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A Multi-Objective Genetic Algorithm for determining efficient Risk-Based Inspection programs

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ABSTRACT

This paper proposes a coupling between Risk-Based Inspection (RBI) methodology and Multi-Objective Genetic Algorithm (MOGA) for defining efficient inspection programs in terms of inspection costs and risk level, which also comply with restrictions imposed by international standards and/or local government regulations. The proposed RBI+MOGA approach has the following advantages: (i) a user-defined risk target is not required; (ii) it is not necessary to estimate the consequences of failures; (iii) the inspection expenditures become more manageable, which allows assessing the impact of prevention investments on the risk level; (iv) the proposed framework directly provides, as part of the solution, the information on how the inspection budget should be efficiently spent. Then, genetic operators are tailored for solving this problem given the huge size of the search space. The ability of the proposed RBI+MOGA in providing efficient solutions is evaluated by means of two examples, one of them involving an oil and gas separator vessel subject to internal and external corrosion that cause thinning. The obtained results indicate that the proposed genetic operators significantly reduce the search space to be explored and RBI+MOGA is a valuable method to support decisions concerning the mechanical integrity of plant equipment.

1. Introduction

Past accidents in several types of industries have demonstrated that equipment malfunction is one of the major causes of unexpected and undesirable events such as toxic and inflammable discharges, fire and explosions. Failures to function properly are usually due to inadequate integrity management systems that may result in cracks, holes, ruptures, and consequently loss of containment of dangerous substances. Therefore, integrity control has been used for guaranteeing aging machineries work in an appropriate manner, assuring plant safety against adverse occurrences [1].

In this context, inspection has been used as a technique to examine the real situation of equipment exposed to damage mechanisms (*e.g.*, thinning, stress corrosion cracking, high-temperature hydrogen attack, mechanical fatigue, brittle fracture), thus reducing the uncertainty of its condition. The aim is to identify these potential damage mechanisms and steer efforts in order to prevent failures by prioritizing systems that need more attention.

Decisions about which equipment should be investigated, which inspection approach will be performed, and when this event will take place have become intricate problems due to the complexity of the involved processes, especially in refineries and petrochemical industries. Thus, Risk-Based Inspection (RBI) has been used to support the decision makers in managing the schedule of those interventions. The fundamental principle of RBI is quite simple: after a user-defined risk target R_t (*i.e.* the acceptable risk) has been chosen, the inspection program is determined in order to not allow the risk level to exceed R_t, thereby avoiding loss of containment and, subsequently, unwelcome effects [2].

Thus, RBI deals with the consequences of holes and ruptures in pressurized equipment in terms of the area affected by the outcome of the possible release of dangerous materials, and then the expenses to execute mitigation solutions to the problems caused by these occurrences. Then, a baseline curve for the risk level $R(k) = P_f(k) \cdot FC$ is estimated over time k by combining the probability of failure $P_f(k)$ and the respective financial consequence FC for each equipment under analysis.

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In this context, Singh and Markeset [3] proposed an RBI planning based on fuzzy logic approach for oil and gas carbon steel pipelines subject to CO_2 corrosion. Khan et al. [4] used the RBI methodology to develop inspection and maintenance strategies that maximize system availability; the approach is applied to the steam generating system of an oil field thermal power plant. Chien et al. [5] developed a semi-quantitative RBI analysis for pressure safety valves (PSV) used in lubricant process units. Li et al. [6] developed an RBI theoretical framework for ship structures using a decision tree method. In Tien et al. [7], an RBI-based model for piping systems has been built in accordance with international standards and local government regulations; the purpose was to provide inspection-related personnel with the optimal planning tools, to enable effective predictions of potential piping risks, and then to enhance the degree of safety in petrochemical industries. Marangone and Freire [8] applied the RBI methodology in the management of mechanical integrity of an oil and gas separator vessel subject to corrosion mechanisms. Vinod et al. [9] applied the RBI methodology for an H_2S-based process plant along with an approach devised for handling the influence factor related to the quantity of H_2S released. Shuai et al. [10] used the RBI technology to assess quantitatively the risk of crude oil tanks in an oil depot in China.

RBI quantitative analysis yields a tool that enables the recognition of the actual equipment's situation, and hence the intervention needs to reduce the risk exposure. Then, the estimation of the risk level $R(k)$ is updated from the data gathered at each inspection epoch in order to continue representing the current condition of the system. In this way, the recommended practice [11] provides guidance on developing an RBI program for fixed equipment (including pressure vessel, piping, tankage, pressure relief devices, and heat exchanger tube bundles) in refining, petrochemical, and chemical process plants. Thus, Ref. [11] aims at providing quantitative calculation methods to determine an inspection plan. Nevertheless, all the aforementioned works have four main disadvantages:

(i) The user-defined threshold R_t for risk level is not taken into account as an objective to be optimized. In other words, the risk measure should be maintained below R_t, but nothing guarantees that this parameter is chosen in the most efficient way. On the contrary, the decision maker solves this problem through a trial-and-error method by changing the inspection program until the risk target is no longer reached.

(ii) This process of not allowing the risk level $R(k)$ to go above the pre-set target R_t also disregards the costs associated with the assigned inspection program. For instance, the risk limit R_t may require an unreasonably high budget if it is chosen to be too low.

(iii) The calculation of the risk measure $R(k) = P_f(k) \cdot FC$ at some time k involves the determination of $P_f(k)$ along with FC considering the loss of containment of a particular equipment. Even though the screening of critical equipment is usually carried out using a simplified qualitative approach, Vinod et al. [9] pointed out that, in general, the number of components to be considered for a quantitative RBI assessment is still very large. Furthermore, the estimation of FC is a very laborious task because of the amount of information required. In fact, determining FC involves the estimation of costs of equipment repair and replacement, costs of damage to surrounding equipment in affected areas, costs associated with production losses and business interruption because of downtime to repair or replace damaged equipment, costs due to potential injuries associated with a failure and environmental cleanup costs. These categories of costs are added up in order to estimate FC.

(iv) Finally, it is not possible to point out how and when the inspection resources should be spent. This means that no guideline on how to plan the inspections is provided, *i.e.*, how to determine which techniques have to be adopted and when they have to be performed in full compliance with international standards and/or local government regulations. For example, decision makers may face problems on how to combine inspection techniques: is it better to perform a number of low-cost/low-effective inspections or fewer inspections with higher effectiveness, but more expensive? By effectiveness of an inspection technique, we mean the ability of detecting and measuring damage mechanisms.

Therefore, this paper proposes an original RBI multi-objective-based framework, which aims at minimizing both the total risk level and the costs related to the inspection program. Hence, a trade-off analysis is required since both objectives are conflicting. In other words, given a planning horizon, the idea is to find the optimal compromise between risk and inspection costs, and thus overcome the aforementioned drawbacks as follows:

(i) The risk target R_t is no longer required *a priori* because risk is now an objective to be minimized. In this way, the decision maker will not be concerned about the inspection policy that maintains the risk level below R_t. In fact, the inspection program will be one of the results of the proposed approach. Moreover, even if the risk must be below a preset target value R_t (possibly to comply with safety regulations), the proposed multi-objective problem also allows taking into account a risk constraint.

(ii) The inspection costs are also handled as an objective. Therefore, as both risk and expenditures with inspection activities are now considered, the resulting inspection program will be of great significance on balancing safety, availability and inspection cost requirements.

(iii) Despite the large number of equipment that should be prioritized in a refining or petrochemical facility as well as the information requirements to estimate the financial consequences, note that FC is considered constant for a particular equipment according to Ref. [11]. In this way, only $P_f(k)$ varies over time k and is updated based on data collected from inspection, implying that $P_f(k)$ and $R(k)$ curves have the same shape. Thus, in our multi-objective approach, the demanding step of computing FC is no longer necessary because we will directly work on $P_f(k)$ instead of $R(k)$, which is equivalent; even if a risk constraint has to be satisfied, as commented in item (i), it can be considered *a posteriori* as FC becomes available;

(iv) Finally, the proposed framework provides the decision-maker with the information on which inspection technique should or should not be performed at each time-step, which in turn defines the inspection program. This piece of information will be associated with each pair of solution (risk or probability of failure; inspection costs), directly identifying which actions should be followed for managing risk to a minimal level.

Thus, in the context of RBI, the multi-objective approach emerges as an alternative to handle the conflicting objectives of risk (or probability of failure) and inspection costs so as to create efficient inspection policies that comply with regulation standards. In a multi-objective optimization, a solution that optimizes all objectives concurrently is very difficult to be reached or it simply does not exist. In this way, instead of having a unique solution as in single objective cases, one may obtain a set with multiple solutions. These solutions, named non-dominated, present a compromise among objectives and usually do not yield an optimal value for either of them individually. Once this set is obtained,