Total Cost of Ownership of melting furnaces: application of a prototypal model to aluminum die casting producers

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Abstract: After reviewing current literature on the Total Cost of Ownership (TCO) methodology and its application to manufacturing contexts, we propose an application of this methodology to secondary aluminum melting furnaces.

A prototypal calculation model is created and tested through three case studies of aluminum die casting companies. We illustrate the model structure and input data used to calculate the studied furnaces TCO. At last, results of the model test are presented and possible developments of the prototypal model are briefly discussed.

Keywords: Total Cost of Ownership, model, case studies, secondary melting furnaces, aluminum, die casting

1. Introduction

1.1. Total Cost of Ownership methodology

The concept of *Total Cost of Ownership* (“*TCO*”) was introduced in the late 1980s as a key evaluation criterion for investments in personal computers (Mieritz and Kirwin, 2005). With a broader perspective, TCO can be defined as “the sum of all the expenses and costs associated to the acquisition, ownership, use and subsequent disposal of a good or service” (Ellram, 1995).

Supporters of TCO methodology claim that companies benefit from its implementation, as TCO improves decision making, facilitates communication and comprehension among departments involved in the purchasing process and allows performance measurement of different investment choices. However, TCO adoption may be prevented by cultural barriers, lack of personnel training and scarcity of resources to implement TCO calculation or to collect input data (Ellram, 1994).

1.2. Melting process and metal melting furnaces

Generally speaking, *melting* is a physical process implying the complete transition of a substance from a solid to a liquid. As regards production of metals, two categories of melting processes can be identified:

- *primary melting*: metallic ores and scraps are converted in metal with defined chemical composition;
- *secondary melting*: metal ingots and scraps are liquefied in preparation for a casting process.

Melting furnaces are machines used to perform either primary or secondary melting, i.e. they raise the temperature of metal charge above its melting point, in order to maximize its fluidity. Some melting furnace can also maintain the temperature of molten metal to a preset value, until metal is required by downstream production phases: thus, they also have a “*holding*” function. Table 1 summarizes characteristics of commonly used melting furnaces.

Table 1. Summary of commonly used melting furnaces

Furnace type (power source)	Working principle	Processable alloys *(M = melting only; MH = melting and holding)*						
		Steel	Cast iron	Aluminum	Copper	Magnesium	Lead	Zinc
Electric arc (Electricity)	Metal is loaded in the furnace and heat is applied by an electric arc between a set of electrodes and the metal charge itself	M	M					M
Induction (Electricity)	Metal is loaded in the furnace and heat is applied by electromagnetic induction of the metal charge		MH	MH	MH		MH	MH
Shaft/Cupola (Coal)	Metal is loaded at the top of a chimney-shaped chamber and, while descending, is heated by an ascending steam of hot gas		M					M
Reverberatory (Natural gas)	Metal is loaded in the furnace and heat is applied by thermal radiation of the metal charge		M	MH	M			M
Rotary (Natural gas)	Metal is loaded in a rotating drum and heated directly by a burner		M	M				M
Pot (Natural gas)	Metal is loaded in a crucible, which is heated by a burner			MH	MH	MH	MH	

2. Research overview

2.1. Objectives

We are interested in applying TCO methodology to the metallurgical industry. In particular, we focus on aluminum die casting companies, which perform secondary aluminum melting. Therefore, our research aims to:

a) review current literature on the TCO, in order to evaluate opportunity to apply TCO methodology to aluminum die-casting producers;
b) create and test a prototypal TCO calculation model focused on secondary aluminum melting furnaces.

2.2. Methodology

In order to achieve research goals (§2.1), we carry out:

1. a *literature review* on TCO methodology, with special, yet not exclusive, attention to its application to the metallurgical industry. In particular, we collect and classify relevant references according to the following procedure:
   a. *references search* in Scopus. The search keywords were obtained by combining "Total Cost of Ownership" with "analysis", "calculation", "model", "evaluation" or similar terms. 544 references were found using such keywords;
   b. *abstracts analysis*, to select only references explicitly addressing the application of TCO methodology to manufacturing or service companies. Thus, the sample was reduced to 272 papers;
   c. *in-depth references analysis*, to select only references explicitly presenting and describing a TCO model. The sample was reduced to 101 papers after this step;
   d. *references classification*, to categorize the selected papers according to significant criteria, e.g. the industrial or economic sector analyzed, the object costs and lifespan stages considered by the TCO model, the viewpoint adopted, etc.
2. *case studies* among aluminum die-casting producers, in order to create and test a TCO model of secondary aluminum melting furnaces. For this purpose, each case study consists of:
   a. a structured interview with the Foundry Manager, to collect input data for the model and identify calculation formulae of relevant cost items;
   b. back-office calculation of the furnaces TCO, based on the input data and on the calculation formulae previously identified;
   c. the final review of the model with the Foundry Manager, to correct any imprecise input data or formulae and to confirm TCO of analyzed furnaces.

3. Current applications of TCO methodology

3.1. The sample

As mentioned in §2.2, we analyze 101 papers, which were published between 1993 and 2015. However, due to page limit, we cite only the most relevant publications in the References section (§6).

As shown in Figure 1, TCO is still widely applied in the ICT sector. However, first applications of the TCO methodology can be tracked in other durable goods sectors (e.g. automotive, metallurgical, building, household appliance). At last, a significant number of models (25%) adopts a generic, multi-sectorial approach.

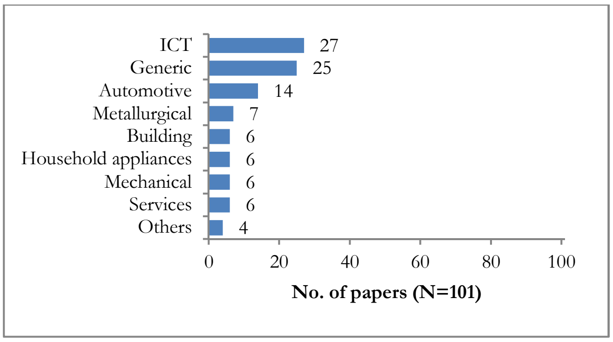

Figure 1. Industrial and economic sectors of TCO models

Figure 2 summarizes papers division by object cost: we notice that most of the papers (52%) focus on the TCO of an end product of service. On the contrary, a minority of them applies TCO methodology to a production machine: interestingly, none of these papers focuses on metallurgical industry.

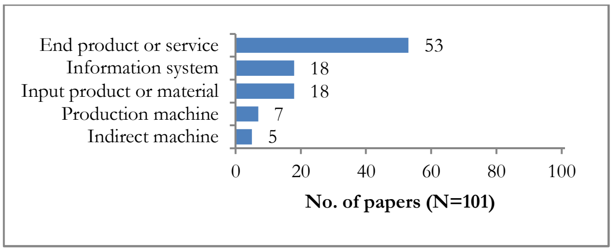

Figure 2. Object costs of TCO models

Figure 3 shows lifespan stages considered by the analyzed models. The "core" stages of goods or services lifespan (purchase & commissioning, utilization and maintenance) are considered by most of the papers. However, few of them investigate costs during the "terminal" stages (research & selection and decommissioning).

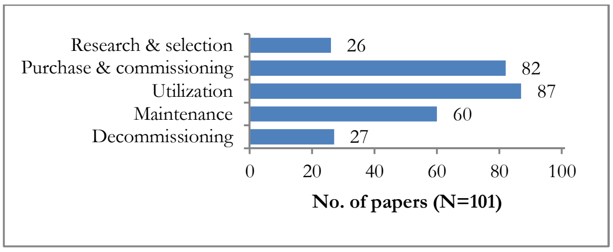

Figure 3. Lifespan stages considered by TCO models

At last, we notice that a slight majority of the papers

(55%) deals with a business-oriented TCO model and a significant number of models (42%) applies to a Business-To-Customer context. Only 3 papers apply TCO to an entire supply-chain, i.e. company, its suppliers and the end customer.

3.2. Literature review

Beyond Gartner Group, Ellram was the first to contribute to TCO theory building. She pointed out the importance of TCO as a method to identify the true cost of a supply relationship (Ellram, 1995). After defining a flowchart to calculate the TCO of purchased goods (Ellram, 1993-1994), she also suggested the following two-dimension taxonomy to classify TCO models (Ellram, 1995):

- *degree of personalization*:
  - *standard* TCO models: a basic model framework is formalized and used systematically for recurring purchasing decisions;
  - *unique* TCO models: a specific model framework is created for a particular purchasing decision which differs significantly from usual ones;
- *cost tangibleness*:
  - *dollar-based* approach: only tangible (monetary) costs are considered;
  - *value-based* approach: both tangible cost and intangible ones (e.g. company reputation, product/service availability) are considered.

Another significant contribution to TCO theory was made by Degraeve, Roodhooft et al. They proposed a TCO-based, multi-period and multi-product model aimed at optimizing a firm's purchasing strategy (Degraeve and Roodhooft, 1998-1999; Degraeve et al., 2004). They also defined a matrix to classify cost items according to three dimensions: level of aggregation, lifecycle stage and cost tangibleness (Degraeve et al., 2005).

Later, Wouters, Anderson and Wynstra (2005) studied key factors which enable or prevent the effective adoption of a TCO methodology within companies.

In the meanwhile, researchers started applying TCO methodology to the supplier selection process, both in manufacturing contexts (Carr and Ittner, 1992; Kim and Sohn, 2009) and in service organizations (Hurkens et al., 2006). Chen and Keys interestingly calculated the TCO of heavy equipment adopting both the manufacturer and the buyer viewpoints, thus generating benefits for both (Chen and Keys, 2009). Despite gradual diffusion of TCO methodology in multiple sectors, a large number of TCO models have continued to focus on ICT investments (van Maanen and Berghout 2002; David et al. 2002; Sohn and Lee, 2006; Kim and Sohn, 2009; Goudarzi, 2014).

Along with Business-to-Business (B2B) application of TCO methodology, authors increasingly developed notable Business-To-Customer (B2C) applications of this methodology. In particular, models to compute the TCO of a car for private owners have been created for the automotive industry (Al-Alawi and Bradley, 2013; Gilmore and Lave, 2013; Myojo and Kanazawa, 2003) and some of them evaluate jointly economic (TCO) and environmental (CO_2 emissions) impact of vehicles (Spitzley et al., 2005).

Despite the TCO methodology is generally applied to direct supply chains (e.g. Caniato et al., 2012), some authors have studied its application to reverse logistics as well (Larsen and Jacobsen, 2014; Tibben-Lembke, 1998)

At last, several authors have explored integration between the TCO methodolody and probabilistic models (Dogan and Aydin, 2001), operations research methods (Garfamy, 2006) and multi-criteria decision methods (Bhutta and Huq, 2002; Ramanathan, 2007).

3.3. Main findings

Based on sample characterization (§3.1) and literature review (§3.2) provided in the previous paragraph, we conclude that TCO is used mostly as a supplier evaluation methodology, although it has spread from ICT sector to a variety of durable good-oriented sectors. Some researches concerning TCO in the metallurgical industry have been carried out, but they focus only on input materials (e.g. metalworking fluids) or end products (e.g. metal castings).

So, application of TCO methodology to melting furnaces seems to be a quite unexplored topic in current literature.

4. Model creation and test

4.1. Structure

We create a standard, dollar-based TCO model for secondary aluminum melting furnaces: Figure 4 summarizes the structure of our model.

At first, we identify five *lifespan stages* of a generic furnace:

- *research and selection*: the need for a new melting furnace arises and the company identifies the most suitable furnace model for its needs;
- *purchase and commissioning*: the furnace becomes owned by and is made available to the company;
- *utilization*: the furnace is fully functional and is actually used by the company;
- *maintenance*: activity needed to preserve or to restore full functionality of the furnace are carried out;
- *decommissioning*: the company decides to get rid of the furnace and they actually dispose it.

During utilization and maintenance stages, four mutually exclusive *operating states* may apply to the furnace, namely:

- *inactivity*: furnace is emptied and turned off;
- *switch-on*: furnace is reactivated and loaded with metal after being turned off;
- *melting*: furnace is operative and energy is used to melt the metal charge;
- *holding*: furnace is operative but the metal charge is fully molten and energy is used to maintain its temperature.

At last, we identify five major *resource groups* which contribute to the furnace TCO:

- the *furnace* itself;
- *tools and machinery*: equipment and machines used to support the melting process (e.g. automatic loading and unloading system);

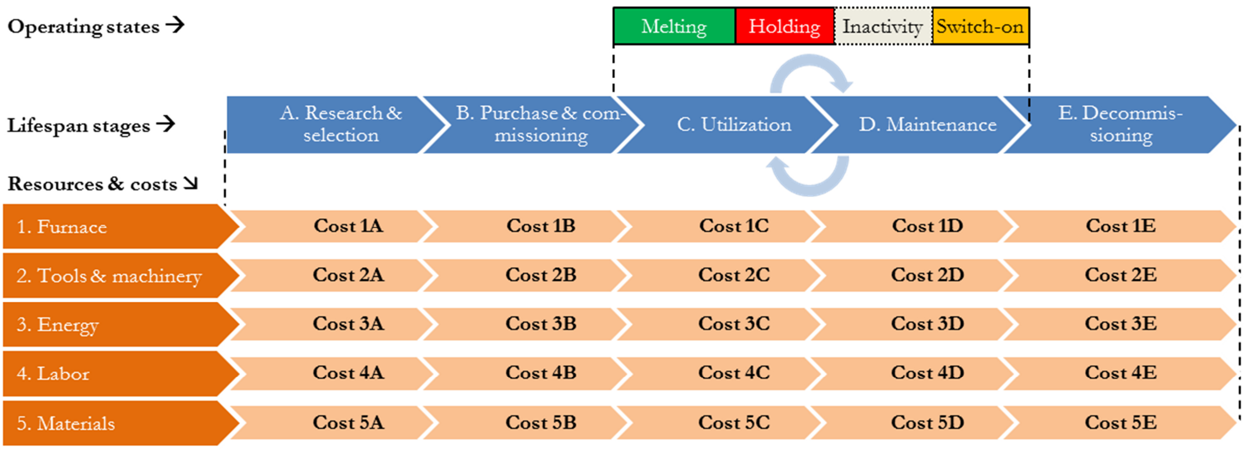

Figure 4. TCO model of secondary aluminum melting furnaces: general structure

- *energy*: power sources consumed by the furnace (e.g. electricity, natural gas, coal, etc.);
- *labor*: personnel assigned to the furnace (e.g. operators, maintenance technicians, etc.);
- *materials*: direct and indirect goods consumed by the furnace (e.g. melting losses, de-slagging salt, etc.).

As a consequence, by crossing the five lifespan phases with the five resource groups listed above, we obtain a set of 25 *cost items* to be considered in our TCO model.

4.2. Implementation

As shown in Table 2, we carry out three case studies of small and mid-sized aluminum die casting producers located in the Province of Brescia.

Table 3 lists the input data collected through the case studies and the data sources used: some data (e.g. technical data, external input costs) are cross-checked between separate sources to confirm their validity.

Table 2. Case studies: companies characterization

	Company		
	A	B	C
Size:			
– small	✓	✓	
– medium			✓
No. of furnaces by type:			
– pot furnaces	1		
– reverberatory furnaces		1	2
Total no. of furnaces:	1	1	2

After defining an appropriate calculation formula for each cost item included in the model, we calculate the TCO of the analyzed furnaces by summing the cost items. For practical purposes, we express the TCO in [€/ton].

At last, we compare our results to evaluations separately made by the interviewed Managers and find that the model results are generally aligned with the Managers evaluations.

Table 3. TCO model inputs

Input name	Input type	U.M.	Source: Die casting company	Source: Furnace manufacturer	Source: Market prices
Technical data:					
– Melting capacity of furnace	scalar	[kg/h]	✓	✓	
– Power source *p* consumption during holding state	vector	[kJ/h]	✓	✓	
– Power source *p* consumption during melting state	vector	[kJ/kg]	✓	✓	
– Power source *p* consumption during switch-on state	vector	[kJ/h]	✓	✓	
Operational modalities:					
– No. of category *e* employees assigned to furnace	vector	[FTE/year]	✓		
– Overall output of alloy *a*	vector	[kg/year]	✓		
– Melting loss of alloy *a*	vector	[%]	✓		
– Production rate (vs. melting capacity)	scalar	[%]	✓		
– Furnace life expectancy	scalar	[years]	✓		
– Daily work shift	scalar	[hours/day]	✓		
– Is furnace turned off during daily closing?	scalar	{0;1}	✓		
– No. of working days in a week (avg.)	scalar	[days/week]	✓		
– Is furnace turned off during weekends?	scalar	{0;1}	✓		
– No. of working weeks in a year (avg.)	scalar	[weeks/year]	✓		
– Number of furnace stops due to holidays	scalar	[events/year]	✓		
– Is furnace turned off during holidays?	scalar	{0;1}	✓		
– No. of required setups in a year	scalar	[events/year]	✓		
– Average duration of setups	scalar	[h/event]	✓		
– Is furnace turned off during setups?	scalar	{0;1}	✓		
– Scheduled frequency of maintenance work *w*	vector	[events/year]	✓		
– No. of extraordinary maintenance works *w* (avg.)	vector	[events/year]	✓		
– Average duration of maintenance work *w*	vector	[h/event]	✓		

Table 3. TCO model inputs *(continued)*

Input name	Input type	U.M.	Source: Die casting company	Source: Furnace manufacturer	Source: Market prices
Operational modalities *(continued)*:					
– Is furnace turned off during maintenance work *w*?	vector	{0;1}	✓		
– Average duration of furnace switch-on	scalar	[h/event]	✓		
Input costs:					
– Furnace purchase cost	scalar	[€]	✓	✓	
– Unit cost of power source *p*	vector	[€/kJ]	✓		✓
– Unit cost of category *e* employees	vector	[€/FTE]	✓		✓
– Unit cost of alloy *a*	vector	[€/kg]	✓		✓
– Cost of tools and machinery due to maintenance work *w*	vector	[€/event]	✓		
– Cost of labor due to maintenance work *w*	vector	[€/event]	✓		
– Other costs during lifespan stage *s*	vector	[€]	✓		

Legend:

- *a* ∈ {alloy1; alloy2; …} set of alloys processed by the furnace
- *e* ∈ {direct; indirect; external} categories of employees assigned to the furnace
- *p* ∈ {electricity; natural gas; coal} set of power sources consumed by the furnace
- *s* ∈ {research & selection; …; decommissioning} modeled lifespan stages of the furnace
- *w* ∈ {work1; work2; …} set of maintenance works carried out on the furnace

4.3. Empirical analysis

After analyzing separately the furnaces to test the TCO model, we carry out a comparative analysis to identify possible analogies and differences among the cost structures of the studied furnaces.

As a preparatory step, we need to standardize the value of input data affected by externalities, such as the market prices and the melting loss of aluminum alloy.

Table 4 and Table 5 summarize our hypotheses concerning input data standardization and corresponding results of TCO calculation respectively.

Table 4. Standardized values of input data

Input	U.M.	Standardized value
Unit cost of electricity	[€/kWh]	0.15
Unit cost of natural gas	[€/Nm³]	0.40
Unit cost of aluminum alloy	[€/kg]	1.80
Melting loss of aluminum alloy	[%]	5.00
Unit cost of direct employees	[€/(h·employee)]	25.00
Unit cost of indirect employees	[€/(h·employee)]	35.00
Unit cost of external personnel	[€/(h·employee)]	30.00

Table 5. Results of TCO calculation

	Furnace ID: A(I)	B(I)	C(I)	C(II)
Type	Pot	Reverber.	Reverber.	Reverber.
Lifespan [years]	10	20	20	20
Output [tons/year]	221.48	720.24	4,500.73	2,340.98
Resulting TCO:				
– [€/lifespan]	728,537	4,164,790	12,909,898	8,466,227
– [€/year]	72,854	208,240	645,495	423,311
– [€/ton]	329.95	289.22	143.44	180.90

Figure 5 and Figure 6 show TCO breakdown by lifespan stage and by resource type respectively: in order to compare results, TCO per metric ton of output metal is displayed. Results comparison highlights some analogies and differences among the studied furnaces.

At first, the TCO of all furnaces is highly impacted by utilization costs: results indicate that about 90÷95% of a furnace costs arise during the utilization stage.

It is worth noting that the three major determiners of the furnaces TCO (energy, labor and materials) are highly affected by both furnace operational modalities and external factors (e.g. market prices of energy and aluminum alloys): therefore, foundries can only partially control the total cost of these resources.

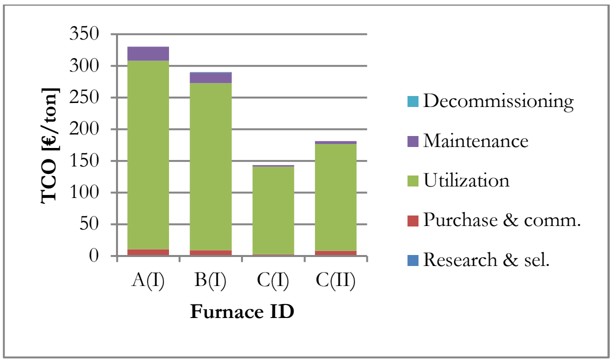

Figure 5. Breakdown of furnaces TCO by lifespan stage

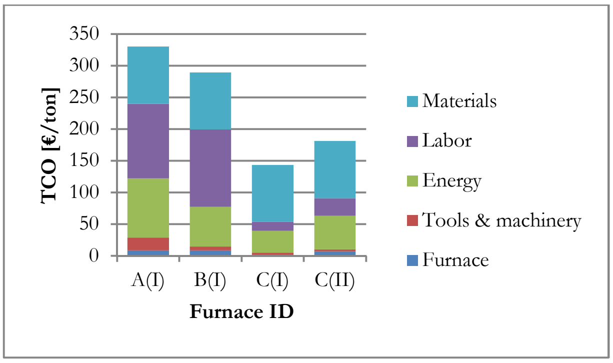

Figure 6. Breakdown of furnaces TCO by resource type

However, company C incurs significantly lower labor costs than companies A and B, probably taking advantage of larger sized and more automated melting furnaces. We also notice that company A has the highest energy cost share on TCO among the sample: this is due to the use of a pot furnace, which is more energy-dispersive than a reverberatory one.

Similarly to other common durable goods, purchase cost of the furnaces marginally affects their TCO. Maintenance accounts for about 2÷7% of the furnaces TCO, though different maintenance policies may imply significant changes in utilization costs as well. For instance, if a company increase the frequency of refractory shell restoration, maintenance costs raise but energy costs decrease due to optimized energy consumption of the furnace.

At last, the contribute of research & selection and decommissioning stages to the furnace TCO is negligible.

5. Conclusions

5.1. Discussion

The TCO methodology is widely used to evaluate products and services and to compare investment alternatives considering the sum off all costs which the customer incurs during the product or service lifespan.

Current literature lacks applications of this methodology to production machines in the metallurgical industry. The model described in this paper is a first attempt to fill this lack: in particular, it addresses secondary aluminum melting furnaces.

Through the analyses presented and discussed in §4.3, we identify the major determiners of a melting furnace TCO. These empirical findings serve as a benchmark and as a starting point for further tests and developments of our prototypal model.

5.2. Limitations and future research

The prototypal model presented in this paper is affected by some limitations, namely:

a) the limited number of case studies conducted;
b) the focus on secondary aluminum melting furnaces, which are a subset of metal melting furnaces;
c) the hypothesis of treating the melting furnace as a stand-alone machine, which may not suit other metal production processes (e.g. steelmaking).

Therefore, further research on this topic include:

1. increasing the number of case studies, in order to refine the model and obtain statistically significant results;
2. investigating the relationship between the model input and the resulting melting furnace TCO;
3. investigating trade-offs between different model inputs, in particular as concerns operating modalities of the furnace;
4. extending the model to other categories of melting furnaces listed in Table 1.

We are currently addressing points 1-3 above through validation of the prototypal model.

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