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Placing the operator at the centre of Industry 4.0 design: Modelling and assessing human activities within cyber-physical systems

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ABSTRACT

The Industry 4.0 vision, grounded on the integration of key technologies and Cyber-Physical-Systems (CPSs), is expected to profoundly modify the manufacturing sector. There is large consensus on the fact that work will change and different skills will be needed. However, whether the organization of work will evolve towards higher responsibility and decision-making of the employees or towards higher technological control is still an open question. The challenge is how to govern this evolution and purposely guide the process of integrating people within CPSs in order to move towards the desired scenario. This paper addresses this challenge, by proposing a methodology to support the design and assessment of different work configurations, jointly considering the uniqueness of human labour and the characteristics of cyber-physical production within a comprehensive framework. The method covers ordinary production as well as irregular scenarios, such as failure detection or maintenance intervention, particularly interesting for human work. The applicability of the method is illustrated through two industrial cases, leading to suggestions for training the personnel and for enhancing the whole cyber- physical-social system. Results include human-centric Key Performance indicators (KPIs) and general guidelines for work design. The approach encourages managers and engineers to clarify their strategy for human resources; develops a multi-perspective awareness on the role of workers; fosters an early detection of possible misalignment between the high-level strategies and the technical interventions on the shop floor. The modelling, analysis and assessment technique developed aims at representing a first step towards formal and quantitative methods to support the design of human work integrated within cyber-physical-systems.

1. Introduction

The concept of a fourth industrial revolution has been initially promoted by the German Government through the program Industrie 4.0, then it has been revisited and supported by other policy makers in several countries and regions (European Commission., 2014). The first industrial revolution was based on mechanization of production processes powered by steam or water; the second one was based on mass production in the assembly lines; the third one was based on automation, information and communication technologies (Thoben, Wiesner, & Wuest, 2017). The fourth industrial revolution is based on Cyber-Physical-Systems (CPS) (Kagermann, Wahlster, & Helbig, 2013); CPS integrate communication and computational capabilities with physical processes to endow physical systems with additional capabilities (Wang, Törngren, & Onori, 2015). Enabled by these technologies, manufacturing, as well as other industrial sectors, is expected to dramatically change:

- the vertical layers of the automation hierarchy start to decompose bypassed by novel applications (Monostori, 2014);
- the horizontal boundaries of the production sites and organizations start to fade as more and more business and manufacturing processes develop across them;
- the distance between design, manufacturing and usage tends to disappear thanks to the integration of product lifecycle management.

By lowering all these barriers, industry opens up to novel behaviours and scenarios hard to predict. In fact the degree of implementation of Industry 4.0 is still limited and there is no experience about the full deployment of this paradigm to a whole economic ecosystem. It is still unclear how this model will interact with the economic geo-political and social trends to shape future work and jobs. In particular, analysts and society are wondering whether Industry 4.0 will contribute to create better conditions to address some of the challenges faced by developed countries such as ageing population, urbanization,

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immigration and unemployment. In particular, there are concerns about the number and quality of jobs in the increasingly technological and digitised production systems. The documents released by the policy makers highlight the relevance of the human factor, the need to prepare the adequate skills to master and sustain the transformation towards Industry 4.0 (European Commission, 2014; EFFRA., 2016; Lazaro, 2017). Some documents particularly stress the continuity of the cultural approach with reference to the theories of socio-technical systems (Kagermann et al., 2013), but research papers mostly pursue enhanced performances through smarter technologies. Overall, how the combination of technical solutions and organization of work will evolve in manufacturing is unknown, and it is believed to develop between two extreme alternatives: the techno-centric and anthropo-centric scenarios (Dworschak & Zaiser, 2014). According to the first one, CPS will dominate and human work will be determined by technology; in the second one, workers will be master and make decisions, supported by CPS.

Therefore the challenge of our society is how to steer the design and deployment of the Industry 4.0 paradigm in the enterprises, and how to purposely guide the process of integrating people within CPS in order to move towards the desired scenario.

This paper contributes to address this challenge by proposing a methodology to support the design and assessment of human work. It is organized as follows: Section 2 provides an overview of previous research on related topics and of the existing needs; Section 3 presents the methodology based on an analysis and design framework and on a methodological path; Section 4 illustrates two industrial application instances; Section 5 discusses the results from the industrial cases, the limitations of the work and avenues for future research; finally Section 6 draws conclusions, by highlighting the contribution of the work.

2. Related work

The study of the interplay between humans and technology has a long record and has been analysed along different perspectives, within a wider geo-political and socio-economic framework. In particular, the following topics need to be mentioned with reference to the present work.

Automation, task analysis and decision-making. The technical progress has succeeded in automating several tasks previously performed by humans. Since Fitts' seminal study (Fitts, 1951), human and machine abilities and limitations have been compared in order to define criteria to automate tasks rather than having them executed by human operators (de Winter & Dodou, 2014). Progressively the focus has shifted from physical to cognitive tasks. As conventional automation can not address the increasing requirements in terms of flexibility and adaptability, manufacturing research is trying to overcome current technological limitations in perception, reasoning, learning and planning (Bannat et al., 2011) and to develop novel systems that combine human and automation (i.e. Horiguchi, Burns, Nakanishi, & Sawaragi, 2013; Zeltzer, Limère, Van Landeghem, Aghezzaf, & Stahre, 2013). The design of automation in man-machine systems is mainly focused on cognitive tasks. Taking inspiration from previous work on human factors (Rasmussen, 1986; Rasmussen, Pejtersen, & Goodstein, 1994), these studies analyse the decision-making process as a sequence of stages, such as situation analysis, value judgement, planning and execution (Abbass, Petraki, Merrick, Harvey, & Barlow, 2016; Sheridan & Verplank, 1978), which can be engineered with different levels of automation in order to obtain the desired performances, in different contexts and situations.

Collaboration, integration and symbiosis. The technologies and architectures that are developing under the umbrella of Industry 4.0 add considerable complexity to the discourse of automation, due to the introduction of autonomous and semiautonomous agents that communicate and interact with networks of applications. The collaboration extends to include human workers, robots (Bannat et al., 2011), other intelligent entities and, according to some scholars, it originates a sort of holistic integration, along different levels of abstraction and coordination (Hadorn, Courant, & Hirsbrunner, 2015). Recent work further built on the concept of collaboration to transform it into a real symbiosis, in which human workers and artificial systems dynamically adapt to each other and cooperate to achieve common goals (Romero, Bernus, Noran, Stahre, & Fast-Berglund, 2016). According to this view, machines and algorithms become the means for workers to continue to work instead of being replaced (Ferreira, Doltsinis, & Lohse, 2014); means to accommodate issues related to ageing (Peruzzini & Pellicciari, 2016), disabilities or inexperience (Romero, Noran, Stahre, Bernus, & Fast-Berglund, 2015) and increase skill match, comfort and wellbeing (Fiasche, Pinzone, Fantini, Alexandru, & Taisch, 2016).

Labour market trends. Besides the technical streams of research mentioned above, also the literature from economics and labour economics provide useful insight on human work. In particular, these studies contribute to shed some light on the underlying phenomena, by observing longer term, cross-sectorial and cross-regional dynamics. An interesting finding is that the overall share of income accrued to workers is declining "in the large majority of countries and sectors"(Karabarbounis & Neiman, 2013), meaning that companies increasingly rely on capital rather than labour (Berger & Frey, 2016b). Moreover, these recent analysis (Berger & Frey, 2016b) have supported previous studies stating that technologies have had a skill-biased effect on jobs, negatively impacting medium skill and routine jobs (Autor, Levy, & Murnane, 2003) rather than low and high skill jobs. According to the analysis by Frey and Osborne (2013), jobs more susceptible to be substituted from technology are routine based, do not require manual dexterity or social interaction. Other research supports that analytical, interactive, and problem-solving skills have become increasingly in demand (Autor et al., 2003; Berger & Frey, 2016a). In order for the labour market to match the demand with the offer, the workers' characteristics should align with the requirements. Stakeholders are dedicating great attention in the identification of the skills and competencies needed for the full deployment of Industry 4.0 in order to prepare adequate curricula. Overall, the literature draws the attention to the importance of people in Industry 4.0 and emphasizes the relevance of education, training and appropriate planning tools in order to build the necessary skills (Gorecky, Khamis, & Mura, 2015; Pinzone, Fantini, Fiasché, & Taisch, 2016).

CPS and human-related applications. The notion of CPS has many facets and has not found a final shared understanding. According to the definition of the National Institute of Standards and Technology (NIST), "Cyber-Physical Systems or "smart" systems are co-engineered interacting networks of physical and computational components" (Cyber Physical Systems Public Working Group, 2016). Other definitions highlight characteristics such as decentralization, dynamism, evolutionary nature, but also openness, context-sensitiveness and the fact that CPS spread through the social and mental world of humans (Horváth, 2014). Given the width and fuzziness of the concept, although surveys on the services enabled by CPS exist (Khaitan & McCalley, 2015), a comprehensive list of applications from a human and manufacturing perspective, is not available. It is therefore necessary to analyse different studies addressing Social-Cyber-Physical Systems (Horiguchi et al., 2013 Horváth, 2014), user interaction (Gorecky, Schmitt, Loskyll, & Zuehlke, 2014; Maguire, 2014), and collaborative context-aware systems (Salkham, Cunningham, Senart, & Cahill, 2006). These papers provide an overview of the evolving technologies and applications and highlight features, goals, means and collaboration approaches. Further insights can be found in papers addressing: (i) applications that keep the human in the loop of control (Sousa Nunes, Zhang, & Sa Silva, 2015) and in the mesh of the CPS (Fantini et al., 2016); (ii) supporting technologies, such as Augmented Reality (Paelke, 2014); or (iii) specific goals, such as workers' safety (Barro-Torres, Fernández-Caramés, Pérez-Iglesias, & Escudero, 2012).

Current challenges and needs. Overall, the above-mentioned streams of literature provide different and complementary viewpoints on human work in relationship with technological systems, but leave gaps. In particular, the stream of research on automation and task analysis provide good methods to model the decision-making processes and the boundaries between human and automation control; the stream of research on collaboration and symbiosis provides a useful perspective on the dynamic adaptation and reciprocal support between human workers and technological systems; the stream of labour market identifies jobs that leverage peculiar human capabilities, hardly replaceable by artificial intelligence and automation. However, due to the extreme complexity of CPS and the latest evolution of the enabling technologies, there are emerging needs for work design that are not thoroughly addressed by the available studies. In particular, the challenges concern:

- how to understand and control the interaction between workers and CPS technologies, which occur at different levels (a);
- how to capture the main value added of work, which includes decision making and problem solving (b), creative actions (c) and social behaviour (d), with reference to individual activities rather than jobs;
- how to take into account the skills and other characteristics of the workers (e) in conjunction with the different circumstances and purposes of CPS (f).

As a mater of fact, there is a lack of frameworks, methods and tools that enrich the physical and process perspective of work to encompass other relevant aspects to properly consider the human role and steer its enhancement in the production systems, taking full advantage and supporting the development of its potential. There are needs for novel approaches to support the design and assessment of work design, in production contexts characterized by the co-presence of human workers and CPS.

In the next section a methodological contribution to address these needs is presented.

3. Analysis and design methodology

Work design is usually needed when a new manufacturing system is to be created, in a greenfield situation, or more frequently when a change to an existing system is foreseen, in a brownfield landscape. As highlighted in Section 2, there is general consensus that humans have a central and crucial role in production systems, as they are the only ones who can govern the systems, address anomalous situations and that can provide flexible solutions in case of need. However, when innovative technical solutions are considered, the attention of the engineers and designers is mainly directed towards the production phase and standard operating conditions, which do not allow comprehending all the facets of human contribution.

The proposed methodology aims at expanding the scope of the analysis and design of human work, by focusing on different scenarios that enable a sharper perspective on the potential and challenges of human integration within the cyber physical production systems. Examples of scenarios are related to failures, product change over, and detection of turbulences that affect the scheduling.

The methodology supports the assessments of different human-systems configurations in order to orient design choices, taking into account the relevant perspectives and components within a comprehensive framework.

More significantly, this approach encourages managers and engineers in clarifying their strategy for human resources; develops a multi-perspective awareness on the role of workers; fosters an early detection of possible misalignment between the high-level strategies and the technical development on the shop floor.

A core component of the methodology is a framework for work analysis and design, which is outlined in the following paragraph.

3.1. Analysis and design framework

The framework illustrated in Fig. 1 addresses the challenges and needs presented in Section 2, on the bases of the following four perspectives and two components.

(a) The abstraction perspective, described in Section 3.1.1, refers to the need of contextualizing the levels of human activity within CPS;
(b) The decision-making perspective, described in Section 3.1.2, refers to the need of focusing on the value added activities related to the identification and selection of options to achieve and improve performances;
(c) The innovativeness perspective, described in Section 3.1.3, tackle the need of taking into account creativeness, which according to the literature is a unique and valuable expression of humans (i.e. Frey & Osborne, 2013);
(d) The social interaction perspective, described in Section 3.1.4, in analogy with the previous one, aims at answering the need for considering another unique and valuable aspect of human activity (i.e. Frey & Osborne, 2013).
(e) The human component, described in Section 3.1.5, contributes to bringing into consideration the skills and other characteristics of the workers relevant for the tasks performance, in the light of the four perspectives and in relationship with CPS;
(f) The CPS component, described in Section 3.1.6, addresses the challenge of considering the different purposes of these technologies in relationship with the humans.

The proposed framework enables the decomposition of the work activities in blocks homogeneously characterized from the four perspectives and enables the analyses of the human and CPS component and their alignment with the activities.

3.1.1. Abstraction perspective

The concept of dealing with a physical and a cyber or digital level is embedded in the notion of CPS. The abstraction perspective allow to highlight an additional holistic level, in which human and social loops develop (Hadorn et al., 2015). In this work the abstraction is meant as the layer in which the activity originates, develops, and impacts. This perspective can be leveraged to identify the types of skills and abilities associated and the possible types of support. By considering the physical and cyber levels embedded in the concept of CPS and the holistic level of human and social loops, the following values for the abstraction perspective are derived:

(AP) Physical – the activity affect the physical process or in general, the physical world
(AC) Cyber/digital – the activity affect the digitalized information
(AH) Holistic – the activity affect concepts or ideas

These levels have been identified because they can be associated with different requirements in terms of workers capabilities and CPS purposes.

3.1.2. Decision- making perspective

Workers are expected to assume more and more the role of decision-makers and problem solvers (Gorecky et al., 2014). It is therefore important to characterize human activities with reference to the main phases that compose this process. Leveraging on the literature on the decision ladder (Lintern, 2010) and task analysis for determining automation levels (Abbass et al., 2016), the several steps of these activities have been summarized in three main phases corresponding to (DI) situation awareness, (DII) analysis and decision making, (DIII) execution. Furthermore, all the activities of reporting, often disregarded by the analysis of decision-making, have been included in a dedicated phase (DIV). These activities are in fact very important as the workers share

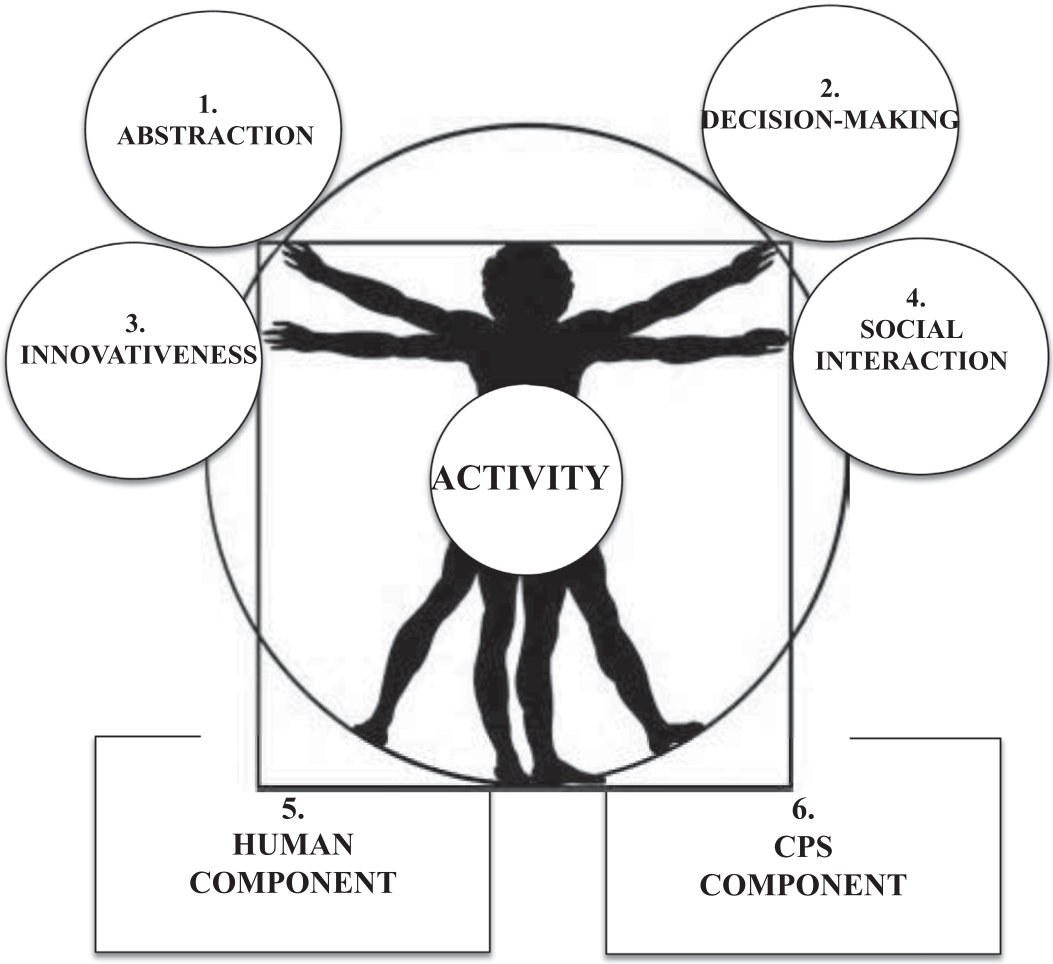

Fig. 1. Analysis and design framework.

information, observations and knowledge, which become available for the other workers as well as for CPS. Finally, we have classified the activities that do not bring any contribution in a dedicated phase (D0). In summary, from the decision-making perspective, activities have represented through the following categories:

(DI) Detect (situation awareness)
(DII) Determine (analysis and decision making)
(DIII) Develop (task execution)
(DIV) Describe (reporting, explaining)
(D0) Other (non value added activities)

3.1.3. Innovativeness perspective

As reported in Section 2, routine tasks are less valued and increasingly substituted by technology, while the opposite stands true for jobs that imply innovativeness and creativity. In this work we ground on the skills, rules and knowledge categories of human performance models (Rasmussen, 1983; Rasmussen et al., 1994) and classify the activities according to the knowledge base they refer to:

(IL) Routine-based, that is based on a practice
(IM) Rules & methods-based, that is based on a shared and standard sets of knowledge tools
(IH) Creative, that develops new solutions and new knowledge.

3.1.4. Social interaction perspective

Although from very different background and angles, Socio-Technical-Systems theories, Lean Production Systems value the social aspect of work: the spirit and social cohesion of teams. Furthermore, the economic studies mentioned in Section 2 underline that among the jobs less susceptible to computerization, there are those that require social interaction. In this work, the presence and quality of social interaction is represented in a scale from a minimum level of no interactions or interactions merely following a standardized procedure; to an intermediate level of complex interactions to achieve an agreement through mediation and negotiation activities; to the higher level of contributing to the social cohesion of the team or the reference community. From this perspective, activities have been classified according to the following categories:

(SL) No or poor social interaction;
(SM) Negotiation/mediation;
(SH) Strengthening social cohesion.

3.1.5. Human component

Work activities, in order to be performed require that the workers have some specific abilities, skills and knowledge. Several frameworks exist to guide the identification of these items, and each individual enterprise can use personalized descriptions. However common models are useful to enable comparison and interoperability across organizations, education, training and employment centres. The O∗NET® Content Model[1] is a de facto standard, already applied to more than 900

[1] https://www.onetcenter.org/content.html. The Occupational Information Network (O∗NET) is being developed under the sponsorship of the US Department of Labour/Employment and Training Administration (USDOL/ETA) through a grant to the North Carolina Department of Commerce.

occupations. The related Advanced Manufacturing Competency Model Clearinghouse from ETA (Employment & Training Administration United States Department of Labor, 2010) also provides a useful reference. Besides, the human component incorporates requirements for safety, wellbeing and other needs (Romero et al., 2015) related to specific conditions of the workers. In particular, these conditions might be permanent, such as age, disabilities (Peruzzini & Pellicciari, 2016), or temporary, such as stress or fatigue.

In this work, we preliminary limit the representation of the human component to the skills, abilities and knowledge as for the O*NET and ETA.

3.1.6. CPS component

The CPS component in this framework focuses only on the services that provide direct support to human activities and to the fulfilment of human needs, while they perform a work activity. In the background, the cyber-physical-systems sense, elaborate, communicate, reason, actuate, collaborate, exert all their functionalities through their distributed architecture, but we capture only the service delivered to the worker. As discussed in Section 2, the literature on CPS is still in an early stage and sound taxonomies for these services are not available. In this work we have taken as a reference groups of services by Stocker, Brandl, Michalczuk, and Rosenberger (2014):

- Intelligent dashboard visualization, or more in general, alert
- Decision support
- Social collaboration (Gurevich, Lanir, & Cohen, 2015)
- Workplace learning

with the addition of

- Worker augmentation (Romero et al., 2016)
- Workplace adaptation (Peruzzini & Pellicciari, 2016)
- Recommendations/guidance (Pirvu, Zamfirescu, & Gorecky, 2016)

The services can be delivered through a variety of means, such as tablet and smart phones, head mounted displays, other wearable devices, desktop/HMI (Stocker et al., 2014), but also specific equipment, such as exoskeletons or collaborative robots (Thoben et al., 2017) or picking systems, put-by-light, and other voice/vision systems (Pirvu et al., 2016).

3.2. Methodological path

The proposed methodology addresses engineers, operations managers, factory designers and work designers at large, assuming that they are planning a novel manufacturing system or the introduction of some changes into an existing setting. Although the methodological path represented in Fig. 2 is generally applicable; it acquires CPS-specificity in junction with the analysis and design framework presented in Section 3.1.

The phases and steps of the methodology are illustrated in the rest of this section, and applied to industrial cases in Section 4.

The starting point of the path is the **Problem Setting**, defining the context in which the work is considered, the purpose and the orientation of the integration of human and technological systems. In particular in this phase the designers have to specify what design options they wish to consider and what are the objectives they want to achieve. For example, they may consider the design option of introducing a health monitoring system to watch the working conditions of a machine tool in order to support predictive maintenance and would like to assess that the skills' requirements match the profile of the personnel and to verify that the time of workers is well valued.

The second phase is **Scoping** and refers to the definition of benchmarks or criteria to be used in the evaluation. In the above-mentioned example, designers consider the introduction of health monitoring system (TO BE) and wish to compare it with the existing system based on Periodic Maintenance (AS IS). The scope includes also the identification of a significant scenario and the critical roles with respect the objectives. In the example, the scenario could be to check the need for possible maintenance intervention on the machine, performed by the maintenance technician.

The **Analysis & Design** phase encourages modelling the workflow, consisting in the sequence of individual activities, triggered by the events of the scenario, that involve the relevant roles for the design option. Each individual activity has to be characterized according to the perspectives of the analysis and design framework described in Section 3.1, paying particular attention to the perspectives that are more tightly related to the strategic objectives. In the example, the event could be the start day. In the AS IS situation, the maintenance technician detects that a maintenance intervention is planned, negotiates with the production planner to decide whether to stop production or postpone the intervention. The production planner would then fill in the planned machine unavailability in the production scheduling. In the TO BE situation, instead, the maintenance technician could check the health monitoring application and evaluate the plots to estimate the remaining time before failure, determine in advance the need for a maintenance intervention to be included in the production scheduling, as a maintenance job.

The methodology suggests, if feasible, to complement the activity modelling with quantitative data: the probabilities associated to the event and to each branch after a split in the workflow and the duration of each activity.

The full deployment of the method leads to a discrete event model that can be simulated to extract synthetic information about one or the combination of more scenarios' development to comprehensively calculate the share of time dedicated to a decision making or requiring a certain skill. However, the methodology can be used without quantitative data as well to determine qualitative aspects. In the example, by summarizing the activities along the whole workflow, it is possible to extract the comprehensive set of skills required for the maintenance technician and to focus on the interactions with the production planner.

The last phase of the methodological path is the **Assessment**, in which it is possible to compare synthetic information about the design option, in the example of introducing a health monitoring system, with equivalent information about the reference option of periodic maintenance. In the example this could mean comparing the skills requirements for the maintenance technicians in the two situations. Furthermore, the comparison would highlight a more streamlined workflow, with the reduction of negotiation activities between the maintenance technician and the production planner. In the example, the criteria could include the maximization of high value activities, such as decision-making or execution and the alignment with existing skills. From this phase, feedback for the design can emerge, as hints or recommendations for the human and CPS components. In the example, skills gaps could emerge with the recommendations to deliver training to the Maintenance Technician in order to prepare this role to analysing and interpreting the health Monitoring plots and to making decisions about maintenance interventions. Furthermore, some hypothesis could be formulated for delivering CPS-based services to increase the effectiveness and efficiency of the activities, aiming for example at supporting the prediction of the remaining time before failures.

4. Industrial case studies

The methodology has been applied to two industrial cases, by considering different design options. The steps performed and the results are illustrated in the Sections 4.1 and 4.2.

4.1. Industrial compressors' plant

The plant produces industrial compressors of relevant dimensions in

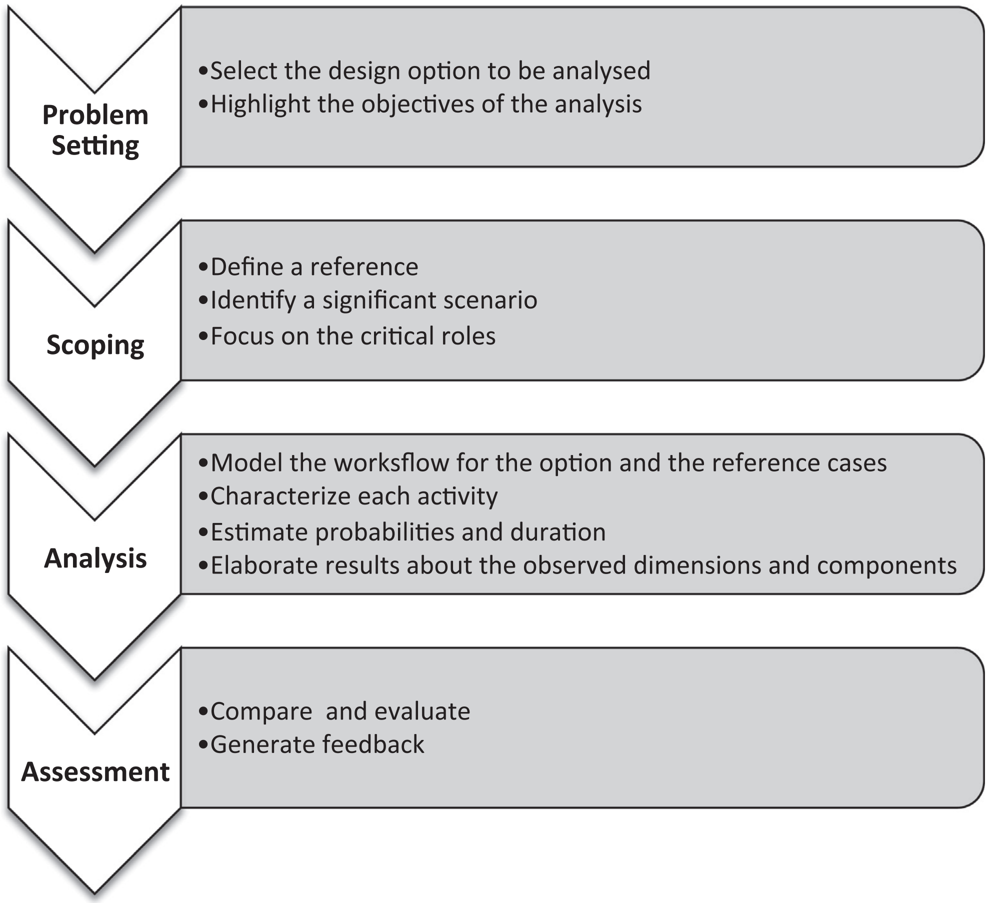

Fig. 2. Methodological path.

small batches. The production is organized as a job shop, and operators are specialized on the type of process and machine.

The maintenance is corrective, in case of failure, and periodic. In both cases, the operator is key in detecting either the problem or the start of a planned maintenance intervention. The high level planning is based on an Enterprise Resource Planning (ERP) and a rather rigid scheduling system. Adjustments to the scheduling have to be decided on the shop floor.

In this context, the methodology has been applied and each step has been annotated:

- Problem setting: the design option consists in an application to guide the operator in making a pre-diagnosis in case of failure instead of opening a free-text ticket to request maintenance intervention with the aim of increasing the valuable use of human activity. During this phase, it was noticed that the KPI to operationalize this objective may differ according to the strategic orientation of the specific enterprise.
- Scoping: the AS IS situation has been selected as a reference for assessing the design option. The case of machine failure has been chosen as significant scenario and the focus has been set on the roles of the operator and the maintenance technician.
- Analysis and Design: the workflow of the activities has been modelled both for the design option and for the reference case, as illustrated in Fig. 3.

In the reference scenario, activities 1–3 are performed by the operator, who: (1) detects a problem; (2) walks to the Human Machine Interface (HMI); (3) opens a ticket. After the ticket is open in the system, activities 4–9 are performed by the maintenance technician, who (4) detects a ticket open; (5) checks machine book; (6) decides if inspection is needed; either (7) inspects the machine; or (8) does not inspect the machine; (9) decides the intervention.

In the design option, activities 1–2 are performed by the operator, who: (1) detects a problem; (2) performs a guided diagnostic with the mobile application. After the guided diagnostic has been completed, the maintenance technician (3) accesses to the diagnostic content from the mobile application and either (4) inspects or (5) does not inspect; (6) decides the intervention.

In this case, the human component has been characterized with reference to the required skills, selected from a subset of thirteen skills relevant in the industrial context and reported in Table 1.

The activities of the workflow for the design option (TO BE) and for reference (AS IS) have been characterized with reference to the analysis and design framework, as reported in the columns 3–7 of Tables 2 and 3.

- Assessment: the comparison between the activities of the in the design option (TO BE) and in the reference setting (AS IS) for the two involved roles led to the following results. The operator showed an increase in the IV activity “Describe”. This shift can be negatively considered as a threat for productivity or positively as a knowledge extraction from the operator to be shared with the maintenance technician. The option also requires additional skills to the operator, namely skill n.5. The share of “field work” for the maintenance technician increases, as some activities such as checking the books or interpreting the notes in the ticket to understand if an inspection is needed have been deleted. Overall the design option appears to make better use of the work. During the assessment phase, in column 8 of Tables 2 and 3, some suggestions for supporting human

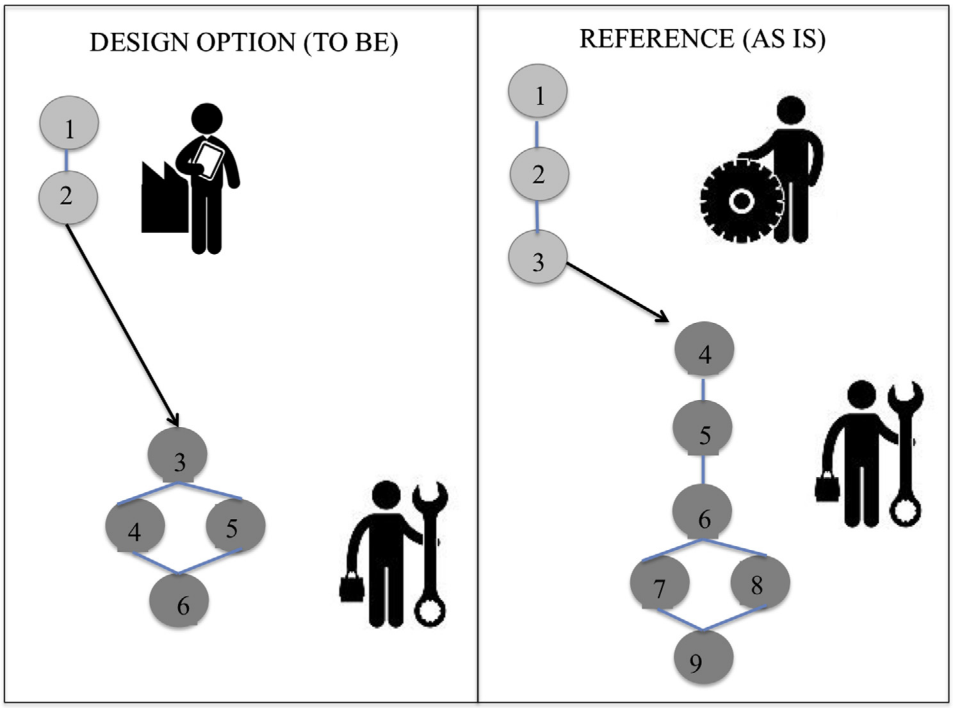

Fig. 3. Case 1 – workflow activities.

Table 1
Case 1 and 2 skills (ETA).

Industrial workplace skills: selected sub-set
(1) Teamwork: Working cooperatively with others to complete work assignments
(2) Planning & Organizing: Planning and prioritizing work to manage time effectively and accomplish assigned tasks
(3) Innovation and Invention: Formulating new ideas for and applications of processes and products
(4) Problem Solving & Decision Making: Applying knowledge of STEM principles to solve problems by generating, evaluating, and implementing solutions
(5) Operate tools and equipment in accordance with established operating procedures and safety standards
(6) Seek out opportunities to improve knowledge of tools and technologies that may assist in streamlining work and improving productivity
(7) Perform routine maintenance on tools, technology, and equipment
(8) Determine causes of operating errors and decide what to do about it
(9) Troubleshoot maintenance problems in accordance with established procedures
(10) Checking, Examining, & Recording: Entering, transcribing, recording, storing, or maintaining information in written or electronic/magnetic format.
(11) Apply techniques for observing and gathering data
(12) Complete required maintenance forms, records, and inspection reports
(13) Other

Table 2
Case 1 characterization design option (to be).

Activity	Description	Perspective				Human Skills	CPS
		ABS	DEC	INN	SOC		
OP.1	Detects a problem	AP	DI	IL	SL	5	Aid 1
OP.2	Performs a guided diagnostic with the app	AC	DIV	IL	SL	5, 7, 8	Aid 2
MT.3	Accesses to the diagnostic content from the app	AC	DI	IL	SL	2, 4	Aid 3
MT.4	Inspects the machine	AP	DIII	IM	SL	2, 4	Aid 4
MT.5	Does not inspect the machine	//	//	//	//	//	//
MT.5	Decides the intervention	AH	DII	IM	SM	2, 4	Aid 4

Table 3
Case 1 characterization reference (as is).

Activity	Description	Perspective				Human skills	CPS
		ABS	DEC	INN	SOC		
OP.1	Detects a problem	AP	DI	IL	SL	5	HMI
OP.2	Walks to HMI	AP	D0	IL	SL		
OP.3	Opens a ticket	AC	DIII	IL	SL	5	
MT.4	Detects a ticket open	AC	DI	IL	SL		
MT.5	Checks machine book	AP	DII	IL	SL		
MT.6	Decides if inspection is needed; either	AH	DII	IL	SL	2, 4	
MT.7	Inspects the machine; or	AP	DIII	IL/IM	SL	2, 4	
MT.8	Does not inspect the machine	/	/	/	/		
MT.9	Decides the intervention	AH	DII	IM	SM	2, 4	

activities were developed:

Aid 1: service to alert the operator, based on real-time elaboration of data coming from the sensors (alert signal activated when the temperature, the vibrations, or the energy consumption exceed the pre-defined threshold);

Aid 2: service application to guide the operator in checking the machine and adding his/her observations and knowledge to integrate the data from the sensors and the machine books to support diagnosis in case of machine failure (limited application of integrating physical sensors data with "human sensor data" (Liu, Chu, & Tsai, 2012; Wang et al., 2014);

Aid 3: service to make the maintenance technician aware of the pre-diagnosis and suggest him/her whether to inspect or to directly plan the intervention (dynamic interactive trouble shooting guide);

Aid 4: service to support the maintenance technician in deciding what intervention has to be planned (intelligent decision support system).

4.2. Aerospace engine systems plant

The plant produces parts for engine systems with application in the aerospace industry. The production system is organized as job shop, the organization follows the socio-technical principles of task identity and involvement of the workers. Workers are very skilled and can perform a several operations with different machines. Production is very flexible. However, in order to increase efficiency the introduction of a robotic cell has been formulated as a design option, the methodology has been applied and each step has been annotated:

- Problem setting: the methodology was applied to Operator working in the new robotic cell. In particular, the objective was to verify if the required skills match the profile of the plant Operators and evaluate possible services for the Operator to increase performances and ease.
- Scoping: the typical profile of the plant operators was taken as the reference; the case of a failure was selected as significant and the focus was set on the operator as the critical role.
- Analysis and Design: the workflow of the activities has been modelled only for the design option, as illustrated in Fig. 4. Each activity has been therefore characterized according to the Analysis and Design Framework, as reported in the columns 3–7 of in Table 4.

Assessment: the characterization and analysis of the activities of the operator led to some considerations: most of the activities require the same set of skills of the job shop, namely skills 1, 2, 5, 7, 10; the activities 11, 14 and 15 require additional skills for which some specific training is needed; according to the orientation of the company, the collaboration and knowledge sharing of the operator with the maintenance technician and with the manufacturing engineer has been highlighted for their social interaction, in order to be supported and encouraged; the activities 11, 13, and 14 have been highlighted as the most critical, leveraging the innovativeness perspective, as they require a wider knowledge of rules and methods. Within the assessment, some suggestions were generated in column 8 of Table 4 as feedback to the design:

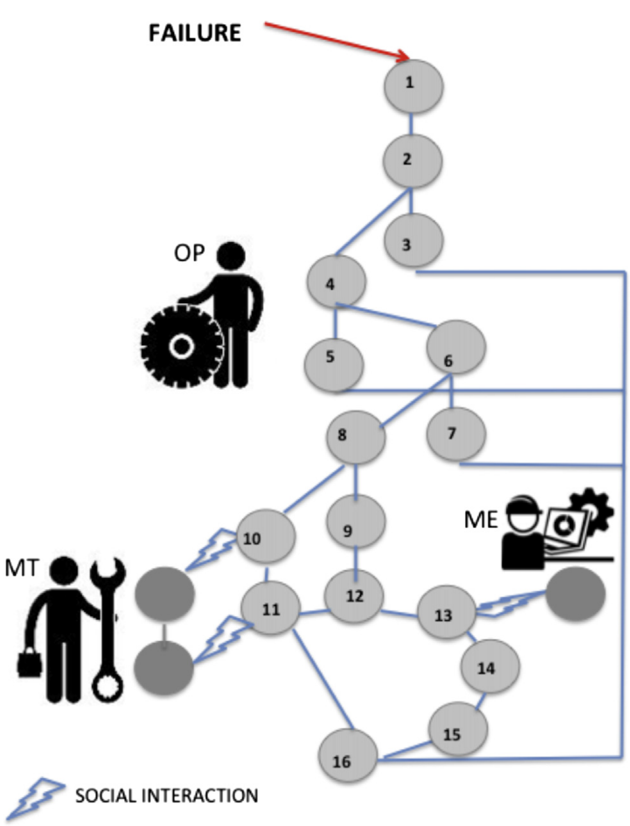

Fig. 4. Case 2 workflow activities for the operator.

Aid 1: service to alert the operator, based on real-time elaboration of data coming from the sensors (alert signal activated if fluids level/ pressure below threshold or part presence sensor detects missing part or tool presence sensor detects missing tool, temperature high or other alarms on);
Aid 2: service to support the identification of the cause of the issue, by distinguishing among problems related to media, raw material, fixture or part problems (intelligent dashboard visualization);
Aid 3: service to guide the activities of addressing problem with media, raw materials, fixture or part problems. Furthermore to guide restoring the machine by bringing in sequence all the components in a safe and correct position, starting from any of the numerous combinations of states in which the process may have stopped (dynamic situation-aware visual instructions);
Aid 4: service to enable and support communication, knowledge sharing related to the machine tool (app to add annotations to the instructions);
Aid 5: service to enable and support knowledge sharing, decision-making related to the part processing (simulation).

5. Discussion

The proposed methodology has been applied to two industrial cases to illustrate how industrial enterprises may address work organization, while considering technological changes, at design time, when different options can be considered and early feedback to the technical projects can still be collected, evaluated and whenever feasible incorporated in the final plans.

The cases considered showed the possibility, through this methodology, to incorporate different strategies and concerns for human work, according to the orientation of the enterprise, which can be expressed through a set of key performance indicators. Some KPI can be calculated on the bases of the categories used to characterize the activities, with reference to one or more workers and to one or more scenarios. Examples of KPI are: percentage of physical activities, percentage of non-value added activities, percentage of activities with high or medium social interaction, percentage of activities with high or medium innovativeness. Some other KPI are referred to the human component. An example is the number of skills required per a role. The enterprises, by defining their objectives in terms of increasing or decreasing each specific indicator, make their human resource strategy explicit and incorporate these performances in the assessment of the design options. The evaluation highly depends on other economic and production performances, but through these KPI, the decision-makers develop higher awareness about the implications of each design option for the workers. However, the partial involvement of the stakeholders, the limited experience with this type of considerations, the prevailing focus on technology lead to a certain level of uncertainty in the evaluation.

In the first application case, for example, the increase for the operator of activities characterized as “describe” has been commented as potentially controversial, while there is a clear shift of the maintenance technician towards a leaner workflow with a higher share of medium innovativeness activities.

In the second case, medium levels of innovativeness and social interaction have been highlighted as a valuable employment of workers, associated with an increase in knowledge sharing.

In both cases, the design option considered entails an increase of the workers’ skills, fostering the development of the human capital in the enterprises.

The two applications cases led to the identification of a set of

Table 4
Case 2 characterization design option.

Activity	Description	Perspective				Human skills	CPS
		ABS	DEC	INN	SOC		
OP.1	Detects a signal or that machine stops	AP/AC	DI	IL	SL	1, 2, 5, 7, 10	Aid 1
OP.2	Checks if raw material or media are missing	AP	DI	IL	SL	1, 2, 5, 7, 10	Aid 2
OP.3	Re-fills the material or media	AP	DIII	IL	SL	1, 2, 5, 7, 10	Aid 3
OP.4	Checks if tools are missing or worn	AP	DI	IL	SL	1, 2, 5, 7, 10	Aid 2
OP.5	Substitutes the tools	AP	DIII	IL	SL	1, 2, 5, 7, 10	Aid 3
OP.6	Checks if problem with the fixtures	AP	DI	IL	SL	1, 2, 5, 7, 10	Aid 2
OP.7	Adjusts/repairs/replaces the fixture	AP	DIII	IL	SL	1, 2, 5, 7, 10	Aid 3
OP.8	Checks if problem with the part	AP	DII	IL	SL	1, 2, 5, 7, 10	Aid 2
OP.9	Adjusts the part location or adjust tool/fixture	AP	DIII	IL	SL	1, 2, 5, 7, 10	Aid 3
OP.10	Calls for support	AP	DIII	IL	SL	1	Aid 4
OP.11	Analyses the problem, consequences and possible causes	AP	DII	IM	SM	8	Aid 4
OP.12	Removes the part	AP	DIII	IL	SL	5	Aid 3
OP.13	Proposes what to do and discusses with manufacturing engineer	AH	DII	IM	SM	1	Aid 5
OP.14	Puts the robot and all moving equipment in a safe position and rests the equipment alarms etc. to prepare the restart.	AP/AC	DII	IM	SL	9	Aid 3
OP.15	Loads the part	AP	DIII	IL	SL	8	Aid 3
OP.16	Restarts the machine	AC	DIII	IL	SL	5	Aid 3

possible suggestions for services that, by leveraging CPS, could support and enhance human work. Furthermore, by abstracting from the industrial cases and extrapolating from the literature, it is possible to identify the types of aids most suitable in relationship with the four perspectives and the human component of the analysis and design framework of Fig. 1. This work, depending on the characteristics of the activities to be supported, led to the following general guidelines for CPS-enabled supporting services:

- **Abstraction:** services to flank/augment sensorial or motor abilities of the workers can support physical activities (AP), examples are mechanisms to adjust the size of the written text on the HMI to the sight of the worker and (Stadler et al., 2017).
- **Decision making:** services to alert the worker whenever certain situations occur can support "Detect" activities (DI); services that model and predict the behaviour the systems, that relates causes and effects can support "determine" activities (DII); services that provide context-aware instructions and guidance support "develop" activities (DIII); services that provide means to easily and seamless store and share information and knowledge can support "describe" activities (DIV).
- **Innovativeness:** services to deliver examples from workers' practices can support Routine-based activities (IL); services to make easily accessible or to propose procedures or tools, on the basis of the task and context can support Rules & methods-based activities (IM); services that foster the proposal of suggestions and ideas can support Creative activities (IH).
- **Social interaction perspective:** services to run multi-stakeholder simulations or optimizations can support negotiation/mediation activities (IM); services to manage virtual presence, chats, and communities of practice can support strengthening social cohesion activities (IH).
- **Human component:** services to customize the workplaces and the human-computer-interfaces to adjust to the physical and sensorial characteristics of the workers can support workers with disabilities or ageing; finally, personalization features can enhance all the other supporting services to adapt to different conditions of the workers, such as stress, fatigue, inexperience-related limitations of towards human-automation symbiosis (Romero et al., 2015).

The results achieved should be interpreted taking into account the limitations of the present work, which can be addressed in future studies. So far the activities have been applied only at design time and have not been validated with the observation at execution time; the characterization of the activities requires some time and effort; quantitative and statistics on data are missing. In future research, it can be worth: to compare models and analysis of human work performed at the design phase with the detection of actual behaviours at execution time; to create libraries of typical standardized activities and aids to be reused upon minor adaptation; to complement the characterization of the activities with numerical variables and to develop tools, such as discrete event simulation, to analyse human work in several scenarios and provide quantitative summaries. Finally, future research could devote further attention to the definition of specific indicators to measure the objectives and assess the achievements of human resources strategies.

6. Conclusions

Policy makers, industrialists, consultants and researchers state the relevance of the human role in the novel manufacturing landscape towards Industry 4.0. However, there is poor knowledge about how to design or adapt production systems taking into account the technological and the human-centric perspectives, aiming at maximizing performance. The proposed methodology for modelling and assessing human activities within cyber-physical systems contribute to fill this gap. The study of two industrial cases demonstrates its applicability to analyse, evaluate and generate design options in real instances. The results of the industrial applications include feedback and suggestions to enhance the whole cyber-physical-social system. Furthermore, these suggestions have been abstracted from the specific scenarios and complemented to provide a set of general guidelines for work design.

Despite its limitations, the present work proposes a novel method to support the design of human work integrated within cyber-physical-system, which highlights strategic perspectives for human roles in the manifold interaction with technology.

Indeed, the method focuses on contributions and behaviour that are peculiar of humans, valuable, not replaceable by technology, based on creativeness, social interactions and problem solving. Besides the method favour the assessment and alignment of the characteristics and requisites for human workers and CPS functionalities, in advanced production systems, during regular production and in critical scenarios, such as failure detection or maintenance intervention. It paves the way towards formal and quantitative methods to model, simulate and verify human activities, which will be enhanced and extended, step-by-step, as the knowledge and experience on Industry 4.0 increase.

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