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Workforce Aging in Production Systems: Modeling and Performance Evaluation

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Abstract

Human factor is considered as a cost effective alternative to expensive automated solutions, as well as an easily interchangeable high flexible resource. However, for many years the influence of human behavior on production system performance has been underestimated and a lot of unrealistic assumptions have been used to simplify the human component modeling.
Nowadays, population aging is acknowledged as a global trend. Among individual factors impacting on workers' performance, high attention is being paid to the age from scientific community, policy-makers and business leaders.
The aim of this paper is to provide some highlights about the main scientific literature findings, regarding aging effects, in a quickly consultable and synthetic form; the elements characterizing human performance could then be included in models and ergonomic evaluation tools.
In the initial part of the paper, demographic aspects and their implications on workforce composition are illustrated; successively, a state of the art of human behavior modeling is provided and main findings on age-related performance characteristics are summarized.

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Keywords: Workforce Aging; Age-related Ergonomics; Manual Assembly lines

1. Introduction

Declines in both fertility and mortality rates result in population aging, a demographic trend consisting of an increase in the proportion of older people in the population. Nowadays, 11.7% of 7.2 billion persons in the world are aged 60 or over. One third of them resides in developed regions (i.e. Europe, Northern America, Japan, Australia and

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New Zealand), more than one fifth of the 1.25 billion people living there. By 2050, the global population aged 60 or over is expected to be more than double, reaching two billion persons (i.e. approximately 21% of the estimated world population). Almost 80% of them will live in developing regions, where the growth rate of the older populations will be four times higher than elsewhere. Nonetheless, developed areas, which will account only for about 2% of the world population growth, will continue to have the highest proportion of older (and oldest) people: one third aged 60 or over, one fourth aged 65 or over. At the same time, the three age groups under 60 (children and adolescents under the age of 20 years; "young" adults 20 to 39 years of age; "middle-aged" adults 40 to 59 years) will continue to converge and decline [1, 2].

Changes in population age composition are reflected in the available workforce age structure. In Europe, working population age trends indicate that the oldest age group (55–64 years) will expand by about 16.2% (9.9 million) between 2010 and 2030, whereas all the other age groups show a declining trend [3]. The employment rates of older workers (55–64 years old) are currently less than 50%, indicating that more than half of older workers prefer to retire earlier. Long-term health problems and chronic diseases increase with age. In Europe, musculoskeletal disorders are the most common occupational diseases (almost 40% of the whole) [4], and about 30% of jobs in Europe today involve poor work postures, handling of heavy objects or repetitive work [3].

From a socio-economic perspective, population aging may have drastic implications. The European Commission's "Active Aging" policy is helping people to stay healthy and in charge of their own lives as long as possible despite aging, in order to continue contributing to economy and society [5]. In fact, in most modern societies, older persons consume more than they produce, and one way to finance their consumption in old age is to work and hence receive labour earnings [1].

Similarly, business organizations are concerned about the potential loss of knowledge deriving from early retirement, as well as age-related declines in productivity. Globalized turbulent markets highly expose capital-intensive industries to the risk of unprofitable underutilization of capacity. Furthermore, the shift towards the mass customization manufacturing paradigm requires manufacturers' extreme production flexibility. However, despite improvements in technology, flexibility cannot be increased without a large contribution of the major flexibility enabler: the human workforce. In fact, in many cases automation is still far from providing reliable solutions at reasonable costs and flexibility is mainly provided by human dexterity and cognition in manual and cognitive tasks.

Today, among individual factors impacting on workers' performance, high attention is being paid to the age from both scientific community and manufacturers. Constrained labour flexibility, loss of efficiency and knowledge transfer are core cross-disciplinary issues in the aging workforce management. In new partially automated – hybrid human/machine mixed-model assembly lines, there is the need for a rethinking of cognitive and physical age-related workers capabilities from a managerial perspective (at the operational, tactical and strategic level).

Despite the need to develop straightforward planning tools for employment needs and skills has become urgent [6], still not enough has been done to incorporate the human component into traditional scheduling theory in the most reliable way possible [7]. Ergonomic studies and human reliability measures have been investigated for production and safety related issues separately [8], and discrete event simulation (DES) tools often neglect the human dynamic behaviour [9]. The aging workforce has to be appropriately modelled and then implemented into labour flexibility instruments, building age-related job rotation scheduling/line balancing tools able to integrate ergonomics into production scheduling [10, 11]. The integration of ergonomic aspects, as well as worker's skills, within traditional production oriented management tools will be crucial for future research [12].

In this article, a literature review about the aging workforce modelling in human-based production systems has been conducted. The authors aim at providing some guidelines to model and integrate physiological aging effects, which affect both health and productivity, in management tools. The next section is devoted to a state of the art in the human behaviour modelling. In the third section, main findings and gaps in research on age-related productivity are summarized. Finally, main general conclusions and future developments are reported in the last section.

2. Human behavior modeling

Huge literature provides models and techniques for describing both hardware and human components in manufacturing systems. Flow oriented techniques and models are so much experienced that can be considered highly reliable in describing hardware behavior. System performance can be predicted in a very effective and efficient way, and system design and management are relatively low complexity tasks that can be carried out by means of commercial sotfware tools.

A different situation occurs in modeling human components. An erroneous assumption in the design and management of human-based production systems is that human performance is easily predictable and stationary both in the short and in the long-term planning horizon. As a result, the influence of human behavior on the overall production system performance may be underestimated. Therefore, models and tools are needed to design and manage human-based production systems; in turn, human-based production systems require appropriate description of human behavior. Ergonomic studies, human reliability measures and models have been widely investigated by decades for production or safety related issues. However, available models and field information are still far to be considered experienced and reliable.

For many years, researchers have tried to model job performance in order to describe, measure and predict human behavior at work. However, individual work performance is a multidimensional latent construct not directly measurable, except by the dimensions and the indicators that constitute it [13]. In particular, if on the one hand the dimensions through which the individual work performance occurs are the same across jobs (e.g. job-specific and non-job-specific task proficiency), on the other hand the indicators that measure the work performance along each dimension may differ between jobs (e.g. work quantity, accidents, absenteeism). Recently, Koopmans et al. [14] first proposed a heuristic conceptual framework of individual work performance in order to better understand its construct. As in [15, 16], mainly two dimensions have been identified: task and contextual performance. The former can be defined as the proficiency with which the worker performs central job tasks [15]; the latter are individual behaviors impacting on the organizational, social and psychological environment in which job tasks are carried out [16]. In accordance with previous reviews, task performance still remains the first dimension of individual work performance.

Moreover, individual job performance indicators can be classified into organizational records and subjective evaluations [13]. Organizational records are considered to be more objective and can be further classified into direct measures of productivity (e.g. number of units produced, number of errors) and personnel data (e.g. lateness, absences, accidents, promotion rates). In manual repetitive production tasks, despite many indicators to assess individual task performance can be used, the task completion time is the most valuable individual task performance measure [17].

In addition to indicators, such as work quantity or quality, which are needed to measure job performance, the assessment of causal variables or determinants of performance variations is also needed to predict them. In regard to this, the theoretical framework for human performance modeling proposed by Baines et al. [18] represents a relevant contribution. Through an extensive review of literature, the authors aimed at finding key human centered factors or determinants that should be incorporated in simulation modeling tools for manufacturing systems. This screening identifies 65 factors affecting direct labor performance and classifies them into two categories: factors about the individual and environmental factors. On the basis of their relevance and measurability, a ranking is proposed: among 30 individual factors, age is ranked third.

In particular, individual factors include demographics (i.e. age and gender), physiology, skills, personal attitude to learn or forget, recovery and tiredness phenomena, in addition to personality and motivation. Learning, forgetting, recovery, and tiredness phenomena cause dynamic variability of human performance [19]. Furthermore, at a given time during the work shift, human performance is uncertain and varies stochastically due to systemic and random factors. Dynamic and stochastic variability of human behavior highly affects system performance (e.g. production performance like flow time, buffer level, work in process or safety performance like system failure rate, accident probability, magnitude of risk) [9].

Vice versa, environmental factors include all those factors beyond the employee's control, such as the technology, the physical work environment, and the organization. Technological factors rely on level of automation, ergonomics of work place, and nature of tasks. Nature of tasks differs according to the level of cognition, i.e. the content of information to be processed which lead to decision-making. Consistently, tasks are distinguished in cognitive and manual tasks, which are responsible for mental and physical fatigue. Organizational factors deal with organizational structure, job flexibility policy, working time models (i.e. distribution of rests), and operations management (i.e. workload assignments and job rotation schedules).

Identifying and quantifying each of these influences and the functional relationships between them is a complex task not yet fully addressed. For example, analytical and numerical simulation models are adopted in production-oriented investigations or event-tree or fault-tree techniques in safety-oriented analyses. Nonetheless, models normally require a huge amount of field data to provide reliable results, and such data are subjected to tight restrictions due to the confidentiality of information. This is the case, for example, of high repetitive manual tasks in assembly lines.

Lastly, human performance models can be classified into models of high- and low-level factors [20]. High-level models aim at representing complex interactions of psychological mechanisms impacting on job performance; low-level models aim at representing basal physiological mechanisms. In contrast to high-level models, low-level models are particularly appropriate for manufacturing simulation because they are relatively simple and may be applied to any individual regardless of specific work context. In Baines et al. [20], an age-related human performance model of low-level factors has been proposed. According to Warr [21], the authors represented the age-related percentage decrease in performance by using a rate of overall performance decrement, which increases task completion times at workstation.

In order to build more complex parametric models able to investigate multiple scenarios, main findings on physical and cognitive aging are summarized in the next section.

3. Age and productivity

Changes in workforce age structure may have an impact on production system performance or productivity. In assembly lines the higher the average age of the assemblers, the higher the risk they cannot meet all the requirements [22]. However, despite several reviews of aging and work productivity have been conducted, the link between age and productivity is still unclear due to the lack of enough empirical evidence. Productivity effects of aging are still difficult to be estimated.

Firstly, productivity is a system attribute rather than an individual one [23]. Even though many medical and psychological studies have tried to measure the average productivity of old employees, individual productivity can be considered dependent on factors such as technological changes and changing demand for skills, and on the social context and the labor market as well. Moreover, the individual dimension of productivity does not take into account the collective benefit deriving from cooperation among workers in working teams or the overall level of the factory productivity.

Focusing on the effects of aging on health, which incontrovertibly affect the individual job performance, key findings are that changes in cognitive and physical functions may occur over the life cycle.

Cognitive performance is affected by fluid and crystallized abilities, each one following relatively independent slopes across the lifespan. Fluid cognitive abilities, such as attention, perception, information processing speed, reasoning and working memory, tend to strongly decline with age, significantly by the age of 50 [24, 25, 26, 27]. Vice versa, crystallized cognitive skills, such as word fluency and vocabulary size, tend to remain more stable. Declines in attentional capacity and working memory may cause difficulty in learning new concepts, recalling uncommon operational procedures, switching tasks or performing concurrent activities. Despite the age-related decline in fluid intellectual abilities is acknowledged as a universal and substantially unavoidable phenomenon, similar for both men and women [28], Schaie and Willis [29, 30] first, and Ball et al. [31] later, demonstrated that it can be halted by specific training programs. Such programs can stabilize, or even reverse, declines in inductive reasoning, processing speed and memory.

Physical aging includes age-related declines in physical, physiological, perceptual and motor processes, and declines in abilities, such as dexterity, strength and endurance. In table 1, main findings are summarized.

Table 1. Physical aging.

Domain	Function	Performance variation	Source
Peak Force	Muscular Strength	It peaks (100%) between the ages of 25 and 30. By age 40, 95%; by age 50, 85%; by age 65, 75%	[32, 33, 34, 35, 36]
		It peaks at age 20, then decreases by 10% per decade until 60	[37]
		It decreases by 12-15% per decade after the age of 50	[38, 39]
Dynamic Actions with Force	Muscular Power	Decline 10% greater than decline in muscular strength between the ages of 20-80 years	[40]
Endurance	Aerobic Capacity	10% loss per decade. In machine-paced tasks, the standard rate demands 80% of the sustainable aerobic capacity of a 40-year-old worker	[41]
		It peaks in the 20s, and declines by 1% per year thereafter	[34]
		At age 65 it is 70% of that at age 25	[42]
		It decreases by about 5-10% per decade after the age of 25 years. After the age of 40, by about 10-15% per decade	[43]
		At age 40 cardiac output is 95% of that at age 30	[44]
Reaction Times	Behavioral Responses	Aged 66-or-over are 30% slower than aged 18-30	[45]
Awkward Postures	Flexibility	It decreases 20% to 30% from age 30 to 70	[46, 47]
Overall Performance	Physiological Function	It peaks at age 30, then declines by 0.75-1% per year	[48]
		20% loss between the ages of 40 and 60	[49]
		Cognitive and physical faculties peak at age 20, then declines by 1% per year	[50]

As in the case of fluid cognitive abilities, deterioration of physical qualities over the life cycle may be reduced through exercises and wellness programs. In work environments characterized by higher physical efforts, keeping workers healthy means increasing not only their abilities but also reducing the risk of injury. In fact, if on the one hand older workers have lower non-fatal injury rates, on the other hand when older workers do get hurt they need more time to recover and suffer fatalities at a higher rate [51]. In manual assembly jobs, characterized by highly repetitive short cycle operations, work-related musculoskeletal disorders tend to be more prevalent in workers aged from 40 to 60.

Fortunately, both decreases in cognitive and physical functions may be offset by experience. In [52] it was found that older workers may use experience to compensate for declines in physical endurance. Czaja [53] noted that experience makes up for cognitive deficiencies while technology reduces physical demands. In what may be called “Compensation Theory”, “experience is the primary determinant of job performance” [52].

It is to keep in mind that the summarized data refer essentially to measurable worker performances, put in relation with age; other factors which affect productivity (learning-forgetting phenomena, cognitive factors and socio-economical motivations) are much more difficult to quantify and involve more directly subjective and individual characteristics.

Conclusions

Rapidly aging societies constrain flexibility, and thus productivity, in human-based production systems. Nowadays, despite improvements in technology, the role of the human workforce is still crucial in flexible production lines. Physical abilities are still required in order to carry out more complex production stages not fully automated such as final assembly operations. Furthermore, cognitive skills are needed by workers to interact with new technologies and to be able to cope with organizational strategies such as job rotation. Therefore, the need for new organizational tools able to take into account age-related changes in workforce productivity is urgent.

In this paper, a survey on human behavior modeling in production systems and age-related changes has been conducted. In literature, it is highlighted how age can be considered one of the most important factors affecting individual task performance. Many aspects are involved in worker performance evolution with age, regarding both physical-physiological responses (muscular strength and power, aerobic capacity and endurance, reaction time) and cognitive capabilities. In any case, it is important to keep in mind that while, on the one hand, work-related musculoskeletal disorders are prevalent in highly repetitive short cycle operations, on the other hand, for more complex tasks, experience, built over years, can compensate age capabilities decline and can assume a predominant importance. Therefore, in production systems in general, choosing the best match between task and worker, aiming at the overall system performance, should be conducted on a case-by-case basis. For example, in Asensio-Cuesta et al. [54], with reference to a job rotation schedule case-study, couples of score tables are built considering on the one hand the job characteristics and on the other hand workers'abilities and limitations. In order to to do so, worker's profiling, on an individual basis, is necessary.

In existing manual assembly systems, the reported literature main findings could serve as general guidelines in order to forecast, approximately, ergonomic evaluation indexes, starting from a picture of the present situation and taking into account the age composition of the employed workforce. Managerial decisions could then be drawn about the priority of actions to be taken, regarding for example equipment improvement (providing tools for the automation of certain tasks, where possible) and/or job rotation and enrichment.

As Streb and Voelpel [55] stated, aging workforce management tools need to be customized, designed to match task requirements to individual changing abilities over time. Following the framework of Prskawetz et al. [56], future research could be also aimed at determining more reliable statistical relationships between aging and its impact on ergonomic risk indicators and job performance at the workplace, in order to forecast effects, assess the acceptability of the situation in the course of time, and so plan actions, such as workplace upgrading or gradual shift with younger personnel with a methodic approach.

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