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Analysis of Long-Term Impact of Maintenance Policy on Maintenance Capacity Using a Time-Driven Activity-Based Life-Cycle Costing

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Abstract: In capital-intensive industries, physical assets and maintenance activities play a relevant and strategic role in terms of providing operational continuity and business sustainability. As a result, maintenance support structures are highly complex and sophisticated. Therefore, maintenance capacity planning must be addressed using reliable techniques to assure the adequate service levels and availabilities of critical assets at the minimum opportunity cost. There has been relatively limited research on how to determine and optimize the maintenance support structure (human resources) in such organizations. This paper proposes a novel technique for dimensioning and optimizing maintenance capacity that combines Time-Driven Activity-Based Costing and Life-Cycle Costing with the Weibull function-based reliability model. Following the main principles of the Design Science Research we propose a sophisticated but simple artifact. Through this model, it is possible to compute maintenance costs and assess both used and idle capacities, considering the behavior over time of the failure rates and the reliability of critical assets within a plant. To demonstrate how the proposed methodology addresses the problem, the model was applied in a real medium-sized Chilean comminution plant and a sensitivity analysis was performed, particularly, to evaluate the relevance of appropriate maintenance workforce planning.

Keywords: Time-Driven Activity-Based Costing (TDABC); Life-Cycle Costing (LCC); maintenance costs; capacity analysis; economic sustainability; mining industry

1. Introduction

Mining involves the extraction and processing of non-renewable resources and it is often seen as an unsustainable activity because the low levels of productivity and efficiency are linked to inexperienced equipment, high labor turnover, and an ageing workforce [1]. However, it must be recognized that mining has great potential to operate more sustainably [2]. According to Hilson and Murk (2000) [3], the search for sustainability in mining activity implies "a continuous strategy to improve environmental protection and promote socio-economic growth". Such strategies must include improved planning and environmental management, labor awareness, progress in stakeholder relations, and sound human resource management [4].

In capital-intensive organizations, such as mining, physical assets are designed and/or selected to perform specific tasks within a given range of conditions and with long life cycles, considering demanding performance requirements with high availability and reliability levels [5]. Consequently, in these organizations, the maintenance and support structures present high complexity and sophistication. Therefore, maintenance function plays a relevant and strategic role in terms of operational continuity and sustainability [6]. Today, maintenance is no longer just a set of operations focused on fixing faults and preserving machines. Rather, maintenance is seen as a long-term strategic function that incorporates all phases of the life cycle, taking into account social, environmental and economic impacts [7,8]. Through the generation of efficient maintenance strategies, under the concept of "integrated asset management" it is possible to transform the conventional perspective of maintenance into an approach that will make possible the improvement of all the aspects of sustainability in an extremely complex and competitive market environment [9]. Furthermore, making maintenance management a more efficient activity will have a positive impact from the point of view of the entire life cycle of a system. This will make a significant contribution from both a technological and organizational point of view, and may lead to a change in a company business model [10]. Therefore, maintenance has a huge impact on economic, environmental, and social performance. In a holistic or systems-oriented thinking approach, the triple bottom line perspective leads to the integration of a multidisciplinary vision to manage critical physical assets as a whole [11]. Thus, one important aspect which has to be addressed is the maintenance capabilities planning and its impact on long-term sustainability [12].

2. Problem Statement

In accordance with the UNE-EN-17007 standard, one of the critical processes of maintenance (support process) is to "provide in a timely manner internal human resources with the necessary skill levels and certification to perform maintenance activities". The availability of labor significantly impacts the efficiency of maintenance. According Shou et al. [13], not having adequate human resources for maintenance activities (with lack of skill, typical in new employees) or the late arrival to perform the activities, these will be deeply affected in their efficiency, costs, and productivity.

Maintenance costs in industries can reach 40% of production costs [14] or more [15]. Furthermore, with the recent advances in the industry, the increase in the level of automation and the complexity of the production systems, the maintenance costs can increase significantly [16]. Therefore, cost accounting and management plays a key role in measuring and mapping production and support systems capacity use. In fact, the International Financial Reporting Standards (IFRS) ([17,18]) standard highlights the importance and the need to permanently evaluate production capacities and the impact that their use has on the costs of products and services.

As Adıgüzel and Floros [19] state, traditional costing systems are not sufficient to meet the needs of capacity planning and workforce use analysis because they allocate overhead costs to products on the basis of a volume-based cost factor. More recently, modern costing systems have been proposed as more suitable for measuring levels of idleness of productive capacities. Among them, the activity-based [20] and the Value Added-based approaches [21,22], are the most cited in the literature.

On the other hand, life-cycle costing (LCC) is also important in this context. The LCC of a physical asset corresponds to the present value of the sum of capital expenditures (CAPEX) and operating and maintenance expenditures (OPEX) over its service life, plus the costs of decommissioning at the end of the asset service life [23,24]. According to Ruparathna et al. [25], recent maintenance management decision-making frameworks are not fully adequate to take into account forthcoming technological advances and complex regulatory and environmental constraints, and there is a significant awareness gap in the integration of sustainability performance, risk, and time-sensitivity factors to encourage dynamic asset management decision-making.

To assess life-cycle costs, we need adequate statistical tools and suitable information systems to successfully predict the future behavior of the costs of ownership [26]. There are several LCC methods reported in the literature, among them, [26,27] are the most cited papers. In the opinion of these authors, conventional LCC methods have two main drawbacks: they lack a reliable measure of the future failure rate behavior, and they deal excessively roughly with the costs of operation and maintenance activities. Roda and others [28] suggest that the methods that adopt ex-ante estimation of life-cycle costs are the most suitable, particularly the ones, which are based on next-event simulation approach. To enhance the accuracy of such cost estimation, lately, a variety of costing techniques have been proposed to estimate prospective costs of ownership, including those involving Activity-Based

Costing—ABC [20,28]. Nevertheless, one of the main drawbacks of ABC is its need for a very large number of drivers and the excessive volume of transactions to determine product or process costs [29]. Time-driven ABC (TDABC) was initially proposed by Kaplan and Anderson [30] as a means through which the difficulties in the implementation of the ABC can be overcome.

Time-driven ABC is recognized as a streamlined and simple technique for the costing of processes and cost objects [29]. With this new approach, a single driver is used, i.e., the time required for the execution of an activity [31]. Thus, using this model, it is possible to measure the resources consumption associated with the degrees of execution of the activities carried out to establish and sustain operational continuity and to highlight idle capacity along time. So far, no studies have been found in the literature that analyze maintenance capacity from a long-term perspective using an ABC model. This is how the first hypothesis is raised, i.e.,: "it is possible to build in a simple manner, a model that analyzes maintenance capacity use in a long-term perspective by analyzing the costs of activities related to the maintenance needs".

Furthermore, it is well known that throughout the life cycle of such physical assets, reliability and performance vary over time [26]. Failure rates fluctuate and, in many cases, maintenance strategies must be reconfigured [32]. Thus, the selection of the maintenance strategy is normally based on the stage of the life cycle in which the asset is. A typical life-cycle model considers three stages: early failures due to faulty material and faulty processing (infant mortality), a second phase with random failures that present a constant failure rate, and the third phase with failures due to ageing, fatigue, etc. [33]. Since these phases have different characteristics in terms of reliability and failure rates, significant effects on the life-cycle costs of physical assets can arise. To achieve higher precision in cost estimation, especially regarding the OPEX, some critical maintenance performance indicators such as availability, maintainability, and reliability, have to be included in the model [34].

In the long term, capacity planning and LCC high degrees of uncertainty will be present. Such uncertainty can lead to difficulties, i.e., insufficient resources or overestimated workload, leading to inadequate infrastructure to undertake such maintenance tasks [35]. As a means of dealing with the high levels of uncertainty, the use of Monte Carlo simulations to represent or estimate projected cash flow values has been proposed [36]. Also, few works have included aspects based on the asset reliability to estimate maintenance and repair costs [37] in a LCC model using the ABC method. In this context, it is necessary to include asset reliability aspects into LCC models will allow better cost estimations and a more accurate maintenance capacity planning.

3. Methodological Aspects

The design science is proposed by Simon [38]. It embodies an exploratory, not an explanatory, approach to research. Through the exploration solutions, "artifacts" are proposed making possible the generation of procedures, techniques, tools, technologies, or products, among others. The design science research (DSR) has lately been proposed as a methodological tool for research in areas related to operations and management [39,40].

The decision of applying design science to assess the relationship between human resources planning and future maintenance needs is based on the fact that this problem has not been properly structured, i.e., decision makers must achieve a solution without having a conclusive formulation which can lead them to either good or bad results (not true or false) and which cannot be definitely proven. The method of design science can handle this type of poorly structured problems through a systematic way [41].

The application of design science to the mentioned problem is based on the adoption and integration of two widely disseminated methods or artifacts: TDABC and Reliability Theory. The main challenge, maintenance workforce planning, with the aim of evaluating or balancing maintenance capabilities with the dynamic behavior of failures in complex productive systems was addressed through the development of a Reliability-based TD-AB costing method, established on a long-term basis.

More specifically, through a design science approach, we were able to develop a method that allows, through the quantification of future costs related to maintenance activities, to verify the convenience of applying or not, major maintenance, as an alternative to progressively expand or balance the maintenance workforce.

From the methodological point of view, the DSR process began with (i) the need to evaluate the costs and the maintenance plan in a milling plant, and (ii) the identification of the lack in the literature of applicable methods or tools to maintenance activities costing problems, using a simple and realistic structure (that takes into account the real needs of future maintenance) in accordance with the future needs of maintenance labor. It was defined as the objective the definition of a method (or artifact) that, taking into account the future projection of the reliability of critical equipment in an industrial plant, it is possible to project the behavior of the needs for corrective or unplanned maintenance interventions, and their costs. Next we devised an integrated structure of methods to implement a solution (TDABC and Theory of Reliability). Finally, we evaluated the results with data from a real case, together with developing a sensitivity analysis, which allowed establishing evaluation criteria for various solution alternatives (performing major maintenance instead of simply expanding human resources to meet these needs of future maintenance). Below we detail the operational steps of each phase of our proposed method.

Regarding the aforementioned steps, this paper proposes a TDABC-LCC model which estimates the maintenance costs of a physical assets in a production system. Through the application of TDABC, such model allows planning of maintenance capacity taking into account Weibull distribution-based reliability aspects. The model was applied in a medium-sized comminution plant located in central Chile. A sensitivity analysis is also presented to test different maintenance strategies over time as well as to gauge the effects on maintenance capacity use.

The DSR-based approach followed six steps: identification of the problem and the reason, definition of the objectives, design of an artifact (Section 4), demonstration, evaluation and communication (Section 5).

4. Time-Driven Activity-Based Life-Cycle Costing

One of the techniques that has been proposed to compute and manage costs more accurately and efficiently has been the ABC. The ABC approach has been extensively studied and many of its benefits have been compared to traditional costing methods. It is now widely accepted that the ABC approach can improve business profitability using sophisticated cost drivers and improved cost measurement capabilities. In addition, through the ability to capture the cause/effect relationship between cost and the product or service, better pricing and profitability comparisons can be achieved [42]. Many authors [43–45] have suggested the combined use of ABC and LCC. However, as has been profusely reported in the literature [46–48], it has been very difficult to adopt the traditional ABC model because of the costs incurred during its implementation and maintenance over time [47]. Another disadvantage in applying ABC models in long-term scenarios, is the high level of variability associated with driver behavior [49–52].

More recently, a new model for costing has been proposed, the TDABC. According to [53], time-driven ABC requires the estimation of only two parameters: the unit cost of supplying capacity and the time required to perform a transaction or an activity. Mainly, its implementation procedure consists of two major phases: the first phase consists of calculating the capacity cost rate(s) by Use the "Insert Citation" button to add citations to this document.

Dividing the total cost by the practical capacity. Thus, through that, the cost per time unit is calculated (Equation (1)). The second phase is devoted to defining the time equations which reflect the demand for resource capacity in a given time frame (they model how time drivers drive the time spent on one specific activity). Such equations allow the allocation of costs to the cost object by multiplying the cost per time unit by the time needed to perform the activity (Equation (2)).

$$Capacity\ Cost\ Rate = \frac{Cost\ of\ Capacity\ Supplied}{Practical\ capacity\ of\ Resources\ Supplied} \quad (1)$$

To quantify the time consumed by each of the activities, the so-called time equations are used. Thus, the time consumed in executing each activity can be expressed in terms of different characteristics called time drivers. The general time equation needed for activity j is given by:

$$t_j = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \cdots + \beta_n \cdot X_n \quad (2)$$

where:

t_j: Time required for executing the activity j
β_0: constant amount of time for activity j
β_n: time consumed per unit of time driver n
X_1: time driver 1
X_n: time driver n
n: number of drivers associated with the activity j

Time equations consider a standard time of execution of the activity plus an incremental time to perform additional activities. Thus, in a TDABC resource costs can be assigned directly to cost objects [54]. There are some applications of TDABC, e.g., in the logistics process [54] and lean manufacturing [55], among others.

In maintenance management only recently, there has been published a couple of papers that address the costs analysis and computation using TDABC. For example, Ref. [56] proposed a time-driven ABC model to estimate maintenance costs, and to give support to identify maintenance activities and organize the maintenance department. More recently, Ref. [57] presented a model for maintenance costing. The model, which is based on the TDABC, enables the identification of the participation that each maintenance activity will have in the total cost of maintenance and, from this, it will be possible to identify the activities, elements, and actions that will have to be improved to lower the life-cycle costs. In addition, the TDABC approach has been used as a means of evaluation of the used and idle capacities, allowing the detection of capacity deficits or excesses of allocated resources over time [19].

Despite its simplicity and wide dissemination, TDABC has not yet been used in LCC models or with multi-period models combined to capacity analysis. Therefore, there is a need for a multi-period TDABC model that allows, combined with information on the asset reliability, to estimate maintenance costs and perform capacity use analysis.

5. Maintenance Interventions and Assets Life-Cycle Management

Maintenance corresponds to the combination of all the technical, administrative and management actions during the life cycle of an asset aimed at retaining it or returning it to a state in which it can perform the required function [58]. Maintenance activities can be classified into three main categories: routine and/or planned maintenance, which consists of regular checks and replacements, corrective or unplanned maintenance, and major maintenance actions (and/or overhaul). The combination of these categories, planned and unplanned, can occur depending on several factors, such as the reliability of the asset, the operational context and its use levels, among others.

Barlow [59] proposed two basic policies of preventive maintenance, these are replacement policies based on age, and at constant intervals. The age-based preventive maintenance policy consists of making preventive replacements at the end of a time interval t_p. If the asset fails before the t_p has been completed, maintenance must be performed at that time, and then, a new preventive maintenance must be rescheduled after a new t_p interval. The second policy (constant intervals) consists of performing preventive maintenance at the end of the t_p operating interval, independently of the number of failures, and the corresponding interventions that may occur during t_p.

Regardless of the maintenance policy chosen, both policies consider the existence of failures, and the consequent corrective interventions. To estimate the failure rate, the Weibull distribution is one of the most used approaches in physical assets management and reliability analysis. According to Weibull's distribution [60], the failure rate in time, $\lambda(t)$, is given by:

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \tag{3}$$

where:

β is the shape parameter, $\beta > 0$
η is the scale parameter, $\eta > 0$
γ is the location parameter, $t - \gamma > 0$

In the case of applying age-based preventive maintenance policy, two maintenance cycles can occur: the equipment operates until the moment of a preventive maintenance (replacement) t_p, or the equipment fails before the planned maintenance. The probabilities of occurrence of each of these two possible scenarios are ruled by the laws of reliability (Figure 1).

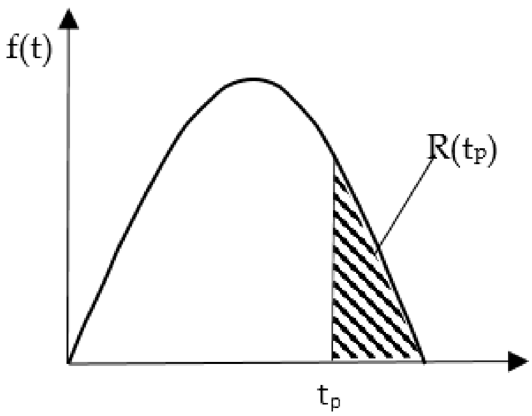

Figure 1. Failure density function and Reliability representation.

As the objective here is to estimate the expected number of preventive and corrective interventions over a given period of time T, e.g., a year, we consider the modeling proposed by [34]. The following equation allows us to estimate the expected length of an entire preventive cycle using the age-based policy:

$$lp_1 = t_p \cdot R(t) \tag{4}$$

Equation (5) estimates the expected (average) length of the corrective interventions using the same, age-based preventive policy:

$$lc_1 = M(t_p) \cdot [1 - R(t)] \tag{5}$$

where $M(t_p)$ corresponds to the Mean Time Between Failures ($MTBF_p$) in a scenario where a preventive intervention at t_p is planned, which is:

$$M(t_p) = \int_0^{t_p} \frac{tf(t)dt}{1 - R(t_p)} \tag{6}$$

Thus, the expected number, in an interval T, of preventive maintenance cycles which come to an end in t_p is given by:

$$Np_1 = \frac{T}{t_p \cdot R(t_p)} \tag{7}$$

In addition, the expected number of corrective activities that will take place over a period of time T is given by:

$$Nc_1 = \frac{T}{M(t_p) \cdot [1 - R(t_p)]} \tag{8}$$

Based on the constant intervals approach, the expected number of preventive maintenance cycles in an interval T which come to an end in t_p. is given by:

$$Np_2 = \frac{T}{t_p} \tag{9}$$

On the other hand, the expected number of failures, and the consequent corrective interventions, in the interval (0, t_p), is denoted as $H(t_p)$, and it is given by:

$$H(t_p) = \int_0^{t_p} \lambda(t)dt \tag{10}$$

Solving Equation (10), the expected number of failures is given by:

$$H(t_p) = \left(\frac{t_p - \gamma}{\eta}\right)^{\beta} \tag{11}$$

Thus, the number of corrective interventions during a period T (Nc_2), is given by:

$$Nc_2 = \frac{T}{t_p}\left(\frac{t_p - \gamma}{\eta}\right)^{\beta} \tag{12}$$

6. Proposed Model

The purpose of this section is to describe a Time-Driven Activity-Based Life-Cycle Costing (TDAB-LCC) model for managing maintenance and the capacity of a physical asset or a group of them. The main aspects related to this model are:

- Multi-period (life cycle),
- Multi-asset system,
- Reliability oriented (Weibull distribution).

The capacity cost rate in a given period of time (CCR_t) is obtained from the division of the total cost of the maintenance resources in period t (RC_t), in \$, by the practical capacity of maintenance activities (in hours) in the same period t (NC_t). Please note that for each period, both resource costs and practical capacities may vary. The model reflects this variation using the sub-index t corresponding to the specific life-cycle period (Equation (13)).

$$CCR_t = \frac{RC_t}{NC_t} \tag{13}$$

The generic form of time equations presented by Equation (2) is modified to include the multi-period characteristic leading to the structure shown in Equation (14):

$$T_{j,t} = \beta_{1,t,j} \cdot X_{1,t,j} + \beta_{2,t,j} \cdot X_{2,t,j} + \beta_{3,t,j} \cdot X_{3,t,j} + \ldots + \beta_{K,t,j} \cdot X_{K,t,j} \tag{14}$$

where:

$T_{j,t}$: Time required for executing the maintenance activity j in period t.
$\beta_{i,t,j}$: Time consumed per unit of time driver i in period t regarding activity j.
$X_{i,t,j}$: Time driver i in period t (i.e.,: number of executions of activity j in period t).

The processes considered in this model are all the maintenance processes (or activities) executed by the production system to maintain all the physical assets available. Therefore, we consider that the time drivers of each process are expressed in quantity of interventions or maintenance actions (Nc_i or Np_i) for a given asset, using a given preventive maintenance policy.

For estimate the time driver i in a period t, $X_{i,t}$, we propose the use of the expected the number of the maintenance actions (preventive or corrective) for each asset category or class.

Therefore, if the age-based preventive maintenance strategy is used, the correspondent time equations can be expressed as shown in Equation (15):

$$T_{j,t} = \beta_{1,t,j}\cdot\left[\frac{T}{t_p\cdot R\left(t_p\right)}\right]_{1,t,j} + \beta_{2,t,j}\cdot\left[\frac{T}{t_p\cdot R\left(t_p\right)}\right]_{2,t,j} + \ldots + \beta_{k,t,j}\cdot\left[\frac{T}{t_p\cdot R\left(t_p\right)}\right]_{k,t,j} \tag{15}$$

On the other hand, if the preventive maintenance strategy, using constant intervals, is used, the correspondent time equations can be expressed as shown in Equation (16):

$$T_{j,t} = \beta_{1,t,j}\cdot\left[\frac{T}{t_p}\right]_{1,t,j} + \beta_{2,t,j}\cdot\left[\frac{T}{t_p}\right]_{2,t,j} + \ldots + \beta_{k,t,j}\cdot\left[\frac{T}{t_p}\right]_{k,t,j} \tag{16}$$

In the case of activities of a corrective type, and in a scenario where the preventive maintenance strategy based on age is being used, the equation of time will be as follows:

$$T_{j,t} = \beta_{1,t,j}\cdot\left[\frac{T}{M\left(t_p\right)\cdot\left[1-R\left(t_p\right)\right]}\right]_{1,t,j} + \beta_{2,t,j}\cdot\left[\frac{T}{M\left(t_p\right)\cdot\left[1-R\left(t_p\right)\right]}\right]_{2,t,j} + \ldots + \beta_{k,t,j}\cdot\left[\frac{T}{M\left(t_p\right)\cdot\left[1-R\left(t_p\right)\right]}\right]_{k,t,j} \tag{17}$$

Finally, the corrective activities that are originated under the existence of the preventive strategy with constant intervals are defined by:

$$T_{j,t} = \beta_{1,t,j}\cdot\left[\frac{T}{t_p}\,H(tp)\right]_{1,t,j} + \beta_{2,t,j}\cdot\left[\frac{T}{t_p}\,H(tp)\right]_{2,t,j} + \ldots + \beta_{k,t,j}\cdot\left[\frac{T}{t_p}\,H(tp)\right]_{k,t,j} \tag{18}$$

Therefore, the time equation can be expressed as:

$$T_{j,t} = \beta_{1,t,j}\cdot[Nx]_{1,t,j} + \beta_{2,t,j}\cdot[Nx]_{2,t,j} + \ldots + \beta_{k,t,j}\cdot[Nx_i]_{k,t,j} \tag{19}$$

where $[Nx]_{k,t}$ represents the number of executions carried out corresponding to the asset k, in period t. The sub-index x could represent the preventive or corrective nature of the activity j, ($x = \{p, c\}$). As the time equations consider the activities of a certain type associated with a number K of different assets, and as, in generic terms, different preventive maintenance strategies may have been defined for each of them (i.e., age-based or at regular intervals) $[Nx]_{1,t}$ values may be defined specifically for each of the assets considered. Thus, the total capacity used in a given period t, UC_t, corresponds to:

$$UC_t = \sum_{j=1}^{A} T_{j,t} \tag{20}$$

The capacity cost rate will also be exposed to changes over time. This may be because the values of the resources used, and the nominal capacity of each period may be altered. If we consider an inflation rate in each period, ι, the total cost of the resources supplied for period t, RC_t, will be given by:

$$RC_t = RC_1 \cdot (1+\iota)^t \tag{21}$$

Finally, the cost of the used capacity for period t is generically given by:

$$UC_t = T_{1t} \cdot RC_1 \cdot (1+\iota)^t + T_{2t} \cdot RC_1 \cdot (1+\iota)^t + \ldots + T_{nt} \cdot RC_1 \cdot (1+\iota)^t \tag{22}$$

By factorizing the previous expression, we have:

$$UC_t = RC_1 \cdot (1+\iota)^t \cdot \sum_{j=1}^{J} T_{j,t} \tag{23}$$

Finally, and to compare the maintenance capacity committed in each period with the planned maintenance capacity (nominal) in the same period, the following simple relation is available:

$$\Delta_t = \frac{NC_t - UC_t}{NC_t} \tag{24}$$

Considering Equation (24), Δ_t represent the percentage of maintenance idle capacity in period t. By using this percentage, it is possible to assess every period the proportion of the maintenance capacity that is expected to be idle according to the projected needs of maintenance activities (corrective and preventive) for each period of the life cycle of the asset(s).

As a means of illustrating the use and benefits of the proposed model, a numerical case that considers two physical assets is presented, and it depicts the significant differences in the analysis obtained through the proposed model compared to a traditional costing method.

The model was applied considering the maintenance of two different equipment units, with different ages, and with different reliability performance. This is demonstrated by the schematic representation of failure rates over time shown in Figure 2. Equipment 1, a ball mill, has a curve consistent with the concept of the bathtub curve, with an infant mortality phase, followed by a phase with a constant failure rate, and finally, with a phase called wear phase, where the failure rate increases along time. Meanwhile, the equipment 2, a crusher, presents a constant failure rate during its entire life cycle (β Weibull parameter equal to 1).

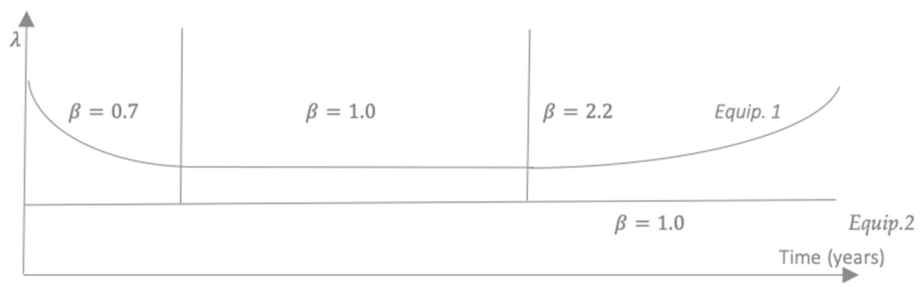

Figure 2. Projected Failure rate for both physical assets.

The maintenance needs were projected considering the preventive maintenance strategy at constant age and according to Equations (7) and (8).

The activities were separated into two categories: planned maintenance activities and corrective maintenance. In total, there are 6 activities for each equipment, summing up 12 time equations. The values in Table 1 represent the unitary execution times for each activity. These values were estimated based on the case presented in [61] and are shown in Table 1.

Table 1. Activity list and its duration.

Activity	Ball Mill (h)	Crusher (h)
Preventive Action #1	5	4
Preventive Action #2	5	3
Preventive Action #3	5	2
Corrective Action #1	36	30
Corrective Action #2	24	18
Corrective Action #3	3	2

Table 2 shows the Weibull parameter values for each equipment.

Table 2. Weibull's β parameters obtained for both physical assets (year 1 to year 10).

	1	2	3	4	5	6	7	8	9	10
Equation (1)	0.7	0.7	0.7	1.0	1.0	1.0	1.0	2.2	2.2	2.2
Equation (2)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

To carry out all the above-mentioned activities, 3 maintenance workers are considered, who perform their functions according to the data shown in Table 3. These workers spend 80% of their working time to these activities and the remaining to other ones in the plant. The annual cost of the three maintenance workers in the first year of analysis is $45,450. In addition, such costs were corrected according to an expected annual rate of inflation of (1%).

Table 3. Operational parameters.

Parameter	Value
Working Days	240
Hours/Day	8
Efficiency Rate	70%
Total Maintenance Hours/Year	3240 Person-hours/Year

Table 4 presents the frequencies in which preventive maintenance interventions are performed.

Table 4. Preventive actions frequencies.

Activity	Ball Mill (h)	Crusher (h)
Preventive Action #1	Monthly	Bimonthly
Preventive Action #2	Monthly	Bimonthly
Preventive Action #3	Weekly	Diary

The time consumed by the maintenance activities of each one of the equipment for the 10 years in analysis are shown in Table 5.

Table 5. Time consumed by maintenance activities and equipment along the planning horizon (year 1 to year 10).

Maintenance Activity	1	2	3	4	5	6	7	8	9	10
Mill: Pl. Maintenance (h)	378	378	378	378	378	378	378	378	378	378
Mill: Correct. Maintenance (h)	59	101	137	162	204	246	288	903	1188	1515
Crusher: Pl. Maintenance (h)	898	898	898	898	898	898	898	898	898	898
Crusher: Correct. Maintenance (h)	28	61	93	126	158	191	223	256	288	321
Total Used Capacity (h)	1363	1438	1506	1563	1638	1713	1787	2434	2752	3112
Total Idle Capacity (h)	1877	1802	1734	1677	1602	1527	1453	806	488	128

This allows estimating the percentage of capacity that has been allocated to maintenance activities in each period (planned and unplanned) as well as the idle capacity that results from such allocation in each period (Figure 3).

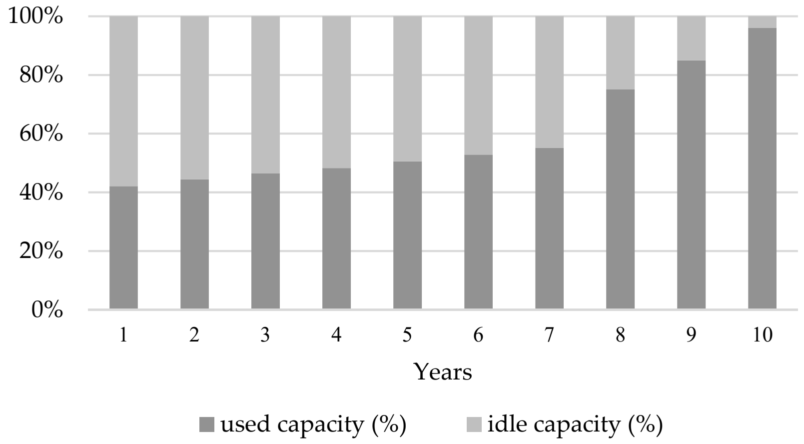

Figure 3. Used vs. idle capacity behavior along the planning horizon.

It can be observed how, as time proceeds, the capacity goes from a low level of usage, to practically fully used. Once the present values of the maintenance labor costs associated with both equipment have been estimated, in addition to the idle capacity, it can be seen that over the ten years of analysis, for an opportunity cost of 10% per year, the idle capacity represents 44% of the nominal total capacity (Figure 4).

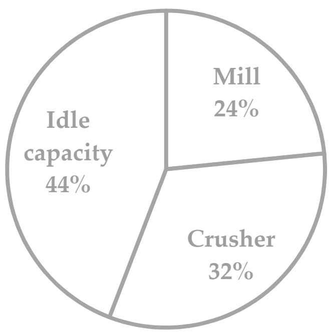

Figure 4. Used capacity by both equipment and idle capacity (in present values).

The costs of all maintenance actions for both equipment, calculated along with the value of the idle capacity for each period, are shown in Table 6.

Table 6. Costs related to maintenance actions (used capacity) and idle capacity for both equipment (year 1 to year 10).

Capacity	1	2	3	4	5	6	7	8	9	10
used capacity	$19,119	$20,374	$21,551	$22,594	$23,909	$25,248	$26,611	$36,612	$41,797	$47,744
idle capacity	$26,331	$25,530	$24,812	$24,233	$23,386	$22,520	$21,635	$12,116	$7418	$1963

To compare the relevance of using the TDABC methodology for the analysis of long-term maintenance costs, it was compared with a traditional method, i.e., a volume-based costing.

For this purpose, the costs per period of maintenance labor were estimated and then prorated, in equal parts, between both equipment. This is because the same amount of product passes through both equipment, as they are in an in-line configuration. Figure 5 shows the comparison between the present values of such costs obtained by both methods.

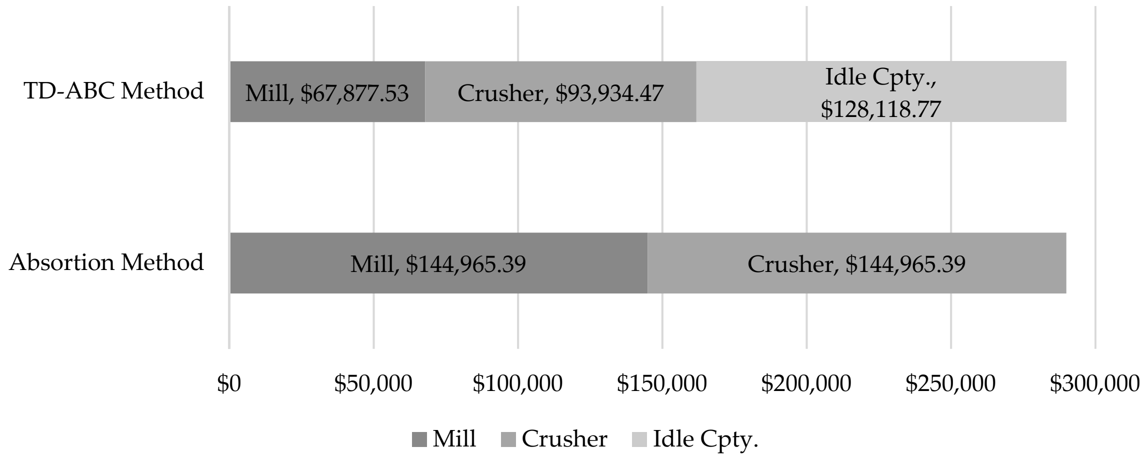

Figure 5. Comparison between traditional (absorption) and TDABC costing.

Please note that the costs obtained through the traditional costing method are identical. This method allocates to the two types of equipment under study the cost of idle capacity using the same proportion of maintenance hours (typical absorption approach). On the other hand, TDABC makes evident the differences between the maintenance needs of both equipment. In addition, this method takes into account the specific behavior of the specific failure rates (reliability) and their impact on maintenance needs, as well as making explicit the remaining idle capacity.

7. Case Study

Chile is the main copper producing nation; considering all the copper produced in the world, this country produced 30% during the last decade [62]. More than 95% of this production is carried out in large mining operations. The remaining is extracted and processed in sites which are considered to be medium-sized (sites that have between 80 and 400 workers). In this sector, the medium-size one, significant problems regarding the human factors have been detected: low productivity, excessive rotation, and low specialization. In a study on productivity in the mining sector, falls in labor productivity are related to the lack of experience of the teams, the high turnover of the workforce and the ageing of the human resources [1]. The limited supply of technical capabilities and skills derives from the fact that the medium-size mining sector has to compete with the demand for human capital from large mining ([63]). As stated by the Productivity National Center (CNP), among the most required skills are those of operators and maintainers of complex machinery, and managers with technical knowledge and human resources administration. Limited in their recruitment capacity, medium-sized companies are forced to carefully monitor the capabilities of their workforce. The following case study is intended as a contribution to the long-term quantification of human resource costs for implementing maintenance plans and to enable capacity planning according to the future maintenance needs in a comminution plant at a medium-sized mining company in central Chile.

7.1. Case Description

In this case study we need to estimate the capacity for a given maintenance plan in a comminution plant located in central Chile. The mining company is located approximately 200 km north of Santiago, in the region of Valparaíso. It has three main areas: Mine, Oxide Plant, and Sulfide Plant. The company has one primary crusher, one secondary crusher, and two fine or tertiary crushers. In addition, they have two crushers before the fine crushers, to separate and select the fine material from the coarse material. The concentration plant consists of the comminution, flotation, thickening, filter, and tailings. Within the milling system, the ball mill is considered a critical equipment, since it is through this equipment that production is kept active in the plant. The ball mill has nine basic sub-systems:

1. Cylindrical drum: It fulfills the function of containing and moving the mineral with the balls that are in charge of the mineral comminution.
2. Pinion-ring gear: Sprocket which transmit the rotary movement to the ring gear, to generate the rotary movement to the cylindrical drum.
3. Reducer: Allows the equipment to start in a smoother way, through an Inching Drive.
4. Lubrication pump: Its function is to provide lubricant to the equipment.
5. Motor: Transforms electrical energy into mechanical energy, to deliver the torque needed to move the equipment.
6. Mill Feed-Discharge heads: Fulfills the function of holding the cylindrical drum and the load contained therein.
7. Clutch: In charge of coupling the Drive assembly with the Pinion-ring gear assembly to transmit rotary motion.
8. Supply chute: Allows the entrance of material to the equipment.
9. Discharge chute: Allows the material to exit from the equipment.

The rated capacity of the equipment is 67 [ton/h], but it regularly operates within a load range of 50 to 55 [ton/h]. In addition, the mill performs ore comminution activities 24 h a day and sometimes stops only for activities related to corrective maintenance. The main data of the equipment can be found in Table 7.

Table 7. Ball mill main characteristics.

Characteristics	Values
Weight	170 [ton]
Length	5.5 [m]
External Diameter	3.5 [m]
Design Maximum Payload	67 [ton/h]
Power	1250 [kW]

According to the company maintenance department, the equipment has no scheduled maintenance plan. The company decided to create a maintenance plan to determine the required maintenance capacities. Initially, a Failure Mode and Criticality Analysis (FMECA) of the Mill was then carried out to determine the critical components of the equipment, from which it was possible to establish that the pinion, the feed-discharge pads, the lubrication pump, the jacking pump, and the discharge grates present the most significant and recurrent failure modes of the milling system. Table 8 shows the critical components that are frequently subject to corrective maintenance and the corresponding failure mode.

Table 8. Main failure modes of ball mill components.

Component	Failure Mode
Lubrication Circuit	Contamination
Jacking Pump	Wear
Spout (Feeding Nozzle)	Wear
Lubrication Pump	Wear
Lubrication Filters	Usage Damage
Pads	Wear
Dynamic Seals Feeding	Wear
Grate Plate (Loading and/or Unloading)	Wear or Breakage

Next, Weibull's statistical distribution was used to determine the reliability parameters of critical systems or components and their respective critical failure modes. Table 9 shows the Weibull parameters for each of the critical failure modes obtained.

Table 9. Weibull parameters for each of the critical component failure modes.

Main Components	β	η	γ
Ring Gear	1.617	16,696	0
Pads	0.709	13,580	0
Lubrication Pump	0.7011	3403	2400
Jacking Pump	2.2206	8448	0
Grate Plates	0.9631	14,574	0

From Table 9 we can see that the critical failure modes associated with pads, lubrication pump and to the grate plates have a behavior defined as premature/infantile ($\beta < 1$). The solution to this problem does not lie in implementing a preventive type of maintenance, but in finding the root cause and eliminating it; this root cause is usually related to poor assemblies, problems in alignment, inadequate knowledge about maintenance of the equipment and its operation, errors in design of the component, among others. Now, from the failure modes of ring gear and jacking pump we can see that both suffer failures due to premature deterioration, since their shape parameter is between $1 < \beta < 4$ (constant failure rate); failures frequently related to low fatigue cycles, corrosion, erosion, mechanical or hydraulic deterioration, low level of maintenance and repair, poor operational condition, among others. The solution to this type of failures lies in the application of a preventive type of maintenance to prevent them from occurring. At this stage, the failure rate is increasing and with the application of preventive actions it would be possible to restore the functioning with a much lower failure rate. In addition, it is worth mentioning that even though the critical modes of pads, change lubrication pump and grate plates have premature/infantile faults, they were also be included as inspection actions in the preventive maintenance plan, as they must be checked in the short, medium, and long term.

According to the operational context in which the company was currently operating, it was proposed to establish a "condition-based" preventive maintenance plan, which was mainly based on lists of equipment checks (daily, weekly, monthly, etc.). In this regard, the optimal frequencies for inspections with equipment detention were determined and the capacities in person-hours were dimensioned to attend the corresponding number of preventive activities. Along with these activities, a certain number of corrective actions for each period was estimated using the expert judgment.

Table 10 shows the data defined for inspections, preventive actions, and repairs for each critical failure mode, as well as the estimated number of workers assigned to such planned or foreseen actions, together with their respective unitary costs.

Table 10. Inspections, preventive actions, and repairs for each critical failure mode.

Critical Component	# of Interventions	Prev. Activity Length	Correc. Activity Duration	Num. of Workers		Cost (US$/Man Hour)	
	t/Month	(h)	(h)	Prev.	Correc.	Prev.	Correc.
Ring Gear	1	5	36	5	4	48.8	8.8
Pads	1	5	24	5	4	48.8	8.8
Lubric. Pump	1	2	3	1	4	8.8	8.8
Jacking Pump	1	2	3	1	4	8.8	8.8
Grate Plate	1	2	11	1	4	8.8	8.8

As commented before, the aforementioned data were basically estimated and proposed using expert judgment, and not based on any quantitative model that took into account aspects related to the risk of failures, behavior of the findings, etc. Therefore, it was decided to establish a model of calculation and long-term projection of these estimates, to allow the evaluation of the performance of the installed maintenance capacities according to the future needs coming from the critical components of the ball mill. As the objective of this case study, besides estimating the long-term costs related to maintenance activities (preventive and corrective), is to analyze the planned capacities to meet the maintenance plan established over a period of 10 years of operation.

Therefore, it was decided to establish a long-term calculation and projection model to carry out these estimations. In this regard, it would be possible to assess the performance of the installed maintenance capacity according to the future needs of the critical components of the ball mill. The objective of this case study, in addition to the estimation of the long-term costs related to the maintenance activities (preventive and corrective), is to analyze the planned capacity to meet the maintenance plan in the long term.

Fur such purpose, it was decided to apply the TDAB-LCC model. Through the application of such model, it was possible to obtain both a very precise and simplified cost estimate, along with a study of the capacity effectively used versus the installed capacity of maintenance resources. The following sections present the details of this application, its results and the subsequent discussion.

As the objective established by the organization was to estimate the cost and use of direct labor to attend the required maintenance actions (preventive and corrective), only the maintenance human resources were assessed in this case study.

To apply the TDAB-LCC approach, activities were grouped into two main processes:

- Planned or preventive maintenance,
- Corrective maintenance actions.

Ten separate time equations were established in two categories and considered the period of 10 years. The first category corresponds to the equations that allow estimating the time consumed by all the preventive actions planned for each of the 5 critical failure modes. The second category of time equations is intended to estimate the times consumed by the corrective maintenance actions associated with the 5 critical failure modes. Those equations were designed based on estimates of the quantities expected for such events during the planning horizon and the age-based preventive policy (Equations (7) and (8)) based on the Weibull approach.

The maintenance person-hours availability was estimated considering: 8 h/day, 240 day/year. Labor consists of 4 maintenance operators, which present 80% efficiency. Moreover, each one of the maintenance workers is dedicated to several different equipment, being just 204 h/year dedicated to the ball mill which is considered in this case study. Thus, 816 h per year was set as the practical capacity. The total annual cost of the maintenance labor capacity corresponds to $60,600.00. Such amount was annually corrected using a discount rate set as 10% per year.

7.2. Results

The capacity cost rate for the first year was obtained as shown below:

$$Capacity\ Cost\ Rate = \frac{\$\ 60,600.00}{816\ \mathrm{h}} = \$\ 74.26/\mathrm{h}$$

That is, given that the driver used to allocate costs to activities is time, this capacity cost rate represents the amount of resources that is consumed by each process in each hour that its execution takes.

The observation of the maintenance processes confirmed that the time consumed depends on the maintenance activity category (i.e., corrective or planned maintenance) and on the failure mode/component which is being maintained. In the following, we discuss the details of the time equations.

The time equations, for the planned maintenance process, consider the time consumed by the sub-processes (or activities) performed to prevent equipment to suffer each one of five failure modes. In this case, the components linked to the main failure modes are ring gear, pads, lubrication pump, jacking pump, and grate plates. According to the estimations made by the maintenance senior responsible in the company, the times required to execute those activities are those shown in Equation (25) (it corresponds to β_i values in Equation (15)) and are measured in hour/number of preventive actions performed to prevent the specific failure.

$$T_{1,t} = 5{\cdot}X_{1,t} + 5{\cdot}X_{2,t} + 5{\cdot}X_{3,t} + 2{\cdot}X_{4,t} + 2{\cdot}X_{5,t} \quad (25)$$

The second time equation corresponds to the process called "corrective maintenance", where β_i values were estimated by the maintenance personnel as well. Equation (26) presents the second time equation:

$$T_{2,t} = 36{\cdot}X_{1,t} + 24{\cdot}X_{2,t} + 3{\cdot}X_{3,t} + 3{\cdot}X_{4,t} + 11{\cdot}X_{5,t} \quad (26)$$

Those time equations were used to estimate person-hour usage during a projected the life cycle using the correspondent capacity cost rate.

As has been commented before, the time drivers of each process are expressed in number of maintenance interventions (N_p and N_c). Please note that for preventive interventions they were defined by the maintenance manager and were considered to be constant along time. In the case of corrective interventions, they were estimated using the correspondent Weibull parameters and Equation (17). Table 11 shows Nc values for each failure mode throughout the life cycle.

Table 11. Nc projected values (year 1 to year 10).

Corrective Maintenance	1	2	3	4	5	6	7	8	9	10
Ring gear	0	1	1	1	2	3	4	6	8	10
Pads	1	1	2	2	3	5	7	9	12	15
Lubrication pump	1	3	10	25	46	75	111	154	205	265
Jacking pump	0	1	3	6	10	14	20	27	35	45
Grate plate	1	1	2	2	3	4	6	8	10	13

Once the respective time equations were solved, the total time allocated to both types of interventions were obtained (Table 12).

Table 12. Total hours allocated to both types of interventions (year 1 to year 10).

Maintenance Strategy	1	2	3	4	5	6	7	8	9	10
Planned Maintenance	505	505	505	505	505	505	505	505	505	505
Corrective Maintenance	41	77	132	209	356	549	787	1074	1046	1796

From the time allocated to each type of maintenance action, and with the corresponding capacity cost rate, the person-hour costs were established (Table 13).

Table 13. Estimated person-hour costs to both types of interventions (year 1 to year 10).

Maintenance Strategy	1	2	3	4	5
Planned Maintenance	$37,519	$37,894	$38,273	$38,655	$39,042
Corrective Maintenance	$3024	$5739	$10,023	$15,959	$27,543
	6	**7**	**8**	**9**	**10**
Planned Maintenance	$39,432	$39,827	$40,225	$40,627	$41,033
Corrective Maintenance	$42,831	$62,074	$85,514	$113,089	$145,911

Finally, the percentages of use and idleness are obtained according to the calculated values (Table 14). Values greater than 100% indicate an overload of the maintenance labor capacity committed by the plan and by the estimated corrective actions. Note the importance of detecting these situations, because this will allow identification of the situations where it will not be possible to attend, with the installed maintenance capacity, all the planned actions, and the eventuality of corrective events needed by the equipment. It is also possible to carry out trade-off analysis to determine which actions will not be carried out because the maintenance capacity required will not be fully available.

Table 14. Estimated capacity use and idleness (year 1 to year 10).

Capacity	1	2	3	4	5	6	7	8	9	10
used capacity (%)	67%	71%	78%	87%	106%	129%	158%	194%	134%	182%
idle capacity (%)	33%	29%	22%	13%	0%	0%	0%	0%	0%	0%

Figure 6 shows the behavior of the capacities according to the estimated values.

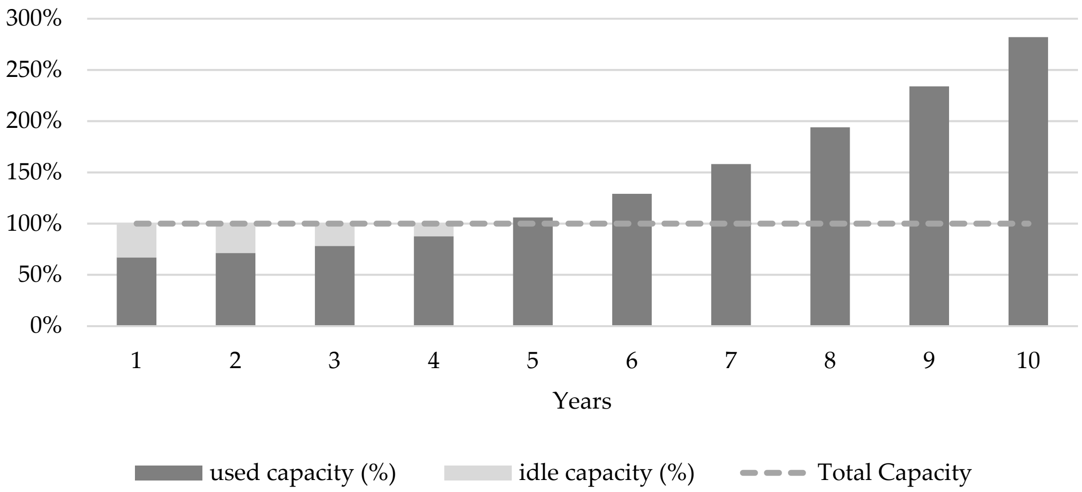

Figure 6. Comparison between used and idle capacity along the planning horizon.

From Figure 6 it can be inferred that by the fifth year an expansion of maintenance capacity would be necessary due to the influence of higher failure rates in the equipment. The components that generate this increase in failure rates over time are the jacking pump and the ring gear (both with values of $\beta > 1$). Finally, taking into consideration the values in Table 13, and an opportunity cost of 10% per year (i), it is possible to calculate the Net Present Value of Maintenance Labor Costs (NPV_{MLC}) of the projected cash flow with the maintenance labor costs in the 10 years considered (Equation (27)). The Net Present Value (NPV) corresponds to U$482,498.39 and can be used as a basis for sensitivity analysis and comparisons, as will be seen in the next section.

$$NPV_{MLC} = \sum_{k=1}^{t} \frac{MLC_k}{(1+i)^k} \tag{27}$$

7.3. Sensitivity Analysis

As a means of validating the model and demonstrating its usefulness in the long-term decision-making process, the proposed model is used to measure the effect of certain decisions regarding the application of overhaul on maintenance capacity requirements.

For all repairable systems, the condition in which the equipment is returned to service, after a repair, may be any of the following "after-repair states": (1) as good as new, (2) as bad as old; (3) better than old but worse than new; (4) better than new; and (5) worse than old. The two most commonly observed states are "as good as new" and "as bad as old". In the case of "as new" condition, the repair is considered perfect and the item is restored to operation with a failure rate very close to or equal to that experienced when the equipment was first put into operation. In the contrary, the "as bad as new" condition implies a minimal repair. In this condition, the item is returned to the condition it had just prior to the failure. As has been commented, the effect of any imperfect intervention generates different impacts in the failure rates. This effect is represented by considering the following general modeling [60]:

The effect on the failure rate of an intervention is represented as follows (Equation (28)):

$$\lambda\left(t_j^+\right) = \lambda\left(t_j^-\right) - \delta_j \tag{28}$$

where δ corresponds to the resulting reduction in λ of a given intervention at the moment t. The parameter δ depends on the level of effort and the sophistication of the intervention executed. This level is constrained as shown in Equation (29):

$$0 \leq \delta_j \leq \lambda\left(t_j^-\right) - \lambda(0) \tag{29}$$

This represents the situation where the actions will not make the system, or equipment, as good as new. Thus, the failure rate function will be written as shown in Equation (30):

$$\lambda(t) = \lambda_0(t) - \sum_{i=0}^{j} \delta_i,\ t_j < t < t_{j+1} \tag{30}$$

for $j \geq 0$, with $t_0 = 0$ and $\delta_0 = 1$. Please note that this assumes that the resultant failure rate reduction caused by the preventive action in t_j lasts for all $t \geq t_j$.

Three scenarios are considered, in addition to the base scenario already described (Strategy I). These three scenarios consider the existence of a major intervention or overhaul with varying levels of complexity and with different degrees of impact on the reliability of the equipment. Such differentiated complexities between the different types of overhaul will certainly have different costs. Based on the analysis of such differences, and their comparison with the possible savings from the reduction of failure rates, and on the future needs to expand the maintenance workforce, it can generate an important information input for the decision-making process.

As we commented before, we assumed three imperfect maintenance scenarios, which impact positively the failure rate function of all failure modes in the same proportion. The Figure 7 shows the effect on the failure rate from the overhaul strategies applied to entire system. As has been commented before, Strategy I corresponds to the situation without overhaul. Strategies II to IV consider the execution of an overhaul the fifth 5 year. As a result, the failure rate will decrease in different degrees (imperfect maintenance). Strategy II considers a reduction to 30% of the failure rate of the fourth year, meanwhile, strategy III considers a reduction of 50% of the failure rate of the fourth period. Finally, Strategy IV, consider the "as good as new" scenario, returning the failure rate after overhaul to 0, in all the system elements.

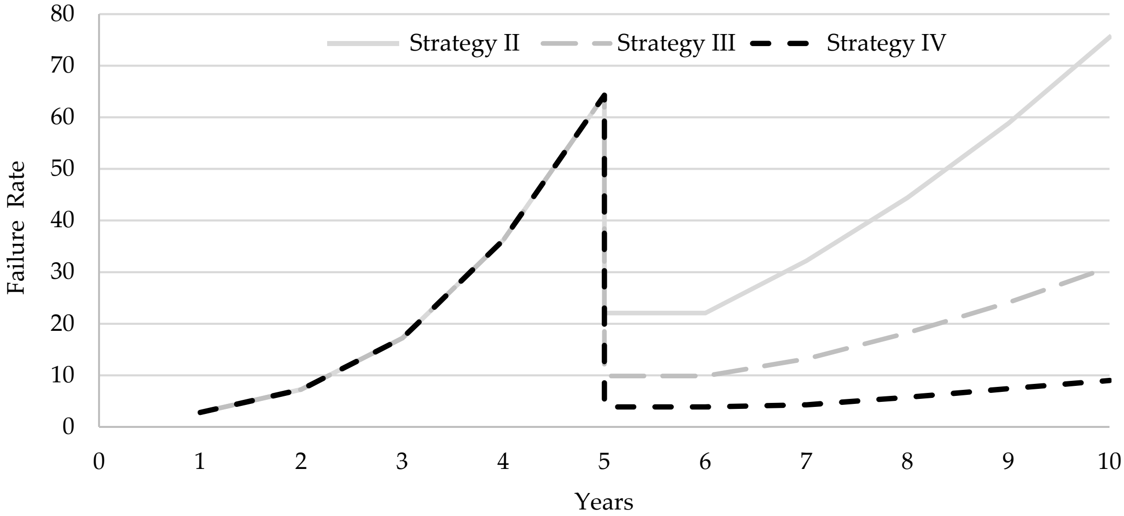

Figure 7. Effect of two kinds of overhaul strategies along the planning horizon.

This approach makes it possible to analyze the behavior of costs (present value) and the use of maintenance capacity. It is also possible to compare the effect of different major preventive maintenance actions. Figure 8 shows the behavior of the used and idle capacities since the overhaul to be made in the fifth year which may lead to a reduction of the failure rate according to Strategies II, III, and IV, respectively. Please note that with these strategies (II–IV) there would still be periods of excessive workload; however, as these are relatively low, this difference can be handled with the overtime, without requiring a major change in the provision of maintenance workforce.

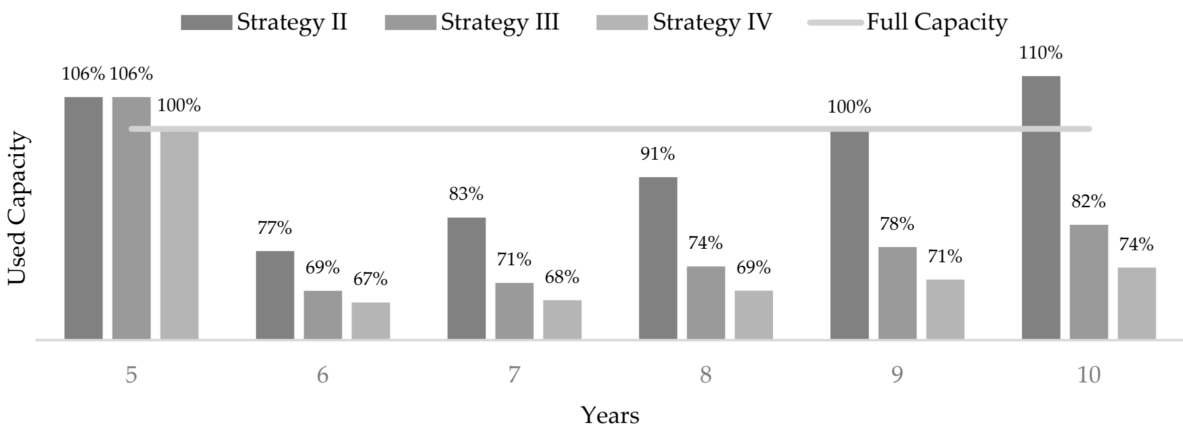

Figure 8. Effects of two kinds of overhaul strategies (II and III) on the maintenance, used capacity along the planning horizon.

Table 15 shows the present values of maintenance labor costs considering the four strategies under consideration obtained from using Equation (27). This analysis allows verification of the convenience of executing an overhaul with their respective costs having the level of maintenance workload in compensation needing to be stable, instead of an increase in maintenance costs as a result of the increase in the failure rate over time.

Table 15. Present values of maintenance labor costs considering the three maintenance strategies.

	Net Present Values of MLC	Maximum Admissible Investment *
Strategy I	$ 482,498.39	
Strategy II	$ 325,841.75	$ 252,297.08
Strategy III	$ 300,577.08	$ 292,986.09
Strategy IV	$ 293,534.42	$ 304,328.36

* To be made in the fifth year.

It can be clearly seen that as major maintenance actions are implemented, workforce capacity needs tend to level off at or near a maximum value, almost totally balanced with the existing capacity. This allows an optimal positioning (trade-off) to be reached between overhaul cost and maintenance capacity increments. The first column presents the net present value of maintenance labor costs in each of the alternative strategies and the second column shows what would be expected to be saved by implementing strategy II, III or IV as compared to the baseline strategy (I). This difference will indicate the maximum admissible investment in the overhaul. If the projected value of the overhaul is greater than this difference, it is not recommended. Also, the expected payback of such investment can be reached only after the fourth year after the overhaul, i.e., in the last year of the full period of ten years.

Regarding the balancing of the workforce, it is possible to avoid drastic changes in the total size of the workforce by making investments in the form of major maintenance interventions. With this type of analysis, it is possible to accurately estimate the maximum economic value that these overhaul costs can represent to avoid fluctuations in the number of maintenance employees.

8. Conclusions and Future Work

By properly managing maintenance capacity and eliminating non-value-added activities, better economic performance can be achieved, as well as a reduction of the impact of failures and positively impacting society through improved safety standards and greater workforce satisfaction (resource overallocation and day-to-day fluctuations).

Since maintenance planning tasks are carried out with long-term timeframes, it is necessary to use methods that allow the estimation of maintenance capacities. Such capacities must be defined taking into account the actual maintenance needs which are determined by the reliability levels and the maintenance strategies defined by the organization. The selection of maintenance strategies may cause different impact on costs and asset performance.

Thus, a model based on a long-term TDAB-LCC approach that determines the level of maintenance capacity needed has been proposed and applied. This model is multi-period (life cycle), multi-asset, and reliability oriented (Weibull distribution), allowing the assessment, in an integrated way, of costs and used capacities. It supports the decision-making process that aims at the dimensioning of the workforce considering the maintenance strategy and the reliability parameters of one or more physical assets according to a long-term perspective. With this calculation it is possible to compare these capacities with the available ones leading to optimized strategies and reduction in maintenance costs more efficiently. Furthermore, with this, it is possible to trace strategies to keep the maintenance workforce in line with the maintenance needs and keep it relatively stable. With this, it is possible to avoid shocks and stressful variability for both the organization and the maintenance workers.

Comparisons with the full costing method were made, and a sensitivity analysis was performed as a way of handling uncertainty. These aspects reinforce the usefulness of the model and its simplicity, when compared with traditional methods. On the other hand, risk was addressed in this work by the integration of the reliability concept into the cost model. This was done using the Weibull distribution. This approach addresses the events associated with failure occurrences in a probabilistic manner and is widely accepted and used by the maintenance community in the mining industry.

The proposed model was used to measure the effect of decisions related to the application of overhaul on maintenance capacity requirements. Three scenarios were considered, in addition to the initial scenario. The additional three scenarios consider the existence of a major intervention or overhaul with varying levels of complexity and with different degrees of impact on the reliability of the equipment. It was highlighted that as major maintenance actions are implemented, workforce capacity needs to be balanced with the existing capacity. A good management of this trade-off will contribute to reach an optimal positioning between overhaul maintenance costs and capacity.

One of the great advantages of the proposed model is the possibility of allocating to the equipment just the capacity that was effectively used, while the unused capacity can be considered period costs in the profit and loss statement. The costs of the excess capacity of the maintenance workforce are not included in the costs of the equipment, but are considered to be overheads which must be managed as period costs by the administration, providing more accurate information on maintenance (life-cycle) costs. Through this model, organizations can improve operational efficiency of the maintenance capacity, levelling such capacities with actual maintenance needs and aligned with the maintenance strategies, avoiding stressful workforce variations along time.

Finally, we can highlight the following additional conclusions. First, the proposed model requires a few parameters for its implementation; specifically, the information on the reliability of the equipment can be easily obtained from the failure history itself or from equipment handbooks. Second, its computational implementation can be achieved without major complexities. Third, the proposed model can be used in combination with any maintenance strategy (perfect, imperfect-as-good-as-new, or imperfect-as-bad-as-old) or others. Finally, it can incorporate non-monetary impacts to compare alternatives in a wider perspective.

As future research directions, we suggest that the developed work would benefit from expanding the model to include additional costs categories, such as indirect costs of human resources selection and recruitment, and hidden costs related to the loss of profitability and externalities due to unplanned operational shutdowns.

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References

1. Mitchell, P.; Michael, B.; Higgins, L.; Steen, J.; Henderson, C.; Kastelle, T.; Kunz, N. *Productivity in Mining: Now Comes the Hard Part, A Global Survey*; UQ Business School Publications: St. Lucia, Australia, 2014.
2. Costa, S.; Scoble, M. An interdisciplinary approach to integrating sustainability into mining engineering education and research. *J. Clean. Prod.* **2006**, *14*, 366–373. [CrossRef]
3. Hilson, G.; Murck, B. Sustainable development in the mining industry: Clarifying the corporate perspective. *Resour. Policy* **2000**, *26*, 227–238. [CrossRef]
4. Hilson, G. Putting theory into practice: How has the gold mining industry interpreted the concept of sustainable development? *Miner. Resour. Eng.* **2001**, *10*, 397–413. [CrossRef]
5. Campbell, J.D.; Jardine, A.K.S. *Maintenance Excellence: Optimizing Equipment Life-Cycle Decisions*; CRC Press: Boca Raton, FL, USA, 2001.
6. Amadi-Echendu, J.E. Managing physical assets is a paradigm shift from maintenance. In Proceedings of the IEEE International Engineering Management Conference, Singapore, 18–21 October 2004; Volume 3, pp. 1156–1160.
7. Jasiulewicz-Kaczmarek, M. Sustainability Orientation in Maintenance Management—Theoretical Background. In *Ecoproduction and Logistics*; Springer: Berlin/Heidelberg, Germany, 2013.
8. Jasiulewicz-Kaczmarek, M. Identification of maintenance factors influencing the development of sustainable production processes—A pilot study. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *400*, 1–16. [CrossRef]
9. Henderson, K.; Pahlenkemper, G.; Kraska, O. Integrated asset management—An investment in sustainability. *Procedia Eng.* **2014**, *83*, 448–454. [CrossRef]

10. Fornasiero, R.; Zangiacomi, A.; Sorlini, M. A cost evaluation approach for trucks maintenance planning. *Prod. Plan. Control* **2012**, *23*, 171–182. [CrossRef]
11. Sénéchal, O. Research directions for integrating the triple bottom line in maintenance dashboards. *J. Clean. Prod.* **2017**, *142*, 331–342. [CrossRef]
12. Franciosi, C.; Voisin, A.; Miranda, S.; Riemma, S.; Iung, B. Measuring maintenance impacts on sustainability of manufacturing industries: From a systematic literature review to a framework proposal. *J. Clean. Prod.* **2020**, *260*, 121065. [CrossRef]
13. Shou, W.; Wang, J.; Wu, P.; Wang, X. Lean management framework for improving maintenance operation: Development and application in the oil and gas industry. *Prod. Plan. Control* **2020**, 1–18. [CrossRef]
14. Knights, P.F. Best-in-class maintenance benchmarks in Chilean open-pit mines. *Maint./Eng. Div. CIM* **2005**, *98*, 93.
15. Bevilacqua, M.; Braglia, M. Analytic hierarchy process applied to maintenance strategy selection. *Reliab. Eng. Syst. Saf.* **2000**, *70*, 71–83. [CrossRef]
16. Lemes, L.C.; Hvam, L. Maintenance Costs in the Process Industry: A Literature Review. In Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management, Macao, China, 15–19 December 2019.
17. De George, E.T.; Li, X.; Shivakumar, L. A review of the IFRS adoption literature. *Rev. Account. Stud.* **2016**, *21*, 898–1004. [CrossRef]
18. International Foundation Standards Board. *IFRS Conceptual Framework Project Summary: Conceptual Framework for Financial Reporting*; IRFS Foundation: London, UK, 2018.
19. Adıgüzel, H.; Floros, M. Capacity utilization analysis through time-driven ABC in a small-sized manufacturing company. *Int. J. Product. Perform. Manag.* **2019**, *69*, 192–216. [CrossRef]
20. Cooper, R.; Kaplan, R. Activity-Based Systems: Measuring the costs of resource usage. *Account. Horiz.* **1992**, *6*, 1–13.
21. Rechiche, A.; Bouami, D. An Hybrid Method of Modeling Maintenance Cost Based on Analytical and UVA Approach. *J. Manag. Account. Res.* **2014**, *14*, 135–141.
22. Simona Elena, D.; Lector, U. UVA Method-innovative approach in economic and strategic management of an enterprise. *Stud. Sci. Res. Econ. Ed.* **2009**, *14*, 25–30. [CrossRef]
23. Fabrycky, W.J.; Blanchard, B.S. Life-cycle costing. In *The Engineering Handbook*, 2nd ed.; Routledge: Abingdon-on-Thames, UK, 2004; ISBN 9781420039870.
24. Blanchard, B.S.; Fabrycky, W.J. *Systems Engineering and Analysis*, 3rd ed.; Pearson Prentice Hall: Upper Saddle River, NJ, USA, 1998.
25. Ruparathna, R.; Hewage, K.; Sadiq, R. Multi-period maintenance planning for public buildings: A risk based approach for climate conscious operation. *J. Clean. Prod.* **2018**, *170*, 1338–1353. [CrossRef]
26. Woodhouse, J. What is the value of asset management? *Infrastruct. Asset Manag.* **2019**, *6*, 102–108. [CrossRef]
27. Woodward, D.G. Life cycle costing—Theory, information acquisition and application. *Int. J. Proj. Manag.* **1997**, *15*, 335–344. [CrossRef]
28. Cooper, R.; Kaplan, R.S. Profit Priorities from Aotivity-Based Costing. *Harv. Bus. Rev.* **1991**, *69*, 130–135.
29. Kaplan, R.S. Improving value with TDABC. *Healthc. Financ. Manage.* **2014**, *68*, 78.
30. Kaplan, R.S.; Anderson, S.R. Time-driven activity-based costing. *Harv. Bus. Rev.* **2004**, *82*, 131–150. [CrossRef] [PubMed]
31. Ruiz de Arbulo López, P.; Fortuny Santos, J.; Vintró Sánchez, C. Costing a product by old and new techniques: Different wines for different occasions. In Proceedings of the 7th International Conference on Industrial Engineering and Industrial Management. XVII Congreso de Ingeniería de Organización (CIO), Valladolid, Spain, 10–12 July 2013.
32. Roda, I.; Garetti, M. Application of a performance-driven total cost of ownership (TCO) evaluation model for physical asset management. In *Lecture Notes in Mechanical Engineering*; Springer Science & Business Media: Berlin, Germany, 2015; ISBN 9783319155357.
33. Guillén, A.J.; Crespo, A.; Macchi, M.; Gómez, J. On the role of Prognostics and Health Management in advanced maintenance systems. *Prod. Plan. Control* **2016**, *27*, 1–14. [CrossRef]
34. Duffuaa, S.O.; Raouf, A. *Planning and Control of Maintenance Systems*; Willey and Sons: Hoboken, NJ, USA, 2015.

35. Dinis, D.; Barbosa-Póvoa, A.; Teixeira, Â.P. A supporting framework for maintenance capacity planning and scheduling: Development and application in the aircraft MRO industry. *Int. J. Prod. Econ.* **2019**, *218*, 1–15. [CrossRef]
36. Farr, J.V.; Faber, I.J.; Ganguly, A.; Martin, W.A.; Larson, S.L. Simulation-based costing for early phase life cycle cost analysis: Example application to an environmental remediation project. *Eng. Econ.* **2016**, *61*, 207–222. [CrossRef]
37. Waghmode, L.Y.; Sahasrabudhe, A.D. Life cycle cost modeling of pumps using an activity based costing methodology. In Proceedings of the ASME 2010 10th Biennial Conference on Engineering Systems Design and Analysis, ESDA2010, Istanbul, Turkey, 12–14 July 2010. [CrossRef]
38. Simon, H.A. *The Sciences of the Artificial*; MIT Press: Cambridge, MA, USA, 1996; ISBN 0262691914.
39. Van Aken, J.E. Management research on the basis of the design paradigm: The quest for field-tested and grounded technological rules. *J. Manag. Stud.* **2004**, *42*, 219–246. [CrossRef]
40. Van Aken, J.; Chandrasekaran, A.; Halman, J. Conducting and publishing design science research: Inaugural essay of the design science department of the Journal of Operations Management. *J. Oper. Manag.* **2016**, *47*, 1–8. [CrossRef]
41. Holmström, J.; Ketokivi, M.; Bridging, A.H. Practice and Theory: A Design Science Approach. *Decis. Sci.* **2009**, *40*, 65–87. [CrossRef]
42. Afonso, P.S.; Paisana, A.M. An Algorithm for Activity Based Costing based on Matrix Multiplication. In Proceedings of the 2009 IEEE International Conference on Industrial Engineering and Engineering Management, Hong Kong, China, 8–11 December 2009; pp. 920–924.
43. Emblemsvag, J. Activity-based life-cycle costing. *Manag. Audit. J.* **2001**, *16*, 17–27. [CrossRef]
44. Emblemsvåg, J. *Life-Cycle Costing Using Activity-Based Costing and Monte Carlo Mthods to Manage Future Costs and Risks*; Wiley: Hoboken, NJ, USA, 2003; ISBN 0-471-35885-1.
45. Kayrbekova, D.; Markeset, T. Activity-based life cycle cost analysis as an alternative to conventional LCC in engineering design. *Int. J. Syst. Assur. Eng. Manag.* **2011**, *2*, 218–225. [CrossRef]
46. Hoozée, S.; Hansen, S.C. A comparison of activity-based costing and time-driven activity-based costing. *J. Manag. Account. Res.* **2018**, *30*, 143–167. [CrossRef]
47. Tarzibashi, O.F.F.; Ozyapici, H. The Impact of the Magnitude of Overhead Costs on the Difference between ABC and TDABC Systems. *Found. Manag.* **2019**, *11*, 81–92. [CrossRef]
48. Santana, A.; Afonso, P. Analysis of Studies on Time-Driven Activity Based Costing (TDABC). *Int. J. Manag. Sci. Inf. Technol.* **2015**, *15*, 133–157.
49. Nachtmann, H.; Needy, K.L. Methods for handling uncertainty in activity based costing systems. *Eng. Econ.* **2003**, *48*, 259–282. [CrossRef]
50. Kishk, M. Combining various facets of uncertainty in whole-life cost modelling. *Constr. Manag. Econ.* **2004**, *22*, 429–435. [CrossRef]
51. Gregory, J.R.; Montalbo, T.M.; Kirchain, R.E. Analyzing uncertainty in a comparative life cycle assessment of hand drying systems. *Int. J. Life Cycle Assess* **2013**, *18*, 1605–1617. [CrossRef]
52. Design, L.; Sun, Y.; Carmichael, D.G. Uncertainties related to financial variables within infrastructure life cycle costing: A literature review. *Struct. Infrastruct. Eng.* **2017**, *2479*, 1–12. [CrossRef]
53. Kaplan, R.S.; Anderson, S.R. *Time-Driven Activity-Based Costing: A Simpler and More Powerful Path to Higher Profits*; Harvard Business Press: Brighton, MA, USA, 2007.
54. Afonso, P.; Santana, A. Application of the TDABC model in the logistics process using different capacity cost rates. *J. Ind. Eng. Manag.* **2016**, *9*, 1003. [CrossRef]
55. De Arbulo-López, P.R.; Fortuny-Santos, J. An accounting system to support process improvements: Transition to lean accounting. *J. Ind. Eng. Manag.* **2010**, *3*, 494–511. [CrossRef]
56. Meddaoui, A.; Bouami, D. Cost modelling in maintenance using time-driven activity-based costing. *Int. J. Product. Qual. Manag.* **2013**, *12*, 247–270. [CrossRef]
57. Aoudia, M. Towards the design of a new framework for maintenance costing. *Contemp. Eng. Sci.* **2015**, *8*, 1475–1483. [CrossRef]
58. BSI. *BS EN 13306:2010: Maintenance-Maintenance Terminology*; British Standards Institution: London, UK, 2010; ISBN 978 0 580 64184 8.
59. Barlow, R.E.; Hunter, L. Optimum preventivemaintenance policies. *Oper Res.* **1960**, *8*, 90–100. [CrossRef]

60. Murthy, D.N.P.; Jack, N. Warranty and maintenance. In *Handbook of Maintenance Management and Engineering*; Springer Science & Business Media: Berlin, Germany, 2009; ISBN 9781848824713.
61. Zamora, I. Design of a Maintenance Plan for Ball Mill in the Mining Company Cerro Negro. Bachelor's Thesis, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile, 2018. (In Spanish).
62. Ocaranza, J.; Arce, O.; Cifientes, C.; Montes, C.; Brantes, R.; Venegas, L.; Maldonado, P. *Anuarios de Estadísticas del cobre y Otros Minerales (2002–2018)*; Biblioteca en Manuel Montt: Providencia Santiago, Chile, 2019.
63. Urrutia, A.U.; Biekert, J.L.C.; Aravena, J.G.; Toledo, R.M.; Gerber, P.C.; Valenzuela, F.V.; Soto, J.F. *Productivity in the Large Scale Copper Mining Industry*; National Productivity Commission: Santiago, Chile, 2017.