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Developing an optimum maintenance policy by life cycle cost analysis - a case study

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Developing an optimum maintenance policy by life cycle cost analysis - a case study

Abstract

This paper focuses on developing maintenance policies for critical assets to improve the production performance based on life cycle cost (LCC) analysis. A general approach is adopted for conducting the LCC analysis. The investigation is based on a case study to demonstrate how an optimum maintenance policy is determined. The relevant LCC structure in the case study is defined for the decision process which involves determination of the optimum life, repair limit and selection of materials, and trade-off between repair and replacement. The LCC analysis is based on statistical data modelling which facilitates decision-making on the optimal replacement of an asset and its remaining life. Based on the optimization and remaining life criterion, the optimal maintenance policy can be made. The results obtained from this case study include selection of the best lining material for use, determination of the optimal time for refractory lining replacement, the hot repair sequence required for maintaining the optimum condition and the repair limit for doing cold repairs before replacement, for one type of electric arc furnaces used in the steel industry.

Keywords

optimum, maintenance, policy, developing, life, study, cycle, cost, analysis, case

Disciplines

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8 **Developing an Optimum Maintenance Policy by Life Cycle Cost Analysis**
9 **— A Case Study**
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Developing an Optimum Maintenance Policy by Life Cycle Cost Analysis — A Case Study

Abstract

This paper focuses on developing maintenance policies for critical assets to improve the production performance based on life cycle cost (LCC) analysis. A general approach is adopted for conducting the LCC analysis.

The investigation is based on a case study to demonstrate how an optimum maintenance policy is determined. The relevant LCC structure in the case study is defined for the decision process which involves determination of the optimum life, repair limit and selection of materials, and trade-off between repair and replacement. The LCC analysis is based on statistical data modeling which facilitates decision making on the optimal replacement of an asset and its remaining life. Based on the optimization and remaining life criterion, the optimal maintenance policy can be made. The results obtained from this case study include selection of the best lining material for use, determination of the optimal time for refractory lining replacement, the hot repair sequence required for maintaining the optimum condition and the repair limit for doing cold repairs before replacement, for one type of electric arc furnaces (EAFs) used in the steel industry.

Keywords: Maintenance policies, asset management, life cycle cost, optimum replacement, remaining useful life

1. Development of Maintenance Policies by Considering Life Cycle Cost Approach

Many quantitative approaches and models have been developed to deal with the maintenance policies but they mostly focused on repair versus replacement of machinery and mechanical systems (Eginhard 1977, Jarddeine 1979, Zhang 2000, Lai 2001, Motta 2002). It is not until recently, when practical attempts have been made to deal with the relationship between maintenance strategies and the overall business objective of organizations (Tsang 2002, Pinjala and Pintelon 2006, Muchiri et. al. 2010, El-Akruti 2012). The same can be said about the development of quantitative models that use LCC to cover the impact of maintenance policies on the overall performance and value contribution to the organization (Khan 2001, Motta. and Colosimo 2002, Hartman 2004, Scarf et.al. 2007, Shahata and Zayed 2008, Lad 2012, Marais 2013).

Considering the relation between maintenance strategies and the overall business objective of organizations, it was proposed that knowledge of developing the LCC approach and models were essential for the formulation of optimum maintenance policies. In order to make some knowledge contribution in such direction, it was decided that a field investigation of an actual case study should be carried out for the dual purpose of developing the LCC approach as realistic as possible and for the application and evaluation of the quantitative optimization model through the use of past operational and cost records.

LCC analysis plays an important role in developing maintenance policies (e.g. Lad and Kulkarni, 2012; Taylor, 2012; Tähkämö et al., 2012; Mahapatra, 2008; Garcia et al., 2008; Shahata and Zayed, 2008; Scarf et al., 2007; Schuman and Brent, 2005; Hartman, 2004; Goralczyk and Kulczycka, 2003). LCC is directly influenced by decisions and activities from system preliminary design to utilization stage including system analysis, evaluation of alternatives or trade-offs. LCC may be reflected by the costs committed to and/or being incurred during the asset life cycle (Blanchard and Fabryky, 2010, p. 585), because asset operational management including maintenance is carried out through the entire asset life (Charles and Alan, 2005; Luan, et al., 2007). El-Akruti (2012) argues that LCC analysis is essential in managing the overlaps among the interdisciplinary activities in assets' life cycle. Maintenance policies development is related to procurement, finance and accounting department which enable investment, funding and budgeting in asset development.

During utilization of assets, maintenance policies are determined upon certain types of maintenance. This process may involve decision makings on outsourcing, upgrading, expansion, support system development, redesign, replacement or retirements of assets. To make these decisions requires for conducting LCC analysis. For example, Ouertani et al. (2008) argue that maintenance is complex and so deserves additional attention. Thus, maintenance policies development needs to be built on LCC among many other organizational activities and through all life cycle stages. Pinjala et al. (2006) discuss the relationship between an organization's business objectives and some of the maintenance activities and Khan (2001) presents that system reliability is related to LCC. A strategic approach to making maintenance strategies and policies has been recognized especially in capital-intensive industries (Tsang, 2002; Pinjala et al., 2006; Muchiri et al., 2010).

Integration of LCC into decision making models requires defining requirements, performance targets, availability of input data, priorities and alternatives for solution, cost contributors and cause-effect relationship; and setting an appropriate cost breakdown structure (Blanchard and Fabrycky, 2010). In the policies development, LCC is a critical factor in decisions related to dealing with one or more issues as follows:

- 1) During the utilization of the asset, replacement cost must be considered as a function of the current system's behavior to establish the remaining costs of the asset life.
- 2) The decision logic on repair/replacement must lead to economically optimized repair frequency and replacement time interval.
- 3) Prediction and estimation of asset condition may require condition monitoring system with breadth and depth for visibility.
- 4) At design phase, the investment as well as system operation and support costs need to be estimated. It is usually difficult to estimate/predict accurately the future operation and support costs.
- 5) Trade-off decisions may involve capital vs. running costs; labor & materials vs. reduced services and reduced safety.

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3 6) Decisions on alternatives need to be made based on the comparison criteria for asset
4 management according to maintenance strategies, policies or methods and balancing
5 the cost of a new item against the cost of maintaining efficiency of the old.
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8 9 2. The Significance of Using Life Cycle Cost Analysis

10 The purpose of conducting a quantitative LCC analysis in developing maintenance policies
11 is to cover the interrelationships between maintenance activities and other relevant life cycle
12 or support activities of the organization in order to avoid sub optimization and achieve
13 maximized economic benefits while maintaining the optimum system performance (Khan
14 2001, Schuman and Brent 2005, Muchiri et. al. 2010, El-Akruti 2012 Marais 2013). The
15 quantitative LCC analysis methods can ensure a realistic selection of the maintenance
16 policies together with associated activities, which maximizes the expected values if they are
17 based on cost minimization and output maximization (Marais, 2013). There are many
18 methods developed for carrying out a model-based LCC analysis using historical data such as
19 using graphical tools (Barberá et. al., 2013) in maintenance decision making. Statistical
20 methods or reliability techniques are also used for maintenance decisions and policy settings
21 (e.g. Motta and Colosimo, 2002).
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27 LCC models can help in developing criteria to improve the overall organizational benefits
28 with the same cost spent or reduce the cost with the same performance maintained in terms of
29 cost/benefit mixtures. For example, in order to find the optimal LCC, control of replacement
30 and/or repair frequencies is needed while considering impacts by/on other activities in the
31 organization. Maintenance control is meaningless unless there is a criterion to tell when the
32 control is serving the overall benefit of the organization. Such criteria do not exist and it
33 involves a search for it in the context of the demand for the asset. The effectiveness of
34 maintenance must allow the asset's performance to meet the demand. It is therefore a two-
35 way interaction. On one hand it is demand for equipment and on the other hand it is the
36 equipment condition. In between, the replacement and/or repair actions must be well planned.
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41 In maintenance control for optimization, there are two tasks to be completed: One is the
42 determination of how to measure the performance for the overall benefit of the organization
43 and the other is identification of the decision criteria with control variables which are
44 manipulated by the replacement function in order to set up a policy. If the performance
45 measures can be laid down clearly and can be met, the performance can be judged in terms of
46 cost for providing the required service to achieve the overall organizational benefit.
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49 Even if availability and performance are specified, one can question the true financial
50 effects of the production at each service level. Thus what are the financial effects of no
51 production time due to repair/replacement and poor quality? What are the financial effects of
52 delaying production resulting from not having equipment available? This gives rise to the
53 need to combine both functions of minimizing LCC to achieve various service levels and
54 maximizing the overall economic benefits for the organization. Finally it needs to remember
55 that the way in which an asset is used in production programs will inevitably influence the
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3 condition of the equipment. Sometimes, the decision is to be made on delaying production as
4 against to using asset with risky condition where deterioration may be rapidly and
5 catastrophically accelerated.
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7 In developing maintenance policies, different decisions are to be made at different
8 hierarchical levels including, e.g. inspection and replacement of component, repair or
9 overhaul of equipment, replacement, etc. The effect of these decisions cannot be separated.
10 Their combined effects on operation and maintenance have to be assessed when dealing with
11 policies development. For example, an optimum overhaul frequency for replacement of some
12 components depends on the frequency of replacement of other associated components. A
13 component may or may not be replaced at times of major overhauls and at time of
14 breakdown. LCC is considered for replacement decision which does not have to be in the
15 strict sense of the word, but perhaps maintenance decisions on repair and overhaul may be
16 taken as synonymous with replacement provided that it is reasonable to assume that
17 maintenance actions return the equipment to as new condition. Therefore it is not a 'one-off'
18 decision, but a series of decisions. Thus the decision structure is complicated and not all
19 decisions can be dealt with by considering LCC at the same time.
20

21 In order to **avoid sub optimization and** determine an optimum maintenance policy that
22 **serves the overall benefit of the organization**, a general approach to developing LCC analysis
23 as given by Blanchard and Fabrycky (2010) has been adopted here by modification as
24 follows:
25

- 26 1) Define system requirements and technical performance measures (TPMs).
- 27 2) Specify the system lifecycle and identify activities by phase.
- 28 3) Develop a cost breakdown structure.
- 29 4) Identify input data requirements.
- 30 5) Establish costs for each category in cost breakdown structure (CBS).
- 31 6) Select a cost model for analysis and evaluation.
- 32 7) Develop a cost profile and summary.
- 33 8) Identify high-cost contributors and cause-effect relationships.
- 34 9) Develop decision making models and set up decision criteria.
- 35 10) Conduct a sensitivity analysis.
- 36 11) Identify priorities for problem resolution.
- 37 12) Identify additional alternatives and select a preferred approach.
- 38 13) Evaluate feasible alternatives and select a preferred approach.

39 The similar process can be found from standards such as AS/NZS4536:1999 (1999) and
40 ISO 15663-3:2001 (2001). By following the adopted approach, an optimum maintenance
41 policy can be determined properly by minimizing LCC while achieving various service
42 targets and maximizing the economic benefits. This will be demonstrated by a case study as
43 shown in Section 3.
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3. Case Study — EAF's Lining Repair and Replacement Policies

This case study focuses on providing the refractory maintenance department and operation department in a particular steel making company with a maintenance policy that guaranties and outlines the economical decision bases for replacement and repair practice. It covers the role of LCC analysis in developing an optimum maintenance policy for an electric arc furnace (EAF) in terms of establishing decision making support quantitative model utilizing LCC data to help asset management:

1. Select the appropriate refractory lining material suppliers based on performance and economical lining life, and
2. Determine the optimal lining replacement cycle and repair intervals and/or limits

3.1 EAF's lining as a critical asset component

EAFs are the most critical assets to maintain the production process in a steel making plant. The main activities applied onto the EAFs are replacement and repair of linings in its main components, which impact on the process availability. Fig. 1 shows a schematic illustration of a 90 ton/heat EAF considered in this case study which is composed of three main components of roof, sidewall and hearth (Gadpayle and Baxi 2014). The roof can be replaced by new standby one with relatively no impact or loss of production. The repair and replacement of the sidewall and hearth are done simultaneously and have direct effect on EAF productivity and refractory lining management and therefore they are considered together in the decision support model development.

The lining within each component is divided into permanent lining and working lining. Working lining is the layer in contact with molten metal and permanent lining is the layer between working lining and the metal structure of the EAF as shown in Fig. 1. The most important element of EAFs with respect to its operation is its working lining. It is the sidewall working lining's life and its replacement that determines the campaign time and the furnace availability. However, both sidewall and hearth are interrelated in terms of the lining layers which are in direct contact with the molten metal. The maintenance policy for working lining, i.e. replacement and/or repair to a large extent impacts on the availability and productivity of the process, resulting in a great effect on the unit cost of liquid steel produced.

(Figure 1 is a bout here)

Repair of simple erosion in localized spots of the working lining can be done between heats during operation using gunning and fettling on sidewall and/or ramming for the hearth while the EAF is hot; this is called hot repair. Repair can also be done after stopping and cooling the EAF by replacing ramming or bricks of damaged areas due to excessive localized erosion; this is called cold repair. The repair/replacement action to be taken on EAFs involves decision making in cyclic manner as illustrated by a tree diagram as shown in Fig. 2. It is clear from the tree diagram that at any stage (at the end of any heat) of production, there is a

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3 decision point where one out of five alternatives is selected. Although due to safety
4 inspection is required after tapping each heat, decisions that are based on personal judgment
5 will not optimize the practice in the absence of a decision support model to determine optimal
6 criteria.
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11 (Figure 2 is a bout here)
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13 The service life of the working lining is dependent on operation conditions and repair
14 practice. The amount and quality of material used and the time required to do hot repair are
15 the main factors in considering hot repair cost. Cold repair is usually resorted to when
16 deterioration or damage cannot be handled by hot repair. It is time consuming because it
17 requires cooling the EAF down which results in a great loss of EAF's availability. The time
18 required for cooling EAF and the time required for repairing are the main factors in
19 considering cold repair cost. Hence it would be more appealing to enhance the quality of
20 lining to withstand the working condition for longer replacement intervals.
21

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24 Two types of lining replacement exist from the procedure shown in Fig. 2. One is
25 replacement of permanent lining and the other is replacement of working lining. Permanent
26 lining replacement takes place after a fixed time period, denoted as, t_p . t_p is adopted as 5000
27 ~ 6000 heats in the current policy in the case study as per designer's recommendation.
28
29 **Ref** Figure 2 Description of the decisions involved in replacement and repair procedure
30
31 operation. The time period between two working lining replacement actions is denoted as t_w .
32 In practice, it may take 2 to 3 or more years before t_p reaches 5000 heats, for example, but
33 working lining replacement may take place from 3 to 9 times in one year depending on
34 demand for production, operation conditions and raw material quality. Therefore, t_w is more
35 relevant than t_p for determining maintenance optimization criteria and the effect of t_p on
36 EAF's refractory cost is relatively small.
37

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40 According to information obtained from refractory lining suppliers and benchmarking
41 done by the case study company, the actual service life and the mechanism of replacement
42 and repair of EAF working lining is different from one steel plant to another depending on
43 environment, raw material and operational conditions. The range of variation of actual t_w
44 from one steel plant to another is in the vicinity of 140 to 500 heats.
45

46
47 Comparatively, t_p is longer than t_w . Permanent lining replacement is at a fixed time period
48 and based on designer recommendation. As a result, it has relatively little or no effect on the
49 economics of EAF lining maintenance and is considered irrelevant to optimal maintenance
50 policy development for EAF lining. Working lining replacement is the most relevant aspect
51 because it is directly related to the overall cost of replacement and repair, and costs and/or
52 losses due to stoppage of the EAF for repair. Consequently an assessment of working lining
53 replacement cost in terms of lining material and the costs and/or losses due to stoppage of the
54 EAF for replacement is required for constructing the LCC model. The costs or losses that
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3 result from the stoppage of the EAF due to repair or replacement are included in the cost
4 breakdown structure as a cost element called stoppage cost.

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6 The maintenance policies concerned in this case study include hot repair, cold repair and
7 replacement of working lining. Cold repair is considered as a partial replacement where the
8 EAF has to be cooled down. Hence it can be concluded that hot and cold repair are as
9 relevant aspects as working lining replacement because they have direct impact on LCC
10 which involves the overall cost of replacement and repair, and stoppage cost. Consequently
11 the hot and cold repair costs in terms of materials used and stoppages should be taken into
12 account in the LCC structure. Furthermore the two types of repair costs need to be considered
13 separately as hot repair is applied as required and hence does not require application decision
14 whereas cold repair requires an application limit as a decision variable in the model and
15 which has to be estimated according to the decision criteria.

16
17 In summary, there is a need to develop cost-effective criteria for determining the optimal
18 maintenance policy based on LCC and each plant has to develop its own convenient
19 replacement and/or repair policy.
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24 25 **3.2 Decision models and LCC criteria**

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27 The aim of this case study is to demonstrate and establish the modeling procedure using
28 LCC to set up a maintenance policy that economically control the replacement and repair
29 practice of refractory working lining in EAFs. The main decisions involved in modeling an
30 economical maintenance policy are:
31

- 32 1) Minimizing the LCC per unit production in treating of replacement and repair, so as to
33 obtain the optimum life of EAF's working lining (economical life);
- 34 2) Determining the cold repair economical limit in terms of cost and life;

35
36 As a result, it involves answering the following questions in this case study:

- 37 1) Which lining type (supplier) is better?
- 38 2) When will lining be replaced in a cyclical manner?
- 39 3) At what sequence is hot repair required relative to lining life?
- 40 4) Is cold repair used before replacement and how to determine the repair limit for use?

41
42 The bases for making these decisions are lining life in heats and LCC. It is intended to set
43 up a maintenance policy to meet the economical targets. That is to reduce LCC while
44 increasing productivity and maintaining the required quality. As a result, those economical
45 targets should be achieved through obtaining an optimum replacement model and a repair
46 limit model.
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51 52 **3.3 Decision models development and integration**

53 *3.3.1 Essential assumptions*

54
55 The relevant assumptions used in this case study are shown below:

- 56 a. Since working lining replacement occurs 3 to 9 times in a year, the unit price of
57 material is assumed to be constant over the replacement period and the unit price may
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3 be updated yearly. Similarly, no cash discounting shall be resorted to.
4
5 b. After new working lining is installed, the lining cost is assumed to be equal to the new
6 working lining cost at zero life and equal to zero at the optimum life, meaning, zero
7 salvage value of lining at replacement so that the depreciation cost would be the full
8 replacement cost.
9
10 c. Operating cost will not be considered in the cost model structure and assuming that it
11 does not change with the age of the lining.
12
13 d. Replacement, hot or cold repair duration is assumed as a time period of stoppage of
14 EAF; “no operation” status.
15
16 e. All “no operation” time periods incurred for hot or cold repair or replacement are
17 counted in calculation of stoppage cost.
18
19 f. The cost of second hand bricks or materials used in cold repair is assumed to be zero.
20
21 g. Cold repair limit is assumed to be evaluated on the basis of the working lining value
22 (remaining age value) at any stage of production.
23
24 h. The remaining age value is evaluated by linear regression using the statistical cycle
25 length data between two replacement actions.
26

27 3.3.2 Models involved and data for modeling

28 The required models involve quantitative replacement modeling and repair limit prediction
29 modeling. Models are developed on the basis of EAF past data that includes the deterioration
30 rate and the constant random failure rate.
31

32 The optimum replacement model and repair limit model can be obtained by statistical
33 analysis and modeling of the EAF past data for determining the optimum lining life. The data
34 obtained for analysis includes cost, operation and refractory lining material data of three
35 different suppliers' lining material types for the latest 5 years of operation. Data on working
36 lining replacement and repair for each supplier material type was collected for each heat and
37 then the data was grouped in a time period of every 10 heats for analysis. Then, the entire
38 cost elements that make up the LCC are determined; which are the costs of operation, repair,
39 stoppage, depreciation, etc. The average LCC per period can be determined. That is the sum
40 of the depreciation cost, and operation and repair costs. The depreciation cost per period
41 keeps decreasing while the operation and repair costs are increasing in usage time of EAF
42 lining. Therefore, the average LCC per period will decrease from commissioning to a
43 minimum level with increase of usage time due to decreasing of average depreciation cost per
44 period. After that, the average LCC per period will start to go up when the increase in
45 average operation and repair costs per period exceeds the decrease in average depreciation
46 cost per period. This minimum level of average LCC per period represents the criterion for
47 determining the optimum replacement point and the time span from the start point of
48 commission of a new working lining to this optimum replacement point represents the
49 “optimum replacement cycle length”.
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The repair limit is related to determining the remaining age value of the lining. Since the optimum lining life is maintained statistically, the remaining age at any service stage can be evaluated by linear approximation as given in Equation (1) with assumption that the final age value (FAV) is equal to zero.

$$L_v = \frac{C_w \times (OH - H_i)}{OH} \quad (1)$$

where, L_v is the remaining age value to be determined, OH is the optimum lining life which is the statistical average life, H_i is the service life of the lining, H_e is the expected remaining life of the lining ($H_e = OH - H_i$), C_w represents the initial age value which is equal to the working lining cost.

3.3.3 Integrating models and decision criteria in practice

The criteria may be divided into procurement and operational decision criteria. The procurement decision criterion is related to the alternatives in terms of types of lining material (suppliers), and the decision criterion variable is the minimum LCC per unit production, denoted for this case as average LCC per heat. The alternative with minimum average LCC per heat is to be selected.

The operational decision criteria are related to the alternative repair routes as shown in Fig. 3, which represent the integration of models within the overall operational procedure with all decision making events indicated.

(Figure 3 is a bout here)

3.3.4 Cost structure breakdown and cost elements evaluation bases for modeling

As decision criteria are based on cost data, various types of costs involved in lining repair and replacement must be outlined. These costs are structurally related as shown in Fig. 4. It should be noticed that some are not used because they either have no impact on the replacement and repair practice or do not change with respect to time or replacement and repair events. The main cost elements that have impact on decision regarding replacement or repair are working lining cost, cold repair and hot repair cost and stoppage cost as shown in Fig. 4.

(Figure 4 is a bout here)

3.3.4.1 Bases for material cost and stoppage cost evaluation

a. Material cost

The material cost is made up of the cost of various components which may be brick or mixes and/or binding material for the lining or the various used components of the repair material. The total material cost (C_m) is calculated by

$$C_m = \sum_{i=1}^n (U_{w(i)} \times U_{c(i)}) \quad (2)$$

where, $Uw_{(i)}$ is the total weight of material component i and $Uc_{(i)}$ is the unit cost of the component i (cost per unit weight).

b. Stoppage cost

In a general sense of production, stoppage time is time loss that could have been utilized for production. The stoppage cost is calculated by considering the following two aspects: One is the loss of operation time or "no operation time" resulting in an ongoing payment of the fixed cost and the second is "loss of products" that could have been produced in the stoppage time and then sold and therefore a possible result of lost benefit. Therefore, the stoppage cost, C_s , is defined as $C_s = NOC + LBNP$, where NOC represents the "no operation cost" which is mainly due to contribution of the ongoing fixed cost and LBNP represents the "lost benefit due to no production" because of "loss of products".

In general, the production benefit during one lining life is calculated by the following:

$$P_{pro} \times A_D \times L_H \times p_s - T_{repair/replace} \times P_{pro} \times p_s - C_{repair/replace} - Others \quad (3)$$

where P_{pro} is average productivity (tons/heat), A_D is average equipment availability in normal production, L_H is lining life evaluated in number of heats, p_s is sale price of the product in unit of dollars/ton, $T_{repair/replace}$ is the time used for repair and replacement in one lining life ($T_{repair/replace}$ is converted into number of heats in the calculation). In this equation, $T_{repair/replace} \times P_{pro} \times p_s$ is equivalent to a cost and named as lost production cost; $C_{repair/replace}$ includes lining material cost utilized and cost paid for man-hours used for repair and replacement actions; and others are those costs associated with necessary facilities and production support.

For the EAF refractory lining case, the replacement of working lining takes place 3 to 9 times during one year and therefore replacement and repair decisions are more related to cost figures during the year for which the production program is determined.

The value of the ongoing fixed unit cost (NOCu) is estimated based on the following:

$$NOCu = C_{Dep-u} + C_{Ins-u} + C_{Adm-u} + C_{Lab-u} \quad (4)$$

where, C_{Dep-u} , C_{Ins-u} , C_{Adm-u} and C_{Lab-u} are depreciation cost, insurance cost, administrative cost and labor cost, respectively. Each of them represents unit cost where the unit time refers to one hour, day or month; or each of them refers to the cost incurred per one heat, respectively.

The "lost benefit due to no production", LBNP, is obtained by

$$LBNP = T_{repair/replace} \times P_{pro} \times p_s \quad (5)$$

where the meaning of each term is the same as in Eq. (3).

As a result, the stoppage cost is evaluated by

$$C_s = T_{repair/replace} \times (NOCu + P_{pro} \times p_s). \quad (6)$$

3.3.4.2 Model cost elements evaluation

Working lining replacement cost (C_w) is broken down into five basic elements, and each of Cold repair cost (C_c) or Hot repair cost (C_h) also includes five basic cost elements as shown in Fig. 4. The material cost evaluation for working lining replacement cost and Cold repair cost is shown in Table 1. Hot repair, however, is defined in terms of gunning and

fettling and hence Hot repair material cost is composed of gunning cost and fettling cost (including cost of material used), i.e. $Chm = Cf + Cg$ where Chm is Hot repair material cost, and Cf and Cg represent the cost of gunning and the cost of fettling, respectively.

3.4 Model formulation

3.4.1 The optimum replacement cycle model formulation

The formulation of replacement is tabulated as shown in Table 1. For simplification, the formulation in Table 1 is only shown in terms of the main variables that give their logical relations with the operation decision criteria. Here, the operation decision criterion is to find the optimum cycle length, $OH_{(t)}$.

$OH_{(t)}$ is evaluated on the base of the minimum average LCC per heat (Cta) determined within the replacement cycle and based on the collected statistical data in each cycle. In utilizing the developed replacement cycle model, after each heat production the operator needs to check whether the optimum replacement cycle length, $OH_{(t)}$ determined by the model is reached in order to avoid doing any further repair beyond that optimum replacement cycle length point and replace the working lining. For the period at which replacement is decided to be undertaken, the hot repair cost per period (Chp) is determined as the maximum hot repair cost per period and denoted as $Chpmax$.

Using statistical analysis, the replacement cycles for each supplier's material type are assessed. The procedure for obtaining the optimum replacement cycle, $OH_{(t)}$ for each supplier's material type is shown by the flow chart in Fig. 5. In the flow chart, Cha , Cra , Cca , Cwa and Cta are average value per heat of hot repair cost, replacement cost, cold repair cost, work lining cost and LCC, respectively; Cr is repair cost; Gp is number of gunning per period and Chs represents hot repair service cost. The rest terms shown in Fig. 5 have been defined in Table 1, 2 and 3.

The average values of model variables and decision criteria are assessed based on average values per material type as shown by the chart in Fig. 6. For each supplier's material type, a representative average cycle (jav) is determined, parameters are plotted and decision criteria are determined based on the following:

- Determining and adopting the optimum life per material type as $OH_{(jav)}$ by comparing the LCC per period ($i+1$) to the previous period (i) for determining the optimum cycle length when $Cta_{(i+1)} \geq Cta_{(i)}$ as illustrated in Table 2.
- Adopting the optimum average LCC per heat as the minimum criterion, $Ctamin_{(jav, t)}$;
- Identifying and adopting the maximum hot repair per period as $Chpmax_{(jav, t)}$; and
- Identifying and adopting the maximum gunning per period as $Gpmax_{(jav, t)}$.

From Fig. 5, all lining material types are compared and the best material type with the minimum average LCC per heat is selected.

A spreadsheet programing is developed of the formulated model which can be used to enter data directly from the start of utilization of the working lining while calculating the optimum life cycle length OH after each heat production.

(Table 1 is a bout here)

(Figure 5 is a bout here)

3.4.2 *The repair limit model formulation*

The repair limit model is developed to help decide whether a cold repair is worthwhile based on the repair limit criterion. The procedure is dependent on the information from the optimum replacement model. The input variables for the model are composed of the output variables of the optimum replacement cycle model and the service life variable. The procedure involved in the repair limit model is based on defining the remaining age value and setting the cold repair limit in terms of remaining age value and service life. The main variables involved in the repair limit model are summarized with their logical relation to operation decisions as given in Table 2 and Table 3. Again, the repair limit can be checked after each heat production if the spreadsheet program is used.

(Table 2 is a bout here)

(Table 3 is a bout here)

3.5 Model results analysis and implication

3.5.1 *Model results*

By entering the required historical data, e.g., operation and maintenance data of each of the three lining types from the three different suppliers for a period of analysis of 5 years into the developed model, solutions are obtained for every working lining replacement of all suppliers' lining material types for the 5 years period. An average replacement cycle is obtained from the solutions for each supplier's lining material type and denoted as the average value for each supplier's lining material. These average solutions for the three different suppliers' lining materials provided basis for comparison and a view on the economics of repair and replacement for decision making based on the LCC per heat, repair cost per heat and the gunning consumption per period. They also provided a view on the impact of using cold repair and/or the change in the hot repair frequency and amount used in terms of gunning and fettling on the optimum replacement cycle length. For the purpose of this paper, it is not possible to present all solutions but as a sample solution, Figs. 6 (a) and 6 (b) show the results from analysis that determined the optimum replacement cycle length and frequency of hot repairs for one supplier lining material. Fig. 6 (a) shows optimization with cold repair done on the lining while Fig. 6 (b) shows the optimization without using cold repair. In the two figures, Cha, Cra, Cca, Cwa and Cta are average values per heat of hot repair cost, replacement cost, cold repair cost, work lining cost and LCC, respectively.

(Figure 6 is a bout here)

3.5.2 Model analysis and implication

The sensitivity analysis provided by the model as shown in Table 4, is based on generated values from historical data considering the main decision variables and their impacts on the overall benefit of the organization.

(Table 4 is a bout here)

From this sensitivity analysis in Table 4, it can be clearly seen that the most important parameter is related to the decision of purchasing the most economical type of material to use. As shown in Table 4, the model managed to rank the three types of refractory materials for purchasing purposes in their order of viability as B, A and C. It also managed to provide the tool for the operational control of the replacement cycle in the presence and the absence of a cold repair requirement. The illustrative 12 life cycle samples assessments indicate the losses incurred as a result of operating with the refractory lining beyond its optimum replacement point in each case. Sample 8 is proven to be the best which is using material type B, with no cold repair used and with an average hot repair per interval that costs \$2226.25. The use of hot repair per interval seems to be higher when using material type A, e.g. in sample 4 which is the best for material type A, the hot repair cost per interval is \$2358.75. Increasing the hot repair for material type A to \$2762.70 helped extending the optimum life of the lining to 370 heats but increased the optimum LCC per ton of liquid steel produced. In case of material type C, increasing the hot repair per interval did not help to increase the life of the lining or reduce the optimum LCC per ton of liquid steel produced.

The hot repair interval for repairing the defects can be modeled by a 3-parameter Weibull distribution given by

$$F(t) = 1 - \exp[1 - (1 + \lambda t^\beta)^\alpha] \quad (7)$$

with α , β of shape parameters and λ of scale parameter where $F(t)$ is cumulative distribution function of the hot repair interval, t (Zhang et al., 2013). In this case study, we got the model parameter estimates with $\alpha = 3.259$, $\beta = 1.387$ and $\lambda = 0.00039$. The model and other 2- or 3-parameter Weibull models could be used further to develop the relation between deterioration rate and repair sequence.

The generated values for the application of the decision variables are summarized in Table 5 for each supplier's material type.

(Table 5 is a bout here)

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3 The implication of using the model outputs in decision making is to determine the
4 optimum policy results in cost reduction for the company. The evidence can be extracted
5 from Table 5 as follows:
6

- 7 • An annual saving of 10% to 15% in the refractory cost with comparing Supplier-A to
8 Supplier-C (about \$1,700,000) is expected to achieve when managerial decision is made
9 for material type selection based on the model output.
- 10 • An annual saving of 2% to 6% in refractory cost is expected to achieve when operational
11 decisions are based on the model output.
12
13

14 15 **4. Conclusion, Recommendation and Further Research** 16

17
18 LCC is a critical and essential measure used in decision making for maintenance
19 management. In this paper, an approach is developed for fitting the LCC analysis procedure
20 into maintenance policies development based on a case study. This approach to the
21 maintenance policies development based on LCC analysis is believed to be a useful guideline
22 which is able to be adapted to other systems in industry. The provided case study gives
23 details of the application of the approach.
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27 Through the case study, it is demonstrated that LCC analysis is utilized to develop a
28 replacement model in which the procedure for analysis for the determination of the optimum
29 policy based on the LCC decision criteria are described. The decision criteria are used as
30 bases for decision making regarding the actions of replacement, repair and selection of the
31 material suppliers. They can be used for decision making within the direct and support
32 functions of the company. Therefore, the developed LCC-based model can serve as a
33 decision support system as illustrated in the case study.
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37 The application of the results is carried out in terms of the values determined by the model
38 analysis for the decision parameters as given in Table 5. A decision process has been
39 developed for using these values together with relations to the management system of the
40 company for decision making. The decision making also allows for taking into account the
41 advantage of arranging replacement or repair of any furnace in utilization when there is no
42 full demand required.
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46 The developed model provides an attractive proposal for top management to adopt. The
47 spreadsheet program application requires a very simple procedure that would not impose any
48 change in the actual operation or managerial practice and can determine the decision criteria
49 for replacement or repair directly from the actual data entered for the particular EAF lining in
50 use.
51

52 The recommendation for application includes:

- 53 • Operational recommendation
- 54 1) Replace the lining at the optimum life or as close to it as possible.
- 55 2) Observe gunning amount for every sequence of 10 heats and use it as an indication for
56 assessing cold repair economical application limit.
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- 3) Cold repair should not be applied if its cost exceeds the limit. If applied, the cost per heat at replacement will be higher than what it is at cold repair application.
 - 4) Even though hot repair should be applied as required, it is better to do it more frequently with small amount than less frequently with big amount.
 - 5) Start to do hot repair approximately after the 20th heat as required.
 - 6) For lining life less than 100 heats, hot repairs should be applied with a frequency from once per every 5 to 4 heats.
 - 7) For lining life beyond 100 heats, hot repair frequency should not be less than once per every 3 heats and it would be increased as required depending on operation condition where it may be done at every heat.
- Managerial recommendation
 - 1) When purchasing lining material, the decision on supplier selection should be based on the criterion of minimum LCC per unit production (per heat or per ton). The criterion relates price to performance for determining the most economical supplier.
 - 2) The model should be updated in case of any future development, changing condition or new suppliers included.

Based on the approach presented and its demonstration through a case study, it is found that the research could be extended further to a few other research areas. The research topics may include:

- Correlation analysis between LCC and operation and/or maintenance parameters,
- The effect of operation parameters on maintenance policy selection and
- Mathematical modeling of failure rate or probability analysis of the deterioration rate of EAF's refractory lining.

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28 **Figure 1** A schematic cross-section of an EAF
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32 **Figure 3** Operational decision criteria and procedure
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34 **Figure 4** Cost structure breakdown in modelling
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36 **Figure 5** Optimum replacement cycle model
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38 **Figure 6** Determining the optimum number of replacement w/o using cold repair
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48 **Table 3** Setting the decision criteria
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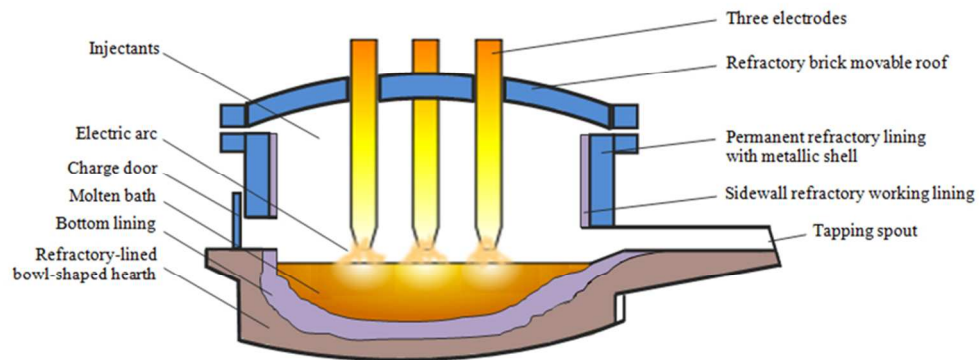


Figure 1 A schematic cross-section of an EAF
241x97mm (96 x 96 DPI)

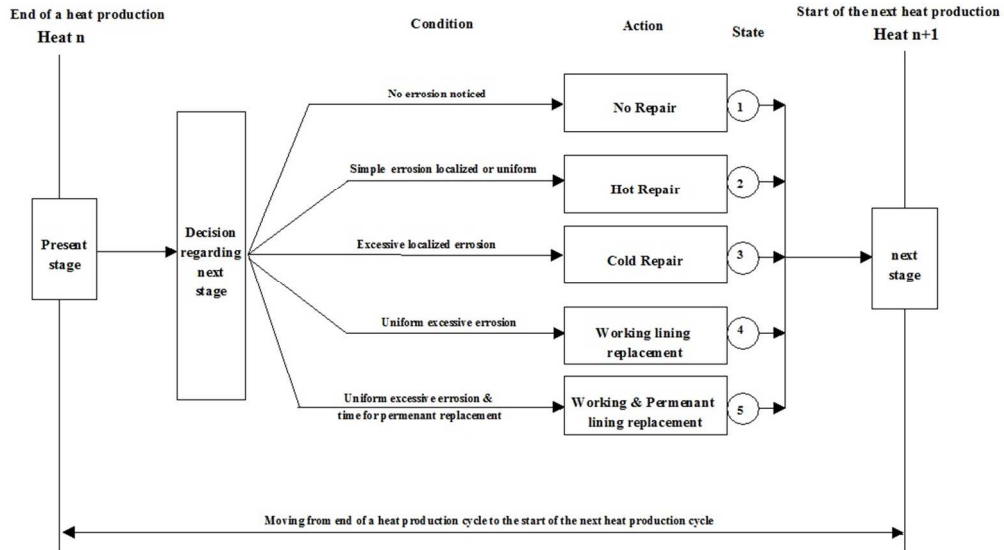


Figure 2 Description of the decisions involved in replacement and repair procedure 283x157mm (96 x 96 DPI)

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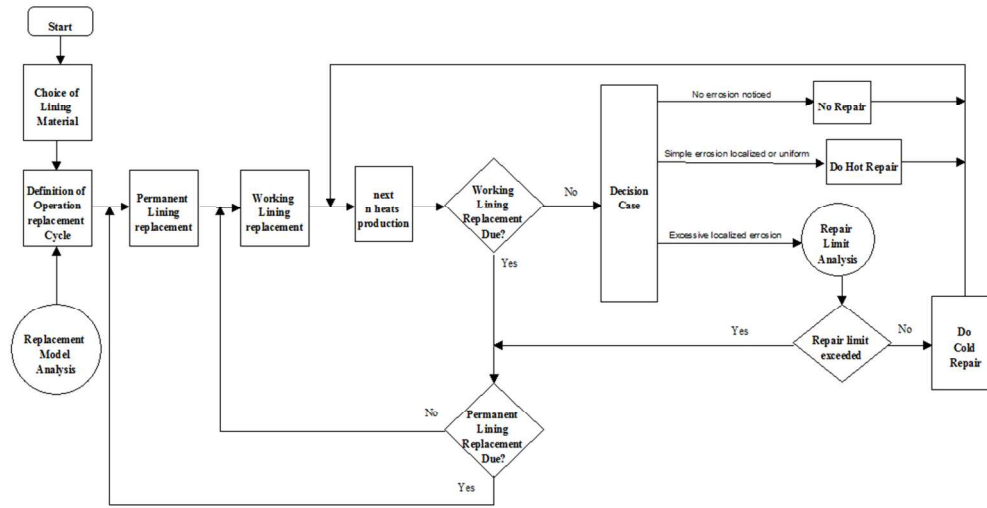


Figure 3 Operational decision criteria and procedure
286x146mm (96 x 96 DPI)

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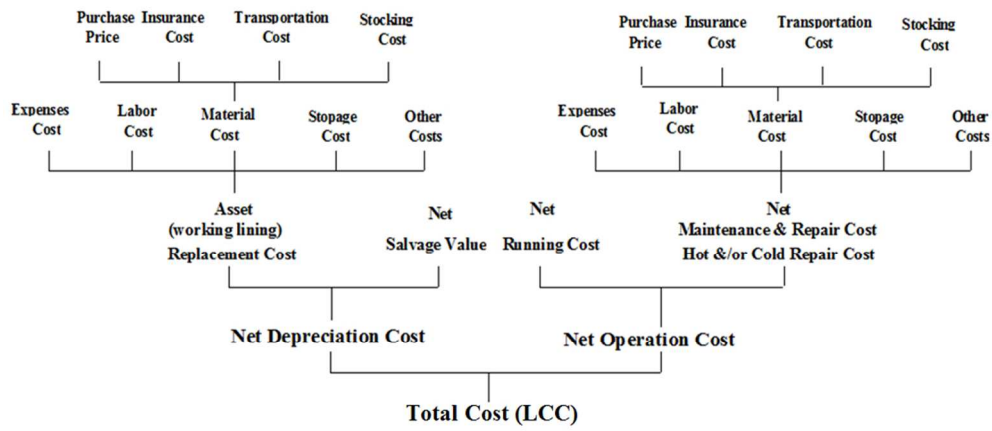


Figure 4 Cost structure breakdown in modelling
275x120mm (96 x 96 DPI)

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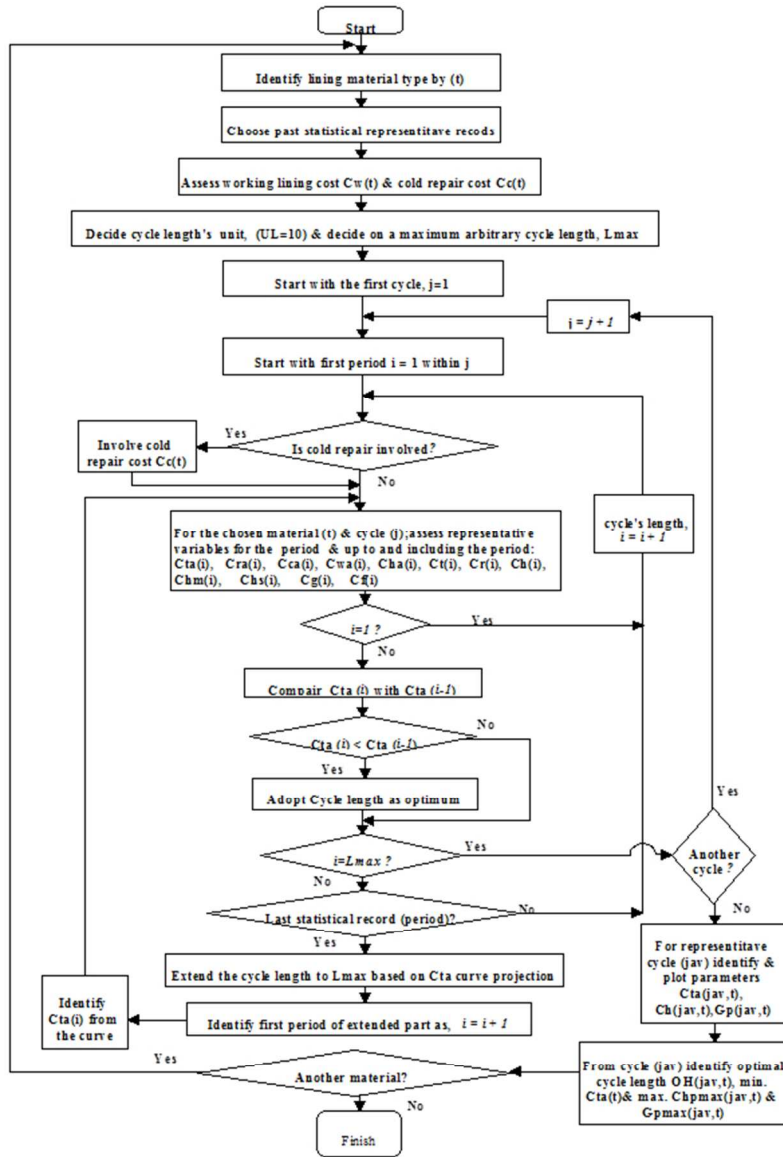


Figure 5 Optimum replacement cycle model
158x237mm (96 x 96 DPI)

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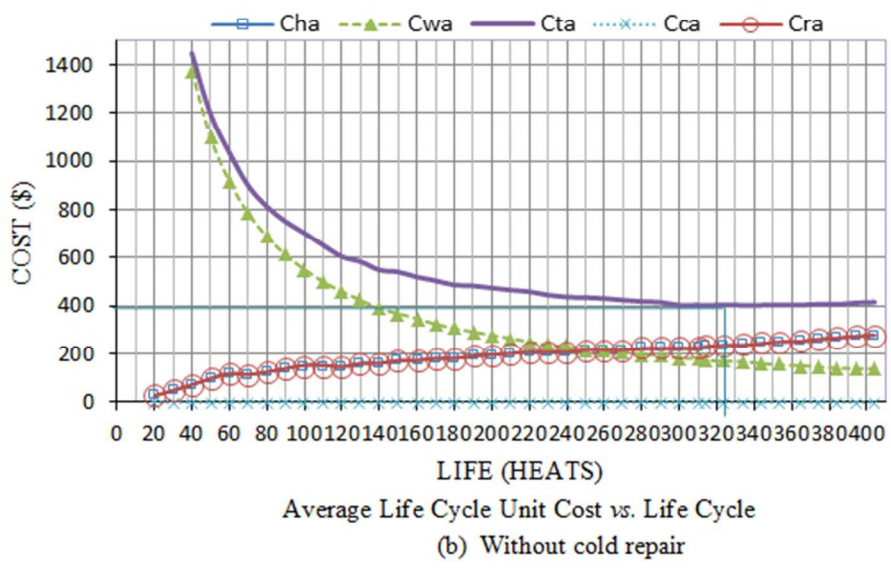
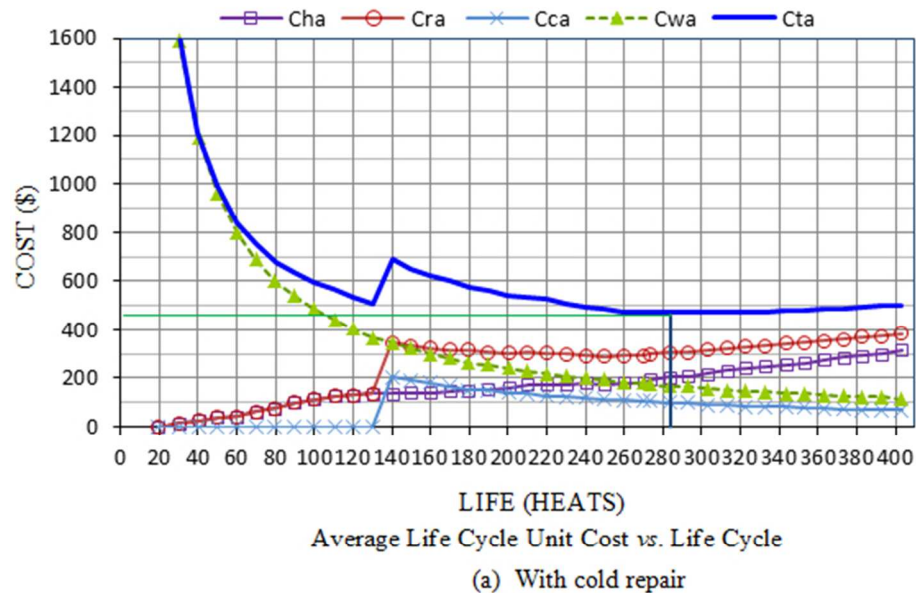


Figure 6 Determining the optimum number of replacement w/o using cold repair
152x193mm (96 x 96 DPI)

Table 1 Formulation of the optimum replacement model

Finalized Input Period Variables				Evaluation Variables		Decision Variable	Decision Criterion	Optimum Solution
1	2	3	4	5=3+4	6	7=6/1	8	9
Service Life or Periods (heats)	Replacement Cost (\$)	Hot Repair Cost (\$)	Cold Repair Cost (\$)	Repair Cost hot & cold (\$)	Cumulative Total Cost (\$)	Average Total Cost (\$)	True or False	Yes or No
(i)	$Cw_{(i)}$	$Chp_{(i)}$	$Ccp_{(i)}$	$Crp_{(i)}$	$Ct_{(i)}$	$Cta_{(i)}$	$Cta_{(i+1)} \geq Cta_{(i)}$	.....
(i)=1	$Cwp_{(1)}$	$Chp_{(1)} = 0$	$Ccp_{(1)} = 0$	$Crp_{(1)} = 0$	$Ct_{(1)} = Cw_{(1)}$	$Cta_{(1)} = Cw_{(1)} / H_{(1)}$	False	No
(i)=2	0	$Chp_{(2)}$	$Ccp_{(2)}$	$Crp_{(2)} = Chp_{(2)} + Ccp_{(2)}$	$Ct_{(2)} = Ct_{(1)} + Crp_{(2)}$	$Cta_{(2)} = Ct_{(2)} / H_{(2)}$	False	No
..
(i)	0	$Chp_{(i)}$	$Ccp_{(i)}$	$Crp_{(i)} = Chp_{(i)} + Ccp_{(i)}$	$Ct_{(i)} = Ct_{(i-1)} + Crp_{(i)}$	$Cta_{(i)} = Ct_{(i)} / H_{(i)}$	False	No
..
(i)=k	0	$Chp_{(k)}$	$Ccp_{(k)}$	$Crp_{(k)} = Chp_{(k)} + Ccp_{(k)}$	$Ct_{(k)} = Ct_{(i-1)} + Crp_{(k)}$	$Cta_{(k)} = Ct_{(k)} / H_{(k)}$	True	Yes

$OH_{(i)} = k$ representing the optimum cycle length to be used for operation decision

Table 2 Identifying variables and defining the repair limit

Model Indication Variables			Operation Life Variables		Model Cost Variables		Decision Variable
Maximum gunning per period (ton)	Maximum hot repair cost per period (\$)	Optimum cycle length (heats)	Gunning per period (ton)	Lining service length (heats)	Cold repair cost (\$)	Replacement cost (\$)	Remaining Age Value (\$)
$G_{pmax(t)}$	$Ch_{pmax(t)}$	$H_{(K)}$	$G_{p(i)}$	$H_{(i)}$	$C_{c(i)}$	$C_{w(t)}$	$L_{v(i)}$

Decision criterion for assessing cold repair limit is $G_{p(i)} \geq G_{pmax(t)}$
The Remaining Age Value is $L_{v(i)} = C_{w(t)} \times (H_{(K)} - H_{(i)}) / H_{(K)}$
The Repair limit is determined by $CRL_{(i)} = L_{v(i)} - Ch_{pmax(t)}$
or directly by , $CRL_{(i)} = C_{w(t)} \times (H_{(K)} - H_{(i)}) / H_{(K)} - Ch_{pmax(t)}$

Table 3 Setting the decision criteria

Life	Remaining Age Value	Cold Repair Cost	Cold Repair Limit	Criterion	Decision
(i)	$L_{v(i)}$	$C_{c(i)}$	$CRL_{(i)}$	$C_{c(i)} \geq CRL_{(i)}$	Replace or Repair
(1)	$L_{v(1)}$	$C_{c(1)} = 0$	$CRL_{(1)}$	No	Repair
(2)	$L_{v(2)}$	$C_{c(2)} = 0$	$CRL_{(2)}$	No	Repair
\vdots	\vdots	\vdots	\vdots	\vdots	\vdots
(f)	$L_{v(f)}$	$C_{c(f)} = \text{value}$	$CRL_{(f)}$	Yes	Replace

Cold repair is applied as long as $CRL_{(i)} \geq C_{c(i)}$, otherwise, there is no replacement at point (f).

Table 4 Sensitivity analysis provided by the model to show advantages and limitations for decisions

Life cycle Sample	Material type	Replacement cost \$	Hot repair cost per interval \$	Hot repair cost \$	Cold repair cost \$	Cold repair application interval heats	Optimum life heats	Optimum LCC per heat \$	Optimum LCC/ton of liquid steel \$	Actual operation life heats	Actual LCC per heat \$	Actual LCC/ton of liquid steel \$	Loss beyond optimum point per heat \$	Average annual loss \$
1	A	50504	2310.38	73932	28576	140	320	478.163	5.31	400	501.5	5.57	-23.34	-58342.50
2	A	50504	2542.47	81359	28576	150	320	501.372	5.57	330	503.45	5.59	-2.08	-5195.00
3	A	50504	2762.70	102220	28576	140	370	490	5.44	330	498.74	5.54	-8.74	-21850.00
4	A	50504	2358.75	75480	28576	150	320	483	5.37	330	483.83	5.38	-0.83	-2075.00
Average	A	50504	2493.57	83247.75	28576	145	333	488.1338	5.42	348	496.88	5.52	-8.75	-21865.62
5	B	54840	2476.00	64376	....	....	260	458.523	5.09	240	462.88	5.14	-4.36	-10892.50
6	B	54840	2344.96	56279	....	....	240	462.996	5.14	240	462.996	5.14	0.00	0.00
7	B	54840	2292.00	68760	....	....	300	412	4.58	310	416	4.62	-4.00	-10000.00
8	B	54840	2226.25	71240	....	....	320	394.9	4.39	320	394.9	4.39	0.00	0.00
Average	B	54840	2334.80	65163.75	....	....	280	432.1048	4.80	278	434.194	4.82	-2.09	-5223.12
9	C	47691	1860.60	27909	....	....	150	504	5.60	120	541.97	6.02	-37.97	-94925.00
10	C	47691	4143.07	58003	28576	140	140	463	5.14	270	476.71	5.30	-13.71	-34275.00
11	C	47691	4607.75	55293	28576	120	120	572	6.36	210	575.5	6.39	-3.50	-8750.00
12	C	47691	1945.45	38909	....	....	200	433	4.81	170	442.8	4.92	-9.80	-24500.00
Average	C	47691	3139.22	45028.5	....	....	153	493	5.48	192	509.245	5.66	-16.25	-40612.50

Table 5 Output values of the model for decision criteria and optimum status

Parameter	Unit	Material Suppliers		
		Supplier-A	Supplier-B	Supplier-C
Replacement Cost	\$	175,490	161,614	152,613
Cold Repair Cost	\$	91,446	91,446	91,446
Maximum Gunning	Ton	5.20	6.0	5.50
Hot Repair Period Length	Heats	10	10	10
Max. Hot Repair Cost per Period	\$	13,682	14,007	15,907
Optim. EAF Working Lining Life	Heats	278	319	229
Cold Repair Limit	Heats	120-to-130	110-to-120	80-to-90
Cold Repair Actual Application	---	Not Feasible	Feasible	Feasible
Total Cost per Heat (Cta)	\$	1,426	1,544	1,652
Total Cost per Ton of Liquid Steel	\$	15.6	16.8	16.8
Expense in Terms of Use	---	Cheapest	Moderate	Most Expensive
Priority for Use	---	First	Second	Third
Optimum Life Achievement	---	Always achieved, or over passed	Rarely achieved but close to	Never achieved and much less
Priority of Safety Base on Optimum Life Achievement	---	Highly safe since it overpass	Moderately safe since it is close to	Low safety since it never reaches
Total Annual Cost based on use of each suppliers material alone	\$	5,436,058	5,887,760	6,298,710
Matrix for Annual Savings or Losses based on Optimum Life Criteria of one EAF				
Material Supplier		Supplier-A	Supplier-B	Supplier-C
Supplier-A		-----	-\$451,703	-\$862,653
Supplier-B		\$862,653	-----	-\$410,950
Supplier-C		\$862,653	\$410,950	-----
Result by Comparing Actual life to Optimum Life		High Savings by not over passing optimum life	Almost zero losses by being close to achieving optimum life	High losses because optimum life is usually not achieved