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Productivity and ergonomic risk in human based production systems: A job-rotation scheduling model

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ABSTRACT

The competitiveness of modern manufacturing systems is based on a high production rate and a high level of flexibility. Despite the high level of automation achieved in production systems, flexibility is often provided by human dexterity and the cognitive capabilities of the workforce, as in assembly lines. In the case of repetitive manual tasks, workers are exposed to the risk of musculoskeletal disorders (MSDs). In these contexts, a high production rate leads to high physical workload, and job rotation is adopted in order to reduce the ergonomic risk. Traditionally, ergonomics and human performance issues have been investigated separately. However, in the design and scheduling of human-based manufacturing systems, a reliable description of human components is required in order to jointly evaluate production system performance and assess workers' risk of MSDs

In this paper, the authors propose a model which aims to find optimal job rotation schedules in work environments characterized by low load manual tasks with a high frequency of repetition (e.g. assembly lines). The model is a mixed integer programming model allowing for the maximization of production rate jointly reducing and balancing human workloads and ergonomic risk within acceptable limits. Risk and its acceptability are evaluated using the OCRA (OCcupational Repetitive Actions) method (ISO 11228-3:2007), widely recognized as an effective tool for the risk assessment of Upper Limb Work related MSDs (UL-WMSDs). Moreover, the different workers' performance due to their respective training levels and skills is considered in the problem formulation.

The model is applied to an industrial case study. Results show the model's capacity to identify optimal job rotation schedules jointly achieving productivity and ergonomic risk goals. Performances of the solutions obtained improve as workforce flexibility increases.

1. Introduction

In globalized turbulent markets, capital-intensive industries are often subjected to the risk of unprofitable underutilization of their production capacity. Production and process flexibility are still recognized as being the most effective answers to both dynamic and uncertain market demand and pressing international competition (Francas et al., 2011). However, in many cases the paradigm of a fully automated factory has failed, since automation does not always provide reliable flexible solutions at a reasonable cost. As an example, in the automotive industry the final assembly stage, providing the highest degree of customization and including the largest number of (complex) tasks, is often the least automated (Kruger et al., 2009; Michalos et al., 2010). In these work contexts, a high level of flexibility, and thus competitiveness, are obtained by increasing the contribution of the human component, since the dexterity and cognition of workers in both manual and cognitive tasks are major flexibility enablers. As a consequence, in many production environments, human labor continues to play an important role and lean forms of automation are ever more adopted as they are reliable and economically effective. In this scenario, increasing attention, both from a scientific and industrial point of view, is being paid to repetitive manual tasks performed in assembly lines, where most frequently workers are subjected to work-related musculoskeletal disorders (WMSDs) and where an increase in production rate leads directly to an increase in physical workloads (Colombini et al., 2002).

WMSDs and loss of efficiency are typical issues tackled by human based production systems (Lotters et al., 2005; Thun et al., 2011). In Europe, WMSDs are the most common occupational injuries (almost 40% of all work-related injuries) and their cost is estimated at between 0.5% and 2.0% of the EU Gross National Product (EASHW, 2010). Moreover, in many EU countries demographic developments have led to an aging of the workforce (Mummolo, 2014; Boenzi et al., 2015; CEDEFOP, 2010). The related deterioration of physical and cognitive performances of workforce

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negatively affects the flexibility of human-based production systems, as in case of manual and semi-automated assembly lines. The need to "develop forward planning tools for employment and skills needs" has become urgent (EC, 2012). There is a need to incorporate the human component into traditional scheduling theory, and to assess the risk of MSDs in the most reliable way. With specific regard to the risk of upper limb MSDs (UL-WMSD) due to the presence of multiple repetitive tasks, as in assembly lines, the OCRA method is widely acknowledged (Colombini et al., 2002). Although several methods for determining risk factors for UL-WMSDs have been developed (Chiasson et al., 2012; Schaub et al., 2012), the OCRA method has been standardized by ISO (with ISO 11228-3 technical standard) and by CEN (with EN 1005-5 (2007), referring, in particular, to the safe design of machinery, under the scope of the EU "Machinery Directive").

Human labor has often been considered as the only cost effective alternative to expensive automated solutions, as well as an easily interchangeable highly flexible resource, able to adapt production capacity and to quickly change product features. Despite this, previously the influence of human behavior on production system performance has been underestimated. Ergonomic studies and human reliability measures have been widely investigated for production and safety related issues separately (Xu et al., 2012). Models are still far from being considered experienced and reliable, since an appropriate and complete description of human behavior is a complex task which has not yet been fully addressed. Complexity dimensions rely on individual, technological, organizational, and social factors. Learning, forgetting, recovery, and tiredness phenomena cause dynamic variability of human performance (e.g. task duration, human reliability in inspection tasks) (Jaber et al., 2013). Furthermore, at a given time during a work shift, human performance is uncertain and varies stochastically due to systemic and random factors (Digiesi et al., 2006, 2009).

In order to smooth workload and the related ergonomic risk among employees, to cross-train them at a low cost, and to increase productivity, job rotation is the most widespread labor flexibility instrument in the case of repetitive assembly tasks (Paul et al., 1999).

In this paper, the authors propose an OCRA-based mixed integer nonlinear programming (MINLP) model aiming at finding optimal job rotation schedules in work-environments characterized by low load manual tasks with a high frequency of repetition (e.g. assembly lines). The model aims at maximizing the production rate of the system jointly reducing and balancing human workloads within acceptable limits.

The paper is organized as follows: in Section 2 a review of scientific literature on models for job rotation scheduling in high repetitive manual tasks is introduced; in Section 3 the OCRA index for UL-WMSDs risk evaluation in multitask jobs is illustrated; in Section 4, the job rotation scheduling problem is formalized; in Section 5, a case study from the automotive industry is presented and discussed; finally, conclusions and possible extension of the work are in Section 6.

2. Ergonomic job rotation scheduling

Traditionally, assembly task assignment and ergonomic evaluations are carried out independently (Xu et al., 2012). Few researches jointly consider physical demands and completion time of tasks in assignment problems, and solve them using heuristic methods (Carnahan et al., 2000a, 2000b; Choi, 2009; Otto and Scholl, 2011). The integration of ergonomic aspects, as well as worker's skills, within traditional production oriented management tools will be crucial for future research (Battaia and Dolgui, 2013).

Repetitive manual work exposes operators to the risk of incurring WMSDs, especially when this work contains, for example, a high percentage of awkward postures or requires the application of force. Job rotation is considered as an appropriate organizational strategy to reduce physical workload (Paul et al. 1999, Boenzi et al., 2013a, 2013b) in human-based production systems (e.g. assembly lines), to prevent musculoskeletal disorders, to increase job satisfaction and thus productivity. Moreover, multi-skilled employees able to perform several tasks in different workstations during the same work shift are required in new hybrid assembly systems, as well as in traditional ones in order to deal with product variability, uncertain demand, and workers' substitution. Due to the heterogeneity in the composition of the labor force, assignment restrictions should also be taken into account.

Carnahan et al. (2000b) were the first in modeling and solving of ergonomic job rotation scheduling problems to prevent back injuries among operators by using integer programming and genetic algorithm. Tharmmaphornphilas and Norman (2007) propose a heuristic method for developing job rotation schedules to reduce the likelihood of lower back injury due to lifting. Seçkiner and Kurt (2006) define a solution procedure for the problem based on a simulated annealing algorithm aiming at minimizing the workload of operators. Azizi et al. (2009) develop a mathematical programming model to balance the effects of rotation intervals on workers' behavior. Costa and Miralles (2009) consider workers' heterogeneity and maximize the number of different tasks carried out by each worker, while maintaining productivity at reasonable levels; this approach has been extended recently using a Mixed Integer Linear Programming approach (Moreira and Costa, 2013). Finally, Otto and Scholl (2013) develop a smoothing heuristic integrated into a tabu search approach.

By following the OCRA ergonomic assessment method, Asensio-Cuesta et al. (2011) propose a genetic algorithm to balance the level of risk to workers caused by highly repetitive manual tasks and to obtain job rotation schedules preventing WMSDs. This genetic algorithm, called "Ergonomic and Competent Rotation" (ECRot), allows the inclusion of workers' competences in the model, in order to assign them different tasks during the work-shift.

Models available in scientific literature provide a solution to the ergonomic problem by considering productivity rate as a constraint. In this paper, the authors build a model able to solve both ergonomic and productivity problems. Through a dual approach, appropriate job rotation schedules are developed, making possible to both increase production rate and reduce the risk of MSDs for the most exposed workers. Features of the proposed model are the joint evaluation of both the overall attained production levels and of the OCRA indexes for workers, also taking into account the possibility of differences among classes of workers (in particular, in terms of task completion time) and individual risk limits. Finally, despite dynamic human performance variability in task execution (see Digiesi et al., 2006, 2009), in this paper a deterministic approach is adopted neglecting time dependent phenomena such as learning, forgetting, tiredness, and recovery. In fact, in the industrial context, the stochastic problem can be transformed into a deterministic one for relatively simple tasks, such as tasks characterized by short completion time (Becker and Scholl, 2006; Otto and Scholl, 2013). Furthermore, following traditional scheduling theory, task completion time is used as a human performance measure, rather than other tangible factors such as human error rate or human reliability.

3. UL-WMSDs risk evaluation in multitask jobs: the OCRA index

The OCRA is a method described in ISO 11228-3 standard that can be used to evaluate the possibility of risk of upper limb work-related musculoskeletal disorders (UL-WMSDs) for workers employed in low load–high frequency manual tasks.

These tasks often entail many adverse factors (high frequency of actions, awkward postures and movement of the upper limbs,

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