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Collaborative Robotics: Assessment of Safety Functions and Feedback from Workers, Users and Integrators in Quebec

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SUMMARY

Since 2010, industry has been using a new type of robot capable of interacting with production workers or simply sharing the same workspace with them. They are called collaborative robots, or cobots. Cobots differ from conventional robots with respect to machine-worker interaction; they accompany workers, assist them and help them perform tasks. However, this technological change also brings with it new risks, especially in production: collision risks (since humans can come into contact with cobots), risks of musculoskeletal disorders (MSDs) (even though cobots are designed to prevent such problems, operators must learn to handle cobots properly to limit or prevent them), psychological and social risks (human stress related to cobot movements and work pace), etc. An exploratory study was conducted to investigate these issues. The purpose of the study was, first, to make occupational health and safety recommendations regarding the use of robots in a collaborative setting and, second, to suggest ways to inform stakeholders about the issues involved in implementing cobotic installations.

There were two parts to the study: a theoretical part focused on examining plans, while a practical part focused on the actual situation in the field. The purpose of the first part was to assess how the robot's safety functions, which are processed by safety-related electronic cards, ensure operator protection within the framework of the four modes of collaborative operation established by standard ISO 10218:2011: (1) safety-rated monitored stop, (2) hand guiding, (3) speed and separation monitoring and (4) power and force limiting. According to standard ISO 13849-1:2015, a safety function of a machine is a function whose failure can result in an immediate increase in the risks to a person's physical safety. For example, the emergency stop on a machine is a safety function. The purpose of the second part of the study was to gather feedback on taking safety considerations into account in collaborative robot integration projects in Quebec. Feedback was collected from three types of participants: collaborative robot users (clients), integrators and workers involved.

The theoretical part was conducted by analysing the technical reference material for three robots: one designed to be collaborative and two conventional robots converted into cobots. In addition, a brief case study illustrated the implementation of a cobotic installation based on the analysis. The field part of the study was carried out by observing cobotic installations in four companies and conducting semistructured interviews with the participants concerned.

The case study of the theoretical part showed that to make a collaborative operating mode safe, a number of safety functions must be combined, depending on the robot. The theoretical component revealed, in particular, that the performance level set by the manufacturer for a safety-related controller is not a guarantee of the overall performance level of the safety function processed by the controller. The controller's electronic card only performs the "signal processing" part of the safety functions. A client who procures a collaborative robot equipped with a controller that meets the performance level set in the standards should not assume that the cobot's safety functions will necessarily meet the requirements of the standards. A robot's safety functions often need to be supplemented by adding an input component, such as a presence-sensing device. In some cases, environmental constraints may be an overriding factor in the choice of a sensing device. Choosing the right component is crucial, because if its safety performance is below that of the processing part, the safety function will be less reliable. The requirements in the standards recommend so-called safety components.

The field part of the study revealed that cobotics is in its infancy in Quebec. Only one of the four companies visited had a cobotic installation that was up and running. The other three were in

the process of cobot integration. Other companies contacted by the study team when recruiting participants for the visits were either planning to procure a collaborative robot or were still thinking about how to integrate it into their production process. The companies visited chose their cobots on the basis of (1) their low cost compared with that of a conventional robot, (2) quick return on investment, (3) being able to reassign workers to more rewarding tasks, (4) space constraints and (5) potential occupational health and safety (OHS) risk reduction. Thus, to judge from what we observed, companies are turning to cobots not necessarily to meet a need for human-machine interaction in production, but rather for financial, spatial and OHS reasons.

The integrators we met confirmed that designing a cobotic installation is a complex task because the technology is very new and involves some very specific safety requirements. The most difficult step, they say, is the risk assessment. Often, it was limited to risk identification. But to know whether a robot can be used in a collaborative context, at the very least the risks of the future installation must be estimated in order to determine the minimum required performance level. The performance level of the safety functions must be equal or superior to this minimum and be consistent with the analysis of the risks associated with collaborative operation.

Last, for safety to be a decisive factor when determining needs and integration, it must be included in each planned functionality of the collaborative application. This inclusion must be implemented through a close dialogue involving the client, the integrator and workers. From what we observed, workers were not very involved in the process of determining needs and integration. Given this low degree of worker participation in risk assessment, which in itself is a complex step, we are proposing that research on the cobotic-related risk assessment process be conducted by incorporating analysis of worker activity. In addition, regarding risk reduction, some aspects are worth investigating further, particularly (1) presence sensing, in modes 1 and 3, with non-safety-related components and (2) the applicability and acceptability of the force limit values indicated in technical specification ISO/TS 15066:2016. Worker proximity to the robot during production requires a risk evaluation focusing on possible contact. In sum, using collaborative robots does not systematically mean that other safeguards are no longer necessary. Risk assessment is always needed at the integration stage, as manufacturers' reference manuals and cobotics standards specify. Depending on the degree of acceptability of the risk in question, safeguards may well be required.

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FOREWORD

This research report is intended for those who have acquired or are planning to acquire a robot for the purposes of collaborative application in production. It will also be of interest to integrators of such robots.

Readers should have some basic knowledge of design standard ISO 13849-1:2015 regarding the safety-related parts of control systems.

We strongly suggest that readers peruse the following glossary of technical terms before tackling the report.

GLOSSARY

PLC: Programmable logic controller.

Category 0 (cat. 0) stop: Stopping by immediate removal of power to the machine actuators (i.e., an uncontrolled stop) (IEC 60204-1:2005+A1:2008, section 9.2.2). See Appendix C for an illustrated explanation of this definition.

Category 1 (cat. 1) stop: A controlled stop with power available to the machine actuators to achieve the stop and then removal of power when the stop is achieved (IEC 60204-1:2005+A1:2008, section 9.2.2). See Appendix C for an illustrated explanation of this definition.

Category 2 (cat. 2) stop: A controlled stop with power left available to the machine actuators, even after the stop has been completed (IEC 60204-1:2005+A1:2008, section 9.2.2). See Appendix C for an illustrated explanation of this definition.

Safety-rated soft limit (or safety-rated soft axis and space limiting): “Limit placed on the range of motion of the robot by a software- or firmware-based system having a specified sufficient safety-related performance. The safety-rated soft limit might be the point where a stop is initiated, or it might ensure that the robot does not move beyond the limit” (ISO 10218-1:2011).

Category: The concept of “category” refers to the “classification of the safety-related parts of a control system in respect of their resistance to faults and their subsequent behavior in the fault condition, and which is achieved by the structural arrangement of the parts, fault detection and/or by their reliability” (ISO 13849-1:2015). That standard identifies five categories in ascending order of robustness: B, 1, 2, 3, 4.

Collaborative robotic cell (or cobotic cell): Circumscribed workspace consisting of a robot and the safeguards required for a given collaborative application.

Declaration of incorporation: Official document in compliance with Machinery Directive 2006/42/EC and concerning partly completed machinery. Partly completed machinery is only intended to be incorporated into or assembled with other machinery or other partly completed machinery, thereby forming machinery to which this Directive applies. The official document mentions a number of aspects, including a declaration spelling out which essential requirements of the directive have been fulfilled (see section B of Annex II of directive 2006/42/EC).

Collaborative workspace: “Workspace within the safeguarded space where the robot and a human can perform tasks simultaneously during production operation” (ISO 10218-2:2011).

SRF (safety-related function): Function specific to an SRP/CS (safety-related part of a control system) of a safety function (SF) and having an ascertained performance level (PL). Unlike an SF, an SRF is an incomplete functional chain that, when twinned with other SRFs, will be able to perform a safety function.

SF (safety function): "Function of a machine whose failure can result in an immediate increase of the risk(s)" (ISO 13849-1:2015). A safety function is a complete functional chain having a performance level (PL) and consisting of three main units: (1) input (e.g., sensor), (2) processing (e.g., safety-related controller, (3) output (e.g., pre-actuator). A safety function can consist of a combination of safety-related functions (SRFs).

Collaborative operating mode: Term used in standard ISO-10218-2:2011 to refer to the specific mode of operation between a person and a robot sharing a common workspace. There are four collaborative operating modes. Each is associated with specific safety requirements. These requirements are presented in standard ISO 10218-1:2011 and are set out in detail in technical specification ISO/TS 15066:2016. The requirements may also be found in the following Canadian and U.S. robotic standards: CAN/CSA-Z434-14 and ANSI/RIA R15.06-2012. There are similarities between these two standards and standard ISO 10218:2011 – parts 1 and 2. In particular, the Canadian standard takes up the two parts of the ISO standard, to which requirements specific to Canada have been added.

Collaborative operation: Human-robot collaboration involving one or more modes of collaborative operation (section 5.5.1 of technical specification ISO/TS 15066:2016).

PL: Performance level is defined in standard ISO 13849-1:2015 as follows: "discrete level used to specify the ability of safety-related parts of control systems to perform a safety function under foreseeable conditions" (ISO 13849-1:2015). PL may take five discrete values, ranging from lowest reliability to highest: a, b, c, d, e.

PL_r: Required performance level. PL_r is determined based on the estimated risk. This is the risk the safety function protects the operator from.

Originally designed collaborative robot: This phrase used in the report refers to any robot initially designed to interact directly with a human. Collaboration with a human may be acceptable depending on the results of an assessment of the risks associated with the robot installation. When the risk assessment confirms the acceptability of the human-robot collaboration or when the robot coexists or interacts with a human in an industrial installation, it is referred to as a "collaborative robot" or "cobot" in the report.

SIL: Safety integrity level. This concept is defined in standard IEC 62061:2005 as follows: "discrete level (one out of a possible three) for specifying the safety integrity requirements of the safety functions to be allocated to safety-related electrical control systems (SRECS), where safety integrity level 3 has the highest level of safety integrity and safety integrity level 1 has the lowest."

OHS: Occupational health and safety.

SRP/CS: Safety–related part of a control system. According to standard ISO 13849-1:2015, this part "responds to input signals and generates safety-related output signals."

Robot system: Also called an "industrial robot system," is a system comprising an industrial robot, end-effector(s) and any machinery, equipment, devices, external auxiliary axes or sensors supporting the robot performing its task (ISO 10218-1:2011).

MSD: Musculoskeletal disorder.

1. INTRODUCTION

1.1 Current Knowledge About Collaborative Robotics

1.1.1 Background

1.1.1.1 Robots on the Rise

The number of robots around the world is increasing every year. The estimated number of industrial robots in operation in various areas of the world for the years 2013–2018 is given in Table 1. In North America, the number of industrial robots is expected to climb by 50% between 2013 and 2018 (IFR, 2015). In Canada, robot sales rose by 4% in 2014 (2,300 robots sold) (IFR, 2015). Around the world, the industries most affected by industrial robots are motor vehicle manufacturing, electrical equipment and electronics manufacturing, metal fabricating, plastics processing, chemicals and food. In Quebec, reliable statistics on the number of robots in operation are not yet available.

Table 1 Estimated number of industrial robots in operation by geographic region and year (IFR, 2015)

Geographic region	2013	2014	2015*	2018*
Americas	**226,071**	**248,430**	**272,000**	**343,000**
North America (Canada, Mexico, USA)	215,817	236,891	259,200	323,000
Asia/Australia	**689,349**	**785,028**	**914,000**	**1,417,000**
Europe	**392,227**	**411,062**	**433,000**	**519,000**
Africa	**3,501**	**3,874**	**4,500**	**6,500**
Number not specified by country**	21,070	32,384	40,500	41,500
Total	**1,332,218**	**1,480,778**	**1,664,000**	**2,327,000**

*Forecast
**Recorded and estimated sales that could not be specified by country

1.1.1.2 Emerging Technology, New Paradigm

The first industrial robot, Unimate, was put to work in 1961 (Glagowski *et al.*, 1992). Between 1960 and 2010 (Figure 1), conventional industrial robot technology and standards underwent considerable changes. These early industrial robots were physically separated from workers by guards. The purpose of the physical separation was to ensure worker safety by allowing the robots to operate at high speed and force. Under these conditions, the mechanical hazards were considered to be a potential source of serious or even fatal injury. As a result, a worker's proximity to these robots was accepted by international standards only when the robots were in teach mode, with a maximum reduced speed of the robot tool centre point of 250 mm/s. Under standard ISO 10218-1:2011, the purpose of this maximum reduced speed is to allow people sufficient time to either withdraw from the hazardous motion or stop the robot.

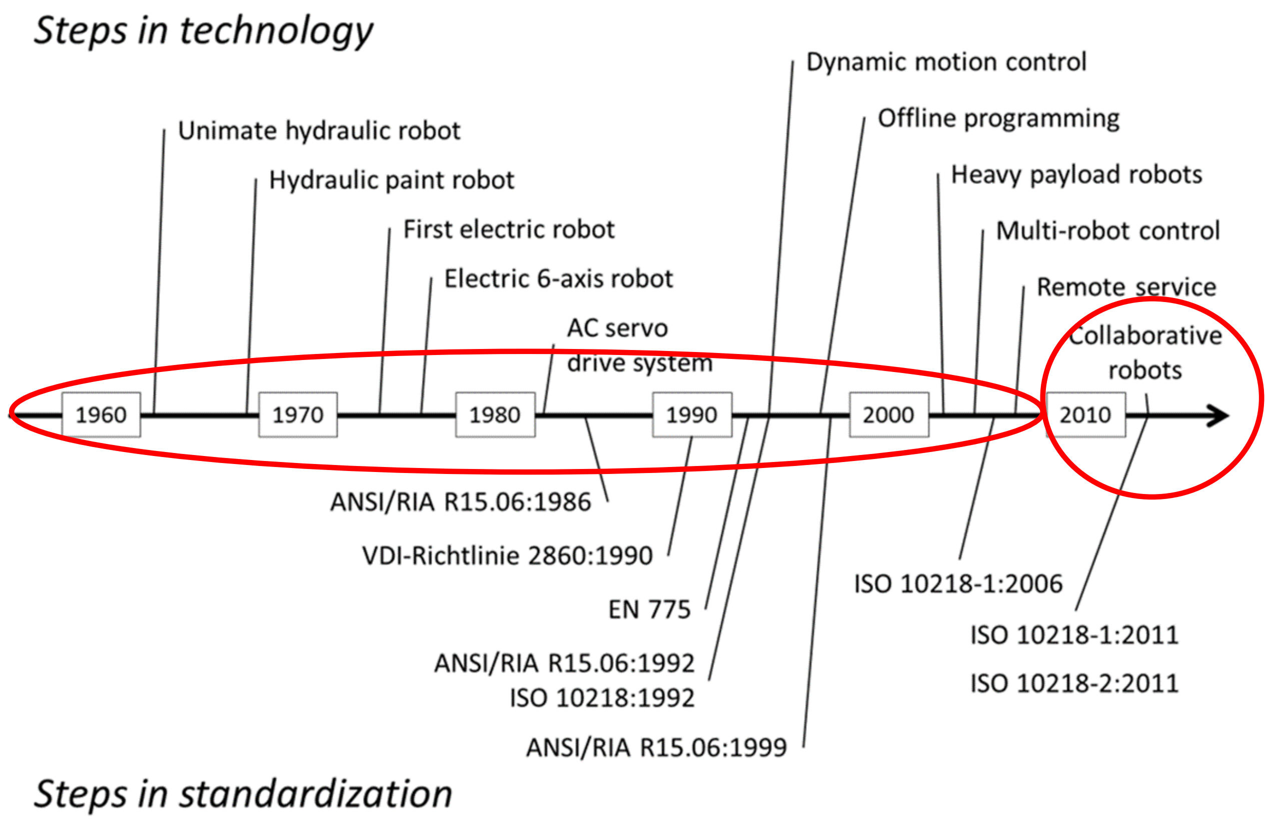


Figure 1 History of industrial robots and their safety standardization (Fryman *et al.*, 2012)

Thanks to technological advances (Figure 1) that facilitated the "increasing autonomy and sensory capabilities of robots coupled with decreasing cost and size of microprocessor controllers," industry began using collaborative robots, known as "cobots," around 2010 (Murashov *et al.*, 2016). This new generation of robots is presented as having the advantage of combining a robot's power, endurance and precision with the skill of a human (ISO/TS 15066:2016). The advent of these new robots in industry caused a paradigm shift with respect to safety. Today, interaction and even contact with humans may be authorized under certain conditions, even during production. The safety of operators involved in collaborative applications is now ensured primarily by the robot's control system and supplemented by its physical characteristics (e.g., low inertia, force or speed limitation, non-aggressive shapes). The control system includes safety-related cards or modules connected to safeguarding devices (e.g., force sensors, occupancy detectors).

These robots represent a significant innovative breakthrough for industry (cf. Futuremag-Arte).[1] Matthias *et al.* (2011) note that having a robot and a human share the same workspace offers greater production flexibility (e.g., easier to change production batches). In addition, this new generation of robots is different in the following respects:

- Acquisition costs would appear to be lower.

1. http://www.arte.tv/magazine/futuremag/fr/nos-collegues-les-robots-futuremag

- Simplified programming in comparison with conventional robotics, bringing the new generation within reach of companies that do not have any specialized inhouse resources (e.g., intuitive human-machine interface, minimum programming). This advantage has prompted people to describe cobots as “plug and play.” However, this term ignores the fact that cobots may require the use of guards, depending on the results of the risk assessment.
- A configuration that combines a robot’s power, endurance and precision with a human being’s intelligence and decision-making ability.

1.1.1.3 Robot Classification and Reference Standards

On the basis of standards ISO/FDIS 8373:2011, NF EN ISO 13482:2014 and ISO 10218:2011, parts 1 and 2, as well as technical specification ISO/TS 15066:2016, the research team divided robots into two main groups: (1) industrial robots and (2) service robots (Figure 2).

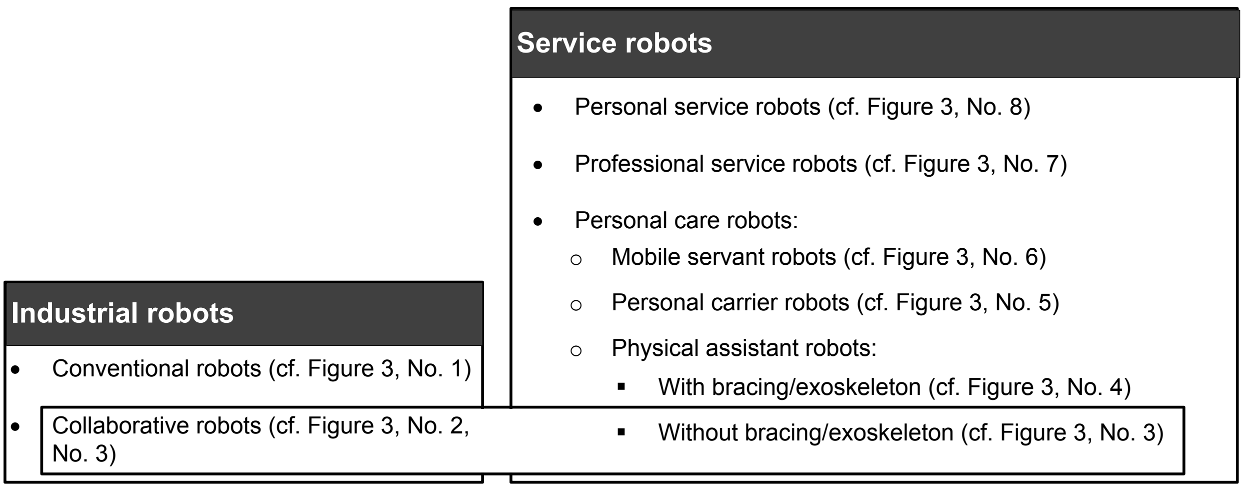


Figure 2 Robot classification

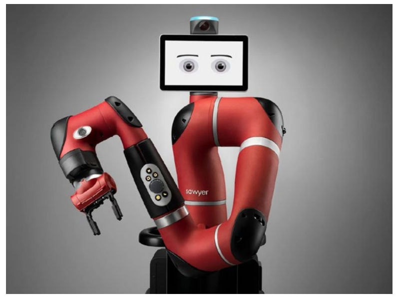
An industrial robot is an “automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications” (ISO 10218-1:2011). This definition of “industrial robot” covers robots used in both conventional and collaborative settings. A conventional setting refers to the use, for production purposes, of a robot that is completely separated from human beings by a protective enclosure. A collaborative setting refers to the use, for production purposes, of a robot that shares a workspace or interacts directly with a human being.

There are also intelligent assist devices (IADs) that are, by design, collaborative systems that help workers move payloads. IADs and hand-guided collaborative robots are used for the same purpose: to relieve workers of part of the task-related physical load. These two types of devices should also have the same ultimate safety objectives, i.e., guarantee worker safety at all times. Their classifications are different, however, as IAD patents are classified internationally in class B66C19/00 – Cranes comprising trolleys or crabs running on fixed or movable bridges or gantries, whereas robots are classified in class B25J9/00 – Programme-controlled manipulators. Furthermore, IADs are programmed devices that can have one or more axes of motion (Colgate *et al.*, 2003). When they have fewer than three axes, they definitely do not belong in the industrial robot class, which requires at least three axes, according to the definition given above. When IADs have three or more axes, they may be similar to hand-guided cobots. Differences between them remain, however. For instance, when the operator releases the cobot's hand-guiding equipment, the cobot must perform a safety-rated monitored stop (ISO/TS 15066:2016). In contrast, in the case of an IAD, releasing the hand-guiding equipment may allow the IAD to move autonomously (Colgate *et al.*, 2003).

A service robot is a robot that performs tasks that are useful to people (personal service robot). It can also be assigned to commercial tasks (professional service robot). A personal assistant robot is a service robot that performs actions that directly help improve an individual's quality of life, such as by:

- Performing household tasks while interacting with individuals or exchanging information (mobile servant robot);
- Transporting a person to a planned destination (person carrier robot);
- Physically helping a user to perform required tasks by supplementing or increasing the user's personal capabilities (physical assistant robot). As Figure 2 shows, physical assistant robots can be with or without bracing. A robot with bracing is often called an "exoskeleton" (see No. 4 of Figure 3). Without bracing, a robot can also be used in industry to help a worker perform a specific task (e.g., grinding in No. 3 of Figure 3). In this case it's an industrial robot. When the same type of robot is used outside of industry, it is classified as an assistant robot.

#1 – Conventional industrial robot



#2 – Sawyer, by Rethink Robotics

#3 – A7.15, by RB3D

#4 – Robotized exoskeleton, by Kawasaki

#5 – Robear, by © RIKEN

#6 – Kompai, by Robosoft

#7 – OTTO, by Clearpath Robotics

#8 – Robot vacuum

Figure 3 Examples of industrial robots (No. 1 to No. 3) and service robots (No. 3 to No. 8)

N.B. The pictures presented in Figure 3 were chosen solely for illustrative purposes. Their selection does not in any way imply a preference for a given manufacturer or model. The pictures come from the following sources: www.istockphoto.com (No. 1 and No. 8); directly from the manufacturer (No. 2, No. 6 and No. 7); www.mdp.fr (No. 3); www.robotblog.fr (No. 4); www.riken.jp (No. 5).

1.1.1.4 Modes of Collaborative Operation

According to technical specification ISO/TS 15066:2016, a collaborative operation is a state in which a purposely designed robot system and an operator work within a collaborative workspace. Under this same specification, collaborative operations may take place by applying the safety requirements associated with one or a combination of the following four modes of collaborative operation:

1) **Safety-rated monitored stop**

   In this mode, the human-robot interaction occurs while the robot is stopped. This is a category 0 or 1 protective stop (see Glossary) triggered when an operator is detected in the collaborative workspace. In the absence of a category 0 or 1 stop, the protective stop can also be a category 2 monitored stop (see Glossary) following a deceleration of the robot. In these situations, the operator may, for example, work on a workpiece carried by the robot. The robot may automatically restart as soon as the operator leaves the collaborative workspace.

2) **Hand guiding**

   The operator uses a hand-operated device to transmit motion commands to the robot control system. The hand-guiding equipment is placed near or directly on the robot end-effector. The equipment incorporates an emergency stop device and an enabling device. In this mode, the robot system can include a function that serves to increase the strength of the operator in order to reduce the physical load (e.g., grinding task in No. 3 of Figure 3).

3) **Speed and separation monitoring**

   In the collaborative workspace, the robot avoids the operator at all times by maintaining a set speed and separation distance. The purpose is to prevent collisions between robot and operator. The control operates in real time. The maximum speed and maximum separation distance can be variable or constant.

4) **Power and force limiting**

   Physical contact between the robot and an operator can occur either intentionally or unintentionally. Robot power and force can be limited either through inherently safe means in the robot's physical characteristics or through its safety-related control system.

A risk assessment will suggest safe operating values for robot speed, separation distance, power and force, depending on the collaborative operating mode used. The safety requirements associated with each mode are set out in technical specification ISO/TS 15066:2016.

Regardless of the collaborative operating mode used, to guarantee operator safety, the robot must be stopped when certain conditions are no longer met, such as when the robot leaves a predefined workspace, when the speed set based on the risk assessment is exceeded or when the robot moves in situations where it is supposed to remain motionless. The functions that stop the robot in the event of a failure to meet these conditions are monitoring functions that are part of the stop functions. These safety functions must meet the reliability requirements defined in the standards (e.g., ISO 13849-1:2015). Safety functions should not be confused with standard functions. These functions, also called "standard control functions," are incorporated in order to contribute to the operation of the machine in production or adjustment mode and generally do not meet safety-related reliability requirements (Baudoin and Bello, 2010).

1.2 Research Problem

1.2.1 New Risks Considered

According to a number of studies, collaborative robotics gives rise to new risks in comparison with conventional robotics (Murashov *et al.*, 2016; Charpentier and Sghaier, 2013):

- Collision risks: No longer isolated from the robot's workspace, the human operator may come close to or even enter into contact with the robot.
- Musculoskeletal disorder (MSD) risks: Even though robots are designed to reduce MSD risks by relieving workers of repetitive tasks, collaborative robot operation can still be a source of MSDs over the long term (e.g., MSDs caused by a repeated change in worker movement and posture out of fear of contact). MSD risks were substantiated in Atain Kouadio and Sghaier (2015): Over a 10-month trial period with the A7.15 (see Figure 3, No. 3), workers who collaborated with this robot experienced wrist pain. The "problems found with maintaining the enabling handle in position to activate the cobot illustrate the likelihood of shifting the MSD issue from one part of the locomotor system to another" (Atain Kouadio and Sghaier, 2015).
- Psychosocial risks: The speed at which the robot collaborates may correspond to a rate of production unsuitable for the operator. Working in a collaborative robotic cell may expose the operator to an excessive mental workload. Operators are no longer focused solely on performing their tasks, but also on constantly anticipating and synchronizing their movements in relation to the robot.

New cobot-related risks are not restricted to new hazards or new possible injuries. They also entail injuries related to conventional robotics outside of production, such as injuries from collisions, which now exist at all times, including during production. The frequency and length of exposure to collaborative robot movements increase the possibility of collisions and therefore the likelihood of injury.

As the use of collaborative robots is fairly recent, at the moment there is little in the way of a history of accidents associated with these machines. In addition, we were unable to find any statistics on conventional robot accidents in Quebec workplaces. Robot-related data are incorporated into data on assembly machines, in accordance with the coding system used by Quebec's Commission des normes, de l'équité, de la santé et de la sécurité du travail (CNESST), because the term "robot" is not used in the coding manual.

Despite the lack of reports on accidents with conventional robots (Malm *et al.*, 2010; Gray *et al.*, 1992), authors such as Charpentier and Sghaier (2012) and Malm *et al.* (2010) have managed to analyse some incidents. These analyses were done to characterize accident situations and to propose risk reduction measures for the design of robots specifically intended to be collaborative and the implementation of collaborative applications. To do so, the authors applied the accident situations to the reality of collaborative operation. For instance, Malm *et al.* (2010) noted that 23 of the 25 robot-related accidents they identified involved operator body parts being crushed between the robot and a rigid object. They emphasize that as human-robot interactions increase, it is expected that human operators will be exposed to more injuries of this type. To address this problem, they suggest that collision detection systems need to have very short reaction times in order to prevent or reduce the impact of injuries. Charpentier and Sghaier (2012) examined 31 serious or fatal accidents involving conventional robots. The surprising thing about their study is that, contrary to a widespread belief in machine safety that most accidents occur during maintenance, close to 2/3 of these accidents (20/31) occurred during production operations. The maintenance activities related to the analysed accidents chiefly concerned cleaning and repairs. Most of the accidents examined involved amputations (21/31), while eight deaths occurred. The body parts most commonly affected were the torso (9 cases) and head (5 cases). Most of these accidents resulted from operator access to mobile parts of the robot owing to a guard or safeguarding device that was bypassed (10/31) or that was inappropriate for use with the robot (10/31). In light of this latest data, it would appear essential to conduct a thorough analysis of future robot use to ensure that planned risk reduction measures do indeed address real uses.

A prospective assessment (Atain Kouadio *et al.*, 2014) imagining future uses (to 2030) of collaborative and physical assistance robots in the workplace was conducted jointly by various organizations in France: the Institut national de recherche et de sécurité (INRS), the Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail (ANSES), the Caisse centrale de la mutualité sociale agricole (CCMSA), the Centre d'expertise nationale en robotique (CENRob), the Centre technique des industries mécaniques (CETIM) and the Commission des accidents du travail et des maladies professionnelles (CAT-MP). The survey sets out four possible future scenarios for robot use, depending on different political, economic and social circumstances: in two of them, robot use is limited primarily to two areas: nuclear and military; in the other two scenarios, this new technology will see strong growth in many different fields: process industries, manufacturing, medical sector, personal assistance, military. The authors of the assessment tried to imagine the future in order to anticipate the effects of collaborative robotics (or cobotics) in scenarios where this technology sees rapid expansion. A wide range of benefits are associated with cobotics, including alleviating biomechanical constraints and physical loads on workers, and helping to keep older workers on the job. The risks associated with this are the ones mentioned earlier. The authors emphasize, however, that in the case of human-robot coactivity, collision, crushing and suffocation are the predominant risks. With the accelerating pace of technological change, robots will be able to move much faster, which may "increase the risks of collision and the potential hazards" (Atain Kouadio *et al.*, 2014). Furthermore, "the more advanced development [of these robots] may paradoxically exacerbate certain risks, such as exposure to magnetic fields strengthened by increases in on-board power. This same on-board power may also increase the risks of fire and explosion" (Atain Kouadio *et al.*, 2014). The authors go even further, arguing that "significant development of the use [of these robots] may weaken society as a whole as a result of a loss of control, related in particular to the risks of hacking and cybersecurity (Atain Kouadio *et al.*, 2014). Some of the new collaborative robot models can communicate remotely over the web. This type of communication is "useful to maintenance officers, who will be able to work on the machine remotely or limit their number of back-and-forth trips by doing an initial assessment remotely" (Parisot, 2014). With industrial facilities now becoming targets in their own right (Pietre-Cambacedes *et al.*, 2015), it is only logical to think that collaborative robots will become targets, too.

Remote communication is possible because collaborative robots have become connected objects. They have thereby joined the category of the Internet of Things. The data from the robot's communicating sensors can be recorded for the purposes of adjusting production remotely, for instance. A collaborative robot is therefore part of a cyberphysical system (Schubert, 2015). The Internet of Things, which has been in existence for 20 years already (Mraz, 2016), and cyberphysical systems constitute the foundations of Industry 4.0. The German government, which coined the term "Industry 4.0," defines it as being:

- digital
- capable of partly or entirely generating a "virtual replica" (Gimélec, 2013) of its production line
- efficient in its use of energy and raw materials
- flexible

Using collaborative robots contributes to industry's flexibility—for instance, in that they can easily be taught to reprogram themselves to suit the desired production run. Nevertheless, it is important to realize that a change in production can create new hazardous situations that must be considered when assessing workstation risk.

1.2.2 Early Risk Management

Given the potential OHS risks associated with cobotics, a number of studies have been conducted in various fields. Here are some examples aimed at improving the design of robots intended for collaboration or dealing with their design terms of reference, to ensure they are safer for the operator:

- **Cognitive ergonomics** with (1) improved anticipation of robot movements to make collaboration more intuitive and therefore safer, (2) optimization of collaboration to make it more fluid:
  - Development of a robot task planner that gives it decision-making autonomy, so that it produces and carries out socially appropriate behaviours (Montreuil, 2009);
  - Planning of robot actions and reactions (e.g., simulation of emotions) in response to human behaviour (Sidobre *et al.*, 2012; Buiu and Popescu, 2011; Kondo *et al.*, 2010);
  - Social traits of human-robot interaction (de Graaf and Ben Allouch, 2013; Moller *et al.*, 2011; Mumm and Mutlu, 2011)
  - Use of virtual reality to study human behaviour in interactions with a robot (DGUV, 2013). The conclusions drawn from these simulations indicated, for example, that a high robot speed increases the operator's workload, as well as anxiety, especially when the robot and the operator are in close proximity. They suggest that high speeds should be avoided in human-robot collaboration;
  - Demonstration of the attributes of augmented reality in facilitating the implementation of an environment more conducive to human-robot collaboration (Green, 2008);
  - Development of an assistance system capable of autonomously detecting situations in which the operator needs help to perform a task (Baraglia *et al.*, 2016).
- **Kinetics** of the moving parts of a robot: Development of a technique to enable robot joints to ensure high intrinsic safety for humans with respect to static collisions with robots[2] (Ahmed and Kalaykov, 2010), and the development of teach programming techniques (Rozo *et al.*, 2016). A study has also been conducted on the improvement of a robot arm

2. Ahmed and Kalaykov (2010) define a static collision as being a situation in which the robot's moving tool strikes a person at a speed below 200 mm/s.

through the addition of artificial pneumatic muscles (Shin *et al.*, 2010). Simulations of the operation of the arm validated the arm's safety characteristics for humans.

- **Risk analysis**: A method of estimating injury severity and probability (Fujikawa and Kubota, 2012), development of a self-check sheet for safe design of collaborative workstations focusing on organizational aspects (Ikeda *et al.*, 2012), and development of an OHS risk estimation tool for use at the design stage of robots that are intended to be collaborative (Matthias *et al.*, 2011).
- **Biomechanics**: Determining reduced speed and force levels, calculating human pain thresholds (Falco *et al.*, 2012; Fujikawa and Kubota, 2012; Kubota and Fujikawa, 2012; Haddadin *et al.*, 2007), the development of maximum force and pressure measuring systems for robot collisions, for the purpose of assisting in the assessment of risks associated with these machines before designing workstations (Huelke and Ottersbach, 2012).
- **Sensors**: Improvement and design of presence sensing systems (Fritzsche *et al.*, 2011; Haddadin *et al.*, 2011).

Reliability of safety-related parts of control systems: A self-check sheet for safe design of collaborative workstations focusing on the concept of "functional safety" (Ikeda *et al.*, 2012).

Given all these developments and the fact that Quebec's Regulation respecting occupational health and safety (ROHS) deals with access to a machine's danger zone while it is in operation (e.g., section 182, (2)), but not the sharing of a human-machine workspace, we feel it is important to anticipate the risks associated with collaborative robots installed in Quebec so that preventive action may be taken in advance (Gouvernement du Québec, 2016). As Murashov *et al.* suggest (2016), studying the safety of workers interacting with these types of machines is necessary before large numbers of potentially unsafe robots are installed in workplaces. This research project lays the groundwork for issuing initial occupational safety recommendations with regard to human-robot interaction in collaborative settings. It also provides the foundations for encouraging debate that will open up pathways toward future avenues of research. Last, it should also be noted that technical specification ISO/TS 15066:2016 was published while this research project was being conducted, which explains why this report does not refer to the detailed contents of that specification.

1.3 Organization of Report

The remainder of this report is divided into four chapters:

- Chapter 2 sums up the research objectives. The primary, "theoretical," objective was to assess the safety functions found on a sample of collaborative robots. The second, "field," objective was to assess how safety is taken into account in collaborative robot integration projects, based on feedback from workers, users and integrators of this type of equipment;
- Chapter 3 presents the theoretical aspect of the study and covers the method that was used, the findings and a discussion;
- Chapter 4 sets out the field aspect in detail. As with the theoretical aspect, the associated method, the findings and a discussion are included;

- Chapter 5 is a conclusion summarizing the findings, recommendations and suggestions for future research.

2. OBJECTIVES

The subject of this research project was industrial robots used in a human-robot collaborative setting. Robots designed to be collaborative, as well as conventional robots transformed into collaborative machines, were studied. The overall objective of the study was to make occupational health and safety recommendations regarding the implementation of robots in collaborative settings and to suggest ways to inform stakeholders about the issues involved in implementing cobotic installations.

There were two parts to the study: a theoretical part, followed by a field part. The two parts addressed, respectively, the two following specific objectives:

1) Assess the way the robot safety functions found on safety-related electronic cards or modules ensure operator protection as part of collaborative operating modes;
2) Obtain feedback from users (i.e., buyers or clients) of collaborative robots, integrators and workers concerned, about how safety is taken into account in collaborative robot integration projects, especially:
    - the challenges faced and problems encountered by collaborative robotics clients and integrators;
    - the occupational health and safety (OHS) risks and the benefits of this technology for workers.

The theoretical part of the study was conducted by the Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST) in Quebec and the INRS in France, as part of a machine safety cooperation agreement. The field study was carried out by IRSST researchers in Quebec.

The study differed from those cited in section 1.2.2 in the following respects:

- The theoretical part focuses on the integration of the industrial robot safety functions used for collaboration with human operators in the workplace, rather than on their design. It raises initial considerations of use to integrators in their implementation of cobotic cells.
- The field part of the study concentrates on specific cases of integration and use experienced in companies, rather than on a laboratory study on design. User feedback is crucial to improving the design of any machine. Figure 13 (see Appendix A), from standard ISO 12100:2010, shows the importance of feedback (users' input) in the risk reduction process. Thus, getting the information about machine use back to the designer and the integrator helps to improve not just safe design, but also the design of future workstations.

3. THEORETICAL PART OF STUDY: ASSESSMENT OF SAFETY FUNCTIONS

This theoretical part of the study assesses the way robot safety functions (SFs) found on safety-related electronic cards or modules ensure operator protection as part of the collaborative operating modes that are implemented.

Under Standard ISO 10218-1:2011, a high degree of reliability is required of safety functions used for collaborative operation: performance level PL d with safety requirements corresponding to those of category 3, as defined in standard ISO 13849-1:2015. To achieve this performance level, a number of manufacturers use an independent electronic card or one integrated by design into the robot controller (safety-related card). Otherwise, they use a unit placed in the robot control box (safety-related module), generally compatible with a wide range of robots. These safety-related cards or modules are dual core so that they can perform calculations redundantly. Many safety functions associated with collaborative operation of a robot are managed by these cards or modules. A safety-related card or module is generally connected to electrosensitive protective devices and receives information from the robot's sensor measurements (e.g., those linked to the robot's actuators), as well as from the instructions of the robot's controller. The card monitors the information in accordance with the planned logic and will force a protective stop in the event of a safety rule breach (e.g., limit breach due to excessive speed or going beyond workspace boundaries).

These cards with complex processing logic are fairly opaque for the final users, who are faced with a lack of recommendations and reference material on the subject. These were the circumstances under which we pursued the objective of the theoretical part of the study by following the method described in section 3.1.

3.1 Method

Figure 4 illustrates the five-step approach taken for the theoretical study.

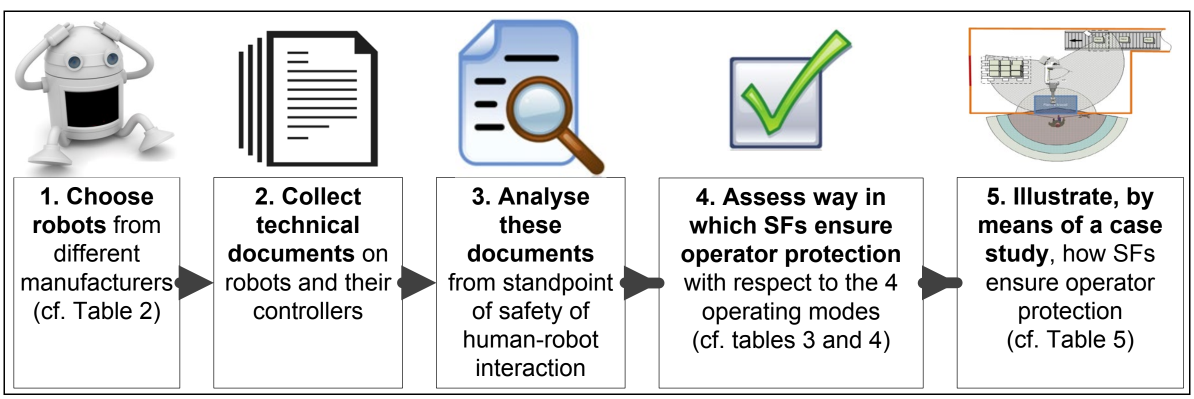


Figure 4 Method followed for theoretical study

Step 1

Three robots made by three different manufacturers were selected for the study. The characteristics—general technical specifications and performance data—of the three units are given in Table 2. These three models were selected because their manufacturers were among the most popular in industry internationally in 2014, at the time the study began. Opting for just three robots meant that our study would not be exhaustive, of course. The number of manufacturers making collaborative robots has since soared, especially at the end of the study period. Our aim in making this choice was to illustrate, with some concrete robotics examples, a few key watch points to pay attention to when implementing collaborative robotic cells. In addition, the choice helped prepare the research team for the field study in which two of the companies visited had one of the three robot models reviewed in the theoretical part of the study.

At the time the robot models were chosen, one of the biggest manufacturers only made and sold robots that were designed to be collaborative. The other two manufacturers were not yet selling such robots, preferring to make conventional robots that could be converted into collaborative machines. That explains the type of robots studied (see Table 2). For confidentiality reasons, the robot makes are not specified in this report. Similarly, the robots' quantitative characteristics, such as speed and payload, are represented by thresholds, though their order of magnitude has been preserved.

Table 2 General characteristics of the three robots studied

	Robot No. 1	Robot No. 2	Robot No. 3
Type of robot	Originally designed as collaborative	Conventional converted to collaborative	Conventional converted to collaborative
Number of axes	6	6	6
Payload	>3 kg	>3 kg	>15 kg
Reach	>700 mm	>800 mm	>1,000 mm
Max. speed (axis)	>170°/s	>710°/s	>330°/s
Controller	Robot-dedicated	Uses a compatible controller	Robot-dedicated
Safety-related card or module	Card part of original design	Module to be integrated	Card to be integrated
SF conformity (***ISO 13849-1:2015* or *IEC 62061:2005***)	Category 3, PL d	– Category 4, PL e: emergency stop of pendant – Category 3, PL d: other	Category 3, PL d
Access and changes to safety parameters	Password required to authorize changes to safety configuration (setting of position, speed, force limits, etc.)		
EC marking (2006/42/EC)	Declaration of incorporation	None	Declaration of incorporation

Step 2

The technical documents reviewed were maintenance manuals, user manuals and general electrical plans of the interconnections between the controller and the robot. The last two types of documents provided information on the inputs and outputs of the safety-related cards and modules and their operation. The documents were available on the manufacturers' websites or were obtained through distributors.

There was more technical documentation available for robot no. 3 than for robots no. 1 and 2. In addition, access to technical personnel for robot no. 3 was easier than for the other two robots. The research team thus had access to the manufacturer and distributor of robot no. 3 for any documentation or assistance it needed.

Step 3

An analysis table (see Appendix B) was developed on the basis of the information contained in the assembled documents. The table is modelled on Table 3.2 in Jocelyn (2012), which was used to analyse the function that stops and prevents the closing movement of the movable platen of a plastic injection moulding machine when the operator opens the guard. The Appendix B table provides a common basis for comparing the technical specifications and performance criteria of the safety functions that can be implemented. These specifications and criteria characterize each safety function and provide guidance for choosing components or parameters to be configured in connection with the function. For instance, the reaction time of the protective stop function presented in Appendix B can be used to calculate the safety distance required to ensure that the hazard (e.g., the moving robot) will be eliminated before the worker reaches the danger zone. In addition, depending on the spatial constraints, the reaction time can guide the choice of robot operating speed, as well as of the occupancy sensor capable of ensuring a stop within the required time limits.

For the analysis, the safety function technical plans available were reduced to simplified block diagrams to make them easier to read and understand. The block diagrams have been left out of the report to preserve the manufacturers' anonymity. Each block diagram illustrates the complete chain of the safety function: input, processing and output. The block diagrams show that all the safety functions go through the same safety-related card or module and act on the same output: the robot brakes. In contrast, they have different inputs, such as an emergency stop button or a presence sensing device. With this information, the safety function analysis tables could be filled in.

Step 4

Summary tables (see Table 3 and Table 4) are based on the analysis. They help to assess how the safety functions that can be implemented ensure the protection of operators in relation to the four modes of collaborative robot operation. As explained below, the safety functions studied are often the result of a combination of safety-related functions available on the safety-related cards or modules.

Step 5

The case study shown in Figure 5, which involved implementing a collaborative robot, is an example of how the identified safety functions ensure operator protection as part of human-robot collaboration. While this example is not exhaustive, it puts an instance of collaboration in context and illustrates the implementation of safety functions provided by manufacturers as a means of making the cobot safe to operate. The case study shows that human-robot collaboration is not necessarily limited to the use of a single operating mode. Nor does human-robot collaboration require the use of the four modes of collaborative operation for the same application. The study shows rather that, depending on the results of the risk assessment for the tasks planned for the cobotic installation, one or more of the four operating modes may be required to ensure operator safety.

The example is an illustration of a quality-control and palletizing cell. The workstation is dedicated to automatically controlling the quality of workpieces that are mechanically conveyed to a robotized palletizing station. If a defect is found, a corrective operation by an operator is required before palletization. For the defect correction, the robot must hold the workpiece still while the worker takes corrective action. This is the collaborative task in question.

The robot cell given as an example consists of three workstations:

1. **A control and unloading station:** This workstation is equipped with a sensor that stops the conveyor when it detects a workpiece. It is also equipped with a workpiece quality control system (visual inspection, for instance).

2. **A palletizing station:** At this station there is a pallet that is empty to begin with. It is filled as the robot moves workpieces to it from the unloading station.

3. **A defect correction station:** This is the collaborative workstation. In some cases, an operator may manually correct defects found in workpieces there (e.g., secure a missing screw) while the robot holds it still. In other cases, the workpiece is removed by the operator.

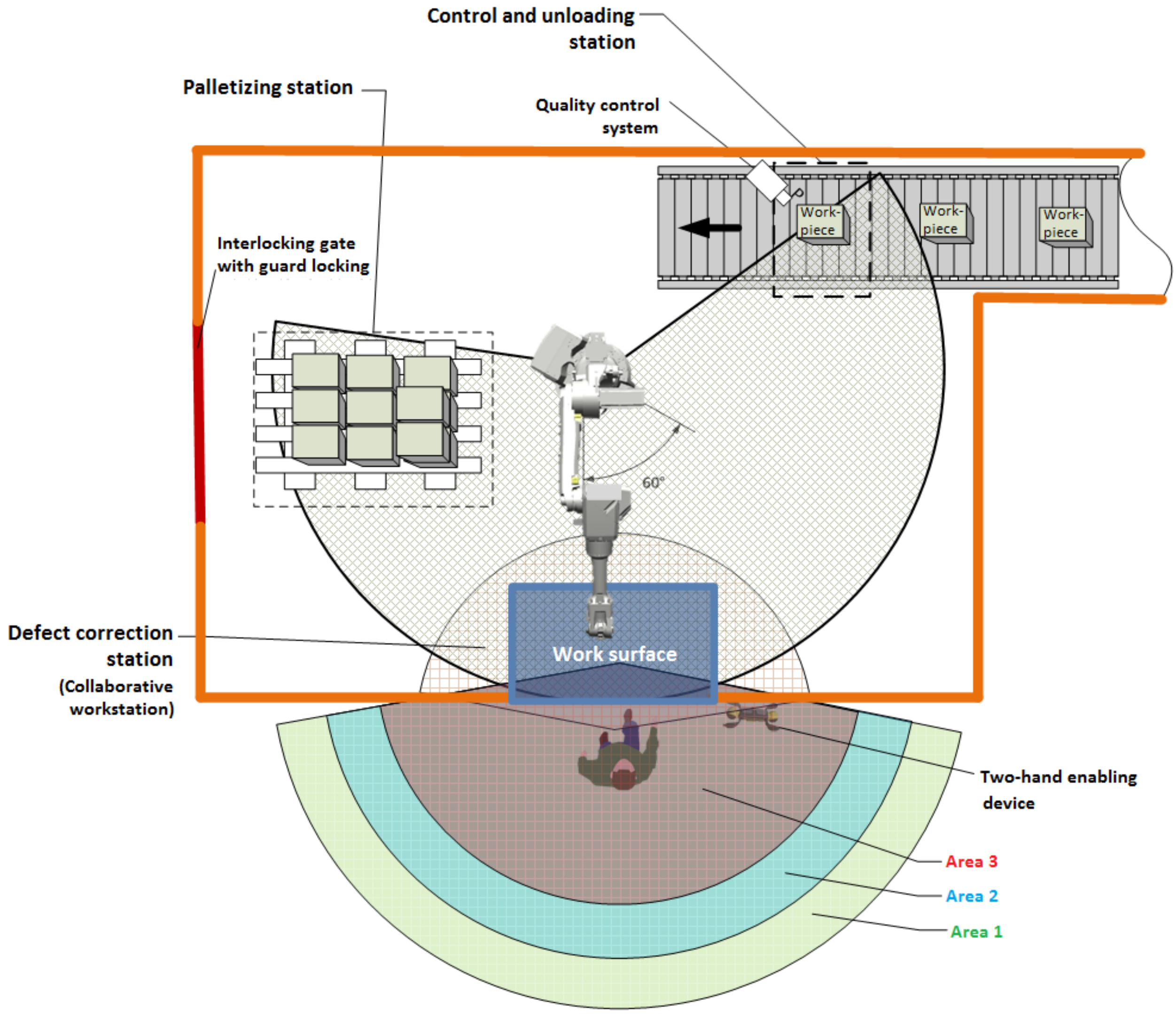


Figure 5 Example of collaborative robotic cell

To implement the cell, we assumed that the integrator followed the general design principles set out in standard ISO 12100:2010 and, in particular, went through the following steps:

- Draw up specifications;
- Carry out risk assessment, taking into account the tasks planned for the cell;
- Choose the collaborative operating mode or modes required for the application;
- Define the safeguards suggested by the risk assessment and dictated by the safety requirements of standard EN ISO 10218-1:2011 respecting the chosen collaborative operating modes;
- If the safeguards involve the control system:
    - Define the safety functions;
    - Determine the performance level of each safety function;

- Ensure that the safety or safety-related functions available on the manufacturers' electronic cards or modules are adequate to meet the real needs of the application. If safety functions are not provided by the cards or modules, implement them by external means (e.g., safety-related controller).

Let's assume that the first design step (specifications) taken by the integrator leads to the choice of the following eight-point sequence to be automated:

- If there are no defects, the robot takes a workpiece from the unloading station and moves it to the palletizing station according to a predefined order (to form a full pallet). During this operation, the conveyor stops when the next workpiece reaches the control and unloading station and remains stopped while waiting for the next operation;
- When a defective workpiece is detected at the quality control and unloading station, the conveyor stops and waits for the robot to move the workpiece to the defect correction station;
- In the case of a defect, the robot picks up the defective workpiece from the conveyor and takes it to the collaborative workstation so that the operator can perform manual operations on it. During this phase, the conveyor moves another workpiece to the quality control and unloading station, then waits for the defect correction and palletizing operations to be completed;
- During the manual defect correction operation (collaborative work), the robot is in safety stop mode and keeps hold of the workpiece;
- The completion of the defect correction operation is confirmed by the operator by means of an actuating control. Once the operator has left area 3, the robot moves the corrected workpiece to the palletizing station and then resumes its normal cycle;
- Regardless of the step of the cycle the robot is in, when the operator approaches the collaborative workspace, a beep sounds when he or she enters area 1. Then, if the robot is in motion, it goes into reduced speed mode when the operator enters area 2. Last, the robot stops safely if the operator enters area 3;
- If the operator is in area 3 and the robot has not completed its trajectory to move a workpiece to the collaborative workstation, the operator has a two-hand enabling device to allow the robot to complete its trajectory at reduced speed;
- If the operator deems that the defect in the workpiece cannot be corrected, he or she pushes a button to release the workpiece so that it can manually be removed from the palletizing process. The robot automatically returns to the quality control station after the operator has enabled the operation and exited area 3. In this case, the robot does not go by way of the palletizing station.

Based on the step 3 analysis, Table 3 and Table 4 guided the implementation of the safety functions for the case study.

3.2 Results

Table 3 presents the safety-related functions (SRFs) involved in the implementation of one or more of the four collaborative operating modes for the three robots studied. These functions are processed by the safety-related card or module of each robot. Each function was assigned to a specific collaborative operating mode based on the research team's analysis.

On the basis of the analysis, the SRFs were also grouped into three generic families (Table 4):

- Stop SRFs: Functions that cause the robot to stop, with or without removal of power, as a result of an external control, a failure or a fault (e.g., deceleration noncompliant with braking ramp);
- Monitoring SRFs: Functions that monitor certain robot characteristics to maintain the stop with power available or to prevent the functions from exceeding preset values (limit violations). These can be speed or spatial limits;
- General SRFs: Functions that are neither stop-related nor monitoring-related (e.g., cyclic brake check).

For the case study, the risk assessment for the cobotic cell guided the research team toward a combination of two collaborative operating modes: "Safety-rated monitored stop" (mode 1) and "Speed and separation monitoring" (mode 3). This decision led to the choice of the following safeguards:

- a laser scanner to detect the presence of the operator near the collaborative workstation
- a sliding gate with an interlocking device with guard locking that secures entry into the pallet unloading area when a collaborative task is in progress
- a two-hand enabling device (hold-to-run control) to control the robot from the collaborative workstation

Table 3 List of safety-related functions (SRFs) by robot and their role in collaborative operating modes

		SRFs, by manufacturer, enabling implementation of collaborative operating mode	Mode* No. 1	Mode* No. 2	Mode* No. 3	Mode* No. 4
Robot No. 1	1	Protective stop (category 2 stop)	✓	×	×	×
	2	Reset following protective stop	✓	×	×	×
	3	Control of category 1 and 2 stops (cat. 0 stop triggered if cat. 1 or 2 stop criteria violated)	✓	×	×	×
	4	Tool centre point position limiting	×	×	✓	×
	5	Joint position limiting	×	×	✓	×
	6	Joint speed limiting	×	✓	✓	✓
	7	Tool centre point speed limiting	×	✓	✓	✓
	8	Separation control: configurable function, but unavailable as is on the robot. To make it available, a safeguarding device must be connected to the safety interface	×	×	✓	×
	9	Tool centre point force limiting	×	×	×	✓
	10	Impulse limiting	×	×	×	✓
	11	Power limiting	×	×	×	✓
Robot No. 2	1	Speed limit of tool centre point or flange	✓	×	✓	✓
	2	Position limit by axis	×	×	✓	×
	3	Speed limit by axis	×	✓	✓	✓
	4	Position limit of tool centre point or flange	×	×	✓	×
Robot No. 3	1	Safe deceleration ramp	✓	×	×	×
	2	Safe stop	✓	×	×	×
	3	Safe stop monitoring	✓	×	×	×
	4	Safe axis speed	×	✓	✓	✓
	5	Safe tool speed	×	✓	✓	✓
	6	Safe axis interval	×	×	✓	×
	7	Safe tool area	×	×	✓	×
	8	Monitoring of axis area	×	×	✓	×
	9	Monitoring of tool area	×	×	✓	×

✓: plays roll in
×: does not play roll in
* Mode 1: safety-rated monitored stop
Mode 2: hand guiding
Mode 3: speed and separation monitoring
Mode 4: power and force limiting

Table 4 Classification of safety-related functions (SRFs) listed in standards ISO 10218:2011, parts 1 and 2, regarding human-robot collaboration and identification of those performed by the robots studied

Generic SRF family	Generic name of SRF	Robot No. 1	Robot No. 2	Robot No. 3
Stop SRFs	Emergency stop	✓	✓	✓
	Safety-rated monitored stop (mode 1)			
	Protective stop (category 0)	✓	✓	✓
	Protective stop (category 1)	×	✓	✓
	Protective stop (category 2)	✓	×	×
	Deceleration control during category 1 or 2 stop	✓	✓	✓
	Hand guiding (mode 2)			
	Emergency stop using hand guiding equipment	×	×	×
Monitoring SRFs	**Safety-rated monitored stop (mode 1)**			
	Monitoring of zero speed of robot	✓	✓	✓
	Monitoring of stationary position of robot	✓	✓	✓
	Hand guiding (mode 2)			
	Monitoring of speed of robot < Speed limit	✓	✓	✓
	Speed and separation monitoring (mode 3)			
	Monitoring of speed of robot < Speed limit	✓	✓	✓
	Monitoring of position of robot	✓	✓	✓
	Robot power and force limiting (mode 4)			
	Monitoring of force < Force limit	✓	×	×
	Monitoring of power < Power limit	✓	×	×
General SRFs	Deliberate reset from outside the collaborative workspace following a protective stop	✓+	?	?
	Software synchronization	✓	✓	✓
	Cyclic brake check	?	?	✓
	Safety-rated monitored stop (mode 1)			
	Presence sensing of an operator in collaborative workspace	✓+	✓+	✓+
	Hand guiding (mode 2)			
	Hold-to-run control using this equipment's enabling device (releasing the control will cause a safety-rated monitored stop)	×	×	×
	Speed and separation monitoring (mode 3)			
	Detection of position of operator in collaborative workspace	✓+	✓+	✓+

✓: SRF present
×: SRF not present
+: Input safety device needs to be added
?: Information not found in reference material

The safeguards described above make use of the control system via the following safety functions, which can be combinations of SRFs:

F1 – Function that slows the robot when the operator approaches area 2

F2 – Robot stop function for collaborative work (cat. 2 stop): stop the robot when the operator enters area 3

F3 – Robot's manual (hold-to-run) control: move the robot at low speed even when the operator is in area 3

F4 – Cat. 0 or 1 protective stop function initiated by the interlocking sliding gate with guard locking

F5 – Manual reset function following triggering of the interlock with guard locking

F6 – Function to release workpiece by pushing a button accessible in area 3

The SRFs for implementing these safety functions are set out in Table 5. They are taken from Table 3 and Table 4. They can therefore be found on the cards and modules of the three robot models studied.

Table 5 Implementation of safety functions required for cobotic cell of example, according to the manufacturers' instructions for the different robots studied

	Robot No. 1 – SRFs required	Robot No. 2 – SRFs required	Robot No. 3 – SRFs required
F1	Limiting of joint speed or limiting of centre point speed	Limiting of speed by axis or limiting of centre point speed	Safe axis speed or safe tool speed
F2	Protective stop function + Stop control function + Reset following protective stop function	Safety stop function	Safe deceleration ramp + Safety stop function
F3	Reset following protective stop + Limiting of joint speed or limiting of centre point speed	Limiting of speed by axis or limiting of centre point speed	Safe axis speed or safe tool speed + Manual operation function
F4	Protective stop (cat. 0 or 1)	Protective stop (cat. 0 or 1)	Protective stop (cat. 0 or 1)
F5	Reset following protective stop function	External reset function	External reset function
F6	Protective stop function + Limiting of position of tool centre point	Safety stop function + Limiting of position of centre point and flange	Safety stop function + Manual operating function

3.3 Discussion

3.3.1 General Specifications

Table 2 provides the characteristics that help distinguish between robots that, by design, are suited for collaborative operation and conventional robots that have been converted so they can be integrated into cobotic cells. "Max. speed" by robot, for instance, shows that, by design, the joints of the robot designed to be collaborative (robot no. 1) have an angular speed (>170°/s) well below that of the joints of the other two robots (>710°/s and >330°/s). Robot no. 1 is designed to be integrated into a cobotic cell and would make it easier to limit the risks involved in integration. Similarly, the electronic safety-related cards or modules are an integral part of robots designed to be collaborative, which reduces the required adjustments that must be made and the possibility of errors during integration.

Nevertheless, even when robots are designed from the outset for human-robot collaboration, the speeds they can reach can still be a hazard for operators. A risk assessment including reaction time and stopping distance calculations should suggest suitable speed values. These values must be restricted and protected to prevent them from being changed illicitly or accidentally, which is the reason for the passwords mentioned in Table 2. In addition, for operational reliability and safety reasons, these speeds must be monitored by safety functions to ensure a response in the event of a possible failure. For instance, for robot no. 3, the configurable (theoretical) maximum speed exceeds 330°/s for the rotational axes and is equivalent to 10 m/s for the linear axes. These extreme values would appear to be incompatible with collaborative work. Care must therefore be taken when specifying speeds to remain within ranges compatible with the risk assessment. Extra care must be taken by users and integrators who procure a safety-related card or module for the purpose of converting a powerful conventional robot into a collaborative robot.

It should also be noted that manufacturers often exaggerate when using the term “safety” with regard to safety-related modules and cards. While the module or card is capable of providing safety, to implement a comprehensive safety function, the modules or cards must be supplemented by the integrator through the addition of other devices (e.g., sensing devices) in accordance with criteria that will enable the required performance level to be achieved for the comprehensive safety function. It would therefore be more accurate to talk about “safety-related” modules or cards. The concept of integrated or configurable safety functions is explained in greater detail below. This study shows that the functions found on safety-related electronic cards and modules are not necessarily “safety functions” as the manufacturers claim, but rather safety-related functions for the simple reason that they constitute only the “processing” block of the safety function chain to be implemented.

Last, manufacturers consider robots originally designed as collaborative to be partly completed machinery. According to the user manuals we referred to, the integrator is responsible for conducting an appropriate risk assessment and for complying with the machinery-related regulations and standards in force. In the case of partly completed machinery intended for the European market, however, the manufacturer must always provide a declaration of incorporation (art. 13, Directive 2006/42/EC on Machinery, The European Parliament and the Council of the Europe Union, 2006). Table 2 shows that robots no. 1 and 3 have the required declaration of incorporation.

3.3.2 Implementation of Collaborative Operating Modes

In Table 4, it can be seen that the safety-related functions that make up the “monitoring SRF” family are the only ones that contribute to all collaborative operating modes. Table 4 also shows the generic safety-related functions prescribed by standard ISO 10218:2011, parts 1 and 2, to achieve each collaborative operating mode. Table 3 lists one or more safety-related functions suitable for a given mode. An examination of Table 3 and Table 4 shows that the existence of one or more safety-related functions for implementing a collaborative operating mode does not mean that the mode was completely configured originally on the robot.

To implement collaborative mode 1 in accordance with ISO 10218-1:2011, the system must be able to detect a human presence in the collaborative workspace. As indicated in Table 4, the three robots studied require the addition of a safety device able to detect a human presence. For instance, for robot no. 1, detection is signalled by the protective device to be installed at the input of the “protective stop” safety function. In the case of robot no. 2, the detection is implemented by means of an enclosure guard sensor. For robot no. 3, a presence in the collaborative workspace is detected by an external detection device connected to a safety-related card. Under the standard, this detection must stop the robot by triggering either a category 1 or 0 protective stop or a category 2 stop. In our case, as shown in Table 4, robot no. 1 can perform category 2 stops, while robots no. 2 and 3 can only do a category 1 stop. When implementing functions, the integrator must therefore pay attention to the robot’s limits with respect to stop categories.

For mode 2, it can be seen in Table 3 that the only functions available on the three robots are the speed limiting functions. To satisfy this mode, the following capabilities are missing: the hand guiding equipment placed near the robot terminal, as well as the emergency stop and enabling device available on the hand guiding equipment. An integrator who wishes to install this mode, or any other mode, must ensure that the robot has all the technical capabilities required to host the collaborative operating mode in question.

Regarding mode 3, all the robots studied had speed limiting functions for maintaining a safe estimated speed. They also included position limiting functions that help maintain a certain separation between the robot and the operator. A protective device (e.g., position sensor) for calculating this separation distance in real time could be installed and configured in order to implement this mode fully. Otherwise, the protective device could be a motion detector (e.g., laser scanner) embedded in the ground, for instance; if the protected space is entered, the intrusion detector orders the robot controller to adjust the speed. The use of this mode is conditional upon the availability of detection devices capable of detecting the operator in real time. These devices must meet safe operation reliability requirements (PL d, category 3). In addition, to implement this collaborative operating mode, the robot needs to be able to change its trajectory dynamically, which most industrial robots available on the market are not able to do. Nevertheless, Winkler and Suchý (2011) show that intentional misuse of a sensor interface can enable a virtual force field created from camera data to be used to avoid a mobile obstacle (the operator, for instance). This method is based on the use of impedance control to allow the robot to change its trajectory in real time relative to a mobile object found in its workspace. An alternative method of preventing the robot from failing to respect the separation distance would be to reduce its speed and then put it into mode 1, if necessary.

As for mode 4 described in standard ISO 10218-1 and detailed in technical specification ISO/TS 15066, it requires limiting the robot's force and power in order to reduce collision risks to an acceptable level. For this mode, speed limiting functions help achieve the required safety level, as limiting the speed restricts the kinetic energy and therefore the power released in a human-robot collision. However, a safety function capable of stopping the robot needs to be available in a collision in the event that tolerable force thresholds are exceeded. As Table 4 indicates, the lack of force sensors on robots no. 2 and 3 makes this mode difficult to implement. For this mode, it is essential to use robots designed for collaborative operation and specifically for mode 4. These robots, generally referred to as "power and force limited robots" (PFLR), have intrinsic characteristics that help reduce risks (e.g., reduced mass, rounded edges, viscoelastic materials). In addition, they generally have safety functions that enable implementation of this mode, such as the contact force monitoring function and the speed monitoring function. Still, it is important to remember that the use of this mode must meet a real need for human-robot interaction and must be preceded by a thorough risk assessment. The safety functions necessary to implement this mode must meet the operating safety requirements laid down in the standards, i.e., PL d and category 3, as well as the absolute prohibition of any contact with certain body parts, such as the head.

In the case of robot no. 2, a force sensor could be installed at the tool centre point (TCP). In this case, however, the robot would not be ordered to stop if the person came into contact with a part of it other than the TCP. An alternative could be to place a force sensor between the base of the robot and the ground. This way, a physical impact would be detected, regardless of the point of contact. In the case of robot no. 1, the faster it moves, the harder it is to stop it, even if it has safety functions other than "speed" allowing power and force to be controlled. In addition, force limiting is possible only if robot no. 1 encounters a physical obstacle (e.g., collision with a human) at the level of its tool or close to it. The chances of stopping this robot operating at full speed or by pressing elsewhere on its arm are low if it comes into contact with an immobile operator or one moving slowly. On the other hand, it is one of the lightest robots, with rounded shapes (no sharp edges), so any potential injury is limited (though not prevented) intrinsically by design.

The “general SRF” family of Table 4 shows that integrating a collaborative robotic cell can be a complex undertaking. As noted in the analysis of the cards and modules of the three robots studied, this complexity is due to a lack of information needed to implement a safety function (see the “?” in Table 4). This is information that may be missing from the technical documentation or unavailable from the manufacturer. Note that even for robot no. 3, where all the reference material, as well as the manufacturer and the distributor, were available for assistance, some questions could be not answered. This complexity is also due to having one collaborative operating mode nested within another (e.g., standard ISO 10218:2011 requires mode 1 to be activated when the enabling handle is released in mode 2). Depending on the application, one mode alone cannot ensure the operator’s safety. A combination of modes may be necessary, such as the combining of modes 1 and 3 in the case study.

3.3.3 Stop Categories and Modes of Collaborative Operation

Standard ISO 10218-1:2011 stipulates that, for mode 1, any violation (unintended motion or failure) of the deceleration ramp when braking must result in a category 0 stop (see Glossary for the definitions of the stop categories, and Appendix C to view how these types of stops operate). This condition is met by all three robots studied (Table 4). As for modes 2 to 4, any violation of the speed or position limit must, according to the standard, cause a protective stop. Section 5.5.3 of the standard stipulates that this stop must be at least category 0 or 1; an additional category 2 protective stop may also be implemented. For modes 2 to 4, a limit violation causes a category 0 protective stop for robots no. 1 and 2. As for modes 2 to 4 for robot no. 3, the protective stop will be a category 0 or 1 stop, depending on the configuration chosen at the time of installation. The stop logic of the three robots studied therefore seems to comply with the standard.

3.3.4 Configuration and Overall Performance Level

A comparison of Table 3 and Table 4 shows that the safety-related functions in Table 3 consist essentially of stop functions and speed, position, force and power monitoring functions. This is an important point that must be considered when integrating the robot into production: the reaction time of the safety function will depend on the sum of the reaction times of each safety-related function (including those associated with protective devices), to which the stop time of the robot must be added. This criterion must be taken into account when determining safety distances.

Some safety functions that go through the safety-related electronic card or module are fully implemented at the robot design stage and meet the minimum performance level requirements: PL_r d, category 3, according to standard ISO 10218-1:2011. This is the case of the emergency stop functions assessed in our study. If not, other safety functions need to be configured (e.g., specifying speed or position limits) or input or output hardware needs to be added (e.g., light curtains for detecting a presence in the collaborative workspace, or a force sensor). The “processing” part of these safety functions is already available on the safety-related cards or modules and meets the required performance level.

The integrator is responsible for maintaining the performance level of the safety function that goes through the card or module by choosing an appropriately reliable input or output component that complies with Table 11 of standard ISO 13849-1:2015. The table shows that the number of components to be added is critical. For example, a functional chain made up of PL e components will have a PL d, i.e., lower, if the chain has more than three components. The performance levels stated for cobot safety functions are often levels that are attainable, but not achieved in reality. To implement the complete chain of a safety function, the integrator often has to combine several safety-related functions available on the manufacturers' electronic cards or modules. The case study presented is a good illustration of this point: Table 5 shows that to make a cobotic installation safe, whether with robot no. 1, 2 or 3, a combination of SRFs may to be required to implement a safety function. The integrator may also use outside components or devices (see Figure 6). The area monitoring functions in the case study (see F1 and F2 in Table 5), in addition to using combinations of SRFs found on the safety-related electronic cards or modules, require outside components such as a laser scanner. The laser scanner, besides having to meet performance level requirements, often involves use of a control module (PLC) that must be programmed or configured, then connected to the safety-related card or module. A safety function must therefore be considered in its entirety. The integrator must make an appropriate, informed decision when choosing the external devices (e.g., protective devices) compatible with the general safety function to be implemented. If function F1 that slows down the robot when the operator is in area 2 is considered to be a safety function, the detection device used must have two detection areas (area 2 and area 3 in the example) and must be compatible with the performance level required for collaborative robotics, i.e., PL_r d. If the sensor does not satisfy that condition, it may be necessary to consider adding another protective device suited to the application.

Table 5 also indicates that, even if the safety-related functions of different manufacturers have similarities, there are still a number of technical differences between them. For example, to implement function F5, robot no. 1 will automatically be reset following a protective stop, whereas for robot no. 3, it will be done by means of an external reset.

The integrator must therefore exercise care and select the appropriate combination of the manufacturer's SRFs, while making sure these functions are not incompatible with one another. SRFs are incompatible in the implementation of a safety function if, together, they reduce the required performance level for the safety function. It is essential for the integrator to remember that a safety function must be complete and must encompass all the elements involved in ensuring safety.

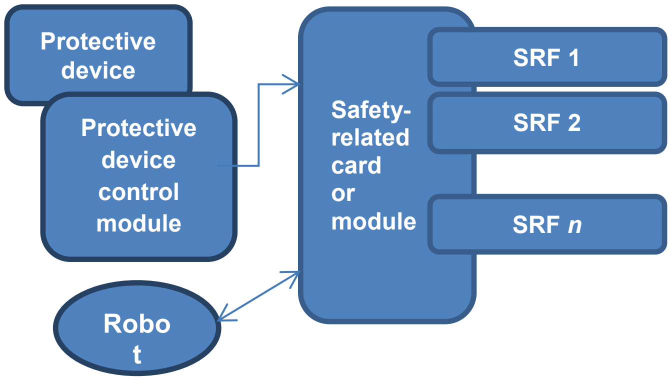


Figure 6 Implementation of a general safety function

3.3.5 Scope and Applicability of Results

In the example illustrated, the research team put itself in the role of an integrator who must design safety functions using the safety-related functions available on the safety-related electronic cards or modules, for the purposes of human-robot collaboration. The case study shows the approach to integrating a collaborative robotic cell, but does not go into detail. The example does not consider all the risks to the safety of people nearby, such as those caused by a person entering the cell. As a result, not all the associated risk-reduction measures are covered. However, the results and observations associated with this theoretical study will serve as cautions to integrators who want to develop a collaborative application from a robot originally designed to be collaborative or from a robot converted to become collaborative.

With regard to the first research objective stated in Chapter 2, it can be concluded that most of the functions found on the safety-related cards or modules covered in the study are safety-related functions (SRFs) rather than safety functions (SFs). The term “safety function” given to these functions by the manufacturers is inappropriate and should instead be replaced with “safety-related function” (SRF).

study presented illustrates the way these SRFs ensure operator protection in relation to various collaborative operating modes. This protection is ensured through combinations of SRFs available on the card or module or provided by added components. According to the requirements of the standards and the results of a risk assessment, it was shown that a combination of collaborative operating modes may also be necessary to ensure operator protection.

The purpose of this part of the study was to compare robots from a theoretical standpoint, essentially based on technical specifications and other information available in the relevant user manuals. In future, the technical performance of different robots will need to be compared concretely in order to provide practical illustrations of how a mode can be implemented differently from one robot to another. As a result, it will be possible to determine the technical limits of implementing a collaborative operating mode on some robots. A practical comparison of this kind could serve as a reference for integrators, as well as for clients. They could know which types of robots are compatible with what collaborative operating modes. They could also know the limits and tricks of the trade for implementing a given mode on a given robot.

4. FIELD PART OF STUDY: FEEDBACK

The second part of the study consisted in gathering feedback on safety considerations for four collaborative robot implementation projects in a business setting. This limited number of cases was due to the fact that only four of the 14 companies in Quebec initially contacted had a robot, already installed or in the process of integration, for a collaborative application. Two other companies contacted had robots originally designed as collaborative, but were still thinking about how to apply them. The remaining eight companies did not have robots of this kind.

The field part of the study targeted three types of participants:

- User (i.e., client): Person or entity that needs a collaborative robot for its production and that normally draws up the specifications intended to be used by the integrator for installation;
- Integrator: Person who designs the workstation, installs the robot at the client's and makes the initial adjustments, in accordance with the agreed specifications. The integrator is either an employee of the company or a subcontractor;
- Worker: Person who works alongside or interacts with the collaborative robot in performing his or her usual duties in the company.

As shown in Figure 7, this part of the study documents the problems encountered and challenges overcome by clients and integrators. It also catalogues the OHS risks and benefits of this technology for workers.

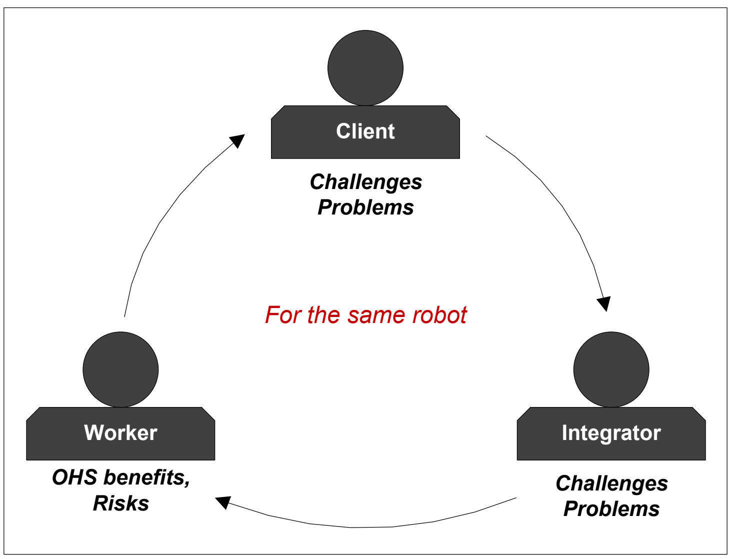


Figure 7 Participants in field part of study

This section begins by explaining the method used and then sets out and comments on the following points: (1) the main characteristics of the four case studies observed, (2) the situation prior to integration, (3) the integration process, problems and solutions found and (4) post-integration follow-up. The results and discussion are presented together for each point. The results are reported in the form of facts observed on site. In general, they are presented in the tables. The discussions consist of either comments on the results, or of recommendations.

4.1 Method

Here is the method followed for the field study:

- Obtain research ethics certificate for authorization to collect information in the field;
- Develop data collection forms for each of three types of participants (see appendixes D, E and F);
- Recruit companies having a cobotic installation;
- Visit four companies having at least one cobotic installation. These companies are labelled A, B, C, D, respectively;
- Conduct a semistructured interview with each participant, using the appropriate data collection form. The three interviews were held the same day or at separate times, depending on participants' availability.

  N.B. For reasons beyond our control, it was impossible to meet with the worker at one of the four companies;
- Observe cobotic installation. If the implementation was still in progress, observe the task to be automated, the final future location of the installation and the test setups (robots and safeguards) for the installation.

4.2 Characteristics of Four Case Studies

This section provides an overview of the case studies conducted in the field and compares them. At company A, three case studies were available: A_1, A_2 and A_3. As the time allotted to visit this company was limited, the data collection focused on the oldest of the three installations: A_1 had been operational for a year and a half and its peripheral equipment was a press brake. A case study was conducted in each of the other three companies: B, C and D.

Figures 8 to 11 illustrate the collaborative applications studied: A_1, B, C and D. They are not necessarily to scale. The geometry of the illustrated robot has been deliberately modified in relation to reality in order to minimize the possibility of readers recognizing the company. The purpose of the diagrams is twofold: to show how space is shared between the worker and the robot, and to make it easier to visualize the main steps involved in the automated task. The numbers or explanations in each figure indicate the order in which the task steps are performed or help to understand the task. Figure 8 and Figure 9 illustrate, respectively, cases A1 and B, where integration had been completed. Figure 10 and Figure 11 are detailed diagrams of cases C and D, respectively, where the integration process was in progress. In Figure 10, installation C is under development, whereas in Figure 11, installation D is at the testing and planning stage.

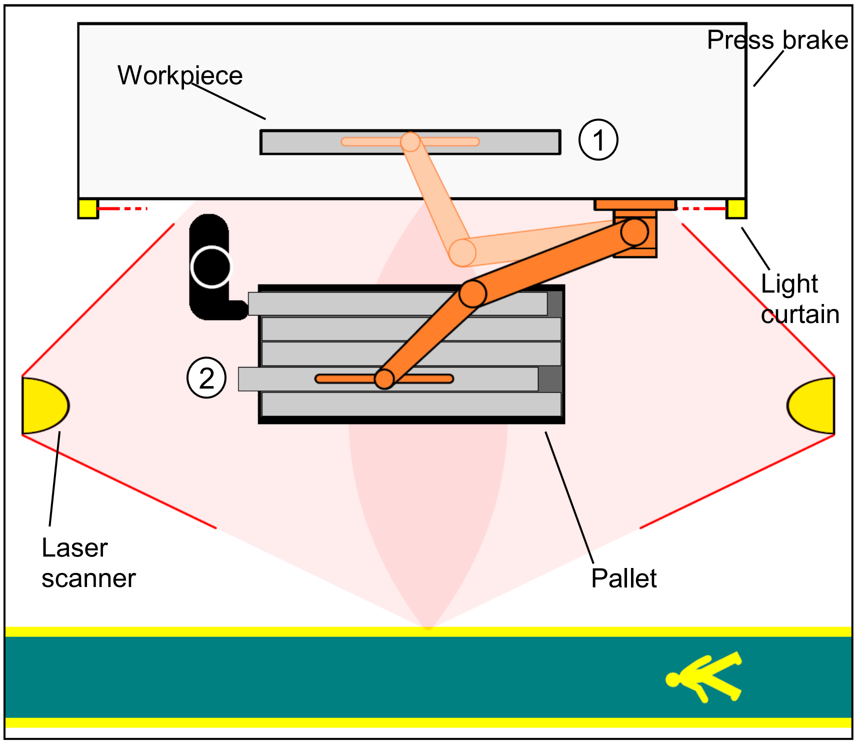


Figure 8 Top down view of collaborative application A_1

In case A_1, the robot slows down when a person enters the collaborative workspace. The robot's reduced speed is triggered when the laser scanner detects a presence. The light curtain only manages safety with respect to the press die. If it detects a presence, the press brake stops.

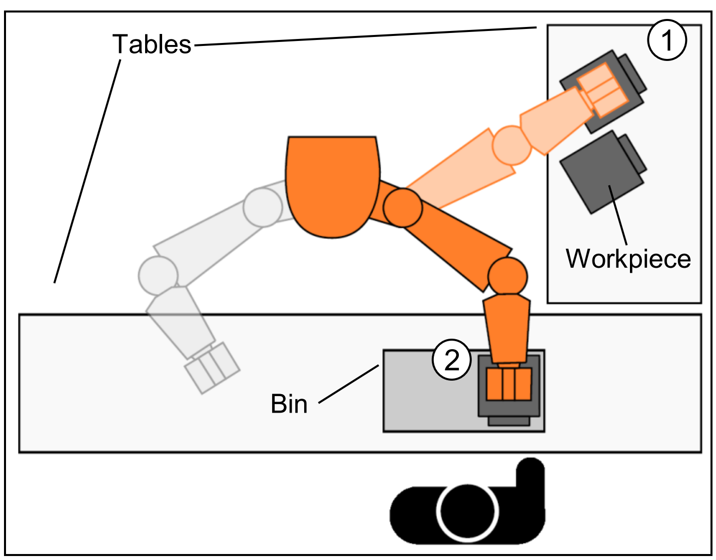


Figure 9 Top down view of collaborative application B

In case B, the robot is operating at production speed. It slows down, however, if its vision system, integrated by design, detects a presence.

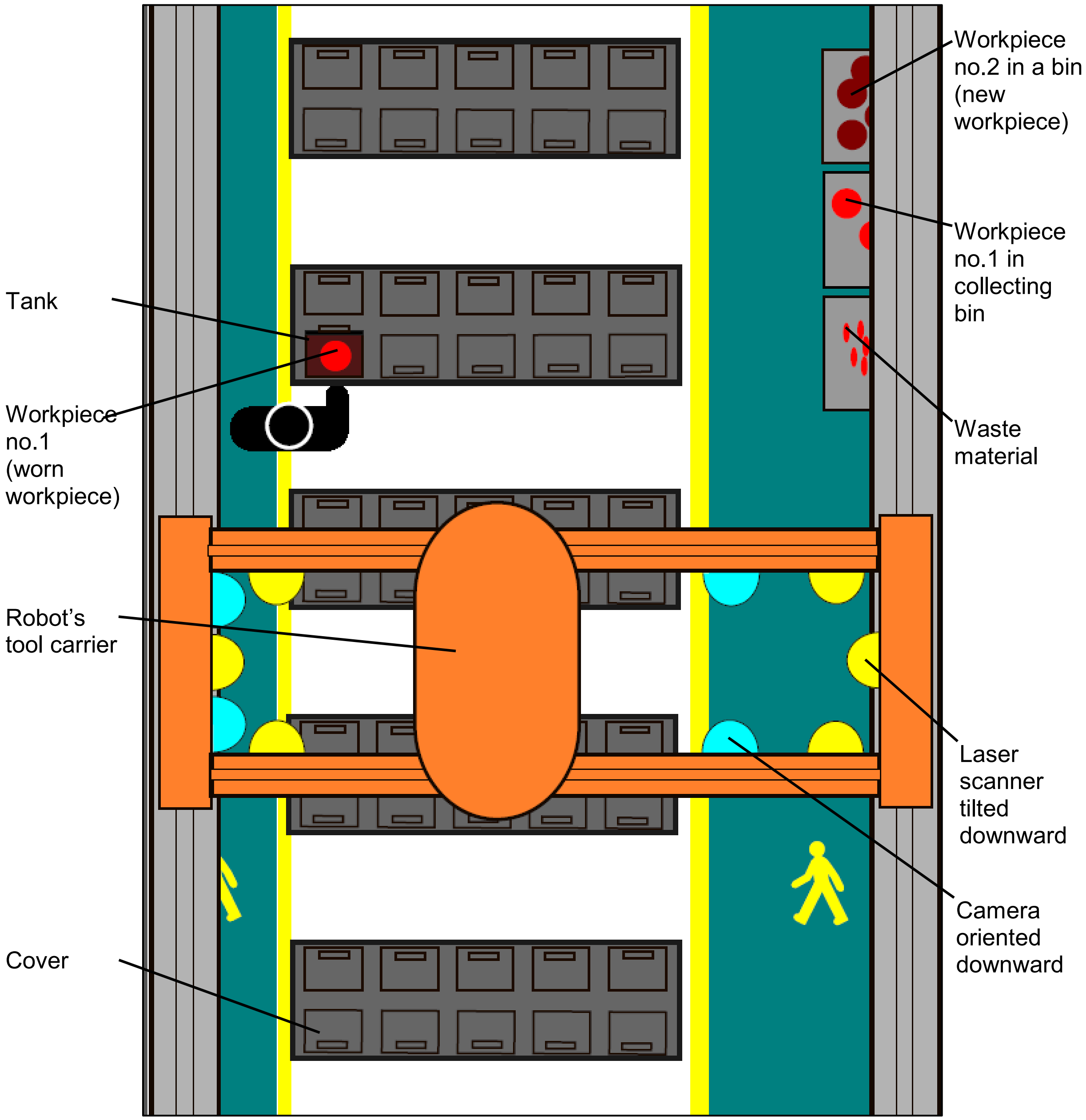


Figure 10 Top down view of collaborative application C

Note: This diagram represents the application we saw at company C. As the safeguards were still being tested, changes may have been made afterwards.

In case C, the robot's reduced speed and a warning sound are triggered when at least one laser scanner or one camera detects a presence. Then the robot stop will be activated if the safety area is entered (the safety radius will be determined later by the integrator).

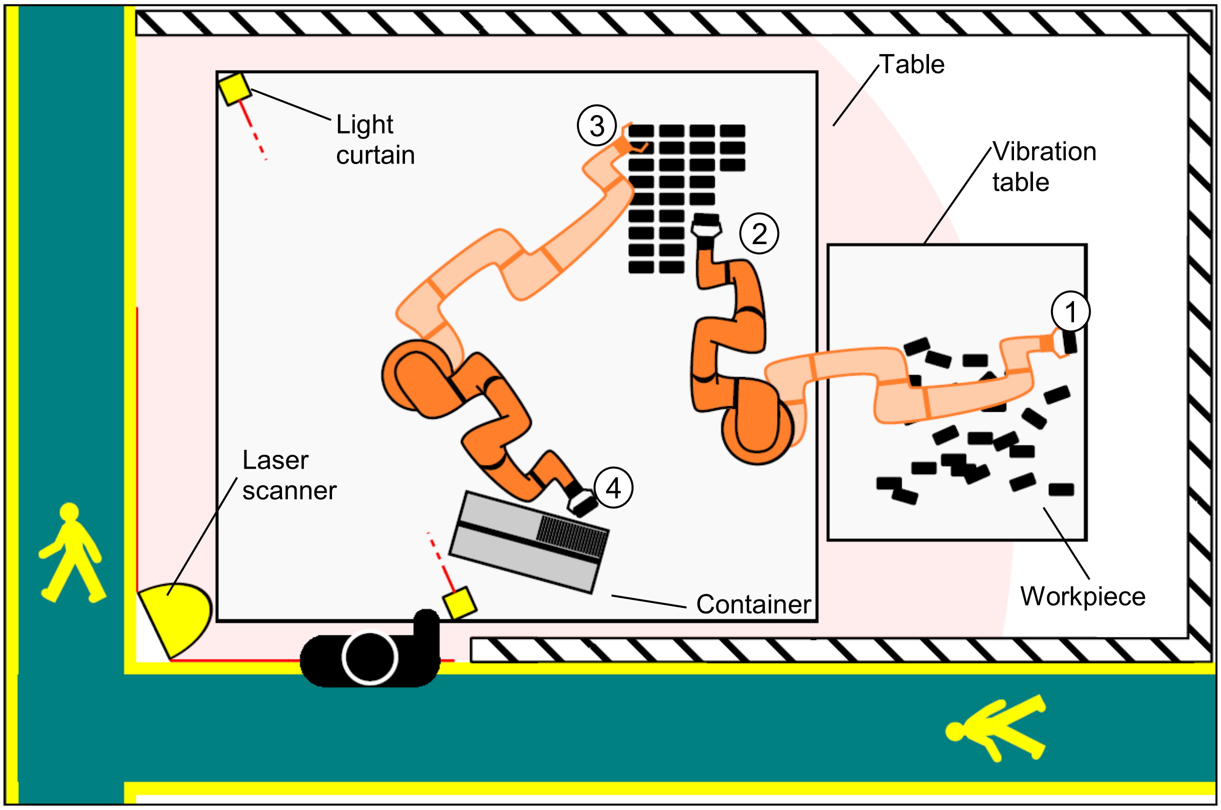


Figure 11 Top down view of collaborative application D

In case D, reduced speed is triggered when the laser scanner detects a presence. Then the robot stop is activated if the light curtain detects a presence.

Table 6 provides an overview of the four case studies.

Table 6 Overview of case studies

	Collaborative application			
	A_1, A_2, A_3	**B**	**C**	**D**
Industry in which company visited operates	Metal	Automation services	Metal	Aerospace
Status of case study	Cobotic cells completed 1½ years ago or less and used for production	Demo application in workshop (proof of concept for a client)	Cobotic cell under development Safeguard operation testing in progress	Cobotic cell in process of integration. Test setup installed
Type of participants surveyed	• Client • Integrator • Worker	• Client • Integrator • Worker (simulation of task)	• Client • Integrator	• Client • Integrator • Worker
Number of robots per cobotic cell	1	1	1	2
Collaborative workspace	• Stationary • With fixed presence detection area	• Stationary • With fixed presence detection area	• Mobile • With mobile presence detection area	• Stationary • With fixed presence detection area
Collaborative operating modes used$^{\Delta}$	3 and 4	4	1 and 3	1, 3 and 4

Δ Standard ISO 10218:2011 identifies four collaborative operating modes, defined in section 1.1.1.4 of this report.

Table 6 shows that cobotics is in its infancy in Quebec, as only company A was using cobotic cells for production in 2015, with permanent safeguards. Note that this was the only case from among the 14 companies contacted. During company recruitment, it was discovered that two of them had ordered or purchased a robot designed to be collaborative; however, they were at the needs analysis stage or were thinking about the integration process, which they were finding particularly complex. This complexity is due, in part, to the difficulty of the risk analysis, which is different from risk analysis for usual machinery, where the worker is safe from hazardous moving parts during production. The difficulty arises because of the specific characteristics of cobots in comparison with regular machinery from a safety standpoint: the complete or partial absence of guards, with the possibility of the worker being injured in the event of a collision. In addition, according to the company, the possibility of injury as a result of a collision generates resistance to change among employees or managers, which further increases the complexity.

The characteristics of the robots used in the case studies are given in Table 7.

Table 7 Robot characteristics

	Collaborative application and associated robot			
	A_1, A_2, A_3	**B**	**C**	**D**
Type of robot	Originally designed as collaborative	Originally designed as collaborative	Conventional converted to collaborative	Originally designed as collaborative
Number of arms	1	2	1	1
Number of axes per arm	6	7	>3 (tool installed on arm adds degrees of freedom)	6
Payload	10 kg	2.3 kg	35,000 kg	3 kg
Reach	R = 1.3 m	R = 1.21 m	L × l ≈ 100 m × 28 m	R = 0.5 m
Max. speed (axis)	180°/s	Unknown	Unknown	360°/s
Max. speed (tool)	1,000 mm/s	1,000 mm/s	1,333 mm/s	1,000 mm/s
Controller	Robot-dedicated	Robot-dedicated	Uses a compatible controller	Robot-dedicated
Safety-related card or module	Card part of original design	Card part of original design	External module	Card part of original design
Safety performance of card or module SRFs	Category 3, PL d (manufacturer's default values)	None	To be determined by integrator	Category 3, PL d (manufacturer's default values)
Access and changes to safety parameters	Password required to authorize changes to safety configuration (e.g., determining of position, speed, force limits). However, no written procedure for this was found			

Table 6 and Table 7 show that collaborative robotics and its applications vary widely. For example, two main cases of robots and their applications can be seen:

- Companies A, B and D: applications in a stationary, limited collaborative space, with robots designed to be collaborative and with small payloads. The presence sensing areas are fixed;
- Company C: an application in a large, mobile collaborative space, with a conventional robot converted to be collaborative and with a very large payload. The presence detection areas are mobile, as the sensors are secured to the moving robotized system.

The robot tasks that are part of their collaboration with workers are summarized in Table 8. The task performed by each robot is called the “main task,” as it represents the brunt of the work that was originally done by the worker.

Table 8 Human-robot collaboration: tasks performed by or planned for robot

Collaborative application and main production task performed by robot			
A_1, A_2, A_3	**B**	**C**	**D**
1. Take the workpiece worked on by the peripheral equipment. 2. Stack it on a pallet. 3. Stop if the workpiece falls, the pallet is full or a collision is detected. Length of production cycle: ≈ 2 h (8 to 12 s to produce each workpiece)	1. Retrieve the moulded workpiece. 2. Stack it in a bin up to maximum capacity. 3. Stop if the workpiece falls, the bin is full or a collision is detected. Length of production cycle: ≈ 2 min	1. Grasp workpiece no. 1 in the tank. 2. Place it in the collecting bin. 3. Move toward the tank. 4. Grasp the material in the tank and put it in the waste (repeat). 5. Move to collect workpiece no. 2. 6. Grasp it. 7. Place it in the tank. 8. Repeat the cycle for the next tank. Length of production cycle: ≈ 45 min	1. Grab the workpieces that are lying in a jumble on a vibration table, thanks to a camera system (task of first robot). 2. Place the workpieces in a predetermined arrangement, according to information supplied by the camera (task of the first robot). 3. Collect the workpieces that are properly arranged and stack them in a container (task of the second robot). 4. Stop when the container is full (case of both robots). Length of production cycle: ≈ 15 min (≈ 5 s per workpiece)

The workers' tasks that are part of their collaboration with the robots are summarized in Table 9. The task performed by the worker is called the "auxiliary task" in the table because it supports the "main task," which is done by the robot.

Table 9 Human-robot collaboration: tasks performed by or planned for worker

Collaborative application and auxiliary production task performed by worker			
A_1, A_2, A_3	**B**	**C**	**D**
• Regularly supervise the smooth operation of the robot. • Realign, on the pallet, the workpieces poorly stacked by the robot. • Retrieve the workpieces the robot has dropped and stack them manually on the pallet. • Reset the robot after a stop. • Change the robot settings when beginning production of a new workpiece. • Remove the pallet using a forklift truck and replace it with an empty pallet.	• Supervise the smooth operation of the robot. • Take away the full bin and replace it with an empty one. • Reset the robot after a stop in the event of a collision or if there are no workpieces.	• Open the cover of the tank for the robot. • Clean up the work area after the robot has performed its tasks. • Close the cover of the tank after the robot has performed its tasks. • Inspect the production process.	• Place a batch of jumbled workpieces on the vibration table. • Collect the containers, once they've been filled. • Check the number of workpieces in the containers. • Check the quality of the workpieces. • Regularly supervise the smooth operation of the robot.

Table 8 and Table 9, along with figures 8 to 11, show that worker-robot collaboration takes the form of complementary tasks and, above all, a shared collaborative workspace. In short, it is essentially human-robot cohabitation rather than true collaboration in which the worker and the robot work simultaneously on the same workpiece during production.

4.3 Pre-Integration Observations

This section on pre-integration of a robot in a collaborative setting focuses on the needs that prompt companies to invest in robots to perform tasks, as well as the content and drawing up of the specifications.

4.3.1 Need to Invest in Robots

Table 10 lists the various factors observed to explain why the companies visited felt the need to invest in robots and particularly cobots: spatial factors (1 company out of 4), visibility (2 out of 4) and economic and human factors (3 out of 4). These families of factors were put together based on the pre-established groupings in section 5 of the data collection form in Appendix D. The "environmental factors" family was changed to "spatial factors" because that was the only type of environmental factor observed. Last, with regard to "other expected benefits," the company's visibility was the sole need and factor indicated.

Table 10 Factors observed to explain investing in robotics, especially cobotics

	Related need	Reason behind need, according to certain companies visited
Economic	Improve productivity to stay competitive	• Product handling by a robot is more reliable. • Robotics is a guarantee of improvement in quality, with automatic traceability of production.
	Reduced labour costs	• The hourly cost of a cobot is reportedly around $5/h, which is less than a worker's hourly wage. • In some cases, a cobot can reduce labour needs by 80%.
	Production management flexibility	• The ease of teach programming for robots designed to be collaborative means that they are flexible for changes to workpieces to be produced or handled. This advantage reduces overall installation and start-up costs. • The fact that robots designed to be collaborative are easy to move increases the range of flexibility for production changes. • The short adjustment times of robots designed to be collaborative.
	Quick return on investment	• Return on investment is around 6 to 8 months, given the low cost of the cobot (< $50,000). • As cobots intrinsically incorporate more safety features than conventional robots, they may, depending on the application, require fewer conventional safeguards (e.g., protective enclosure, interlocking guards with guard locking). For example, one company had not added any safeguards to its collaborative application (case B), whereas another had added only a laser scanner (case A_1).
Human	Improved working and safety conditions for workers	• Robotization has, depending on the case, helped reduce exposure to MSDs (cases $A_1$and D), address the mechanical hazards of using a press (case A_1) or reduce process-related risks (e.g., thermal) (case C). N.B. The risk reduction observed had to do with the elimination or reduction of a worker's time of exposure to the risks associated with his or her old task. However, human-robot collaboration itself gives rise to new risks (e.g., collision).
	Elimination of low-value-added jobs and creation of supervisory or robot-programming jobs	• Some workers have seen their working conditions improve when they moved into higher-value-added jobs supervising the operation of cobots and peripheral machinery. For example, in case A_1, the low-value-added task involved bending and stacking over 500 workpieces per shift.

	Related need	Reason behind need, according to certain companies visited
Spatial	Optimal use of space	• Cramped workspace: Company A opted for cobotics because of the restricted work area it had available. With conventional robotics, it would have had to install a protective enclosure that would have encroached on a traffic lane, making it impassable.
Visibility	Promote the company	• Having a collaborative application is an indication of a company's ability to innovate and stand out from the competition. For company D, a collaborative application is a way of showcasing its technological capability to clients, competitors and the company's other outlets. It's also a means of developing expertise in the area of collaborative robotics. A non-collaborative robotics solution would have been possible and maybe even more cost effective, but company management really wanted to test the potential of collaborative robotics.

The main reasons for choosing a collaborative application, for the cases observed, are the low cost of a cobot compared with that of a conventional robot, the quick return on investment, the elimination of low-value-added tasks, being able to reassign workers to more meaningful tasks, space constraints, raising the company's visibility through the adoption of a new technology and the production flexibility a cobot offers. On the other hand, it is important to ensure that the planned production changes are taken into account when conducting risk assessments. The risk reduction measures to be implemented must protect workers against the riskiest task among the possible production changes.

These reasons, which vary from one company to another, show that the companies we visited also chose cobotics because they had needs other than simply for human-robot interaction. From what we observed, economic factors and OHS play a major role in decisions about such applications.

4.3.2 Specifications

4.3.2.1 Content of Specifications

Three of the four companies did not set out their needs by drawing up formal specifications. The clients defined the minimum specifications for the desired installation orally or in short written messages (e.g., email). They took the following points into consideration to varying degrees prior to integrating the cobotic cell into production. The proportion of companies that considered the point in question is given in parentheses:

- Project goal (4/4)
- Description of application or process to be developed (4/4)
- Robot selection criteria (2/4) – Cost of installation, precision and robot cycle time were considered. In contrast, anthropometry and the operator's new workload were not considered. At companies B and C, the robot was already on site, long before the idea of integrating it, so the choice of robot did not apply in their cases
- Production volume, cycle time, characteristics (weight, dimensions, materials, appearance, etc.) (4/4) – Cycle time is a significant variable in robot projects, for synchronizing other machinery involved in the production process, for determining the robot's minimum speed, etc.

- Number of workpieces to be processed (4/4)
- Peripheral operations upstream and downstream, machines involved in process (4/4)
- Environment in which robot will operate (4/4) – For example, temperature, humidity, available space, electromagnetic interference
- Safety-related specifications (3/4) – At companies A and C, the OHS committee discussed the safety-related specifications. Company D said it would be calling in an OHS consultant to confirm its risk assessment and its current specifications with respect to the standards in force. At company B, the safety-related specifications had to do with the trajectory of the robot's arm. The trajectory should entail the least possible risk for the worker. For this reason, arm movements to the inside and close to the robot's body were preferred. All in all, the client deemed that the presence sensing system of its cobot was sufficient to protect workers. In addition, it judged that the light plastic workpieces handled by the robot were fairly safe.

  It was interesting to note that at companies A, C and D, safety considerations went beyond protecting workers against collisions with the robot. Measures were also taken (cases A_1 and C) or planned (case D) to protect workers against machines near the robot or against aggressive environmental conditions:
  - Company A considered the hazards of the press brake and the workpieces it handled. It reduced them by adding fixed guards and a light curtain. It informed workers about the risks of cuts from the sharp burrs on the workpieces
  - At company C, the safety radius will be determined by a risk analysis that considers the displacement speed of the robot and the range of where the workpiece might be dropped
  - Company D plans to assess the risks associated with the vibration table with a view to taking appropriate risk reduction measures
- Implementation schedule and deadline (4/4)

4.3.2.2 Worker Consultation

At two of the four companies (A and D), the client consulted the worker who would be sharing the robot's operating space. However, the only purpose of the consultation was to explain the integration project to the worker and draw on the worker's knowledge of the task to be automated. Despite the consultation, the worker's involvement during the integration process was neither sustained nor significant. At company C, the employer chose to consult a manager who was well informed about the task to be automated, rather than the worker, for internal reasons. At company B, the client did not consult the worker because it deemed that the installation was not complex.

From the point of view of safety and ergonomics, and according to Marsot *et al.*(2014), the worker concerned should be involved right from the time the specifications are drawn up, regardless of the extent of the anticipated OHS risks. Involving someone else who knows or has an idea about the task to be automated will only partially solve the risk reduction problem. Asking someone else will not reveal all the characteristics of the work activity. Workers are the ones best placed to provide information on the performance of their tasks and the associated constraints. On the basis of these constraints, they will be able to help the integrator choose and confirm the best means of risk reduction. By getting workers involved, the integrator will run less of a risk of hindering the performance of the worker's task by choosing unsuitable means of risk reduction.

4.3.2.3 Interactions with Integrator

At three of the four companies (A, C and D), the integrator was very involved in drawing up the specifications. In two cases, the integrator was also the client, as the idea of investing in cobotics was his, while in the other case, the main client asked the integrator to write up the specifications. At companies A and D, the integrator was involved right from the start of the project. At company C, the integrator became involved part way through the project, when the task had been completely automated and the company realized that a worker would be needed in or near the collaborative workspace.

4.3.2.4 Recommendations Regarding Specifications

The specifications should be drawn up in a formal, structured document that deals with the points mentioned in section 4.3.2.1. This document could be the result of iterative development as the project progresses (Marsot *et al.*, 2014). In addition, it should include consideration of the worker's future task and activity (i.e., when collaborating with the robot) based on the current task (i.e., work activity to be automated). Marsot *et al.* (2014) propose a structured approach of this kind that can be followed by small and medium-sized businesses and give, as an example, a case study documented in Daille-Lefèvre *et al.* (2015). This approach is discussed in section 4.4, after Table 13.

4.4 Integration: Process Observed

The integrator had to meet the requirements of the client mentioned in section 4.3. The approaches to satisfying work environment requirements that were followed by the different integrators are summarized in Table 11. Table 12 provides an overview of the production-related approaches, while Table 13 gives details on the approaches taken to address safety.

Table 11 Steps followed by integrators to meet work environment requirements

Approach observed on site	**Companies concerned**			
Respect cobotic cell location chosen by client (e.g., cramped area beside one or more aisles with traffic; automated solution can be reproduced at other facilities of the company).	A		C	D
Design a robot system that can operate safely in spite of various environmental constraints: weight of forklift trucks, presence of dust or electromagnetic field, temperature, brightness, presence of steam or corrosive gases.	A		C	D

Table 12 Steps followed by integrators to meet production requirements

Approach observed on site	**Companies concerned**			
Find out about the task to automate.	A	B	C	D
Choose robot (by going to robotics trade fairs or by comparing the performances of several models with regard to the intended task). N.B. Companies B and C already had their robots.	A			D
Become familiar with how the robot operates, learn how to program it with the supplier's help.	A		C	D
Choose tool (manipulator) best suited to the task (e.g., company A opted for a tool that behaves like a human hand so that it didn't have to make changes to the adjustment of the existing light curtain). N.B. This stage did not concern company C because its tool was the same one it had been using with a conventional robot.	A	B		D
Find the best way to integrate the robot into the production cycle (e.g., optimize the trajectory, study the two-way communications between the robot and the machines or protective devices with which it has to communicate, opt for two robots instead of one to coordinate with the work cycle required per workpiece).	A	B	C	D
Automate the task or convert the conventional robot into a collaborative one, while achieving, at a minimum, the same level of production as prior to the integration (respect initial cycle time).	A	B	C	D

Table 13 Steps followed by integrators to meet safety requirements

Approach observed on site	Companies concerned			
Use machinery safety standards:				
o CSA Z434-2003	A			
o ISO 12100:2010, ISO 10218-1 and -2:2011, ISO 13849-1:2015 and -2:2012, EN 954-1			C	
o ANSI/RIA R15.06-2012, SISTEMA software				D
Carry out a risk assessment:				
o Identify the risks associated with the robot system – verbally	A			
– through robot operational testing			C	D
– by hiring an outside consultant		B	C	
o Estimate and evaluate risks				
– by hiring an outside consultant		B	C	D
Choose safeguards on the basis of preceding point and other types of constraints	A		C	D
Estimate the performance level required for the safety functions related to certain safeguards			C	D
Choose appropriate safeguards according to:				
o Performance level required			C	D
o Category desired	A		C	
Test safeguards on a test setup (outside of the cobotic cell)			C	D
Install safeguards by connecting them to either the robot or the peripheral equipment, as appropriate	A		C	
Test the safeguards in the work environment, make adjustments as needed	A		C	
Verify the operation of the safeguards:				
o by conducting error tests (≈10 times)	A			
o as the installation changes during the integration process			C	

The preceding tables show that the integration processes varied from one company to another. While the robots designed to be collaborative that were seen in the field were compliant with the standards discussed in Chapter 3 (based on ISO 10218-1:2011), it was noted that not all the integration-related safety requirements described in section 5.11 of standard ISO 10218-2:2011 were taken into account, especially with respect to risk assessment. Key points, such as the determination of machine limits (other than those related to production), risk estimation and risk evaluation, were sometimes not covered in the integration method; nor was the verification of safeguards to ensure they adequately reduce risks. This verification is essential to prevent accidents (e.g., injury caused by a blow to the head) and occupational diseases (e.g., shifting of MSDs to another part of the body). This prevention effort should help avoid the costs associated with occupational injuries, such as changes in a worker's quality of life, a victim's medical fees and losses in productivity. In a number of the companies visited, the analysis process was not documented in accordance with the requirements set out in section 7 of standard ISO 12100:2010. Last, in three out of the four companies, taking safety into account in the integration process was not a priority in relation to production requirements. There would therefore seem to be a need to clarify what an approach to integration that includes safety should be.

Risk prevention should be included earlier in the integration process. Requirements relating to production, the environment and safety are actually interdependent. They must all be considered together at the design stage. For instance, at company D, the cramped robot installation area, located at the intersection of two busy aisles, had an influence on the distance at which a person had to be detected (short distance). In turn, this relatively short distance meant that the speed of the robot during production had to be reduced in order to guarantee a monitored stop in time if the light curtain were breached. That speed likely had to be slower than what the client originally wanted in order to optimize production. Moreover, a light curtain was chosen instead of a pressure-sensitive mat because the mat could not withstand having forklift trucks run over it repeatedly. This shows that a client's full range of requirements has an influence on the safeguards to be implemented. All the requirements should therefore be incorporated into the decision-making process as early as possible.

It would have been easier to implement all these requirements if, right from the outset, the specifications had been drawn up on the basis of an open, constructive dialogue involving the client, the integrator and the workers concerned by the installation, in accordance with the concept of "integrated prevention" explained in Marsot *et al.* (2014). These authors propose a functional analysis of needs that includes the safety aspect of the future use of the installation. This approach involves establishing the functions of the system to be designed. For each required function planned, the parties involved discuss the reason for it, the impact on the process, the people involved in the process, the way the function will operate (e.g., process, operating mode, necessary tools), the work environment in which the function will operate, and the time and frequency of performance. For each of these aspects, prevention is taken into account by matching up the potential occupational health and safety risks for workers with the means to address them, based on similar cases. The risk assessment must consider the entire collaborative production task, as well as the associated work environment (section 5.11.2 of standard ISO 10218-2:2011). While primarily machine-design oriented, this approach is transposable to the integration of a new workstation based on human-robot collaboration.

The company's OHS committee (e.g., company A) can play a significant role in this, as risk assessment is a consensus-based process. Still, the chief party concerned, the worker who will be interacting with the robot, has been excluded. In companies B and D, the integrator had an outside consultant do the risk assessment. In company C, the integrator was a consultant and he was also tasked with the actual risk assessment. The integrators interviewed said that designing the cobotic cell in its future work situation is hard to do, especially when it comes to analysing robot-related risks and there is a possibility of physical contact with a human.

Last, the involvement of workers in the risk assessment process was generally very minor or non-existent. Yet workers are the ones whose workstations are being altered, who are the most knowledgeable about the main task to be automated and who will work alongside or interact with the robot while being exposed to the risks. So to achieve optimum results, it is essential to have workers participate actively in the integration process. Sections 4.3.1 and 4.3.3 of technical specification ISO/TS 15066:2016 make the same point.

These observations underscore the need to equip companies to carry out risk assessments that incorporate analysis of a worker's activity so that appropriate decisions to minimize cobotic cell risks can be made. From this perspective, tools such as guides for safe implementation of a cobotic cell or reference material presenting case studies in greater detail than that in Chapter 3 may provide examples for companies to follow.

4.5 Integration: Problems Encountered

The safety-related problems encountered were primarily experienced by the integrator. These problems were chiefly technical in nature. Those that concerned clients mainly had to do with sticking to schedules and budgets. Some problems had already been solved by the integrator by the time we visited (Table 14). Others were being studied (Table 15).

Table 14 Problems solved in field by integrators

Safety-related problem solved	**Company concerned**
Have the programming code and understand it so as to be able to reduce the speed of the robot in the event of an intrusion. The integrator got help from the manufacturer. Save the worker from having to reposition the robot several times a day, whenever there's a production change, to reduce the risk of MSDs. To do so, the client and the integrator installed a rail that automatically adjusts the position of the robot according to the type of workpiece to be produced.	A
Be creative to find the safest, most productive trajectory.	B
Detect an intrusion despite an aggressive operating environment by using a colour recognition camera system to detect specific colours and materials. This discovery took at least a year's worth of technological testing under various environmental constraints.	C

Table 15 Problems currently faced or foreseen in field by integrators

Safety-related problem currently faced or foreseen in implementing collaborative operating mode 3 or 4	Company concerned
Regarding mode 3, choice of optimum combination (compromise between safety and security) of safeguards to cover areas not currently covered. Manage resistance to change to complete project on time. Problem deciding on adequate safety distance between robot tool and worker, as well as the acceptable stopping time.	C
Regarding mode 3, problem programming speed change (from production speed to reduced speed) due to: o limited space that imposes a short stopping distance and therefore a reduced production speed o reduced speed that affects company productivity o choice of speed thresholds Regarding mode 4, problem choosing force limit values.	D

According to the observations (Table 15), mode 3 with a set separation distance would seem hard to implement properly. Technical specification ISO/TS 15066:2016 provides precise details on the complex calculations associated with it. As mentioned in Chapter 3, the stopping time and the speed reduction time must not be limited to robot response time, but should also include the reaction time associated with each component added to the stop function chain. Research that facilitates the understanding of these calculations would be of benefit to integrators. It would help clarify the aspects of the technical specifications that should be taken into consideration.

4.6 Integration: Risk Reduction Measures Chosen

According to standard ISO 12100:2010, risk reduction follows risk assessment. Although no proper risk assessments had been done at companies A, B, C or D at the time of the visits, risk reduction measures had been chosen by the integrators and clients at these companies. Overall, the measures included safeguards for implementing collaborative operating modes, working training and management of the configuration settings for the robot and cybersecurity.

4.6.1 Collaborative Operating Modes

As noted in the theoretical example of Chapter 3, a mode or combination of modes was used depending on the company's production needs and worker safety concerns. Mode 2, "Hand guiding," was not used in any of the observed cases. This may be explained by the fact that (1) this mode is suited to cases where worker dexterity and know-how cannot be replicated completely by a robot because the worker's task is too complex to automate fully; (2) this mode is useful when direct interaction between a human and the moving robot is required during production. In the case studies observed in the field, the worker's initial main task could be fully automated, as it was essentially a low-value-added task. Furthermore, as mentioned earlier, in the companies visited human-robot collaboration was chosen for reasons other than a need for direct interaction with the moving robot during production.

As the visits took place before the publication of technical specification ISO/TS 15066:2016, the analysis of the safeguards used to implement the collaborative operating modes observed was based on the standard in force at the time of the integration process, i.e., ISO 10218:2011, parts 1 and 2. However, a few comments regarding technical specification ISO/TS 15066:2016 were made. For instance, the description of mode 3 in standard ISO 10218-1:2011 and its implementation in standard ISO 10218-2:2011 do not prescribe any safety-rated monitored stop (i.e., mode 1), whereas technical specification ISO/TS 15066:2016 includes it (Figure 12).

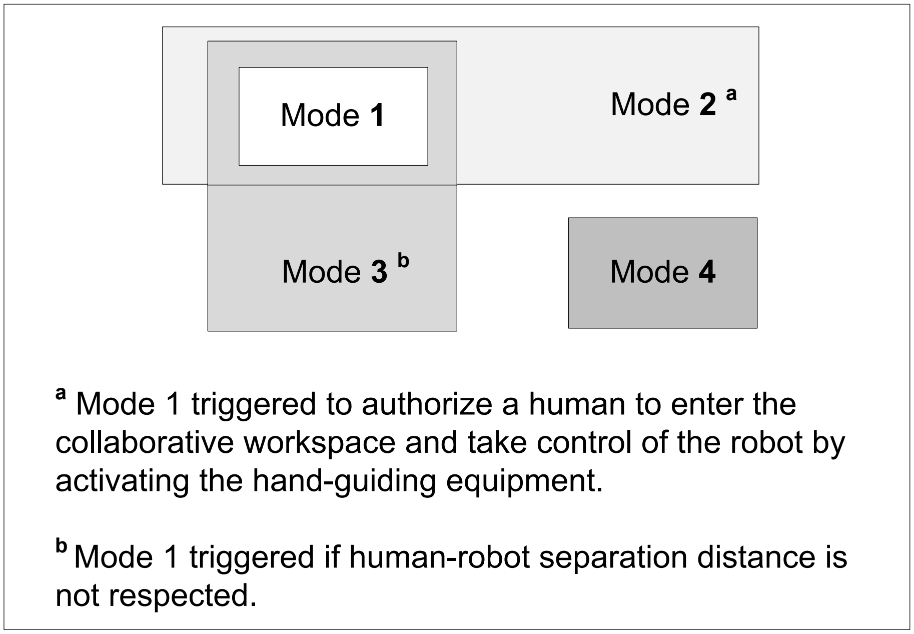


Figure 12 Collaborative operating modes and systematic combinations prescribed under technical specification ISO/TS 15066:2016

The collaborative operating modes chosen by the companies visited are indicated in detail in Table 16. The modes are as follows:

- Mode 1: safety-rated monitored stop
- Mode 3: speed and separation monitoring
- Mode 4: Power and force limiting by inherent design or control

Table 16 Collaborative operating modes used, planned or in testing in companies visited

Mode	Case studied	Safeguard for implementing mode	Original safeguard	Added safeguard
1	C (in testing)	Robot stopped if intrusion into safety area. Automatic restart as soon as person leaves safety area and warning area. Any intrusion is detected by a combination of safety laser scanners and colour detection cameras. Addition of a safety-related programmable logic controller (PLC) that manages the implementation of safety functions.	✗	✓
	D (planned)	Safety light curtain that triggers a monitored stop if it is breached.	✗	✓
3*	A_1, A_2, A_3 (used)	Two laser scanners installed at a fixed separation distance in relation to the robot. Each detects the intrusion, which triggers the reduced speed. In case A_1, it is set at 25% of the production speed of 1,000 mm/s. In cases A_2 and A_3, it is set at 50% of the production speed, which is already low, but actual value is not known. Boundaries drawn on the ground to delimit collaborative workspace.	✗	✓
	C (in testing)	Issue a warning and trigger a reduced speed in the event of an intrusion into the warning area. This warning area corresponds to a given separation distance in relation to the robot tool. An intrusion is detected by a combination of four detection cameras and six safety laser scanners. Addition of a safety-related PLC that manages the implementation of safety functions. The final level of the reduced speed remains to be determined.	✗	✓
	D (planned)	Laser scanner installed at a fixed separation distance in relation to the robot. It detects an intrusion, which triggers the reduced speed (actual level to be determined according to calculations of stopping time and stopping distance).	✗	✓
4	A_1, A_2, A_3 (used)	Force limiting, with force thresholds set by integrator.	✓	✗
	B (used)	Force limiting through use of springs at joints.	✓	✗
	D	Force limiting, with force thresholds to be set by integrator.	✓	✗

Mode	Case studied	Safeguard for implementing mode	Original safeguard	Added safeguard
	(in testing)			

✓: yes; ×: no

*In companies using mode 3, the problem of controlling the separation distance between the worker and the robot is solved by freezing it in advance through the fixed placement of a presence sensing device. Controlling the speed consists in changing the speed once a presence is detected (shifting down from production speed to reduced speed).

The companies (C and D) using mode 1 chose to do so to prevent collisions between the robot and the worker. At companies A and C, mode 3 was used to control the collaborative workspace and ensure the safety of the people in the space. At company D, although the client acknowledged that mode 3 makes the space around the robot safer, the mode was primarily chosen in order to minimize deterioration of the robot's brakes from repeated stops, thanks to the reduced speed. At company A, the speed value was determined according to the integrator's visual impression. For cases C and D, the final reduced speed values will be determined based on a risk assessment and testing. The reaction time of the protective devices and the safety distance were the decisive factors in the choice of safeguards for modes 1 and 3 at companies C and D. In the case of company A, the integrator proceeded by process of elimination: choose a reasonably priced device (so 3D scanners were excluded) that could be installed easily (so horizontal light curtains were excluded) and that could withstand forklift traffic (so pressure-sensitive mats were excluded). Mode 4 was used when it was an intrinsic part of the physical characteristics of the robot or its servo-control (i.e., control system for following an instruction). When this mode was implemented by means of a servo-control system, the integrator had to set the acceptable physical impact force limit for humans.

4.6.2 Considerations Regarding Integration of Safeguards

4.6.2.1 Use of Concepts from Collaborative Robotics Standards

In Division XXI of Quebec's ROHS dealing with machines, there is no reference to a Canadian, European or international standard on machine safety. Furthermore, the terms "robot" and "cobot" do not appear in the regulation. Companies therefore find themselves facing a regulatory vacuum when they want to use a cobot, as the concept of a shared workspace is unknown in Quebec legislation. Nevertheless, standards do exist that provide integrators with guidelines to follow in robotics and, more specifically, cobotics.

Half of the integrators surveyed did not design their implementation by applying a collaborative operating mode logic, as presented in the standards on cobotics. Companies A and B instead analysed the desired application, and then chose their safeguards based on their needs. These safeguards consisted in presence sensing devices and the robot's intrinsic ability to stop in the event of a collision. The integrators in these two companies first learned of the existence of collaborative operating modes when they met the research team. At the same time, they also found out about concepts such as "performance level (PL)" (ISO 13849-1:2015) and "safety integrity level (SIL)" (IEC 62061:2005). These are essential concepts for meeting the performance requirement common to the four modes of collaborative operation: have PL d, category 3, safety functions (see section 5.4.2 of standard ISO 10218-1:2011). It is worth noting, however, that the standard allows other performance criteria for the control system, provided that:

> *The results of a comprehensive risk assessment performed on the robot and its intended application may determine that a safety-related control system performance other than stated in 5.4.2* [i.e., PL d, category 3] *is warranted for the application.*
>
> *Selection of one of these other safety-related performance criteria shall be specifically identified, and appropriate limitations and warnings shall be included in the information for use provided with the affected equipment* (ISO 10218-1:2011).

In contrast, at company A, the integrator was aware of the concept of category. Exceptionally, the cobot of company B did not meet the performance level required under standard ISO 10218-1:2011. Despite that, the robot was sold and used as a cobot. That would appear to be due to the fact that the physical characteristics of this robot intrinsically limit its impact force, as well as its speed (its motors are not very powerful). It has rounded edges and corners and shock absorbers at the joints. An advantage of this cobot is its ability to communicate visually with the worker, which means that the worker can anticipate its movements more easily.

At companies C and D, the integrators knew the standards in force respecting collaborative robotics and safety-related control systems. As a result, they were able to follow a systematic approach that optimized the integration process. They began by thinking about the collaborative operating mode to be implemented and then chose the appropriate safeguards for this mode. By opting for a given mode, the minimum safety requirements to be met to protect workers who enter the collaborative workspace are already established. The next step is to choose the safeguards to meet those requirements. Unlike at companies C and D, companies A and B took an intuitive approach.

4.6.2.2 Reliability of Safety-Related Control Systems

At company C, the simplified method of standard ISO 13849-1:2015 could not be applied, as not all the protective devices are “safety” devices: the laser scanners are, but not the cameras. To get around this problem, the integrator applied the fundamental principles of standard ISO 13849-1:2015 drawn from obsolete standard EN 954: 100% of the principles of EN 954 and 80% of the principles of standard ISO 13849-1 were followed, according to the integrator. For example, the default modes of the different devices were studied and tested over an extensive period. The integrator dealt with the environmental aggressors (e.g., dust, electromagnetic fields). As the risk is very high, various kinds of redundant protective devices (six laser scanners and four detection cameras) are part of the plan to guarantee detection of a human presence, in spite of the aggressive and changing environment. Nevertheless, the integrator will have to find a good balance between reliability and safety because, as the number of components increases, the overall reliability of the system declines.

At company D, the risk estimation led the integrator to a required performance level of PL_r e (n.b., the robot was acquired before the risk estimation was done). According to the integrator, this justified the purchase of a PL e laser scanner. It is important to remember, however, that the processing part of the robot’s safety functions is of type PL d, category 3. According to the principle of combining the safety-related parts of control systems (Table 11 of standard ISO 13849-1:2015), it is impossible to achieve an overall performance level of PL e if one of the components has a lower PL. In the case of company D, human-robot collaboration should be avoided, unless the company changes its performance level target in the event that the risk has been overestimated. Otherwise, the robot that was originally designed to be collaborative should be used as a conventional robot, i.e., inside a protective enclosure.

This observation underscores, first of all, the importance of estimating the risk of the future activity before acquiring a so-called collaborative robot in order to make sure, before the acquisition, that it does indeed meet safety needs. At the same time, it also underlines the fact that robots designed to be collaborative are not systematically used without supplementary guards or protective devices. However, the plug-and-play label given to so-called collaborative robots suggests that their integration is quick and easy and does not require any safeguards, which is not always the case. The assessment of installation-related risks (i.e., the robot, nearby equipment that could impact an active worker's safety, the constraints the worker must operate under) will dictate whether the robot can be used in collaboration with a worker. Once again, a risk assessment, including an analysis of the worker's activity, is recommended in this kind of situation. Last, the use of SISTEMA software (IFA, 2016), as company D is doing to design its safety functions, makes the task easier. Still, knowledge of the standards on which the software is based (ISO 13849-1 and 2) is essential in order to use it properly and interpret the results correctly.

4.6.2.3 Management of Human-Robot Collisions (Mode 4)

Company D wants to use mode 4 as a supplementary safeguard. It intends to base itself on the nomogram of technical specification ISO/TS 15066:2016 to adjust the cobot's threshold force values. This implementation and the required adjustments will have to be done in a very rigorous fashion, as technical specification ISO/TS 15066:2016 notes, in its introduction, that collaborative operation is a developing field, and the values indicated in the TS are expected to evolve in future editions.

It is recommended that the values chosen for the collaborative application be discussed with an ergonomist and with the workers. Technical specification ISO/TS 15066:2016 acknowledges the benefits of the input of ergonomics (e.g., improvement in worker posture) in facilities where human beings and robots collaborate. Ergonomics also has the advantage of studying the entire work activity in which the worker is involved at the workstation with a view to making further improvements, such as choosing the appropriate speed of production to reduce the worker's mental workload, increasing the worker's manoeuvring room, and choosing the positioning of the robot so as to prevent any possible contact with the worker's head. The permissible force values given in Annex A of technical specification ISO/TS 15066:2016 exclude the head. In some of the companies visited, however, the robot was moving at the height of the worker's head. Furthermore, it would seem very difficult for an integrator to guarantee that a worker will never bend over, for whatever reason, and put his or her head in the robot's range of motion.

In addition, if using mode 4, it is essential to make sure the robot can stop, whatever its speed and position. That seems difficult for some manufacturers of robots designed to be collaborative, as their robots, which are being used at companies A and D, only detected collisions at low speed.

4.6.2.4 Other Means of Risk Reduction

Personal safety equipment

In addition to the safeguards associated with the collaborative operating modes, personal protective equipment (PPE) was worn by workers, at the employers' request: safety goggles, hearing protection, safety footwear. The PPE worn by workers sharing the robot's workspace was identical to the equipment they wore before the cobotic installation. The use of a cobot in the company's facilities therefore did not result in any changes in the wearing of PPE.

Stop and emergency stop

An emergency stop button is also available for stopping the robot if something happens. However, pressing the button does not stop hazardous nearby equipment, such as the press brake of case A_1. As stated in section 193 of Quebec's Regulation respecting occupational health and safety (ROHS), it is important that:

> *Any stopping device or switch for a machine belonging to a group of machines that are wired to operate in series, including an emergency shut-off switch, shall in addition be designed to stop serial upstream and downstream machines if their operations constitute a danger for worker safety* (Gouvernement du Québec, 2016).

One accident already occurred (EPICEA,[3] file 14546) in which a worker working on a conventional robot to recover moulded workpieces was injured by the robot when it started up unexpectedly. The opening of the guard gates caused a safe shutdown of the injection moulding machine, but not of the robot. The reverse situation is quite conceivable, too, in the case of installations where the stop control of a collaborative robot causes it to shut down, but does not shut down adjacent machinery.

Integrators can consult standard ISO 13850:2015 to find out and apply the standard design principles for an emergency stop function.

Staff training

At company A, the integrator provided the worker with practical training on the new task. Training was also given to maintenance and adjustment staff.

At companies B and D, there are plans for the integrator to train workers so they can quickly take charge of the cobotic installation.

At company C, the decision to train the worker once the integration has been completed is being reconsidered. At the moment, the client feels that there will be little impact on the worker's task. Nevertheless, the research team is of the opinion that workers should be informed about how the presence sensing system operates, so that they know when and where they can work safely in the collaborative workspace.

Ultimately, everyone with a connection to the cobotic cell should be informed about the operation of the installation and the associated risks. Workers who collaborate with the robot should be given practical training on their new workstation.

[3] http://www.inrs.fr/publications/bdd/epicea.html

Management of safety and other program parameters

Management of the values of the various parameters of the cobot program (both operational and safety-related) is crucial in preventing accidental or inappropriate changes. Examples of safety parameters are speed, force and Cartesian coordinate limit values that must not be exceeded. Section 5.4.2 of technical specification ISO/TS 15066:2016 states that safety parameters must be protected against unauthorized and unintentional changes by password protection or similar security measures. Under standard ISO 10218-1:2011, only authorized personnel are allowed to make changes to control systems that use safety-rated soft limits (see Glossary). In addition, any change must be protected and secured by requiring a password to be entered.

Company C is going to put an organizational management plan in place to provide a framework for computer security, including management of passwords, access and changes to PLC programs (e.g., security bypass procedure). At company D, only the integrator is allowed to manage the values of the safety configuration parameters. He accesses the parameters by means of a password that only he knows (there are no plans so far to implement a password for the program in general). These are two examples of best practices to be applied. Note that at least two serious or fatal accidents have occurred in Quebec when automated machinery program changes were made (CNESST, 2002; CNESST, 2004). A software life cycle management plan is therefore needed (IEC 61508-3 2010), as well as a change management plan (CAN/CSA C22.2 No. 0.8-12, 2012).

Note that the possibility of setting a robot's parameters and controlling it remotely was seen in the applications of companies B (handled workpiece gripping and placing speed) and C (for purposes of unjamming, remote operation from a control room). These situations require particularly rigorous management of the conditions of access to safety-related parameters (e.g., cobot travel speed).

4.7 Post-Integration Observations

4.7.1 Documentation Resulting from Integration

Once the robot has been integrated, instructions for the cobotic cell must be written (see section 7.2 of standard ISO 10218-2:2011). The instruction handbook must be made available to workers and other staff members concerned, especially new employees, in order to ensure everyone is given the same thorough training. Similarly, the technical documentation must be kept up to date and together in the same place known to all these people, in order to minimize the possibility of mistakes when the cobotic cell is repaired or its automated or computer system is updated. These practices, which did not exist at companies A and B, were already in place at company D for other machinery. This company was planning to apply the same practices to its cobotic cell.

4.7.2 Company Assessment

At the time of our observations, only company A had cobotic cells that were in operation. At that company, the client's objectives in terms of the economic, human, environmental and other factors that justified its decision in favour of cobotics were achieved. At company B, it will be up to their client (see Table 6) to determine whether the objectives associated with these factors are met. As for company C, the client could already see the productivity gains from its installation, even though it was still in the testing stage. At company D, it was still too early to make an assessment of the installation in progress. Nevertheless, companies C and D, where the integration process had not yet been completed, could still foresee the benefits of cobotics.

4.7.3 Type of Interaction with Worker

The collaboration observed or anticipated in the companies visited came down essentially to sharing the same workspace, during full production, in order to supervise the operation of the robot, manage incidents, check production quality, collect a batch of workpieces produced or to clean. The advantages and disadvantages for the worker with regard to these collaborative facilities, according to the participants, are set out in detail in Table 17 and Table 18. The incidents that have occurred in the companies visited and that we were told about are described in Table 19.

Table 17 Positive impacts of cobotics according to participants

Positive impact for worker	**Company**			
Less of a physical workload and reduced risk of MSDs, as most of the handling is done by the robot	A	B		D
No mental workload related to anticipating the robot's movements, as the worker only spends short times in the collaborative workspace	A			
Reduced risks related to the process or to machinery near the robot (e.g., in case A_1, the worker now spends about 1 h near the machine, as opposed to 8 h formerly)	A		C	
Intuitive interaction during collaboration		B		
New task is more interesting and rewarding than the old one	A		C	D
Greater latitude in activities, as operator no longer required to be present continually, in contrast with former task	A			

Table 18 Negative impacts of cobotics according to participants

Negative impact for worker	Company			
Risk of getting caught between the tool and the arm of the robot, or between the robot and a fixed wall				D
Risk of getting pinched by the tool of the robot or between the robot's joints		B		
Risk of getting cut by burrs on workpiece	A			
Risk of impact (collision) with cobot or workpiece	A	B	C	D
Anxiety about workpiece being handled, as its movement is hard to anticipate	A	B		
Mental workload: monitoring hard to manage when more than one robot malfunctions simultaneously	A			
Need to develop new strategies to prevent collisions. For instance, always face the robot and keep it in your field of vision, no matter what activity is in progress in the collaborative workspace	A			
Awkward posture: • Having to bend under the robot when checking workpiece quality or retrieving workpieces produced	A			
• During robot teaching, as the robot arm to be handled is positioned at height. The teaching takes approximately 5 min.	B			

Table 19 Incidents in companies visited

Incident	Cause	Possible improvement	Company
Repeated breakdown of motors at joints even though payload limit not exceeded	The torque acting cyclically on the joints causes the motor to break down. This torque is created by the size and weight of the tool and the moving workpiece handled by the robot	Be sure to consider this factor when choosing the tool and the robot. Choose what is mechanically the least demanding trajectory. Ask the manufacturer to make the motors more robust	A
Being taken by surprise by the robot	Oscillations of the robot arm due to a servo-motor control problem	Ask manufacturer to correct the servo-motor control problem	B

Overall, the workers we met gave a favourable assessment of their cobotic installation, especially because their physical workload had been reduced. The change was also an opportunity for them to perform a less monotonous, more rewarding job than their old one (e.g., become the robot's supervisor). Faced with the new working conditions created by cobotics (i.e., the complete or partial lack of guards), the workers overcame their anxiety by testing the stopping of the robot in collisions. Last, their fears were more related to the objects handled by the robot (e.g., sheet metal) than to the robot itself. When assessing risk associated with tasks in the cobotic cell, it is therefore important to consider hazards related to the workpieces the robot will handle and to the robot's tools. For instance, a knife handled by a robot is a hazard that must be taken into account when assessing the acceptability of risk in a context of human-robot collaboration. The risks indicated in Table 18 were confirmed using facilities already in operation or during the testing phase. As for Table 19, possibilities for improvement are suggested to address the causes of incidents that have already occurred.

As the implementation of collaborative robot systems is still in its early stages in the companies visited, it would be interesting to do a follow-up at these same companies in a few years. With follow-up—and the benefit of hindsight— incidents, risks and the benefits of this technology for workers could be documented. Furthermore, as there was no sustained worker involvement in either the needs specification process or the integration process, it would be interesting to see whether risks not documented by either the client or the integrator, owing to a lack of regular consultations with workers, had repercussions on the operation of the cobotic cell.

5. CONCLUSION

This exploratory research project consisted of two parts: (1) a theoretical part on three robots intended for human collaboration, and (2) a field part conducted in four companies in Quebec.

The theoretical part involved selecting three robots, each made by a different manufacturer, in order to study the safety-related functions they propose for the implementation of collaborative robotic cells. In classifying the functions, it was found that most of them fall into two categories: stop functions and monitoring functions. Although the safety-related functions from different manufacturers have similarities, there are a number of technical differences between them. Table 5, for instance, shows, for function F5, that following a protective stop, the robot will be reset either automatically or by means of an external reset, depending on the manufacturer. These technical differences can have an impact on safety. Vigilance is therefore required on the part of the integrator when choosing and implementing these functions. Furthermore, it is important to remember that the implementation of a safety function may require the use of external devices, as well as combining several safety-related functions found on safety-related electronic cards or modules.

The availability of safety-related cards or modules that can be integrated into conventional robots to make them collaborative has given rise to a transitional period. As these cards or modules are a lot cheaper to buy than an actual collaborative robot, it is hardly surprising that users of conventional robots are tempted to convert them into collaborative machines. In cases like this, integrators have to be especially careful, as they must choose the most appropriate reduced speed and force levels to address the risks of conventional robots, which are inherently more powerful.

The field study revealed that a range of factors influence the choices that must be made for a collaborative application. Given the small sample size for the analysis (four companies), other companies should be surveyed and a review of the literature should be conducted to produce an exhaustive inventory of these factors. Such an inventory would be useful in developing a tool to help users and integrators choose the type of robot that will safely meet their needs. As no such tool currently exists, here are some of the points they should consider before undertaking a robot integration project: the required performance level (PL_r) for the robot’s safety functions in order to reduce the risks associated with collaboration (the PL_r will be suggested by the analysis of risks), the cost, the precision required to perform the task and meet the quality standards, the payload (weight of the tool required for the task combined with the weight of the workpiece being handled), the need to reduce physical constraints, spatial constraints, the company’s need to raise its visibility and reputation with its clients and competitors, and the possibility of completely or partially automating the worker’s main task. Last, the degree to which it will be possible to automate the worker’s task in the future installation will guide the choice of collaborative operating modes required.

As the case of company C showed, observed modes 1 and 3 cannot always be implemented with safety functions of known reliability that can be calculated using the simplified method of standard ISO 13849-1:2015. Reliability can be easily estimated only if all the detection devices used are “safety devices,” in other words, no vision or other devices of unknown reliability (e.g., cameras, Kinect devices). As for the other mode observed in the field, mode 4, caution must be taken in using it, as technical specification ISO/TS 15066:2016 that suggests limit values has only just been published and is still subject to change. Furthermore, the document is a technical specification and not a standard. Ideally, the risk of collision should be regarded as a residual risk that, in some cases, can be covered by mode 4. When assessing risks, integrators can use technical specification ISO/TS 15066:2016 as a guide to suitable limit values. As the technical specification suggests, it is a good idea to consult an ergonomist to confirm the chosen limit values, while still complying with all Quebec OHS laws and regulations.

This study highlighted the following needs in the field:

- The need to assess the risks associated with a cobotic installation;
- The validity of involving the worker whose task is to be automated in the needs determination and integration process for this type of installation;
- The optimum choice of presence sensing devices for implementing collaborative operating modes 1 or 3, in a context where environmental constraints represent an overriding factor in the selection of such devices;
- The appropriate choice of limit values for collaborative operating mode 4. Technical specification ISO/TS 15066:2016 notes that the limit values it suggests are subject to change. This means that research needs to be conducted to question those values, depending on the specific work situation, or could go so far as to propose safety values for specific contexts. In this case, a biomechanics specialist should be consulted;
- Practical comparison of the technical performance of different robots, to provide a concrete illustration of how the implementation of a mode can vary from one robot to another. This will provide better knowledge of the technical limits to implementing a given mode on certain robots. This last research suggestion can be regarded as a practical version of the theoretical considerations presented in Chapter 3 of this report.

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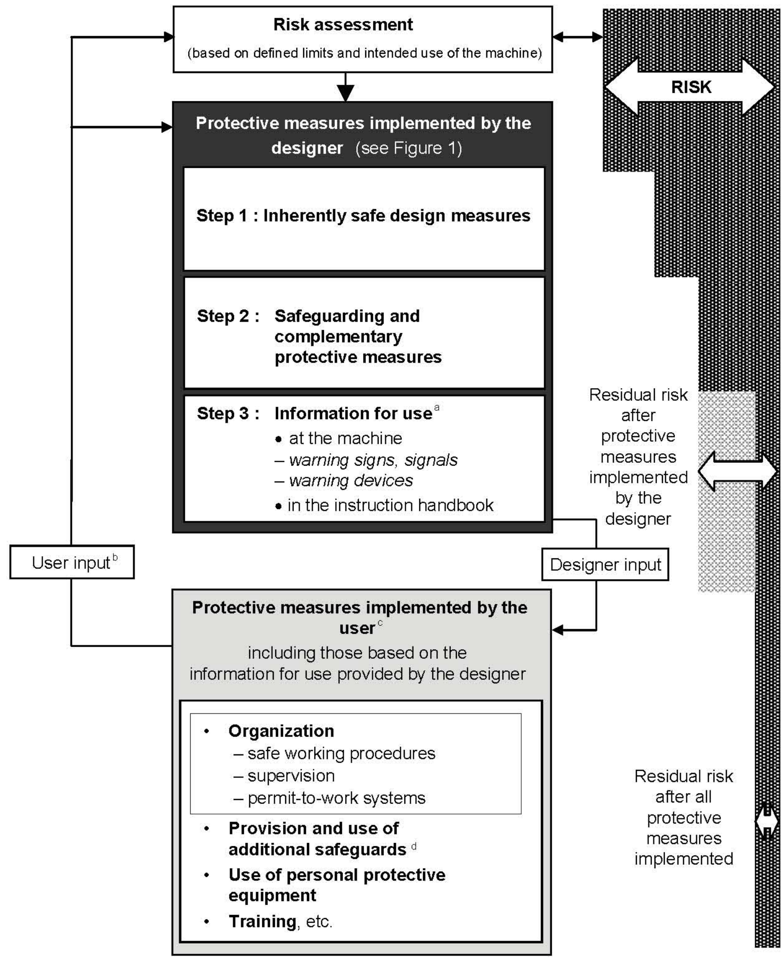
APPENDIX A – RISK REDUCTION PROCESS

ISO 12100:2010(E)



[a] Providing proper information for use is part of the designer's contribution to risk reduction, but the protective measures concerned are only effective when implemented by the user.

[b] The user input is that information received by the designer from either the user community, regarding the intended use of the machine in general, or from a specific user.

[c] There is no hierarchy between the various protective measures implemented by the user. These protective measures are outside the scope of this International Standard.

[d] These are protective measures required due to a specific process or processes not envisaged in the intended use of the machine or to specific conditions for installation that cannot be controlled by the designer.

Figure 2 — Risk reduction process from point of view of designer

 11

Figure 13 Risk reduction process from point of view of designer (ISO 12100:2010)[1]

1. Permission to use excerpts from standard ISO 12100:2010 was granted by the Standards Council of Canada (SCC). No further reproduction is permitted without the prior written permission of the SCC.

APPENDIX B – EXAMPLES OF ANALYSIS TABLES FOR IDENTIFICATION AND TECHNICAL SPECIFICATIONS, BY SAFETY FUNCTION

Table 20 Identification of protective stop function

Safety action: Robot ceases all movement and program execution is paused **Hazardous parts:** Robot and its tool **Safety action trigger:** Detection by a protective device (pressure-sensitive mat, light curtain, etc.) that complies with standard *ISO 13849-1:2015* and that does not reduce either the category 3 or the PL d of the protective stop function **SF validity condition:** Valid throughout the operating mode

Table 21 Specifications of protective stop function

SF initiation conditions	Can be initiated for any operating mode. Cannot be initiated when an emergency stop function has been initiated
SF interface	**Inputs:** Power supply terminals of protective device. The protective device must be added to the collaborative robotic cell **Processing:** Safety-related electronic card **Outputs:** Joint motors and brakes
SF description	Controlled stop of robot + control (monitoring) of its stop position + robot left powered up. Program execution is paused. Once the protective device ceases detecting a presence, the robot starts up again automatically, if there's no reset button, or can be restarted manually by pressing the reset button
Priority in relation to other simultaneous functions	Priority over standard functions and other safety functions, except emergency stop and except category 0 stop, because if there's an anomaly in the protective stop input or output signal (button or system), then a category 0 stop is triggered
Interaction with other SFs	Support function: Control of protective stop
Other SFs acting on same hazardous parts	All the SFs implemented on the robot
Maximum SF reaction time	524 ms
Frequency of SF operation	From every cycle to infrequent
Restart conditions	Reset signal detected: – automatic (automatic restart), or – manual (reset button must be pressed)

Performance criteria	**PL d** (ISO 13849-1:2006) N.B. On condition the components added to implement this safety function allow this PL to be maintained, in compliance with Table 11 of standard ISO 13849-1:2015
Software specifics + settings	Associated inputs/outputs, to be configured through user interface. When a joint is at rest after the triggering of a protective stop, its speed must remain below a certain threshold, in rad/s. The joint is monitored to prevent anything larger than a determined deviation (in rad) in relation to the position it occupied at the time the speed was measured below that threshold. Any violation detected with respect to these criteria triggers a category 0 stop
Other specifications	**Category 2 stop**
Elements that can generate errors – Watch points	N/A

N/A: Not applicable

APPENDIX C – PROVISIONAL TIME CHARTS FOR EACH CATEGORY (TYPE) OF STOP

Figures 14 to 16 illustrate the definitions of stop categories 0, 1 and 2 given in the glossary of this report. The three charts are taken from Baudoin and Bello (2015) on the design of servo-driven presses. As for these presses, the speed of a robot's joint motors behaves in the same way, depending on whether the stop is category 0, 1 or 2.

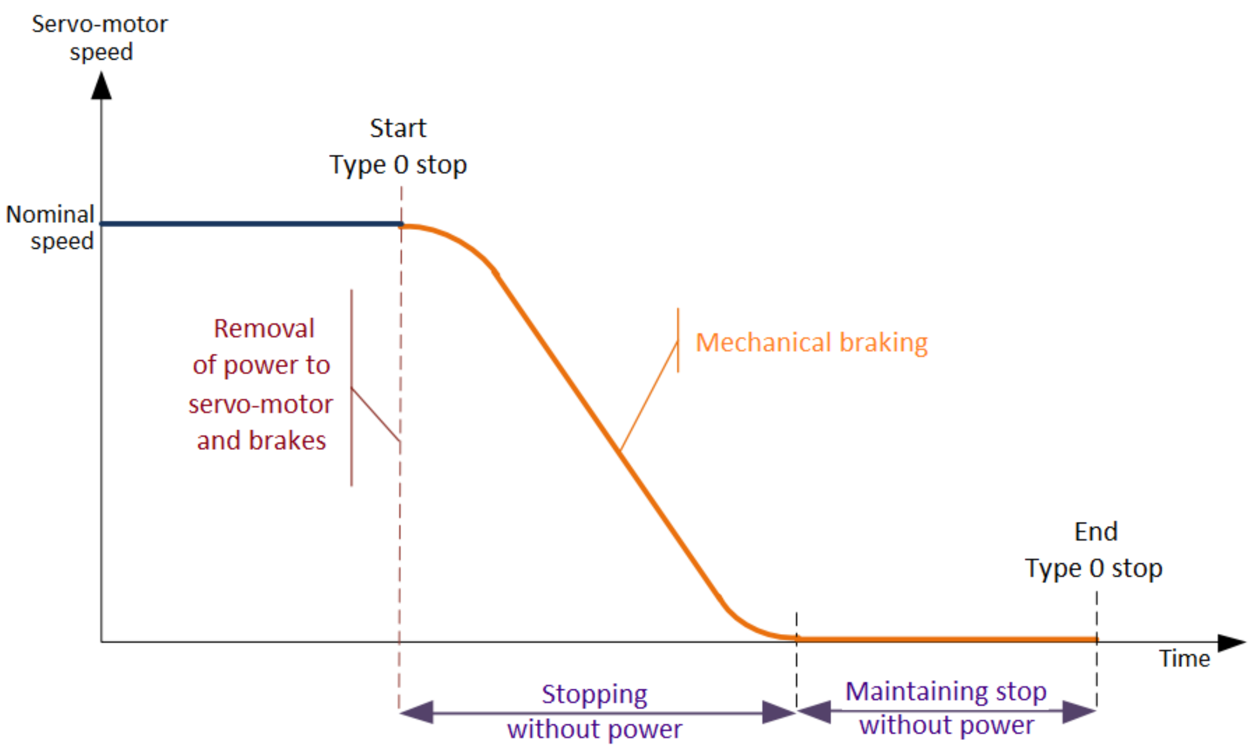


Figure 14 Illustration of a category 0 stop, taken from Baudoin and Bello (2015)

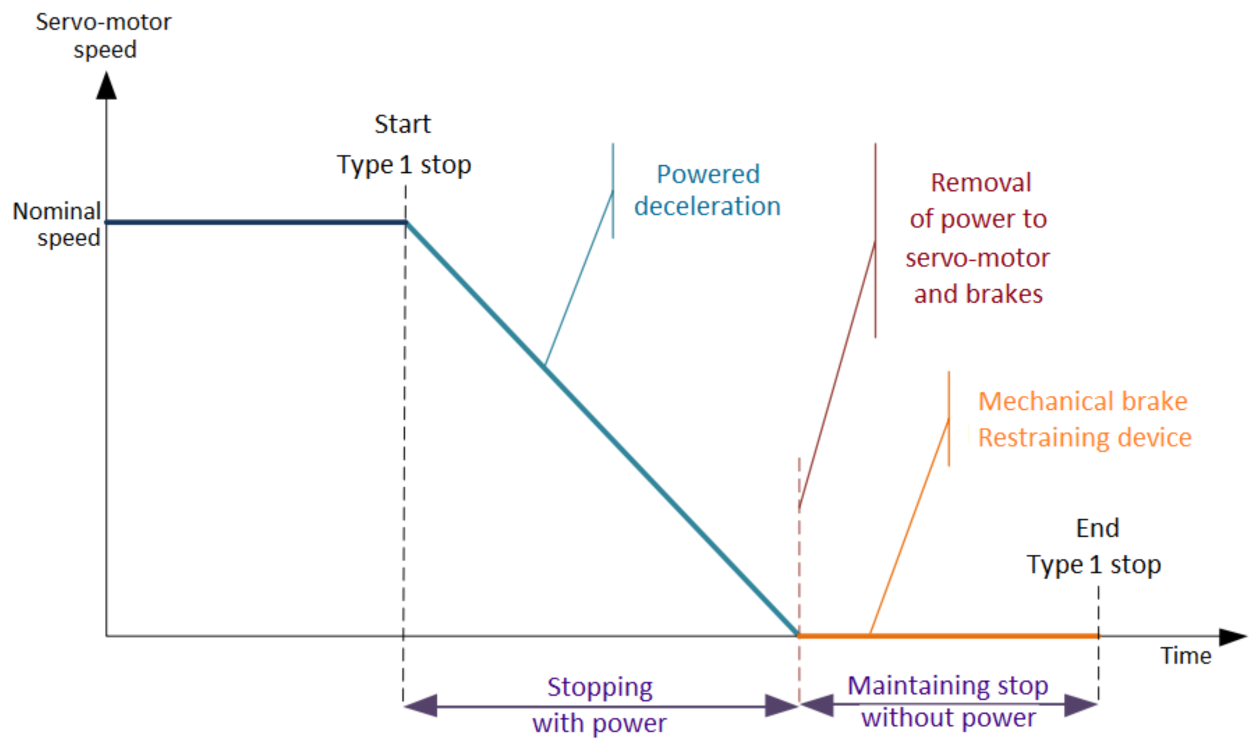


Figure 15 Illustration of a category 1 stop, taken from Baudoin and Bello (2015)

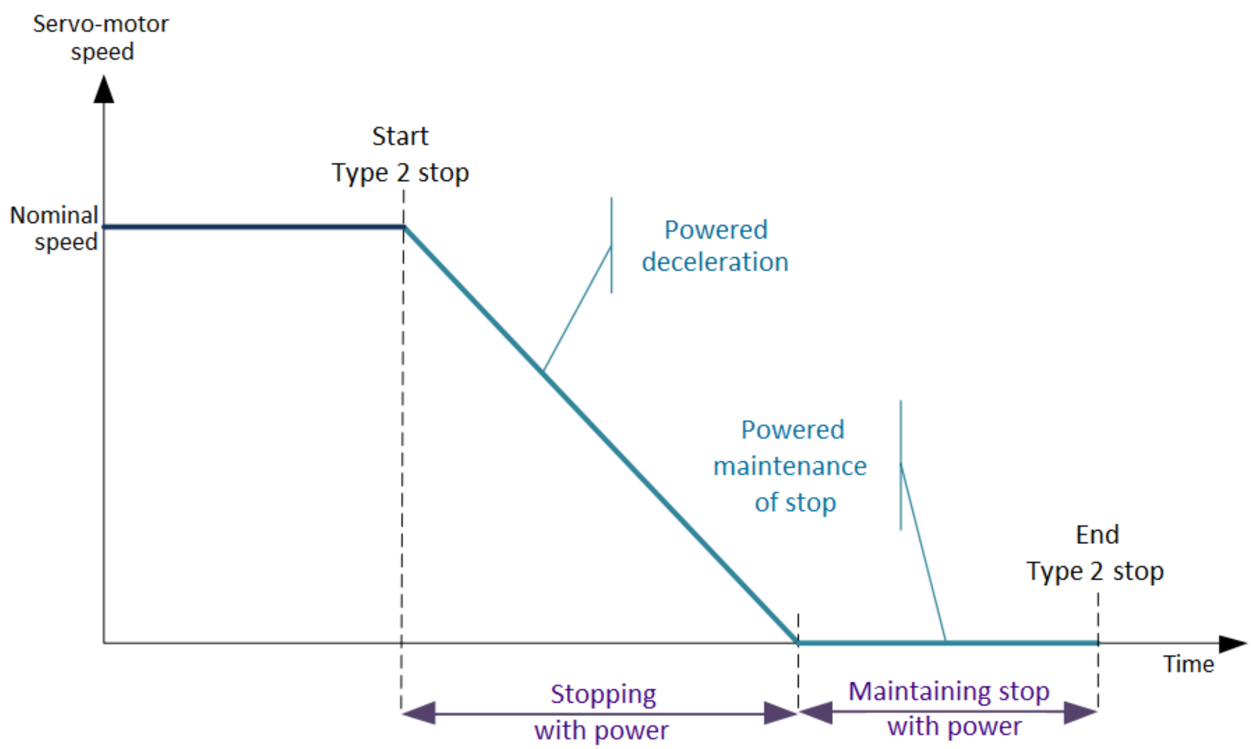


Figure 16 Illustration of a category 2 stop, taken from Baudoin and Bello (2015)

APPENDIX D – CLIENT DATA COLLECTION FORM

Research project **2014-0046 – Client** data collection form

Completed by: ______________________________________**Date:** ___________________

1. Identification of client (person giving work to integrator)

First name	Surname	Title/Function	Contact info.
Company (name, address)			
Factory/site where **cobot** is installed			
Place interview conducted			

2. Process TO BE ROBOTIZED (describe process prior to cobotic installation)

Link between **worker's task** and **products** or **process:**

Workers' tasks:

1) ____

2) ____

3) ____

Products, process:

1) ____

2) ____

3) ____

3. Robotized process that was PLANNED at the start (before final integration)

Describe process. Provide a drawing if necessary.

Robot's tasks	***Tasks intended to be performed by worker during robot's tasks***

4. Robotized process ACTUALLY implemented (if ≠ preceding)

Describe process. Provide a drawing if necessary.	
Robot's tasks	***Tasks actually performed by worker during robot's tasks***
How do you explain these differences between the planned and actual processes, especially with regard to safety-related specifications?	

5. Need for robotics (Factors that prompted company to install a cobot)

Check factors concerning company and explain on lines below, as needed.

☐ **Economic factors**

- ☐ Improve productivity
  ____
- ☐ Need to be more competitive
  ____
- ☐ Reduce product-related labour costs
  ____
- ☐ Increase production management flexibility (e.g., robots can adapt to different tasks)
  ____
- ☐ Improve quality (e.g., task repeatability, production traceability, and therefore quality tracking)
  ____
- ☐ Low cost of robotization and return on investment (< 2 years on average)
  ____

☐ **Human factors**

- ☐ Improve working conditions and safety (e.g., reduce MSDs, workloads)
  ____
- ☐ Reassign workers to new jobs (e.g., more rewarding jobs)

____

☐ Layoffs

____

☐ **Environmental factors**

- ☐ Need to limit clutter and other spatial constraints (conventional robotics unsuitable)
  ____
- ☐ Improve environmental performance of process (e.g., reduced airborne emissions compared with original manufacturing process)
  ____

☐ **Other expected benefits**

- ☐ Showcase company (e.g., a robot symbolizes company's ability to adapt, make good impression on customers, inspire greater confidence)
  ____
  ____

6. Drawing up specifications

People consulted when drawing up specifications:

☐ **Worker** who is supposed to work alongside the cobot

Was he/she consulted? (Yes/No)   Degree of involvement? (Low/Medium/High)

If so, when? For what purpose? ____

____

____

☐ **Integrator**

Was he/she consulted? (Yes/No)   Degree of involvement? (Low/Medium/High)

If so, when? For what purpose? ____

____

____

Sections of **specifications** given to integrator:

- ☐ Project goal
- ☐ Description of application or process to be implemented
- ☐ Robot selection criteria (on basis of price, scope, worker-related conditions to do with robot morphology or workload)
- ☐ Production volume, cycle times, characteristics (weight, dimensions, materials, appearance, etc.)
- ☐ Number of workpieces to be processed
- ☐ Peripheral operations upstream and downstream, machines involved in process
- ☐ Robot's working environment (temperature, humidity, etc.)
- ☐ List of documents provided to integrator: reference material on workpieces processed and associated documents
- ☐ Schedule and completion deadline
- ☐ Other (specify): ____

Was a risk assessment planned? (Yes/No)   Was it done? (Yes/No)

If so, what did the **assessment** concern: Formally/ Informally?

- ☐ Conventional robot installation?
- ☐ Cobotic installation?

Explain the **detailed safety-related requirements** mentioned in the **specifications:**

Requirement chosen	Reasons for choice

7. Solution research and validation phase

(robot and other equipment or components)

Describe the solution research process.

- *Choice of robot and safeguards, by whom?*
- *Testing of different robots and safeguards, by whom?*
- *Demonstrations, with outside help or not?*
- *Others aspects?*

Describe the solution validation process.

At what points did you intervene in the solution research and validation (client-integrator cooperation). Explain.

8. Staff training

Type of staff	☐ Production	☐ Maintenance	☐ Setup/Adjustment
Trained by whom?*			
***Normally, the trainer should be the integrator, so that staff can quickly take over operation of the new installation and ensure the project is successful.**			

9. Assessment and feedback

Objectives achieved regarding:	Planning and reality: **Discrepancies? Explain.**
☐ Economic factors?	
☐ **Human** factors (**safety** aspect, especially)?	
☐ **Environmental** factors?	

☐ **Other** expected benefits?	

Choices that fostered collaboration:

+	Explain

Choices that hampered collaboration:

–	Explain

Problems encountered during cobot integration process (from design to installation)? Was interacting with the various people involved (supplier, integrator, workers, etc.) easy or difficult? Explain.

Specifications

What would you do differently if you had to go through another cobot integration project? Explain.

10. Documents collected

- ☐ Specifications
- ☐ Other (specify): ____

Source: *Robotisation – Mode d'emploi – Réussir son projet de robotisation*, Techniques de l'Ingénieur, ISBN: 978-2-85059-127-3

APPENDIX E – INTEGRATOR DATA COLLECTION FORM

Research project **2014-0046 – Integrator** data collection form

Completed by: ______________________________________**Date:** ___________________

1. Identification of integrator

First name	Surname	Title/Function	Contact info.

Employer (name, address)	
Factory/site where **cobot** is installed	
Place interview conducted	

2. Robot

Make: ____________________________ Model: _________________

☐ Cobot originally designed as such?

Conventional robot transformed into cobot with:

☐ Safety card?

☐ Safety module?

Number of axes: ____Payload: _______ Weight of robot: ______ Reach: ________

Speed range

→ **Axes:** ____

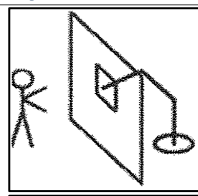
→ **Tool centre point:** ____

☐ Access and remote control? Specify: ____

Other special technical specifications:

3. Collaborative cell implemented (**check** the appropriate **drawing** or **draw your own**)?

Application type?
(Source: *ISO 10218-2:2011*, Annex E)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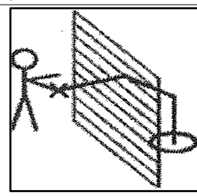
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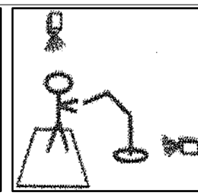
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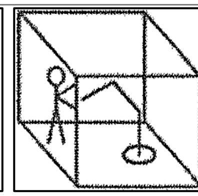
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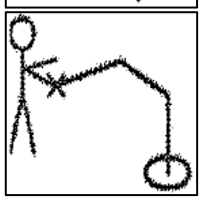

☐

Cobot used for:

- ☐ **Direct interaction**
- ☐ **Coactivity**
- ☐ **Autonomous – *Why?***

4. <u>Planned</u> operating process of cobot in relation to worker

(especially useful in cases where worker cannot be observed)

Describe process. Provide a drawing if necessary.	
Robot's tasks	***Worker's planned corresponding tasks***

5. Safeguards used, by collaborating mode

Collaborating mode	**Associated safeguards (e.g., SFs, guards)**	**Is this an original safeguard?**	**Is it an added safeguard?**	**Why added? How added?**
1. Safety-rated monitored stop				
2. Hand guiding				
3. Speed and separation monitoring				

4. Power and force limiting by inherent design or control				

6. Integration process – **From receipt of specifications to installation of cobot:**

Ask the integrator to describe the integration process. Note it down. Complete the description by asking one or more of the following questions if integrator does not deal with them.

As needed: Questions to help integrator describe integration process

- ☐ 1) **Standards used** (*ISO 12100:2010, ISO 10218-1:2011, ISO 10218-2:2011,* etc.)?
- ☐ 2) **Risk assessment by task** (e.g., learning, production)? **How?**
- ☐ 3) **OHS risk identification:**
  Tests run? Which ones?
  For what task(s)?
  What OHS risks were found?
- ☐ 4) **Estimated required PL or SIL for each SF? How?**
- ☐ 5) **Modes of collaboration: reasons for** choice?
- ☐ 6) **Required safeguards: method** of choosing them?
- ☐ 7) **Safeguards** chosen **according to SF reaction time?**
- ☐ 8) Choice of **limit values** (speed, force, etc.): **approach?**
- ☐ 9) **Management** of configured **parameter** settings: **password or other** option?
- ☐ 10) **System design validated?**
- ☐ 11) **System implementation validated?**
- ☐ 12) **Instructions written up?**
- ☐ 13) **Instructions provided to** client?
- ☐ 14) **Technical documentation up to date?**
- ☐ 15) **All technical documents** kept in **one spot?**
- ☐ 16) **Company staff trained by integrator** so they can take over quickly?
- ☐ 17) **Assessment** of technical, economic and human aspects conducted **after** robot cell in operation for a few months?

7. Meeting of specifications

7.1 Production requirements		
Requested by client, and **why?**	**Actually integrated** into cobot **or added by integrator,** and **why?**	Requirements met **how?**

7.2 Safety requirements		
Requested by client, and **why?**	**Actually integrated** into cobot **or added by integrator,** and **why?**	Requirements met **how?**

7.3 Other requirements		
Requested by client, and **why?**	**Actually integrated** into cobot **or added by integrator,** and **why?**	Requirements met **how?**

8. Problems solved and existing or foreseeable obstacles, in connection with safety of human-robot interaction?

9. Documents collected

- ☐ Installation plans
- ☐ Risk assessment
- ☐ Determination of PL or SIL required by safety function
- ☐ Other (specify): ____

Annex E – Examples of collaborative robotic cells

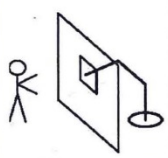
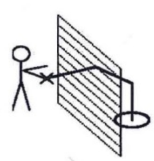
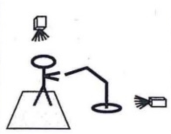
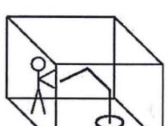
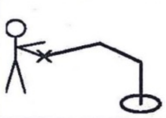
(Source: ISO 10218-2:2011, Annex E)

Annex E

(informative)

Conceptual applications of collaborative robots

NOTE For requirements see 5.11

Type of application		Description	Safeguards	Objectives
	Hand-over window	– autonomous automatic operation within safeguarded space – robot moves into window – no interruption of automatic operation during access	– fixed or sensitive guards around the workspace – reduced speed and reduced workspace near the window – no robot workspace outside the window – when lower edge of the window less than 1000 mm safeguards according to 5.10.3	– loading, Unloading – testing, benching, Cleaning – service
	Interface window	– autonomous automatic operation within safeguarded space – robot stops at an interface window and can then be moved then manually outside the interface.	– fixed or sensitive guards around the workspace – reduced speed and reduced workspace outside and near the window – hold-to-run control for guided movement	– automatic stacking/ de-stacking – guided assembling – guided filling/ un-filling – testing, benching, cleaning – service
	Collaborative workspace	– autonomous automatic operation within a common (collaborative) workspace – robot reduces speed and/or stops when a person enters the common (collaborative) workspace	– person detection system using one or more sensors – reduced speed according to the distance (5.11.5.4) – robot stops safely when prohibited space accessed and possible automatic restart after clearance if properly safeguarded	– common assembling – common handling – testing benching, cleaning – service
	Inspection	– autonomous automatic operation within safeguarded space. – a person enters the collaborative workspace while robot continues operation with reduced speed and reduced travel	– fixed or sensitive guards around the workspace – person detection system or enabling device – reduced speed and reduced workspace after entering the workspace – measures against misuse	– inspection and tuning of processes, e.g. welding application
	Hand-guided robot	– application specific workspace – moving by hand guiding – moving hand guided along a path	– reduced speed – hold-to-run control – collaborative workspace depending on hazards of the application	– hand-guided assembling, painting, etc.

APPENDIX F – WORKER DATA COLLECTION FORM

Research project **2014-0046 – Worker** data collection form

Completed by: ____ **Date:** ____________________

1. GENERAL INFORMATION

1.1 Identification of workers

First name	Surname	Title/Function

Employer (name, address)	
Department/Unit	

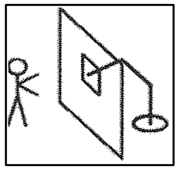
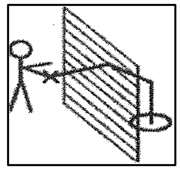
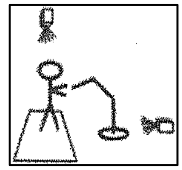
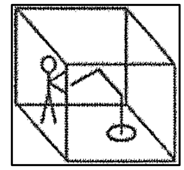
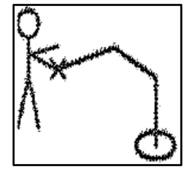
1.2 Robot

Make	
Model	

1.3 Layout of robot cell

(Check the appropriate drawing or provide your own drawing of the robot cell, if needed)

Workstation/ Task to be performed	

Layout of collaborative cell (Source: *ISO 10218-2:2011*, Annex E)	 ☐  ☐  ☐  ☐  ☐

2. HOW ROBOT CELL WORKS IN PRACTICE

2.1. Work cycle

Description of a normal production cycle	a. Initial state (robot, worker, products/materials): – – – b. Work phases (role of robot, role of worker or others): #1 : #2 : #3 : #4 : #5 : #6 : #7 : c. Final state (robot, worker, products/materials):

	– – – Length of a work cycle:
Other robot-related operations: Why? Actions required? Frequency?	Stop: Start-up, reset: Adjustments: Maintenance:

2.2 Details of production work phases requiring interaction with robot

Work phase (prod.)	**Robot's task**	**Worker's task**	**Type of interaction**	**Risks**	**Misc.** (robot speed/trajectory, worker position, etc.)
#					
#					
#					
#					

2.3 Risk reduction measures (RRMs) implemented for worker

RRMs	Details	Work phases
Reduce speed, force		#
Protective guards on robot		#
Fixed guard		#
Safety devices		#
Procedures		#
Theoretical and practical training	(content, length, apprenticeship or mentoring period, etc.)	#
PPE	☐ Gloves ☐ Hard hat ☐ Goggles ☐ Safety footwear ☐ Other:	#

3. IMPACTS ON WORKER

Positive impacts		Negative impacts	
– Reduced physical load, MSD risks	☐	– Collision with robot	☐
– Increased rate of production	☐	– Apprehension, fear (hard-to-foresee movements, speed, etc.)	☐
– Reduced risks	☐	– Mental workload (rate, monitoring)	☐
– Intuitive interaction	☐	– Physical workload (rate)	☐
– Other (good things):	☐	– Loss of decision-making latitude, autonomy	☐
		– Emergence of other MSD-related issues	☐
		– Other (problems):	☐

4. MISCELLANEOUS INCIDENTS, REMARKS

Events	Causes	Possibility of improvement