European Journal of Operational Research 241 (2015) 708–718

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Production, Manufacturing and Logistics

Investigating work-related ill health effects in optimizing the performance of manufacturing systems

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ARTICLE INFO

Article history:
Received 10 September 2013
Accepted 5 September 2014
Available online 30 October 2014

Keywords:
Operations research
Optimization
Serial assembly line
Workplace risk factors
Work-related health problems

ABSTRACT

Working environment affects human health condition and performance. Human Factors (HF) scholars aim to elaborate this effect. However, HF studies mostly focus on employee occupational health and safety elements and their consequences on employee health conditions. They do not take into account Work-related Ill Health (WIH) risk factor effects at the system level. In contrast, operations research studies usually assume that operators involved in a system have identical performances and rarely consider WIH risk factor effects in optimizing system performance. This paper proposes a 2-state Markov chain model to quantify WIH risk factor effects and thereby estimate their economic impacts in optimizing a serial assembly line's performance. Results of this research demonstrate between 0.52 percent and 8 percent increase for the total cost of the system as WIH risk levels change. This paper opens a new window to understand economic consequences of WIH effects, and to enhance systems performance by investigating working conditions.

1. Introduction

Work-related Ill Health (WIH) risk factors have been shown to have negative consequences for employees health (e.g., Punnett & Wegman, 2004; Rijn, Huisstede, Koes, & Burdorf, 2010). They subsequently interrupt the balance of the working environment and reduce employees overall work performance. This interruption creates a substantial economic burden on organizations (Goggins, Spielholz, & Nothstein, 2008). For instance, the annual Occupational Health and Safety (OHS) costs were estimated to be $77,181 million in private industries of the US (e.g., Leigh, Waehrer, & Keenan, 2004). Furthermore, the economic costs for work-related ill health have been estimated by some European nations between 2.6 percent and 3.8 percent of gross national product (EUOSHA, 2001). Human Resource and Skill Development Canada (HRSDC) have reported that occupational injuries cost over $19 billion annually (HRSDC, 2010).

Due to health and safety consequences of WIH risk factor effects, 4.4 million non-fatal injuries were reported in the US annually (Schulte, 2005). With different categories of occupational health problems, Musculoskeletal Disorders (MSD) are among the most common lost-time, and on job productivity loss injuries (e.g., WSIB, 2010).

Practitioners addressed the importance of Human Factors (HF) in operations systems. Operations management text books also contain sections on human issues. However, the health-related performance variations of employees have been infrequently considered in Operations Research (OR) studies (e.g., Neumann & Dul, 2010). OR models deal with complex decision making and optimization problems in many areas of manufacturing systems, including capacity planning (e.g., Huang & Ahmed, 2010; Christiansen et al., 2011), production strategy and throughput analysis (e.g., Matsubayashi, Ishii, Watanabe, & Yamada, 2009), resource assignment (e.g., Bravo & Gonzalez, 2009) and scheduling problems (e.g., Winandsa, Adanb, & Van Houtumc, 2011). A review of OR studies shows that they have usually focused on technological aspects such as machine breakdown (e.g., Xia, Xi, Zhou, & Lee, 2012) and system characteristics such as demand uncertainty (e.g., Cao, Li, & Yan, 2012). They have rarely considered causes and effects of work-related employee health-states. OR studies usually assign a fixed value to employee performance and do not investigate WIH risk factors and their effects on the employee capabilities that influence the performance of systems, in optimization models (e.g., Al-e hashem, Baboli, & Sazvar, 2013; Brahimi, Dauzere-Peres, Najid, & Nordli, 2006). Therefore, it is essential to consider WIH risk factor effects in system performance evaluation.

In contrast, HF studies have mostly focused on occupational health and safety aspects and their subsequent effects on employee health-states (Neumann & Dul, 2010). HF, used interchangeably with ergonomics here, is defined as being concerned with the understanding

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http://dx.doi.org/10.1016/j.ejor.2014.09.032
0377-2217/

of the interactions among humans and the other system elements, in order to optimize human well-being and overall system performance (IEACouncil, 2000). HF studies seldom have accounted for WIH risk factor effects for a system level optimization. They usually have focused on employee health conditions and limited to performance measures at individual and workstation levels (e.g., Neumann & Dul, 2010).

Epidemiology and ergo-economic studies are two major groups in HF research considered in this paper. Studies in the first group include epidemiological investigations, analyzing working environments and determining WIH risk factors affecting human health and, subsequently, their operational characteristics (e.g., Kerr, Frank, Norman, Wells, & Neumann, 2001). A WIH risk factor is a variable that is associated with an increased chance of occupational health problems. Epidemiology studies show that the most common WIH risk factors can be categorized into two main groups:

1. Physical risk factors. Some examples include repetitiveness of tasks, handling heavy loads, spine compression, peak spinal loads, peak lumbar shear, extreme hand and arm postures, and task invariability (e.g., Driessen et al., 2010; Kerr et al., 2001).
2. Psychosocial risk factors. Some examples include decision making latitude, job control, temporal pressure, work demands, and job stress (e.g., Bongers, Kremer, & ter Laak, 2002; Vandergrift, Gold, Hanlon, & Punnett, 2012).

The second group of HF studies, have tried to justify ergonomic interventions in terms of economic and financial indicators. They have shown that direct compensation costs, associated with work-related health problems, only contribute to a small percentage of the total expenses related to poor HF working environments. A major portion of the expenses comes from hidden or indirect costs, including employee replacement, administration, and productivity loss charges. These indirect costs are estimated to be between 1 and 10 times of direct costs (Leigh, 2011). Unlike OR models, the both categorized groups of HF studies do not usually account for common system characteristics such as buffer capacities, demand and the dynamically changing condition of operation systems (Rose, Orrenius, & Neumann, 2013). Thus, it is essential to integrate HF effects into OR models.

In this paper, we propose an optimization model for a serial system, including physical and psychosocial WIH risk factor effects. The aim of this model is to make a connection between OR and HF research streams by considering causes and consequences of employee work-related health and productivity variation, for minimizing the total cost of the assembly system. A modeling approach is developed that, first, determines the relationship between known WIH risk factor measures and their subsequent effects on employee health conditions. Then, these health conditions are modeled using a 2-state Markov chain and are integrated into an optimization model, while accounting for WIH risk factor effects. Other features of the system such as customer demand, inventory capacity, and production costs are also included. The developed model is numerically tested to evaluate the effect of different work-related MSD on the performance of the operation system.

The remainder of the paper is organized as follows. Section 2 introduces the assembly system and their operational elements. It also describes major steps in the modeling approach in order to integrate WIH risk factor effects into the optimization of the assembly system performance. In Section 3, the proposed model is numerically tested by considering work-related low back and shoulder pain WIH risk factors. The developed model is examined with different scenarios to comprehensively evaluate WIH risk factors and their impacts on optimized financial and operational elements of the system. In Section 4, the advantages of investigating WIH effects are discussed from managerial perspective. Section 5 concludes the paper.

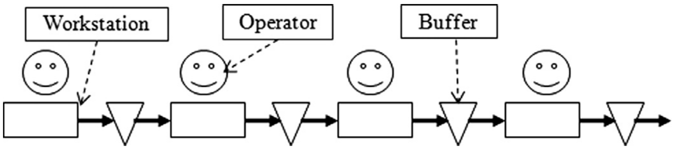

Fig. 1. A serial assembly line with four workstations.

2. Model development

This section introduces an optimization model integrating WIH risk factor effects. From different manufacturing structures, let us consider a serial assembly with limited capacity buffers between workstations. This structure is widely used in OR literature as well as manufacturing environment (e.g., Iwasea & Ohnob, 2011). For this paper, we assume that this sample assembly line includes four serial workstations and there is an operator for each of them to accomplish assigned assembly tasks, as shown in Fig. 1. Product assembly starts from the first station. The operator of this station carries out initial assembly tasks. Then, the incomplete product will be transferred to a buffer between first and second stations. This process continues until the product assembly is completed in all four stations. The final product will be transferred from the fourth station into the inventory to fulfill demand. Production is during regular and over-time hours. Backlog is not allowed and if the throughput of the assembly line cannot fully satisfy customer demand, it is assumed that subcontractors will fulfill the unmet demand during each given time period. WIH risk factors affecting the operators' performance, and machine failure vary the performance of the assembly line. However, our goal in this paper is focused on the effect of WIH risk factors when the performance of the assembly line is optimized. Therefore, it is assumed that machines used in the assembly line work perfectly, and the production rate of workstations depends on the performance of the operators. Operators who are working in the assembly line have a probability of having work-related MSD for a given time period due to the negative effects of WIH risk factors (e.g., Punnett & Wegman, 2004). These effects change the operators' health status. In order to replicate the health condition changes, happened in a real working environment, the authors categorize the operators' health states taking into account work-related health evolutions, resulted from previous epidemiology and HF studies (e.g., Kerr et al., 2001). Epidemiological studies use different measurement tools to evaluate the effect of WIH risk factors in developing MSD symptoms in different human body area (e.g., Dawson, Steele, Hodges, & Stewart, 2009). They usually divide their case studies into people with and without work-related pain (e.g., Sim, Lacey, & Lewis, 2006). Furthermore, recent HF studies have considered the contribution of the work-related pain in developing productivity loss for human (e.g., Campo & Darragh, 2012). Therefore, for this paper, the health condition of the operators is categorized in two states. They would be healthy without having any MSD or may have pain due to musculoskeletal problems. These work-related health states are characterized as 0 and 1, where 0 indicates the "healthy" state and 1 indicates the "pain" state with productivity loss.

It is assumed that an operator is 100 percent productive in the healthy state. However, the operator in the pain state has a lower production rate because of (a) the on-job productivity loss, when he/she has pain or injury and stay at work (presenteeism) or; (b) the replacement of a new worker, who has less competence and skills than the injured absent operator during the given time periods. The health-state changes can take place because of physical and psychosocial risk factors. As risk levels increase, the probability of the health-state change increases for affected operators.

According to the defined health-states, a 2-state Markov chain is generated for each operator to calculate the steady-state probability of being in the health-states. Then, the total cost model of the