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An Assessment Tool for Digital Enhancement of Operators on the Production Shop Floor

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Abstract

The Operator 4.0 represents a relatively recent paradigm and research field within the transformation potential heralded by the promises of Industry 4.0. However, there is a lack of practice-oriented tools, grounded in sound theory, to support manufacturers to implement the Operator 4.0 successfully. To narrow this gap, this paper presents the assessment tool developed within the «Digitally Enhanced Operator» project. The tool covers 3 areas of analysis: Work Organization & Shop Floor Characteristics, Operators' Situation Awareness & Decision Making, Technological Support. A set of dimensions and a four-level maturity scale are defined. This work contributes to advance our knowledge and to help manufacturers consider the Organizational, Human and Technological aspects in their journey toward the Operator 4.0, a foundational building block of the Industry 4.0.

Keywords: Operator 4.0; Industry 4.0: Digital Maturity; Situation Awareness; Decision Making; Maufacturing

1. Introduction

The Industry 4.0 vision, grounded on the integration of key technologies and Cyber-Physical-Systems, is expected to profoundly transform manufacturing enterprises. According to [1], Industry 4.0 can be subdivided into three main paradigms: the smart product, the smart machine and the augmented operator.

When a manufacturing company considers their roadmap towards successful digital transformation, the evidence captured in the literature demonstrates that the focus has been mostly on the smart product and the smart machine [1]. A clear example is that readiness indexes and maturity models, which identify incremental levels of implementation of these paradigms in manufacturing enterprises, have been also proposed (e.g. [2]).

Besides, the concept of the augmented operator or Operator 4.0, defined by [3] as "smart and skilled operator who performs work aided by machines if and as needed", represents a relatively recent paradigm and a growing research field combining several academic disciplines [4].

According to this human-centric view, Operators play the key role of strategic decision-makers and flexible problem-solvers [5] in the context of increasingly complex, socio-cyber-physical manufacturing systems [6]. Indeed, their effectiveness increasingly depends on situation awareness [7] and interventions developed by leveraging on and collaborating with the artificial systems from the initial understanding of the situation to the final decision and performance [3], [5].

To date, [8], [9] proposed a maturity model focused on Operators 4.0 but aiming at investigating their proficiency on a set of Industry 4.0-related skills and competencies, while neglecting the other enablers to support the Operators 4.0.

Therefore, notwithstanding the relevance of the above-mentioned contributions, it can be highlighted a lack of actionable models and tools, which are theory-based and practice-oriented, that can enable manufacturing companies to move forward the Operator 4.0 paradigm and implement it successfully [10], [11].

With the aim of narrowing the current gap, this paper presents a practice-oriented tool grounded in theory to assist manufacturers in their implementation of the Operator 4.0 paradigm. The proposed maturity model and assessment tool were developed within the «Digitally Enhanced Operator (DEO)» project by following the method proposed by [12].

The rest of the paper is structured as follows. First, the DEO project is briefly described to provide the much necessary context to understand the identified need and the scope that needed to be addressed. Then, the research methodology, the assessment tool and a preliminary application case are described. Finally, the contributions of our study and directions for future research are outlined.

2. The "Digitally Enhanced Operator" project

The DEO project aims to radically strengthen the abilities of the production shop floor operators, focusing on 3 interrelated areas to build a human-centred production organization: Autonomy, Situation Awareness and Teamwork.

So far, production managers have been responsible for the holistic coordination of production. An autonomous approach supported by enabling technologies should be established to enable the operators with the right level of autonomy and responsibility to make decisions. To increase the responsibility of the operators in production, there is need for continuously updated production status, implications of status, and precise projections of what will happen in the future. In other words, the operators need support to obtain good situational awareness. This also includes reducing the exposure of the individual operators to information they do not need. At the same time, operators depend on effective coordination in their teams to take a larger area of responsibility. This is hampered by the fact that the team members can be spread in time (working different shifts), rooms (working different places in the factory) and skills (cross-functional teams). The digitally enhanced autonomous operator therefore needs new mechanisms for effective coordination in his team.

The focus of the DEO project is thus on how to enhance the operators on the production shop floor by utilizing enabling technologies, but without a clear method or tool to support the analysis phase of the digital transformation journey, the DEO project characterized the need for developing such assessment tool. The purpose of the maturity model and tool is to analyze and evaluate the level of digital support given to the production operators in their daily activities and tasks, and point out the needs and priorities for digitalization efforts on the production shop floor toward the Operator 4.0.

3. Research process for the development of the DEO maturity model and assessment tool

With the focus of addressing the identified gap pertaining maturity models and tools supporting the transformation of an organization to adopt the Operator 4.0 paradigm, the approach taken in this study was to choose from the literature an existing structured approach for building a maturity model assessment tool (e.g. [12]–[15]). Among these contributions, the framework proposed by [12] was taken as reference for the current work, as it provides a step-by-step guideline based on the six main phases reported in Table 1 (i.e., scope, design, populate, test, deploy and maintain).

Table 1 Research Process

Phase by [12]	**Description**
Scope To define to which domain the maturity model is applied and main goal(s) (i.e., descriptive, prescriptive and comparative)	DEO maturity model and assessment tool allow to assess the current status of operators working directly on the shopfloor of those manufacturing companies willing to embrace Industry 4.0 (i.e. descriptive goal) and, to provide them guidelines through successful cases to further exploit Industry 4.0 potentialities (i.e. prescriptive goal).
Design To determine the design or architecture for the model to meet the intended audience needs	Following state-of-the-art research, DEO maturity model is structured as a multi-dimensional maturity model in which dimensions are organized hierarchically. Maturity is represented as four stages where higher stages build on the requirements of lower stages.
Populate To define what needs to be measured in the maturity assessment and how this can be measured	A review of extant scientific literature related to the "Operators 4.0" was performed to identify the analysis dimensions, appropriate questions and the maturity level descriptions.
Test To test both the construct of the model and the model instrument for validity, reliability and generalizability.	An online focus group involving the research team and 3 external experts was organized in June 2020. The experts involved are research scientists with over 20-years-experience on manufacturing industry, and industry-driven research projects. A pilot application of the assessment tool was performed in GKN, an aeronautic manufacturing company.

Deploy Application of the maturity model in target companies.	The model deployment is on-going. Results will be shown in future works.
Maintain To maintain the model's growth and use	The model maintenance will always be an on-going activity to ensure the alignment of the tool with companies' needs and research updates.

4. The Assessment Tool for Digital Enhancement of Operators on the Production Shop Floor

4.1. DEO maturity model

The proposed maturity model and assessment tool cover three main areas of analysis:

- Shop Floor Characteristics and Work organization, which is related to micro-/macro-level work organization [16] and shop floor contextual variables.
- Operators' Situation Awareness and Decision Making, which focuses on situational awareness, autonomy and decision-making aspects in real life production environments [17]
- Technological Support, which refers to the services enabled by Industry 4.0 technologies that provide direct support to human activities and to the fulfilment of human needs [10], [18].

Within each of the three above-mentioned areas, 20 dimensions and related questions are defined by leveraging on state-of-the-art research. Furthermore, a four-level maturity scale is outlined, and a description of each level is illustrated in terms of major requirements and measures for the level. They are described in the followings and some examples provided in Table 2.

- Shopfloor Characteristics & Work organization

The first three dimensions relate to the shop-floor environment, organization and work-related aspects of the manufacturing company. Analysing these grounding dimensions allows to provide more effective and coherent suggestions for improvements.

With respect to the shop-floor environment, complexity, uncertainty and flexibility are key aspects to take into consideration. Complexity relates to highly customised products with tailored characteristics and high number of complex processes; uncertainties refer to both processes and demand; flexibility concerns alternative parts, resources, routings for different products.

Regarding work organization, it is important to highlight that Industry 4.0 aims at the full digital integration of whole manufacturing processes in the vertical and horizontal dimensions. Moreover, according to [11] and [16], in smart factories with higher levels of technological complexity, operators are empowered through higher levels of task variety and job autonomy, and the cognitive demand they experience increases. In addition, team working and higher interaction are fostered in digitalized production environments because the information flow and the interdependency between different activities increase [19]. Finally, operators will have more flexibility in terms of time and physical location of the work.

- Situation Awareness & Decision Making

Operators will have more decision making and problem-solving tasks in the highly automated and digitalized factories of the future [17]. To make effective (i.e. timely and appropriately) decisions, operators will need to collect information from different elements of the shop floor environment, such as the status of orders, machines, inventories, interconnected departments, etc. depending on the context of the decision making [20]. Obtaining all needed information will form their Situation Awareness (SA) which is described as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" [21]. There are mainly three levels of SA defined for operators, according to Endsley. At the most basic level, "Perception" allows the operator to observe physical quantities more precisely – or observe quantities not visible to the human eye (e.g. radiation), provided by measurement tools (e.g. thermometer). At the next level, putting physical observations or quantities into context requires the "Comprehension" ability. This requires knowledge of the manufacturing context on the operator, which is built according to the operational (e.g. process, task), organizational (e.g. the team that operator belongs to) and user-centric (e.g. competency profile of the operator) dimensions of context [22]. At the highest level of Endsley's SA model, the "Projection" ability consists of not only reason over the current state, but also over the project measurements and observations into a future state [21].

Besides SA, operators should be given the right autonomy to be able to proceed with their decision-making tasks effectively. The operator's autonomy refers to the authority and ability to make production scheduling and control decisions including the problem solving. It is very difficult to successfully implement the decision support systems in sociotechnical shops before clarifying the shop floor autonomy [23]. The case studies of [20] illustrate that the autonomy of the operators enables rapid reaction to unexpected events on the shop floor. However, the authors also conclude that the local decision makers lack the plant-wide status (e.g. the priorities of incoming parts with respect to stock levels and downstream operations) when making (re)scheduling decisions. These local decisions can be made in a timely and appropriate manner while fulfilling the plant-wide goals, if such information and constraints are incorporated into these decisions, namely building the SA of the operators. Technological support plays a significant role to build the SA and support the decisions of the operators, as described in the next section.

- Technological Support

The Operator 4.0 is enhanced by the adoption of specific technologies allowing him to improve his performances on different areas within the manufacturing operating activities

[24]. Starting from the cognitive support that the operators can have on the situation awareness [7], Industry 4.0 technologies enable the operator to be guided in the decision-making process enhancing the problem solving capabilities on the shop-floor [25]. Concerning the cognitive support and the need to enlarge the spectrum of skills required to operate in an advanced factory, Industry 4.0 technologies are adopted also to streamline the training process of operators within manufacturing plants [10]. Technologies facilitate the creation of hybrid teams composed by robots and people [26], but also stimulate collaboration among colleagues [3]. Industry 4.0 technologies not only provide a cognitive support, but they enable to stimulate the social sustainability of industrial plants through smart sensors assessing the vital signs of operators during the working activities [27] and they also concretely provide a physical support introducing industrial robots and high level of automation [28].

Table 2 Examples of Maturity Levels

SHOP FLOOR CHARACTERISTICS & WORK ORGANIZATION
Team Working
L1 - The tasks are assigned to individuals
L2 - The tasks are assigned to individuals, there are informal teams
L3 - The tasks are assigned to formal teams
L4 - The tasks are assigned to self-managed, formal teams
DECISION MAKING & SITUATION AWARENESS
Autonomy - Problem solving
L1 - The operators always need support and/or authorization to solve problems
L2 - The operators frequently need support and/or authorization to solve problems
L3 - The operators sometimes need support and/or authorization to solve problems
L4 - The operators usually do not need support and/or authorization to solve problems
TECHNOLOGY SUPPORT
Situation Awareness support
L1 - The required information is not provided or provided with paper-based format
L2 - The required information is provided in a digital format, but they are dispersed and presented only through static/fixed tools (Computer, monitors)
L3 - The required information is provided digitally based on available and well-organized data, KPIs are calculated and displayed in real-time to provide better understanding, they are offered through both fixed and/or mobile (wearable) devices (Tablets, Smart watch, smart glasses)
L4 - The required information is provided digitally, data available in real-time and well organized, KPIs and predictions are available in real-time and are dynamically offered through fixed/mobile tools that interact with the operator's cognition (AR, IPA)

4.2. DEO maturity assessment procedure

DEO maturity model is embedded in a digital tool that is meant to be used as a support tool during the company assessment. The responses gathered from manufacturing managers are reported in the spreadsheet, prepared in advance for the analysis of the company. Indeed, once the response sheet is filled, the preliminary analysis of the maturity level is automatically performed by the tool. The dashboard shows the numerical (i.e. scores) and graphical (i.e. radar chart) results both of the integrated score received by the company and the single scores referred to each single analysis dimension.

The assessment process is meant to be guided by an external consultant who conducts the audit but actively involves shop floor managers and operators in evaluating the current status of the company and deriving recommendations for improvement. Specifically, DEO maturity assessment can be divided into the following steps:

a. Securing the management commitment and defining the goal and scope of the assessment.
b. Collecting data through field observations and interviews with shop-floor managers and operators in order to mitigate subjectivity.
c. Synthesizing data to assign the maturity level and identify strength and improvements.
d. Sharing the assessment results and validating them with industrial stakeholders.
e. Developing specific, tailored, actionable recommendations.

5. Preliminary test: the GKN case

GKN designs and produces high-tech, high-value jet engine components for the world's largest aircraft engine manufacturers in the global aviation industry. Ten-year long-term contracts with customers stabilize the demand for product type and volume, and therefore, all products are made-to-stock. The production process consists of discrete and complex manufacturing processes and it is organized as job shop cellular process. Utilizing the tool, the company characteristics are mapped as follows:

1) Shop floor Characteristics & Work Organization

Complexity: Complex product and process characteristics with high precision requirements, a large number of discrete manufacturing processes, complex routings, qualified resource (i.e. equipment, operator, tooling) requirements, and work centers with shared resources for all product groups.

Uncertainty: Uncertainty is imposed by the complex product and process characteristics. Some examples are unscheduled machine downtimes owing to different causes such as technical and mechanical errors, malfunctioning parts, missing consumables, leakages, and collisions.

Flexibility: There are some alternative machines for certain operations with similar and lower technological features as well as alternative routings for some products that involve manual operations with longer processing times.

Orientation: The organization is divided into departments hierarchically from top level management, to product groups, and down to production cells. The shop floor is organized in accordance with the processes. Hierarchical levels and departments coordinate horizontally and vertically.

Team: There are formal teams structured to perform the tasks at product group levels and processes.

Task variety: Operators are assigned to a great variety of

tasks, including production operations, simple maintenance, short term planning, monitoring and reporting.
Task typology: Operator is responsible both for the performance and management of the operation, requiring both physical and cognitive effort.
Mobility: Operators are usually responsible for the order within the production cell and moves along with the product.

2) Operator's Decision making & Situation Awareness
Performance objectives: Delivery date adherence and quality conformity are prioritized performance measures, and incorporated to the scheduling and control performance, aligned across the organizational levels. There are monitors on the shop floor, visualizing these metrics and guiding the shop floor personnel on their actions. The shop floor performance is also measured in terms of resource utilization.
Autonomy (Work tasks, Work scheduling, Problem solving): The shop floor autonomy is high. The dispatching decisions are usually made by the supervisors/foremen of the work centers. Shop floor personnel also have the authority to take reactive control decisions (e.g. resequencing, reallocation of jobs) in the face of events. However, any situations perceived to be a crisis involve planners and other functional departments. In some departments, the shop floor personnel are also allowed to make overtime decisions on their own.
Situation Awareness (Perception, Comprehension, Projection): In terms of perception, operators use information systems and conduct daily morning meetings at different departments, discussing the status of resources, materials, quality, and production orders. There is incomplete view on location of materials and equipment (e.g. fixtures). In terms of comprehension, the impact of order status is visualized on the monitors, helping them to react on late deliveries. No projection support is provided yet.

3) Technological Support
Situation awareness support: Customized MES for monitoring and controlling the cell, machine and job status. There are monitors visualizing the KPIs real time.
Decision support: ERP system for production planning, also available on the shop floor desktops.
Collaboration support: Internal instant messenger tool used to facilitate the communication and coordination between defined contact points. Customized tool for detecting and communicating the underlying causes of machine breakdowns
Physical support: Automated machines in production cells.
Health& productivity support: No technological support.
Training support: Training courses support by digital media.

Suggestions for Improvement
Based on the results of the mapping and analysis of the case company according to the DEO maturity model, some preliminary suggestions for the digital enhancement of the operators are proposed. First, the MES system generates large amount of data on the machining cells, which are not fully utilized yet. Generated big data might be exploited to improve performances by monitoring specific KPIs through process mining and data analytics, leveraging on both the tracking of real time data and the exploration of historical data. Further, the operator is required to perform different activities which require a certain level of information and situation awareness, as well as exchanging detailed and specific technical data. Smartwatches can be used either to retrieve information or send them. Another possibility is to use these devices to give to the worker or planner comprehensive information from a work order, read or set status information. Augmented reality (AR) can also provide some opportunities in GKN's production operations. These devices can be used to enable remote control of maintenance operations and training of operators. When machine breakdowns occur, the operator contacts the service engineer from the maintenance service supplier. The service supplier is in another location and have to commute to the facility for initial inspection. By AR solution, this inspection could be managed remotely. Furthermore, the engineer can guide the operator to do simple maintenance tasks. By incorporating process instructions into AR glasses, operators can also have remote training.

6. Discussion and conclusions

A key challenge facing most of the manufacturing companies fully engaged with the Industry 4.0 digital transformation of the shopfloor is how to address the human-centred pillar related to the operator. Although there is a gradual uptake of automation, the new reality is not a replacement of the human operator, but rather a transformation of their role and responsibilities in the manufacturing context. Consequently, when considering the implementation of the Operator 4.0 paradigm, a focus on enabling technologies is limited and prone to failure. For this reason, the approach taken in the DEO project was driven by the needs of the manufacturing companies and more comprehensive, where technology was merely one of the three areas of analysis. The initial application results of the proposed maturity model and assessment tool are promising. It is necessary to evaluate its application in a much larger sampling of manufacturing companies across multiple industries. This will contribute to the refinement of the assessment tool, building the reference cases and generating the family of implementation strategies based on the recognized patterns of analysis.

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