Maintenance Outsourcing: Issues and Challenges

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Abstract All products and systems are unreliable in the sense that they degrade and fail. Corrective maintenance (CM) restores a failed item to an operational state and effective preventive maintenance (PM) reduces the likelihood of failure. These maintenance actions can be done either in-house or can be outsourced to an external agent. We focus on the maintenance being outsourced and look at the issues involved from the perspectives of the owner of the asset and the agent providing the maintenance service.

1 Introduction

Every business (mining, processing, manufacturing, and service-oriented businesses such as transport, health, utilities, communication) needs a variety of equipment to deliver its outputs. Equipment is an asset that is critical for business success in the fiercely competitive global economy. Equipment degrades with age and usage and ultimately becomes non-operational. Rapid changes in technology have resulted in equipment becoming larger, more complex, and expensive. Businesses incur heavy

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losses when their equipment is not in full operational mode—delays in delivery of goods lead to higher customer dissatisfaction and loss of goodwill.

Maintenance activities are actions to reduce the likelihood of equipment becoming non-operational and to restore non-operational units to operational state. For most businesses, it is no longer economical to carry out the maintenance in-house. There are a variety of reasons for this including the need for a specialist workforce and diagnostic tools that often require constant upgrading. In these situations, it is more economical to outsource the maintenance (in part or total) to an external agent through a service contract. Campbell [7] gives details of a survey where it was reported that 35 % of North American companies had considered outsourcing some of their maintenance.

Governments (local, state, or national) and private businesses own infrastructure (roads, rail, and communication networks, public buildings, dams, etc) that were traditionally maintained by in-house maintenance departments. Here also, there is a growing trend toward outsourcing these maintenance activities to external agents so that the owners can focus on their core activities.

In maintenance outsourcing the maintenance of an asset (equipment or infrastructure) owned by the first party (the owner or customer) is carried out by the second party (the service agent who is also referred to as the "contractor" in many technical papers) under a service contract. In this chapter, we look at maintenance outsourcing from both the owner and service agent perspectives and discuss the issues involved, review the literature, and discuss some of the challenges for future research.

The outline of the chapter is as follows. We start with a brief discussion of maintenance and of outsourcing in Sects. 2 and 3, respectively. Section 4 reviews the current status of maintenance outsourcing and gives a brief literature review. In Sect. 5 we propose a framework to study maintenance outsourcing and discuss several relevant issues. Section 6 deals with the game theoretic approach to maintenance outsourcing and Sect. 7 looks at Agency Theory and its relevance to maintenance outsourcing. We deal with the criteria for the selection of service agents to carry out maintenance in Sects. 8 and 9 deals with some topics for future research. We conclude with some comments in Sect. 10.

2 Maintenance

Maintenance actions can be broadly divided into two categories.

Corrective Maintenance (CM): These are maintenance actions performed when the asset has a failure (in the case of equipment) or has degraded sufficiently (in the case of infrastructure). The most common form of CM is "minimal repair" where the state of the asset after repair is nearly the same as that just before failure. The other extreme is "as good as new" repair and this is seldom possible unless one replaces the failed asset with a new one. Any repair action that restores the asset state to better than that before failure and not as good as that of a new asset is referred to as "imperfect repair".

Preventive Maintenance (PM): These are actions carried out to fix minor problems in case of infrastructure (e.g., small potholes in a section of a road) or components that have degraded in the case of equipment due to age and/or usage. The policy used for initiating such actions can be age, usage, and/or condition. As a result, there are several different kinds of PM policies and in the context of equipment some of the well-known ones are the following:

- Age-based maintenance
- Clock-based maintenance
- Opportunistic maintenance
- Condition-based maintenance

The more investment made in PM actions the more likely CM costs are reduced. But, for any asset there is an optimal level of PM effort that will achieve a proper balance between these costs. Most books on maintenance [4, 26, 28] include models to obtain the optimal PM effort.

Maintenance of an asset involves carrying out several activities as indicated in Fig. 1 (adapted from Dunn [9]).

The three key issues are:

- (D-1): **What** (components) need to be maintained?
- (D-2): **When** should the maintenance be carried out?
- (D-3): **How** should the maintenance be carried out?

3 Outsourcing

Businesses (producing products and/or services) need to come up with new solutions and strategies to develop and increase their competitive advantage. Outsourcing is one of these strategies that can lead to greater competitiveness [11]. It can be defined as a managed process of transferring activities performed in-house to some external agent. The conceptual basis for outsourcing (see, Campbell [7]) is as follows:

1. Domestic (in-house) resources should be used mainly for the core competencies of the company.

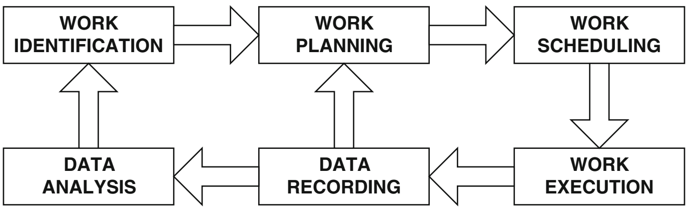

Fig. 1 Activities in asset maintenance

2. All other (support) activities that are not considered strategic necessities and/or whenever the company does not possess the adequate competences and skills should be outsourced (provided there is an external agent who can carry out these activities in a more efficient manner).

However, there are some disadvantages of outsourcing the maintenance and these are indicated below.

- Dependency on the external party carrying out the activities.
- Cost of outsourcing.
- Loss of maintenance knowledge (and personnel).
- Becoming locked into a single external party when the cost of switching is high.

4 Maintenance Outsourcing: Current Status and Literature Review

Outsourcing of maintenance involves some or all of the maintenance actions (PM and/or CM) being carried out by an external service agent under a service contract. The contract specifies the terms of maintenance and the cost issues. It can be simple or complex and can involve penalty and incentive terms. We look at the issues in outsourcing from both the owner and service agent perspectives.

4.1 Owner Perspective

4.1.1 Outsourcing Equipment Maintenance

The advantages of outsourcing maintenance are as follows:

- Better maintenance due to the expertise of the service agent.
- Access to high-level specialists on an "as and when needed" basis.
- Fixed cost service contract removes the risk of high costs.
- Service providers respond to changing customer needs.
- Access to latest maintenance technology.
- Less capital investment for the customer.
- Managers can devote more resources to other facets of the business by reducing the time and effort involved in maintenance management.

For very specialized (and custom built) products, the knowledge to carry out the maintenance and the spares needed for replacement must be obtained from the original equipment manufacturer (OEM). In this case, the customer is forced into having a maintenance service contract with the OEM and this may result in a non-competitive market. In the USA, Section II of the Sherman Act [16] deals with this problem by making it illegal for OEMs to act in this manner.

When the maintenance service is provided by an agent other than the OEM often the cost of switching prevents customers from changing their service agent. In other words, customers get "locked in" and are unable to do anything about it without a major financial consequence.

4.1.2 Outsourcing of Infrastructure Maintenance

As mentioned above, it used to be the case that infrastructures were owned and operated by governments. Recently, there has been a growing trend toward selling these assets to private businesses that either lease them back to the government or to the operator of the asset. The maintenance of the asset is often outsourced as it is again viewed as not being the core activity of the business that owns the asset. A complicating factor is the additional parties involved and these are shown in Fig. 2.

For example, in the case of a rail network, the operators are the different rail companies that use the track and the maintenance is outsourced to specialist contractors. The government plays a critical role in terms of providing loans to and/or acting as a guarantor for the owner and the regulators are independent authorities responsible for ensuring public safety. The role of maintenance now becomes important in the context of safety and risk. For further discussion, see Vickerman [38].

4.1.3 Decision Problems

There are three different outsourcing scenarios that depend on which of the three activities in maintenance (D-1, D-2, and D-3) are being outsourced. These are indicated in Table 1.

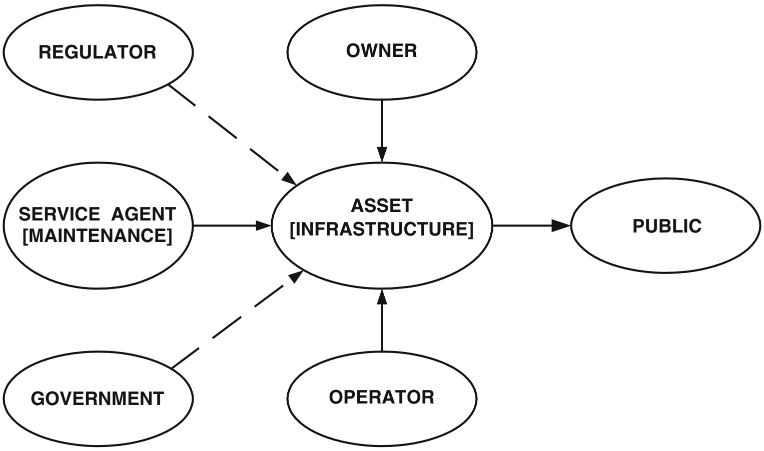

Fig. 2 Different parties involved in the maintenance of infrastructure

Table 1 Different contract scenarios

Scenarios	Decisions	
	Customer	Service agent
S-1	D-1, D-2, D-3	-
S-2	D-1	D-2, D-3
S-3	-	D-1, D-2, D-3

In scenario S-1, the service agent is only providing the resources (workforce and material) to execute the work. This corresponds to the minimalist approach to outsourcing. In scenario S-2, the service agent decides on **how** and **when** and **what** is to be done is decided by the customer. Finally, in scenario S-3 the service agent makes all three decisions.

For the owners of both equipment and infrastructure the decision problems are (i) whether to outsource or not, (ii) what maintenance activities to outsource, and (iii) how to implement and manage the process.

4.2 Service Agent Perspective

The service agent who provides the maintenance needs to operate as a service business. This implies that issues such as return on investment (ROI), number of customers to service (market share), location of operations, and range of service contracts to offer are some of the variables that are important in the context of strategic management of the business. The type of contract depends on the needs of the customers and this can be either standard or customized. At the operational level, the service agent needs to deal with issues such as scheduling of maintenance tasks, spare part inventory control, etc.

The pricing of the different service contracts offered is critical for business profitability. If the price is too low, the service agent might end up making a loss instead of a profit. On the other hand, if it is too high there might be no customers for the service. The price of a contract must cover the maintenance costs and estimating the cost is a challenge due to information uncertainties.

4.3 Literature Review

The literature on maintenance outsourcing deals mainly with the owner perspective and is focussed on management issues. More specifically, attempts are made to address one or more of the following questions in a qualitative manner.

- Does outsourcing make sense?
- Are the objectives achievable?
- Is the organization ready?

- What are the outsourcing alternatives?
- What maintenance activities should be outsourced?
- How should the best service agent be selected?
- What are the negotiating tactics for contract formation?

Some of the relevant papers are Campbell [7], Judenberg [15], Martin[23], Levery [20] and Sunny [32]. Stremersch et al. [31] look at the industrial maintenance market.

Unfortunately, cost has been the sole basis used by businesses for making maintenance outsourcing decisions. Sunny [32] looks at what activities are to be outsourced by looking at the long strategic dimension (core competencies) as well as the short-term cost issues.

Bertolini et al. [5] took a quantitative approach and used the analytic hierarchy process (AHP) to make decisions regarding the outsourcing of maintenance. On the application side, Armstrong and Cook [2] look at clustering of highway sections for awarding maintenance contracts to minimize the cost and use a fixed-charge goal programming model to determine the optimal strategy. Bevilacqua and Braglia [6] illustrate their AHP model in the context of an Italian brick manufacturing business having to make decisions regarding maintenance outsourcing.

Tarakci et al. [33] investigated the coordination issues between an equipment owner and a service agent in a long-term maintenance outsourcing contract scenario. The equipment has an increasing failure rate and the agent performs both CM and PM. Incentive contracts that induce the agent to choose the maintenance policy that optimizes the expected total profit for both parties are studied. It is shown that a contract based on a combination of a target uptime level and a bonus produces the desired win–win situation. Tarakci et al. [34] extend the analysis to the situation where the owner has multiple pieces of equipment and uses multiple service agents to perform the maintenance.

Tarakci et al. [35] study the effects of learning when the contract between an owner and an agent consists of a fixed fee plus a cost subsidy for each maintenance action (CM and PM) performed. Learning occurs on the part of the agent which leads to cost and time reductions for PM actions. They demonstrate that a well-designed payment scheme can induce the agent to use a maintenance strategy which maximizes the owner's expected total profit.

Tseng et al. [36] look at a maintenance outsourcing problem where, in the contract terms, one or more time points are specified at which the owner can replace the equipment with new technology if it becomes available. If a replacement occurs then the agent has the flexibility to change the maintenance schedule for the remaining part of the contract period. The value of these switch points is analyzed for different types of contract payment methods.

In Almeida [1], the owner has more than one objective to optimize and is faced with choosing a contract from a set of alternatives. Each contract alternative specifies different values for response time, service quality, dependability, and cost. The best alternative is selected using the ELECTRE I method for multi-criteria decision making combined with utility functions. Lisnianski et al. [21] consider aging equipment with an increasing failure rate. With a piecewise constant approximation for the failure rate, a Markov process is used to model the operating times and repair times. The service agent offers a number of options involving different repair rates and costs to the owner and the optimal choice is made by comparing expected costs over a specified contract period.

A few game-theoretic models have also been proposed and these are discussed in a later section.

5 Framework for Maintenance Outsourcing Study

A proper framework to study maintenance outsourcing needs to include both owner and service agent perspectives and involves several interlinked elements. This is indicated in Fig. 3 for the case of single owner and service agent. Section 4 looked at two of the elements— namely, the owner (customer for the maintenance service) and the service agent (provider of maintenance service).

The number of owners and service agents can be one, few, or many and these lead to different markets for maintenance outsourcing (see Sect. 5.3). In Sects. 5.1 and 5.2 we look at the remaining elements and related issues. Also, the owner population can be homogeneous or heterogeneous in relation to factors such as usage profiles, attitude to risk, etc. Similarly, the service agents can be either homogeneous or heterogeneous in relation to factors such as size, competency, quality of service, reputation, risk profile, etc.

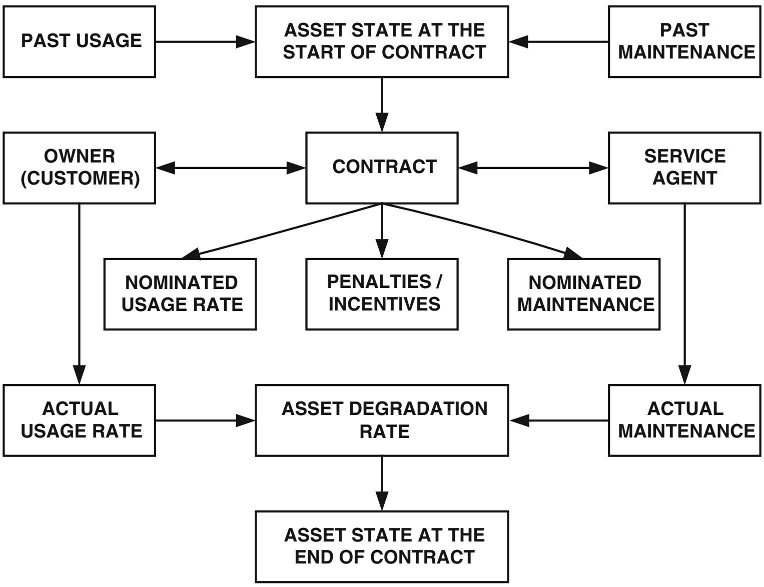

Fig. 3 Framework for study of maintenance outsourcing

5.1 Asset and Asset State

In the case of a new asset, the initial state is determined by the decisions made during its design and construction (or manufacture). The asset reliability characterizes the probability of no failure and decreases with age. The field reliability also depends on the operating stress (load) on the asset and the operating environment. The stress can be thermal, mechanical, electrical, etc., and the reliability decreases as the stress increases and/or the environment gets harsher.

The asset state at any given time (subsequent to it being put into operation) is a function of its inherent reliability and past history of usage and maintenance. This information is important in the context of maintenance service contracts for used assets. The information that the service agent (and the customer) has can vary from very little to a lot (if detailed records of past usage and maintenance have been kept).

Finally, for some assets, the delivery of maintenance requires the service agent to visit the site where the asset is located (for example, lifts in buildings and roads) and for others (mainly industrial equipment) the failed asset can be brought to a service center to carry out the maintenance actions.

5.2 Contract

The contract is a legal document that is binding on both parties (customer and service agent) and it needs to deal with technical, economic, and other issues.

5.2.1 Technical Issues

There is a growing trend toward functional guarantee contracts. Here, the contract specifies a level for the output generated from equipment, for example, the amount of electricity produced by a power plant, or the total length of flights and number of landings and takeoffs per year for aircraft. The service agent has the freedom to decide on the maintenance needed (subject to operational constraints) with incentives and/or penalties whether the target levels are exceeded or not. For more on this, see Kumar and Kumar [18].

In the context of infrastructures, there is a trend toward giving the service agent the responsibility for ongoing upgrades or the responsibility for the initial design resulting in a Build, Own, Operate, and Maintain (BOOM) contract.

5.2.2 Economic Issues

There are a number of alternative contract payment structures. The following list is from Dunn [9]:

- Fixed or Firm price
- Variable Price
- Price ceiling incentive
- Cost plus incentive fee
- Cost plus award fee
- Cost plus fixed fee
- Cost plus Margin

Each of these price structures represents different levels of risk sharing between the customer and the service agent. According to Vickerman [38], an increasing issue in privatized infrastructure is the appropriate incentives needed to ensure adequate maintenance of the infrastructure as a public resource.

5.2.3 Other Issues

Some other issues are as follows:

Requirements: Both parties might need to meet some stated requirement. For example, the customer needs to ensure that the usage intensity and operating loads of the asset do not exceed the levels specified in the contract. These can lead to greater degradation (due to higher stresses on the components) and higher servicing costs to the service agent. Similarly, the service agent needs to ensure proper data recording.

Contract Duration: This is usually fixed with options for renewal at the end of the contract.

Cheating: In maintenance outsourcing cheating by both owner and service agent are issues that need to be addressed. Cheating by the owner occurs when the nominated usage is higher than the actual usage and the service agent is not able to observe this. Similarly, cheating by the service agent occurs when the actual maintenance is below the nominated maintenance and the owner cannot observe this. Information, monitoring, and penalties/incentives can reduce and eliminate the potential for cheating.

Dispute Resolution: This specifies the avenues to follow when there is a dispute. The dispute can involve going to a third party (legal courts).

Unless the contract is written properly and relevant data (relating to equipment and collected by the service agent) are analyzed properly by the customer the long-term costs and risks will escalate.

5.3 Maintenance Outsourcing Market

Whether the maintenance outsourcing market is competitive or not depends on the number of customers and service agents. Table 2 indicates the different market scenarios. These have an impact on issues such as the types of service contracts available to customers and the pricing of the contracts.

Table 2 Maintenance outsourcing market scenarios

Number of customers	Number of service agents	
	One	Few
One	A-1	B-1
Few	A-2	B-2
Many	A-3	B-3

6 Game Theoretic Approach

Game theory is a set of ideas and principles that provide an effective guide to strategic business decision making. Any game must have at least two players (individuals or businesses) with the payoffs to the players being interdependent. The optimal decision by a particular player depends on what that player expects the other players involved to do. An important assumption of game theory is that players will always act rationally (choose their best action).

In a static game, the players have a single 'move' and do not know the actions taken by their rivals. This may be because the players move simultaneously. The players in a dynamic (sequential move) game make their decisions in a well-defined order and the game proceeds in a sequence of stages. In any type of game, an action is the decision that a player makes at a particular move. A strategy specifies what actions a player takes at each move in the game and so is a complete and exact plan, detailing what the player will do in any contingency that may arise.

In games with complete information, the payoffs are common knowledge among all the players. In games of incomplete information, some players do not know the payoffs of some of the other players. In a dynamic game with perfect information, all the players know the entire history of the game when it is their turn to move. Imperfect information implies that some players have only a partial idea of the history of the game. Games may be either cooperative or non-cooperative. In cooperative games players can communicate and, most importantly, make binding agreements. In non-cooperative games players may communicate, but binding agreements are not possible.

The most well-known and widely used solution concept in game theory is Nash equilibrium (NE). An NE is a set of strategies for all the players such that no player has an incentive to change their strategy unilaterally, given the strategies chosen by the other players. Dynamic games are solved using the technique of backward induction where optimal strategies are determined while proceeding from the final stage to the initial stage of the game.

Various applications of game theory can be found in Chatterjee and Samuelson [8], Osborne [27] and Watson [40]. The game theoretic approach allows maintenance outsourcing to be studied from both the customer and service agent perspectives. The information available to each player and their attitudes to uncertainty and risk also need to be taken into account.

6.1 One Customer and One Service Agent

First consider the case where there are only two players—one customer and one service agent. This is scenario A-1 from Table 2. When there is a dominant player then we have a leader–follower situation where the actions of the follower depend on the actions taken by the leader. This situation can be formulated as a two-stage dynamic or 'Stackelberg' game.

Let the service agent be the leader in this particular formulation. Given a set of options $\{A_1, A_2, ..., A_n\}$ offered by the agent (with the value of the decision variable for option i being θ_i), the customer chooses the option which optimizes his/her objective. This generates the customer's best response function $A^*(\theta_1, \theta_2, \ldots, \theta_n)$ as shown in Fig. 4. Using this response function, the service agent then optimally selects the values of the decision variables $\theta_1, \theta_2, ..., \theta_n$ to optimize his/her objective.

Murthy and Ashgarizadeh [24] use this type of formulation for the case where the equipment has a useful life L, failures occur according to a homogeneous Poisson process and repair times are exponentially distributed. The two options offered by the service agent are

- Repair all failures over the useful life L for a fixed fee P but also incur a penalty cost of α for each unit of equipment downtime that is incurred above the value τ
- Repair each failure over the useful life L at cost C_s for each repair

Murthy and Ashgarizadeh [24] give a complete characterization of the agent's optimal pricing strategy $\left(P^*, C_s^*\right)$ and also discuss the effect of varying the model parameters on the optimal strategy.

6.2 Multiple Customers and One Service Agent

Murthy and Ashgarizadeh [25] again use the Stackelberg game formulation with the same two pricing options offered by the agent. They extend their earlier model by assuming that the agent has also to decide the number of customers M to service. This is scenario A-2 from Table 2. In this case, a customer's failed equipment will have to wait for repair if one or more other pieces of equipment from other customers have already failed. M is now an extra decision variable for the agent and a complete characterization of the agent's optimal strategy $\left(P^*, C_s^*, M^*\right)$ is again given.

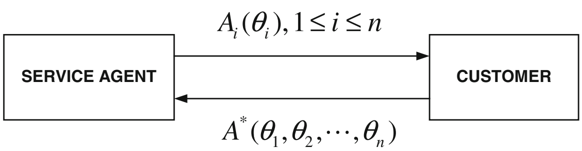

Fig. 4 Stackelberg game formulation

Ashgarizadeh and Murthy [3] extend the model further by assuming that the agent uses S repair facilities to service the M customers. This is scenario A-3 from Table 2. The agent's optimal strategy $\left(P^*, C_s^*, M^*, S^*\right)$ with respect to pricing structure, number of customers to service, and number of repair facilities to use is specified.

6.3 Multiple Service Agents

So far, there are no game theory models in the literature which deal with the competition between service agents for the outsourcing of equipment maintenance. This is an open area for research.

6.4 Nash Formulation

If there is no dominant player and players choose their actions either in a cooperative or non-cooperative manner, then a static or 'Nash' game formulation is required.

Jackson and Pascual [14] consider a service contract for aging equipment with terms which specify the frequencies for PM actions and equipment replacement. In their model, the optimal price for the contract is determined by negotiation between the owner and the agent (a Nash bargaining solution) instead of by solving a Stackelberg game. Wang [39] looks at a maintenance contract problem for large and expensive equipment (aircraft, ships, power plant) where the OEM is the only possible service provider. The delay-time concept is used to model the failure behavior of the equipment. Three different contract options are considered, one where the agent is responsible solely for the maintenance and two which involve specified tasks being performed by the owner. Each option requires certain levels of reliability and availability to be satisfied and the optimal parameters for each are again found by negotiation. The cases where both parties have perfect information and where there is information asymmetry are also discussed.

7 Agency Theory

Agency Theory deals with the relationship that exists between two parties (a principal and an agent) where the principal delegates work to the agent which performs that work and a contract defines the relationship. Agency theory is concerned with resolving two problems that can occur in agency relationships. The first problem arises when the two parties have conflicting objectives and it is difficult or expensive for the principal to verify the actual actions of the agent and whether the agent has behaved properly or not. The second problem involves the risk sharing that takes place when the principal and agent have different attitudes to risk (due to various uncertainties).

According to Eisenhardt [10], the focus of the theory is on determining the optimal contract, behavior versus outcome, between the principal and the agent. Many different cases have been studied in-depth in the principal–agent literature and these deal with the range of issues indicated in Fig. 5. Agency theory has also been applied in many different disciplines. For an overview, see Acekere [37].

7.1 Issues in Agency Theory

Moral hazard: Moral hazard refers to the agent's lack of effort in carrying out the delegated tasks. The two parties in the relationship have different objectives and the principal cannot assess the effort level that the agent has actually used.

Adverse Selection: Adverse selection refers to the agent misrepresenting their skills to carry out the tasks and the principal being unable to completely verify this before deciding to hire them.

Information: To avoid adverse selection, the principal can try to obtain information about the agent's ability. One way of doing is contacting people for whom the agent has previously provided service.

Monitoring: The principal can counteract the moral hazard problem by closely monitoring the agent's actions.

Information Asymmetry: The overall outcome of the relationship is affected by several uncertainties. In general, the two parties will have different information to make an assessment of these uncertainties.

Risk: This results from the different uncertainties that affect the outcome of the relationship. For a variety of reasons, the risk attitude of the two parties will differ and a problem arises when they disagree over the allocation of the risk.

Costs: Both parties have various kinds of costs. Some of these depend on the outcome of the relationship (which is influenced by uncertainties), on acquiring information, monitoring, and on the administration of the contract.

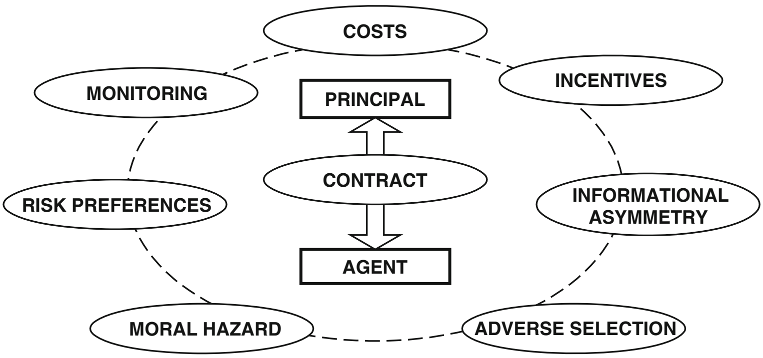

Fig. 5 Agency theory issues

The focus of principal–agent theory lies in the trade-off between (1) the cost of monitoring the agent's actions and (2) the cost of measuring the outcomes of the relationships and of transferring the risk to the agent.

7.2 Relevance to Maintenance Outsourcing

All of the above issues in Agency Theory are relevant to maintenance outsourcing problems. The customer is the principal and the maintenance service provider is the agent. The key factor is the contract which specifies what, when, and how maintenance is to be carried out. This contract needs to be designed taking account of all the relevant issues.

The customer and service agent both potentially face moral hazard. This can occur for the customer when the service agent does not do proper maintenance in order to reduce costs and it can occur for the agent when the customer uses the asset in a manner different to that stated in the contract. Adverse selection can also occur when the customer makes an inappropriate choice from an available pool of potential maintenance service providers (the B scenarios in Table 2). Both parties also possess different information about asset state, usage level, care and attention of the asset, and quality of maintenance used and this asymmetry affects the outcome of their relationship.

Scenario A-1 of Table 2 corresponds to the classical principal–agent model with a single principal (customer) and a single agent (maintenance provider). The interaction that takes place between the principal and the agent can be modeled as a multi-stage dynamic game with the principal as the dominant player. In stage1 of the game, the principal offers a contract to the agent. The agent decides whether to accept or reject this contract in stage 2. If the decision is accepted then, in stage 3, the agent chooses a 'work level' (e.g., service quality or capacity) for the contract period from a set of alternatives. The extra player 'Nature' is also involved during the contract period (the equipment is subject to random failure). What Nature does, together with the effort used by the agent, determines the outcome for the principal for the period (e.g., total equipment downtime and hence total profit).

If the principal cannot assess the agent's effort (moral hazard) then the contract offered must contain incentives for the agent to provide quality service. An example might be where the contract consists of a fixed fee plus penalties for excessive downtime. Kim et al. [17] discuss this type of principal–agent model involving performance-based contracting for equipment subject to infrequent Poisson failures. Plambeck and Zenios [29] use dynamic programming to solve a principal–agent problem where the equipment is used over a finite number of periods. In each period, the equipment can be in one of two states (working or failed) and the transitions between states are influenced by the actions taken by the agent. The agent performs both CM and PM and can exert high or low effort for each type of action. An optimal payment scheme is derived which induces the agent to maximize the principal's expected total discounted profit over the entire planning horizon. So far, Kim et al. [17] and

Plambeck and Zenios [29] are the only cases from the literature where appropriate stochastic formulations are used to model equipment failures.

In the remaining five scenarios of Table 2, there are multiple principals and/or multiple agents involved. In scenarios A-2 and A-3, the equipment under consideration could be a particular brand of lift installed in different buildings within a city. In this case, all the equipment is maintained either by the OEM or an agent of the OEM. There is an extensive literature dealing with the design of contracts for multiple principal/multiple agent problems (Macho-Stadler and Perez-Castrillo [22], and Laffont and Martimort [19] is a small sample of the papers from this literature) and all the Agency Theory issues are still relevant.

The results from the literature on multiple principal/multiple agent problems cannot be applied directly in the maintenance outsourcing context. Thus, new models which contain the required stochastic formulation for equipment failures need to be developed for this application area.

8 Criteria for Rating and Selection of Service Agents

A business is often faced with the strategic decision of whether to develop its own resources to perform maintenance or purchase the required skill and performance from external service agents. To make this decision the business needs to analyze whether maintenance forms a part of its core competencies or whether it only makes a minor contribution to the value chain. Once the business has decided to outsource it also needs to decide on the criteria to select the best service agents.

The selection criterion needs to be governed by the strategic intent of the business and the use of the outsourcing process to meet its goal. Therefore, the selection of the service agent is influenced by the reasons for outsourcing. These reasons can be one or more of the following:

- Concentrating on core activities
- Reducing the maintenance costs
- Spreading the business risk
- Downsizing the organization
- Supplementing the knowledge to achieve the business goals
- Bringing strategic knowledge to meet its requirement
- Facilitating the building up of competence outside the organization

In many contract situations with a large number of service agents participating, the selection of contractors is usually made in two phases (1) the pre-selection phase and (2) the final selection phase. We discuss these briefly and for more details, see, Straub and van Mossel [30].

8.1 Pre-selection Phase

In the pre-selection phase of a service contract process, the selection criteria are based on the following:

- Technical capabilities: The service agent must have the knowledge, the organizational structure, and the resource capabilities to meet the contractual agreements. That is, the service agent must have the correct organization (number of people and their competence) and equipment, etc., to carry out the maintenance as stated in the contract on time and correctly. Often, service agents enter a contract but lack the organizational capability to deliver the agreed performance and this creates bottleneck problems for the owner of the asset.
- Experience with similar equipment: Although the service agent might have the required manpower and competence, the agent may have had no experience in maintaining the asset under consideration. This can result in problems with the delivery and quality of service. Often it takes some time for the service agent to understand all the factors that can cause equipment downtime and this causes bottlenecks when the agent is dealing with a specific asset for the first time.
- Financial health of the service agent: Often owners are influenced by the reputation and capabilities of the service agent and fail to do a thorough analysis of the service agent's financial health. If the service agent is financially weak there is a risk that the agent might not be able to fulfill the contract or even go bankrupt due to cash flow problems.
- Innovative capability of service agent: In recent times, the innovative capability of the service agent has become a dominant factor in an agent being awarded the contract. If the agent has the reputation for being innovative, it provides assurance to the owners of the assets that new and innovative maintenance solutions will ensure better performance, higher quality, and/or reduced costs.
- Demonstrated good governance/moral integrity of the service agent: Good governance is reflected in factors such as transparency in action and moral integrity. Service agents who exhibit these characteristics are preferred to those who lack them.

8.2 Final Selection Phase

The final selection procedure involves a detailed and in-depth analysis of the criteria used in the pre-selection phase. Some of these are listed below.

- Business plan, vision for implementation of new and proven technology: The owners of assets should demand and examine the business plan of the service agents and assess these plans in terms of the implementation of new technologies, training of personnel, and other actions to facilitate innovations.
- Special focus should be given to evaluating the service agent's quality assurance process and its implementation.

- Past experience and performance of the service agent should be assessed by talking to previous customers of the service agent.
- Once short-listed, the owner of the asset must evaluate the team members that will be involved in carrying out the maintenance activities. This assessment is based on the qualification and experiences of each member with respect to the maintenance of similar assets.
- Proper data collection system for monitoring and reporting: The owner needs to pay special attention to this and use the information collected to improve the effectiveness of maintenance.

8.3 Selection of Service Agents: Practice at Swedish Rail Administration

In order to increase the effectiveness and efficiency of the maintenance process, the railway administration (Trafikverket), started to open up its maintenance contract for market competition [12, 13]. That is, anyone with the capability to deliver the contract could participate in the contract tendering process. Since railway maintenance is specialized and needs special tools and skills, there were only a few service agents in Sweden who could perform the service. This provided an opportunity for service agents from other European countries to bid for the contract. Today at least four service agents have been awarded contracts, based on their competence, capability, and price, for carrying out maintenance in different regions.

The selection of service agents at Trafikverket, in general, involves the following steps [12]:

1. Pre-qualification of contractors: This is performed at the Head office level and all the contractors or service agents planning to bid for a contract must register and be approved by the committee based on their capability, past performance, ethics, etc.
2. Announcement of contract: The contract is advertised in most of the listed major newspapers with a short description of the job and the contact details of the persons responsible for the contract.
3. Contract procurement process: During this step, potential contractors are informed about the type, scope, duration, and other relevant descriptions of the contract. Based on this information, interested contractors submit bids for the contract.
4. Pre-selection: Based on the details of the submitted bid and other relevant information about contractor, the client (infrastructure manager) selects 2–3 contractors to initiate the contract negotiation process.
5. Contract negotiations: During this step, the contract together with the scope of the work and the related price tags, etc., are discussed in detail with the selected potential service agents. This step also leads to the final selection of the service agent most suitable for the contract.

6. Study and analysis of contract: After selecting the service agent, the client and service agent both study and analyze the contract and enter into agreement whereby the contract is defined at a detailed level.
7. Signing of contract and its implementation as per the time and delivery plan.

9 Topics for New Research

As mentioned earlier, most of the literature on maintenance outsourcing is qualitative with only a small number of papers taking a quantitative approach. A proper study of maintenance outsourcing requires (1) an interdisciplinary approach involving science, engineering, technology, mathematics, and management and (2) a more quantitative approach to evaluate different maintenance contracts and identify the best contract taking into account the interests of the different parties involved.

Game theory and Agency Theory provide the foundations for building models to study maintenance outsourcing. However, most of the literature on game theory and Agency Theory consists of models that have very basic stochastic formulations. We suggest a multi-step approach to conduct new research of relevance to maintenance outsourcing.

Step 1: Develop a comprehensive framework that deals with the science, engineering, technology, and management issues in an integrated manner for a proper study of maintenance outsourcing.

Step 2: Identify the key elements, the variables to characterize these elements, and the interaction between the variables.

Step 3: Develop a simple model. This would imply a single stage (so that from a game theory perspective a static game formulation is used) and only two players—the owner of the asset and a single service agent. The objective functions for the two players would involve stochastic model formulations for failures and costs over a pre-specified contract period. The model formulation needs to look at contract specification (tasks to be carried out, incentives and penalties, monitoring schemes to detect cheating, etc.). Alternate scenarios can be considered which lead to different Stackelberg and Nash game formulations. The aim is to devise and evaluate contracts which ensure there are no incentives for cheating and that both parties reveal full information.

Step 4: Improve on the model of Step 3. This implies a multi-stage formulation and more than two players. This introduces new issues such as the owner having the option to change the service agent, competition between the agents, etc. These models need to incorporate learning effects and other factors such as customer satisfaction and loyalty (which lead to the renewal of contracts) and many other issues.

One further area where considerable research needed is a study of the role of data and information and their impact on the optimal strategies of the different players involved.

9.1 Maintenance Outsourcing in Railways

The rolling stock (engines, bogies, and wagons) interacts with the track and the degradation of the track and rolling stock is influenced by the interaction between them. It is affected by the condition of the rolling stock and of the infrastructure and by several other factors such as load, speed of travel, etc.

The owners of the infrastructure and the rolling stock can each outsource their maintenance so that there are several service agents involved. The different contracts between the owners and service agents are indicated in Fig. 6. This scenario implies several different players and the decision making needs to take into account the interaction between the different variables.

The need for an interdisciplinary approach to solve the maintenance outsourcing problem is highlighted through the following observations:

- Science: The degradation process due to the interaction between the track and the rolling stock.
- Engineering and Technology: The assessment of the condition of the track and the rolling stock (and for other variables such as axle load, etc.).
- Economic: The evaluation of the cost of maintenance; the consequence of failure resulting in the rolling stock and/or track being out of action, etc.
- Management: The drafting of the contract and the setting up of systems to collect relevant data and information.

The authors are currently looking at the structures of different contracts and models to evaluate each type of contract and to choose the best option.

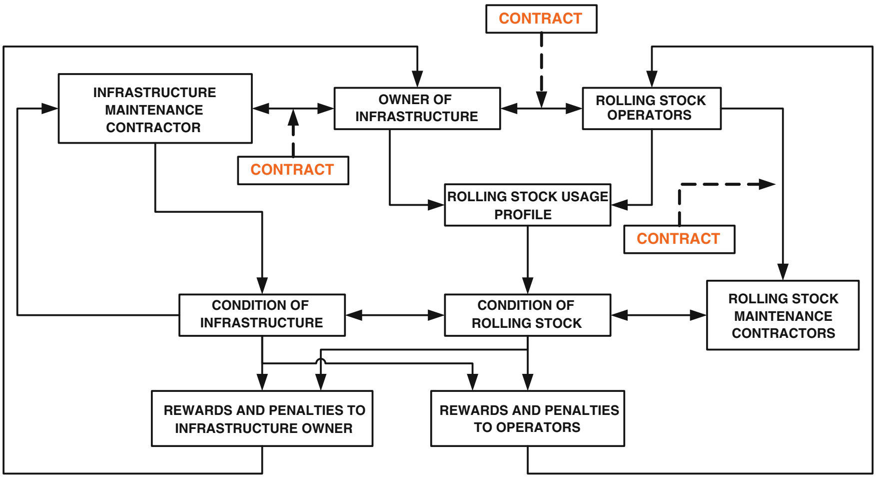

Fig. 6 Key elements and their interaction

10 Conclusions

We have looked at maintenance outsourcing and the issues that need to be addressed in the maintenance outsourcing context. A proper study and evaluation of maintenance outsourcing requires a quantitative approach. Game theory and Agency Theory provide good starting points to build new models which look at maintenance from both the owner and the service agent perspectives. This chapter gives a brief introduction to these two topics and defines some areas for possible future research.

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