI	10.052	1.499	6.70	0.000
CV2	58.828	8.036	7.32	0.000
ln(ICC)*ADI	2.4323	0.4406	5.52	0.000
ln(ICC)*CV2	12.949	2.368	5.47	0.000
ADI*CV2	-37.755	5.237	-7.21	0.000
ln(ICC)*ADI*CV2	-8.573	1.543	-5.56	0.000
(d) ln(SMM1)				
Constant	-8.425	1.821	-4.63	0.000
ln(ICC)	-1.9903	0.5352	-3.72	0.000
ADI	9.823	1.191	8.25	0.000
CV2	56.717	6.383	8.89	0.000
ln(ICC)*ADI	1.5530	0.3500	4.44	0.000
ln(ICC)*CV2	8.437	1.881	4.49	0.000
ADI*CV2	-36.466	4.160	-8.77	0.000
ln(ICC)*ADI*CV2	-5.620	1.226	-4.59	0.000
(e) ln(LUC)				
Constant	-7.550	2.044	-3.69	0.000
ln(ICC)	-2.8646	0.6008	-4.77	0.000
ADI	9.198	1.337	6.88	0.000
CV2	54.418	7.165	7.60	0.000
ln(ICC)*ADI	2.1381	0.3928	5.44	0.000
ln(ICC)*CV2	11.456	2.111	5.43	0.000
ADI*CV2	-34.887	4.669	-7.47	0.000
ln(ICC)*ADI*CV2	-7.585	1.376	-5.51	0.000

Table 3 – Coefficients of fitted models

Given Tables 2 and 3, it is now possible to write the linear equations that relate the three inputs with the respective response (see Equations 10-14). Since all the p-values are equal to zero, all the factors are significant. The coefficients used to write the equations come from the column Coef in Table 3.

	R-Sq(adj)
ln(WWA)	90.49%
ln(SMH2)	90.74%
ln(PPB)	89.28%
ln(SMM1)	91.67%
ln(LUC)	90.74%

Table 4 – R-Sq(adj) for each linearization

$$\ln(WWA) = -6.793 - 2.4158 \ln(ICC) + 8.599\ ADI + 51.938\ CV2 + 1.8172 \ln(ICC)\times ADI + 10.047 \ln(ICC)\times CV2 - 33.161\ ADI\times CV2 - 6.622 \ln(ICC)\times ADI\times CV2 \quad (10)$$

$$\ln(SMH2) = -7.938 - 2.4919 \ln(ICC) + 9.452\ ADI + 55.639\ CV2 + 1.8919 \ln(ICC)\times ADI + 10.194 \ln(ICC)\times CV2 - 35.700\ ADI\times CV2 - 6.775 \ln(ICC)\times ADI\times CV2 \quad (11)$$

$$\ln(PPB) = -8.826 - 3.2938 \ln(ICC) + 10.052\ ADI + 58.828\ CV2 + 2.4323 \ln(ICC)\times ADI + 12.949 \ln(ICC)\times CV2 - 37.755\ ADI\times CV2 - 8.573 \ln(ICC)\times ADI\times CV2 \quad (12)$$

$$\ln(SMM1) = -8.425 - 1.9903 \ln(ICC) + 9.823\ ADI + 56.717\ CV2 + 1.5530 \ln(ICC)\times ADI + 8.437 \ln(ICC)\times CV2 - 36.466\ ADI\times CV2 - 5.620 \ln(ICC)\times ADI\times CV2 \quad (13)$$

$$\ln(LUC) = -7.550 - 2.8646 \ln(ICC) + 9.198\ ADI + 54.418\ CV2 + 2.1381 \ln(ICC)\times ADI + 11.456 \ln(ICC)\times CV2 - 34.887\ ADI\times CV2 - 7.585 \ln(ICC)\times ADI\times CV2 \quad (14)$$

Now, each variable's influence will be analyzed individually. Given the fact that the coefficients of each variable do not change their sign nor suffer alterations in their order of magnitude from method to method (as per Table 3), this analysis will be made only for ln(WWA), being the reasoning similar for the remaining ones.

4.1.1.1 The constant

The constant corresponds to the y-intercept of the regression equation. Therefore, when ICC = ADI = CV2 = COM = CAN = 0, ln(WWA) is equal to -6.793. Clearly, the model is not applicable in this situation, as for a null ICC it would be expected the WWA to be identically equal to zero. Nevertheless, this constant leads to a WWA = $e^{-6.793} \approx 0.001$ when all the other variables are equal to zero.

4.1.1.2 ln(ICC)

The slope is negative and equal to -2.4158. However, this does not mean that when ln(ICC) (or ICC) increases, ln(WWA) decreases because ICC is also included in three combinations of variables, namely ln(ICC) × ADI, ln(ICC) × CV2 and ln(ICC) × ADI × CV2.

Generally, it is possible to say that when all the other variables are held constant, an increase of one unit in ln(ICC) (which corresponds to an increase of $e \approx 2{,}718$€ in ICC or in IC since CC is constant) results in a variation of -2.4158 + 1.8172 × ADI + 10.047 × CV2 – 6.622 × ADI × CV2 in ln(WWA). Since an increase of the IC is expected to generate an increase of the TIC, it is important to assure that this variation has a positive value. This only happens when the following conditions are verified:

$$\mathrm{CV2} \geq \frac{2.4158 - 1.8172 \times \mathrm{ADI}}{10.047 - 6.622 \times \mathrm{ADI}} \quad (15)$$

$$\mathrm{ADI} \leq 1.517 \quad (16)$$

$$\mathrm{CV2} \leq 0.274 \quad (17)$$

4.1.1.3 ADI

The slope is positive and equal to 8.599. However, ADI is also present in three combinations of variables, namely ln(ICC) × ADI, ADI × CV2 and ln(ICC) × ADI × CV2). Therefore, there are special conditions in which an increase of ADI results in an actual increase of WWA.

Generally, it is possible to say that when all the other variables are held constant, an increase of one unit in ADI results in a variation of 8.599 + 1.8172 × ln(ICC) – 33.161 × CV2 – 6.622 × ln(ICC) × CV2 in ln(WWA).

4.1.1.4 CV2

The slope is positive and equal to 51.938. However, CV2 is also present in three combinations of variables, namely ln(ICC) × CV2, ADI × CV2 and ln(ICC) × ADI × CV2. Therefore, there are special conditions in which an increase of CV2 results in an actual increase of WWA.

Generally, it is possible to say that when all the other variables are held constant, an increase of one unit in CV2 results in a variation of 51.938 + 10.047 × ln(ICC) – 33.161 × ADI – 6.622 × ln(ICC) × ADI in ln(WWA).

4.2 Integration of Commonality and Cannibalization in the TIC

The extent of commonality (COM) is calculated as explained in Chapter 2.1 and the extent of cannibalization (from now on referred to as CAN in opposition to Λ) is calculated as explained in Chapter 3.1.

Given TIC, COM and CAN, an expression can be derived that relates these three measures and results in TICI.

The said expression takes in consideration several aspects:

1) TICI depends on TIC, COM and CAN;
2) TICI is equal to TIC affected by a factor completely determined by COM and CAN;
3) For COM = CAN = 0 (the normal case, when neither commonality nor cannibalization are taken into account), TICI = TIC;
4) For simplicity, it is considered that the function is linear;
5) For CAN = -3.65, TICI = 0 because it is extremely easy to find a replacement and no stock needs to be kept;
6) For CAN = 16.35, TICI = 1.223 × TIC because this assures that for the whole range of CAN, the average TICI is equal to TIC;
7) When COM increases and CAN is kept constant, TICI decreases;
8) When CAN increases and COM is kept constant, TICI increases.

Having these aspects in mind, the function is:

$$\frac{\mathrm{TICI}}{\mathrm{TIC}} = \begin{cases} \psi_1, \mathrm{CAN} \leq 0 \\ \psi_2 + 0.075 \times \mathrm{CAN}, \mathrm{CAN} \geq 0 \end{cases} \tag{18}$$

Where both ψ's are given by:

$$\psi_1 = \left[(-0.777 \times \mathrm{COM} + 1)\left(\frac{\mathrm{CAN}}{3.65} + 1\right)\right] \tag{19}$$

$$\psi_2 = \left[(-0.777 \times \mathrm{COM} + 1)\left(-\frac{\mathrm{CAN}}{16.35} + 1\right)\right] \tag{20}$$

Equations 18-20 clearly describe the influence of COM and CAN in TICI; in fact, when COM increases, TICI decreases (the coefficient is negative, -0.777) and since CAN's coefficient is positive both for CAN < 0 ($^1/_{3.65} = 0.27$) and for CAN > 0 ($^1/_{-16.35} + 0.075 = 0.01$), when CAN increases, TICI also increases.

The same reasoning that led to Equations 15-17 applied to the remaining Inventory Control methods conclude that the method works preferentially when Equations 21-23 are verified:

$$\mathrm{CV2} \geq \frac{3.2938 - 2.4323 \times \mathrm{ADI}}{12.949 - 8.573 \times \mathrm{ADI}} \tag{21}$$

$$\mathrm{ADI} \leq 1.5 \tag{22}$$

$$\mathrm{CV2} \leq 0.274 \tag{23}$$

The area described by these equations is presented in grey in Figure 3:

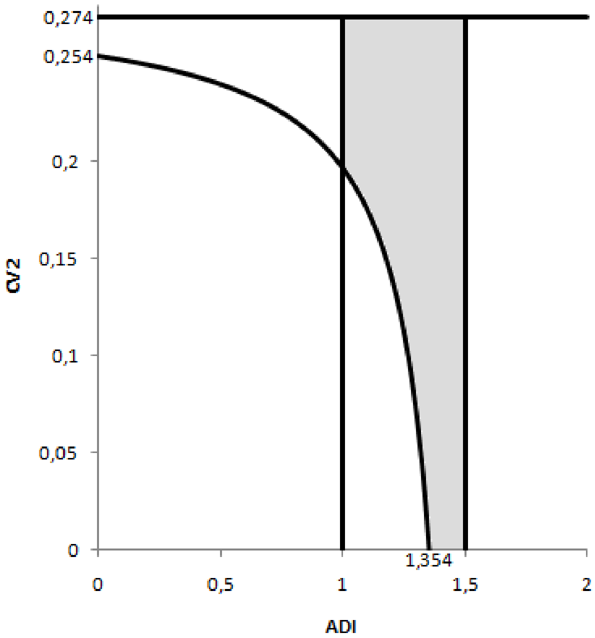

Fig. 3 – Admissible region for ADI and CV2

Making use of Equations 10-14 and 18-20, it is now possible to easily calculate TICI given the five required inputs: ICC, ADI, CV2, COM and CAN. These inputs are subject to the following conditions:

$$\mathrm{ICC} \geq 0 \tag{24}$$

$$\mathrm{CV2} \geq \frac{3.2938 - 2.4323 \times \mathrm{ADI}}{12.949 - 8.573 \times \mathrm{ADI}} \tag{21}$$

$$\mathrm{ADI} \leq 1.5 \tag{22}$$

$$\mathrm{CV2} \leq 0.274 \tag{23}$$

$$0 \leq \mathrm{COM} \leq 1 \tag{2}$$

$$-3.65 \leq \mathrm{CAN} \leq 16.35 \tag{7}$$

5 Conclusions

The present study has three main parts and, accordingly, three important results. First, it was described a method that allows to measure the potential a component has to be cannibalized (Λ). For this method, an historical demand and record of performance is required and the method clearly states if a component is a good or bad candidate for cannibalization. In fact, throughout literature or inside the industry it was not found any single method to assess cannibalization in any way, so this comes as a major breakthrough.

It was also performed several statistical analysis in order to overcome the complexity of five different Inventory Control methods, namely WWA, SMH2, PPB, SMM1 and LUC. Linear Equations 10-14 relate the inputs (ICC, ADI and CV2) with the response (TIC) avoiding the difficulty inherent by using the definition of each method.

Another major innovation was studying the impact of commonality and cannibalization in the Inventory Cost. The derived formula is based in some reasonable assumptions and relates the TICI with TIC, COM and CAN (Equations 18-20). Analyzing these equations, it is clear that the extent of commonality has a negative impact in TICI, whereas the potential a component has to be cannibalized has a positive impact in TICI. This is due to the fact that high component standardization allows stocks to be reduced since the parts to be kept are identical and maintenance providers must invest more in their stocks when it is expected that it is very hard to get a replacement from the market.

6 Recommendations

Future research shall be made in order to assure a better linearization of the Inventory Control methods. The performed linearization is limited because it only works correctly in the interval shown in Figure 3 and a broader interval is desirable.

In addition, the cut-off line required to the method to calculate Λ is intrinsically related to the performance of the maintenance provider. It may be interesting to find a more generic, universal solution.

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