Exploring the integration of the human as a flexibility factor in CPS enabled manufacturing environments: methodology and results

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***Abstract*— Cyber Physical Systems (CPS) are expected to shape the evolution of production towards the fourth industrial revolution named Industry 4.0. The increasing integration of manufacturing processes and the strengthening of the autonomous capabilities of manufacturing systems make investigating the role of humans a primary research objective in view of emerging social and demographic megatrends. Understanding how the employees can be better integrated to enable increased flexibility in manufacturing systems is a prerequisite to allow technological solutions, as well as humans, to harness their full potential. Humans can supervise and adjust the settings, be a source of knowledge and competences, can diagnose situations, take decisions and several other activities influencing manufacturing performances, overall providing additional degrees of freedom to the systems. This paper, studies two different integration models: Human-in-the-Loop and Human-in-the-Mesh. They are both analysed in the context of four industrial cases of deployment of cyber physical systems in production.**

Keywords*— Cyber Physical Systems, human-centric manufacturing, Industry 4.0, ergonomic work environments, Knowledge and competences.

I. INTRODUCTION

Cyber Physical Systems (CPS) have the potential to introduce dramatic changes in different fields [1] and are expected to contribute to the transformation of manufacturing to a new era, namely Industry 4.0 [2]. The introduction of CPS, the integration of manufacturing processes and the strengthening of autonomous capabilities in production systems change the framework for human work.

There is general consensus on the relevance of this theme, for its implications for employment, skills requirements and ageing population [3]. Moreover, there is increasing awareness that in manufacturing, human capabilities are fundamental [4] and cannot be easily substituted [5]. However, due to the fairly and these emerging technologies [6].

The adoption of CPS aims at increasing the flexibility and adaptability of production systems but risks to fall short unless human capabilities, needs, and behaviours are considered as an integral part during the design of these systems.

Human presence is both contributing to the overall systems' capabilities (ability to address unplanned situations, by bringing experience and knowledge) but also introduces constraints (error prone, variation, fatigue, misjudgement) that need to be considered from the outset to ensure harnessing the full potential of CPS in production.

The purpose of this work is the identification of the industrial needs and preliminary requirements for the integration of humans in production systems based on CPS in order to be consistent and synergetic with the pursue of flexibility.

The rest of the paper is organized as follows. Section II overviews the related work of considering integration of the human in CPS and Section III describes the proposed methodology to implement this integration. Section IV introduces the industrial use cases where the proposed research approach will be tested and Section V summarizes the identified preliminary requirements for its application in these industrial use case scenarios. Finally, Section VI rounds up the paper with the conclusions and points out the future work.

II. RELATED WORK

A. CPS in Production

Cyber-physical systems radically change the way how production systems are being considered, deconstructing the hierarchical rigid production organizations, converting them into more heterarchical structures. With this, all the production components are cooperating and collaborating with each other, promoting a truly interacting system.

represented in a cyber counterpart, responsible for its information processing. By means of this logical layer, all the production components are interacting, enabling an unprecedented transparent information flow exchange and processing.

CPS have been built for many years mainly in research labs. They are also now starting to find their way into actual production systems. There is a large volume of related work using Multi-Agent Systems (MAS), Holonic Manufacturing System (HMS) or Service Oriented Architecture (SoA) [7] [8] [9] were similar concepts were applied.Cloud-based technologies [8] and backbone reference architectures [2] for CPS are also being researched.

B. Automation, cognitive automation (work task analysis), Human-in-the-Loop

There is a long track of studies on human and automation defining criteria for assigning tasks to machines rather than to humans [10], depending on their abilities and limitations [11]. Furthermore, as conventional automation can not meet the increasing requirements of manufacturing in terms of flexibility and adaptability, several research streams investigate how technology can support the execution of tasks that require human intervention. Cognitive automation, human-robot cooperation [12], human-automation systems (i.e. [13] [14] are some of the main relevant researched topics. However, CPS shows novel characteristics of autonomy, reactivity, pro-activeness [15]. The integration of humans in these types of systems is being researched from different angles: human-machine interface [16]; human in the loop of control [17] and coordination [18], besides the ICT architecture mentioned in section A. This recent literature appears rather scattered and, due to the still rather low degree of diffusion of CPS in production, with low empiric base. However this research is rich of stimuli and notions valuable for setting novel empiric research frameworks.

C. Extraction and integration of Human Knowledge

Despite the increasing recognition of the importance of integrating human operators' knowledge and cognitive capabilities into automated and semi-automated manufacturing systems, very limited research has been aimed at proposing methods to enable systemic elicitation of operators' knowledge in a way that makes such knowledge accessible and usable as part of the wider system's control and planning strategies. Some examples of such work include [19] where a set of specifications is given to assist system designers with the optimization of the integration of the operator into responsive production systems. A special emphasis is made here on the need for adaptive interfaces as well as the importance of utilizing notions of distributed decision support system approaches such as multi-agent systems. Doltsinis et al [20] emphasise on the need for capturing operator's actions during the ramp-up phase. Operator's hardware and software adjustments during the ramp-up phase were recorded and used as part of a reinforcement learning approach to derive generalised policies for adjustment strategies leading to faster ramp-up. In this case operator's actions were essentially utilised to limit the search space for optimal process and hardware tuning exploration. Instead of relying on entirely data-driven approaches for integrating operators' knowledge, Konrad et al [21] highlight the need for semantic contextual mapping when it comes to integrating operators' implicit knowledge with process data. Another case in which human operator's knowledge needs to be captured is the case of diagnostics and maintenance decision support. Operator's observations were used as part of a Bayesian networks-based framework for diagnostic support in the SelSus project [22]. In this case human observations were fed as an extra evidence source which is then used for marginal probability update during diagnostic reasoning. Furthermore, in some studies the role of human operator is recognised in supporting the design of next generation systems and machines such as in [23] where the activities of maintenance personnel is captured, generalised using contextual semantic models before deriving maintenance-relevant KPIs such MTTR for component and machine families. In a general sense the notable rapid advances in interactive machine learning approaches [24] combined with advances in HMI design [25] gives rise for new opportunities for further systemic integration of human operator's knowledge in the design and operation of flexible and responsive manufacturing systems.

III. PROPOSED APPROACH, METHODOLOGY AND RESEARCH FRAMEWORK

For exploring the integration of the human in CPS, the proposed approach includes a scenario-based methodology and a multi-dimension analysis framework.

A. Scenario-based methodology

The scenario-based methodology consists of four main steps.

First of all, the scope and boundaries of the system impacted by the introduction of CPS are defined.

As a second step, the AS IS situation is analysed: the organizational context and the relevant performances are characterized and the objectives and constraints of the production system are identified.

Then, the TO BE situation is envisioned and developed considering different scenarios corresponding to different phases of the production systems' lifecycles and to their different possible states in order to preliminary identify challenges and opportunities with reference to the roles of humans.

The gap analysis between the AS IS situation with its objectives and constraints and the TO BE scenarios with all the associated issues represents the critical step. The gap analysis identifies the barriers to be overcome and the enablers that can be exploited so that the employees can better contribute to increase the flexibility and the overall performance of the system. As a result, the industrial needs can be identified and the requirements gathered. The gap analysis requires the detailed description and study of the human activities in the TO BE scenarios consistently with what specified in the AS IS situation.

B. *Multi-dimension analysis framework*

The proposed framework to guide the analysis of the scenarios is based on three main dimensions:

C. *Lifecycle phases* - In order to properly investigate the needs and requirements for effective operations in production systems based on CPS, it is important not to limit the analysis to the production phase, but to consider all the other phases of the production system's lifecycle as well (see Figure 1). In particular the configuration and ramp-up phases are very relevant for novel flexible and adaptable systems, furthermore they usually are hardly automatable and thus depend on human intervention. In these phases the application of change management approaches to smoothen the transition is especially relevant.

Figure 1 Lifecycle phases of manufacturing systems

D. *System states* - Similarly, it is important to extend the description of the scenarios to include other states of the system in addition to is normal processing state, such as testing, set-up, failure or maintenance (see Figure 2). In these states, the human contribution may also be particularly relevant.

Figure 2 States of manufacturing systems

E. *Integration Models* - Finally, the framework includes two main types of involvement for humans in a CPPS. The first type of scenario is referring to human roles operating as part of the control loop for CPSs, as illustrated with the icon at the bottom of Figure 3~~Figure 3~~ and corresponding to the levels 1 and 2 of the ISA 95 standard [26]. The second type of scenario concerns humans interacting with cluster of CPS and applications, as illustrated with the icon at the top of Figure 3~~Figure 3~~. This relates to the levels 3 and 4 of the same standard.

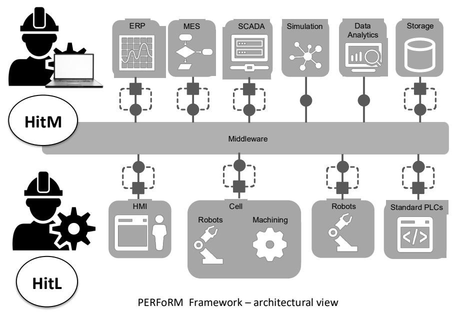

Figure 3 Human integration types and architectural view

The first type of integration named **Human-in-the-Loop** (HitL) may involve different types of human activities that influence the overall performance and bring flexibility to the system.

The Human-in-the-loop scenarios outlined in Figure 4 encompass the following types of activities: overseeing and adjusting the set points, directly commanding the system, being a source of data (identification, early detection, reporting, etc.), introducing deviations/disturbances (errors, oversights, voluntary of involuntary deviations from the standards, etc.).

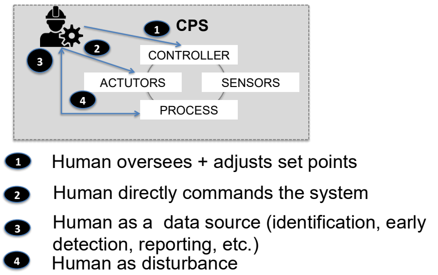

Figure 4 Human in the Loop integration and activities

The second type of integration, named Human-in-the-Mesh (HitM), involves the different types of human activities outlined in Figure 5. These activities are related to the interactions with the CPS network and applications and include the supported interaction with other human roles.

While the HitL type of scenario has been studied in different application domains, the HitM can be considered as an emerging model, still lacking a clear definition and not well explored yet.

However, some types of human activities that may influence the performance and the flexibility of the manufacturing systems have been preliminary identified: receiving alerts, identifying situations and intervening, analysing and changing the plans. Furthermore, any of the previous activities, if tracked, can be used for knowledge extraction.

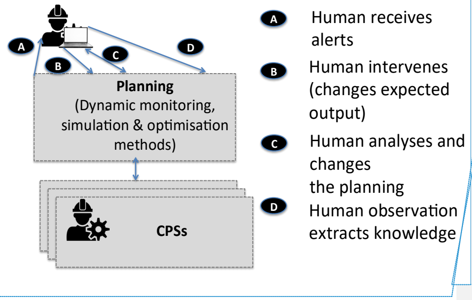

Figure 5 Human in the Mesh integration and activities

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The research approach has been applied to four industrial use cases.

IV. INDUSTRIAL USE CASES

The research approach has been applied to four industrial cases belonging to different industries: aerospace, automotive, home appliances and industrial machinery. All companies aim to improve the performances of their manufacturing systems, especially in terms of flexibility and adaptability, through the introduction of CPS.

The first case concerns a job-shop for the fabrication of parts with high variety and relatively small volumes. The company intends to build some micro-flow cells that perform a sequence of processes for similar parts and can be easily reconfigured to adapt to different processes and parts.

The adoption of CPS within semi-automated cells has several implications: increased automation and support for the operators, on the one hand; higher and novel requirements for competences and flexibility for several roles in the factories, on the other hand.

The second case concerns a low volume assembly line, with variable demand in terms of quantity and mix. In order to be competitive in an industry characterised by very high volumes and high levels of automation, the company is building a micro-factory. The factory will have working areas and cells, within a CPS architecture, with different levels of human intervention associated with different self-adaptation and self-regulation capabilities of the systems.

The third case concerns a job shop, in particular the fabrication of low volume high variability parts, managed through Computer Integrated Manufacturing (CIM) functionalities and human adjustments. The company aim at leveraging the introduction of a CPS architecture to improve the adaptation of the production planning and scheduling to the emergence of failures or breakdowns. The aim is to better support the human awareness and decision making to provide the required flexibility.

The fourth case concerns an assembly line for high volume and low variability products. Work is organized according to the Lean model. The company aims to improve the reconfiguration phase of the line, by exploiting the data and elaboration capabilities of CPS.

Although none of these use cases can provide the research with a CPS production environment already in operation, they offer the opportunity to test and validate the approach and to gather their needs and requirements for human integration.

The approach has been preliminary applied to these use cases, limited to one or two main scenarios for each company.

In total seven scenarios have been selected to ensure a good coverage of the research framework as illustrated in Figure 6~~Figure 6~~. They cover two phases of the manufacturing system lifecycle and four different states.

Four of the scenarios match the Human-in-the-Loop integration type, referring to the following human roles: the operator in the reconfigurable production cell, the operator in the micro-flow cell, the operator in the assembly line, the operator in the fabrication cell and the maintenance operator in the maintenance role.

Three of the scenarios match the Human-in-the-Mesh integration type. They refer to several human roles, interacting with one another in order to make decisions. These decisions concern: production and maintenance re-scheduling and reconfiguration of the production system.

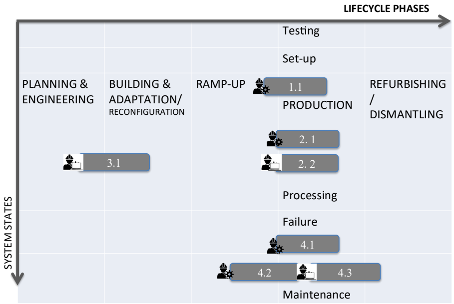

Figure 6 Map of the selected scenarios in the common framework

The types of human activities identified for HitL and HitM, as outlined in Figure 4~~Figure 4~~ and Figure 5~~Figure 5~~, have been instantiated and shortly described for each human role.

The analysis of each individual activity included the elaboration of the potential impact on the performances and the identification of possible issues, barriers or enabling factors, which provided the ground for recognizing the needs and extracting the requirements.

V. RESULTS

The analysis of the selected use case scenarios and the analysis of the gaps between the AS IS and full potential of the TO BE scenarios brought out to significant results. The two types of integration HitL and HitM and related activities have been validated. Furthermore for each of them the industrial needs and requirements have been preliminary identified, according to three main categories: Human Resource Management & Organization, Production Management methods, and Technology.

A. *Human-in-the-Loop requirements:*

Human Resource Management & Organization
Skill/job flexibility
Technological competences (i.e. robots)
Increased process and quality analysis competences TPM (Total Productive Maintenance) approach
Consultation among colleagues
Feedback mechanism to the operator to support valuable behaviour and discourage non-valuable
Production Management methods

Routine training
Human task monitoring, alerts in case of possible errors
Alerts in case of unexpected/anomalous events or systems’ behaviour,
Condition-based instructions to support diagnosis and reporting and to guide interventions
Context-aware guidance to prepare interventions (i.e. tools and spare parts for maintenance)
Technology.
Mobile devices with context aware (role, location) support
Support visual inspection with sensors
Support testing (geometrical, power train, fatigue, etc.)
Virtual presence (for consulting expert colleagues: sharing view, screen, info, voice connection or chat)
Multimodal interaction (voice, image, gesture recognition, sound lights, etc.) to alert and to support field-work
Suitable/wearable device to support field-work
Asset tracking (tools and spare parts)
Localization and turn-by-turn navigation to retrieve machines, tools, spare parts.

B. *Human-in-the-Mesh requirements:*

Human Resource Management & Organization
Competences in complex system modelling & simulation
Skills/training in in decision-making
Alignment of responsibility and authority
Alignment of the objectives and incentives with desired performances
Knowledge transfer from experts to less experts decision makers
Production Management methods
Incremental models
Multi-objective (multi-stakeholder) decision making
Caption of decision-making patterns by experts
Technology.
Mobile, context aware (role, location) support
Intuitive representation of alternatives and trade-offs
Decision support enhanced by experts’ decision- making patterns

These requirements have been collected from the four industrial companies involved in the use cases, who are in the process of transforming part of their factories to become adaptable and reconfigurable through CPS. Therefore they reflect the needs for human integration in CPS production, as perceived by the companies in this stage of their path.

For the integration of HitL, very high relevance is attributed to the skills of people. The introduction of CPS changes their roles and responsibilities. Operators will have to extend their competences along three main directions: the production processes, the responsibility and role awareness and the involved enabling technologies. With reference to the production, operators will have to acquire knowledge and skills on specific fabrication processes. Additionally, they are required to enlarge their competences to take care of additional responsibilities regarding quality and maintenance. Furthermore, human integration will require powerful means to guide and support the intervention of operators. In particular, the requirements encompass methods and tools for both collaboration between humans and interaction with CPS, by exploiting the potential of connecting the physical world, the sensorial perceptions and dexterity of the operator, the sensing and monitoring capabilities of the devices, with the digital world of product specifications, process flows, quality standards.

For the integration of HitM as well, very high relevance is attributed to human competences, but also to organizational factors affecting the motivation of employees. The complexity, variability, unpredictability of HitM integration and activities requires companies to increasingly focus their attention on all the organizational factors to positively influence human behaviour and performances. In the HitM scenarios, the emphasis is on decision-making activities in complex situations, in which there are trade-offs among different objectives and potential conflicts or misalignments among different stakeholders. The industrial needs encompass methods to address these challenges. Requirements for modelling and simulation methods for complex systems are extended to incorporate some special features, such as incremental development and extraction of humans’ decision-making patterns. It is very interesting to notice that the latter aims at mitigating the risk of divergence and alienation between the digital and human world.

A common element for the use cases is that all the four industrial companies involved in the research evaluate the human role as the main element of the use cases. All of them claim that the skills of employee need to be empowered, but the human role is still considered as core in the CPS production scenarios.

VI. CONCLUSIONS

This paper summarises the approach, methodology and results of the effort dedicated to preliminary identify industrial needs and requirements to take advantage of humans as flexibility drivers in Cyber Physical Systems (CPS) applied in production. In particular, the achievements concern the definition of two main types of scenarios for human integration and the identification of industrial needs concerning human resource management & organization, production management methods and technological aspects. As the research has been developed in parallel with the process of adoption of CPS by the industrial cases, the results are to be considered as preliminary and need to be validated with the evidence that will be progressively accumulate after the CPS environment will be fully deployed.

Future work will further develop the analysis of the industrial cases to cover more scenarios and roles in order to complete and validate the analysis of requirements. Furthermore, novel research opportunities will be offered through the study of CPS in operation. In particular, investigations about knowledge extraction from human observation and design methods for the visualization of key factors for decision making appear as two particularly promising research directions.

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