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Rethinking Jidoka Systems under Automation & Learning Perspectives in the Digital Lean Manufacturing World

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Abstract: This paper proposes *Jidoka* (automation with a human touch) as the main guiding principle for SMEs digital transformation; understood as the continuous increase of levels of automation and intelligence at their shopfloors in an economic, social and technological sustainable way. It stresses the forgotten dual nature of *Jidoka* as an 'automation approach' as well as a 'learning system', capable of simultaneously improving the efficiency of manufacturing processes and cultivating the workforce skills needed to develop and/or adopt advanced automation solutions. The paper aims to remind the developers of automatic control systems in the Industry 4.0 era that it is only through human-machine mutual learning, characterized by cyber-physical-social interactions (cf. *Jidoka 4.0 Systems*), that sustainable higher levels of automation and intelligence can be achieved. Human operators need to know the processes that are being automated, so that, at the same time, this knowledge can be continuously updated and processes improved as digital technologies evolve: "Incorporating human learning, gives automation its human touch".

Keywords: Jidoka Systems, Digital Lean Manufacturing, Cyber-Physical Systems, Lean Automation, Balanced Automation, Autonomation, Human-Machine Mutual Learning, Machine Tools 4.0, Human-Machine Interfaces 4.0, Operator 4.0, Industry 4.0.

1. INTRODUCTION

This paper has been inspired by Bainbridge's (1983) work on the *"Ironies of Automation"* and its criticism that developers of automatic control systems do not take appropriate account of the human beings that will ultimately use and interact with their systems. A criticism levelled more than 30 years ago, which it is still considered valid today, see – e.g. Baxter et al. (2012) and Strauch (2017). For example, Eason (2001) highlighted in his research that the ten most advocated *user-centred design methods* for Information and Communication Technologies (ICT) systems developments, seen as socio-technical systems, found in the scientific and grey literature were being limited used by their developers. This situation has specific and significant relevance in the context of SMEs' manufacturing systems evolution towards *"Cyber-Physical Production Systems"* (cf. digital and smart manufacturing systems) in the new Industry 4.0 era, as SME managers will need to make well founded decisions on the type (i.e. cognitive and physical) and level (i.e. from totally manual to totally automatic spectrum) of automation solutions to be developed and/or adopted, and on the proper integration of human beings (cf. operators) to their production systems during their digital transformation journey – as they follow a maturity model. Therefore, SME managers face the challenge of capturing at each maturity stage the idea of an appropriate type and level of automation, a *"Balanced Automation"* solution (Camarinha-Matos et al., 1995-97), when considering their manufacturing competitiveness drivers for flexibility, quality improvement, and productivity, but taking into account their well-known economic limitations and best use of their human operators (Romero et al., 2015), when progressing towards unmanned manufacturing systems.

In this progression, the role of humans in manufacturing environments has evolved from human operators loading, operating and unloading machines in the Industry 2.0 to more decision-oriented activities such as systems' supervision in the Industry 3.0 and 4.0 eras. Nevertheless, the adoption of new types and higher levels of automation at the shopfloor has historically been not that easy and inexpensively for SMEs when it comes to replacing skilled operators at their production lines and/or manufacturing cells as observed during the Industry 3.0 or CIM era.

In this context, we would like to revisit and reflect in this paper about two well-known automation approaches and their possible integration: *"Lean Automation"* (Chen et al., 2010) and *"Balanced Automation"* (Camarinha-Matos et al., 1995-97) – in order to socially, technically, and economically support SMEs in the further development and adoption of *"Autonomation"* solutions defined as 'automation solutions with a human touch', and known as *"Jidoka Systems"* in the lean manufacturing world (Ohno, 1988). The reason, we strongly believe that an *"Autonomation"* approach can serve as a stepwise development and adoption strategy towards higher levels of automated and mistake-proofing operations, and a polyvalent *"Shojinka"* (cf. multi-task and multi-skill) workforce at the SMEs shopfloor.

2. AUTOMATION APPROACHES REVIEW

In this section, we discuss in detail the complementarity of *"Lean Automation"* and *"Balanced Automation"* approaches towards cost-efficient and human-inclusive "*Autonomation* or *Jidoka Systems"* for manufacturing SMEs.

Lean Automation – is about applying the right amount of automation to a given task; stressing the robustness, reliability and simplicity of the automation solution (Chen et al., 2010).

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Furthermore, *Lean Automation* challenges automatic control systems' developers with the following solution requirements according to Jackson et al. (2011): (a) choosing the right level of automation as well as the right automation solution-type, (b) developing automation solutions, which are flexible and reconfigurable in order to adapt to new demands during their lifecycle, (c) handling complex equipment without being an expert through intuitive user interfaces, and (d) changing and implementing changes in a given automation system solution in an agile way.

Balanced Automation – is about addressing a manufacturing environment, e.g. a SME shopfloor, with the right combination of anthropocentric, technocentric and economic approaches, with the adequate weights, and the achievement of a right balance between automated, manual and hybrid automation solutions to design or re-engineer a production system in order to satisfy different local environment requirements and criteria (Camarinha-Matos & Afsarmanesh, 1996). Hence, *Balanced Automation* solutions represent a true challenge for automatic control systems' developers since the development of hybrid balanced solutions to cope with a variety of automation levels and manual approaches at the shopfloor is a much more challenging than developing purely automatic solutions (Camarinha-Matos & Afsarmanesh, 1997).

Autonomation – was a concept coined by Ohno (1988) in order to originally describe a type of automation that enables machines to work harmoniously with their human operators and features intelligent capabilities by automatically stopping a process, by man or machine, in the event of an abnormally, a problem, such as equipment malfunction, quality issues, or late work (Baudin, 2007). Moreover, *Autonomation* stresses the application of usability engineering principles to human-machine interfaces in order to reduce training costs, enable the human operators to become multi-skilled, and prevent mistakes when interacting with automation systems (Baudin, 2007).

3. JIDOKA SYSTEMS EVOLUTION

"Jidoka" stands for both a technique and a system in the lean manufacturing world (Ohno, 1998). As a *technique,* 'Jidoka' describes a set of automation systems' design principles that aim to separate human activity from machine cycles in order to allow a human operator to attend multiple-machines, preferably in different types of working in sequence and as a *system,* 'Jidoka' is a specific system (or sub-system) in a machine that detects abnormalities and further controls feedback by means of *"Andon"* alarms (Baudin, 2007).

First Generation *Jidoka Systems,* or 'Jidoka 1.0 Systems', were characterised by mechanical gadgets, known as *"Poka-Yokes"* in the lean manufacturing jargon, capable of detecting an undesired or an abnormal state in a manufacturing process, and stop it so as not to produce a defective product. Later on, Second Generation *Jidoka Systems,* or 'Jidoka 2.0 Systems', were upgraded and characterised by the addition of an *"Andon"* visual and/or audio alarm features in order to effectively notify human operators about a quality or a process problem in a manufacturing process. With the advancement of operational technologies, a Third Generation *Jidoka Systems,* or 'Jidoka 3.0 Systems', emerged. These systems are characterised by new hardware- and software-enabled features capable of not only detecting, but supporting human operators in the fault diagnosis of the problem at hand by means of analog and digital sensor signals processing and error code lists, also known – 'Jidoka rules'. Currently, with the emergence of the Industry 4.0 technologies (viz. IoT, CPS, Edge), a Fourth Generation *Jidoka Systems,* or 'Jidoka 4.0 Systems', has started to arrive to the shopfloors characterised by diverse software and hardware components such as sensors, actuators, controllers and advanced analytic capabilities able now to early-detect and diagnose a problem, and in some cases correct it before it actually occurs.

4. DEVELOPING A POLYVALENT "SHOJINKA" WORKFORCE AND INCREASING AUTOMATION BY MEANS OF JIDOKA SYSTEMS

An *"Autonomation"* approach can be seen as a more affordable approach for SMEs digital transformation, and can allow at the same time an up-skilling and/or re-skilling phenomenon at their workforce due to a 'balanced combination' of *full automation* and *autonomation* at their manufacturing cells and production lines, where: (a) 'automation' – can takeover already standardized manufacturing processes with low-probabilities of abnormality, and (b) 'autonomation' – can assist operators and automatic control systems' developers in the standardization and gradual full automation of still unstable processes with semi-automation solutions, allowing humans to be assisted by smart gadgets (e.g. *"Digital Poka-Yokes"*), and *Jidoka Systems* to be progressively perfected in a human-machine mutual learning process. Such 'mutual learning' (see Ansari et al., 2018a) will result in well-designed automation systems, addressing the *"Ironies of Automation"*. It will enable cooperation between 'automation systems' and 'human operators' in a balanced automation manufacturing environment (e.g. a SME shopfloor) and facilitate the creation of a competent workforce with 'multi-skills' for detecting, investigating and eliminating wrong techniques, unaccepted operation variations, raw materials defects, and machine and/or human errors in manufacturing operations.

4.1 Autonomy and Learning in Human-Machine Systems

According to Vanderhaegen (2010), the control of autonomy and the possibility of 'mutual learning' in human-machine systems, such as *Jidoka Systems,* requires the application of two main knowledge and automation management strategies. The first strategy refers to and it is based on the management of *"static knowledge"* – defined as 'know-how' that relates to the knowledge already in the human-machine system (i.e. its *Jidoka rules*). It controls the optimal balancing between the decisional autonomy of human operators and the automated (machine) system in order to make the global human-machine system autonomous. The second strategy refers to and it is based on the management of *"dynamic knowledge"* – defined as 'know-how-to-cooperate'. It makes cooperation activities such as human-machine mutual learning possible, allowing to control dynamically the autonomy of a given human-machine system by the other sub-systems. Namely, the *Autonomation sub-system* responsible to manage the autonomy of the machine sub-system in case of automation degradation or new abnormal situations, and in such cases, alerting and transferring control to the human operator, including the available information at the machine about the problem at hand (e.g. via incorporated troubleshooting support tools). This in order to support the human operator in detecting, investigating and eliminating the issue. And the *Automation sub-system* itself with the 'autonomisation capabilities' of auto-learning (e.g. machine learning) about the problem at hand (self-diagnosis) and solving it based on same and/or similar error occurrences troubleshooting solutions.

4.2 Better Human-Machine Interfaces for Mutual Learning

Human-Centred Automation is defined as automation designed to work cooperatively with human operators in pursuit of stated objectives (Billings, 1996) – such as human-machine mutual learning in the case of modern *Jidoka Systems.* Thus, *Human-Centred Automation* emphasizes that automation functionality should be designed to support human performance and human understanding of the automation sub-system in human-machine systems. In order to do so, *Human-Automation Interaction,* or cooperation, is needed and is defined as the way human operators control and receive information from an automation (sub-)system, and how an automation (sub-)system receives and processes inputs from the human operators (Sheridan & Parasuraman, 2015). Moreover, *Human-Machine Interfaces* are defined as interfaces that allow user inputs to be translated into signals for machines, and machines in turn to provide required results to the user, the human operator, ranging from knowledge discovery to information visualizations in multiple forms (e.g. digital dashboards, augmented reality, virtual reality) (Sheridan & Parasuraman, 2015).

Within modern *Jidoka Systems, Human-Machine Interfaces* should be designed and engineered as innovative 'feedback sub-systems' capable of facilitating the mutual learning of humans and machines. According to Ansari et al. (2018a), new and improved *Industrial Internet of Things (IIoT) sensors* (viz. delay, proximity, vibration, pressure, torque and angle, humidity, temperature, voltage, caliper, current, liquid level, flow, RFID, machine vision, etc.), and *Artificial Models* and *Computational Algorithms* can facilitate different machine learning approaches based on: (a) supervised algorithms – which "assume that their training examples are classified or labelled (i.e. learning relationships between a set of descriptive features and a target feature are predefined)", (b) unsupervised algorithms – which "training examples are unclassified (i.e. learning relationship are not predefined)", (c) semi-supervised algorithms – which "use unlabelled data with a small amount of labelled data to improve learning accuracy", and (d) reinforcement algorithms – which "employ different scenarios for discovering the greatest reward action in a trial-and-error process by collecting feedback from the environment" (see Fürnkranz et al., 2012), and machine learning strategies based on (a) information-based learning – "employing concepts from information theory to build models (e.g. decision trees)", (b) similarity-based learning – building a model based on similarities between objects or past and forthcoming occurrences (e.g. K nearest neighbour)", (c) probability-based learning – "building a model based on measuring how likely it is that some event will occur (e.g. Bayesian network)", and (d) error-based learning – "building model based on minimising the total error through a set of training interfaces (e.g. multivariable linear regression) (see Kelleher et al., 2015). While novel *cyber-physical interactive devices* merging the cyber- and the physical- worlds, such as *Augmented Reality, Virtual Reality* and *Haptic technologies,* can facilitate the learning and training of the human operator in human-machine mutual learning systems (e.g. Digital Assisting Systems – see Hold et al., 2017). The great advantage of using *Augmented Reality* for learning and/or training is that human operators can interact with the real world 'physical' objects and simultaneously access virtual (real-time) information for guidance in their field-of-work and field-of-view (see Webel et al. 2013). Furthermore, *Virtual Realty* offers a three-dimensional and interactive environment, which provides enhanced visualization, interactivity and free exploration of complex 3D-objects and their environment (Li et al., 2003). Therefore, enabling human operators to better understand, e.g. maintenance and troubleshooting procedures of a machine tool in safe environment (see Bao et al., 2018). In addition, *Haptic Technologies* can assist human operators with 'haptic hints' (vibration stimuli) for task comprehension in both realities environments. Moreover, these technologies and their devices can support 'lean practices' such as: Just-in-Time (JIT) information provision, Total Quality Management (TQM), and Total Productive Maintenance (TPM) (see Mora et al, 2017; Romero et al., 2018; Romero et al., 2019).

5. EXEMPLARY CASE

Due to the Fourth Industrial Revolution, SMEs face the need of an upgrading process towards developing and integrating Machine Tools 4.0 (Xu, 2017), Human-Machine Interfaces 4.0 (Papcun et al., 2018), and human Operators 4.0 (Romero et al., 2016a, 2016b). In order to facilitate this upgrading process in an affordable way for SMEs, *Jidoka Systems,* understood as a technique and a system as well as a sustainable automation and learning approach, will guide the 'retrofitting' of machine tools and manufacturing cells at SMEs' shopfloors in order to increase their self-awareness, self-maintenance, and self-optimisation capabilities.

While upgrading machine tools and manufacturing systems is not novel in itself, and is done on a regular basis across industries, using *Jidoka* as a guiding principle can help to eliminate unnecessary complexity and/or expenses while at the same time ensuring the envisioned return of investment on integrated 'automation' and 'autonomation' solutions. In the following, we will briefly discuss an exemplary case of upgrading (retrofitting) a CNC machine tool using the *Jidoka* principle.

In case the of a CNC machine tool, we are interested in identifying and predicting potential issues before they occur. This is in line with a 'predictive maintenance' framework. In this situation, we focus not only on the capability, but also on the cost, complexity, and 'ease-of-use'. One common issue for CNC machine tools is the prediction of tool-wear (e.g. see Sezer et al., 2018). Changing the tool too late, the wear can cause quality issues for the products manufactured. Changing it too early implies that we waste valuable manufacturing resources. While for large batch-size production, experience- or model-based tool-wear predictions are available, this is not the case for a highly-flexible production (small batch-size) that we commonly find on SMEs' shopfloors. However, in those cases, the tool-wear is a highly desirable information input to ultimately reduce resulting scrap parts and other quality problems.

Using the *Jidoka* principle, we first utilize the information that is available in the machine tool. In the case of modern CNC machine tools, several sensor readings of e.g. tool-path, dynamometer readings, etc. are available. When access to this information is an issue, installing a single board computer (e.g. Arduino, Beagle-bone, or Raspberry-pi) based 'bridge' to access and communicate the sensor readings from the PLC to a cloud-based system is a first step. Following, we can analyse the behaviour and develop a machine learning based tool-wear prediction algorithm that is solely based on the already included sensors (e.g. Lenz et al., 2018). If that is not possible for reasons such as missing sensors in the machine tool, we can additionally utilize low-cost additional sensors (e.g. the aforementioned vibration sensor or acoustic sensors) to augment the original readings. The single board computer can be used to combine the two incoming readings. Once we have a working tool-wear prediction model, we create information on the current system state. If this state deviates from the target, an action must be taken. An essential element of 'cyber-physical systems' is their capability to take action by themselves, so freeing the human operator from simple, repetitive tasks. For example, tool-wear can be automatically adjusted or the tool automatically replaced. Only when action is of high importance, as indicated by different pre-established trigger levels (see Zhang et al., 2018), the human operator must intervene. In this case, the interaction between the information system and the human operator is crucial. We need to ensure that the tool-wear prediction is put in context of the production plan (a.k.a. can the next part be safely manufactured with a high probability?), the maintenance resources (a.k.a. do we have capacity and replacements available when the change needs to happen?), and first and for most include this information in the workflow of the human operators. Here, *Augmented Reality glasses* are a possible approach, however, a simple text-based system (e.g. a SMS to a mobile phone) directly pushing the notification to the human operators' handheld devices is already a significant step forward.

6. DISCUSSION

Based on the literature review and field-research (cf. *Gemba walks*) conducted for writing this paper, it was striking to found out how *Jidoka*, as one of the two pillars of *Toyota Production System (TPS),* has been limited studied and merely reduced to the single idea of "stopping a process, when an abnormality has been detected, so processing defects can be avoided". *Jidoka* is much more than "error catching", it is an essential principle, a method to create a 'learning organisation' able to continuously improve the quality of its (manufacturing) operations and develop a conscious and continuous learning system in its workforce.

Such learning system, at organisational and individual level, supports ten of the ten fundamental skills needed to work at todays and future manufacturing environments, according to the World Economic Forum report on "Future of Jobs – The 10 skills you need to thrive in the Fourth Industrial Revolution" (WEF, 2016): (1) complex problem solving and (2) critical thinking – since in a *Jidoka* process, once a problem has been identified at its site (cf. *Genchi Genbutsu*), it will be deeply analysed (e.g. using the Five Whys tool) and solved with a countermeasure intended to permanently eliminate the root-cause of the problem; (3) creativity and (4) cognitive flexibility – since *Poka-Yokes systems* design, part of *Jidoka Systems,* requires science, but also art, in order to create innovative solutions to detect and avoid errors; (5) people management, (6) coordinating with others and (7) negotiation – since a *Jidoka* process calls for bringing together all problems and their potential solutions to all those affected to gather their ideas and get agreement on a solution (cf. *Nemawashi*); (8) judgment and decision-making – since a *Jidoka* process involves making a conscious decision between 'automation' and 'autonomation'; (9) emotional intelligence – since *Jidoka* respects the people and recognises human capability within an automation system; and (10) service orientation – since *Jidoka Systems* serve both internal and external customers, since 'autonomation' gives human operators more time to focus on high value-added activities and (external) customers products with superior quality.

As a final point, human-centred automation systems, such as *Jidoka Systems,* together with the advances of Industry 4.0 technologies, will result in better human-machine cooperation systems characterized by cyber-physical-social interactions, knowledge exchange, and reciprocal learning, which we can refer to as *"Jidoka 4.0 Systems"* (Ansari et al., 2018b).

7. CONCLUSIONS

From an *Automation* perspective, and a *Lean Automation* view, employing modern *Jidoka Systems* effectively can allow SMEs to tackle the waste(s) of making defective products, and support the needed automation flexibility to enable a competitive high-mix, low-volume production, and from a *Balanced Automation* view, *Jidoka Systems* can help SMEs managers to strategically manage their limited financial investment for automation due to economic and workforce constraints during their digital transformation journey towards SMEs 4.0. Moreover, from a *Learning* perspective, and an *Autonomation* view, modern *Jidoka Systems* will enable a 'continuous improvement' of SMEs manufacturing systems' flexibility, production quality, and productivity, and a 'continuous learning' of the workforce, since *Jidoka Systems* aim to develop and enhance human capabilities, rather than their immediately replacement for full automation solutions. Thus, allowing SMEs to rise the complexity of their manufacturing systems at the same time they rise the qualifications of their workforce.

In this paper, we have advocated for a gradual introduction of full automation operations of formerly manual functions in order to allow the workforce to drive the change towards semi-automated and/or fully-automated processes based on their manufacturing processes knowledge. Through a gradual development and/or adoption of *Jidoka Systems,* instead of adopting directly full automation solutions, we believe SMEs can found a sustainable approach to support learning in their workforce, streamline their manufacturing processes and boost their productivity in an affordable way.

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