On the role of human operators in the design process of cobotic systems

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Abstract
Industrial cobotics is presented as a way of business competitiveness by combining human skills and decision making with robotic advantages. The place and safety of humans in cobotic (collaborative robotic) systems are the subjects of much discussion. This article provides a qualitative overview of the main multidisciplinary fields related to the place of human operators during the design process of humans–robots' systems and discusses paths for effective consideration of the human challenge during this kind of design projects. The added value of this article is its multidisciplinary aspect. Readers will find in this article a technological overview of cobotics, different methodologies and design models focused on final users, interesting examples of evaluation indicators potentially adapted to an effective consideration of humans during the design process of cobotic systems (economic, technical, and human) and guidelines seeking to support cobotic system designers to succeed considering final users during the design process.

Keywords Cobotics · Humans–robots' interactions · Ergonomics · Human-centered design

1 Introduction

Recently, collaborative robots (called also cobots: see the next section) have acquired significant importance in the industrial sector. They are increasingly presented as one of the keys to business competitiveness of companies in general, and to the growth and survival of small and medium enterprises (SMEs), by combining human decision-making power with the strength, endurance and precision of the robot. This combination seems to be a potential solution to meet current needs for flexibility and agility related to fluctuating demand and the globalization of competition. While the deployment of these technologies is still limited, their future looks very promising.

The place of human operators in this context gives rise to many discussions, including vigilance about their safety, questions related to their health, the reduction of the hardship of their work, the reduction of musculoskeletal disorders risks and the revaluation of their place by transforming their roles from operators doing all the work manually to pilots managing and supervising collaborative robotic cells.

However, implementing a handling aid does not guarantee that the risk of musculoskeletal disorders (MSDs) will be reduced. In this sense, the health problems and difficulties caused by the use of exoskeletons[1] are the subject of much discussion and criticism (Theurel et al. 2018). This is why human dimensions must be studied and considered with particular attention during the implementation of a human–robot system (or the integration of any new technology).

This article provides a qualitative overview of the main multidisciplinary fields related to the place of human operators during the design process of humans–robots' systems, and discuss paths for effective consideration of the human challenge during this kind of design projects. For this purpose, four multidisciplinary topics are covered in this article:

– First, we start this article with a presentation of the technological aspects regarding collaborative robotics. This will allow us to know the panel of technological possi-

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[1] Handling assistance robots carried by users.

bilities in terms of robots, their interaction modes with humans and their limits defined by safety standards.
- Second, we will briefly discuss the concept of “collaboration” between humans and robots. This part aims to clarify the possibilities of interaction between humans and robots in the context of current technological developments, and help to unify the representation of “collaboration” in the context of collaborative robotics.
- Then, we will present a summary of the main disciplines and give some examples of proposed methods and models that have been interested in considering humans during technological design projects. This will provide feedbacks about the subject of this article, even if they have been developed in other contexts (human–computer interaction for example), it still provides a good inspiration to succeed this challenge in the context of collaborative robotics.
- Finally, we will also introduce evaluation indicators that can be adapted to the multidimensional aspect of humans–robots’ design projects.

After presenting the four multidisciplinary topics, we will end this article by discussing the main points of vigilance during the management of cobotic design projects, to combine performance, health and skills development while remaining within technological feasibility.

2 Industrial cobotics: technological elements

2.1 Classification of industrial robotics

To study the role of end-users during the design of human–robots’ systems, it is essential to have an overview of existing robotic solutions, to understand their potential for interaction with humans and to be aware of the safety standards governing the field of collaborative robotics.

Contrary to the precise definition of “industrial robot” in the robotics community as a “manipulator, multi-application, reprogrammable, automatically controlled, programmable on three or more axes, which can be fixed on site or mobile, for use in industrial automation applications” (ISO 8373). There is no common definition for cobots and collaborative robots. If we go back in time, we find that the original definition of the word “cobot” referred to mechanically compliant devices (COmpliant roBOT), intended for use in haptic interfaces (Colgate and Peshkin 1999). Later, the term “cobot” was used by robot producers and industrials to refer to a new type of robots with sufficient safety devices (mechanical and/or electronic) able to safely operate in the same workspace with humans. The word “cobot” has thus taken another meaning of (COllaborative-roBOT) designating robots sharing the same workspace with human operators (Moulieres-Seban 2017).

Some classifications of industrial robotics exist. For example, the INRS[2] (INRS 2018) classifies these technological innovations according to the degree of interaction between humans and robots:

- Coexistence or sharing of workspace: humans and robots contribute to the realization of distinct tasks in the same space–time environment;
- Direct collaboration: the human and the robot work simultaneously on a common task;
- Indirect collaboration: the human and the robot take turns working on the same task;
- Physical assistance: in this case, the robot provides physical assistance to the professional gesture by relieving the operator in the execution of his movements.

To explicitly illustrate the various types of these industrial robotics technologies, we propose to classify them according to the degree of interaction with humans by distinguishing two types of solutions (Fig. 1) (Bounouar et al. 2019):

- Robotics solutions that incorporate the conventional elements of industrial robotics. In this context, the robot carries out the tasks independently, without any human intervention. The main development concerns the possibility of removing safety elements such as barriers or grids, in favor of immaterial devices such as light barriers or laser scanners. Collaborative manipulator robots can naturally fall into this category.
- Cobotic solutions that require human presence to perform tasks. In this context, cobots, exoskeletons or remotely controlled manipulators are guided by users. These cobotic solutions are used to help the operator accomplish his task by guiding his movements, increasing the force exerted or compensating the weight of an object or a tool. Depending on the operating scenario, manipulators and mobile robots can be considered as cobots if their operation involves the presence of users. In these cases, human presence is not considered exclusively as a degraded mode of operation.

To summarize, cobots are user-guided and require a permanent human presence to perform their tasks. On the other hand, collaborative robots, once programmed, autonomously perform their tasks. The common characteristic of these new technological devices is their ability to share the same workspace with human operators, which allows possibilities for interaction between humans and robots. This is why it

[2] The French National Research and Safety Institute.

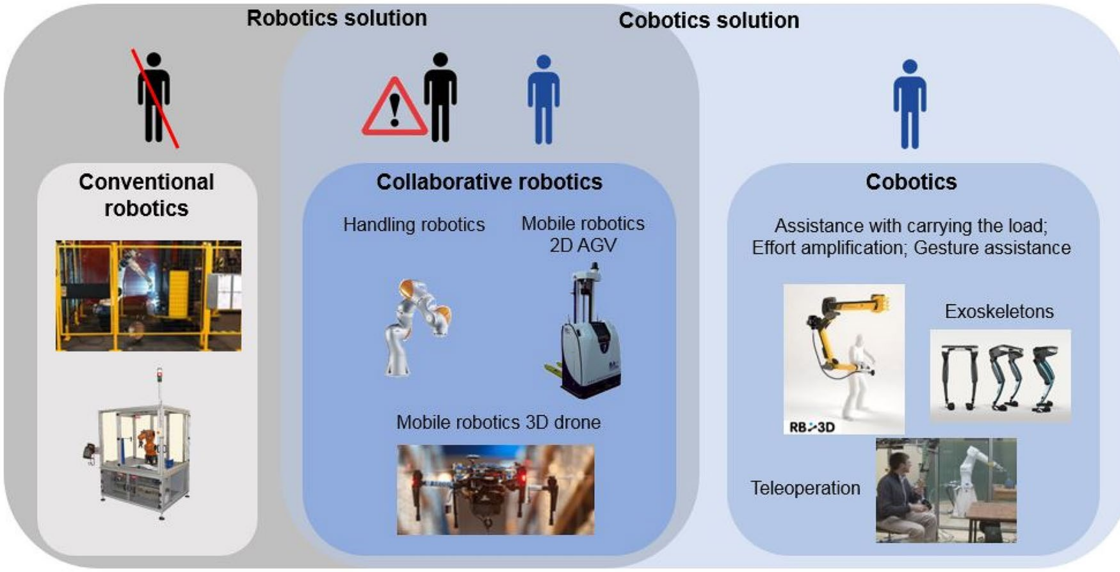


Fig. 1 Classification of industrial robotics

is important to consider humans in the design process of human–robot systems. To protect the health of users in this context, the modalities of interaction are strictly framed by security standards. These modalities are briefly presented and discussed in the following section.

2.2 Modality of human–robot Interaction

According to industrial needs in terms of workspace and the spatio-temporal distribution of tasks between humans and robots, the safety characteristics of the robotic system must be adapted. The NF EN ISO 10218 (1 and 2) and ISO/TS 15066 standards governing the field of collaborative robots provide four types of preventive measures (Prevention Guide 2017).

A. Safety monitored Stop: according to this preventive principle, when a person enters the collaborative workspace voluntarily or accidentally, the robot must stop its movement and maintain a safety stop. When the person leaves the robot's perimeter, the robot resumes its movement.
B. Hand guiding: the operator directs the robot's movements, at limited speed, using a sustained action control device. This type of manual guidance in the production step is different from manual guidance in the robot's training step so that it memorizes the trajectories in the operating mode.
C. Speed and separation monitoring: the robot environment is monitored by a vision system that follows the operators' position. Depending on the speed and the distance of separation between humans and robot, the robot adapts its speed. The speed, minimum separation distance and other parameters must be determined by a risk analysis. When an operator exceeds the minimum safety separation, the robot stops.
D. Power and force limiting: this principle is particularly suitable for the implementation of robotic solutions that require direct collaboration between operators and the robot. In this case, operators are required to work close to the robot and, if necessary, to be in contact with it. This preventive measure is based on the elimination of risks on these cases of contact between an operator and the moving parts of the robot (risk of collision, shock, crushing, etc.). These contacts, if they occur, must not be dangerous to the health and safety of operators. The power limits to be respected for the different parts of the body should be determined accordingly to the Technical Standard (TS15066) (Fig. 2). The risk analysis is decisive on the feasibility of implementing this collaborative solution principle.

Currently, in the industrial context, interaction modes 1, 2 and 3 are the most frequently implemented. Which means that there is—in most cases—no direct interaction between robots and humans because within these interaction modes, the robot is stopped to avoid contact with humans (modes 1 and 3) or it is totally guided by the human operator (mode 2). Interaction mode 4 is the only mode that opens the possibility of a real interaction between humans and robots (this means that the robot performs autonomous movements and interacts with humans: tools preparation for example). This observation leads us to specify the meaning of "collaboration" between humans and robots before discussing the process of designing humans–robots' systems. Throw the

Body region		Specific body area	Quasi-static contact: Maximum permissible pressure [a] p_S N/cm²	Quasi-static contact: Maximum permissible force [b] N	Transient contact: Maximum permissible pressure multiplier [c] P_T	Transient contact: Maximum permissible force multiplier [c] F_T
Skull and forehead [d]	*1*	*Middle of forehead*	*130*	*130*	*not applicable*	*not applicable*
	2	*Temple*	*110*		*not applicable*	
Face [d]	*3*	*Masticatory muscle*	*110*	*65*	*not applicable*	*not applicable*
Neck	4	Neck muscle	140	150	2	2
	5	Seventh neck muscle	210		2	
Back and shoulders	6	Shoulder joint	160	210	2	2
	7	Fifth lumbar vertebra	210		2	2

Fig. 2 Biomechanical limits extract (ISO TS 15066)

following section we will precise our meaning of "collaborative robots" by briefly comparing the essential characteristics of collaboration and cooperation between humans and the current technological development of "collaborative robots".

2.3 Concept of "collaboration" between humans and robots

Work between humans takes often a shared form (Sheridan 2002), in which two or more agents work together on the same task. In everyday life, many projects and work situations take this collective form (Hoc and Lemoine 1998; Benchekroun and Weill-Fassina 2000). They are considered cooperative or collaborative. Collaboration and cooperation are studied in several scientific disciplines, each with different concerns, culture and vocabulary. Finding a universal definition of collaboration is, therefore, a difficult task (Chellali 2009). In this sense, the limits and the differences between these two working modes generate different viewpoints (Kozar 2010; Hord 1981). Defining collaboration and cooperation not being the purpose of this article, we will briefly discuss in this section some fundamental characteristics defining the attitude of a work to be collaborative or cooperative, which is similar to the method of definition by cluster concept.[3]

A. The notion of Collaboration between the humans

Marx (1867) formally defines cooperative work as a group of individuals working together for a shared goal. Clarke and Smyth (1993) refer to Deutch's (1962) definition "co-operation is the situation where the movement of one member towards the goal will to some extent facilitate the movement of other members towards the goal" and affirm that there must be, to speak of a situation of cooperation, a common goal recognized by all the members working towards its realization. (Pavard, 1994). In the same sense, Terveen (1994) defines collaboration as a process in which two or more agents work together to achieve common objectives. From this definition, result the following essential characteristics for collaboration:

- Agree on common objectives to be achieved;
- Planning, allocation of responsibilities and coordination of tasks to be performed: agents must decide how to achieve their objectives, what actions each agent should take, and how to coordinate actions among themselves;
- Shared context: agents must be able to monitor progress towards their objectives. They must monitor what has been achieved and what remains to be done. They must assess the effects of actions and determine whether an acceptable solution has been found (Salas et al. 1995; Shu and Furuta 2005);
- Communication: any collaboration requires communication to define objectives, negotiate how to proceed, allocate tasks, and evaluate progress and results;
- Adaptation and learning: collaboration has a history, both short term within the same session and long term over several sessions.

These characteristics give a good idea of these complex working forms between humans. The next section

[3] The notion of 'cluster concept' goes back to the fundamental criticisms of the classical theory of definition by Ludwig Wittgenstein and describes a concept with a list of associated attributes (Flemisch et al. 2014).

briefly discusses the case of "collaboration" between humans and technological systems (robots, computers, etc.) and explicit our representation of collaborative robots.

B. Human–robot "collaboration"

In this section, we are interested in the concept of collaboration between humans with technological systems, this concept probably first concerned Human–Computer Collaboration (HCC). Terveen (1994) indicated that HCC was inspired by two main areas: artificial intelligence and human–computer interaction. These two disciplines have given rise to two different approaches to the treatment of HCC: the emulative (human emulation) and the complementary (human complementary) approaches. While the first approach aims to equip the machine with capacities like those of humans to bring it to collaborate, the second approach focuses on the asymmetric aspects of the two types of agents and the distribution of roles between them.

According to Pavard (1994), the notion of cooperation systematically refers to a human activity, and it will only be possible to talk about human–system cooperation when this system becomes intelligent. Which can be formulated through a set of criteria:

1. Have a common objective (which implies the ability for each partner to display the objective they are pursuing and to have meta-knowledge about the activity being carried out);
2. Be able to access information on the purpose of the partner throughout the resolution session;
3. Have a communication tool;
4. Be able to adapt to the partner's changing behavior over time.

Rather than judging in binary mode the cooperative aspect of a human–machine system, another interesting approach to describe cooperation consists of defining levels of collaboration and cooperation of a human–machine system (Parasuraman et al. 2000; Pacaux-Lemoine et al. 2011; Pacaux-Lemoine and Vanderhaegen 2013).

Collaboration with Humans is no longer only about communication (written or oral) as is the case with computers. New opportunities are emerging; robots can move (by driving or walking) (Patle BK et al. 2019). They can emit and capture visual signs and sound information (Mavridis 2014). They can also interact with physical objects in the environment.

Thanks to technological development in the fields of information acquisition and artificial intelligence, several studies are being carried out to equip robots with communication skills (Taizo Miyachi et al. 2017; Jahani and Kavakli 2018; Baltzer et al. 2019), gesture perception and recognition (Fontmarty 2007), intention prediction and movement anticipation (Piçarraa 2018; Zhang et al. 2006).

Most of these programmed and developed demonstrators show, at best, the ability of a system to achieve a few simple exchanges with a user, or to recognize an object or a gesture in a restricted application context and, for the moment, far from being usable in industrial conditions.

In this article, by "collaborative robots", we refer to programmable technological tools that can share the same workspace with human operators. Their utility (assistance, cooperation, or collaboration) depends on the design methodology and relevance to the real needs of potential users. To ensure the relevance of an investment on a collaborative robotic cell, the needs of future users must be defined in advance and the characteristics of the new humans–robots' systems must consider the future users from the beginning of the design process Trentesaux and Millot (2016).

The following section presents examples of interesting methods and design project management models used to ensure that final users are effectively considered during design projects.

3 Human-centered design methodologies

Most of the methods and design project management of this section have not been developed within the new context of humans–robots' systems design projects and do not necessarily consider all the challenges of collaborative robotics (safety, acceptability, profitability, etc.) but they still represent an important source of inspiration and can be adapted to the context of collaborative robotics.

3.1 User-centered design

ISO 9241 provides a framework for human-centered design. A human-centered approach should follow, among others, the principles listed below:

A. The design is based on an explicit understanding of users, tasks and environments:
   The design of products, systems and services should consider their users and who may be affected (directly or indirectly) by their use.
B. Users are involved throughout the design and development process:
   User participation in the design is a valuable source of knowledge about the context of use, tasks and how users are likely to work with the future product.
C. The design is driven and adapted by a user-centered evaluation:

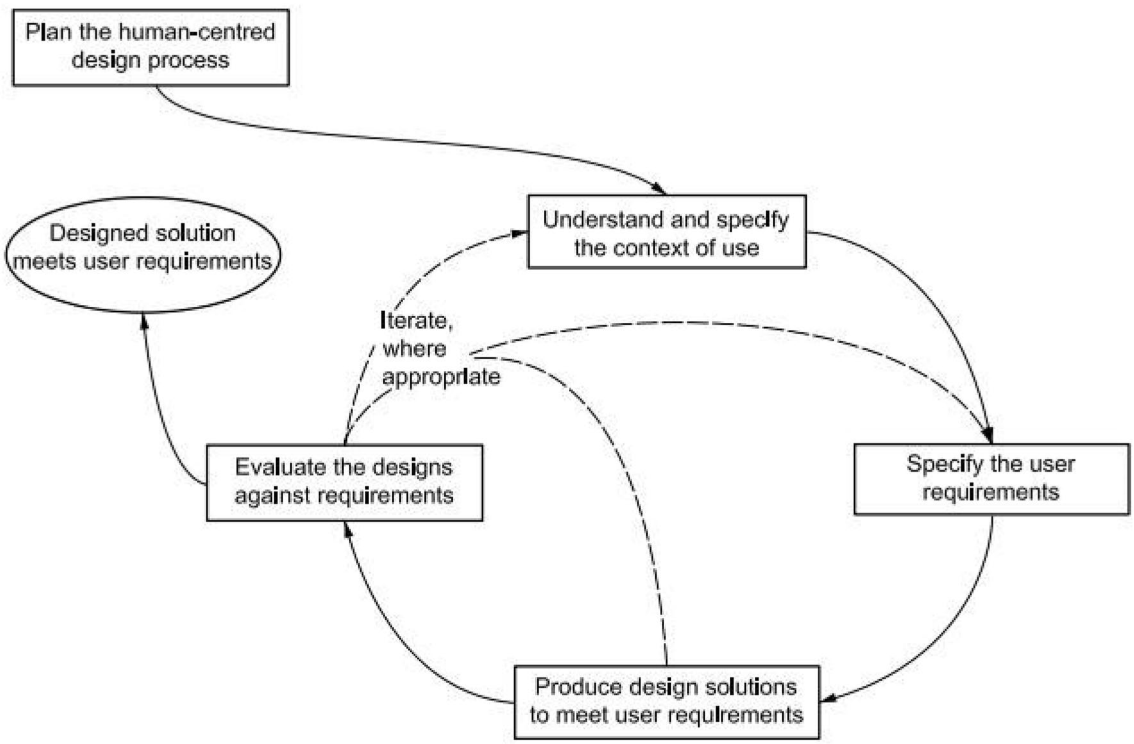


Fig. 3 Interdependence of user-centered design activities, source: ISO9241(2010)

Evaluating and improving the design based on feedbacks of users is an effective way to reduce the risk that the final system will not meet the needs of users or the organization.

D. The process is iterative:

Iteration implies that descriptions, specifications and prototypes are revised and refined when a new information emerges during design.

E. The design team includes multidisciplinary skills and perspectives:

The user-centered design team must be sufficiently diverse to ensure that the different aspects of the design are considered. An additional benefit of a multidisciplinary approach is that team members become more aware of the constraints and realities of other disciplines; for example, technical experts may become more sensitive to user problems and users may become more aware of technical constraints.

Figure 3 illustrates the interdependence of human-centered design activities. This is not a linear process, but rather an illustration of the fact that each step of the user-centered design uses the results of previous mandatory steps as input elements. After each evaluation, the return to the appropriate previous step is carried out.

Interesting scientific contributions dealing with user-centered design and providing feedback on the implementation of this approach exist (Norman and Draper 1986; Bodker 1999; Buur and Soendergaard 2000; Boy 2013; Wever and al. 2018).

To overcome the challenges that arise from the management of multiple subsystems during the design and development of sociotechnical systems, interesting proposals consisting of building an integration plan of human capabilities and limitations during the design process have been developed (Fitts et al. 2008; Boy and Narkevicius 2014). This integration plan is usually formalized in the form of a Human Systems Integration (HSI) program that integrates human-centered aspects with organizational (industrial engineering) and technological (systems engineering) aspects.

The potential benefits of a human-centered design in the context of designing human–robot systems are obvious. Multidisciplinary, iterative design or user involvement during the task allocation between humans and robots stage and during the evaluation and testing phases of potential solutions are all necessary in the design of cobotic systems.

3.2 Design thinking

The Design Thinking (DT), made popular by IDEO and Stanford University, is an approach based on empathy and using tools and methods to enable multidisciplinary teams to innovate by matching user expectations, technological feasibility and economic viability (Brown and Barry 2011).

As the previous presented approach, the objective of the design thinking approach is to move away from traditional design frames that focus on the process results (the object created), to a design based and nourished by the real needs of future users. It is articulated on iterative steps whose primary source of inspiration is the understanding of the individuals for whom we want to innovate (end-users, operators, and managers). In this approach, rather than developing the entire product (service, space, technology, organization, etc.) for months and presenting its final form to the customer, only the requested bricks should be developed and tested with users in short loops, in real context until finalization and implementation (Mathieu and Hillen 2016).

There are several variants of processes in design thinking, the most popular is the one developed by the Stanford University d.school which defines the five-step process (Empathize, Define, Ideate, Prototype, and Test) that logically follows one another but should not be taken as a linear process (The Bootcamp Bootleg 2013).

3.3 Activity-centered design

Among the interesting fields that consider human aspects in design projects, there is the activity-centered design or activity-centered ergonomics, which is a field based on the consideration of real work to provide inputs for design projects.

Several studies (Jones 1983; Clot 1998; Hubault et al. 1997) have highlighted the many forms of variability encountered in everyday work situations (Garrigou et al. 2001). The performance levels required in terms of quality and productivity are often maintained by operators. Since, they are not simply executors of the standards provided by the organization, nor passive observers in the event of difficulties encountered. Indeed, the proper functioning of industrial installations depends on the knowledge deployed by operators to manage the various variabilities and anticipate their potential raisons and effects (Garrigou et al. 1994). This discontinuity between what is requested from operators (the prescribed task) and what it requires to achieve it (the activity) should be considered during design processes.

The activity-centered ergonomics (Theureau and Pinsky 1984; Daniellou 1987; Maline 1994; Garrigou et al. 1995) has developed interesting design and project management approaches to consider real work during design processes. These approaches could be structured within three main stages: analysis, simulation and support (Barcellini et al. 2013).

- *Project and work analysis*: this stage focuses on understanding the project (identification of the current prescribed work, the humans impacted by the future situation, health and performance data related to the project, etc.) and on the real work of operators by identifying the sources of variability, and the strategies implemented by operators to meet the industrial objectives.
- *Simulation*: this step is the meeting of top–down (from expert knowledge) and bottom–up (from the analysis of real work) approaches, it makes it possible to produce forecasts on difficulties that operators could encounter in their future activity (Garrigou et al. 2001). The simulation does not aim to prescribe the "right way" to carry out the tasks, but to take into account the potential forms of future activity, to check their acceptability, and to feed the reflection with the aim of continuous analysis-simulation-design, until finding acceptable solutions by the different intervening parts of the project.
- *Support*: this step aims to ensure that the preferred scenarios are validated by the project's decision makers, and that they are implemented.

One of the central aims of an ergonomic approach is to achieve agreements for the joint development of health, performance and people (Benchekroun 2016). By focusing the dialogue between the parts of the project on work and activity (Benchekroun 2015a, b), and by orienting choices towards the search for solutions that widen the "margins of manoeuvre" of operators, so that in the face of variability, they can implement consistent solutions with their diversity and their own variability (Guérin et al. 1991).

This approach has been tested in a cobotic context recently by (Bitonneau 2018) and (Moulieres-Seban 2017) to meet an industrial need of the Ariane Group. To limit the risks related to poor human integration in design projects, a "Human Integration Readiness Levels" has been proposed by Moulieres-Seban (2017). This indicator, based on NASA's "Technology Readiness Levels" and "Human Factors Engineering Process Integrating Points", combines maturity levels (9 levels) with Safran's[4] project management approach.

3.4 User-centered design models

In addition to the approaches and communities briefly presented in the previous section, several authors have made valuable contributions of design models interested in considering human dimensions during the development of human–machine systems. The main objective of this section is to highlight fundamental aspects during the design process of human–machine systems, and to take inspiration from some interesting examples of design project management models to formalize guidelines for the specific context of cobotic systems design (last section).

[4] Safran is an international high-technology group.

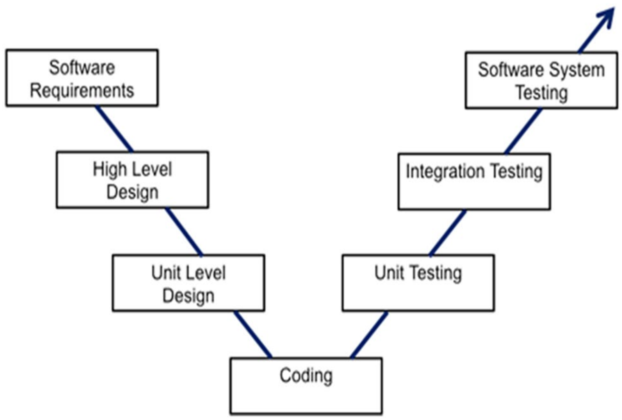


Fig. 4 V-shaped model adapted by Coutaz (1987)

The Boehm cascade model (1981) is one of the first models developed to meet industrial needs in terms of productivity and software quality. This model describes the software life cycle as a succession of eight steps summarized in Fig. 4. Although the cascade model was one of the most widely used models in companies during the 1990s, it imposes some constraints. For example, the reversals are limited to a return to the immediately preceding step. This does not encourage changes and tends to quickly stabilize the product. The consideration of users is limited to the first step of needs analysis; they are no longer really considered in the following stages (Kolski 1995). Coutaz (1987) proposed an adaptation of the V-shaped model to consider human dimensions by incorporating steps considering user's point of view (Fig. 5). However, the model still represents a linear design process, although many studies have shown that interactive applications are developed by a succession of iterations of the design process (Caffiau 2009).

Unlike the previous model, the spiral model introduced by Boehm et al. (1984) represents an iterative process (Fig. 6). This model seems interesting for the development of highly interactive software, as needs are formulated in a progressive way, risks are analyzed and resolved as they are encountered before starting detailed development, and solutions are prototyped and evaluated since the beginning of the design cycle.

However, this model presents some disadvantages. It does not explicitly integrate analysis of user's needs and activities, even if its process involves them (Riahi 2004). The number of iterations that can be significant could make this process costly (Caffiau 2009).

The starting point of each iteration being risk analysis, makes this model a model mainly adapted to the design of applications for which application safety is an essential element (Caffiau 2009).

Other iterative models considering user needs exist. For example, the model developed by Hartson and Boehm-Davis (1993) (Fig. 7) allows the integration of specific steps related to users, such as analysis of their tasks, precision of their needs and assessment of the adequacy of developed products/interfaces with these needs. Several other authors have contributed to the development of methodological frameworks that consider human dimensions in the design process of interactive systems. Examples include the model developed by Long and Denley (1990) which highlights the importance of evaluation and iterations during the design process. Pacaux-Lemoine et al. (2017) highlighted the lack of attention paid to the correct integration of humans in Intelligent Manufacturing Systems and provided solutions based on Human–Machine Cooperation principles to retain humans in the process control loop with different levels of involvement identified by the levels of automation. Schieben et al. (2009) developed the "Theater-System Technique", a method for agile designing and testing of system behavior and interaction concepts. This technique is based on the Wizard-of-Oz approach (WoOz), used for the evaluation of machine's functionalities (originally, for automatic speech or gesture recognition) where a human "wizard" hidden behind a curtain is emulating the functionality of a machine (Kiss et al. 2008). For the design work, the members of the design team use the theater-system for the generation and test of design ideas. After collecting the first ideas of the design within the design team, the theater-system can be used for assessments of user expectations.

Curtis and Hefley (1994) also developed a model including parallel steps from user interface engineering and software engineering during the design process. Rasmussen et al. (1987) developed the Cognitive work analysis (CWA), an original framework for the analysis, design, and evaluation of complex sociotechnical systems. Focusing on information behavior on the job, the CWA assumes that to be able to design systems that work harmoniously with humans, one has to understand: the work actors do, their information behavior, the context in which they work, and the reasons for their actions. Based on the analysis of information behavior, this framework first evaluates the system already in place, and then develops recommendations for design. Another original approach dedicated to the design and the evaluation of human–machine systems and their cooperation, called U-shaped method, has been developed (Millot 1990; Millot and Roussillon 1991). This approach consists of two phases:

A top–down phase of modeling the human–machine system: This step consists of analyzing the system to be interfaced and aims to define the various foreseeable cases of malfunctioning and thus to prepare the next stage of analysis of human tasks. Once the system modeling has been completed, an analysis of the prescribed human tasks aims to establish the activities that users will have to perform. This analysis must consider the model of the various users, in terms of limits and physical and cognitive resources.

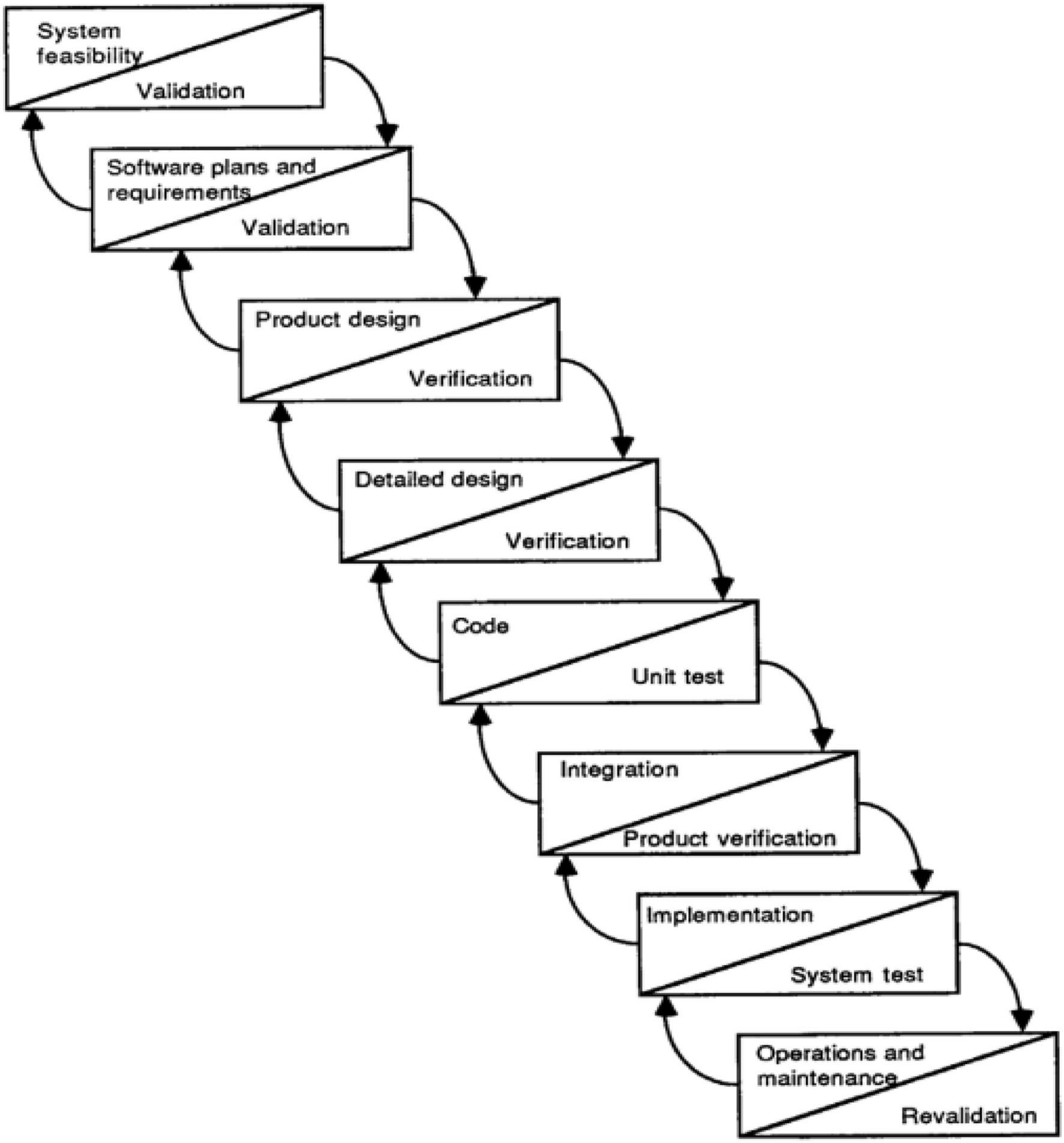


Fig. 5 Cascade model of software development (Boehm 1981)

A bottom–up phase consisting of the evaluation of the overall system: The evaluation phase aims at validating the designed interactive system in the top–down phase. Considering the usability of the human–machine system and its performance.

Some studies have shown that, in practice, designers perform several steps of the design process in parallel, choosing their design tasks pragmatically (Caffiau 2009). To avoid a terminal rejection of the designed products, the star model developed by Hix and Harston (1993) (Fig. 8) proposes a design model allowing iterations between the different steps of the process (task analysis, needs specification, prototyping, conceptual design, and implementation) through an intermediate evaluation step.

As in any technological design project, the evaluation phase has a primary role to ensure that the designed system meets the organization's objectives and requirements. In the case of collaborative robotics, the evaluation of potential human–robot solutions requires the consideration of complementary challenges: economic, human and safety. The following section presents examples of complementary indicators that could be used to ensure that the developed human–robot systems meet the different challenges related to collaborative robotics. In the next section, we will explain

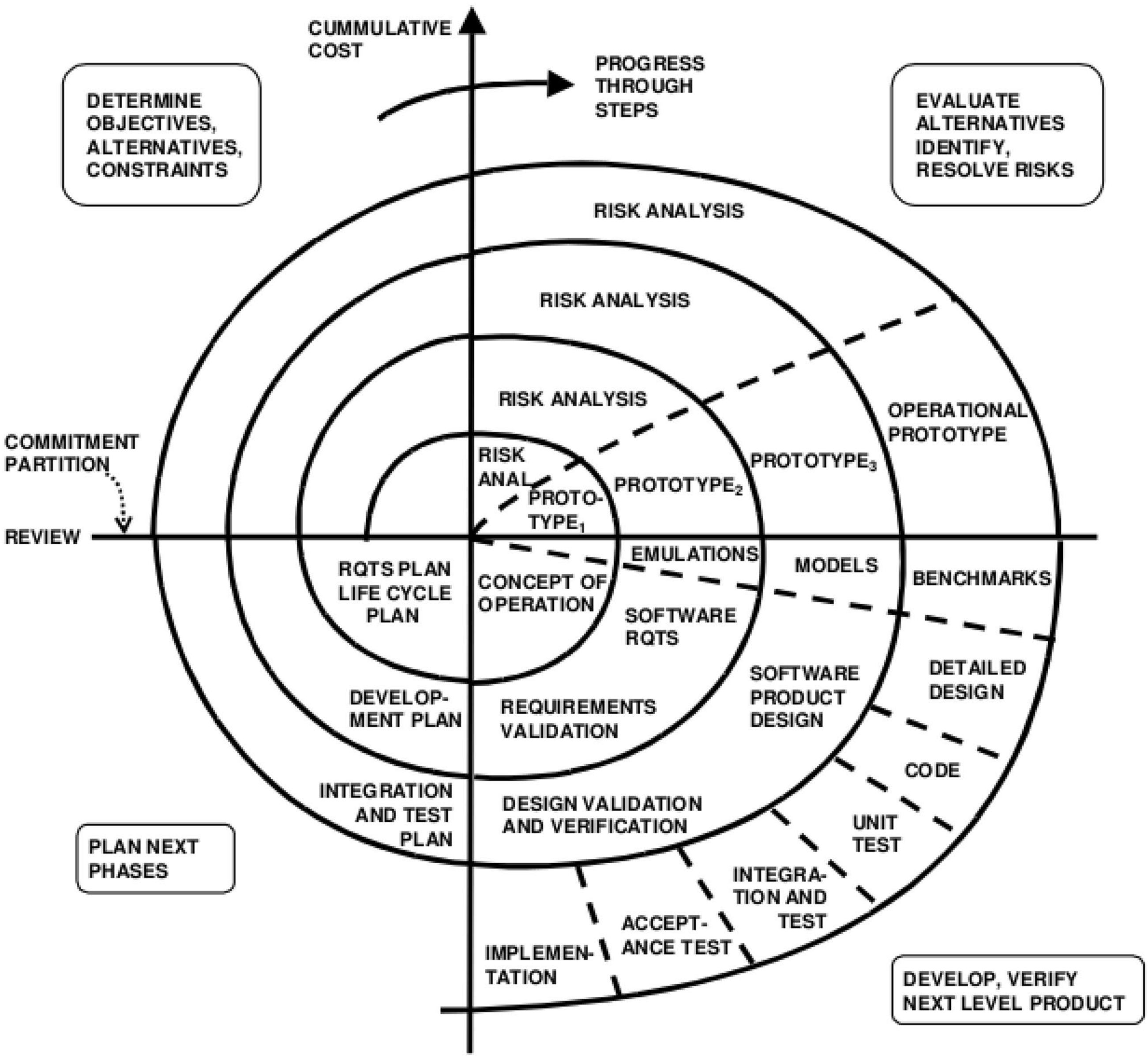


Fig. 6 The spiral model developed by Boehm (1984)

in more detail the assessment of human dimensions as the dimensions related to cost-effectiveness and safety are often considered in any technological design project.

4 Evaluation of collaborative human–robot applications

The final and iterative evaluation steps consist of making a judgment/assessment of the product to be designed (service, technology, organization, etc.), by considering various criteria and challenges related to adequacy with user requirements, economic benefits, and technological and safety dimensions.

While the profitability, security and technological feasibility are measurable by experts, the consideration of users are much more difficult to quantify, and often require qualitative methodologies to be evaluated, such as user testing, participatory simulation, ergonomic analysis, and the use of questionnaires. These types of evaluations require the definition of rigorous experimental protocols, which aim to define the data to be collected and how it will be analyzed. The following section introduces important indicators and dimensions to be considered during cobotic projects.

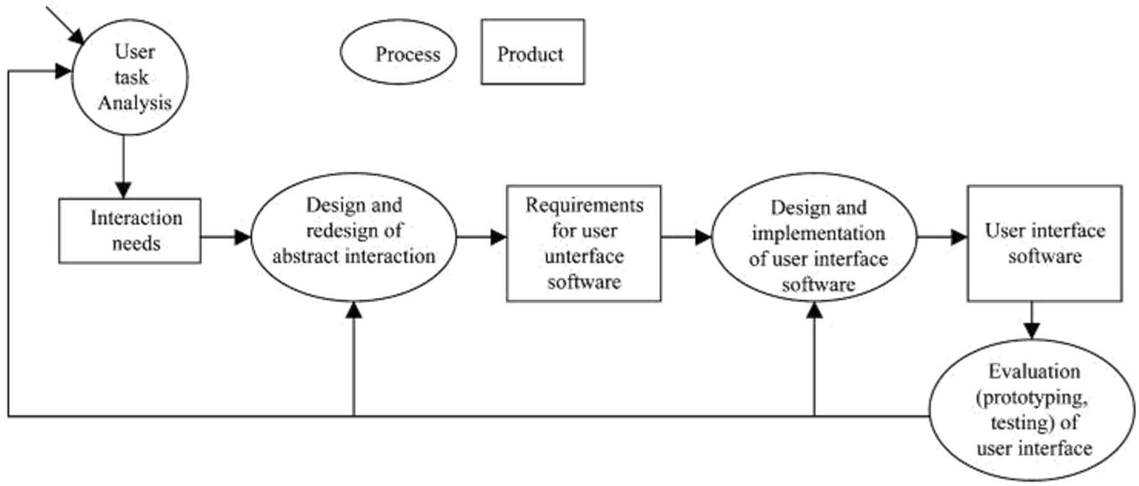


Fig. 7 User interface design cycle according to Hartson and Boehm-Davis (1993)

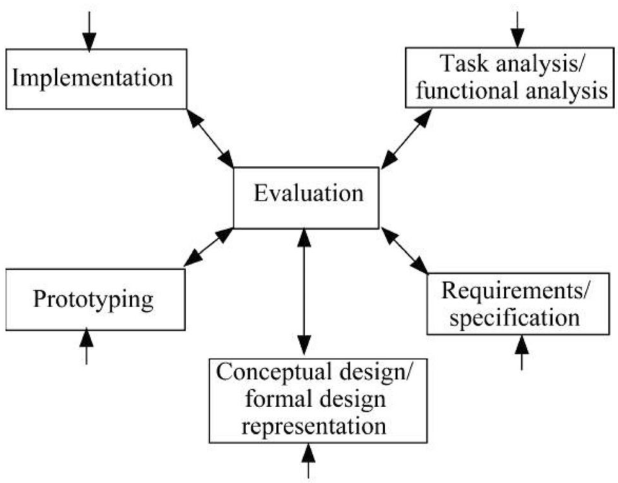


Fig. 8 Star design model Hix (1995)

1. Technical and economic criteria
   Like the incorporation of any other means of production, the investment on collaborative robotic cells is predominantly determined by technical and economic criteria. It is natural that the dimensions related to the costs incurred for the purchase and commissioning of the robotic cell, the impact on the quality and productivity of the workstations concerned, the return on investment and the forecast of the maintenance operations generated are discussed and considered.
2. Criteria related to technology and safety aspects
   The discussion of technological possibilities during the process design of collaborative Humans–Robots' applications, their feasibility and their adequacy with current safety standards has a major place in the design process.
3. Criteria related to the consideration of users

A. Biomechanical and physiological criteria

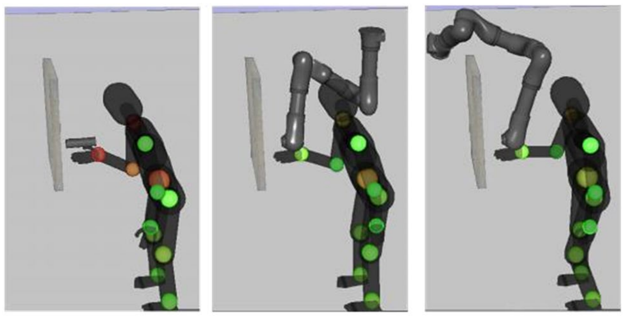
Biomechanical and physiological criteria could be used to select robots that generate the least effort solicitation from users. Kuli´c and Croft (2007) used physiological measures to assess the emotional status of users during interaction with robots. They measured the heart rate, skin conductance and facial muscle contraction of potential users while observing the robot's movements.

To evaluate the acceptability of collaborative robots, Weistroffer et al. (2014) used measurements of users' heart rate and skin conductance immediately after interaction with a robot.

Maurice et al. (2017) presented a method for ergonomic evaluations of co-manipulation activities and its application to the design of collaborative robots. In this work, several ergonomic indicators such as body balance, force and movement generation capacity, head rotation dexterity, and body kinetic energy were defined to estimate the different biomechanical demands that occur during manual activities, quantify the influence of each robot parameter and identify those that should mainly be modified to improve ergonomic performance. These indicators were measured using dynamic virtual simulations for different human and robot characteristics. The method was applied to the optimization of a robot morphology to support a drilling activity (Fig. 9).

B. Acceptability and usefulness

The introduction of a new technology constitutes an important change in the organization and the activity of



(a) No robot **(b)** Robot R_1 **(c)** Robot R_2

Fig. 9 Overview of the drilling activity performed without help and with the help of two different collaborative robots. The colored spheres represent the instantaneous level of effort Maurice et al. (2017)

operators. Introducing a technology is also a change on a socio-organizational system Bobillier-Chaumon (2016). To avoid rejection by users, the acceptability must be studied and addressed at an early stage of design projects.

Bobillier-Chaumon (2016) distinguished in his synthesis three theoretical approaches to the notion of acceptability. The first concerns models that seek to better design technologies to make them more usable and compatible with users' needs and activity.

The second approach concerns social acceptability models that seek to predict the intentions of use of these technologies by inviting the future users to establish a technology assessment in advance. Many theoretical models have aimed to specify the determinants of technological acceptance, the most widely used model is the Technology Acceptance Model (TAM) developed by Davis (1989). This model explains the acceptability process by two main subjective factors: perceived utility and perceived ease of use. These two factors would influence attitudes and intentions to use the technology at stake. Some approaches propose to combine the TAM with other theoretical paradigms to overcome its shortcomings. This is the case of Dishaw and Strong (1999) who criticized the TAM for its lack of interest in the tasks performed or to be performed by users. These authors propose to articulate this model with another theoretical approach: Goodhue and Thompson's (1995) Task Technology Fit (TTF) model, which seeks to verify whether the functionalities of the technologies are in line with the activity of users. Their work shows that technology would be more accepted and have more positive effects on individual performance if it matches the expected tasks.

Using virtual reality, Weistroffer et al. (2014) determined some subjective characteristics of acceptability of human–robot collaboration by operators. Two types of factors were considered, the first ones are related to robots and focusing on their appearance, movements, and level of intelligence. The seconds are related to the interaction and concerning the spatial distribution between the robot and the operator, the temporal distribution of tasks, the level of interaction and the level of control over the robot tasks. Bordel et al. (2014) illustrated that no matter how optimal an innovation may be technologically speaking; it is only as effective as it is acceptable from a user standpoint. This acceptability can only be obtained if the technology is developed by engineers in liaison with social science specialists. INRS[5] (Wioland et al. 2019) recently published the preliminary results of a study addressing the acceptability/acceptance of exoskeletons by users. This study aimed to investigate the blocking or facilitating parts of incorporating these tools into industrial organization, their impacts on health and safety of users and the quality of the interaction. Subrin et al. (2019) determined the acceptability factors of a collaborative robotic solution for a polishing operation of large composite parts. By interviewing operators, they determined four expected factors:

- *The cobot control*: it must allow the operator to move the system easily and to always keep control of the work;
- *Utility*: the system must be useful to help the operator without removing his expertise;
- *Ease of use*: the system must be easy to use and easy to learn;
- *Impact on work*: the system must achieve operator quality in an acceptable time.
- Usability and ease of learning

  According to ISO 9241-11, usability is "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use".

  Questionnaires and scales are used to collect users' opinions on ease of use, satisfaction, and experience related to interaction with a system. Ranging from 2 to more than 100 questions, these tools are adapted to one type or different types of products and can investigate several dimensions considering the subjective assessment of potential users. As an example, we cite the EUCS (End-User Computing Satisfaction) scale proposed by Doll and Torkzadeh (1988), composed of 12 questions and dedicated to the evaluation of websites. ASQ (After Scenario Questionnaire) developed by Lewis (1995), consisting of 3 questions and focusing on the evaluation of any type of products. Perceived website usability measurement scale developed by Wang and Senecal (2007), composed of 8 questions and focusing on websites. UMUX (Usability Metric for User Experi-

[5] The French National Research and Safety Institute for the Prevention of Occupational accidents and Diseases.

	The System Usability Scale Standard Version		Strongly disagree 1	2	3	4	Strongly agree 5
1	I think that I would like to use this system.		○	○	○	○	○
2	I found the system unnecessarily complex.		○	○	○	○	○
3	I thought the system was easy to use.		○	○	○	○	○
4	I think that I would need the support of a technical person to be able to use this system.		○	○	○	○	○
5	I found the various functions in the system were well integrated.		○	○	○	○	○
6	I thought there was too much inconsistency in this system.		○	○	○	○	○
7	I would imagine that most people would learn to use this system very quickly.		○	○	○	○	○
8	I found the system very cumbersome to use.		○	○	○	○	○
9	I felt very confident using the system.		○	○	○	○	○
10	I needed to learn a lot of things before I could get going with this system.		○	○	○	○	○

Fig. 10 SUS Scale, by Brooke (2013)

ence) developed by Finstad (2010), composed of only 4 questions and adapted to any type of system. SUS (System Usability Scale), one of the most widely used scales, proposed by Brooke (1996, 2013), and aims to anticipate users' usability of any type of system, composed of 10 questions, including 5 inverted ones (Fig. 10).

The following steps explain how to calculate the usability score and obtain a score out of 100:

- For items 1, 3, 5, 7 and 9 subtract 1 from each score;
- For items 2, 4, 6, 8 and 10 calculate 5—(minus) each score;
- Calculate the sum of the 10 scores;
- Multiply the sum by 2.5.

Vanderhaegen (2011) proposed and discussed two case studies to introduce possible future Advanced Driver Assistance Systems perspective implementing competences such as learning or cooperative learning.

D. Acceptance, satisfaction, and ownership over time

During design projects, we can distinguish three times of collection and analysis of the usability trajectory (Quiguer 2013). Before use, even before the person has been able to manipulate the device, the study of acceptability, which has been introduced in this section, attempts to predict the potential use of a technology based on the subjective representations of future users. Once the system has been developed, a second step of study focuses on understanding, what will determine the acceptance of the technology.

Finally, once the system has been implemented, it is important to look at its appropriation by users and to question their satisfaction with the use in daily activity. Based on these evaluations, the evolution of the system must be discussed to avoid rejection by operators after the investment.

The examples of indicators presented in this section are intended to allow consideration of multidisciplinary issues related to the design of human–robot systems. The different human-centered indicators highlight fundamental dimensions to be considered before investing in expensive robotic cells, such as acceptability, usability and perceived utility. Taking these dimensions into account would avoid rejection by users after the investment.

5 Discussion and conclusion

5.1 Recommendations for cobotic system designers

The design process of human–robot systems should not only focus on technical studies, but it must also include the human challenge of the future system. This could be done be analyzing the current activity of the human operators. Based on the previous parts of this article (the overview of collaborative robotics, human-centered design methodologies and Evaluation of collaborative Human–Robot applications), we propose in this section some guidelines to cobotic systems designers to better consider final users during the design process.

Before starting the design process, the project team should be multidisciplinary to ensure that the multi-issue aspect is properly considered. It is one of the foundations of a user-centered design (Sect. III.1). A multidisciplinary project team should include the operators involved in the project as they are the specialists of the workstation and it is them who would work using the collaborative robot, managers (production, quality, etc.) to ensure that the possible implementation of the cobotic system does not affect the quality and the productivity of the workstation, a company direction representative to discuss the economic viability of the investment and discuss budget matters, an ergonomist to conduct the analysis of the current activity and guarantee effective participation of the operators all along the design process, a psychologist to evaluate the acceptability and usability of the robotic cell by future users, a robot integrator and a robotics research institute to study the technical feasibility, guarantee the safety of the future users and implement the chosen technological solution.

At the beginning of the project, the team should focus on understanding the current organization. This is done by defining the objectives, identifying the tasks to be robotized, the people affected, their expectations and the economic and organizational constraints related to the project (budget, importance of the position in the production process, etc.). During this understanding phase, the team project should analyze the operators' activity to understand the difficulties encountered and the strategies initiated to manage them in their daily work (as described in the activity-centered design: Sect. III.1). This could be done through observations, interviews, and an analysis of the documents related to the workstation (productivity monitoring, performance objectives, and job descriptions).

The design steps must be participative and iterative (principles of user-centered design: Sect. III.1), based on the elements from the understanding step. Starting with a stage of ideation of cobotization scenarios (as in Design Thinking: Sect. III.2), which must be discussed, evaluated and prioritized through organizational simulations. Then, the "favoured" scenarios must be studied to propose technological solutions with their budget envelopes. These solutions, once accepted by the organization, must be simulated to evaluate their spatial and temporal behaviors and their potential impacts on system performance. Subsequently, a step of risk analysis (a mandatory step to certify the conformity of the collaborative robotic cell to security standards: Directive 2006/42/EC, ISO 10218–2:2011 and ISO/TS 15066:2016), evaluation of the usability and acceptability of the solution by operators will determine whether the solution is potentially suitable, and therefore ready to be prototyped, or there is a need to edit some aspects of the solution.

After the validation of the solution, its implementation and feedback from experiences would make it possible to develop the cobotic cell according to its acceptance by the operators and the organization, thus, avoiding rejection after the investment.

5.2 Conclusion

Cobotics presents several perspectives for the future. It would allow companies to monitor fluctuations in customer demand, increase competition, reduce repetitive operations, etc. However, the integration of a collaborative robot is not neutral. This involves a change in the work organization, a reassignment of operators, a change in teamwork, etc.

In this article, an overview of industrial cobotics was provided, the notion of "collaboration" between humans and robots in the context of current technological development was briefly discussed, different methodologies and design models focused on final users were discussed and evaluation indicators potentially adapted to an effective consideration of humans in the design process of cobotic systems were presented.

After having presented these multidisciplinary aspects related to collaborative robotics, we have formulated in the previous section a set of guidelines for human–robot systems designers. These recommendations highlight the importance of the participative structuring of the design team, the preliminary stages of the current activity understanding and the iterative design and evaluation steps to achieve a design combining productive performance, health and safety, and to avoid the potential negative impacts of the cobotic cell on performance, on users and on the collective work of human operators.

In the first time, these guidelines were practiced during a design process of a collaborative robotic cell to improve a recycling laundry pods' workstation within laboratory conditions (Bounouar et al. 2020). During this experience, the current activity was analyzed through observations and interviews with users. Improvement scenarios were proposed, discussed and prioritized. After that, a feasibility study was carried out and led to technical prototyping. This prototype made it possible to evaluate the proposed solution and to collect feedbacks from voluntary users. Currently, these guidelines are being applied on a more formal experience, within a collaborative robotic cell design project aiming at assisting human operators on a refining workstation of a French industrial SME,[6] which produces fragile mechanical parts for the aeronautics sector and requiring a very high level of reliability. This industrial application will enrich and refine the proposed guidelines.

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