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Optimal support strategy for mechanical systems under contract realm

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Abstract

Purpose – Original equipment manufacturers (OEMs) start providing support to products that helped them in sustaining their business worldwide. The customers are entering into contracts with the OEM, to get the required level of performance but at minimum possible cost. It required the work distribution between OEM/service provider and the client, and may formalize through contract. The contract structure depends upon the number of player involved (customer, OEM and third party) and the support activity. The different contract alternatives can be formulated and the best one may be selected on the basis of minimum Life cycle cost. The paper aims to discuss these issues.

Design/methodology/approach – In this work, mathematical models are developed; which are implemented on a real life problem. The developed models are optimized in context to preventive maintenance schedule.

Findings – In this research, important issues are listed; research steps and mathematical models are presented. The problem has been identified from the literature perspective for mechanical systems. A methodology for formulating and selecting the optimal contract structure is also proposed. The model has been implemented on a real life problem, in which the OEMs provide support to their make installed at Compressed Natural Gas workstation in National Capital Region, India.

Originality/value – The research results of this paper will contribute both academic and empirical value.

Keywords Availability, LCC, Contract structure, Maintenance and reciprocating compressor, Supportability

Paper type Research paper

Nomenclature

a	restoration factor
A	operational availability
A_R	required operational availability
A_A	actual availability
C	customer
C_{aq}	acquisition cost of a system
C_{C_i}	cost of ith subassembly within the system
C_{fix}	fixed cost to perform each corrective or preventive action, which includes the cost of material required like lubricating oil, etc.
C_{fixOH}	fixed cost to perform the overhaul that includes the cost of material required like lubricating oil, etc.
C_{fixI}	fixed cost associated with every inspection action
d	discount rate per annum
D_i	demand of ith subassembly per annum

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d_{ij}	distance from demand location i to a candidate site j
$E[C_{CA}]$	expected cost of corrective action during any investigation period for a system
$E[C_h]$	expected cost of holding the spares during any investigation period for a system
$E[C_{IA}]$	expected cost of inspection during any investigation period for a system
$E[C_L]$	expected logistics cost during any investigation period for a system
$E[C_{OH}]$	expected cost of overhauls during any investigation period for a system
$E[C_{OP}]$	expected operation cost during any investigation period for a system
$E[C_{PA}]$	expected cost of preventive action during any investigation period for a system
$E[C_T]$	expected contract cost paid by the customer
$E[C_t]$	expected cost of transportation of spares during any investigation period for a system
$E[N_{CAi}]$	expected number of corrective action of ith subassembly in the system
$E[N_{Ii}]$	expected number of inspection of ith subassembly in the system
$E[N_{OHi}]$	expected number of overhauls of ith subassembly in the system
$E[N_{PAi}]$	expected number of preventive action of ith subassembly in the system
$E[P_C]$	expected penalty cost during any investigation period for a system
$E[S_T]$	expected cost of support during any investigation period for a system
$E[TDT]$	expected downtime for which the system is not available
L	operating life of the system, in years
L_c	labour cost per unit time
L_{PCA}	lost of average sales of product per unit time, during the uneven breakdown or failures
L_{PPA}	lost of average sales of product per unit time due to preventive actions
m	support activities during a planned operating period
$MTTCA_i$	mean time to perform the corrective action on ith subassembly of the system
$MTTI_i$	mean time to perform inspection on ith subassembly of the system
$MTTOH_i$	mean time to perform overhauls on ith subassembly of the system
$MTTPA_i$	mean time to perform the preventive action on ith subassembly of the system
n	number of subassemblies in a system
$N(t/V)$	conditional number of failure
O	no. of operators required for operating the system
OEM	original equipment manufacturer
O_c	overhead cost per unit demand
P	profit generated per unit of product sold
PVc	present value of LCC
Rs	Indian national rupees
R_L	revenue lost due to maintenance actions
S	salary of one operator per day
S_c	storage cost per unit
S_{SC}	supervisory staff cost per unit
T	total time
t_i	inspection interval for ith subassembly of the system
t_{OHi}	overhaul interval for ith subassembly of the system
T_{opr}	actual operating time
t_{pmi}	preventive maintenance interval for ith subassembly of the system
TP	third party support provider
V_n	virtual age of the unit at the time of the nth repair completion
$V_{(n-1)i}$	virtual age of the component before carrying out a particular maintenance action

X	the percentage of profit wanted to generate from the support services	β	shape factor, defines the shape of distribution in Weibull
X_n	preventive maintenance interval		
Y	required level of availability	η	scale parameter, defines where the bulk of the distribution lies in Weibull
α_i	cost per unit distance per unit demand		

1. Introduction

In today's fast-paced global markets, along with the continuous breakthrough in technology, are driving customers to put more emphasis on the functional requirements (availability, overall equipment effectiveness, etc.) of a system. Original equipment manufacturers (OEMs) are therefore, continuously searching new policies to prove them competitive that make customer satisfied. From the new strategies point of view, the company's products containing good aesthetics, functionalities and technologies, forced them to shift their traditional business perspective to a more sustainable and customer oriented.

For a simple product, the manufacturer is responsible for all kind of support, whereas for a complex product, the manufacturers continued to use the warranty to provide maintenance with repairing all failures that occur within the warranty period. Since, over the last few decades, OEMs have started offering the extended warranty which provides the customer with coverage beyond the normal warranty period. But, now the trends have been shifted towards support, that an OEM provider to their customers.

Support facilitate the sale of products, levers the customer satisfaction (Athaide *et al.*, 1996), raises revenue (Berg and Loeb, 1990), responds to a prominent solution of problems (Xu *et al.*, 2006) and create opportunities for OEM to survive in market competition (Hull and Cox, 1994). Therefore, support emerges as a key factor in the success rate of a product in general, and the company in particular (Cooper and Kleinschmidt, 1993). The capability of OEM for providing the support to their products is known as supportability (Asjad *et al.*, 2012).

OEMs are capable of providing support to their manufactured, but due to certain constraints (like time, traditional business, location, etc.) however, the OEM can in-turn enter into an outsourcing of support with a third party support provider. At the same time, the customer may also want to participate in order to, retain some in-house control, reduce the OEM dependency and minimize the incurred cost. Thus, at any operating stage, the system can either be supported by a single and/or combination of players (customer, OEM and third party); for which it is necessary to have a business relationship throughout the useful life. The business relationship can be formalized through contract and depends upon support activity, player's involvement, etc.

The contracts are as per the agreement for ensuring minimum customer's requirements (like availability, overall equipment effectiveness, etc.) and in case the support provider fails to meet the requirements, a penalty may be charged by the end user. The imposed penalty affects their business and makes them cautious for timely execution of their responsibilities. The different outsourced support activity, i.e., operations, inspection, corrective maintenance, preventive maintenance (PM), overhauls, etc., do contribute the contract cost and shifted life cycle cost (LCC) to higher side. So, there is a need to balance the support responsibility among the players, through contract, to minimize the system LCC. Thus, the contract structure can be seen as a way of providing the support at the minimum possible LCC.

The inherent failure and repair characteristics like time to failure distribution, time to repair distribution, failure modes, possible degrees of restoration, etc., of mechanical system are established by its design (Barabady and Kumar, 2007). Further, PM can also be used to improve system performance. However, PM again consumes resources and time thereby affecting LCC. Thus, PM may be optimized to ensure reliable operation of the system but at minimum possible cost (Barabady and Kumar, 2007), thereby minimizing the cost incurred and thus, the LCC. The contract structure with maintenance optimization may further lead to reduction in system LCC. These aspects in context to supportability are needs to be addressed at the design stage of a product.

The objective of this paper is to present how to integrate LCC appropriately in contract assessment to determine the best possible structure from technically viable alternatives. The contract structure that ensured a minimum level of operational objectives while ensuring the profit to the support provider is chosen for further analysis. Further, the optimization of the PM schedule has been carried out in order to maintain the sustainability of systems at minimum possible cost. The developed methodology has been applied to a realistic problem, whereas the sensitivity analysis demonstrates the robustness of the proposed research.

Organization of the paper is as follows: an overview of focused literature is presented in Section 2, whereas the third section presents the mathematical models for estimating the O&M cost. Section 4, proposed the framework for the formulation and selection of best structure among of feasible contract structure. Section 5, presented a real life problem, for which the results has been validated. The sensitivity analysis and optimization of PM schedule for a reciprocating compressor has been presented. Section 6 concludes the work and also suggests the future scope of research.

2. Literature review

The support has been reported in literature with wide application in academics, research, industrial application, etc.; and is known by different names, such as installation, commissioning, documentation, training, maintenance, service, logistics, warranty, equipment upgrading, etc. (Blanchard and Fabrycky, 1998; Goffin, 1999; Wilson *et al.*, 1999). Support entails all activities that ensure the system sustainability obtained by failure free operating period during their useful life (Loomba, 1998).

Knecht *et al.* (1993) studied that product characteristics, like reliability, have a strong influence on product support. The customers are increasingly becoming dependent on the support providers for various operations and maintenance activities (Kumar and Markeset, 2007). Fink *et al.* (2007) suggested that the service provider should develop improved products and services, as well capacities and capabilities to improve their customer satisfaction.

Increased support options available for a product are key determinants in users' product purchased decision (Lele and Sheth, 1987). Helander and Moller (2007) introduced the three roles of OEMs in the provision of support: equipment supplier; solution provider; and performance provider. Therefore, OEMs make provisions for support either by offering it directly, or through their own network of service centres, channel intermediaries, authorized independent third-party service centres or by combination of these, through contracts (Loomba, 1998). The various types of engineering contracts and their governing mechanism that are widely applied in industrial application were studied by Dhillon (2002) and Betty (1993).

According to Schuman and Brent (2005), contracts suited both for the service providers and the facility owners are the most desirable. The contracts for maintenance support have been studied by number of researchers, some of the recent are Jackson and Pascual (2008), Yeh *et al.* (2011) and Chang and Lo (2011). However, there is no such study reported in the literature that deals with all the issues relevant to support contracts (Asgharizadeh and Murthy, 2000).

To get maximum benefits from the support/services, the support provider must optimize their capabilities in terms of available expertise, equipment and operations and maintenance strategies to reduce the cost (Markeset and Kumar, 2005), thereby reducing the contract cost and hence the LCC. Thus, distribution of support activity among the player may also lead to reduction in LCC. Thus, there is need to explore the contract structure that will minimize the LCC, i.e. the optimal selection of contract based on LCC.

Su and Chang (2000) proposed a periodic maintenance policy for multi-state system and derived the optimal number of maintenance activities that minimized the product LCC. The optimization of PM (Bartholomew-Biggs *et al.*, 2009) is based on optimal maintenance interval required for LCC minimization. Wang (2010) developed a model for maintenance service contract design, negotiation and optimization, in which the author studied three options depending on the extent of outsourced maintenance activities. The LCC can be minimized through optimized maintenance schedule, and thus, PM schedules have a great impact on LCC. However there is no such attempt has been made in the literature to demonstrate the integrated approach that consists of contract, LCC and maintenance schedule for assuring the objective function of customers. The following important observations have been derived from the literature:

(1) Support option for a product may affect the OEM business.

(2) Support can be provided by the OEM, third party and customer and their combinations, through formal contract. There is paucity of mechanism for distributing the support activity among the players' and hence presents a good scope for further research.

(3) Maintenance optimization in context to support has not received much attention.

(4) Although there is a vast amount of literature has been reported on support, LCC, contract, maintenance schedule and its optimization, etc.; yet there seems to be a large gap in integrating of these aspects in context to support.

Beside the above mentioned gaps, the major drawback of existing literature is the lack of mathematical models and methodology that can be applied to provide support. The subsequent section develops the mathematical models that will be helpful in analyzing the support impact on system performance and LCC.

3. Mathematical modelling

Most of the users are unable to specify their support requirement. The specifications are mostly in terms of functional as well physical requirements and some of them are linked to an operational availability. The availability indicates how well the system performs its intended function and can be sustained through regular upkeep, etc. The availability of the system can be enhanced by incorporating the support actions throughout their useful life. However, further analysis is required to identify the support activities to improve the systems operational objectives.

3.1 Specify the support activities

Failure affects the system performance in general, and the customer's business in particular, can be measured in terms of operational availability, spares consumptions, resources requirements, etc. Thus, it is necessary to quantify the support requirement in order to counter the failure effect. The support may vary from customer to customer, e.g. one user may be interested in getting the support in terms of corrective maintenance while the other may or may not be interested in the same. However, the corrective maintenance is more important in initial ages, while preventive schedule may be effective in later stages. Thus, proper quantification of support requirement is essential before its execution.

3.2 Connecting user supportability requirement with system performance measure

Customers specify their requirements in terms of performance measures like availability, LCC, process capability, overall equipment effectiveness, productivity, etc. The support provider must express these in terms of decision variables related to support. For example, if customer has specified LCC and availability requirement, the following approach may be used.

3.2.1 Availability. Customers do specify requirements in terms of performance indicators like availability, etc., which the support provider must express these in terms of decision variables related to spares, maintenance actions, etc. In general, availability is defined as the expected proportion of time for which the item is operating. The availability is also expressed as the ratio of actual operating time to the total time. Mathematically, availability (A) is expressed as:

$$A = \frac{\text{Actual Operating Time}}{\text{Total Time}} \tag{1}$$

Let the total time be T hours and $E[TDT]$ be the expected downtime for which the system is not available. Thus, actual operating time, T_{opr}, is given as:

$$T_{opr} = T - E[TDT] \tag{2}$$

$$A = \frac{\text{Actual Operating Time}}{\text{Total Time}} = \frac{T_{opr}}{T} = \frac{T - E[TDT]}{T} \tag{3}$$

The $E[TDT]$ is given by:

$$E[TDT] = \sum_{i=1}^{n} \left(E\left[N_{I_i}\right] \cdot MTTI_i + E[N_{CM_i}] \cdot MTTCM_i + E\left[N_{PM_i}\right] \cdot MTTPM_i + E[N_{OH_i}] \cdot MTTOH_i \right) \tag{4}$$

where, $E\left[N_{I_i}\right]$, $E\left[N_{CM_i}\right]$, $E\left[N_{PM_i}\right]$ and $E\left[N_{OH_i}\right]$ are the expected number of inspection, corrective, preventive and overhaul actions, respectively, during the investigation period, where, suffix i indicates the ith component/subassembly of a mechanical system.

$MTTI_i$, $MTTCM_i$, $MTTPM_i$ and $MTTOH_i$ are the mean time for performing the inspection, corrective actions, preventive actions and overhauls on the ith component/subassembly of the system respectively. $MTTCM_i$ includes the actual time spent in repair as well as the time for which the system is waiting for maintenance personnel, spare parts, etc. Thus, for improving the system availability, the designer may improve the maintainability and reduce the maintenance delays during the planning horizon. The operational availability is, therefore, expressed as:

$$A = \frac{T - \sum_{i=1}^{n} \left(E\left[N_{I_i}\right] \cdot MTTI_i + E\left[N_{CM_i}\right] \cdot MTTCM_i + E\left[N_{PM_i}\right] \cdot MTTPM_i + E\left[N_{OH_i}\right] \cdot MTTOH_i\right)}{T} \quad (5)$$

The expected number of failures depends on the reliability, maintainability and maintenance schedule-related parameters of the system, which are to be optimized while designing the support plan.

3.2.2 LCC. LCC, in general, includes design and development cost, production and construction cost, operation and maintenance cost, system retirement and phase out cost. LCC may be categorized in many different ways, depending on the type of system and purpose of the analysis. In this research, LCC is defined as the sum of acquisition cost, the discounted sum of contract and support cost, which may in turn, depends upon operation, inspection, corrective, preventive, overhauls and logistics costs for the intended use of the system.

Let the expected life of the system be L years and d be the discount rate per annum. Assume that the cost structure of support, penalty clause and contract remains same throughout the operational life of a system. Then, LCC expressed in term of present value of cost becomes:

$$PV_C = C_{aq} + \sum_{j=1}^{L} \left\{ \frac{1}{(1+d)^j} \left(\sum_{k=1}^{m} E[C_T]_k + E[S_T]_k \right) \right\} \quad (6)$$

C_{aq} is the system acquisition cost, which is derived from the cost that manufacturers incur in concept and definition, design and development, manufacturing, assembly, installation; $E[S_T]_k$ is the support cost that includes all the cost associated with the different activities subsequent to equipment delivery in the field, throughout its life cycle and are carried out by the customer itself; and $E[C_T]_k$ is the expected contract cost which depends upon the support activity that are executed by the support provider. For estimating the contract and support cost, an activity-based costing for each support activity is required.

The overall support activity for any mechanical systems may include all or any of the following: operations, inspection, corrective, preventive, overhauls and logistics cost; depends upon to customer and product requirements. The mathematical models for each activity are developed and described below.

3.2.2.1 Operation cost. Operation is the one of the primary necessity for any system, that may has a significant impact on supportability domain. In present study, operation cost is estimated as:

$$E\left[C_{op}\right] = O \times S, \text{ Rs per day} \quad (7)$$

where, O is the number of operators per day and S is the salary of an operator per day.

3.2.2.2 Inspection cost. Inspections are performed at regular or scheduled intervals to check, if a component has failed or is likely to fail in near future. Based on the outcome of an inspection, planned maintenance is taken up. A certain amount of fixed cost C_{fixI} is associated with each inspection, which may include the tool and equipment cost incurred for carrying out the inspection. Thus, expected cost of an inspection, $E[C_{IA}]$ is estimated as:

$$E[C_{IA}] = \sum_{i=1}^{n} \left\{ (MTTI_i \cdot L_C + C_{fixI}) \cdot E[N_{I_i}] \right\} \quad (8)$$

where, $E[N_{I_i}]$ is the expected number of inspection for ith subassembly and is calculated as:

$$E\left[N_{I_i}\right] = \frac{T}{t_i} \quad (9)$$

where, t_i is the inspection interval of ith subassembly of the system; T is the total time; C_{fixI} is the fixed cost associated with every inspection action, which may include the cost of non-recurring elements like oils, grease, etc.; L_C is the labour cost per hour; and $MTTI_i$ is the mean time to inspect the ith subassembly of the system, in hrs.

3.2.2.3 Corrective action cost. Corrective actions are meant to repair the system when it suddenly breaks down or stops. This may include removal/repair and/or replacement of the failed components to bring the system back to its operational state. The corrective action cost comprises the labour cost, component cost, fixed cost and the associated loss of revenue. The expected cost of corrective action, $E[C_{CA}]$, for a system for a given investigation period is estimated as:

$$E[C_{CA}] = \sum_{i=1}^{n} \left\{ \left(MTTCA_i \cdot (R_L + L_C) + C_{C_i} + C_{fix} \right) \cdot E\left[N_{CA_i}\right] \right\} \quad (10)$$

where, $MTTCA_i$ is the mean time required to perform the corrective action of ith component/subassembly within the system; C_{fix} is the fixed cost to perform each corrective or preventive action, which includes the cost of material required like lubricating oil, etc.; C_{C_i} is the cost of ith subassembly within the system; L_C is the labour cost per unit time; $E\left[N_{CA_i}\right]$ is the expected number of failure for ith component/subassembly of the system; and R_L is the revenue lost per unit of time and is given as:

$$R_L = P \cdot L_{PCA} \quad (11)$$

where, P is the profit generated per unit of product sold; and L_{PCA} is the lost of average sales of product per unit time, during corrective actions.

3.2.2.4 Preventive action cost. PM actions include adjustment, replacement and repair. The expected cost of PM $E[C_{PA}]$ for a system comprising n components is given below:

$$E[C_{PA}] = \sum_{i=1}^{n} \left\{ \left(MTTPA_i \cdot (R_L + L_C) + C_{C_i} + C_{fix} \right) \cdot E\left[N_{PA_i}\right] \right\} \quad (12)$$

where, $MTTPA_i$ is the mean time to perform that preventive action of ith subassembly in the system; C_{fix} is the fixed cost to perform each corrective or preventive action, which includes the cost of material required like lubricating oil, etc.; C_{C_i} is the cost of ith subassembly within the system; L_C is the labour cost per unit time; and $E[N_{PA_i}]$ is the expected number of PMs for the ith subassembly of the system, and is given as:

$$E[N_{PA_i}] = \frac{T}{t_{pmi}} \tag{13}$$

where, t_{pmi} is the PM interval for the ith subassembly of the system; T is the total time; and R_L is the revenue lost per unit of time due to failure/breakdown and is given as:

$$R_L = P \cdot L_{PPA} \tag{14}$$

where, P is the profit generated per unit of product sold; and L_{PPA} is the lost of average sales of product per unit time, during planned maintenance.

3.2.2.5 Overhaul cost. Overhaul is the process of restoring the entire system back to a condition that is close to "as good as new". It involves partial or complete disassembly of product, inspection of parts, repair and/or replacement of worn out parts and then returning the system to its operating stage. The expected cost of overhaul, $E[C_{OH}]$ for an investigation period is estimated as:

$$E[C_{OH}] = \sum_{i=1}^{n} \left\{ \left(MTTOH_i \cdot (R_L + L_C) + C_{fixOH} \right) \cdot E[N_{OH_i}] \right\} \tag{15}$$

where, $MTTOH_i$ is the mean time required to perform component/subassembly overhauls in the system; C_{fixOH} is the fixed cost to perform overhaul action, which includes the cost of material required like lubricating oil, etc.; L_C is the labour cost; and $E[N_{OH_i}]$ is the expected number of scheduled overhauls for each component/subassembly of the system, and can be given as:

$$E[N_{OH_i}] = \frac{T}{t_{OHi}} \tag{16}$$

where, t_{OH} is the overhaul interval for ith subassembly of the system; T is the planned operating period; and R_L is the revenue lost per unit of time due to failure/breakdown and is given as:

$$R_L = P \cdot L_{PPA} \tag{17}$$

where, P is the profit generated per unit of product sold; and L_{PPA} is the lost of average sales of product per unit time, during PM.

3.2.2.6 Logistics cost. Objective of logistics, in context of support is to ensure the availability of needed spares that includes movement of inventory, spares, from origin to destination, so as to satisfy customer's support requirements. In the present study, the logistics cost is taken as the summation of inventory holding and transportation cost associated with the spares. For its estimation, it is required to estimate the spares requirements, which are based upon the number of failures and preventive replacements or repairs.

Note: maintaining the spare parts inventory has certain hidden costs associated with it. The procurement of these parts involve direct cost, however, their regular upkeep requires the continuous involvement of personnel and other associated factors like electricity, telephone, internet, etc. Hence while estimating the logistic cost these factor must be taken into account.

The holding cost of spares is given by:

$$E[C_h] = \sum_{i=1}^{n} \{(D_i \cdot (C_{C_i} + S_C + S_{SC} + O_C)\} \tag{18}$$

where, C_{C_i} is the cost of ith subassembly within the system; S_c the storage cost per unit; S_{SC} the supervisory staff cost per unit; and O_c the overhead cost per unit, which includes the electricity bill, etc. The other cost component in the logistic cost is the transportation cost, which may calculated as:

$$E[C_t] = \sum_{i=1}^{n} (D_i \cdot \alpha_i \cdot d_{ij}) \tag{19}$$

where, D_i is the demand per annum, of ith subassembly; α_i is the cost per unit distance per unit demand; and d_{ij} is the distance from demand location i to candidate site j.

Thus, the expected logistics cost $E[C_L]$ for a particular component/subassembly may be calculated as below:

$$E[C_L] = \sum_{i=1}^{n} \{D_i \cdot (C_{C_i} + S_C + S_{SC} + O_C + (\alpha_i \cdot d_{ij}))\} \tag{20}$$

Based on the above, the support cost is the summation of all the activities required for providing the support to the system. Thus, the expected cost of support is given as:

$$E[S_T] = \sum_{k=1}^{m} E[C_{op}] + E[C_{IA}] + E[C_{CA}] + E[C_{PA}] + E[C_{OH}] + E[C_L]\} \tag{21}$$

3.3 Contract cost

Hansen and Mowen (2006) studied that traditional costing has focused on companies manufacturing products and ignored the costing of the services, that is the OEM offer to support their customer's through contract. The cost estimation of support has not been worked out in the literature, which depends upon the support activities being executed by the support provider. As presented earlier, the support activities may vary according to customer, product, usage and time. Thus, the contract cost depends upon support activities and the profit expected by the support provider. The expected contract cost is estimated as:

$$E[C_T] = E[S_T] \times (1 + X) \tag{22}$$

where, $E[C_T]$ is the expected contract cost paid by the customer to the support provider; $E[S_T]$ is the expected cost of support during any investigation period for a system; and X is the percentage of profit wanted to generate from the support services.

3.4 Penalty cost

A penalty on the support provider is imposed as per the contact and its terms and condition. It means if the support provider fails to meet the terms and conditions of the support contract, the penalty will be charged. The penalty cost is the amount of compensation payable by the support provider in the event of failures of meeting the required performance level. If A_R is the required availability and A is the actual availability, then the expected penalty cost is calculated as:

$$E[P_C] = [(A_R - A_A) \times R_{CA}] \quad \text{if } A_R > A_A \\ = 0 \quad \text{Otherwise} \tag{23}$$

where, R_{CA} is the $P{\cdot}L_{\text{PCA}}$ and is the revenue lost due to unavailability of the system; P the profit generated per unit of product sold; and L_{PCA} the lost of average sales of product per unit time, during the uneven breakdown or failures.

3.5 Support profit

The supportability service generates revenues (Goffin, 1999); however opportunities for profit may be lost because of not meeting the customer requirements caused by poor support. Therefore, at any stage, it is necessary to evaluate the support profit for providing the support. Support provider wants maximizing profit from the support services at the lowest cost, for which they have to design the support. The maximum profit come from improved operational, inspection-based repair, corrective, preventive, overhauls and logistics strategies. Consequently, support profit will also be improved through effective and efficient support. The profit generated from the support can be calculated as:

$$\text{Support Profit } E[S_P] = E[C_T] - E[S_T] - E[P_C] \tag{24}$$

After incorporating the different models in the above equation, we can also get:

$$\text{Support Profit } E[S_P] = X \cdot E[S_T] - [(A_R - A_A) \times R_{CA}] \quad \text{if } A_R > A_A \tag{25}$$

where, $E[C_T]$ is the expected contract cost paid by the customer; $E[S_T]$ is the expected cost of support during any investigation period for a system; $E[P_C]$ is the expected penalty cost during any investigation period for a system; A_R is the required operational availability; A_A is the actual availability; $R_{CA} = P{\cdot}L_{PCA}$ and is the revenue lost due to unavailability of the system.Where, P is profit generated per unit of product sold; and L_{PCA} is the lost of average sales of product per unit time, during the uneven breakdown or failures.

Each support activity do contribute some cost in LCC, this cost will further be increased if the support activity will be outsourced, consequently affecting the LCC. Thus, there seems to be a scope of having a tradeoff between the contract structure and system's LCC. The contract can be chosen on the basis of LCC to the customer and at least minimum profit to the support provider. Thus, a mechanism is required that formulates the number of contract alternatives, and is given in subsequent section.

4. Contract alternatives

OEM starts providing assistance to their product, both in terms of tangible and intangible, which will help them to withstand in today's competitive environment. Support depends upon the type of activities (operations, inspection-based repair, corrective maintenance, PM, overhauls, spares, resources, etc.) that are required for continuous operation of the systems. Effective support is cost intensive, as it requires man, material and machine which will be available in optimum quantity with minimum delay, so there should be a tradeoff in between the activities and costs through the planned support activity.

The mechanical systems are supported by the OEM and the customer, through a formal contract. But, in most contracts, the customer does not object to the involvement of a third-party support provider as long as the contract is executed by the OEM along with the responsibility of meeting the end user's expectations. From the view point of OEMs, it makes sense to execute the contract exclusively by them, only if the end user is located closer and the work load involved can be handled effectively. On the other hand, the customers want to involve in the contract, as they need some in-house control which reduces the OEMs dependency, cost, etc. Depending upon the involvement of OEM, customer and third party, the various contract alternatives may be formulated. For example in one situation the OEM takes the full responsibility as customer and third party does not want to participate in providing the support, then it leads to one contract; whereas, the other case all players may agree for providing the support, then leading to different contract structure. The penalty clause is associated with the contract, and makes the support provider cautious. Distribution of penalty will also kept in mind during the synthesis of contract structure, as it will helpful in timely execution of support activity, thus, the penalty dimension may also be added during contract formulation. The support activities and players, as stated earlier, are listed in Table I, based on which the different contracts alternatives may formulate.

The following assumptions are made while formulating the contract alternatives:

(1) operational availability is the main criterion for imposing penalty and evaluating the penalty based on the gap, i.e. achieved and required level of availability;

(2) the player who is responsible for corrective maintenance will be liable to pay the penalty, as delays, in general, are associated with the unplanned maintenance;

(3) the system fails randomly, which leads to its breakdown; and

(4) support resources, e.g. spare parts, etc. are available, whenever and wherever required.

Based on the above assumption, there are 728 contracts alternatives, as given in Table II.

A description of one of the contract structure, i.e. CS.4 selected from Table II is described with the help of Figure 1. CS.4 is a particular case of contract, in which the OEM takes the responsibility for ensuring the logistics, whereas third party executed inspection-based repair, corrective maintenance, PM and overhauls and system may operate by the customer. Thus, the customer has to pay cost for getting all the maintenance support except operating cost, whereas the penalty will bear by the third, if any.

Table I. Dimensions for contract

Support activity	Support player
Operations (Op)	OEM
Inspection based repair (I)	
Preventive maintenance (PM)	Third party (TP)
Corrective maintenance (CM)	
Overhaul (OH)	Customer (C)
Logistics (L)	
Penalty (P)	

Operations (Op)	Inspection-based repair (I)	Corrective maintenance (CM)	Preventive maintenance (PM)	Overhauls (OH)	Logistic (L)	Penalty (P)	Contract structure (CS)
C	C	C	C	C	OEM	C	Cs. 1
C	C	C	C	C	TP	C	Cs. 2
C	C	C	C	OEM	C	C	Cs. 3
C	TP	TP	TP	TP	OEM	TP	Cs. 4
OEM	C	TP	C	C	OEM	TP	Cs. 5
OEM	C	TP	C	C	TP	TP	Cs. 6
OEM	C	TP	C	OEM	C	TP	Cs. 7
OEM	C	TP	C	OEM	OEM	TP	Cs. 8
TP	OEM	TP	C	TP	C	TP	Cs. 9
TP	OEM	TP	C	TP	OEM	TP	Cs. 10
TP	OEM	TP	C	TP	TP	TP	Cs. 11
OEM	OEM	OEM	C	C	C	OEM	CS. 12
OEM	TP	OEM	C	C	C	OEM	CS. 13
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
TP	TP	TP	TP	TP	TP	TP	CS.728

Table II. Contract alternatives

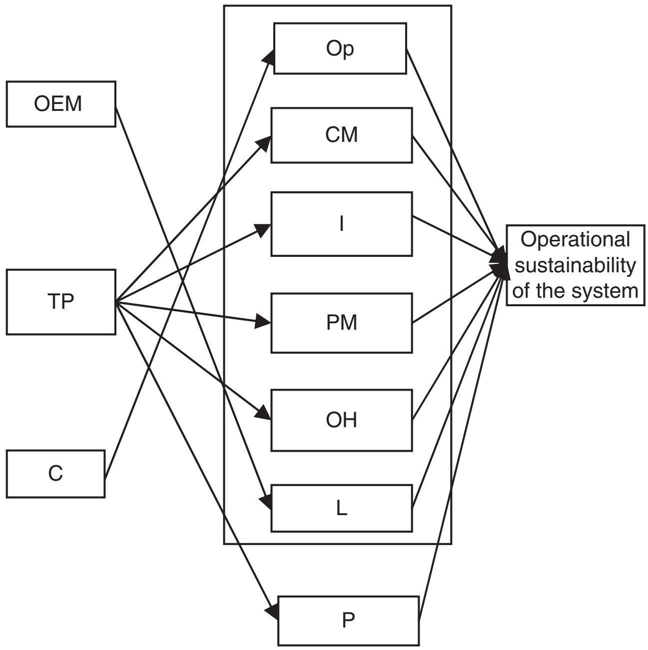

Figure 1. Contract alternative (CS.4)

The contract alternatives depend upon the type of support activity and players involved, throughout the operational life of a system. The cost depends upon the work executed by other player, which can be reduces by outsourcing the less number of activities by the contractor and/or OEM. An optimum contract alternative is required to acceptable for all the players, as support activity is linked with the cost paid by the customer as well profit gained by the OEM and third party. So there is a need to strike off between the support activity, responsibility, profit and penalty among the players.

The LCC is a function of contract and if there is change in contract structures then it will leads to change in LCC. Therefore, the system LCC can be minimized to certain extent by selecting the appropriate contract structure. The steps to identify the best contract that will lead to minimum possible LCC is described below.

Step 1: Identify the system, support requirement, including the support period and penalty

Consider the system for which support is required. Its support may either be provided by a single and/or combination of players (OEMs, third party and customer). Identify also the requirement, including the support period and penalty.

Step 2: Identify the support players

Identify the player(s) that can support to the system, which may either be a single and/or combination of players (OEMs, third party and customer). Refer Table I for the details.

Step 3: Formulate various contract alternatives

The contract structure is a function of supportability scenario, support activity, support period and penalty, which are helpful in formulating the contract alternatives. Refer Table II for details.

Step 4: Select a contract alternative among the possible alternatives

Consider the system for which support is required. Its support may either be provided by a single and/or combination of players (OEMs, third party and customer). Identify the player(s) that can support to the system.

Step 5: Estimate the LCC for a particular contract throughout the operating life

Each action of the O&M support does involve some cost, and hence, LCC of the system. The LCC is estimated using the Equation (6) of Section 3.

Step 6: Select the next contract alternative and repeat the steps, i.e. Go To Step 4

Check the cost contribution of each contract structure, i.e. its LCC, thus, Go To Step 4, to select the other contract structure, and estimate its LCC.

Step 7: Select the best alternative on the basis of LCC

Each contract structure has its own LCC and on the basis of which the best contract is selected. Estimate the ICC, the best alternative is one with the minimum system LCC.

The stepwise methodology can be used for the selecting the optimal contract structure that promises at least minimum profit to the support provider, while ensures the minimum LCC to the customer. However, the maintenance may affect both the cost and performance of the system. Therefore, the further reduction in the LCC can be possible, if the optimization of maintenance actions will be carried out. After expressing all the variable costs in terms of system support, the problem can now be formulated as:

Minimize LCC

Subject to: availability $\geqslant A_R$

Support profit $\geqslant 0$

The optimized PM schedule will not only improve the performance but also reduce the cost and penalty. Thus, a further scope can be seen in optimization of PM schedule in context to contract cost, availability, penalty and thereby the profit. In order to get insight of the concept presented above, the real life problem is taken into consideration to illustrate the proposed methodology.

5. A case study

A case study is presented on the basis of an ongoing research work being carried out in collaboration with Burckhardt compression, which is one of the leading manufacturers of gas compressors in the world. The compressors are expected to run 24 hrs a day and the downtime costs are very high, the customer expects a very high level of availability of the order of 98 per cent. As for any other mechanical system, such high level of sustainability can be achieved only through extensive supportability. As a part of the purchase deal, the customer wanted Burckhardt to take the responsibility of support through contract while ensuring a minimum service level. In case this service level is not met, a heavy penalty gets charged to Burckhardt, which is proportional to the downtime. As can be seen, the performance requirement for the contract is very stringent; that is why the Burckhardt wanted to transmit some of his liability to a third party support provider.

Due to the experience gained over last ten years, Burckhardt is inclined not only in continuing support but even to extend them for the whole systems' operating life. As stated earlier, the minimum LCC becomes one of the criteria for system purchase. Looking at the present situation, it is required to have a mechanism to generate and evaluate various contract alternatives with an objective of minimizing the LCC subject while ensuring the minimum profit to the support provider. The methodology presented in Section 4 is helpful to the Burckhardt in selecting the contract structure that ensures the supportability objectives at the minimum possible cost. The Burckhardt multi-stage reciprocating compressor consists of 18 subassemblies, connected in series, subjected to random failures over its useful life. The failure of any subassembly will lead to the breakdown of entire system, thereby affecting the customer's operational objectives.

It has been assumed that the reciprocating compressor operates continuously and fails randomly at any instant of time. It has also been assumed that corrective, inspection, preventive and overhauls activity is initiated as soon as failure occurred and at their scheduled interval. The operations of compressor accumulate in between the failures which may be measured in term of operational availability. The operating life of the compressor is taken as 12 year which is equal to 72,000 operating hours (as the system is on an average running 500 hrs per month), for which the different support activity has been executed in order to maintain their sustainability. The inspection-based repair is scheduled at every 1,000 hrs, whereas PM and overhauls are carried out at an interval of 2,500 and 15,000 hrs, respectively. The type of inspection and corrective actions are minimal, whereas the preventive and overhauls are of perfect type. Whenever, the PM is scheduled, then there will no inspection-based repair, however at every 15,000 hrs, only overhaul is executed and hence no PM and inspection-based repair will carried out. So, the expected number of inspection-based repair, PM and overhauls are 57, 24 and four, respectively.

The data are collected from the Burckhardt compression for a multi-stage reciprocating compressor, which includes cost, preventive schedule interval, corrective, preventive, replacement time and design characteristic (reliability parameter) for each subassemblies, and is given in Tables III and IV. However the costs of subassemblies are not included.

Now, it is required to estimate the number of failures (corrective maintenances) in each year, considering age at the start of that year and restoration achieved due to each inspection-based repair, preventive repair and overhauls, if any, in that years. The age at the start of the each year depends on the age at the end of the previous year and the degree of restoration achieved by different maintenance actions. Every time a preventive repair or overhaul is performed the age is change thereby affecting the number of failure. Lad and Kulkarni (2012) developed the model to calculate the number of failures in any year, as:

$$N(t|V) = -(V_n/\eta)^{\beta} + \left(\frac{t+V_n}{\eta}\right)^{\beta} \tag{26}$$

Characteristics	Data
Fixed cost of corrective and preventive maintenance per module, C_{fix}	Rs 2,500
Cost of Inspection based repair associated per module, C_{MI}	Rs 200
Fixed cost required to perform the overhaul action per module, C_{fixOH}	Rs 11,000
Labour cost for maintenance (Rs/hr); L_c	Rs 1,000
Supervisory cost per demand of a compressor module, S_{SC}	Rs 150
Storage cost per demand of a compressor module, S_c	Rs 100
Overhead cost per demand of a compressor module, O_c	Rs 50
Distance travel (average) from origin to destination, d_{ij}	10 Km
Cost per Km, α	Rs 1,500
Mean time to overhaul, MTTOH	36 hrs
Production rate when the corrective action has been executed, L_{PCA}	480 kg/hr
Production rate when the preventive action has been executed, L_{PPA}	160 kg/hr
Percentage of profit, shares from sale, P	Rs 9
Salary of one worker, S	Rs 12,000
Operating life, T	72,000 hrs
No of operator required, O	1 per 8 hrs
Acquisition cost, C_{aq}	Rs 15 million
Inflation and or discount rate, d	0.1

Table III.
Cost data

where, η is the characteristic parameter of a component/subassembly/system; β is scale parameter; and V is the virtual age, which may be calculated after incorporating the maintenance action.

The concept of virtual age was first introduced by Kijima (1989). Under this concept, a unit accumulates age during each period of operation. After each failure or preventive action, repair (corrective or preventive) "removes" some of this accumulated age. Consider a unit of equipment that at any point in time, is in one of two states, functioning or repair (corrective or preventive); and assume that the unit is initially (at time $t=0$) functioning. Let X_n denote the duration of the period between the ($n-1$)th repair completion, and the nth repair; and let V_n denote the virtual age of the unit at the time of the nth repair completion. Kijima's model of virtual age is:

$$V_n = V_{n-1} + (1-a)X_n \tag{27}$$

where a is some constant such that $0 \leqslant a \leqslant 1$, and $V_0 = 0$. Thus, $1-a$ captures the degree of equipment restoration achieved through repair action. It is assumed that preventive action is performed after a fixed time interval t_{PM}. While using system improvement model shown in (27), different degrees of restoration can be used for corrective and preventive repair. Thus, the length of an interval for which the equipment functions depends on the virtual age of the equipment at the beginning of the interval. Note that perfect repair ($a=0$), and minimal repair ($a=1$) are both special cases of this virtual age model. These models are utilized in order to calculate the expected number of failure when different maintenance action are incorporated during the operating life of the system. The models are implemented on module level, therefore the required corrective action under the scheduled maintenance actions are calculated.

A simulation model is developed in MATLAB 7.12.0 (R2010a), to calculating the number of failure after incorporating all the maintenance action for each suassembly of multi-stage reciprocating compressor. The MATLAB code is based

Table IV. Design and maintenance characterstics

Sl. no.	Subassembly name	No. off.	η	β	MTTI (in hrs)	MTTR (in hrs)	MTTCM (in hrs)	Insp. interval hrs (t_i)	Preventive interval hrs (t_{pm})	Overhaul Interval hrs (t_{OH})
1.	Subassembly no. 1	3	12,000	1.9	1	2	10.4	1,000	2,500	15,000
2.	Subassembly no. 2	2	24,000	2.3	1	3	11.4	1,000	2,500	15,000
3.	Subassembly no. 3	1	6,000	1.5	1	1	9.4	1,000	2,500	15,000
4.	Subassembly no. 4	1	30,000	2.4	1	4	12.4	1,000	2,500	15,000
5.	Subassembly no. 5	1	18,000	1.9	0.5	1	9.4	1,000	2,500	15,000
6.	Subassembly no. 6	1	18,000	1.6	1	1	9.4	1,000	2,500	15,000
7.	Subassembly no. 7	3	18,000	1.7	1	2	10.4	1,000	2,500	15,000
8.	Subassembly no. 8	2	18,000	1.2	0.5	0.5	8.9	1,000	2,500	15,000
9.	Subassembly no. 9	2	12,000	2.1	0.5	1	9.4	1,000	2,500	15,000
10.	Subassembly no. 10	2	12,000	2.1	1	1	9.4	1,000	2,500	15,000
11.	Subassembly no. 11	1	30,000	1.9	0.25	0.5	8.9	1,000	2,500	15,000
12.	Subassembly no. 12	1	30,000	2	0.25	0.5	8.9	1,000	2,500	15000
13.	Subassembly no. 13	2	18,000	1.8	0.5	2	10.4	1,000	2,500	15,000
14.	Subassembly no. 14	2	12,000	1.6	0.5	2	10.4	1,000	2,500	15,000
15.	Subassembly no. 15	1	50,000	1.5	0.5	4	12.4	1,000	2,500	15,000
16.	Subassembly no. 16	3	25,000	2.3	0.25	3	11.4	1,000	2,500	15,000
17.	Subassembly no. 17	3	25,000	2.5	0.25	2.5	10.9	1,000	2,500	15,000
18.	Subassembly no. 18	3	35,000	2.3	1	2	10.4	1,000	2,500	15,000

upon the Equations (26) and (27), by gives the expected number of failure for each subassembly of a multi-stage reciprocating compressor in each year.

So, far we obtained the expected number of failure, inspection, preventive and overhaul actions. All of these data are then incorporate in the cost models in contract alternatives, so as to find out the contract structure that will give to minimum LCC with assured support profit. The 728 contract are formulated, among them, 395 are those that give assured profit to the support provider. The two best contracts gives minimum LCC while ensuring the minimum support profit to the contractor(s) are listed in Table V. The obtained structure are corresponds to CS.12 and CS.13, respectively, that gives the minimum LCC while ensuring the support objectives of all players.

The contract strucutre for minimum LCC is obtained, which also ensured profit to the support provider. But, as availability is a function of maintenance which further depends upon the its type and frequency. The PM affect both the avaibility and cost, therefore it beniftis are seems to optimzie the PM schedule. Thus, the problem is to determine the optimal values of t_{PM} that minimize the LCC of the above contracts subject to availability of the system.

However, to obtain the optimal PM interval for machine, the number of failures need to be estimated every time the PM interval changes. Thus, it becomes very time consuming. In order to reduce the simulation effort, a regression-based approach is used. The best fit has been obtained in accordance with R^2-value, which indicates how good is the fit, and accordingly the model has been fitted for different subassemblies. The devloped regression models give the value of expected number of failure with respect to PM schedule, and for a fixed number of inspection interval and overhauls. The regression analysis for each subassembly of the multi-stage reciprocating compressor is given in Table VI. The regression model is then fitted in the cost models which then putted in the LCC model, the modified LCC model is then used for optimization purposes.

Maple 13 has been used to solve the optimization problem and the obtained numerical results are interm of LCC and optimized PM schedule. Using the global optimization technique, the optimal values of PM interval that minimize the LCC subject to avaibaility constraint is 12,970 hrs and its corresponding LCC is Rs 28.04 million which is same for both contract strucutre. Table VII, compare the LCC from which it can be concluded that optimization of PM will further reduce the system LCC.

The reduced LCC is substantial, as it will not only improve the customer satisfaction but also helpful in gaining the competition. Therefore, it can be concluded that, optimzation of PM schedule in the contract alternative will be helpful in attaining the efficient support at the lowest possible cost. Hence, contract structure CS.12 and CS.13 with optimized PM schedule for the multi-stage reciprocating compressor of Burckhardt compression has been recommended for enhancing their support at the minimum possible LCC.

An important practical issues in the application of the proposed methodology is the estimation of the required model parameters. Since, the cost parameters cannot always remain constant and may vary with respect to time. So, it is important to know the effect of variation in cost on the robustness of the solution obtained from the proposed approach. To investigate this issue, a sensitivity analysis was conducted using some of the cost

Table V. Contract structure and its corresponding LCC

Contract Structure	Op	I	CM	PM	OH	LO	P	LCC in Rs million
CS.12	OEM	OEM	OEM	C	C	C	OEM	35.93
CS.13	OEM	TP	OEM	C	C	C	OEM	35.93

Sl. no.	Description	No. off.	Regression model	R^2-value
1.	Subassembly no. 1	3	$E[N_{CAi}] = 4E{-}09(t_{pmi})^2 + 0.000(t_{pmi}) + 0.030$	0.999
2.	Subassembly no. 2	2	$E[N_{CAi}] = 3E{-}06(t_{pmi})^{1.408}$	0.997
3.	Subassembly no. 3	1	$E[N_{CAi}] = 0.076(t_{pmi})^{0.601}$	0.987
4.	Subassembly no. 4	1	$E[N_{CAi}] = 9E{-}07(t_{pmi})^{1.447}$	0.998
5.	Subassembly no. 5	1	$E[N_{CAi}] = 2E{-}08(t_{pmi})^2 + 0.000(t_{pmi}) + 0.131$	0.963
6.	Subassembly no. 6	1	$E[N_{CAi}] = 0.006(t_{pmi})^{0.669}$	0.997
7.	Subassembly no. 7	3	$E[N_{CAi}] = 0.003(t_{pmi})^{0.736}$	0.993
8.	Subassembly no. 8	2	$E[N_{CAi}] = 0.433(t_{pm})^{0.237}$	0.941
9.	Subassembly no. 9	2	$E[N_{CAi}] = 2E{-}08(t_{pmi})^2 + 0.000(t_{pmi}) - 0.052$	0.999
10.	Subassembly no. 10	2	$E[N_{CAi}] = 2E{-}08(t_{pmi})^2 + 0.000(t_{pmi}) - 0.052$	0.999
11.	Subassembly no. 11	1	$E[N_{CAi}] = 5E{-}09(t_{pmi})^2 + 7E{-}05(t_{pmi}) + 0.041$	0.989
12.	Subassembly no. 12	1	$E[N_{CAi}] = 5E{-}05(t_{pmi})^{1.070}$	0.999
13.	Subassembly no. 13	2	$E[N_{CAi}] = 0.001(t_{pmi})^{0.835}$	0.995
14.	Subassembly no. 14	2	$E[N_{CAi}] = 0.013(t_{pmi})^{0.664}$	0.977
15.	Subassembly no. 15	1	$E[N_{CAi}] = 0.005(t_{pmi})^{0.536}$	0.988
16.	Subassembly no. 16	3	$E[N_{CAi}] = 4E{-}06(t_{pmi})^{1.363}$	0.999
17.	Subassembly no. 17	3	$E[N_{CAi}] = 4E{-}07(t_{pmi})^{1.573}$	0.996
18.	Subassembly no. 18	3	$E[N_{CAi}] = 2E{-}06(t_{pmi})^{1.334}$	0.998

Table VI. Regression model for each subassembly of a system

Contract structure	Estimated LCC million	Optimized LCC million	% Gained through optimization
CS.12	Rs 35.93	Rs 28.04	21.95
CS.13	Rs 35.93	Rs 28.04	21.95

Table VII. Comparsion of optimized results for both contract

parameters. In sensitivity analysis, the optimization procedure is repeated with small variation in some of the cost parameters. Fixed cost of performing (C_{fix}) the preventive and corrective maintenance, labour cost (L_C), revenue lost due to corrective maintenance (R_{CM}), transporation cost per unit distance (α) and revenue lost due to preventive maintenance (R_{PM}) are varied in the range of ±10 per cent. It can be seen from the table the optimum value obtained does not change. The model parameters C_{fix}, L_C, R_{CM}, α, and R_{PM} are assumed to be constant through the life of the reciprocating compressor, however, many times these values may change. The results obtained in Table VIII indicate the robustness of the the model against small variations in these parameters.

The research proposed in this paper aim at capturing realistic situations in support through maintenance optimization of a multi-stage reciprocating compressor and provided practical solutions to the designers. It can help the designer in simultaneously optimizing the contract, PM, availability and LCC, whereever applicable. The study is limited to the application of optimization of PM interval on a mechanical system, in general, multi-stage reciprocating compressor in particular, under contract realm that gives minimum LCC.

6. Conclusion and discussion

Contract in support context have been over-sighted, despite their impact on the system LCC and performance of a product. In this paper, the focus has been made on contract for enhancing the performance of mechanical systems but at lowest possible cost. The work highlighted the issues of the integrated contracts, availability, PM and support from the

S. no.	Parameter	Level I (−10%)	Level II (basic value)	Level III (+10%)
1.	C_{fix}	Rs 2,250	Rs 2,500	Rs 2,750
	LCC in millions	Rs 28.02	Rs 28.04	Rs 28.06
	% Change	0.08	na	0.08
2.	L_C	900	1,000	1,100
	LCC in millions	Rs 27.96	Rs 28.04	Rs 28.12
	% Change	0.291	na	0.291
3.	R_{CM}	Rs 3,888	Rs 4,320	Rs 4,752
	LCC in millions	Rs 27.97	Rs 28.04	Rs 28.11
	% Change	0.25	na	0.25
4.	α	Rs 1,350	Rs 1,500	Rs 1,650
	LCC in millions	Rs 28.02	Rs 28.04	Rs 28.06
	% Change	0.08	na	0.08
5.	R_{PM}	Rs 1,296	Rs 1,440	Rs 1,584
	LCC in millions	Rs 27.97	Rs 28.04	Rs 28.11
	% Change	0.26	na	0.26

Table VIII.
Sensitivity analysis

life cycle perspective. The solution methodology has been proposed for the formulation and selection of best contract structure based on minimum LCC with assured profit to the support provider.

The model allows optimization of contract structure and PM schedule to minimize the LCC subject to availability and support profit constraints of the customer and the support provider. The developed models have been implemented on a realistic problem, in which the OEM provides support to their makes. First the LCC has been optimized in context to contract alternative subject to profit constraint while further reduction in LCC can be achieved through maintenance optimization. The sensitivity results validated the robustness of the obtained solution.

Though the paper particularly focuses on mechanical systems, the issues highlighted here are also quite emerging in other sectors like civil infrastructure (like roads, building and dams, etc.), electronics system, service sector, defense, etc. The research results of this paper will contribute both academic and empirical value. Some of the futuristic aspect of further research has been listed below; which will be helpful for carrying out further research:

(1) The variation in work distribution can be made accordingly with respect to time; i.e. more than one contract can be executed during the product life cycle.

(2) The customer, product, and third-party service provider population may be heterogeneous.

(3) In this research minimization of LCC is considered as an objective function. As an extension other objective functions like maximization of support provider profit, etc. could be used.

Some of these extensions are currently being investigated by the authors.

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