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Introduction of symbiotic human-robot-cooperation in the steel sector: an example of social innovation

Valentina Colla[1,*], Antonius Schroeder[2], Andrea Buzzelli[1], Dario Abbà[3], Andrea Faes[3], and Lea Romaniello[4]

[1] Scuola Superiore Sant'Anna, TeCIP Institute, ICT-COISP Center, Pisa, Italy
[2] Technische Universität Dortmund, Sozialforschungsstelle, Germany
[3] POLYTEC s.r.l., Borgo Chiese, Italy
[4] ILVA S.p.A., Taranto, Italy

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Abstract. The introduction of new technologies, which can support and empower human capabilities in a number of professional tasks while possibly reducing the need for cumbersome operations and the exposure to risk and professional diseases, is nowadays perceived as a must in any industrial field, process industry included. However, despite their relevant potentials, new technologies are not always easy to introduce in the professional environment. A design procedure which takes into account the workers' acceptance, needing and capabilities as well as a continuing education and training process of the personnel who must exploit the innovation, is as fundamental as the technical reliability for the successful introduction of any new technology in a professional environment. An exemplary case is provided by symbiotic human-robot-cooperation. In the steel sector, the difficulties for the implementation of symbiotic human-robot-cooperation is bigger with respect to the manufacturing sector, due to the environmental conditions, which in some cases are not favorable to robots. On the other hand, the opportunities and potential advantages are also greater, as robots could replace human operators in repetitive, heavy tasks, by improving workers' health and safety. The present paper provides an example of the potential and opportunities of human-robot interaction and discusses how this approach can be included in a social innovation paradigm. Moreover, an example will be provided of an ongoing project funded by the Research Fund for Coal and Steel, "ROBOHARSH", which aims at implementing such approach in the steel industry, in order to develop a very sensitive task, i.e. the replacement of the refractory components of the ladle sliding gate.

Keywords: robotics / human-robot cooperation / steel shop / ladle / maintenance

Résumé. Introduction de la coopération humaine-robot symbiotique dans le secteur de l'acier : un exemple d'innovation sociale. L'introduction de nouvelles technologies, capables de soutenir et d'autonomiser les ressources humaines dans un certain nombre de tâches professionnelles tout en réduisant le besoin d'opérations encombrantes et d'exposition aux risques et aux maladies professionnelles, est aujourd'hui perçue comme un must dans tous les domaines industriels, industrie de transformation incluse. Cependant, malgré leurs potentiels, les nouvelles technologies ne sont pas toujours faciles à introduire dans l'environnement professionnel. Une procédure de conception qui tient compte de l'acceptation, des besoins et des capacités des travailleurs ainsi que d'un processus de formation continue du personnel qui doit exploiter l'innovation est aussi fondamentale que la fiabilité technique pour l'introduction réussie de tout nouveau technologie dans un environnement professionnel. Un cas exemplaire est fourni par la coopération symbiotique homme-robot. Dans le secteur de l'acier, les difficultés pour la mise en œuvre de la coopération symbiotique homme-robot sont plus grandes par rapport au secteur manufacturier, en raison des conditions environnementales, qui dans certains cas ne sont pas favorables aux robots. D'un autre côté, les opportunités et les avantages potentiels sont également plus importants, car les robots pourraient remplacer les opérateurs humains dans des tâches répétitives et lourdes, en améliorant la santé et la sécurité des travailleurs. Le présent article fournit un exemple du potentiel et des opportunités de l'interaction homme-robot et explique comment cette approche peut être incluse dans un paradigme d'innovation sociale. En outre, un projet en cours financé par le Research Fund for Coal and Steel, "ROBOHARSH", sera mis en place, qui vise à mettre en œuvre une telle approche dans l'industrie sidérurgique

* e-mail: colla@sssup.it

afin de développer une tâche très sensible : le remplacement des composants réfractaires du sliding gate de la louche.

Mots clés: robotique / coopération homme-robot / aciérie / louche / entretien

1 Introduction

In the last years [1], service robots which are designed to perform tasks requested by users, have evolved toward a more active cooperation with humans, in order to jointly exploit the strengths and capabilities of both operators and robots by overcoming their limitations. Symbiotic human-robot-cooperation in this respect is the optimal arrangement of the abilities of robots taking over (standard) human activities (in the production process) as much as possible and reasonable (new human-robot work division, replacement of hazardous or repetitive activities by robots). This arrangement aims at combining the capabilities of robots for achieving high productivity in structured environments and the capability of humans to quickly adapt in unstructured environments. The intervention of human operators is mostly devoted to performing the challenging jobs requiring sensitivity, advanced sensing and reasoning capabilities adapting unplanned, unforeseeable or ever changing situations; in addition or complementary robots make use of their ability, e.g. to handle high loads with high precision without depletion or to face harsher and potentially harmful tasks. To gain the maximum advantage from these respective strengths, operators and robot must work in close cooperation sharing the same workplaces, tools and fixtures. Robots and humans in the same loop reduces the need to invest in expensive equipment to help the robot cope with an unstructured environment, and at the same time avoids strenuous and repetitive work that wastes the human capabilities, and expose the operators to potential risks for their health and safety [2].

Some preliminary applications of such a concept in industrial environments are already available [3], although there is still a delay with respect to other applications (such as medicine, rehabilitation and entertainment), due to the high variety of tasks, the skills required from the operator, the unconditioned environment and the safety regulations. The manufacturing industry, which already saw in the last decades a wide and intensive diffusion of robotic systems, is very committed to implementing such kind of human-robot cooperation, also including advanced means to experience a deeper and more immersive interaction of the human operator with robots. For instance, the so-called haptic interfaces go far beyond the tele-operation tools, which are currently adopted in the professional environments and allow a more natural interaction and even replication of natural human movement by means of a robot.

The ever increasing demand for deeper cooperation between humans and robots obviously raises also the need for investigating the psychological, ethical and social aspects related to the future evolution of workplaces that can derive by the implementation of such technology. A number of technical limitations but also non-technical barriers still need to be overcome for implementing and advanced symbiotic cooperation between humans and robots even in the manufacturing industry [4]. An interesting ethnographic field study at three manufacturing sites and a grounded theory analysis of observations and interviews on the impact of human-robot cooperation in the industrial environment was proposed in [5].

Within the steel industry, the difficulties for the implementation of symbiotic human-robot-cooperation are greater with respect to the manufacturing sector, due to the environmental conditions, which in some cases are not favourable to robots. High temperatures, dusts, emissions of hot off-gases and steam, very variable light conditions, presence of toxic and/or aggressive substances, huge dimensions of machineries and workpieces can represent considerable obstacles for the use of even traditional robotic cells, as some of its sensors, actuators and cameras might not properly work or even could be damaged. Moreover, there are tasks where the human sensitiveness and skills appear difficult to replace by an autonomous machine, as even minimal errors can cause a situation implying high risks for the workers and considerable losses in terms of material and energy. On the other hand, the opportunities and potential advantages are also greater, as robots could replace human operators in repetitive and heavy tasks, by improving workers' health and safety.

All the human related aspects (human-robotic interaction, health and safety, enhancing abilities, skills, acceptance, etc.) should be seen in an integrative and overarching innovation approach. Within a new innovation paradigm [6], the approach of Social Innovation [7–9] offers a concept that integrates technological innovation and workplace innovation into a social innovation process, embedding all the relevant aspects and actors into the research and development activities right from the beginning. Besides, e.g. health & safety issues and learning issues, an innovative participation process with the organizational development and participation of affected people (workers, foremen, instructors, operators, trainers, learners, etc.) [10] is needed.

The present paper will provide an overview of the potential and opportunities of human-robot interaction and will discuss how this approach can be included in a social innovation paradigm. An ongoing project funded by the Research Fund for Coal and Steel and entitled "Robotic workstation in harsh environmental conditions to improve safety in the steel industry" (ROBOHARSH), aims at implementing the first example of human-robot interaction in the steel industry by including such approach in a social innovation paradigm.

The paper is organized as follows: Sect. 2 describes the social innovation paradigm, Sect. 3 is devoted to introducing the technical subject of ROBOHARSH, while Sect. 4 presents the main challenges which are faced in such project. Section 5 introduces some Key Performance

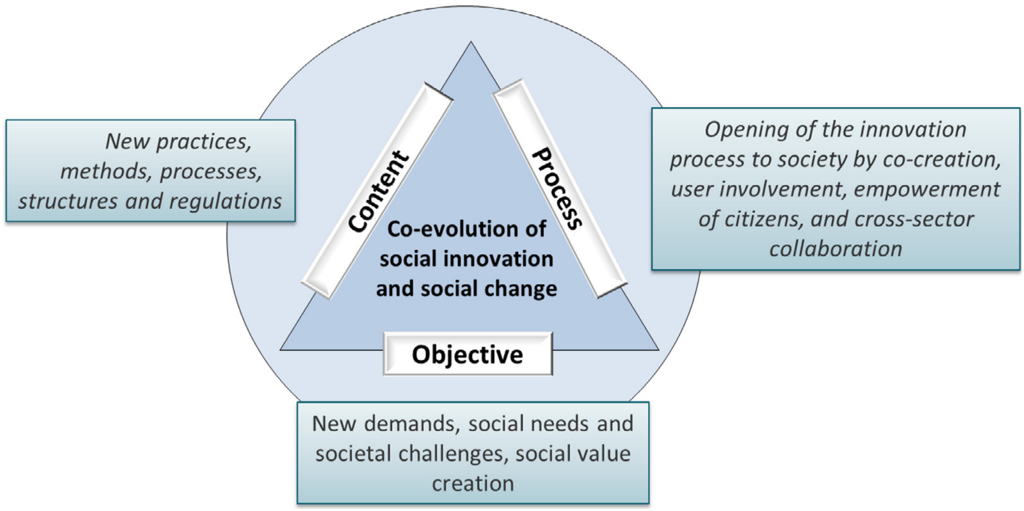


Fig. 1. New innovation paradigm.

Fig 1. *Nouveau paradigme de l'innovation.*

Indicators (KPIs) which have been identified in order to evaluate the performance of the robotic system once installed in the plant, while Sect. 6 provides some concluding remarks.

2 The social innovation paradigm

A new innovation paradigm is overcoming the technology-focused understanding of innovation by integrating technological developments into a social innovation process [11]. Against the background of the findings in innovation research and the clear emergence of complex innovation activities, technology-oriented innovation is more and more changing to socio-technical system development. This sort of fundamental change process, involving the entire institutional structure and the associated way of thinking and basic assumptions, can be interpreted in terms of the development of a new innovation paradigm [8]: opening fundamentally new perspectives on recognized problems and thus simultaneously unlocking new possibilities for action. The approach is characterized by three key categories:

- (1) new comprehensive contents leading to new practices;
- (2) modified, not only technology demanded objectives;
- (3) social innovation processes embedding all the relevant actors and considering impact right from the beginning (see Fig. 1).

Based on this a new symbiotic technological-social/human-societal relation has to be developed within an innovation process, not just focusing on technological possibilities but on new practices (of working in this case). Material (technologies, assets, physical resources), competences (skills, know-how, common understanding) and meaning (ideas, motivations, emotions) have to be taken into account.

The new innovation perspective is combining technological innovation with social and economic innovation. It is opening the view from a narrow and pure technological view to an overarching perspective focusing on societal challenges and demands, integrating societal, environmental, economic impact right from the beginning, looking at co-creation integrating the potential, knowledge, resistance, etc. of the (end) users.

Again, this new innovation approach includes modified and more comprehensive objectives: solutions for societal challenges and impact are in focus. And it is concerning changing subjects of innovations: new technologies alone are not solving recent and upcoming societal challenges, new or modified social practices are needed as well as cross-sector embedding innovations. The solution of a social demand (also from a company perspective) is in focus and not requirements of the technology for the implementation through users, adjustment of humans to technology.

Within such an approach, a symbiotic human-robot-cooperation and interaction has to be embedded in the triangle of technology (what is technological possible), organisation (what is efficient and useful) and human (what is desirable, helpful, needed to improve the current situation), and its interfaces: changes of one area will always affect the two others as well. These interrelations (see some examples in Fig. 2) have to be considered as they might support or hinder the success of the innovation.

The social innovation approach is opening the innovation process to society and users, in case of the human-robotic interaction mainly to the operators: not serving any longer as pure information and feedback giver but as co-creators of the new robotic interface. Consequently ROBOHARSH incorporates human related aspects (human-robotic interaction, health and safety, enhancing abilities, skills, acceptance, etc.) in an integrative and overarching innovation approach. The innovation process

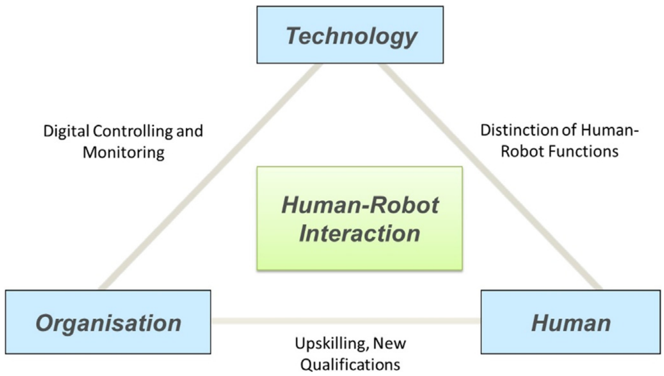


Fig. 2. Technology, Organisation, Human Interplay.

Fig 2. *Technologie, Organisation, Interaction humaine.*

Fig. 3. The ladle in the steel shop.

Fig 3. *La louche dans l'aciérie.*

has to be accompanied by change management to receive a broader understanding and persuasiveness of intended adjustments, the affected staff has to be trained for the implementation of the new technology, the new production processes and the end users of the innovation (technicians, operators, and other workers) have to be embedded in the innovation process. Last but not least, the impact on society (e.g. environment, consumer behaviour, regional acceptance, regional qualification level for new staff) has to be taken into account. Beside ROBOHARSH, other projects like GT VET [10,12], COCOP (www.cocop-spire.eu) and "Facts4Workers" (http://facts4workers.eu/) show the relevance and improvement of human-centred manufacturing within a new innovation approach as well.

ROBOHARSH is an example to couple a technological innovation with the investigation of vocational and social aspects, also overcoming non-technological barriers preventing a wide diffusion of advanced robotic systems in the steelworks. Taking into account that every technological innovation is also a social innovation process, the development process is integrated in a broader company related strategy, integrating all the relevant stakeholders and end users, thinking implementation and impact right from the beginning of the process (from the idea over intervention and implementation to impact) – not only for the production process but for the people concerned (inside and outside the production line). Furthermore, more general societal impacts are taken into account if relevant (e.g. environmental aspects).

3 The technical problem faced in the ROBOHARSH project

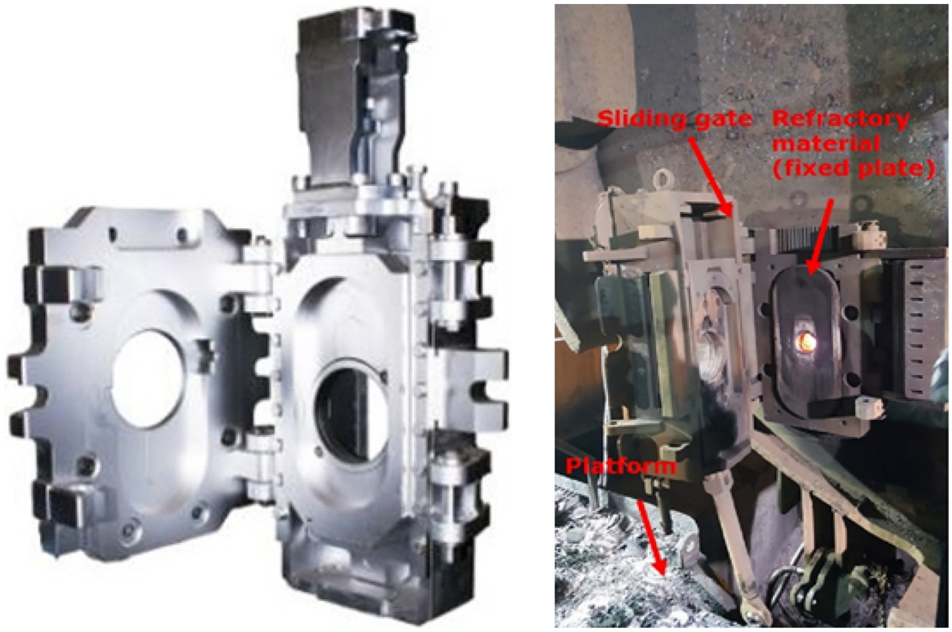
The ROBOHARSH project aims at implementing symbiotic human-robot cooperation in the harsh environment of a steel shop (see Fig. 3), in order to develop a very sensitive task, i.e. the replacement of the refractory components of the ladle sliding gate.

The ladle is a container through which the molten steel is transferred to the continuous casting station, where the steel is casted and solidified into semi-finished products, such as slabs, blooms or billets. Figure 3 refers to ILVA Taranto Works, where the work described in this paper is being developed: the ladles here have a diameter of about 5.75 m and a height of about 6.0 m.

The sliding gate, which is depicted in Figure 4, is located at the bottom of the ladle and hosts the tap hole (also called "arrester") through which the steel flows after completion of the steelmaking process by regulating the flow of the liquid steel through its mobile component, which is actuated by means of a hydraulic cylinder. The cylinder aligns the movable plate with the corresponding hole in the arrester. At the end of the tapping phase, the ladle is carried to a suitable maintenance area of the drawer, for the restoration of the refractory components and other necessary monitoring operations.

Both fixed and mobile components hold a refractory wear that need to be regularly replaced (some components are replaced after each cast, while other ones are replaced after five-six subsequent casts). Their replacement also requires a cleaning operation to be performed through the oxygen torch. The perfect adherence of the refractory material to the metallic structure is ensured by a layer of adhesive mortar, but a very precise collocation of each piece is fundamental and even minimal misalignments can cause leaks of liquid steel during operations, which have detrimental effects. Just to exemplify, the density of the hot liquid steel in the ladle is comparable to the water density at room temperature, therefore the accuracy required for the placement of the refractory component is in the order of magnitude of the millimetre.

This complex maintenance operation is of paramount importance in order to guarantee the reliability and safety of the slide gate during service: if it is not properly performed, the risk of a leakage of molten steel arises during the following steelmaking process, which can imply huge damages and even serious injuries for the operators. The maintenance process implies a series of complex operations where both precision and force must be jointly applied and where many tools and workpieces are handled by at least two operators. Currently this maintenance operation is manually performed, as the operators' skill and ability is fundamental to guarantee the required accuracy in the positioning of the refractory material. On the other hand, the temperature close to the bottom of the ladle can overcome 60 °C and the weight of some of the refractory



a) b)

Fig. 4. An example of the sliding gate.

Fig 4. *Un example du sliding gate.*

pieces to be replaced can lie around 20 kg. Thus the operators are exposed, in the short term, to the risk of hands/feet injuries and, in the long term, to problems related to stress, repetitive strain and back injuries.

4 The challenges of the ROBOHARSH project

The project ROBOHARSH aims at practically demonstrating through a real full scale installation that workers' safety protection in the steel shop can be improved by applying a special industrial robotic cell capable to reliably operate in harsh environmental conditions and allowing human-robot cooperation in order to jointly develop the complex tasks of ladle sliding gate maintenance. The robotic cell is also expected to improve the reliability of the slide gate operation in terms of service life and ladle operator safety.

A standard industrial robotic cell is unsuitable to accomplish the complex series of operations, due to scarce repeatability and level of skill and sensitivity required by some operation (e.g. new refractory material final collocation). Apart from the already mentioned problem of position accuracy for the refractory components, it is worth mentioning that the adhesion of such components to the sliding gate is ensured by a layer of mortar which is manually applied, and whose thickness and regularity is only visually checked and depends on the skill of the operator. Moreover, the position of the bottom part of the ladle with respect to the moving platform depends on the angular accuracy of the machine, which supports and rotates the ladle, and such accuracy is in the order of magnitude of the degrees. Moreover, the wear of the components as well as the amount and position of the material to remove in the cleaning operations are not repeatable, vary each time and are unpredictable. Finally, the operational environment is highly unstructured and a number of different operations with different tools and workpieces are required (e.g. cleaning, replacing and fixing the different components of refractory material).

The operators overcome all the above-mentioned problems by repeating manual and visual checks and by adapting the sequence of manual operations, but from the point of view of a robotic implementation of the maintenance procedure, a standard fully automated robotic cell with suitable features to work in such harsh operating environment cannot provide this level of flexibility.

The adopted robot is an ABB IRB 7600 325/3.1 with Foundry plus protection. The terminal part of the robot arm is covered by a stainless steel lining, which protects it from exposure to high temperatures and hits, by avoiding accidental damages during the normal operation condition. The robot is also equipped with a collision detection system which stops the robot in case of collision. The maximum tool weight (plus maximum refractory weight) is 325 kg and the maximum reachable distance is 3.1 m. Figure 5 provides the main dimensions of this robot. Due to the heavy duty environment and the heavy tools to be used, one of the biggest versions produced by ABB was selected considering its features in terms of load and working area.

In order to partly overcome all the uncertainties in the relative position of the robot with respect to the sliding gate, flexible and smart solutions must be elaborated for both establishing reference points on the ladle and smart designing and conditioning of the whole working environment. Therefore, the industrial robotic cell needs some

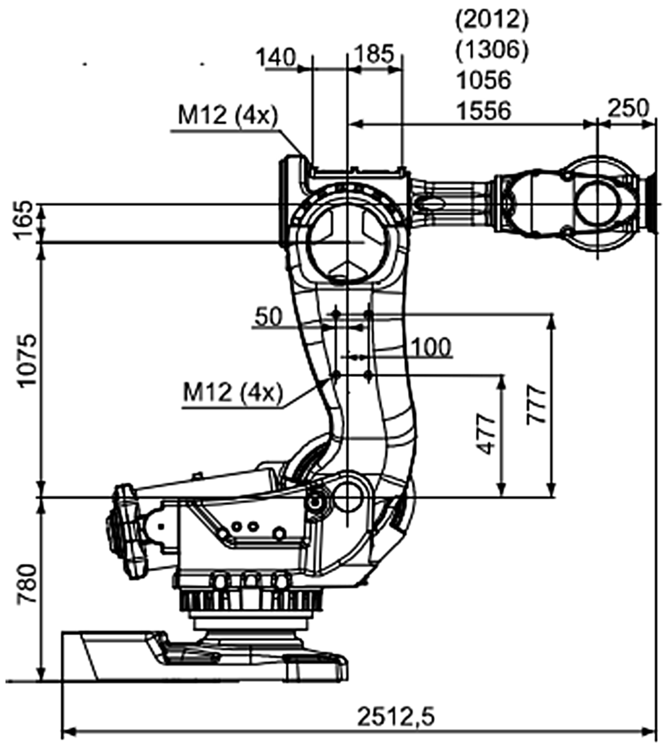


Fig. 5. Diagram of the robot with indications on the dimensions of the main components (from ABB specification sheets).

Fig 5. *Diagramme du robot avec des indications sur les dimensions des composants principaux (à partir des fiches techniques de ABB).*

adaptations and ad-hoc equipment and procedures, in order to operate in presence of high temperatures, dusts, steam and other disturbances while keeping their reliability and requiring sustainable maintenance operations.

A preliminary analysis and a basic engineering were developed during the first months of the project, which allowed to define some basic commercial components that are necessarily bought when accomplishing the project approach.

Unfortunately, the sequence of very high specific operations that must be accomplished by the robot implies that many of the tools to be handled by the robot will have to be ad-hoc designed and engineered within the project itself. They are based on commercial components that must be modified in order to provide them with all the features allowing accomplishment of all the tasks. Such modifications are part of the work to be developed in the incoming months of the project.

Figure 6 provides an overview of the robotic cell, where the most relevant components are highlighted. The area occupied by the robotic cell (excluding the equipment for holding and turning the ladle) is approximatively 14.2 m × 6.6 m. The main components for the robotic and video systems are as follows:

– 1 robot;
– 2 manipulator to weightlessness;
– 3 ventilation system;
– 4 PLC and UPS system;
– 5 monitoring system;
– 6 CCTV system;
– 7 vision system 2D and 3D.

The industrial robot comes equipped with a vision system in order to not only monitor all the operations but also to provide indications to the robot control. Special tools and actuators are being constructed to specifically handle the different components of the sliding gate. The application of a vision system enhances the flexibility and adaptability of the system. On the other hand, human supervision and even cooperation (in those operation in which human skill and sensitivity is essential) must be ensured in a safe way, by thus avoiding any burdensome operations for the workers.

To sum up, the human-robot cooperation is being applied in order to leave to the operators the most delicate and sensitive tasks (such as, for instance, the mortar application, the fine tuning of the plates placement after location or the final checking of the hole cleanliness), which cannot be safely and precisely performed by the robot. On the other hand, the robot performs all the heavy tasks, such as removing, lifting and positioning the refractory components. The vision system supports robot control and allows the operators to perform more accurate and safer inspections from a remote position (e.g. the operator can stay inside the air-conditioned container instead of being in proximity of the ladle bottom, while a vision tool is placed by the robot near the components to be inspected). A complex sequence of acknowledgments allows the operator to preliminary check, validate and authorize all the different operations of the robot.

Due to its complexity, the task of maintenance of the ladle sliding gate can actually be considered a benchmark for robots application in the steel industry with respect to other challenging operations, where human intervention is still considered the most reliable solution, despite the harsh environmental conditions. The demonstration that a symbiotic human-robot cooperative approach can replace full human-based operating practice in this task opens a wide range of further possibilities of applications in tasks that are really challenging for the personnel, with a huge perspective potential for reduction of health and safety risks.

A fully autonomous robot cannot replace the human operator, but it is quite evident that a robotic support to replace the heaviest operations could highly contribute to protect the workers' health and safety and to minimize failures. Therefore, the selected operation is a perfect benchmark to experiment a cooperative environment with a robot working together with operators. The ergonomics of the operators' working positions as well as their interaction with the robot will be deeply investigated through modelling and simulations, in order to make the interaction between operators and robot not only safe but also easy and natural. Furthermore, a great attention will be paid to the personnel training, professional qualification, acceptance and motivation, the consortium being aware that a pervasive deployment of human-robot

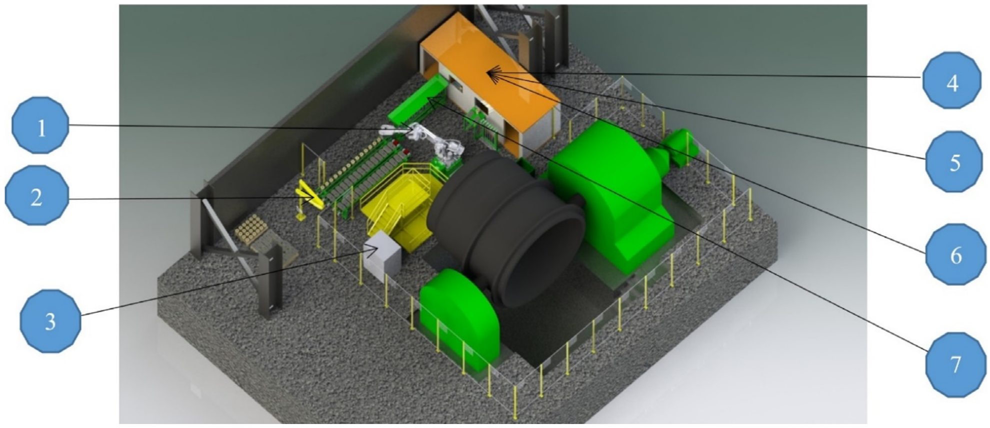


Fig. 6. Overview of the robotic cell.

Fig 6. *Vue d'ensemble de la cellule robotisée.*

cooperation in the steel sector is slowed by a number of non-technical barriers, and thus any social aspect need to be deeply analysed.

5 Key performance indicators for the system

To show the impact of the technological development within a social innovation process, a list of numerical Key Performance Indicators (KPIs) has been elaborated to assess the validity of the developed system and its benefits with respect to the manual operation. These KPÍs are of both quantitative and qualitative character, partly measurable within the project lifetime, partly only when it comes to implementation in the real production process. Already existing data for the KPÍs will be listed or measured at once – for target/actual performance comparison, variance comparison, demonstrating the performance of the innovation process. The selected KPIs are clustered, depending on the kind of impact they mostly address, encompassing technological, organizational and social impact, and the transferability of the solution:

5.1 Increased safety and health

- A.1 (Reduced) number of physical activities within the operation (number of activities done by the robotic cell) – this can be justified during the project (using the final list of new division of tasks between operator and robotic cell);
- A.2 number of heavy weight activities supported by the new supporting facility within the robotic cell – this can be justified during the project;
- A.3 (reduced) number of physical discomforts and occupational diseases – justifiable outside the project life span;
- A.4 rate of near miss, lower operation failures – justifiable within and beyond the project life span;
- A.5 average temperature perceived by the operator during the activity of the replacement of the refractory components of the ladle sliding gate.

5.2 Personnel development

- B.1 Duration and up-skilling components of required training (higher qualification);
- B.2 rate of acceptance with the new system;
- B.3 increased job satisfaction;
- B.4 new established working practice, fall back in old practices;
- B.5 level of working comfort (expected to be better working in a container).

5.3 Organisational development

- C.1 Rate of incorrect operations causing problems when the ladle is in operation;
- C.2 average time to complete the whole procedure.

5.4 (Social) innovation process

- D.1 Integration of the users/operators and stakeholders in the innovation process (co-creation);
- D.2 intensive: frequency (e.g. how often the operators are involved in the innovation process);
- D.3 extensive: number of concerned stakeholders and users (who and how many);
- D.4 rate of improvement suggestions through users/ operators and stakeholder, changes in the objectives and processes.

5.5 Transferability

- E.1 Number of sliding gates typologies (among those ones which are currently on the market) where the robotic cell could be adapted and estimated cost of adaptation (= design cost);
- E.2 number of steelmaking sites where the solution could be applied with minor modifications;
- E.3 number of steelmaking sites where the solution could be applied with relevant modifications;

– E.4 number of processes outside the steel sector where the proposed robotic cell could be adapted.

6 Conclusions

Every technological innovation is also a social innovation, especially when it comes to a new functional and operational working division between robots and humans. Embedded in a new innovation paradigm, technological development is more effective and (in the long term) more efficient when technological, organizational and social impact is reviewed right from the beginning of the project, integrating the existing competences and experience of the operators in a co-creation process. Even robotic replacement of human activities leads to new ways of human supervision and cooperation (human skills and sensitivity are still needed, leading to a higher qualification for running the robotic cell). Improving the working conditions by increasing health and safety, reducing operation failures and near misses, and establishing new working practices will in the end not only improve the production process but also the competitiveness of the company, and in this case the steel industry.

Not only focusing on technology as such but its integration in a social innovation processes will guarantee a higher effectiveness and efficiency of the solution and its sustainability. Barriers and obstacles will be solved within the innovation process and not afterwards. This, in the end, is affecting competitiveness in a positive way.

The ROBOHARSH project represents a first attempt to introducing a human-robot cooperative environment within the steel sector and represents a relevant challenge not only from the technical but also from the social point of view, as it introduces a dramatic modification in the standard operating practice. The project is still in its initial phases, but, even at this stage, many efforts are spent in order to take into account the requirement of the plant technicians, to involve them in the design activities and to figure out a performance evaluation procedure where social aspects are also taken into account, fully in accordance to the paradigm of the social innovation.

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