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Choosing the optimal intervention method to reduce human-related machine failures

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ABSTRACT

This paper presents a novel method to quantify the effects of human-related factors on the risk of failure in manufacturing industries. When failures can be caused by operators, the decision maker must intervene to mitigate operator-related risk. There are numerous intervention methods possible; we develop a revenue model that provides the decision-maker with a systematic tool to perform a cost-benefit analysis, balancing the advantage of risk reduction, against the direct cost of the intervention method.

A method is developed to incorporate human-related factors, in addition to machine-related factors, in machine failure analysis. This enables the revenue model to use the expected uptime and the probability of failure, given the operator skill level and working conditions, to calculate the expected revenue associated with each intervention method. A case study of a manufacturing company is considered incorporating two possible intervention methods: reducing the production rate to provide more cognition time and adding a shift expert to guide the operators. Different courses of action are chosen for the various skill-shift scenarios presented.

1. Introduction

The performance of a human–machine system is a factor of the performance of the hardware, as well as the correct operation of the hardware by the operators. One indicator of performance is reliability and to assess reliability, we can analyze the risk of failure of the system. The "risk of failure" is widely used and well understood by practitioners but is often not clearly defined (Zuashkiani, Banjevic, & Jardine, 2009). In our case, we define risk as the potential for a machine to become non-operational and quantify it by probability. Within this context, there are many reliability and failure risk models that deal with the machinery. But there are few that incorporate the role of human operators on uptime and overall performance. The first step in our analysis is to have a model to incorporate both Machine-Related (MR) and Human-Related (HR) factors. This can provide us with an all-encompassing assessment of failure risk. To achieve this, we use the Proportional Hazards Model (PHM), a commonly used tool to model the time of failure of equipment (Ghasemi & Hodkiewicz, 2012; Si, Wang, Hu, & Zhou, 2011). A PHM yields the hazard rate which can be affected by factors specific to the machine, the environment, or the humans within the human–machine system. The PHM has most often been used with quantifiable MR covariates, such as readings from vibration sensors or oil analysis. However, this usage can be expanded by including non-MR type factors (Centrone, Kiassat, Garetti, Banjevic, & Jardine, 2010; Kiassat & Safaei, 2009). The fact that this common and versatile model accommodates the inclusion of HR covariates, in addition to MR factors, makes the PHM an excellent model for our analysis.

Once we evaluate the risk facing the system, we may choose to intervene and reduce or eliminate it. Any intervention method pursued should have the benefit of reducing failure risk; it would also have the disadvantage of incurring a direct cost. Given the trade-off between risk reduction and direct cost, we develop a revenue model to perform a cost-benefit analysis for choosing the best intervention method. Given the machine factors, such as working age; operator factors, such as skill level; and the direct cost of the intervention method as well as its risk reduction factor, the best intervention method is selected as the one that results in the highest system revenue. In the absence of an analytical method for choosing among intervention methods, subjectivity and personal biases enter into the decision-making process, distancing it from being an evidence-based process. Providing a systematic tool to a Decision-Maker (DM) to choose the optimal intervention method is the main contribution of this paper.

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The general framework of the methodology discussed in our paper is portrayed in Fig. 1. Skill quantification is a necessary component but is not a part of our contribution. The loopback is not discussed in the paper; however, it is a necessary component if additional impactful HR factors are identified.

This paper is organized as follows. In Section 2, we perform a literature review, laying out the existing related work and pointing to the gap in the existing knowledge. Section 3 introduces the PHM, used as our failure analysis model to incorporate HR factors. This leads to Section 4 which discusses the development of the revenue model. Section 5 considers the case study of a manufacturing company and applies the revenue model to the data set. Section 6 provides a recap and suggests possible directions for future work.

2. Literature review

There has been much research on assessing human reliability and incorporating it into the overall risk analysis. But the literature is sparse when it comes to performance measurement models that incorporate human-related risk assessments. Barroso and Wilson (1999) consider a manufacturing environment and focus on estimating the overall effect of human reliability. However, their approach is not risk-based, but rather focuses on identifying sources of human error and reducing them. Horberry, Burgess-Limerick, and Steiner (2010) discuss human factors and their effects on operations and maintenance in a mining context but do not attempt failure prediction. Similarly, Kolarik, Woldstad, and Lu (2004) develop a model to monitor and predict an operator's performance using a fuzzy logic-based assessment. But the purpose of their work is to solely provide a human reliability assessment, without providing any methods for risk reduction. Blanks (2007) discusses the need for improving reliability prediction, paying special attention to human error causes and prevention, but does not mention any predictive techniques for human reliability.

Carr and Christer (2003), and Dhillon and Liu (2006) focus on the maintenance workforce performing repair work at times when machines are not being used for production purposes. Reer (1994) discusses human reliability in emergency situations. Our discussion focuses on the production workforce during the operation of the machines. Our emphasis is not on decreasing the mean time to repair but on improving the mean time between failures. A further distinguishing feature of our work is its proposal for managerial interventions, or proactive measures, to deal with the risk stemming from the operators in the human–machine system.

Peng and Dong (2011) use a Markov chain approach for uptime prediction. Vrignat, Avila, Duculty, and Kratz (2012), discuss an approach, where they draw observations from the process to generate an availability indicator to be used by a DM to plan actions dynamically. The authors also mention the PHM as a tool. Our work is also helping the DM to plan actions dynamically. A major difference between our work and the two aforementioned works is that, in our case, the observations from the process include HR factors. There are studies, such as Biskup (2008) and Teyarachakul, Chand, and Ward (2011), which consider HR factors, specifically skill and operator learning, and their effects on system performance. But their scope is on production scheduling and not on failure risk analysis.

Castanier, Berenguer, and Grall (2003), discuss a continuously deteriorating machine where each maintenance operation makes sense at various stages. The DM can choose to run-as-normal, perform preventive repairs, or preventive replacement. Each has the benefit of improving the system a certain amount and each has the cost of taking the system out of production for certain duration. There is a certain element of cost-benefit analysis in this work that is similar to ours. But there is no mention of human-related factors either. Neither with the work of Vrignat et al. (2012) nor with Castanier et al. (2003) is there a deeper focus on the specific causes of degeneration. All causes leading to machine degeneration are combined together. The cost benefit analysis is not related to the specific risk culprits.

Burkolter, Kluge, Sauer, and Ritzmann (2009) propose personnel selection criteria to minimize risk during the operation. Karaulova and Pribytkova (2009) acknowledge the human role within the overall reliability analysis but simply make generalized comments, such as better ergonomic design or improved human–machine interface, as means of risk reduction. While studies such as Blumenfeld and Inman (2009) and Huang, Chiu, Yeh, and Chang (2009) note the impact of inferior operator skill and other HR factors on quality and performance, neither has a risk reduction scope. Our scope is different from all of these in that we propose intervention methods to deal with the HR risk in the short-term planning horizon. In addition, we supply the DM with a cost-benefit analysis of intervention methods. There are no other works in the literature that enable the DM to choose the optimal course of action in maximizing revenue by minimizing failure risk stemming from the operators in a human–machine system.

3. Evaluating intervention methods for human-related risk

The PHM is a common tool for analyzing the risk of failure and this is especially true when the PHM is parameterized using the Weibull baseline (Jardine, Banjevic, Montgomery, & Pak, 2008; Sikorska, Hodkiewicz, & Ma, 2011). The PHM relates the time of an event, such as failure, to a number of explanatory variables known as covariates. Several factors, including the equipment age or specific system characteristics, may influence the equipment's hazard rate, which is the rate of transition out of a non-failed state to a failed state.

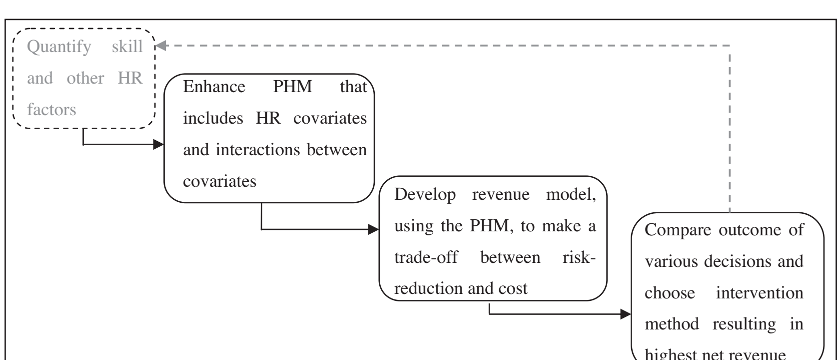

Fig. 1. General framework of approach discussed in this paper.