CIRP ANNALS 2008
Manufacturing Technology

Adaptive automation and human factors in manufacturing: an experimental assessment for a cognitive approach

Doriana M. D'Addona[a] (2), Fabrizio Bracco[b], Andrea Bettoni[c], Nariaki Nishino[d] (2), Emanuele Carpanzano[c] (1), Alessandro A. Bruzzone[e] (1)

[a] *Department of Chemical, Materials and Industrial Production Engineering, University of Naples Federico II, Italy*
[b] *Dipartimento di Scienze della Formazione, University of Genoa, Italy*
[c] *Department of Innovative Technologies, University of Applied Sciences and Arts of Southern, Switzerland*
[d] *Department of Technology Management for Innovation, School of Engineering, The University of Tokyo, Japan*
[e] *Dipartimento di Ingegneria Meccanica, Energetica, Gestionale e dei Trasporti, University of Genoa, Italy*

Despite increasing automation levels and digital solutions, production systems still very much rely on the inescapable contribution of the human factor. The changing relationship between man, the technological system and the organization framework together with the increased complexity result in high risks for workers' safety and their psychophysical health. Adaptive factory automation and management solutions integrating the man in the loop are proposed in order to achieve production performance, workers safety and well being in a balanced way in varying boundary and exogenous conditions. Particularly, this paper presents new methods and the related recent case studies in different sectors.

Human aspect; complexity; man-machine system

1. Introduction

While automation in manufacturing dates back to the first industrial revolution, the increasing manufacturing systems' complexity and technology advancements require nowadays reliable tools to plan, assess, and drive the production chain in order to get the planned goals. Many methodologies have been developed to face the organisational aspects by considering the production plant capacity, customer demand and products characteristics [1, 2]. At the level of production shop-floor, the growing flexibility of production means calls for automation systems whose behaviour is driven by dynamically adapting management policies [3]. In the last fifty years automation evolved dramatically along several generations: from the direct involvement of workers in the manufacturing process, to intelligent automation systems where workers play a supervisor role [4]. Indeed, the introduction of new technologies impacts on the complexity of manufacturing system management and requires to promote harmonisation between automation and the human factors [5], especially considering the cognitive workload related to manufacturing operations at different decisional levels.

This paper proposes a methodology, validated in two selected industrial cases, to integrate cognitive workload into the design of workplaces to match the human safety and well-being necessities and tasks' cognitive requirements. Specifically, a new framework to classify the fabrication tasks of production processes according to their cognitive complexity and the required capacity enables an anthropocentric optimisation of the manufacturing activities.

2. Automation and human factors

2.1. Interaction challenges

Human factors and human performance limitations, resulting in errors and violations, are the main contributors to accidents and injuries in complex systems [6]. A common approach aimed at reducing this incidence has been to transfer to automation a variable portion of the tasks that were previously performed by the human operator.

Table 1. The continuum of shared responsibility between human and automation, adapted from [7].

Level of automation	Role	
	Human	System
1. None	Decide, act	None
2. Decision support	Decide, act	Suggests
3. Consensual decision	Concur	Decide, act
4. Monitored decision	Veto	Decide, act
5. Full automation	None	Decide, act

The shared responsibility between human and automation could be broadly located along a continuum, as represented in Table 1. Notwithstanding the successful integration, many issues occur when considering the relationship between humans and automation; the problems are essentially [7]:

- *Out-of-the-loop condition*: the difficulty of operators to have a clear and complete picture of the automation states and processes, lead to a diminished ability to detect possible automation failures and to regain manual control.
- *Surprising mode transitions*: operators may become unaware of changes in the operating mode performed by automation.
- *Skill loss*: pervasive automation will decrease the opportunity for training manual skills, which will be ineffective in case of an urgent manual control of the system.
- *Automation-induced errors:* while automation may compensate or reduce some typical human errors (counting, remembering, monitoring, etc.), more automation could lead to new, unexpected forms of human errors.
- *Behavioural adaptation*: automation may grow the perception of safety and operators could adapt their behaviour taking higher risks.

- *Inappropriate trust:* trust in automation could change according to the perception of its reliability. When this perception is biased, inappropriate trust will result as misuse, disuse and complacency.
- *Job satisfaction*: automation could be perceived as a threat to workers professional profile, especially when it is introduced without a proper transition and a management care for reskilling their workers.

In order to face the described issues, a comprehensive approach to map them and an effective strategy at different and relevant levels, is required. The identification of the intervention areas and gaps is a crucial step to build a coherent system capable to harmonize the automated components with their human counterpart. In current efficiency-driven contexts the cognitive level, that acts as the interface between human and automation, is responsible for the workload impacting the worker. Much of this impact is determined by the decisions taken in the design of the automation processes as well as by the organizational strategies; therefore, the organization level must be included in the analysis.

Table 2 shows the gaps and the involved processes for the cognitive, organizational and technological levels.

2.2. Design guidelines

Traditional approaches to enhance the human-automation interaction are based on the Fitts list [8] reported in Table 3. Such a list allocates functions considering the information processing stage and static conditions. A more effective approach should assign the functions according to the task, the operator, and the situation considering the system dynamics: adaptable automation allows the operator to decide the level of control according to the list reported in Table 1. Adaptive automation can change the control level by automatically adjusting itself to the operator's performance, operator's state and the system status [9].

The drawbacks of adaptive automation regard the task of continuously monitoring the operators' state and environment by using sensors. In addition, adaptive automation should be able to quickly change the automation level in a timely manner taking into account unpredictable operators responses. Furthermore, operators may abuse or misuse the adaptive automation for personal advantage, e.g. by slowing down the production pace.

Finally, if the adaptation pattern is not perfect, the operators may not understand it and could think the automation is performing erratically, thus increasing the likelihood of new forms of errors.

Solutions to minimise these drawbacks depend on the effective implementation of interfaces to support the operators' mental models of the system's state. Multimodal feedback could help the operator to gain awareness about the system, by means of multiple sensory cues such as haptic, peripheral visual, auditory, and tactile. Another solution is to design automation that can fit operators' mental models, instead of forcing them to change their expectations to the new operational modes. When automation involves networks of operators interacting with complex systems in a tightly coupled manner, small events may cause huge effects, due to the reverberation of signals along the network.

3. A new systemic model for man-in-the-loop automation

In order to represent operators' safety and well-being according to the recent findings and theories [10], a systemic model is required; the model includes the cognitive and physical well-being aspects of operators interacting with automation [11]. Basically, the main aspects are:

- the human operator: actions, errors, violations, mental models, expectations, skills, culture;
- the team: team cooperation dynamics;
- the organization: managerial decisions, policies, culture, vision;
- the physical environment: temperature, noise, layout;
- the social environment: external pressures;
- the tools: technology and automation level;
- the rules: procedures, guidelines, checklists, laws;
- the task: unexpected, habitual, repetitive, etc.

These features can be regarded as interacting, like fragments of a bowl that dynamically move in order to fill in the gaps that may arise at their borders (Figure 1).

Table 2. Cognitive, organizational, technological gaps and processes.

Gap	Process
Cognitive gaps	
C1: Interfaces could provide too much data and impair operators' situation awareness	Interface design
C2: Automation dynamics cause the out-of-the-loop condition, where operators have poor mental models about the system's states	Automation design
C3: High workload or excessive underload due to inappropriate integration with automation	Job design and automation design
Organizational gaps	
O1: Workers are assigned to jobs with marginal attention to matching their skills with the demand	Job design, job allocation
O2: Workers skills do not evolve to align with what is needed in automation-dominated working environments	Human resources management
Technological gap	
T1: Workplaces do not consider the specific anthropometric and functional characteristics of each worker	Workplace design, automation design

Table 3. Fitts list: relative strengths of humans and automation [12].

Information processing stage	Humans are better at...	Automation is better at...
Data acquisition	Detecting small amounts of signals Detecting a wide range of signals	Monitoring Detecting signal beyond human capability
Data analysis	Perceiving patterns Making generalizations Making innovative associations	Ignoring noise in data Making quantitative assessments Applying precise criteria Storing and recalling a huge amount of data
Action selection	Improvising, making flexible solutions Reasoning inductively and correcting errors	Repeating procedures consistently Reasoning deductively
Action implementation	Flexibly switching between actions Adjusting dynamically	Performing many complex operations in parallel Responding quickly and precisely

Figure 1. The well-being bowl.

The water in the bowl represents the operators' well-being, whose optimal level depends on the dynamic interaction among the main aspects of a system; well-being level is determined by the gaps that the fragments create at their borders.

Sometimes an action aimed at increasing well-being could take into account only one fragment; but changing just one part could lead to breaking the bowl if the other elements do not adapt to it.

Automation design should be guided by this model to promote harmonization of the fragments' behaviour by changing its role according to the degree of control (Table 1). Adaptive automation could provide a flexible fragment that copes with the inherent variability of the production system [9] coming from human and organizational factors, process changes and productivity needs. The constant adaptation enables the system to fill the gaps ensuring operators' well-being.

This vision can be translated into a framework that supports a seamless adoption of a man-in-the-loop automation approach reducing the risk of negative gaps. Basically, only by making the most out of the capabilities residing in the human dimension of the factory, it is possible to unleash automation's full potential and to enhance productivity and well-being.

Figure 2 shows the proposed man-in-the-loop automation system within the factory; the focus is not only on the optimization of production performances but it includes also the human operator as a full-fledged part of the whole process. However, it is not enough to consider the human dimension only as one of the controlled variables of the automation system; human dimension must be integrated into the management of the control loop to couple automation's efficiency with the flexible human mind set. This approach presents a twofold interaction:

- the human acts as a decision maker who works in synergy with the control system at a decisional level;
- the human acts also at operational level taking part to the controlled production process where the interaction is played on a more operative field.

The two different cooperation roles could trigger the risks listed in paragraph 2.1 and cause suboptimal results for the operators' well-being and the production performance. To reduce the risks and smooth their negative influences, each role requires a careful management taking into account its specificity.

The proposed man-in-the-loop automation framework requires to set goals specifically aimed at enhancing the working conditions by constantly monitoring a stream of physiological measures to detect in real time any deviations from personalized safe patterns and propose mitigation actions aimed at mediating or mitigating the cognitive demand that the worker is experiencing. It also requires reconfigurable automation policies that apply in the distributed automation structure [13] to explore and possibly eliminate the sources of cognitive gaps such as skill mismatching and alienating duties.

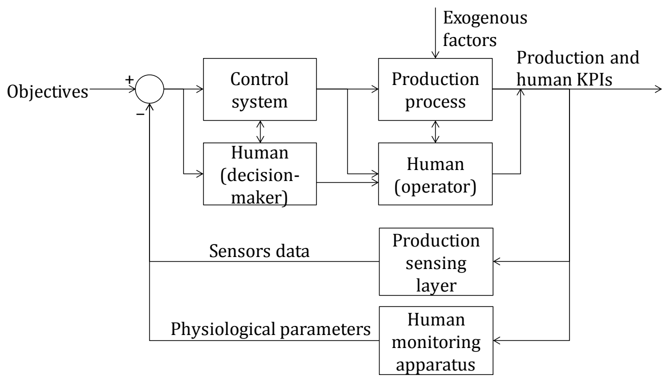

Figure 2. Framework for human-in-the-loop factory adaptive automation.

4. Model implementation in demonstration cases

4.1 Adaptive automation in air traffic control

Mental workload in air traffic management is a crucial factor for safety. Human errors typically occur both in underload and overload conditions, the former because operators are disengaged by the task, the latter because they are overwhelmed. In the interaction with automation, changing the number, quality, rate, dynamics of stimuli and data presented on the display is crucial to maintain a proper level of workload.

A passive Brain-Computer Interface (pBCI) was developed [14] in order to track operators' brain activity (EEG), which is considered a reliable, sensitive, real-time, and continuous measure of mental workload. The pBCI was integrated in an air traffic control simulator and was tested for its capacity to produce adaptive solutions in real-time, according to the mental workload measured by means of operators' brain activity. When operators' under- or overload is detected, the system automatically triggers adaptive solutions (e.g. displaying only critical alarms, highlighting the aircraft currently speaking, animating the icons related to a short term collision, and displaying only the aircrafts that are relevant for the task at hand).

The pBCI is able to activate adaptive automation solutions during high-workload scenarios, while it does not activate them during periods of normal workload, in order to avoid underload. In addition, the pBCI induces a decrease in the perception of mental workload by the operators when adaptive solutions are activated. Behavioural performance analysis demonstrated that the task performance significantly increased when adaptive automation solutions were triggered (Table 2: C3).

4.2 Automation in the white-goods industry

The white-goods industry is characterised by work-intensive production environments where humans are mainly employed to assemble a highly diversified range of products manufactured in continuously changing and relatively small lots. Such production and high production pace, due to the automation component of the line, poses serious cognitive demands to the workers.

The involved white-goods industry uses continuous flow production lines with a takt time fluctuating next to one minute and a number of product variants exceeding one hundred. In the past, the company tried to map the workforce capabilities (experience on the job, management of safety and quality aspects) in order to establish a personal skill matrix for each worker. However, the lack of a systemic approach to the human-automation interaction prevented any substantial improvement in adapting the workplaces, and the production system at large, to the characteristics and condition of the individual workers [15].

To overcome these obstacles and create human-centred workplaces, several tools have been introduced in three distinct phases: 1) knowledge creation, 2) production line design and 3) line operation [16]. The tools and the gaps are:

- the *KNOW Platform*, a shared repository based on a semantic representation of factory demands and workforce capabilities in terms of knowledge, skill, personal needs (KSN) and physical, intellectual and sensorial (PIS) capacities with the software infrastructure to support concurrent access of both data provider and data consumer tools;
- a set of *Worker Profilers*, to characterize individual workers, targeting an individual user and a specific area including: a scanning tool for anthropometric measurement (value stream manager), a three-step methodology and tool for the assessment of functional capacities (occupational doctor) and an integrated tool for the evaluation of skills, knowledge and personal needs (team leader);

- the *Job Designer*, allows to define the job content for each workstation considering and balancing, in a single environment, the production line from multiple perspectives including the cycle time as well as skills, functional capacities, and the ergonomic impact (Table 2: C3; T1; O1);
- the *Job Allocator*, a decision support tool based on linear optimization that suggests to the team leader, for each shift, the worker-workplace allocations by matching the skills, knowledge and capacities residing with those required by the production plan; the tool considers also the personal allocation preferences defined by the workers (Table 2: O1);
- the *Training Needs Detector*, a tool dedicated to the human resources management that reasons in the long-run by pondering the gaps between required skills in the production and those provided in the actual job allocations in order to identify persistent skill shortages towards the definition of personalized training paths (Table 2: O2).

For the validation of the new approach and developed tools, two lines, one for microwave ovens and another for fridge production, were modelled relying on the representation capabilities offered by the KNOW Platform. The single jobs at each workstation were designed trying at the same time: (i) to balance the workload by shifting the tasks among workstations to cope with the upper limit set at 90% of takt time; (ii) to distribute the tasks with critical requirements, to balance the cognitive burden and increase the possibility that a pool of workers can effectively and completely match the skill demand; (iii) to reduce the risk of musculoskeletal disorders due to ergonomically impacting tasks in some workstations. Job allocation tests were carried out off-line involving team leaders to compare their choices with those offered by the linear optimizer.

The improved workplace adaptability results in the reduction of cumulative trauma disorders and psychological stress. The availability of an all-encompassing digital solution capable to characterize, from a human-centric perspective, both workers and production lines allows to integrate all necessary human-related information and permits to support production facilities improvement in terms of skill-matching, ergonomics and safety. Furthermore, the integration of multi-perspective tools provides environments that promote awareness of all the human-related aspects at a glance, thus fostering first-time-right solutions and reducing the several design iterations that were necessary before. Finally, the long-term analysis of mismatch at the boundaries of human-automation interaction allows to redesign a more human-aware automation and to promote training activities to fit workers' profiles to automation needs.

5. Concluding remarks

In the context of emerging smart factories, the reported analysis examines the potential cooperation that can bring to a synergic human-automation solution when the roles are modulated on the basis of the automation level. The described industrial cases elicit the current issues experienced within an automation dominated environment that impacts production systems productivity and workers' well-being.

The proposed model for worker-aware adaptive automation shows how human well-being drivers are harmonised in the automation design. According to this model, well-being is achievable only by implementing adaptability and flexibility within a sociotechnical system; automation becomes the keystone of this human-in-the-loop adaptive approach to production. The new factory automation integrates seamlessly human and digital decision-making by monitoring production performances and workers' physiological parameters; this scheme permits the reintroduction of the man-in-the-loop within factory automation.

This new framework has been validated in the experiments carried out in two different domains showing respectively how:

1) a dedicated tool can relief mental workload while operating in the context of adaptive automation;
2) an integrated toolset, covering different phases of factory design and operation, can support human-centric automation.

The proposed automation model can address the identified gaps. The obtained results prove, qualitatively and quantitatively, that the integration of the human factors analysis, within automation design, is a compelling condition for a synergic improvement of manufacturing performance and human well-being at once. Specifically, the experimental assessment presented in this paper shows the effectiveness of the proposed model that permits to overcome the trade-offs of automated manufacturing environment and humans well-being through a synthesis of the technical and psychological tools.

Future work must employ methods and tools presented in this paper to face the gaps outlined in Table 2, in different manufacturing contexts and at any phase of the production process.

Nowadays the human-automation synergy is fundamental for a sound development of the innovative production scenarios according to new emerging paradigms, like Industry 4.0 or Society 5.0. Particularly, the acceleration of scientific and technological innovations will make the automation role more and more important and pervasive. Consequently, the future evolution of manufacturing industry should tackle the challenge to properly balance the industrial targets with the workers well-being, by means of human-in-the-loop adaptive automation systems.

References

[1] Vollmann, T.E., Berry, W.L., Whybark, D. C., 1997, Manufacturing planning and control systems. Irwin/McGraw-Hill.

[2] Hopp, W. J., & Spearman, M. L., 2011, Factory physics. Waveland Press.

[3] Carpanzano, E., Cesta, A., Orlandini, A., Rasconi, R., Valente, A., 2014, Intelligent dynamic part routing policies in plug&produce reconfigurable transportation systems. CIRP Annals-Manufacturing Technology, 63(1), pp. 425-428.

[4] Yamaguchi, K., and Kosaka, T., 2012, Transition of Machining System and the Latest Robot Cell, Journal of the Japan Society for Precision Engineering, 78(8), pp. 670-673 (in Japanese).

[5] Onnasch, L., Wickens, C. D., Li, H., Manzey, D., 2014, Human performance consequences of stages and levels of automation: An integrated meta-analysis. Human Factors, 56(3), pp. 476-488.

[6] Reason J., 1997, Managing the risks of organizational accidents, London: Ashgate.

[7] Endsley, M.R., and Kiris, E.O., 1995, The out-of-the-loop performance problem and level of control in automation. Human Factors, 37(2), pp. 381-394.

[8] Fitts, P. M. 1951, Human Engineering for an Effective Air Navigation and Traffic Control System, National Research Council, Washington, DC.

[9] Carpanzano E. and Jovane F., 2007. Advanced automation solutions for future adaptive factories. CIRP Annals - Manufacturing Technology, 56(1), pp. 435-38.

[10] Hollnagel E., 2014, Safety-I and safety-II: the past and future of safety management. Farnham, Surrey, UK, Burlington: Ashgate Publishing Company.

[11] Bracco, F., Brunel, C., Piccinno, T.F., Sedaoui, A., Tazi, D., 2015, Promoting safety through resilient organization managers: Different ways of being resilient, Proceedings of the Third SAF€RA Symposium, Paris, 9-10 Feb. 2015.

[12] Lee, J.D., and Seppelt B. D., 2006, Human factors and ergonomics in automation design. Handbook of Human Factors and Ergonomics, Third Ed., pp.1570-1596.

[13] Valente, A., Mazzolini, M. and Carpanzano, E., 2015, An approach to design and develop reconfigurable control software for highly automated production systems. Int. J. of Computer Integrated Manufacturing, 28(3), pp. 321-336.

[14] Aricò, P., Borghini, G., Di Flumeri, G., Colosimo, A., Bonelli, S., Golfetti, A., Babiloni, F., 2016, Adaptive automation triggered by EEG-based mental workload index: a passive brain-computer interface application in realistic air traffic control environment, Frontiers in human neuroscience, 10, 539.

[15] Bettoni, A., Cinus, M., Sorlini, M., May, G., Taisch, M. and Pedrazzoli, P., 2014, September. Anthropocentric Workplaces of the Future Approached through a New Holistic Vision, IFIP International Conference on Advances in Production Management Systems, pp. 398-405.

[16] May, G., Taisch, M., Bettoni, A., Maghazei, O., Matarazzo, A., Stahl, B., 2015, A new human-centric factory model, Procedia CIRP, 26, pp.103-108.