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# Plastic Injection Moulding Machines with Auxiliary Equipment

## Safety During Maintenance and Production Interventions

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STUDIES AND RESEARCH PROJECTS

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MECHANICAL
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RISK PREVENTION

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We thank the companies that allowed us to visit their plants for data collection purposes. As we respect the privacy of the stakeholders and companies that took part in the study, we have agreed not to publish their names. However, two of the plants involved asked to be listed as participants in the study, namely Plastiques GPR Inc. and IPEX St-Jacques.

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# SUMMARY

The risks related to the interaction between plastic injection moulding machines and their auxiliary equipment (e.g. robots, conveyors) are not well known by the people in the industry, and these risks can sometimes lead to fatal occupational accidents. The aim of this research project is to study the safety of workers who use horizontal plastic injection moulding machines with auxiliary equipment. Its objective is to evaluate the safety of the people working in the mould area of this type of moulding machine by identifying the risks and analyzing the risk reduction means for maintenance and production tasks.

Analyzing depersonalized CSST intervention and accident reports and examining standards and guides related to this subject provided an understanding of the hazards to which the users of these machines are exposed. These documents offered up-to-date knowledge about the current best risk reduction practices. Also, eight plant visits made it possible to observe workers performing maintenance and production work. The observed maintenance work involved injection moulding machine maintenance: mould polishing and mould cleaning. Production work involved insert installation, changing moulds, production tests, and operational tests (production of moulded parts).

The risks noted in the plants were documented, as were the observed risk reduction means. Analysis of the observed risk reduction means identified both the strong points and aspects that require improvement. These observations also allowed us to characterize the workers' practices for ensuring their safety during maintenance and production interventions in the mould area of this type of moulding machine. Three typical means of risk reduction were identified:

1) Use of a partial lockout procedure, whereby a padlock is attached to the console or a guard to avoid start-up by a third party;
2) Use of safety functions: the workers have complete confidence in the machine's control system and auxiliary equipment for ensuring their safety. To access the mould area, they open the interlocked or interlocked with guard locking movable guards, use pressure-sensitive floors detecting any presence in the mould area, and use the emergency stop function;
3) Inspection: before entering the mould area, they check that the means of protection installed on the machines is operating properly and, before using hoisting equipment to handle the mould, they check the condition of the hoisting equipment.

No lockouts as defined in the Quebec *Regulation respecting occupational health and safety* were observed. According to the participants met during the visits, such lockouts are used only for major maintenance and repair work. Furthermore, observing that safety functions were widely used during interventions in the mould area prompted the research team to ask the participants about the reliability of these safety functions and about the integration of the auxiliary equipment control system with that of the moulding machine. The integrators who were met emphasized the difficulties they encounter in evaluating this reliability: insufficient knowledge of the standards in force, for example. To guide them, an example of an *a posteriori* evaluation of a safety function is provided in this report for use in studying the feasibility of such a procedure and for identifying its difficulties and limitations.

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# PREFACE

With the exception of chapter 6, this document is intended particularly for workers on horizontal plastic injection moulding machines with auxiliary equipment, their employers, and the machine integrators and designers. As for chapter 6, it is intended for integrators and designers of safety-related control systems. To understand the chapter, besides being familiar with the control systems, it is necessary to have basic knowledge of the ISO 13849-1:2006 or NF EN ISO 13849-1:2008 design standard, which is titled “Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design.”

Chapter 6 presents a case study aimed at making this standard more accessible and comprehensible. Several integrators and designers whom we met during field work told us that they found the design standards for safety-related control systems difficult to understand and apply. While remaining true to the notions presented in ISO 13849-1, chapter 6 makes the standard easier to understand by applying it to an existing control circuit. To delve further into the case study, we refer the reader to chapter 3 of the third work listed in the bibliography of this report.

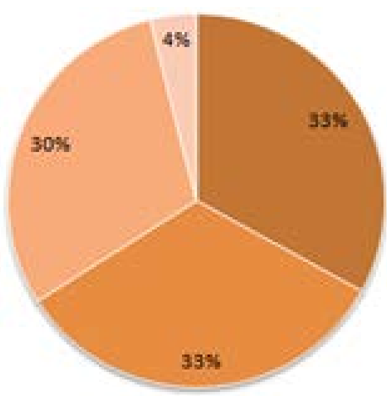
# 1. INTRODUCTION: BACKGROUND

## 1.1 Overview of the Quebec plastics processing industry

In Quebec, the plastics processing industry comprises nearly 500 establishments and employs some 30,000 people [1]. The deliveries made by the industry total $3.8 billion dollars, and 96% of them are for the packaging, transportation and construction markets [1]. Figure 1 diagrams the shares of the markets that make up the industry. According to Industry Canada [2], two subsectors of the plastics processing industry are involved in its activities: (1) the machinery subsector and (2) the mould subsector. The former consists of manufacturers of machines used to make plastic products. The products are made using processes such as extrusion, thermoforming, blow moulding, rotational moulding, and injection moulding. The latter subsector focuses mainly on making moulds. For each plastic part, a unique mould must be made according to the client's specifications. The mould is installed on the machine (a press) that operates using one of the above-mentioned processes. Whenever a new model of part is to be made, the mould must be changed, followed by production tests to check that the press is properly set up. Preventive and corrective maintenance are also required to ensure the press remains operational [3].

**Other markets (4%)**
Housewares and service items (household containers, dishes, utensils, garden hoses)
Electronics and electrical hardware (computer cases, telephones, calculators, wires, cords, cables)
Furnishings (radio and television cases, frames)
Clothing and accessories (hangers, zippers)
Printing and advertising (signs, display cases, binders, credit cards)
Recreational (games and toys)

**Transportation (30%)**
Automobile interiors and exteriors
Automobile structural parts
Parts for heavy trucks
Aerospace parts
Marine containers
Parts for rail transport




**Packaging (33%)**
Rigid (containers, bottles, gas bottles)
Semi-rigid (EPS foam and polyurethane products)
Flexible (garbage bags, shopping bags, film, sheets)

**Construction (33%)**
Exterior cladding
Piping (pipes, fittings, tubing)
Plumbing fixtures
Leaves, casements (doors, windows, shutters)
Frames
Baseboards mouldings
Partition walls
Insulation

Packaging
Construction
Transportation
Other markets

**Figure 1 – Market shares of the Quebec plastics processing industry [1, 3].**

From an occupational health and safety (OHS) standpoint, the plastics processing industry is in group 2 of the six priority groups identified by the Commission de la santé et de la sécurité du travail (CSST) [4]. According to the CSST, the groups were established on the basis of various parameters, in particular the similarity of business activities and the frequency and severity of occupational injuries [4]. The lower a group's number, the higher the group's priority. As the industry is a member of group 2, the Act Respecting Occupational Health and Safety (AOHS) [5] imposes on it a prevention program that includes four mechanisms: (1) a prevention program; (2) a health program specific to the establishment; (3) an occupational health and safety committee; and (4) a safety representative. These mandatory prevention mechanisms and the fact that the plastics processing industry has been placed in group 2 imply that the industry is among those for which occupational injuries are a significant issue and that attention should be paid to resolving the issue. Table 1 presents the OHS risk level in various plastics manufacturing sectors for the period between 2000 and 2009. The data in the table are taken from the CSST website [6].

**Table 1 – Risk level by plastics manufacturing sector.**

| | **Risk level** | |
|---|---|---|
| **Manufacturing sector** | **SMEs** | **Overall industry** |
| Plastic packaging and film material, non-laminated sheets | High-extreme | Extreme |
| Plastic plates, sheets (except packaging) and laminated forms | Low | Low-moderate |
| Plastic pipes and pipe fittings | Low | Moderate |
| Plastic parts for motor vehicles | Moderate | Moderate-high |
| Parts (except bags, pipes, sheets, laminated forms, motor vehicle parts, etc.) | Moderate-high | Moderate-high |

According to the CSST data for 2000–2009, the risk level for the Quebec plastics processing industry varies from low to extreme, as table 1 shows. The data also indicate that, for plastics processing SMEs as well as for the industry as a whole:

- Overexertion by workers is the main cause of occupational injuries (risk of an ergonomic nature);
- Being hit by objects is the least serious cause of occupational injuries.

Also for the 2000–2009 period and for the overall industry, three-quarters of the fatal accidents involved workers trapped or crushed by operating machines. These machines were either the press itself or auxiliary equipment, such as a carousel [6]. We note that this finding relates directly to the subject of this research report.

## 1.2 Origin of this study

In 2008, the IRSST published a research report that described a concrete risk analysis process applied to an injection moulding machine [7]. The process is based on ISO Standard 14121:1999 [8]. The risk reduction means on this machine were analyzed and commented on. A guide based on the report was also published [9]. However, the risks related to the interaction between the machines and their auxiliary equipment (robots, conveyors, pelletizers, hoisting apparatuses, stepladders, ladders, etc.) are less well known to people in the industry and were not catalogued in the above-mentioned report. Nonetheless, these hazards sometimes result in industrial accidents. Consequently, this research aims to study the safety of injection moulding machines that have auxiliary equipment.

## 1.3 Operation of an injection moulding machine and its auxiliary equipment

Figure 2 diagrams a horizontal injection moulding machine and its main parts.

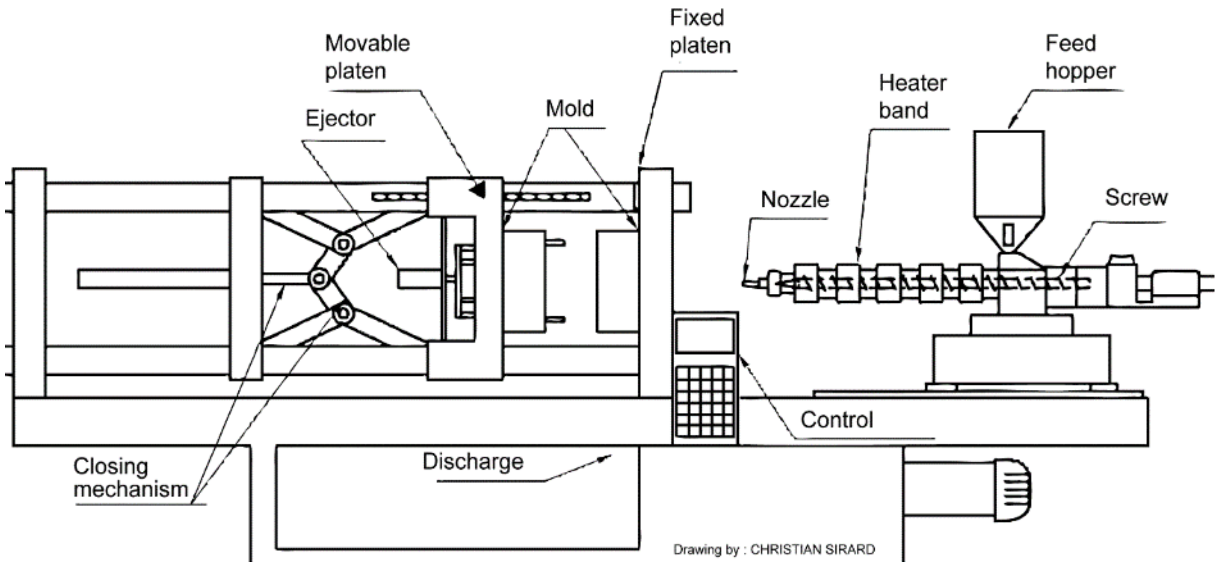



**Figure 2 – Diagram of a horizontal injection moulding machine.**

A plastics injection moulding machine usually works as follows [7, 10, 11]: the feed hopper is supplied with plastic pellets, either manually or by an automated system. The pellets are gravity-fed through a feed chute into the transfer chamber, which contains a reciprocating screw. The plastic is melted by heating the injection unit (the temperature can reach up to 200°C [12, 13]) while the reciprocating screw moves the material through the transfer chamber. When moving in the direction of the mould, the screw also functions as a piston for injecting the melted plastic under pressure into the mould cavity through a nozzle the fits into an opening in the fixed part of the mould installed on the fixed platen. The moulds are at a temperature that allows the injected melted plastic to cool and solidify. During the cooling process, the reciprocating screw moves in the direction of the hopper to receive more granules and prepare for the next injection. After a predetermined period that gives the parts enough time to solidify, the mould opens. Once the mould is open, ejectors emerge to extract the moulded items or to free them in order to make them easier for a robot (auxiliary equipment) to remove. Once the items have been removed, the mould clamping mechanism activates, pushing the movable platen: the mobile part of the mould clamps onto the fixed part and closes the mould. The closed mould is now ready to receive another injection of melted plastic and the cycle repeats.

As mentioned earlier, plastics injection moulding machines can be used with auxiliary equipment. Dobraczynski and Chatain [13] divide the equipment into three groups:

- **robotic equipment**, designed for loading and unloading moulds;
- **injection-moulded parts processing equipment**: degating, sprue sorting, counting and automatic storage devices, conveyors, etc.;
- **mould assembly, connection, disassembly and storage equipment**.

The authors suggest that quality requirements and the desire to increase productivity explain the decision to use robotic equipment and parts processing equipment. Pendular manipulating robots and rail mounted robots are used. Depending on their nature, they have access to the mould area laterally or from above ("mould area" refers to the space between the mobile and fixed parts of the mould). The robot's movements, synchronized with those of the mould, are very fast in order to minimize the length of the injection cycle. The robot's arm must have left the mould area before the mould closes. The type of parts to be manufactured determines the characteristics (e.g. type, size) of the robot's grippers. Robots can be equipped with articulated jaw grippers for extracting sprue or can incorporate suction cups for extracting the manufactured parts. They can also be used for sorting parts and sprue and for sending the sprue directly to a granulator in order to recover the plastic and reuse it in a future plastics injection process. The parts may be placed on a conveyor that deposits them into containers. It should also be noted that part extraction devices exist; these are related to robots but are not called such due to their control mechanism, which is entirely different from that of robots [14]. Unlike robots, the devices often have no feedback loop constantly controlling their position [14].

Use of mould assembly, connection, disassembly and storage equipment is justified by the need to minimize part production start-up time [13]. This type of equipment facilitates and accelerates the handling and installation of the mould on the press's fixed and mobile platens. For example, quick mould clamping mechanisms exist for attaching the moulds to the platens [13, 14]. Roller top carts, which can be raised or lowered to the machine's height, can be used to move and transport the mould. To move heavier moulds, an overhead hoist fitted with a hook can be used. Overhead hoists, such as overhead travelling cranes, are hoisting devices used to handle the moulds.

# 2. RESEARCH OBJECTIVES

The objective of this study is to analyze maintenance and production interventions on injection moulding machines with auxiliary equipment by identifying risks and analyzing means for reducing these risks in order to evaluate the safety of individuals in the mould area. More specifically, the study aims to:

- identify the risk components associated with injection moulding machines with auxiliary equipment during maintenance and production interventions;
- identify the means used in plants to reduce these risks;
- characterize the workers' intervention practices to ensure their safety when performing maintenance and production work on injection moulding machines with auxiliary equipment;
- identify and analyze the choice of risk reduction measures for each of these maintenance and production intervention practices;
- evaluate the effectiveness of these risk reduction measures.

**Limitations and scope of the study**: This study focuses on horizontal plastic injection moulding machines. Our observation of the risks and analysis of the risk reduction measures concern only interventions in the area shown in figure 3.

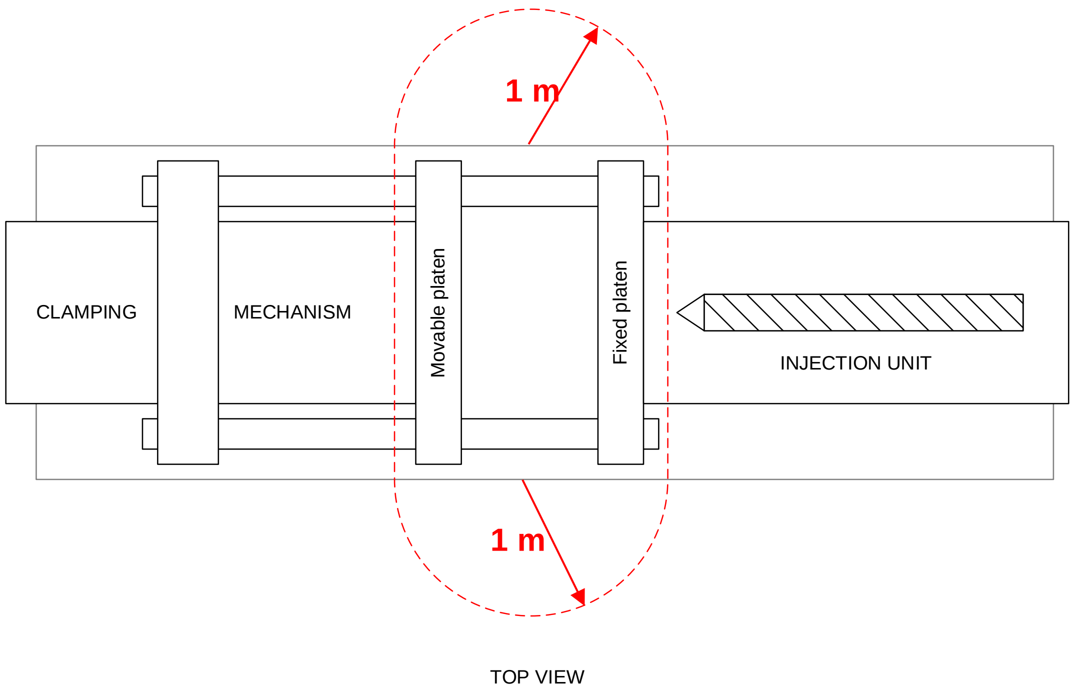



**Figure 3 – Area covered by the study.**

This area includes the mould area, the area of the opening for discharging the manufactured parts, and an area of approximately one metre[1] on either side of the machine. This perimeter makes it possible to consider the risks inherent in the equipment that is located around the machine and that may compromise the safety of a worker in the mould area during maintenance and production operations. In this study, “maintenance” includes both maintenance and repair work on the machine, while “production” refers to any operation involved in moulding parts, changing a mould, installing inserts on the mould, or performing production tests. The study is limited to identifying the risks. The study results have no statistical value.

[1] The choice of this radius was based on table 3 of ISO 13857:2008 [15] in which, for movement limited only to the shoulder and armpit level, a minimum safety distance of 850 mm is recommended. Thus, the worker is at risk if he is located within an 850 mm radius of the hazardous phenomenon. As in our case the worker’s arm can be free of movement, a 1 m radius was chosen to allow for the possibility of the worker’s voluntarily or accidentally leaning and thus entering the mould area.

# 3. METHOD

The methodology used can be divided into five steps:

1) **Collect the preliminary data (literature review)**

Some 30 CSST accident and intervention reports were analyzed to gain an understanding of the various contexts in which accidents on plastic injection moulding machines and their auxiliary equipment have occurred. This understanding makes it possible to better grasp the risks to which the workers who work on these machines are exposed. Standards and manuals were also consulted to learn about trade practices relating to the safety of these machines and of interventions on them.

2) **Develop the data collection tool**

A data collection tool was developed to gather data during visits to companies active in the plastics industry. A preliminary visit allowed the first version of the tool to be improved and validated. The final version, which will be found in Appendix A, is the one used for the seven other visits.

3) **Collect the data on visits to companies**

Eight visits to six plants were made to collect data. The data were obtained by observing maintenance and production operations in the mould areas of injection moulding machines by speaking with the persons in charge of OSH, mould set-up technicians, maintenance technicians, operators (the data collection tool guided the discussions), by photographing and video-recording the workplace, and by studying various documents (e.g. schematics of the visited machines, lockout placards, training reports, machine inspection forms). The collected data made it possible to identify the risks present on the machines and their auxiliary equipment and those related to the work situation for the observed operation. These data also allowed us to identify the risk reduction means used in the companies and their characteristics in order to evaluate their effectiveness. For example, operation tests of movable guards were carried out to check whether they functioned effectively as required by Quebec machine safety regulations [16].

4) **Compile and organize the collected data**

After the visits, the collected data were complied and organized into an analysis grid. This made it possible to easily identify the components of each risk noted during the observed operations for the machine-auxiliary equipment systems. The preventive and protection measures that were associated with these risks and were used or observed were also compiled.

5) **Compare the identified risk reduction measures with those found in the literature**

The observed risk reduction measures were compared with those identified in the literature. This comparison enabled us to formulate recommendations on the safety of maintenance and production interventions in the mould area of horizontal injection moulding machines with auxiliary equipment.

# 4. RESULTS

## 4.1 Accident analysis

An analysis of industrial accidents involving plastic injection moulding machines in Quebec was performed as part of this study. The CSST's Legal Services Department granted the research team access to intervention reports and to accident reports that had been depersonalized in order to protect the confidential nature of some of the information they contained. In all, 30 CSST accident and intervention reports were analyzed to allow the researchers to better identify the risks associated with plastic injection moulding machines and their uses in companies. It should be noted that the reason for analyzing these CSST reports was not to produce a sampling that was representative of the entire plastics industry. This step focused instead on preventing work accidents by ensuring that the various aspects of risks, interventions, interveners, and causal agents of the accidents were considered.

The following points summarize the main results arising from the analysis of the 30 reports:

- The 30 reports concerned 26 accidents and/or interventions involving plastic injection moulding machines, one accident/intervention related to a rubber injection moulding machine, one accident/intervention related to a thermoforming machine, and two others related to blow moulding machines. However, the examples presented in this section and the main topics developed therefrom relate only to injection moulding machines.
- For the most part, small companies (fewer than 50 employees) were involved.
- The ratio of injured women to men was one woman to six men. Information on the woman-man ratio in the Quebec plastics processing industry is not available in the literature.
- The accident victims' positions in the companies and job descriptions included:
  - Machine operators or monitors: they check the quality of the products on several machines simultaneously when the machines are operating in automatic mode. When the machines are operating in semi-automatic mode, they collect the part in the mould area at the end of each cycle. They check that the machines are operating properly but are usually are not involved in set-up. When faced with a problem (e.g. unjamming), they usually decide whether to call for a technician or resolve the problem themselves.
  - Packagers: they are normally responsible for boxing the finished products at the end of the machine's conveyor and for operating certain controls of the injection moulding machine.
  - Production managers: they start production on the machines and perform the necessary set-up. They intervene when jams or other production problems occur and also to change moulds.
  - Electricians: they make electrical-type repairs.
  - Mechanic-supervisors/technicians: they perform production adjustments and maintenance.

- Several of the companies involved in these accidents/interventions did not have active occupational health and safety committees or safety practitioners (OHS officers), as required by the AOHS for the priority 2 group.
- Several accidents occur when the set-up technician is absent or unavailable, in which case the task is performed by a person not qualified to do so. Such situations occur especially during the evening shift.
- Interventions on the machines often take place without any formal, established, and safe work procedures being in place. The worker improvises the work process required during the intervention while having a profound ignorance of the considerable risks involved.
    - *Example 1*: A worker climbed on an injection moulding machine to remove parts stuck in the mould, reaching over the locked movable guard. No work method for unjamming had been established. Thus the unjamming was done in an informal and unstructured manner.
    - *Example 2*: When changing the barrel head and disassembling the injection unit part (the cylinder's shut-off pin), the heating elements of the cylinder should not be turned off; otherwise the plastic will harden and bind the parts of the machine together. A worker climbed onto a grid platform, took a sledgehammer and struck one of the parts to dislodge it. Another worker positioned himself on the opposite side to recover the part. When the part moved, the plastic in the transfer chamber caught fire and was shot outside the barrel toward the worker standing above. When the hot plastic landed on his left hand, the worker stepped back, tripped over the pipes and cables located behind the platform and fell to the ground, fracturing his left elbow. Following the accident, a safe work procedure, which included checking the temperature before and during the work, was implemented and formalized. In addition, when a work order is generated for the task of disassembling the injection unit part, the new work procedure is now automatically included with it.
- Work procedures, if they exist, are often unsuitable and/or unsafe. Production interventions (e.g. lubricating, spraying silicone) are often performed inside hazardous zones.
    - *Example 3*: In a company, a work method to prevent the plastic part from sticking to the mould consists of, every 10 to 15 cycles, using three-step mobile stairs to allow an operator to climb onto the platform located above the machine's hydraulic unit. Using silicon spray, the operator lubricates the two mould rods positioned above the mould. This task is performed while the machine is running. A worker had three of her fingers crushed while performing this operation.
- The circumventing of established, safe work procedures by untrained workers, who appear to go beyond their roles and tasks, is a causal agent that shows up frequently in the CSST reports. A machine operator has not been trained to adjust or fine-tune the machines and, in theory, should not do so. However, for unobvious reasons, the worker departs from his usual planned task (e.g. an operator whose tasks are usually limited to checking the quality of the parts decides, on his own, to make adjustments to the machine in order to resolve a quality control problem). If the machine is not equipped with fixed guards, interlocked guards and/or effective protective devices, this type of intervention can be very dangerous. Relying on the worker's training and experience as the primary risk reduction measure is not a

preferred approach at any time. A hazardous situation is exacerbated when the worker has not been trained or is inexperienced.

- The circumventing of established, safe work procedures by an experienced and trained worker is another, if somewhat surprising, causal agent that appears in the CSST reports. In these cases, the interventions diverge from safe work procedures for unobvious reasons.
    - *Example 4*: The accident occurred when the injured worker was training another worker to operate the machine. As the trainee was operating the machine, the worker attempted to make an adjustment from the bridge (hydraulic platform with several nozzles). The nozzles needed to be aligned in the mould cavity. When the worker had the nozzle in his hands, he asked the trainee to operate the mechanism while the machine was in movement and his fingers got caught between the bridge and the press. The established work method was not followed: the adjustment was made by a second operator despite the fact that the machine should be operated by a single person. In addition, a pressure sensitive mat was in place and the protective devices were functional. However, the worker was able to get around the pressure sensitive mat, which would stop the machine when stood upon, by staying to the side of it. This allowed him to enter the danger zone. The machines controls were not safe, as the buttons were not labelled for the action to be performed.
- Circumvention of the guards on injection moulding machines is often mentioned in the reports. The interveners climb onto the machine by going over the guard. Another type of circumvention involves the protective devices (neutralizing the position switches, safety valve, etc.).
    - *Example 5*: A worker’s left hand got caught in the mould when he tried to recover sprue by reaching over the machine’s guard. He wanted to inspect the sprue and, being quite tall, he attempted to recover the sprue himself instead of letting the robot do it. The machine was in semi-automatic mode. With his right hand, he inadvertently pressed the button to close the mould instead of the button to open the injectors. In front of the machine, access to the mould is protected up to a height of 160 cm by an interlocked movable guard. The guard above the mould was not interlocked, as the interlocking mechanism had been neutralized by an outside firm 12 years earlier when it was installing the robot. The neutralization went unnoticed until corrective action was taken following the accident.
    - *Example 6*: A mechanic-supervisor was making production adjustments to the extruder in preparation for a new production run. With the machine in automatic mode, he entered the mould area to perform a task. When the worker’s thorax was positioned between the two sections of the mould, the industrial programmable logic controller (PLC) ordered the extruder to close the mould. The worker was fatally crushed while the danger zone was accessible and the protective devices were neutralized. Interlock devices were installed in negative actuation mode and were activated when the guards were closed. There was no certification to the effect that their contacts were the forced opening type. A pin holding down a hydraulic valve was observed. Steel plates attached to the chassis held down the mobile part of the safety position switches. As a result, the machine was able to operate at all times. An electrical bypass had been installed to neutralize the pressure sensitive mat. All the mechanics and supervisors as well as the employer and

head mechanic were aware that the devices had been circumvented for several years and that the mat had been inoperative for several months. Adjustment work was done with the machine in automatic mode. Lockout was not performed because the heating in the injection unit could not be shut down as that would result in the plastic's solidifying, entailing a production delay of several hours. There were verbal instructions to the effect that before a worker entered the mould area, the automatic cycle should be stopped by removing the safety key for the duration of the intervention. When removed, the safety key allowed the operator to transfer the controls to manual mode and thus to immobilise the moving parts. It also made it possible to activate a safety latch that mechanically locked the mould. The latch, which is operated by a pneumatic actuator and controlled by the PLC, is located near the saw-toothed safety bar that blocks the mould. The latch is activated when the emergency shutoff or one of the protective devices is activated or the safety key is removed. During the accident, the safety key was in its place on the control panel and the machine was in automatic mode.

- Another example of a causal agent identified by the CSST to explain the accidents relates to damaged or unadapted protective devices.
    - *Example 7*: A safety light curtain is easily circumvented due to its position on the floor and its size, which is not large enough to prevent access to the danger zone.
    - *Example 8*: When checking an injection moulding machine, a technician had his right hand crushed between the moulds when the access door was open. Due to the wear on the microswitch and the improper adjustment of the sliding door, the cycle was accidentally started when the technician leaned on the top of the still-open door.
- A factor that comes up often in the reports is the absence of guards or presence sensing devices (e.g. pressure sensitive mats on platforms) or, in other words, using machines that are not compliant with the safety standards for plastic injection moulding machines.
    - *Example 9*: A machine equipped with a movable guard without an interlock device (transparent sliding panel on the front of the machine). In addition, a guard held in place by magnets and not complying with the characteristics of a fixed guard, had been removed.
- Lack of training is often cited as a causal agent.
- The reports made it possible to confirm that the main risks remain crushing and burns. These risks are located at the mould area and base level.
    - *Example 10*: The thermal degradation of ABS thermoplastic used in an injection moulding machine caused gas to be ejected when a worker was using a blowtorch to heat scraps from a moulded part caught in the matrix. The ejected gases caught fire, causing burns to the worker's arm and hand.
- Less obvious risks were recorded (the control panel falling while being handled; projection of parts; electric shock).
    - *Example 11*: Two cases of electric shock in two plants were noted when the technicians who were changing a heating band (240 V) of the ejector's reciprocating screw cut the cable clip. The on-off button for the heating bands was in "on" position and the

machine's isolating switch was in operation. In one case, a fall of 1.5 m to the ground occurred.

  - *Example 12*: A metal block that was jammed in a plastic injection moulding machine was ejected and struck the leg of a prospective foreman.

- Lockout is generally not practised in the companies. It was noted that the CSST required lockout when changing moulds in one case. However, the plants generally do not apply lockout procedures when changing moulds due to the need, for the above-mentioned reasons, to maintain the injection unit at a high temperature. It would also appear that the injection moulding machines are not designed to allow the electrical power supply of the heating unit to be separate from that of the hydraulic system (i.e. the electric motor that operates a hydraulic pump that, in turn, operates the hydraulic cylinders and motors).
- It also appears obvious that the companies have not performed risk analysis to identify the risks and validate the necessity and effectiveness of the risk reduction measures.
- When seals were affixed to the machines, it was repeatedly noted that corrective action was taken in the 24 to 48 hours after the seals had been placed. The effectiveness of this corrective action remains difficult to assess solely through these reports.

## 4.2 Overview of the applicable standards and guides

This section provides an overview of the risks discussed in the literature (standards, guides, regulations) regarding horizontal plastic injection moulding machines and their auxiliary equipment and of the best safety practices for these machines and for interventions on them.

### *4.2.1 Machine and auxiliary equipment: risks*

The risks associated with machine-auxiliary equipment systems are the combination of those associated with each part of the system.

**Horizontal plastic injection moulding machines: risks**

As the accident analysis results show, workers who work on these machines are exposed to the risk of serious accidents. While some accidents result in amputations [17], others may be fatal. According to Beauchamp *et al.* [17], the accident risks on these machines are related mainly to unexpected movement of the injection unit, to the existence of many pinch and shear points, to electric current, to heating bands, and to hot materials that can flow or be projected in any direction. There is also a fall hazard due to the presence of oil leaks from the machine [17]. In addition, ergonomic risks related to the handling of heavy parts and to awkward work postures, especially when adjusting and maintaining the machine, exist [17].

**Auxiliary equipment: risks**

Hoisting apparatuses, such as overhead hoists and overhead travelling cranes, can make handling the mould easier. Unfortunately, these apparatuses are also a source of risk, as the worker may be crushed or struck by the load being handled [18]. According to Marinatchi and Arsenault [18], severe or fatal accidents related to the use of overhead hoists and travelling cranes often result from, among other things, the overloading of the hoist slings and the hoisting apparatus, the inappropriate use of the hoisting apparatus, the poor condition of the apparatus, and the proximity of workers during manoeuvres. Nonetheless, for hoisting the mould, the British

Plastics Federation (BFP) [14] recommends using the aforementioned hoisting apparatuses rather than lift trucks. Using a lift truck alters how the load is controlled when the mould change is done by two or more workers, not to mention the physical damage that the lift truck can cause to the means of protection (guards and protective devices) in place [14]. Besides the hoisting apparatuses, other auxiliary equipment can be hazardous for workers. We will focus on the risks observed during our visits.

Accordingly, parts- and sprue-removal robots and parts-removal devices offer several advantages, including that of eliminating the need for the operator to enter the mould area [14, 19]. However, the equipment can also cause serious bodily harm [14] due to the associated risks: risk of being crushed by its grippers; risk of being struck by the robot, moving removal device, or load that it drops; or risk of being crushed between part of the robot or moving removal device and a fixed object or between two parts of the robot or moving removal device [3, 14]. Even if the hazards associated with robots and parts-removal devices are similar, the probability and severity of the harm associated with them may differ [14].

Parts outfeed conveyors, such as belt conveyors, present entanglement hazards, entrapment hazards, and crushing hazards in the nip point of a carrying idler, drive pulley, or tension pulley [20].

Generally speaking, according to NF EN 201 [21], auxiliary equipment can create hazards for which solutions must be found:

- the moving parts accessible due to changes made to the initial protective measures in order to incorporate or remove auxiliary equipment;
- the accessible moving parts of auxiliary equipment;
- altered visibility of the injection moulding machine due to the addition of auxiliary equipment;
- intervention areas made inaccessible on the machine due to the addition of auxiliary equipment.

### 4.2.2 Machine and auxiliary equipment: risk reduction measures

**Horizontal plastic injection moulding machines: protective measures**

If the machine is used without auxiliary equipment, it should include the protective measures described in table 2, whose subscript numbers refer to figure 4. Table 2 shows that the two standards mostly recommend the same types of guard for the various danger zones. However, in contrast to NF EN 201:2009, ANSI/SPI B151.1 – 2007 specifies by name the guard to install, which makes it possible to visualize its location on the machine. Similarly, the HSE [23] and BPF [14] recommend protection measures similar to those recommended in one or the other of these two standards for the danger zones. The numbers in figure 4 refer to the guards by hazardous zone.

For large machines, additional protective measures are recommended [14, 21, 23], including, among other things, the following:

- sensitive protective devices that detect the presence of a worker (e.g. sensitive mat, surface detector) between the fixed and moving parts of the mould;

- control devices of powered moving guards when closing. Such devices should be of the hold-to-run type and meet the recommendations of the EN 201 standard [21] (e.g. adequate visibility of the mould area from the control station, difficult-to-neutralize device);
- component part (difficult to circumvent) of the guard that prevents it from closing when a worker is in the safeguarded hazardous zone.

Moulding machines that allow an entire body to enter the space between the operator's guard (or the mould area light curtain) and the mould area *per se* are considered to be large. In our case, as the machines are used with auxiliary equipment, the changes made to the initial protective measures to allow the auxiliary equipment to be installed should provide a level of safety at the very least equivalent to the original level, although some sources [14, 21, 22] are satisfied with an equivalent level. The protective measures must make the system's hazardous zones inaccessible.

**Table 2 – Means of protection suggested by the ANSI/SPI B151.1-2007 and NF EN 201:2009 standards.**

| Danger zone | Means of protection | |
|---|---|---|
| | **EN [21]** | **ANSI [22]** |
| Mould area (between the fixed and movable platens) | ML or MI, MB (3, 4, 6) | - Operator's guard (ML) (3)<br>- Guard opposite the operator side (ML) (4)<br>- MB<br>- ESD and LC for large machines |
| Area under the mould | ML or F (5) | Top guard (ML or F) (5) |
| Core and ejector mechanism movement area | F or ML or LC (3, 4, 5, 6) | Top guard (ML or F) (5) |
| Clamping mechanism area | ML or F (if access required for maintenance or repair) (1, 2, 11) | F or ML (1, 2, 11) |
| Evacuation opening area | F or ML or DES (12) | F or M (12) |
| Nozzle area | ML or combination: F and ML (7, 8, 9, 10) | - Unperforated purge guard (ML) (7)<br>- Insulating blanket on the injection barrel (against skin burns) (8) |

Key

**F**: **F**ixed guard
**ML**: **Movable** guard with **L**ocking device
**MI**: **Movable** guard with **I**nterlocking device
**MB**: **M**echanical **B**locking device for the movable platen (this mechanical lock [9] protects against the mould accidentally closing)
**ESD**: **E**lectro-**S**ensitive **D**evice
**LC**: **Li**ght **C**urtain
**(1, 2, etc.)**: Numbering of the guards in figure 4

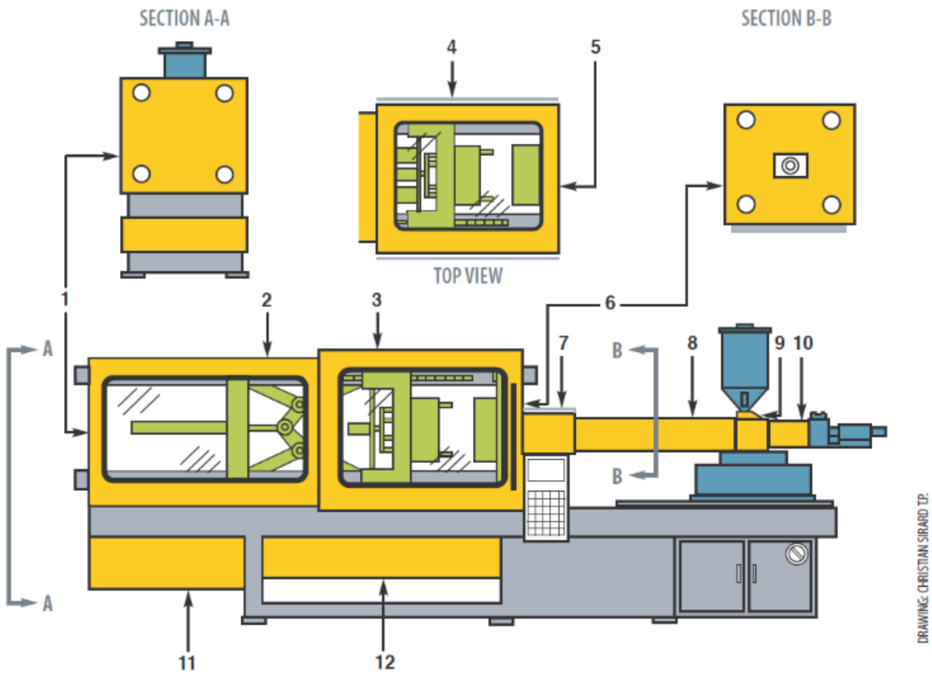



**Figure 4 – Guards on a horizontal plastic injection moulding machine [9].**

**Auxiliary equipment used with the machines: risk reduction measures**

Overhead hoists and travelling cranes

An ASFETM checklist [24] lists the points to check on an overhead hoist or travelling crane. An ASPHME guide [18] that is more detailed than the grid suggests safety measures to be applied to prevent hoisting device-related accidents. The two documents equip employers and workers to safely use the devices and to comply with the Quebec Regulation Respecting Occupational Health and Safety (ROHS) [16]. The regulation requires that hoisting devices "be used, maintained and repaired in such a manner that its use does not compromise the health, safety or physical well-being of workers" [16].

Robots

United States standard ANSI B151.27-2003 [25] suggests safety practices for integrating, maintaining and using robots in the mould area of plastic injection moulding machines. It calls for a visual inspection of the machine-robot system to be performed before any intervention on the machine. This makes it possible to determine whether the system is damaged and ensure that the emergency stop function is operating properly, for example. It requires that the worker in the machine have mastery of the machine-robot system in order not to become the victim of start-up by a third party. To accomplish this, applying ergonomic concepts (e.g. visibility of the danger zone), among others, in the machine design is crucial [26, 27]. In addition, starting the robot must always be intentional, especially after a means of protection has been reinstalled or following a loss of power. Each control station of the machine-robot system must include an easily accessible emergency stop device that is used only for emergency shutdowns. The emergency stop must override all other controls. Activating any of the emergency stop devices must bring the system to a complete halt: the machine, the robot, and all other auxiliary equipment and sources of danger associated with the machine. At the very least, the machine-robot system must have a means for disconnecting the power supply. This means must be located outside the system's danger zones and have lockout capability.

Suvapro [28] recommends that the robot have low-speed and step-by-step controls during adjustment and maintenance. In addition, he recommends a protective housing on small handling robots that serve the machine. Similar to the housing for small robots, he recommends a protective enclosure for larger robots. The doors of the enclosure should be electronically monitored. If the enclosure has openings, they should not allow access to a danger zone. If the worker has to enter the enclosure, the associated auxiliary equipment must be switched off and verified as such and its protective devices free of any defects or circumvention. The BPF [14] has formulated several recommendations regarding the design of the enclosure. For example, the perimeter fence should be 2 m high and located at least 45 cm from the maximum working envelope of the robot. However, the research team feels that these dimensions are intended as general guidelines and that only an assessment of the risk presented by the installation to be implemented will allow them to be properly determined. In addition, the interlocking system for the protective enclosure should not only be through the controller but also be served by a hard wired backup circuit that cannot be influenced by the programmable electronic system [14]. Nonetheless, the selected means of protection should also result from a risk assessment performed preferably at the robot's design/preinstallation planning stage [14].

Pick-and-place devices

Pick-and-place devices should be fitted with fixed or interlocked guards that block access [14]. For example, for a pick-and-place device mounted on top of an injection moulding machine, fixed guards should be installed to prevent access to the side where it delivers the parts produced and to the mould area from above. A protective enclosure similar to that used for robots may be installed. Obviously, it will be smaller than the robot enclosure, as pick-and-place devices have a smaller minimum working envelope. A risk assessment will indicate which type of guard should be installed.

Conveyors

Regarding the risks inherent in belt conveyors, for example, Giraud *et al.* [20] recommend using adequate fixed guards, such as in-running nip fixed guards.

### Injection mouling-auxiliary equipment system: inherent prevention

Safety functions are attributed to the above-mentioned means of protection (interlocked guards and enclosures). A safety function is a "function of a machine whose failure can cause an immediate increase in the risk or risks" [29]. ISO 12100 [29] considers that the safety functions are part of the inherent prevention measures applied to machine control systems. For example, a safety function can consist of instantaneously stopping or reversing one of more hazardous movements when a guard is opened. A safety function can also consist of maintaining the value of a reduced speed. In our case, the safety functions are handled by the control system shared by the machine and its auxiliary equipment. In some cases, the safety functions are handled by safety components, standard components dedicated[2] to safety, or standard components.

[2] "Dedicated" means that outside input must be provided to bring the safety PLC to the same level as a safety component [32]. Compared with a standard PLC, a safety PLC is more reliable, the risk of accidental activation being very low [33].

However, the IFA [30] maintains that the use of components not dedicated to safety, such as standard PLCs, is to be avoided in complex subsystems with the same design (homogenous redundancy) used to reduce medium or high risks. These kinds of subsystem should be ruled out because they are not effective enough to detect faults (hidden design faults, for example) [30]. For all these reasons and in such cases, the IFA [30] recommends using safety PLCs rather than standard PLCs. Safety PLCs often assist the user (in avoiding compiling errors and failures) during safety-oriented programming and parameterization and provide the necessary access protection [30]. Lastly, the IFA [30] states that use of safety components or standard components dedicated to safety instead of standard components in the design of a safety function facilitates estimation of its performance level. This is due to the fact that the safety components or standard components dedicated to safety will satisfy the performance level estimation requirements; the performance level can even be provided with the component [30]. Unfortunately, designing a safety function with standard components is more difficult; the users themselves have to verify the standard component's conformity with the standard's requirements (in this case, NF EN ISO 13849-1:2008 [31]).

The lack of information about a component, from either the designer or the manufacturer, is a factor that makes this verification more complex or even impossible [30]. Thus, it is preferable that an integrator make secure a horizontal plastic injection moulding machine or any other machine using safety components or standard components dedicated to safety. For the integrator, it will be a much easier way of estimating the performance level of a safety function of the machine and thus of quantifying the level of risk reduction provided by the safety function. Comparing this level of risk reduction to the risk reduction objective will make clear whether additional risk reduction means are required [29, 31].

Furthermore, according to the design principles of the control circuits governing the safety functions, it is recommended to separate the standard control functions from the safety functions [34]. It is preferable to control the safety functions using hardwired logic instead of a safety PLC, as the failure modes of hardwired safety functions are better known than those of safety PLCs [7, 32, 35]. In contrast to a safety function, the role of a standard control function is only to assist with the machine's operation in production or adjustment mode [34]. Although the role of a safety function is to ensure the safety of the machine's user, this guarantee (or reliability) is not 100%. This means that when a user enters the mould area and ensures his[3] safety by opening a guard, the risk of the mould's accidentally closing is nonetheless present. However, it is acceptable to consider that one is safe if the stop function for the guard opening is very reliable. For it to be so, it is important to ensure that a safety function provides the risk reduction required with respect to the hazards from which it is protecting the machine user (chapter 6 of this report presents a case study on this issue).

**Injection moulding-auxiliary equipment system: safe work methods**

Safety functions, such as reduced speeds and hold-to-run controls, can be required when implementing work methods. In Quebec, under section 186 of the ROHS [16]:

> When a worker must access a machine's danger zone for adjustment, unjamming, maintenance, apprenticeship or repair purposes, including for detecting abnormal operations, and to do so, he must move or remove a guard, or neutralize a protective

[3] The use of masculine pronouns to refer to persons of either sex is intended solely to facilitate reading and with no discriminatory intent.

device, the machine shall only be restarted by means of a manual control or in compliance with a safety procedure specifically provided for allowing such access. This manual control or this procedure shall have the following characteristics:

(1) it causes any other control mode or any other procedure, as the case may be, to become inoperative;
(2) it only allows the operation of the dangerous parts of the machine by a control device requiring continuous action or a two-hand control device;
(3) it only allows the operation of these dangerous parts under enhanced security conditions, for instance, at low speed, under reduced tension, step-by-step or by separate steps.

Along the same lines, the Suvapro [28] checklist also encourages the use of low-speed modes and step-by-step controls to ensure worker safety on injection moulding machine during adjustment and maintenance operations. Another way to improve the safety of interventions in the mould area is to lock out the machine and any hazardous equipment located nearby. Under section 185 of the Quebec ROHS [16], lockout is the means imposed in Quebec (subject to the above-mentioned section 186) before intervening in a machine's danger zone for repair, adjustment, and maintenance purposes.

Always with a view to protecting the worker, his work station and environment must be suitable: clean, uncluttered, with noise at an acceptable level or, if it is not, the worker must wear hearing protectors and a written warning reminding workers to wear their hearing protectors must be clearly visible [28].

To be safe when **operating** the injection moulding machine, all guards must be in place and must provide adequate protection [23]. Checking that the means of protection are functioning properly is crucial. For example, opening or removing a guard with an interlocking device should prevent the movable platen from moving. This is also what is recommended by the IRSST's safety checklists for horizontal plastic injection moulding machines [9].

To make **maintenance** interventions safer, the HSE [23] recommends monthly inspections of the safeguards, more extensive than the operational checks. The HSE's recommendations for operation and maintenance are prompted by the fact that a large number of accidents are due to removal of protective devices provided with the injection moulding machine or to their deterioration (especially during maintenance [14]), which was corroborated by our analysis of the accident and intervention reports.

To make **mould changing** interventions safer, the HSE [23] recommends prevention measures to be applied before, during and after the intervention. For example, before beginning to change the mould, the injection unit should be retracted from the mould, the core pulling mechanism and ejector couplings should be isolated, and the lifting equipment used to remove and install the mould must be adequate. During mould changing, two work methods are possible:

<u>1. Mould changing with guards/interlocks in use</u>

The HSE [23] prefers this method. It recommends checking that the core/ejector mechanism will not move when the operator's guard is open. If it is necessary to work in a guarded danger zone, all parts of the machine should be made inoperative by activating the emergency stop, even if the guards and interlocks are operational. If, during the mould changing procedure, no powered movement is required for a prolonged period, locking out the machine is recommended.

2. Mould changing with guards/interlocks removed

The HSE [23] recommends using this method only if no other option is available. In such cases, it calls for the injection moulding machine to be locked out.

For its part, the Caisse nationale suisse d'assurance en cas d'accidents (CNA) [36] recommends an 11-step procedure for installing the mould: (1) assemble the fixed and movable parts of the mould using fasteners (e.g. clips) if not equipped with a guidance device (this step is performed away from the machine); (2) hook these two joined compartments onto the hoist; (3) move the mould and position it against the fixed platen's centring device; (5) remove the hoist's hooks and slings; (6) close the guard (not specified but, based on the plant visits described in section 4.3 of this study, we assume it is the guard on the operator's side); (7) move the movable platen to the mould (clamping movement); (8) open the guard; (9) attach the mould to the movable platen; (10) remove the fasteners holding the mould compartments together; and (11) make the necessary adjustments to the machine. After the mould is changed, it is recommended to check that the installed means of protection are functioning properly by performing the same checks recommended by the HSE for maintenance [23]. The HSE [23] makes a point of emphasizing that these post mould changing checks do not exempt a worker from checking that the means of protection are functioning properly before operating the machine.

It should be noted that workers who intervene on the machine-auxiliary equipment system to perform inspection, maintenance, production, adjustment, or other work must be trained and competent for carrying out their tasks [28]. At all times, it is the employer's duty to make available to workers the work and maintenance instructions and the personal protective equipment (PPE) necessary for the work they are to perform [28]. The PPE may be hearing or eye protectors, protective footwear, or protective gloves [28]. For their part, the workers must comply with the work and maintenance instructions and wear the PPE.

## 4.3 Description of the visits made and tasks observed

Besides the results mentioned earlier, the literature review was also used to develop a data collection tool, the final version of which is presented in Appendix A. The tool has five parts:

- Part A: initial contact and questions of a general nature (in a meeting room);
- Part B: identification of the injection moulding-auxiliary equipment system studied (at the system);
- Part C: information on the injection moulding-auxiliary equipment coordination (at the system);
- Part D: risk identification (at the system);
- Part E: identification of the risk reduction measures, tests (at the system).

Using the data collection tool during its visits, the research team questioned various interveners, depending on the functional testing of the means of protection and on the type of task observed. The intervener in question could be an OHS manager, a maintenance technician or mechanic, an injection moulding machine operator, or a mould changer. To be able to describe the tasks, it is important to place them in the context in which the visits took place (table 3). It should be noted that in table 3, when a single visit was paid to a plant, the visit and the plant are identified with the same letter. When more than one visit was paid to a plant, a number accompanies the plant letter. In all, eight visits were made: the preliminary visit, D1, in particular to develop the data collection tool, and seven visits to collect data. Note that at plant D, visits D1 and D2 consisted of observing the same machine-auxiliary equipment system, while at plant F, the two visits allowed two different systems to be studied.

First, we note that all the participating plants are relatively large in size. Although the majority of plants in the industry are small- and medium-sized companies (SMEs), our efforts to arrange visits at some of them (around 30 were contacted by telephone or email) were in vain. As a result, the available means (physical and human) observed may be larger than those in SMEs. Nonetheless, the visits remain relevant because the risks are the same for all injection moulding machines as are the tasks to be performed. What can differ between SMEs and large companies are the risk reduction means in place. Thus, the risks identified in this study (leaving aside the means of protection in place) are universal but the risk reduction solutions observed undoubtedly reflect the most advanced practices in the industry. Incidentally, the analysis of the accident reports, which is discussed in section 4.1, allowed us to collect data on the risk reduction means specific to the plants we did not gain access to (mainly SMEs), in addition to obtaining information on the types of accident.

**Table 3 – Context of the visits.**

| | Visit | Number of employees | Positions of the persons interviewed | Observed configuration | Machine tonnage (tons) | Machine's year of manufac-ture |
|---|---|---|---|---|---|---|
| **Plant A** | A | 70 | Electromechanic<br>Mould assembler<br>Management coordinator<br>HSF manager | Machine<br>+ 2 conveyors<br>+ travelling crane* | 600 | 1997 |
| **Plant B** | B | 200 | Production manager<br>Set-up technician, mould assembler<br>Chief mechanic | Machine<br>+ 3-axis robot<br>+ travelling crane | 1,000 | 1996 |
| **Plant C** | C | 200 | Department head<br>Electromechanic<br>Mould tester technician | Presse<br>+ 3-axis robot<br>+ conveyor<br>+ travelling crane | 2,200 | 2002 |
| **Plant D** | D1<br>D2 | 80 | Technician (mould assembler, set-up technician, start-up)<br>Manufacturing technician | Machine<br>+ 6-axis robot<br>+ 2 conveyors<br>+ pelletizer | 200 | 2004 |
| **Plant E** | E | 100 | Mechanic<br>Safety coordinator<br>Plant manager | Machine<br>+ 3-axis robot<br>+ 1 conveyor<br>+ travelling crane | 1,000 | 1998 |
| **Plant F** | F1 | 450 | OHS manager<br>Electromechanic | Machine<br>+ 3-axis robot<br>+ conveyor | 3,500 | 2008 |
| | F2 | | Training manager<br>Electrotechnician | Machine<br>+ 6-axis robot | 720 | 1999 |

*Although an overhead travelling crane is always found in the plants, it is listed here only when it was used to perform the observed tasks.

It should be noted that the auxiliary equipment listed in the observed configurations is virtually always the same. However, despite this apparent similarity, these machines can be placed in relation to each other in many different ways. The configurations that the research team observed are diagrammed in figure 5.

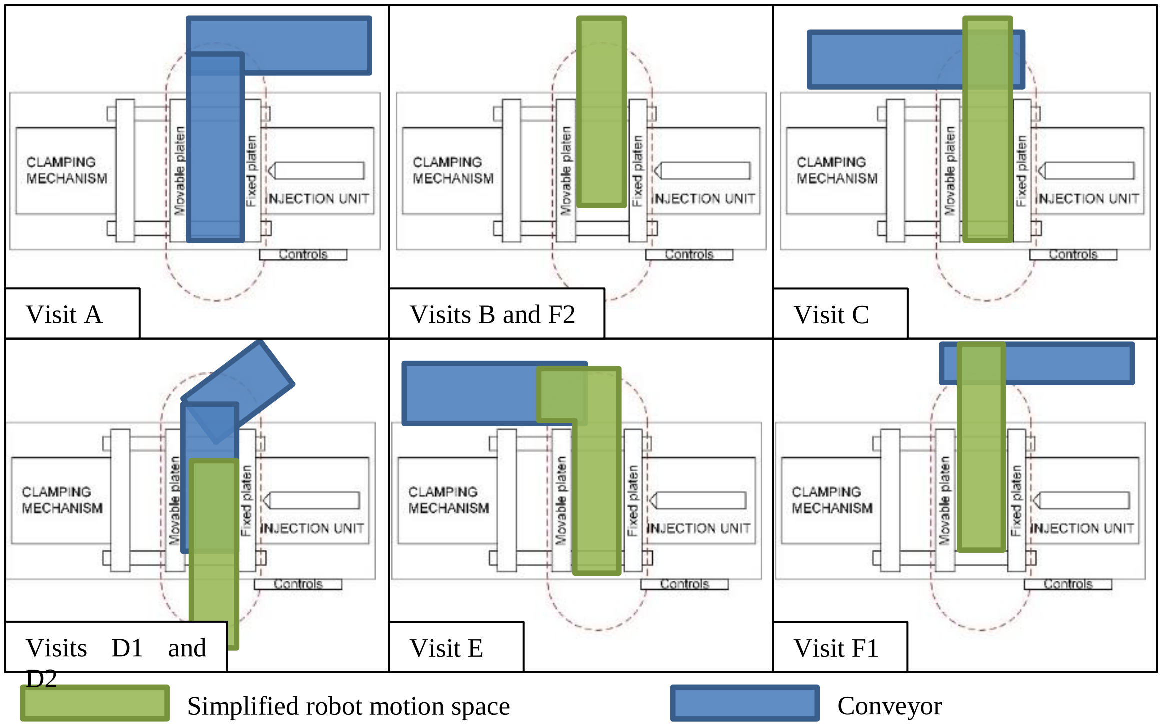



**Figure 5 – Schematic diagram (not to scale) of the various configurations of the injection moulding-auxiliary equipment systems observed.**

This diagram shows only the auxiliary equipment that impinges on the study zone, which is outlined by the red dotted line. Note, too, that the machine-auxiliary equipment systems are viewed from above and that the third dimension should not be overlooked. For example, the parts may be recovered by gravity drop onto a conveyor or by a robot that moves along either the operator side or the opposite or from above. Many other parameters will influence the position and size of the auxiliary equipment. In addition, contrary to all the other plants visited, in the visits to plant D, the robot was located on the operator side. However, in that case as in visit C, the robot moves respectively in the path of the operator's movable guard or of the movable guard opposite the operator (and not above). One consequence of this arrangement is that it allows the injection moulding machine to be operated when a movable guard is open; the robot's enclosure then takes the place of the movable guard.

Now that the general context of the visits has been described, we can briefly examine the characteristics of the observed tasks before turning to the results that meet the main objectives of this study, namely to identify the risk components and the risk reduction measures implemented in the plants. As in a duly performed risk analysis, which would require a more comprehensive study, each risk that we identified is related to the one or more tasks that expose the workers to it.

Depending on the availability of the resources in the plants, we were able to perform functional tests of the means of protection (visits A, B, E, F1, F2) and observe the following tasks, detailed descriptions of which will be found in Appendix B: mould disassembly (visits A and E), mould assembly (visits A, B, C, and E), insert replacement (visit D1), mould cleaning (visit F1), mould polishing (visits C and F1), and production tests (visit C).

The size and complexity of moulds mean that the mould changing period may last anywhere from an hour (visit E) to a more than seven-hour workday (visit C) and require one person (visit A) or up to four persons (visit C). The mould assembly and disassembly operations observed during visits B and E were performed by two persons. The mould cleaning and polishing operations observed require one person each and may be performed simultaneously. In this case observed during visit F1, the chosen risk reduction measure was to apply a padlock on the control panel (cf. section 4.4.1 and chapter 5). Another use of padlocks was noted during visit A but for an intervention involving only one person. This consisted of using a padlock to physically prevent the operator's guard from being closed (cf. section 4.4.1 and chapter 5).

Each of the interventions observed by the research team is regularly planned and occurs at different intervals depending on production. Corrective interventions are more difficult to observe because they cannot be foreseen far enough in advance. Nonetheless, the eight visits provided a wealth of collected data and made it possible to draw a very complete picture of the identified risk components and of the various protective measures implemented by the plants.

## 4.4 Risk components and risk reduction means used in the plants

The risks observed in the plants have been collated in a table in Appendix C based on their four components: hazards, hazardous situation, hazardous event, and associated injury. The means used by companies to reduce these risks are also complied in the table. However, these risk reduction means mainly involve inherent prevention, means of protection (guards and protective devices), and PPE. In addition, in the table in Appendix C, each risk reduction means is accompanied by a number enclosed in parentheses. These numbers correspond to the risk component at which the risk reduction means is aimed. The choice of type of risk reduction means listed in the table is explained by its practical character: these risk reduction means are often generic and may, therefore, correspond to several plants at the same time, whereas the other means, depending on the plant visited, had special characteristics that should be noted. In addition, even if the risk reduction means related to the safety control circuits for the visited machines appear similar in terms of the input and output of the safety functions used, the processing of these safety functions is handled by components assembled in configurations that can vary from one system to another. In the following two subsections, we will examine the risk reduction means used (other than those in Appendix C) and the various control system configurations encountered. In 4.4.1, we will note that the safety of the workers observed in the mould area depends largely on the control system's functioning properly due to the extensive use of safety functions. It is therefore important to examine these configurations in order to understand their strong and weak points.

### *4.4.1 Other risk reduction means used*

**Warnings and signs**

Various signs and messages are found on the equipment to warn of the risk of accidents (figure 6). For example, besides noting the presence of high-speed moving parts, the text in figure 6 warns the user about the possibility of crushing injuries and death. To avoid such incidents, the message says not to operate the machine with the gates or guards open or removed or reach into or enter the danger zones while the machine is operating.


**Figure 6 – Warning message affixed to the frame of the machine.**

This English-language message is used in a plant where some of the operators do not understand English. For safety purposes, it is desirable that such messages be in a language understood by all the workers. In cases where the message came on the original machine and is in a foreign language, a translated version of it in the workers' language can be posted next to it.

In the event of irregularities (e.g. emergency stop triggered, open operator's guard), the machine's control panel alerts the machine operator by means of a display. In some plants where the gates of the robot safety enclosure include a locking or interlocking device, indicator lights signal when it is authorized to enter the protected area (see the "permission to enter protected area" indicator light in figure 7).

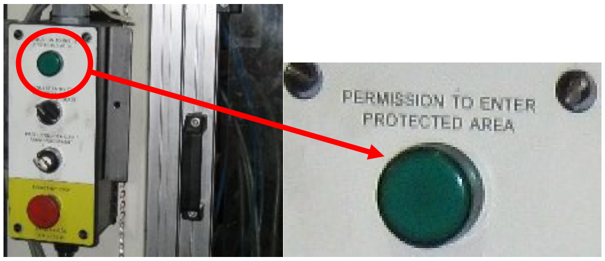



**Figure 7 – Green indicator light signalling that the enclosure gate can be opened.**

**Work methods**

The visited plants do not have procedures that explain the steps involved in repairing the injection moulding machine, changing or cleaning the mould, performing production tests, or installing inserts. However, they do have written safety measures that the worker must follow in order to intervene safely in the mould area. On reading these measures, we noted that they can be classified into three types: (1) use of a partial lockout/blockout procedure; (2) use of safety functions; and (3) inspection. These three types of measure describe the maintenance and production interventions observed in the mould area. While observing tasks, we noted work methods that included safety measures that could be used as examples and others that should be prohibited.

<u>Use of a partial lockout procedure</u>

At plant A, a partial lockout procedure is recommended for mould changing operations. This partial lockout consists of affixing a padlock to the operator's guard (movable and interlocked) and its rail so as to ensure the gate cannot be closed (figure 8). This procedure prevents the accidental closing of the operator's guard, which, when closed, allows the movement of moving parts in the mould area. This operator's guard locking procedure should be combined with the actual lockout of the auxiliary conveyors in this area (figure 9) to prevent them from unexpectedly starting while the operator is positioned on them to gain access to the mould area. Accidental start-up of the conveyor would cause the worker to slip and fall onto the mould area's guide cylinder.

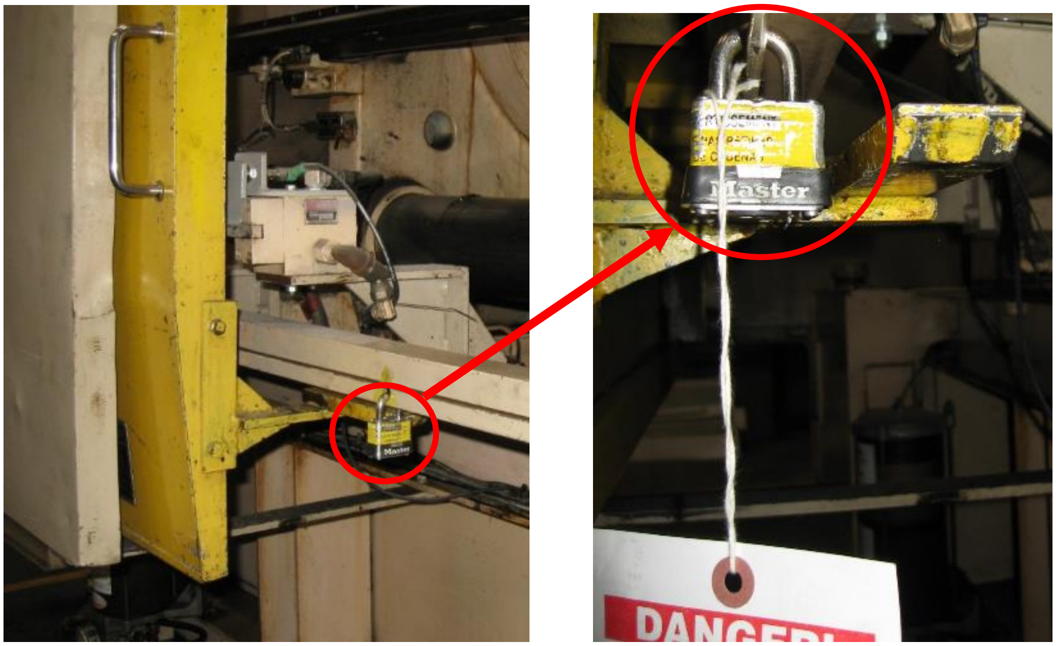



**Figure 8 – Partial lockout: the padlock blocks the operator's guard on its rail.**

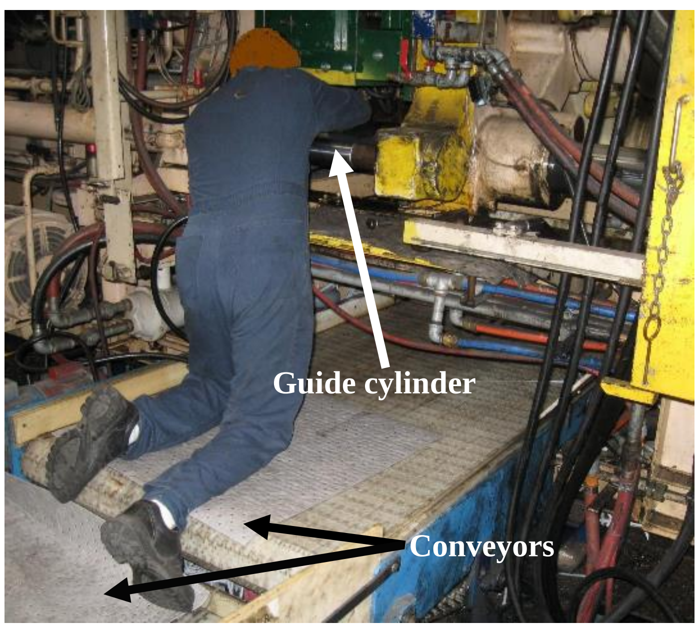



**Figure 9 – Worker installing a mould while kneeling on a conveyor.**

During visit F1, when the mould was being polished and cleaned (preventive maintenance), the various workers blocked access to the control panel by installing a Plexiglas sheet over it. The sheet was locked out and the single key for the padlock was placed in a lockout box to which each intervener had attached his personal padlock (figure 10).

(1)

(2)

**Figure 10 – Partial lockout/blockout: group lockout (1) and control panel lockout (2).**

Some plants, in particular A, B, C, and D, apply lockout procedures for their injection moulding machines or auxiliary equipment. However, these procedures are used only for major maintenance and repair tasks. One of the procedures attracted our attention because it limited the lockout only to the machine’s electric power supply (lockout of circuit breakers). It should always be borne in mind that hydraulic, pneumatic and other forms of energy can be released unexpectedly when performing a task. A risk analysis of the machine must be made to know which energy sources threaten workers’ safety when performing specific tasks and how these energy sources should be isolated and blocked. It is important to be aware of the potentially hazardous energies associate with auxiliary equipment (e.g. robots, conveyors, pelletizers). The workers we met told us that they never locked out the nearby robots or conveyors when working in the mould area. They were content with putting the auxiliary equipment into its initial starting position (for robots) and then switching it off or unplugging it. For unplugged equipment, we recommend placing the electric plug in a lockout device onto which a locked-out hasp is attached by way of ensuring that a third party does not plug in the equipment.

Use of safety functions

The partial lockout/blockout described above involves the use of various safety functions, such as those related to the operator’s guard and to the mechanical blocking bar (or mechanical stop bar). Each of these safety functions prevents the movement of a moving part in the mould area: movable platen, cores, ejectors. These same types of security function, in particular those related to the operator’s guard, were much relied on when the observed tasks were being performed during our visits. Another safety function used is the emergency stop function. At plants B and D, the procedure for intervening on the injection moulding machine or in the robot enclosure requires that the emergency stop be activated after all the motors and pumps of the machine and the robot have been simply switched off. Moreover, at plant B, the procedure requires that the sign (figure 11) warning that a human is working inside the machine be affixed to the machine's control console (using the Velcro preinstalled for the purpose). Our observations indicated that the procedures were followed in both plants.

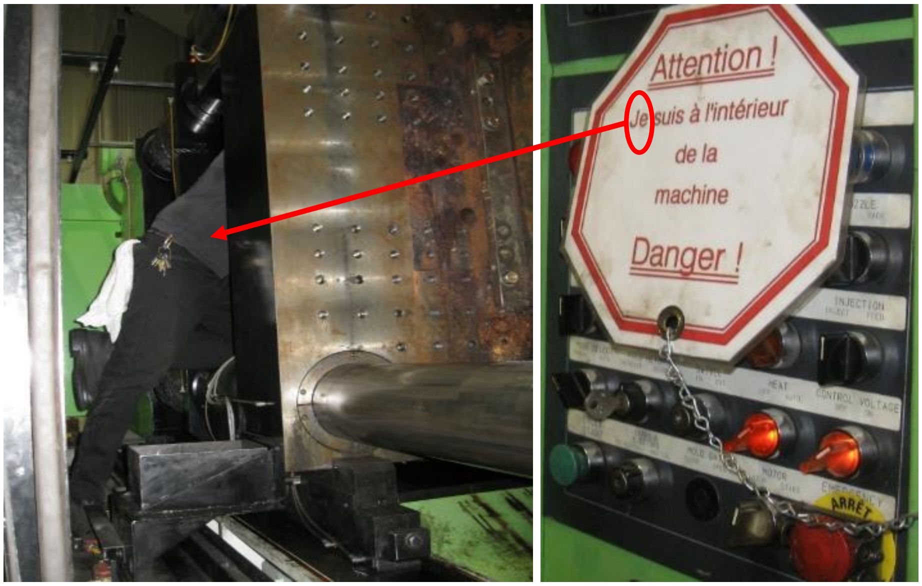



**Figure 11 – Sign warning that an unseen worker is inside the machine.**

<u>Inspection</u>

Plant D carries out a daily visual inspection of its overhead travelling carne. At plant C, an annual, in-house inspection of the travelling crane is performed. Other plants have their travelling crane inspected by an outside party (manufacturer or subcontractor), namely plant F (four times a year) and plants A, C (in addition to the in-house inspection), D, and E (all once a year). Plant B has not had its travelling crane inspected but acknowledges that it should be done.

Inspection of the means of protection is performed in at least three of the plants. In at least two, such an inspection is required. According to the plants, the inspection is done quarterly, daily, or after the mould is changed or major maintenance work on the machine has been performed. Ideally, such inspections should be done before and after every intervention in the mould area, much like the mould changing inspection recommended by the HSE [23]. The pre-intervention inspection allows the worker to ensure he will be safe, while the post-intervention inspection is important for checking that the operation of the means of protection has not been altered.

The observed mould changers carry out a visual inspection of the condition of the mould hoisting and attachment accessories before using them. Unfortunately, one mould changer used a hook despite there being a defect in its latch. Although the mould is held by two hooks, if the defective latch gave way, the mould could partially come loose and strike someone.

In addition to the above-mentioned risk reduction means, in table 4 we present others that we observed. They facilitate or make safer performance of the three types of procedure presented (i.e. partial breakout/lockout procedure, use of safety functions, and inspection).

**Table 4 – Risk reduction means that facilitate performance of the presented procedures.**

| Visits | Risk reduction means |
|---|---|
| **B** | Protection from start-up by a third party: shutdown procedure for the injection moulding machine and auxiliary equipment + lockout of the emergency stop button with a key controlled by the operator placing one leg or more in the machine |
| **B, D1** | Work strategies developed to reduce the number of return trips between the operator side and the opposite side (during mould assembly) |
| **B** | Placing of visual guides on the mould to facilitate hose connection (reduces the mental effort required of the worker and speeds his work) |
| **C** | Indicating the power cable connection points on the mould to facilitate electrical connections (reduces the mental effort required of the worker and speeds his work) |
| **A. C** | Compliance with the rules governing the handling of loads with a travelling crane (section 255 of the ROHS [16]) (figure 12 below) |
| **D1** | Switching off the hydraulic motor before entering the mould area or robot enclosure |
| **E** | Key required to manually advance the mould available only to the mould changers |
| **E** | Key required for reset in cases where the robot leaves its axes. Key available only to the person responsible for maintenance |
| **F1** | Limited access for activating and deactivating the robot: the employees have cards providing different levels of access based on their position in the company. The robot can be activated/deactivated only with an electrical technician-level or higher card. |

**Figure 12 – Example of handling a mould with an overhead travelling crane.**

### Training

In discussions with a manager and workers at plants A and D, it was noted that they are aware of the risks to which they are exposed when performing their tasks and in the plant in general. This awareness of the risks, apparent in the discussions as well as in the behaviours observed, grew out of their involvement in the risk management process in the plant. Their involvement helped train them in occupational safety.

Most of the plants train their employees on the use of hoisting apparatuses and accessories. In terms of training, plant C stood apart: during a discussion with the plant manager, we noted that he placed a strong emphasis on training (e.g. OHS, travelling cranes, lift trucks, first aid, electromechanics). The manager takes advantages of slack production periods to send employees for theoretical and practical training, which requires sound management of time and resources. He strongly believes in continuous training for his employees because he feels that the better one is trained, the less vulnerable one is. This is very much in line with the literature on the subject. For example, Beauchamp *et al.* [17] contend that, in view of the many hazards associated with injection moulding machines, it is impossible to overstate the importance of training operators and workers who work near this equipment.

**Information**

Even if much information is contained in the training notes, it is necessary to ensure that the trainer adequately conveys it. For example, a trainer unfortunately told an electrical technician met during a visit that "The injection moulding machine is a four." In discussing the matter with him, we understood that he wanted to say "This is a category 4 injection moulding machine." The notion of category[4], explained in ISO 13849-1 [31], is a characteristic reserved for safety components and safety functions but not for the machine as a whole. The electrical technician, despite being very skilled in the design of standard control systems, unfortunately did not use the proper term for a notion exclusive to safety related control systems.

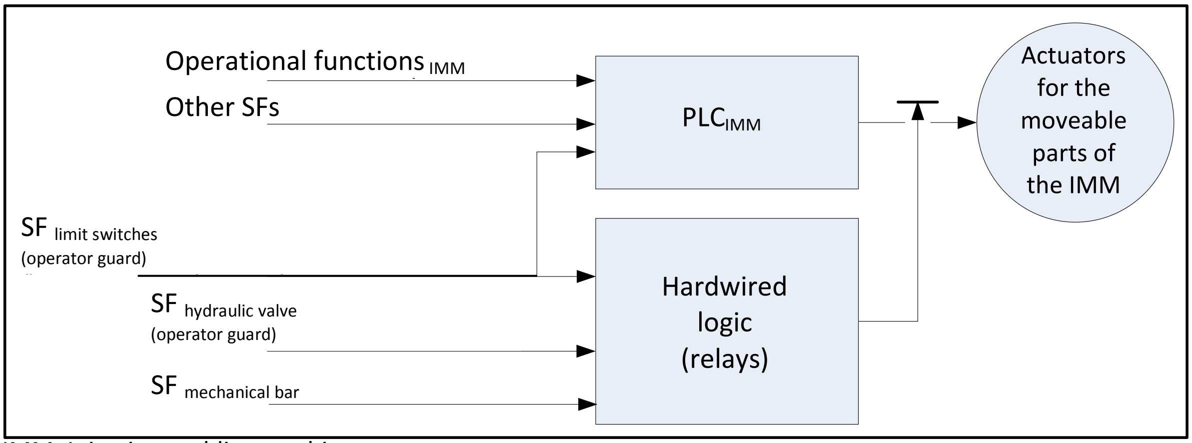
Sadly, no equipment integration plans were to be found at one of the plants. Fortunately, most plants had the initial plans for their machines and plans after auxiliary equipment had been integrated. It is a good idea to document, in plans and in writing, any changes made to a machine's control circuit. It leaves a trail that can be followed by a new worker who wants to understand how the facility was conceived and implemented, whether for his personal knowledge or to make repairing or modifying the machine easier. Having information about the circuit to be worked on is a means of reducing the risk of an accident. Having machine plans increases the likelihood of a successful repair or modification. Also, in the long run, if the personnel change, the successors will be able to find their around the machine's control circuit more easily.

### 4.4.2 Field report on safety-related control systems

As mentioned earlier, we will examine the configurations encountered during our visits. They are diagramed on the basis of explanations provided by the persons questioned during the visits. During visit F1, we were able to examine the plans for the injection moulding machine and its robot. This confirmed the configuration previously diagrammed on the basis of discussions with the workers taking part in the study. The discussions with company spokespeople also helped inform us about the approach used to integrate the components and auxiliary equipment with the injection moulding machine.

Based on discussions with the participants, we noted that there are three possible configurations for communication between the machine and the integrated components. These are diagrammed in figures 13, 14, and 16.

[4] By "category" we mean the classification of the security-related parts of the control systems based on their architecture, defect resistance, and way of acting after one or more defects [31].

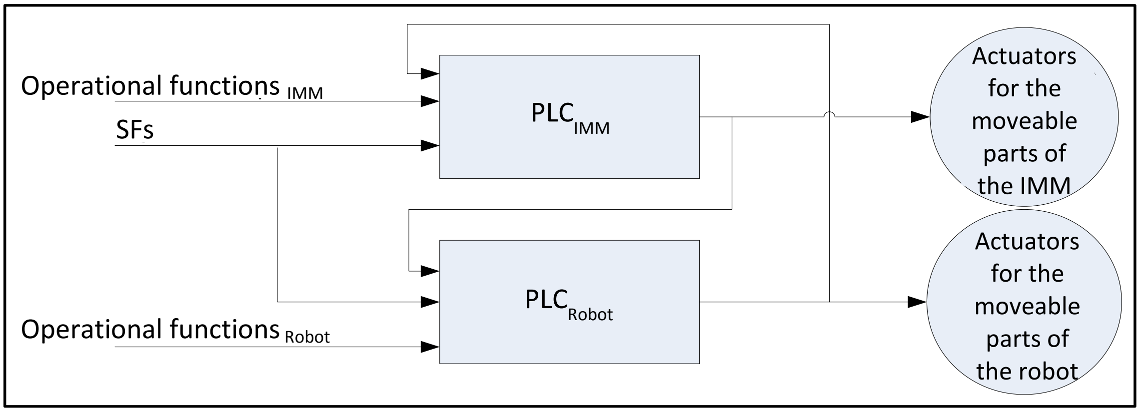


IMM: Injection molding machine

**Figure 13 – Diagram of the configuration of a control system consisting of a PLC and a hardwired logic module (plant A).**

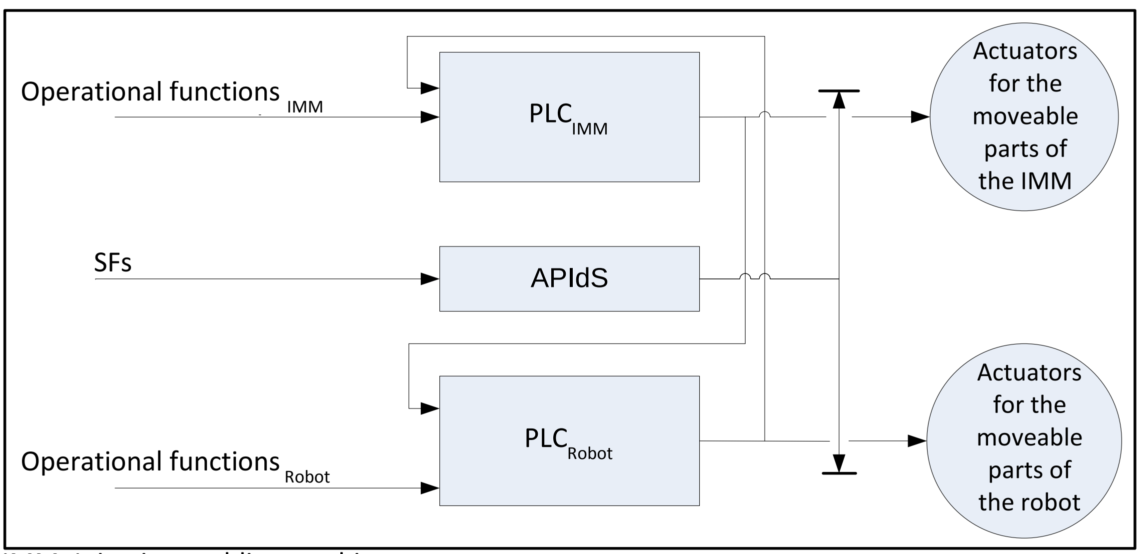
Looking at figure 13, we note that if the injection moulding machine's PLC fails dangerously, the safety control functions' input into it will not be executed and will therefore neither stop nor prevent the movement of moving parts. Fortunately, the safety functions related to the operator's guard and the mechanical blocking bar go through the hardwired logic module (this creates a redundancy). If we open the guard, despite the failure of the PLC, the relay will open the circuit, which will deactivate the actuators of the machine's moving parts. This configuration is safe only with respect to the safety functions of the operator's guard and the mechanical blocking bar; if we activate the emergency stop or any other safety function, nothing will stop should the machine's PLC fail. because they are part of the "Other SF" category shown in the preceding diagram (where SF stands for "safety function"). It would be better to connect all safety functions to the hardwired logic module, although it is also important for these safety functions to remain simple.

The PLCs shown in figures 13, 14 and 16 process both operational functions and safety function. For the reasons stated in section 4.2.2, it is preferable to separate the processing of the safety functions from that of the operational functions and to use a hardwired logic module for the safety functions (like at plant A). However, when the system to be secured is complex and the number of safety functions large, a safety PLC can be used [33] but not an standard PLC. Even if the safety PLC can manage both the safety functions and the operational functions, it is preferable that all safety functions be managed separately by the safety PLC. Unfortunately, the participants in the visits could not confirm whether their PLC was a safety PLC; the term was unknown to them. Based on proposals in the literature, figures 15 and 17 suggest safety improvements for the configurations found in plants B, C, D, E, and F. We note that, in these proposals, the operational functions are processed only by the PLCs while the safety PLCs process the safety functions.




IMM: Injection molding machine

**Figure 14 – Diagram of the configuration of a control system consisting of two interacting PLCs: one for the moulding machine and one for the robot (plants B, D, E, and F).**




IMM: Injection molding machine

**Figure 15 – Suggested improvement for the configuration at plants B, D, E, and F.**

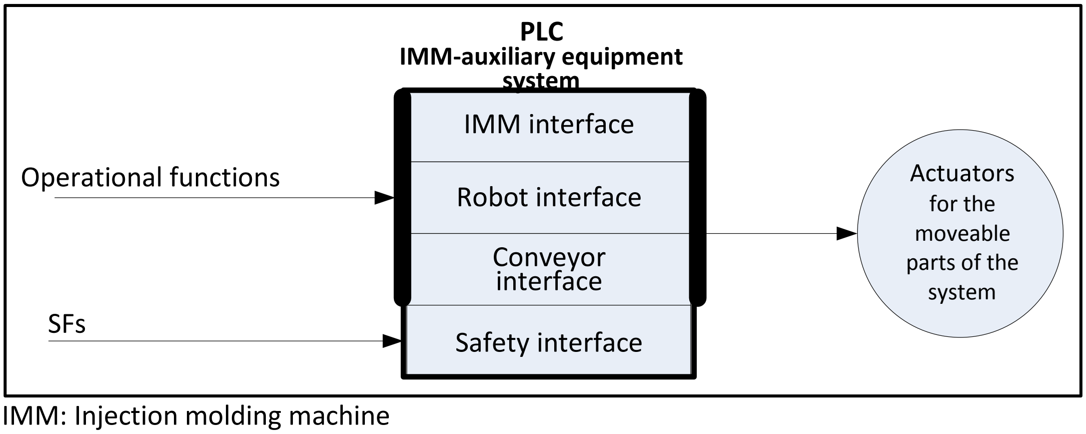



**Figure 16 – Diagram of the configuration of a control system using the same PLC for the moulding machine and its auxiliary equipment (plant C).**

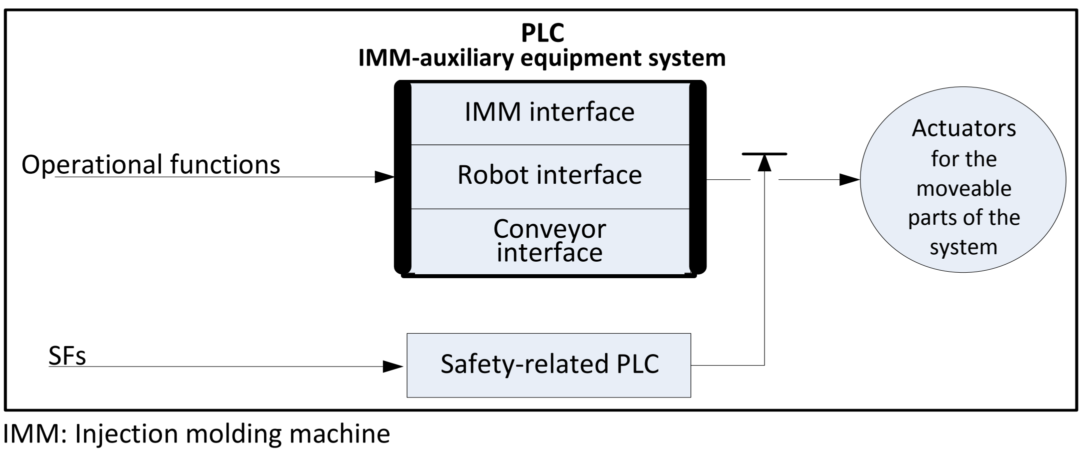



**Figure 17 – Suggested improvement for the configuration at plant C.**

As for the integration of auxiliary equipment with the moulding machine's control system, it emerged that, generally speaking, only the robot was integrated with the moulding machine. The conveyors were often independent of the system, except for the conveyor at plant C, which was integrated into the system, though only for automatic mode. For example, at this plant, activating the emergency stop using a button other than the one for the conveyor would stop the conveyor but only if it were operating in automatic mode. Incidentally, during visit F1, the conveyor was seen to start moving unexpectedly from time to time. This is a potentially hazardous event if a worker happens to be walking on the conveyor in order to gain access to its electrical control cabinet. This problem of sudden start-up should be resolved and another access route to the electrical cabinet considered. table 5 summarizes the context in which the auxiliary equipment and programmable unit were integrated with the injection moulding machine's control system.

**Table 5 – Overview of the context for integration with the injection moulding machines.**

| Visit | Injection moulding machine designed to accept auxiliary equipment | Integration by a plant employee | Integration by the equipment manufacturer (m) or an outside firm (f) | Integration based on plans |
|---|---|---|---|---|
| A$^{\Delta}$ | No | Yes (relay block) | No | Yes |
| B | Yes | Yes (robot) | Yes (robot) (m) | Yes |
| C | Yes | Yes (robot + conveyor in automatic mode) | Yes (robot) (m) | Yes (robot), no (conveyor) |
| D$^{\Delta}$ | Yes | Yes (robot) | Yes (robot) (m) | Yes |
| E$^{\Delta}$ | Yes | No | Yes (robot) (m) | Yes |
| F1$^{\Delta}$ | Yes | No | Yes (robot) (m) | Yes |
| F2 | Yes | Yes (robot) | Yes (robot) (f) | Yes |

$^{\Delta}$ Conveyor(s) (located in the study area) independent of the moulding machine control system and the robot control system.

During the visits, although the participants we met were aware of the serious hazards posed by the injection moulding machines, some were unaware of and others had not grasped the concept of validating their integration or design. They took it for granted that the integrated components were in a given category because they found it complicated to check the category level actually reached, feeling that the existing standards were difficult to understand and apply. Some integrators we met during visits (electrical technicians) did not know of the existence, definition, or importance of the “safety function performance level” concept, which allows the reliability of a safety function to be estimated and the attainment of the required level of risk reduction to be verified). Others knew a little about it but were unaware of how to estimate a safety function’s performance level post integration. Questions were sometimes asked about the safety level (reliability) of their integration. This on-the-ground finding explains why we wrote chapter 6 of this report.

Specifically, chapter 6 describes an *a posteriori* validation process for a safety function of a horizontal plastic injection moulding machine used without auxiliary equipment. This safety function was designed according to the hardwired logic principle. A PLC manages the machine’s operational functions. The part processing the safety function is thus separate from the part processing the operational functions. This process consists of studying the feasibility of such a validation procedure by estimating *a posteriori* a safety function’s performance level in order to assess its reliability.

It is important to consider human safety beginning with a technology’s design stage: inherent prevention. Chapter 6 provides an opportunity to make integrators and designers aware of the importance of adapting the reliability of a machine’s safety function to the level of risk reduction required for the machine’s operator. However, before we examine that topic, chapter 5 presents a discussion of the risk reduction means encountered in the plants, prompting a few thoughts.

# 5. DISCUSSION

We noted that, by their very operating principle, plastic injection moulding machines can expose workers to significant hazards. The contextualization and accident analysis results presented earlier in this report clearly illustrate this reality and indicate the need for continuing work that can help make them safer. The data collated in this study also make it possible to paint a more substantial picture of the reality experienced by workers in the industry, who are exposed to hazardous situations that can sometimes have dramatic consequences. Reading standards, technical data sheets, and other reference documents, analyzing accidents, and visiting companies are all important sources of information that can be of assistance when describing the reality of the work environment of these machines.

## 5.1 Standards and reference documents

Although the risks posed by injection moulding machines are relatively well known and various solutions have been advanced in many documents, including standards, questions remain regarding the concurrent use of auxiliary equipment that can expose workers to other hazardous situations. This auxiliary equipment (robots, conveyors, pelletizers, hoisting apparatuses, stepladders, stairs, etc.) is also the focus of studies and recommendations made in various documents but, surprisingly, although the accident reports show that accidents in the plastic processing industry can originate from the interaction between such equipment and an injection moulding machine, the adequacy of the solutions generally proposed for such machine-auxiliary equipment systems remains practically unexplored.

The risks generated by each of these pieces of auxiliary equipment and the resulting situations are typically detailed in various distinct documents (standards and manuals for conveyors, robots, overhead travelling cranes, etc.). However, the work environment in which this equipment is used concurrently with an injection moulding machine has, to the best of our knowledge, yet to be considered.

To this reality can be added the actual work environment in which certain tasks are performed. Although the normative documents mostly recommend solutions that are well adapted to the tasks performed in a goods production context, the prescriptive recommendations for certain interventions are not always well adapted to workers' needs. For example, EN 201 [21] recommends cutting power to heating elements when the emergency stop is activated. However, this recommendation is not followed in several cases for practical reasons. Also, the recommendations regarding allowable openings in the evacuation area can, in some cases, prevent parts from being discharged.

## 5.2 Summary of the accidents

The accident analysis carried out in the framework of this project revealed several deficiencies, in particular ones related to the workers' strictly following procedures and to the circumventing of protective devices. It also brought to light a reality in which the workers' needs are not always considered when designing and implementing risk reduction means.

### 5.2.1 Work procedures

Mentioned in connection with several accidents, the absence of formal procedures is directly related to a lack of work organization. On the other hand, while it is often true that the work procedures, when they exist, are followed poorly or not at all, in several cases it is the lack of particular functions developed at the design stage specifically to facilitate the work that makes such work-arounds necessary. While these breaches of procedure may also be due to workers' being unaware of the procedures' existence, it has to be admitted that even experienced persons and those responsible for safety in the company do not always follow them. It even happens, in some cases, that, due to a lack of knowledge or following an ill-advised decision, the procedures can put the workers following them at risk and expose them to the main identified hazards such as crushing and burns.

This reality points to problems such as the lack of safety training, an erroneous perception of risks, and a lack of appropriate resources for meeting the safety objectives. Although these issues, which affect companies of every size, are outside of the scope of this study, they should nonetheless be considered in other works due to the high number of cases in which this "root cause" is identified.

### 5.2.2 Risk management

#### 5.2.2.1 Lack, malfunction, and incompatibility

The accident analysis also revealed that, in many cases, risk reduction means such as guards and protective devices were missing, damaged, non-functional, or incompatible with the work situation. The causes of this state of affairs are similar to the problems related to the application of procedures: that these situations occur is often due to a lack of information or available resources, and the reality in plastics processing plants is not very different from that in several other industries. There are many reference documents on this subject and implementing the solutions they recommend should fall to the manufacturer or to the company that uses the equipment.

In the case of plastic injection moulding machines, the recommendations for the risk reduction means and protective devices that should be used are relatively consistent from one document to the next. It is usually agreed that particular attention should be paid to protecting the mould area and that guards (fixed or movable) should be used to prevent access to it. Usually, the guard should be equipped with several redundant interlocking devices and a mechanical stop bar should also be operational. The absence of any of these protections indicates a significant lack of knowledge on the subject.

Although protective devices were damaged or non-functional in some accidents, the root causes can be attributed to how the work is organized, which is again beyond the scope of this study. It could be that some of these situations result from a poor understanding of the importance of periodic checks of safety functions due to placing too much trust in these functions.

Lastly, the failure to observe basic safety principles regarding the installation of some of these protective devices (e.g. a fixed guard held in place by a magnet, an easily circumvented light beam safety device or sensitive mat, a movable guard without any interlocking device) is also the cause of several accidents. This situation is also strongly related to a lack of basic knowledge about safety principles among various interveners in the company.

#### 5.2.2.2 Circumvention

Another consequence of the apparent conflict between workers' needs and the solutions implemented to reduce risks, circumvention of risk reduction means such as guards and protective devices on moulding machines is often mentioned in the reports. In several cases, the circumventing is made necessary by a disconnect between the task that a worker must perform and the solution imposed on him by the equipment manufacturer or plant management.

In addition, the solutions recommended in the standards can sometimes be incompatible with some tasks that workers must carry out. While all of these cases are, of course, open to interpretation, when, for example, a worker has to climb on the machine to gain access to the mould area above the guard in order to perform a task or when a sensitive mat is intentionally neutralized, it is not unreasonable to believe that the protection provided to the worker limits him or prevents him from performing the task in the most efficient or effective way.

#### 5.2.2.3 Application of lockout

Generally speaking, the accident analysis shows that lockout of the moulding machine and auxiliary equipment was not performed rigorously or at all in several companies. Under section 185 of the ROHS [16], all repair, maintenance, and unjamming tasks should be performed with the equipment locked out. However, the studied cases show that the tasks involved do not specifically concern equipment repair problems for which the application of lockout procedures is generally more widespread.

Accordingly, the studied cases that involve setting up and adjustment for production purposes do not make lockout mandatory. In theory, however, the unjamming (of sprue) and machine maintenance (changing an injection barrel head) should normally be done when the machine is isolated from its energy sources.

### *5.2.3 Non-compliance with procedures and trade practices*

Although the accident analysis carried out as part of this study shows that work organization, in its broad sense (no risk analysis, no or few procedures, few resources, etc.), can often be perceived as deficient, we also note that very few cases actually called into question the methods and technical solutions normally recommended by the standards and other reference documents identified.

The root causes almost always relate to non-compliance with procedures and work practices or to the improper use or inadequate implementation of a proven technology. One of the most dreaded accidents in the mould area is when a worker is fatally crushed. Unfortunately, in one case where this occurred, it appears that neutralization of the protective devices was the cause of the accident. In another case, where a worn switch appears to have been the cause of the accident, the switch itself would not normally have been able to cause the regrettable incident because at least one other switch installed as a backup should have taken over and prevented the machine from restarting in accordance with widely known normative recommendations. Due to the length of time they spend in the mould area, mould changers are the workers who appear to be the most at risk, though fortunately no accidents related to mould changing were recorded. Nonetheless, it remains important to continue considering the reasons why such devices are neutralized and safety procedures are not followed.

## 5.3 Analysis of the risk and risk reduction means

Following the visits to the plants, a compilation of the observed risk reduction means was produced. Classified according to a hierarchy established in machine safety standards, these means range from inherent prevention (elimination of hazards or significant reduction of the risk) (table 6) to the implementation of organizational type measures (training, warning, personal protective equipment) (table 8) and protection, such as guards and protective devices (table 7).

Alongside this process, an analysis aimed at identifying the risk components in the mould area was developed by the members of the research team. This analytical grid, which is included in Appendix C, lists the main risks identified during the visits and correlates them to the risk reduction means used by the companies. Cataloguing and analyzing these risk reduction means made it possible to draw a general picture of the solutions implemented by the companies.

**Table 6 – List of risk reduction means observed and the plants concerned: inherent prevention and risk reduction by design.**

| Risk reduction means observed | Visits |
|---|---|
| Use of the parts-removal robot to reduce exposure to production-related risks | B, C, D, E, F1, F2 |
| Intentional manual action required to set in motion all or part of the system | A, B, C, D, E, F1, F2 |
| Source capture ventilation system | C |
| Non-slip surfaces | A, B, C, D, E, F1, F2 |
| Adding platforms on the fixed and movable platens and fixed ladders for mounting and dismounting from them | F1 |
| Small non-slip platform attached to the machine | A, B, C, E |
| Mould clamping movement conditional on the robot's position | B, C |
| Movement of the robot conditional on movement of the platen | B, C |
| Rollerless belt conveyor | A, B, C, D, E |
| Low voltage | A |
| Slow closing speed of the motorized guard | B, E, F1 |
| Use of a catwalk | C, F1 |

**Table 7 – List of risk reduction means observed and the plants concerned: guards and protective devices.**

| Risk reduction means observed | Visits |
|---|---|
| Operator's guard (movable, locked) | A, B, C, E, F1, F2 |
| Guard (movable, locked), side opposite the operator | A, B, C, E, F1 |
| Robot enclosure with locked access door | C, D, F1, F2 |
| Fixed discharge guard, operator side | A, C, D, E, F1, F2 |
| Fixed discharge guard, side opposite the operator | C, E, F1, F2 |
| Emergency stop device used in addition to a locked movable guard | A, B, C, D, E |
| Mechanical blocking system for the movable platen | A, B, C, E, F1, F2 |
| Guardrail/handrail for stairs and catwalk | C, F1 |
| Addition of in-running nip fixed guards | F1 |
| Emergency stop device for the machine-auxiliary equipment system in automatic mode | C |
| Emergency stop device for the conveyor | A, F1 |
| Fixed discharge guard, operator side, for the part of the belt located under the mould area | A, D |
| Sensitive mat in the mould area preventing movement of the system's moving parts, including the motorized operator's guard | C, F1 |
| Enabling device for robot programming pendant | B, C, D, E, F1, F2 |
| Sensitive edge | B, C, E, F1 |

**Table 8 – List of risk reduction means observed and the plants concerned: organizational type measures (training, warning, PPE).**

| Risk reduction means observed | Visits |
|---|---|
| Lockout/blockout of the control panel (except the ES) | F1, F2 |
| Job-specific gloves | A, C, D, E, F1 |
| Safety goggles | A, C, D, E, F1, F2 |
| Lowering the mould temperature to 80°C with water circulation before intervening | E |
| Visor | F1, F2 |
| Training on use of hoisting apparatuses and accessories | A, C, D, E, F1, F2 |
| Protective footwear | A, B, C, D, E, F1, F2 |
| Check of hoisting accessories | A, B, C, D, E, F1, F2 |
| Regular inspection and maintenance of hoisting apparatuses | A, C, D, E, F1, F2 |
| Keeping the floor clean (person assigned the task or everyone's responsibility) | C, D |
| Hearing protector | A, D |
| Organizing heavy objects near the mould area (e.g. in drawer carts, on a retractable table installed on the catwalk railing) | A, B, C, D, E, F1, F2 |
| Use of a stepladder sufficiently high and with enough steps to avoid having to jump | A, B, D, E, F1, F2 |
| Use of a stepladder or adapted footstep to make access easier | A, B, C, D, E, F1, F2 |

All the visited plants had access to each of the risk reduction means described above. In figure 18, the risk reduction means observed during the plant visits are broken down by type (these are the risk reduction means integrated into the analytical grid in Appendix C and summarized in table 6, table 7 and table 8). This chart shows a varied distribution of the solutions implemented by the plants[5] for each system visited. In most of these cases, the inherent prevention and risk reduction means are among the least common. This distribution can be explained by the fact the work situations differ from plant to plant and machine to machine. For example, the mechanical blocking bar is used for only one of the systems where the operator-side guard was permanently open to allow the robot to pick the parts in the mould area.

[5] The emergency stop is normally considered a supplementary means but was included in the list of safeguards.

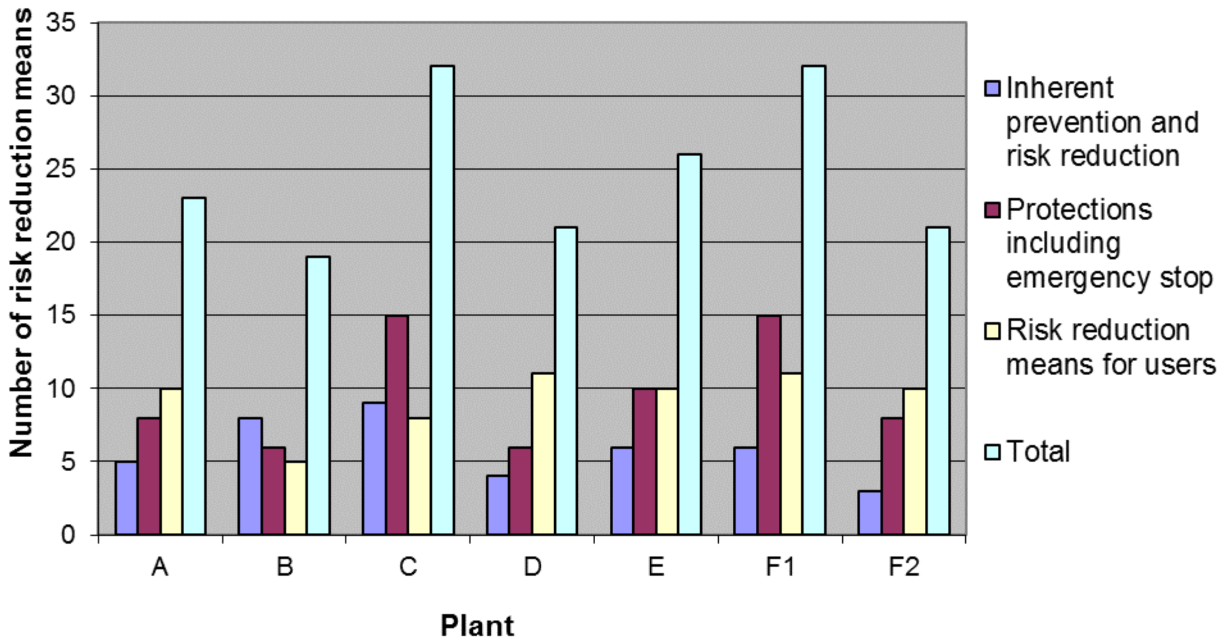



**Figure 18 – Distribution of the risk reduction means for the systems visited in the plants.**

Of the 43 risk reduction means identified and entered in the analytical grid, only five are used in all of the plants:

- intentional manual action required to set in motion all or part of the system;
- non-slip surfaces;
- protective footwear;
- check of hoisting accessories;
- organization of heavy objects near the mould area.

The distribution of the risk reduction means is interesting and shows that the plants use what appear to them to be the means best adapted to the reality of their particular set-ups when, for example, a robot or conveyors are used in combination with the injection moulding machine. The different pieces of auxiliary equipment used in the process sometimes make adaptation necessary. For example, in a case mentioned earlier, the mechanical blocking bar that is supposed to prevent the mould from closing if the operator-side guard is open had to be deactivated so that the robot could pass through the guard opening, whose interlocking function had been neutralized. Also, additional safety functions must sometimes be incorporated into the control circuit of the injection moulding machine (robot enclosure, emergency stop on the conveyor, etc.)

On the other hand, for most of the visited plants, the risk identification performed by the research team shows that all the identified hazardous situations are covered by at least one risk reduction means.

## 5.4 Good practices and deficiencies observed in the plants

The plant visits allowed us to observe the practices used by the workers in their usual environment. As each of the observations focused, in particular, on a specific task, namely changing the mould, the differences and similarities could be identified.

Generally speaking, the workers who were assigned this task performed it in a way that guaranteed their safety using the means available to them. A few exceptions aside, the main deficiencies noted stemmed mostly from the equipment's non-compliance with the normative recommendations. It should be understood that, if the workers sometimes placed themselves in a hazardous situation, it was mainly because risk reduction means were not available.

Good practices observed:

- Mould design modified so as to minimize the jamming of the parts produced, as such this jamming required intervention in the mould area. This reduced the workers' frequency of exposure to the hazards present in the area.
- Activating the emergency stop before intervening in the mould's danger zone. This practice constitutes an additional safeguard and helps reduce the probability that a failure or inadvertent manoeuvre could result in the machine's starting.
- Indication of the presence of workers in the mould clamping zone by posting a sign easily seen by the other workers (figure 11, p. 28).
- Handling the mould using overhead travelling cranes in a safe manner (the load kept as low as possible at all times, no one beneath the load, checking of slings, etc.) (figure 12, p. 29).
- Addition of a proximity detector to improve monitoring of the proper functioning of a hydraulic valve used as an interlocking device.

Deficiencies or problems observed:

- Necessity for workers to climb onto the sliding guide rails to reach some parts of the mould (figure 19).
- Non-compliance of the fixed guards, which do not completely cover the danger zone and allow residual access to hazards.
- Non-compliance of certain procedures. In one case in particular, the procedure required that all the guards with interlocking devices of the robot enclosure be opened before intervening, in order to reduce the risk of an accidental start-up. This requirement was not complied with during our observations.
- Slippery or cluttered (figure 20) surfaces.
- Stepladders and other equipment inadequate for the work and increasing the risk of falls (e.g. rickety stepladders, narrow steps) (figure 21).
- Non-compliance of certain interlocking devices installed in negative actuation mode, which is counter to normative recommendations.
- Some enclosures equipped with access doors not fitted with interlocking devices.

**Figure 19 – Mould assembler-fitter standing on the guide bars.**

**Figure 20 – Worker on a step partially obstructed by clamps.**

**Figure 21 – Worker on a stepladder with narrow steps.**

### 5.4.1 Differences among the plants

Although the plants each identify the solutions that appear to them to be best for the situations they encounter, the differences noted during our visits show that sometimes, when faced with more or less identical hazardous situations, the plants do not always adopt the same solutions. For example, several of the observed injection moulding machines were large enough to allow a worker to enter the mould area, exposing himself to one of the most dangerous and potentially fatal situations recorded. Yet only two injection moulding machines included a sensitive mat able to detect a worker's presence, despite the fact that normative documents recommend this solution [14, 21, 23]. Is this state of affairs due to the different levels of knowledge of the persons responsible? While the choice of this measure is based solely on an assessment of the risk, it is not far-fetched to assume that, generally speaking, users find it hard to imagine how a person can be working inside the machine without being seen by the person who starts the machine via the control panel. Once the worker has entered the mould area, his safety depends entirely on the machine's control system functioning properly. Although solutions exist (surface detector, light beam safety device observed on the machine, key transfer systems), as long as manufacturers are not actually required to install such solutions on their machines, users will base their choices largely on their own perception of the risks involved and also on the advantages and disadvantages that come with these solutions.

## 5.5 Mould changing and machine operating tasks

The production tasks we observed were mainly changing moulds and operating the injection moulding machine. One of the biggest hazard on injection moulding machine is the mould clamping mechanism. When it is moving, the platen on which the parts of the mould move create a very large crush zone in which the forces at play are extremely powerful (sometimes on the order of a meganewton). The consequences of being crushed in this zone are very severe and can result in death.

On most of the large injection moulding machines we observed, the space between the parts of the mould is large enough for part or all of a worker's body to enter (figure 22). If the platen closed when a worker was inside the crush zone, he could be fatally crushed. The workers responsible for changing the moulds are directly exposed to this hazardous phenomenon. They have to enter the machine, remove the mould to be replaced, and install the new mould. A large part of this work is done when the workers are partially or completely exposed to the crush zone. It is therefore essential that the machine's movable platen remain stationary at that time.


(1)

(2)

**Figure 22 – Upper body of a worker in the mould area (1) and whole body of a worker in the area (2).**

Machine operators are also exposed to this significant risk and even more frequently. On injection moulding machines operating in semi-automatic mode, their task is to frequently remove from the mould the parts produced. During each production cycle, they have to open the operator-side guard and place their hands or their whole body into the mould clamping area to remove parts from it. As on mechanical and hydraulic presses, where the risks are similar, it is mainly for this reason that the normative recommendations for protecting the mould clamping area are extremely strict. Without exhaustively describing them, we will note that the operator-side movable gate must be equipped with redundant interlocking devices (electric, hydraulic). In addition, a mechanical blocking bar must prevent the platen from closing if the operator-side guard is not closed. This safeguard is considered sufficient to reduce the risk to which the operators are exposed to a tolerable level.

Are these risk reduction means adapted and sufficient to ensure that mould changers are protected? Does using the risk reduction means put in place to protect the machine operators provide a tolerable level of safety for the mould changers? They are two distinctly different tasks performed in the same danger zone: on the one hand, the operators must extend their arms into the mould clamping area to pick the parts several dozen or even hundreds of times a day; on the other hand, the mould changers must enter the mould area entirely, albeit only several times a day (on several machines).

An estimate of the typical risk would doubtless show that the severity of the potential injury in these two work situations would be deemed serious or severe and the probability of the hazardous event's occurring (e.g. unexpected closing of the mould) would be deemed "low" due to the risk reduction means put place. By referring to the values prescribed by several risk assessment methods [37], the frequency of exposure to a hazardous situation at least once per work shift would be considered high in both cases. The three risk estimation factors—severity, frequency or length of exposure, and probability of the hazardous event's occurring—are therefore similar for both tasks.

It is probably the last estimation factor, which describes the possibility of avoidance, that could make a difference. In all likelihood, if an operator has his hand or arm in the clamping area, it is possible to imagine that, at the moment when the platen started moving, he might have enough time to pull it out of the danger zone to avoid an accident. However, it is harder to imagine that a mould changer standing inside an injection moulding machine to perform his job would find it as easy to extricate himself in time. We could therefore say that the possibility of avoidance is very low or practically nil. The influence of this factor on the risk assessment results is generally the lowest. For example, the risk chart shown in figure 23 lowers by one level the risk index relative to situations for which the possibility of avoidance is deemed possible.

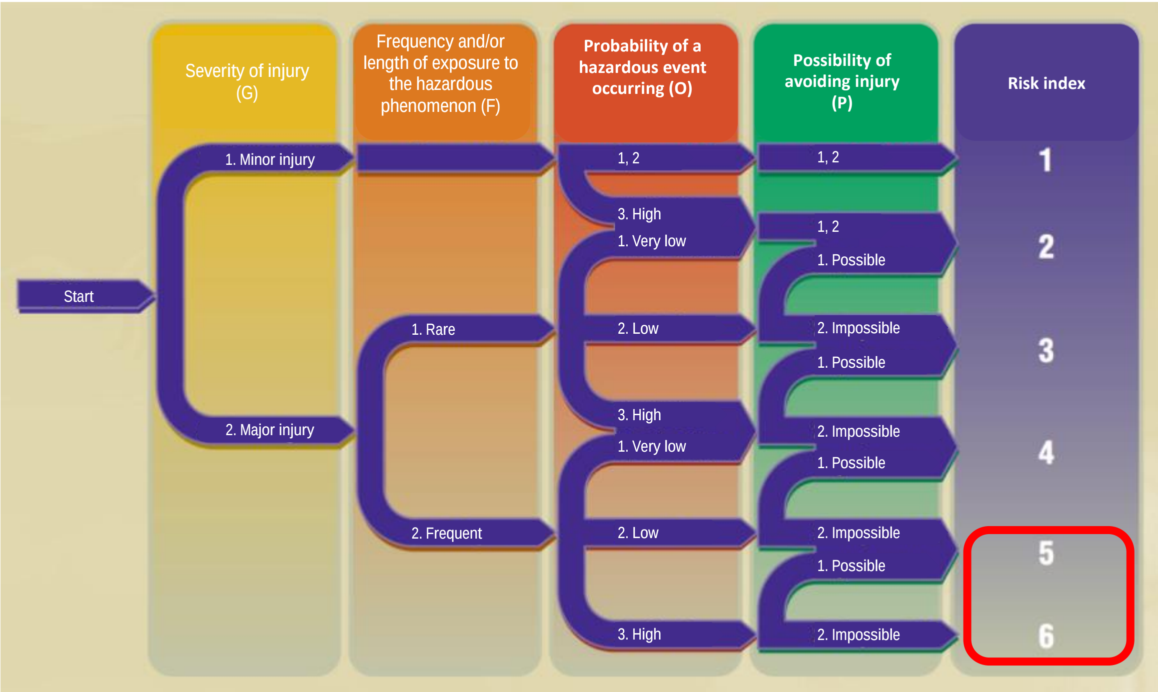



**Figure 23 – Risk chart [38].**

It is widely understood that we should not rely on the possibility of avoidance to reduce the risk in a given situation, although this factor will be used to estimate risk for the purpose of comparing risk levels. Is this difference enough to justify using different risk reduction means? Are the solutions for protecting operators equally worthwhile for protecting mould changers?

The observations made in the plant enabled us to note that several risk reduction measures used by operators are also used to protect setup and mould changing personnel (e.g. use of interlocked movable guards alone or in combination with putting a padlock on the guard, putting a padlock on the control panel, and activating the emergency stop button). Incidentally, the HSE [23] specifies that the guards should be favoured but that, due to bypassing and to control systems that are not compliant with trade practices, lockout can be used. In both cases, the HSE [23] recommends the use of the emergency stop as a supplementary means.

### 5.5.1 Lockout

Lockout is the risk reduction method that, *a priori*, seems to be the safest for performing the mould changing task. Properly applied, this procedure would provide one of the most secure protections to the workers. By isolating the machine from its energy sources and locking out the isolating devices with a personal padlock, the workers should be ensured of a very high level of protection against the possibility of the platen unexpectedly starting to move, whether due to a technical fault or to an accidental (by a third part or the operator) or intentional (by a third party) start-up command.

### 5.5.2 Lockout application problems

As the accident analysis we prepared and the observations we made during the visits show, lockout is not part of the toolbox used at most of the plants studied. Applying a lockout procedure in accordance with trade practices was not done at any of the visited plants. It appears that various conditions make lockouts difficult to apply. What are the reasons? What is behind the decision to implement other measures?

Injection moulding machines are powered by electricity. This energy is used in particular to power the motors of the hydraulic pumps that, in turn, power the hydraulic cylinders that move the movable platen. Electricity is also used to power the heating elements surrounding the transfer chamber in which the plastic is melted before being injected into the mould.

Some maintenance and repair tasks, such as disassembling the injection unit part, that were identified during the accident analysis must be performed when the plastic is melted in the chamber. The time required to raise the temperature of this part of the machine can be relatively long and the solidification of the plastic in the event of a power cut can result in a production delay of several hours. Also, the computers and controllers used to control the machines can require a long rebooting process if they are stopped.

Although these concerns are justified, it is also true that the heating elements, computers and control circuit controller are often powered by the same source as the electrical motors of the hydraulic pumps. Cutting the power supply to these motors would therefore cut the power to the heating elements and computers, with the consequences mentioned above. On this subject, CSA Standard Z460-05 [39] recommends that the heating elements, computers, and controllers be powered by another lockout-capable source or that an isolating switch be installed directly on the hydraulic pump motor.

Extracts from CSA Z460-05, Annex K (informative):

K.1 Set-up (no motion)

> On plastics moulding machines where it is necessary to maintain heat to a plasticising unit or power to a programmable logic controller or microprocessor during set-up, a separate lockable energy-isolating device for a motor, pump, or other equipment that could expose an employee to a hazard should be used.

Moreover, very practically and as observed during the visits, installing the various parts of the mould during the mould changing process requires that the movable platen be moved several times. If locking out the machine is not, strictly speaking, impossible in this situation, applying it would certainly be burdensome.

Lastly, taking a cue from section 185 of the ROHS [16], which stipulates that locking out is mandatory for maintenance, repair, and unjamming tasks, some tasks, such as changing a tool, may be carried out when the machine is locked out. Changing a mould is similar to changing a tool but can easily be interpreted as not being a maintenance or repair task and certainly not being unjamming. Based on such an interpretation, lockout is not viewed as an obligation by several companies.

### 5.5.3 Lockout alternatives

For all these reasons, it appears that the companies have developed and currently use methods and measures as an alternative to lockout. However, although lockout is not used, the workers do not blindly expose themselves to the risks present. From stopping the motor via the control panel to posting a warning sign, several methods are used.

#### 5.5.3.1 Use of means of protection

When designed according to normative requirements, plastic injection moulding machines incorporate several risk reduction means to make the mould area safer. As mentioned earlier, the operator-side guard should be redundantly locked (hydraulic and electric), the rear machine guard should be locked (usually only electric), and a mechanical stop bar or other blocking system should mechanically prevent the mould from closing if the operator-side guard is not closed. These means, designed and used by the operators, are almost always used as an alternative to lockout by the mould changers observed during the visits. Instead of locking out the machine's energy sources at the source, these workers or those responsible for them deem that the protection provided to the machine operators is sufficient for performing their work. In concrete terms, as soon as the operator-side guard is open, all hazardous movements are stopped. This being the case, why worry about the machine restarting?

According to the information obtained during the visits, this confidence in the machine's control system is not always grounded in a deep familiarity with the design requirements for the safety-related control circuits, as described in chapter 6 of this report. The results of the questionnaire used during the plant visits and relating to respondents' knowledge in this area, in particular knowledge of ISO 13849-1:2008 [31] and CEI 62061:2005 [40] show that these requirements are virtually unknown or, if known, very poorly understood by the people in the workplace. This is a problem shared by a very large number of users worldwide. Strictly applying these standards presents a significant challenge with respect to both interpretation and implementation. The representatives of the standards committees responsible for these documents are aware of these problems and work is under way to make them easier to understand by users. An ISO-IEC task force focused on combining the two above-mentioned standards recently distributed a questionnaire, one of whose goals is to better understand these problems and the context in which the standards are applied by their users.

For the time being, however, the safety of the workers called on to intervene on these machines is based on the presumed reliability of the control circuits. The visits revealed several deficiencies relative to the trade practice-compliant design of the guards and other means of protection. Basic safety principles were not applied (safety interlock switch not installed in positive mode, partial alteration of safety-related parts of the control circuit without redundant contact switches, etc.). In addition, most of the injection moulding machines described during the visits are equipped with standard PLCs to which are connected several safety functions. However, these PLCs should normally not be used alone to handle safety functions, as this has the effect of increasing the risk of failure-related accidents for the operators as well as the mould changers.

Replacement of lockout by safety-related systems that use control circuits designed according to the strict rules imposed by the design standards is not a subject of relevance only to injection moulding machine users. Every day, a large number of users of a very wide range of machines deal with situations where lockout, even when applied in conformance with current Quebec laws and regulations, presents problems and appears to be a significant drag on production. The *CSA Z460-05* standard [39] is one of the first documents in Canada to open the door to lockout alternatives, in particular the use of means of protection. Its recommendations are naturally cautious and include performing a risk analysis based on the task beforehand.

Although this idea is appealing, it raises very relevant questions about comparing the safety that can be provided by, on the one hand, a lockout procedure and, on the other hand, a protection system based on a safety-related control circuit. While mould changers appear comfortable with the idea of entering the mould clamping area to perform their work and leaving their safety in the hands of a sometimes not very reliable control circuit, they are usually not receptive to the idea of, for example, replacing a mechanical coupling on the machine’s hydraulic pump without first isolating and locking out the energy source of the electric motor.

It would therefore be advisable to ensure that the basic principles and corresponding normative requirements be applied to each of the risk reduction means currently used before allowing them to be used in lieu of a lockout procedure. The level of reliability of the operator-side movable gate matters little if access to the danger zone can be gained simply by opening the gate of an unlocked robot enclosure, as is currently the case in at least one of the visited plants.

#### 5.5.3.2 Putting a padlock on the open interlocked guard

A variant on using the typical means of protection described in the preceding chapter consists of using a padlock to block the operator-side guard or gate in open position. One of the visited plants used this method in conformance with the recommendation found in Appendix K of the *CSA Z460-05* standard [39] respecting lockout:

> K.1 Set-up (no motion)
> [. . .] For a plastics moulding machine that complies with applicable safety Standards, the controlling safety gate should be locked in the open position, with the power source(s) used for controlling motion and movement in the mould area turned off.

According to this approach, when no platen movement is required during the setting phase, it is appropriate to block the gate in open position using a padlock. Here, too, the protection provided to the workers is based entirely on the proper functioning of the safety-related circuits when the injection moulding machine is used. The authors of the standard made a point of mentioning that the machine must be one "that complies with applicable safety Standards."

However, the technique observed in the plants had several shortcomings. On at least one occasion, the padlock that should block the gate was installed in the wrong location on the gate's guide rail, which would not prevent the gate from closing. Also, given the high number of movements required to carry out the task, the lock, which has to be removed every time the platen was moved, was not always reinstalled.

While opening the operator-side guard prevents the start-up of parts inside the mould area, nothing prevents a person from closing the gate from the outside in order to restart the machine even if a worker is inside the mould area. How to make sure that no one is inside the sometimes very large mould area? This question relates directly to the standards' recommendation on the safety of injection moulding machines when they propose installing a presence detection system directly in the mould area of large machines. As mentioned earlier, only two of the machines in the plants visited were equipped with a sensitive mat that served this purpose.

Reading the relevant standards shows that alternatives to this recommendation are possible, as recommended in section 5.2.3 of ISO 14120:2002 [41]:

> As far as practicable, movable guards shall be designed and positioned such that during normal operation they are prevented from closing with persons in the danger zone. Where this is not predictable, other means shall be used to prevent parsons from remaining undetected within the danger zone.

If blocking the gate using a padlock as is done in this plant does not protect the workers against the possibility of the control circuit's failing, it could nonetheless be considered a worthwhile method for dealing with situations where a worker is inside the mould area and not visible. A worker who affixes his personal padlock beforehand in order to block the gate in open position ensures that no one else can restart the machine while he is in the mould area.

#### 5.5.3.3 Other considerations

In its Annex K.3, CSA Z460-05 [39] suggests an alternative to lockout when it is necessary to move the platen while the operator-side guard is open:

> K.3 Extrusion blow and injection blow moulding machines (set-up with motion)
> During setting operations, when movement is necessary with the operator's safety gate open, the requirements specified in Clause 6.5 of ANSI/SPI B151.15 and Clause 8.5 of ANSI/SPI B151.21 should be followed.

No situation was observed during which movements of the platen or mould were necessary while the gates were not closed. This standard recommendation would therefore not apply in any of the cases observed.

#### 5.5.3.4 Using the emergency stop

In standardization, the emergency stop device is usually considered a supplementary protection measure in that it helps reduce the risk only in certain situations and will be used together with the means of protection (guards and protective devices). This device is often installed in several places around injection moulding machines. If auxiliary equipment such as conveyors or robots is added, it is common practice to install additional emergency stop devices on or near the equipment. According to ISO 13850 [42], the emergency stop devices should be positioned so as to be easily and safely switched off or on. In the mould area, which is usually devoid of emergency stop devices, the use of a “portable” emergency stop button is an alternative that was observed in one of the visited plants. The workers intervening at this location had access to these emergency stop buttons, which were connected by cable to the machine-auxiliary equipment system’s safety-related circuit. These workers therefore enjoyed a supplementary security function that otherwise would have been lacking.

The emergency stop function is normally intended to deal with hazards that arise or to reducing existing hazards that are potentially harmful or damaging to persons, the IMM or the work in progress [42]. This definition makes it clear that the emergency stop devices should be used by the workers at the moment when hazardous situations occur or, in some cases, just before they do. Use of the emergency stop to prevent the machine from restarting is nevertheless very widespread in the plants. In some cases, in fact, it is the only risk reduction means available, especially near some conveyors with accessible nip points.

As with other protective devices, such as movable guards, that are used to prevent the machine from restarting, the use of emergency stop devices is based on the reliability of the control circuit to which they are connected. The reliability issues discussed earlier also apply here, directly and every bit as significantly. The important difference in this case is that, unlike a movable guard, which has to be opened to gain access to the danger zone and which thereby automatically stops the machine, use of an emergency stop is based only on an intentional action by workers. If the worker deems there is no need to activate the emergency stop to protect himself, he will be exposed to, among other things, the machine’s restarting.

This practice, which is very widespread and used almost automatically by the workers observed during the visits, is often used in addition to opening one or more of the guards. While this way of working provides additional safety protection, it should never be the only one available to workers.

## 5.6 Mould polishing and cleaning tasks

As mentioned earlier, maintenance tasks—cleaning the mould and polishing its cavity—were observed at plants C and F. At plant C, no lockout was applied for mould polishing and cleaning operations; the workers relied on the proper functioning of the means of protection in place. However, during visit F1, the control panel (emergency stop button excluded) was locked out using a group lockout. However, this was not a lockout as defined in section 185 of the ROHS

[16], as the hazardous energy sources were not isolated. As with the lockout of the operator-side guard mentioned earlier, the lockout of the control panel consisted in preventing the accidental start-up by a third party of the equipment's moving parts but not of an unplanned start-up due to a control system fault or failure.

From conversations with the participants met we learned that lockout as defined by the ROHS was applied in their plants only for major maintenance and repair work and not for preventive maintenance (cleaning, polishing). This is explained by the fact that, during mould polishing and cleaning, production tests are required from time to time in order to evaluate the finish on the moulded part, to adjust the polishing as the operation went on, and lastly to check the mould cavity. It is therefore obvious that repeatedly drawing on energy sources is necessary during these maintenance tasks that we observed. Considering that, in order to polish and clean the mould, the workers have to enter the mould area by moving the guard that immobilizes the moving parts in this danger zone, we can say that this procedure adheres to the spirit of section 186. However, it should be noted that the emergency stop button on the control panel where a padlock is applied is outside of the cover blocking the panel. This is an intelligent way of providing a means to avoid or limit the harm in the event a start-up due to a control system fault or failure occurs: pushing the emergency stop button is all that is required, although the button has to be easily accessible and the safety function connected to it has to be reliable.

Lastly, basing ourselves on the analytical grid in Appendix C and on the duration of the maintenance and production tasks observed (Appendix B), tasks which are performed mainly in the mould area, the risks inherent in these two types of intervention are basically similar in a given plant, as the problem arises from the same situation: the worker enters the mould area and the duration or frequency of exposure to the hazards present in the area remains high. The only differences relate to: the risk of the load carried by a robot falling (protection), ejection of metal shavings (maintenance), and contact with liquid cleaners (maintenance).

## 5.7 Protection of auxiliary equipment

As defined in the scope of this study, which is presented in the research objectives, the auxiliary equipment considered during the visits had to be installed in or have an impact on the safety of the workers inside an area of approximately one metre around the mould area on the operator side and on the opposite side.

Robots, conveyors, and overhead travelling cranes are the auxiliary equipment that were most frequently identified often during the plant visits. The risk reduction means for this auxiliary equipment varies greatly and are sometimes independent of the operation of the injection moulding machine (based on tests performed during visits). Typically, the hazard created by the robots moving above the mould zone or behind the machine (in one case) and those of the conveyors installed under the mould area or behind the machine are inaccessible due to the installation of an enclosure (figure 24). On the other hand, we did observe – on the F2 visit, for example – that the opening created in the protective enclosure so that a conveyor could cross it is large enough to allow a person to enter the enclosure while the enclosure's doors are locked and the machine-auxiliary equipment system is operating. In the future, it would be desirable for these openings to be small enough, or for other means of protection to be installed, so as to prevent entry through them. For example, when large items that require large openings are being moulded (waste bins, for example), light beam safety devices could be considered. Also, it would be preferable to equip the injection moulding machine with a robot that accesses the mould area from above, as access from the side unfortunately involves having to neutralize some means of protection. This was the case, for example, for the guard opposite the machine operator at plant C. This measure eliminates the risk reduction means that provide redundancy in the safety-related control system.

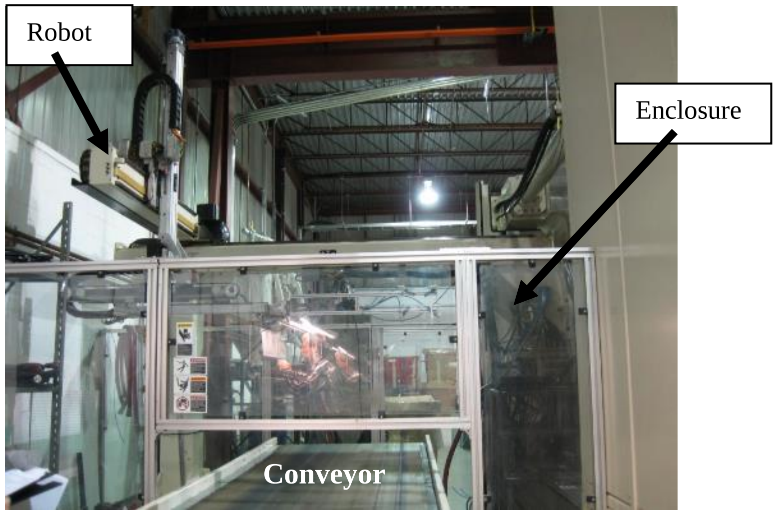



**Figure 24 – Protective enclosure around the robot and the part of the conveyor with an accessible nip point.**

The design criteria for these safeguards are defined in standards such as ISO 14120 [41] in which the authors strongly insist that access to the zone should be possible only when the hazardous movements are stopped by the opening of an access door, for example. Despite these recommendations, several danger zones were accessible. In some cases, the very dimensions of the guards did not prevent access (from above, from below, or across). Also, some access doors were not equipped with interlocking devices or interlocking with guard locking devices. In addition, the robot enclosures were mostly not designed to the standard requirements, such as those found in the CSA Z434 robot standard [43], in which the size of the enclosures is directly related to the range of the robot's movements in order to reduce the risk of entrapment or crushing.

We also noted in table 5, p. 34, that several injection moulding machines have the advantage of being equipped with a control circuit that facilitates the addition of auxiliary equipment such as robots and conveyors. The machine's safety-related control circuits can thus be "extended" to stop robot or conveyor movement in the event that one of the guards is opened or the emergency stop is activated. It is interesting to note here that, generally speaking, the result of opening the guard opposite the machine operator side was to stop the same components that activating the machine's emergency stop does. This situation is not ubiquitous, however, and in some cases, the auxiliary equipment's safety-related control circuits were completely independent of the machine's. In other words, in some cases, a conveyor, for example, would not be stopped when a guard was opened or the emergency stop activated, whence the importance of in-running nip guards (figure 25).


**Figure 25 – In-running nip guard installed on a carrying idler of a conveyor.**

No overhead travelling crane that could move above the mould area was connected to the machine's control circuit to prevent it from moving when a worker was inside the mould area. The main form of protection for this piece of equipment took the form of instructions given and training provided to its operator.

# 6. CASE STUDY: *A POSTERIORI* VALIDATION OF AN INJECTION MOULDING MACHINE SAFETY FUNCTION AS PER ISO 13849-1

Earlier, section 4.4.2 explained the problems encountered by in-plant integrators. One of the significant problems raised remains *a posteriori* validation ("*a posteriori*" here meaning post-design) of the safety functions relative to the components they integrate. To better understand the scope of these problems and propose a procedure for carrying out an *a posteriori* validation of a safety function, a feasibility study was carried out. The study used the horizontal plastic injection moulding machine in the IRSST's Machine Safety Laboratory, to which, along with the machine plans, we have been granted extensive access. The machine offers relevant points to explore with respect to safety-related control systems. Although this report concerns that type of injection moulding machine and the related auxiliary equipment, the case study presented in this chapter focuses solely on the machine. As it is a feasibility study, we felt it was better to begin with a simple case study and limit ourselves only to the injection moulding machine. For this case study, we decided to place ourselves in a context similar to that encountered by integrators: to deliver a verdict on the level of safety (reliability) of a control circuit designed by a third party and to do so without support from the designer. With respect to auxiliary equipment, we feel that in-plant integrators could use this process based on ISO 13849-1 [31], about which they should have a minimum of knowledge. We also think they could contact the manufacturer of their machine to complete their analysis of the control circuits (for more information on the process, see chapter 3 of reference [3]).

The standards relevant to the topic, the validation process applied, the results of the process, a discussion of the results, and several relevant conclusions are presented below.

## 6.1 Safety-related control systems: machine safety standards

Control systems play an important role in machine safety. In this field, there are currently two design standards applicable to safety-related control systems: CEI 62061:2005 [40] and ISO 13849-1:2006 (or NF EN ISO 13849-1:2008, whose content is identical) [31]. The latter replaces EN 954-1:1997, which was cancelled on December 31, 2011. The qualitative principle of categories (related to the safety-related parts of a control system), adopted by EN 954-1, was retained in ISO 13849-1:2006, which added to it a new probability (quantitative) notion: the performance level (PL). This is the "discrete level used to specify the ability of safety-related parts of control systems to perform a safety function under foreseeable conditions" [31]. Five performance levels are identified: a, b, c, d, and e, going from the highest mean time to dangerous failure ($MTDF_d$) to the lowest (PLa corresponding to the lowest performance level). As for the category, it is one of the criteria for determining the PL. There are five categories: B, 1, 2, 3 and 4, from lowest to highest.

## 6.2 *A posteriori* validation: preliminary steps

### *6.2.1 Studied safety function*

CEI 62061:200 and NF EN ISO 13849-1:2008 require that the safety function be identified and specified before being designed. At this step in the process, the two normative references for design can be envisaged. Earlier, the accident analysis made it possible to confirm that:

- the main risks on a plastic injection moulding machine remain crushing and burns;
- these risks are located in the mould and nozzle areas.

This explains the choice of the studied safety function, which is called "stop and prevent the clamping movement of the movable platen by opening the operator's guard." It protects against one of the machine's main hazard when the operator's guard is open (figure 26). On the machine studied, the safety function is identified as follows:

- **safety action:** stop the clamping movement of the machine's movable platen;
- **dangerous element:** movable platen;
- **safety action trigger:** opening the operator's guard;
- **the function's validity condition:** valid during the entire operating mode.


**Figure 26 – The studied machine and its operator's guard [7].**

Once identified, the safety function must be specified in order to establish its limits and identify its characteristics (e.g. its inputs and outputs, its priority with respect to other functions, its maximum reaction time).

### 6.2.2 Choice of standard

ISO 13849-1 applies to the electric and non-electric (e.g. hydraulic, pneumatic) parts of safety-related control systems. For its part, CEI 62061 also concerns safety-related controls systems but only electric, electronic, and programmable electronic ones. In the present case, a reading of the safety function circuit allowed us to determine that the types of energy involved are electric and hydraulic. Identifying these energies obviously enabled us to choose the design standard adapted to the safety function to be validated: ISO 13849-1. This process is therefore based on applying this standard and consists of several steps.

## 6.3 A posteriori validation: subsequent steps

### 6.3.1 Determination of the required performance level ($PL_r$)

$PL_r$ is the PL “applied in order to achieve the required risk reduction for each safety function” [31]. It is the key part of the process because, ultimately, the validation consists of verifying whether the estimated PL is greater than or equal to the $PL_r$.

In our case, the $PL_r$ of the studied safety function is “e.” This value is provided by section 5.2.1 of the Type C standard for plastic injection moulding machines, EN 201:2009 [21]. When the $PL_r$ is not available in any Type C standard, one way of determining it is to use the chart in ISO 13849-1.

Once the $PL_r$ has been determined, the criteria necessary to reach a conclusion on the validity of the estimated PL must be inventoried. To decide on the PL of the safety-related part of the control system (SRP/CS) executing the safety function, the following applicable points should be considered:

1) determination of the designated architecture;
2) estimation of the mean time to dangerous failure ($MTTF_d$);
3) estimation of the average diagnostic coverage ($DC_{avg}$);
4) estimation of the measures against common cause failure (CCF);
5) verification of the safety-related software requirements (not applicable in our case as no software is involved in the safety function’s performance);
6) verification of the measures against systematic failure;
7) verification of the ability to perform the safety function in the planned environmental conditions.

### 6.3.2 Determination of the designated architecture

The designated architecture is the architecture for a given category. As the $PL_r$ is an “e,” the designated architecture must correspond to that of Category 3 or 4 as per figure 5 of NF EN ISO 13849-1:2008 (figure based on Table K.1 of this standard). Determining the designated architecture is comprised of the following three steps:

**1) Identify the hardware structure (in this case, hydraulic and electric) that performs the safety-related function and identify the corresponding components.**

This required that an analysis of the circuit’s normal operation be carried out beforehand. As a result, we identified a two-channel structure.

**2) Study the fault behaviour of the safety-related circuit.**

A study making it possible to understand the circuit’s fault resistance had to be carried out. It aimed to distinguish the components responsible for diagnosing faults from those responsible for the operational part. To accomplish this, an analysis in the presence of faults (FMEA: failure mode and effects analysis) was performed. It allowed us to:

- distinguish the components involved in the operational part of the safety function from those involved in the diagnostic part;
- verify the eligibility criteria for categories 3 and 4 regarding the safety function's fault resistance and its behaviour in the presence of fault.

In particular, the FMEA consisted of studying the effect of different unique faults on each of the components involved in the safety function's performance (figure 27):

- the limit switches: S151A, S151B, and S175 as safety function inputs. They are installed on the operator's guard to detect when it is opened;
- the interlock relays: K01, K02, and K03. At the beginning of the FMEA, we did not know if these relays had an operational or diagnostic role;
- the electrical controls of the hydraulic distributors: Y101 and Y171 as safety function outputs.

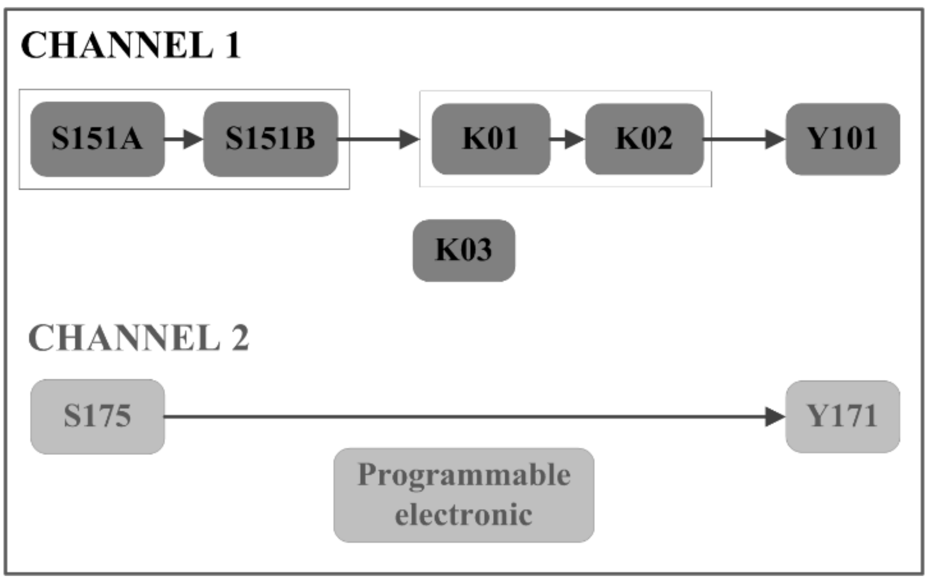



**Figure 27 – Architecture of the studied safety function.**

Two types of unique fault were studied: the component blocked in activated state and the component blocked in deactivated state. Both types of unique fault were studied for each of the three following scenarios: (1) operator's guard closed; (2) operator's guard being opened; and (3) operator's guard being closed again. We were unable to study one component not mentioned above: a programmable electronic board that we suspected was responsible for the diagnosis. Unfortunately, we were unable to obtain information about it due to the lack of sufficient information from the manufacturer and the designer. In terms of the diagnosis, we therefore considered its input as null. In light of the characteristics of switches S151B et S175 and how they were installed, we deemed them to benefit from fault exclusion. The manufacturer's information indicated that these switches have positive-break contacts. In addition, we observed on the machine that they are installed according to the principle of positive mechanical action.

Lastly, the FMEA revealed that:

- the failures at the source of the unique faults do not lead to loss of the safety function;

- the unique failures are detected to the extent that is reasonably possible;
- relays K01 and K02 play a data processing role in the operational part of the safety function while relay K03 plays a diagnostic role, whose diagnostic coverage (DC) could be quantified in accordance with the ISO 13849-1 criteria.

**3) Select the designated architecture based on the two preceding points.**

figure 27 diagrams the architecture of the studied safety function, as deduced from the investigations and conclusions of the analyses described in the preceding paragraphs. This architecture, which is compatible with the Category 3 requirements, shows that the safety function involves two channels.

### 6.3.3 Estimation of the $MTTF_d$, $DC_{avg}$, and CCF and verification of the other criteria

From Table K.1 of the standard, we deduce that, to satisfy a PL = e, the studied safety function must belong to one of the following groups of requirements:

$$\begin{cases} 62 \text{ years} \leq MTTF_d \leq 100 \text{ years} \\ \text{Average } DC_{avg}, \\ \text{so } 90\% \leq DC_{avg} < 99\% \\ \text{Category 3} \end{cases} \quad \textbf{OR} \quad \begin{cases} 30 \text{ years} \leq MTTF_d \leq 100 \text{ years} \\ \text{High } DC_{avg}, \\ \text{so } DC_{avg} \geq 99\% \\ \text{Category 4} \end{cases}$$

Using the following equations taken from the standard and applied to our case, we were able to calculate the $MTTF_d$ and $DC_{avg}$:

$$MTTF_d = \frac{2}{3}\left( MTTF_{d\ C1} + MTTF_{d\ C2} - \frac{1}{\frac{1}{MTTF_{d\ C1}} + \frac{1}{MTTF_{d\ C2}}} \right) \quad (1)$$

or:

$$MTTF_{d\ CANAL\ 1} = \frac{1}{\frac{1}{MTTF_{d\ S151A}} + \frac{1}{MTTF_{d\ K01}} + \frac{1}{MTTF_{d\ K02}} + \frac{1}{MTTF_{d\ Y101}}} \quad (2)$$

$$MTTF_{d\ CANAL\ 2} = \frac{1}{\frac{1}{MTTF_{d\ Y171}}} \quad (3)$$

$$DC_{avg} = \frac{\frac{DC_{S151A}}{MTTF_{d\ S151A}} + \frac{DC_{K01}}{MTTF_{d\ K01}} + \frac{DC_{K02}}{MTTF_{d\ K02}} + \frac{DC_{Y101}}{MTTF_{d\ Y101}} + \frac{DC_{Y171}}{MTTF_{d\ Y171}}}{\frac{1}{MTTF_{d\ S151A}} + \frac{1}{MTTF_{d\ K01}} + \frac{1}{MTTF_{d\ K02}} + \frac{1}{MTTF_{d\ Y101}} + \frac{1}{MTTF_{d\ Y171}}} \quad (4)$$

We note that the $MTTF_d$ and DC for switches S151B and S175 do not appear in these equations due to the fault exclusion assigned to them.

The $MTTF_d$ and DC values per component (cf. appendices E and F) were determined on the basis of arbitrary choices related to the conditions of use of the safety function, information from the manufacturer, and data from ISO 13849-1, such as $B_{10d}$ (the “number of cycles until 10% of the components have a dangerous failure" [31]). These parameters were calculated for the two contexts of use: one in the plant and one in the laboratory.

As for the CCFs, they are "failures of different items, resulting from a single event, where these failures are not consequences of each other" [31]. Concerning the estimation of the measures to counter them, assumptions and, for the most part, information provided by the manufacturers of the injection moulding machine and the safety function components made it possible to establish a score to estimate the measures against the CCFs. In our application, this score is independent of the context in which the machine was used (plant or laboratory). Among the assumptions, we supposed that the designer had adhered to the basic principles relating to the machine's environment (principles covered by Category B) because the injection moulding machine was CE certified. Among the manufacturer's information, we found the separation at the wiring level: the wired logic was separated from the machine's programmable electronics. Table F.1 ("Scoring process and quantification of measures against CCF") of ISO 13849-1 was used for this part of the analysis.

For the performance level of a machine's safety function to be determined, two last criteria must be met: the systematic failure and the ability of the SRP/CS to execute a safety function in the planed environmental conditions. Not having sufficient information from the designer or the manufacturer to verify fulfillment of these two criteria and seeing as how the purpose of the endeavour was both to highlight the difficulties of such an *a posteriori* estimation process for the PL of a safety function and to suggest an estimation process, we assumed the designer had implemented and verified the measures designed to satisfy these two criteria. Consequently, we were able to determine the PL of the safety function.

Most of the assumptions in the study were based on the analyses of the studied circuit and on information found in the manufacturer's manual. The analyses had been debated by various experts working in safety-related control systems.

## 6.4 *A posteriori* validation: results

An initial series of calculations was made using an Excel spreadsheet to estimate the PL based on the various analyses of the safety function circuit and the assumptions described earlier. The calculations consisted of obtaining the $DC_{avg}$ and $MTTF_d$ values for each component and the $MTTF_d$ for each channel in both use contexts (cf. Appendix D) of the safety function. Equations 1 to 4 above, together with the component's technical characteristics, were entered in Excel to come up with these values. The characteristics are presented in appendices E and F. table 9 and table 10 present the results for this first step.

To verify and compare results, a second series of calculations to re-estimate the PL was made, this time using the SISTEMA (Safety Integrity Software Tool for the Evaluation of Machine Applications) software tool. As equations 1 to 4 are integrated by default into SISTEMA's calculation process, all that needed to be done was to enter the technical characteristics for the safety function components. It was based on these characteristics that the $MTTF_d$ and $DC_{avg}$ were obtained on SISTEMA. table 11 and table 12 present the results of this second step. These estimates were made for both of the study settings: the IRSST laboratory setting and a Quebec plant setting. The conditions of use (e.g. frequency of activation) of the safety function in the laboratory were defined on the basis of its actual use at the IRSST. On the other hand, they were chosen arbitrarily for the plant setting. The conditions are presented in Appendix D.

**Table 9 – Plant setting: results obtained using Excel and analysis of the circuit for the *a posteriori* estimation of the PL.**

| Calculated parameters and criteria to be verified | State of the parameter or criterion | | |
|---|---|---|---|
| Designated architecture: 2 channels with diagnostic | Verified by analysis of the circuit and satisfactory | | |
| Resultant $MTTF_d$ | 66.67 years → high $MTTF_d$ | | |
| $DC_{avg}$ | 98.43% → average $DC_{avg}$ | | |
| Score against CCFs | Minimum score of 65 obtained | Category 3 | |
| Category B requirements | Assumed to be satisfactory | | |
| A single fault of any component does not result in the loss of the safety function | Verified by analysis of the circuit and satisfactory | | **PL = e** |
| Provided that this is reasonably doable, the single fault is detected | Verified by analysis of the circuit and satisfactory | | |
| Measures against systematic failure | Some were deducted from the circuit plans; others were assumed to be satisfactory | | |
| Ability of the SRP/CS to execute the safety function in the planned environmental conditions | Assumed to be satisfactory | | |

**Table 10 – Laboratory setting: results obtained using Excel and analysis of the circuit for the ex-post estimation of the PL.**

| **Calculated parameters and criteria to be verified** | **State of the parameter or criterion** | |
|---|---|---|
| Designated architecture: 2 channels with diagnostic | Verified by analysis of the circuit and satisfactory | |
| Resultant $MTTF_d$ | 100 years* → high $MTTF_d$ | |
| $DC_{avg}$ | 19.64% → Null $DC_{avg}$ | |
| Score against CCFs | Minimum score of 65 obtained | |
| Category B requirements | Assumed to be satisfactory | Category ? |
| A single fault of any component does not result in the loss of the safety function | Verified by analysis of the circuit and satisfactory | **PL = ?** |
| Provided that this is reasonably doable, the single fault is detected | Verified by analysis of the circuit and satisfactory | |
| Measures against systematic failure | Some were deducted from the circuit plans; others were assumed to be satisfactory | |
| Ability of the SRP/CS to execute the safety function in the planned environmental conditions | Assumed to be satisfactory | |

*Although Excel calculated an $MTTF_d$ of 127 years, the value 100 is shown because the standard requires limiting this parameter to 100.

**Table 11 – Plant setting: results obtained using SISTEMA for the *a posteriori* estimation of the PL.**

| **Parameters** | **Values posted by SISTEMA** |
|---|---|
| Category | 3 |
| Score to counter the CCFs | 65 (fully met) |
| Resultant $MTTF_d$ | 66.67 years (high) |
| $DC_{avg}$ | 98.43% (average) |
| PL | e |

**Table 12 – Laboratory setting: results obtained using SISTEMA for the ex-post estimation of the PL.**

| Parameters | Values posted by SISTEMA |
|---|---|
| Category | Software readout: Not all the requirements for the selected category [in this case category 3] have been met. Please check the list of requirements under the the subsystem's Category tag. |
| Score against CCFs | 65 (fully met) |
| Resultant $MTTF_d$ | 100 years (high) |
| $DC_{avg}$ | 19.64% (null) |
| PL | ——— |

## 6.5 *A posteriori* validation: discussion

### 6.5.1 Validity of the results

#### 6.5.1.1 Impact of the assumptions

Sections 6.2 to 6.4 showed that several assumptions and logical deductions resulting from the circuit analyses had to be made in order to estimate the PL of the studied safety function. It should be noted that assumptions, mostly based on these analyses, were made about:

- the conditions of use (e.g. activation frequency) of the safety function taken into account by the designer;
- the designer's compliance with the requirements necessary to control, prevent, and avoid a systematic failure;
- the ability of the studied safety function to perform in the planned environmental conditions;
- the function of certain components;
- the reliability data for certain components, which could not be obtained and which were taken from the tables found in the standard.

These assumptions influence the estimated PL. For example, table 9 and table 10 along with figure 28 show that a different PL can be obtained depending on the conditions of use chosen, whence the impossibility of making a pronouncement on this PL.

How can such a difference in the results for the Laboratory and Plant settings be explained when they are for the same safety function for the same machine? figure 28 shows the graphs for the resultant $MTTF_d$ and the $DC_{avg}$ as well as the straight line marking the beginning of the attainment of $PL = PL_r = e$ for our case. The curves were obtained by varying the conditions of use of the safety function between those of the two extreme settings, i.e. Plant and Laboratory. Because, in our case, the resultant $MTTF_d$ and $DC_{avg}$ values depend on the safety function's context of use, these parameters changed, which is reflected in their respective curves.

For the Plant setting (table 13 of Appendix D), the assumed conditions of use, the calculations, and the analyses made it possible to obtain results that satisfied all requirements for attainment of $PL_r$ = e. However, for the Laboratory setting (table 14 of Appendix D), one of the $PL_r$ attainment criteria could not be met: the category (neither 3 nor 4 had been attained) due to a null $DC_{avg}$. A null $DC_{avg}$ was found instead of the low or average $DC_{avg}$ required by Category 3 or the high $DC_{avg}$ required for Category 4. The equation of the $DC_{avg}$ calculation (equation 4), which depends on the equation for the $MTTF_d$ by component (equation D.2 in Appendix D), shows that, with a smaller annual average number of uses, a lower $DC_{avg}$ is obtained. Thus, as seen in figure 28, the null $DC_{avg}$ obtained for the Laboratory setting is due to the annual average number of uses of the safety function, which is clearly lower than in the Plant setting.

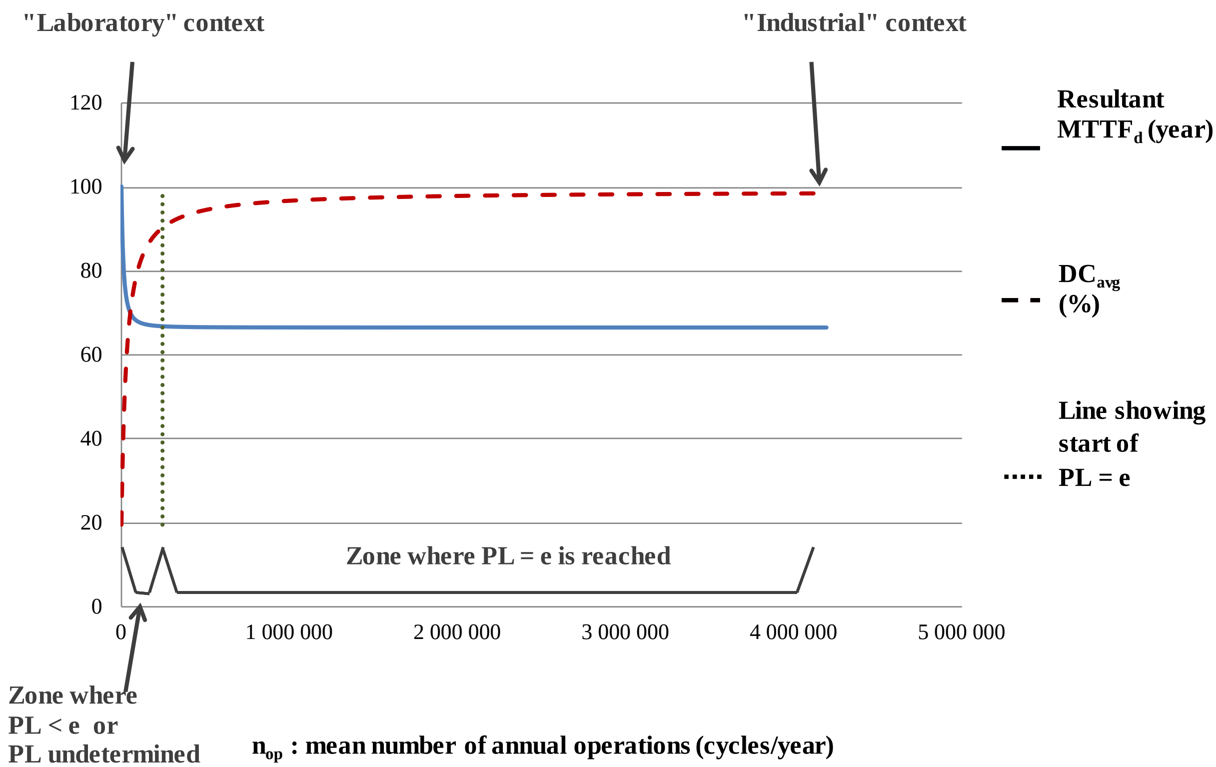



**Figure 28 – Impact of the annual average number of uses on the resultant $MTTF_d$, the $DC_{avg}$, and the PL.**

In contrast to the Plant setting, in the Laboratory setting, in addition to failing to attain the $PL_r$, an indeterminate PL was obtained. This is due to the fact that the ex-post estimation process is based on a standard that imposes a simplified PL estimation method:

- Based on the standard's designated architectures, obtaining Category 2 is impossible because it requires, among other things, a low $DC_{avg}$ whereas the calculated $DC_{avg}$ is null. Nor can lower categories can be attained as they require a single channel whereas we have two. That is why we concluded that the category is indeterminate, which explains the indeterminate PL found.
- The PL for the Laboratory setting could be determined by using a calculation method other than the standard's simplified method, which is based on "designated

architectures." Among the other calculation methods, section 4.5.1 of the standard mentions, for example, "Markov modelling, generalized stochastic petri nets (GSPN)" [31].

#### 6.5.1.2 Impact of the person validating

Another factor influences the *a posteriori* estimated PL: the person who analyzes the safety function and determines the assumptions. In this study, we had to validate a safety function for which we did not know the process or logic that were used during design. As a result, we put ourselves in the designer's shoes and attempted to imagine what he was thinking when designing the circuit. This meant we had to do some reverse engineering. For example, we supposed that the programmable electronic card identified in the safety function architecture played a diagnostic role. Lacking sufficient information from the manufacturer and designer about this card, the possibility of a null DC was raised. This assumption brings up a limitation of *a posteriori* validation: without information from the manufacturer or designer, it is impossible to know the functions of cards that integrate programmable components. This observation would suggest that it would be easier to *a posteriori* validate circuits including "elementary" electronic components. We have thus understood that, depending on whether or not this process is supported by the designer, the available information has enabled us to arrive at either tangible facts or deductions or assumptions that could lead to different results.

If different people attempted to perform this validation exercise, each on his own, it would not be surprising if they arrived at different interpretations regarding the architecture and the parameters that make it possible to pronounce on the PL. Case in point: a $PL_r$ estimation study by Hietikko, Malm, and Alanen [44] shows that several factors, such as the experience of the person conducting the exercise and the assumptions made, contribute to differences in the estimated $PL_r$. This situation observed with respect to estimating the $PL_r$ is equally plausible in our case of *a posteriori* estimation of the PL. This clearly demonstrates the significance of the person validating the results. One way to compensate for this situation is to have the process overseen by a team of experts (as was the case in our study) in order to compare various lines of reasoning and arrive at a more informed result. However, this is not always feasible in companies.

Despite everything, it appears obvious that a validation exercise of this type must be thoroughly documented and the assumptions clearly recorded in order to understand the limitations. These limitations are provided in this report to users of the ISO standard in order to prevent or better guide any changes they make to a safety-related control circuit. As we noted for the plastics industry, integrating auxiliary equipment (e.g. robot, conveyor) with existing injection moulding machines can result in the security-related control circuits being modified.

### *6.5.2 Excel and SISTEMA: comparison between results relative to ISO 13849-1*

#### 6.5.2.1 Plant setting: comparison between results

For the Plant setting, regardless of whether the calculations were done by Excel or SISTEMA, table 9 and table 11 show similar results from every point of view: the score against CCFs, the resultant $MTTF_d$, the $DC_{avg}$, the category, and the PL.

Note: When one of the parameters calculated by SISTEMA has an erroneous value or indicates the need to change a component in time, the software displays message to keep the user on guard. (The display uses red crosses.) For example, in our case, it warned about various per-component $MTTF_d$ that were too low (less than three years). The software warned that it would be necessary to ensure the component concerned was changed in time.

#### 6.5.2.2 Laboratory setting: comparison between results

For the Laboratory setting, table 10 and table 12 show that the same results are obtained for the following parameters with both Excel (together with the analyses to determine the PL) and SISTEMA: the score against CCFs, the resultant $MTTF_d$, the $DC_{avg}$, and the PL. As for the category, both programs also agree, as they show that Category 3 is not attained for the Laboratory setting:

- Excel shows that Category 3 is not attained due to the null $DC_{avg}$ (i.e. less than 60%);
- SISTEMA indicates that not all the Category 3 requirements are met. When looking under the subsystem's Category tab, as the program suggests, we note that the only conditional box to remain unticked is the "$DC_{avg}$ is low or average" box. The characteristic of a low $DC_{avg}$ is $60\% \leq DC_{avg} < 90\%$, while that of an average $DC_{avg}$ is $90\% \leq DC_{avg} < 99\%$. However, the found $DC_{avg}$ is null, which explains the unticked box.

The null $DC_{avg}$ found is compatible only with a Category 1 or B. However, for the reasons mentioned at the end of section 6.5.1.1, it is impossible to decide on a category and, consequently, on a PL. Based on our analyses and on the Excel and SISTEMA results, we confirm that the category and PL are undetermined for the Laboratory setting.

When using SISTEMA, we noted that the software decides on the PL without questioning the user on the meeting of two requirements that make it possible to reach a conclusion on the PL. These are:

- systematic failure;
- ability to execute a safety function in the planned environmental conditions.

For this reason, everyone who uses SISTEMA should remain vigilant: he should verify these two requirements himself before confirming the PL found by the software. This implies that a basic understanding of the standard is necessary before using the software.

#### 6.5.2.3 Comparison between the PL and the $PL_r$

To validate the PL, it is compared with the $PL_r$. In the Plant setting, with both Excel and SISTEMA, the PL obtained was "e," like the $PL_r$, thus satisfying the criterion. In the Laboratory setting, on the other hand, the opposite was true. Having this *a posteriori* estimation guided by a team with several years' experience in the design of safety-related control systems optimizes the results obtained—without, however, ensuring certainty—to the extent that the designer had applied NF EN ISO 13849-1:2008.

## 6.6 *A posteriori* validation: conclusion

A process for validating a safety function of a horizontal plastic injection moulding machine was presented. The validation consisted of estimating *a posteriori* the safety function's performance level. For technological reasons, the process was based on the NF EN ISO 13849-1:2008 design standard. For the Plant setting, the estimated PL satisfied the $PL_r$ = e. For the Laboratory setting, the PL was indeterminate and did not satisfy the $PL_r$.

Given the assumptions that had to be made to carry out such a validation without assistance from the machine's designer, *a posteriori* estimation of a safety function's PL can produce results that should be considered with caution:

- The necessary reverse engineering is not easy to perform without input from the designer. Depending on the person who undertakes the process, the results related to the chosen conditions of use, to the interpretation of the analysis of the circuit, to the $MTTF_d$, to the $DC_{avg}$, and to the score against CCFs may differ and consequently affect the estimated PL. It is therefore necessary to assemble a team that has experience in safety-related control systems in order to optimize the accuracy of the results. Incidentally, it would be interesting to study the differences in the validation results for a given circuit performed by different experts.
- This work required that several assumptions be made. The main difficulty of the study stems from the lack of data that only the designer could have provided. The uncertainties related to these assumptions have an influence on the estimated PL. For example, we made the assumption that all measures against systematic failure had been implemented by the designer. If this assumption were shown to be false, the PL would be impossible to determine; one of the requirements making it possible to estimate it would not be met and, accordingly, would no longer satisfy the $PL_r$. Another way of optimising the accuracy of the results is to minimize the number of assumptions by calling on the designer to the fullest possible extents. Unfortunately, this is not always feasible. Thus, users in companies will have to deal with assumptions and missing data if they want to carry out a similar exercise based on ISO 13849-1. To compensate for this lack, receiving assistance from the manufacturer would be a worthwhile alternative.

# 7. CONCLUSIONS

In the end, the research objectives of this study were achieved, as we were able to:

- identify the risk factors and causal agents related to accidents involving horizontal plastic injection moulding machines with auxiliary equipment (sections 4.1 and 4.2);
- survey the risk reduction means found in the literature (section 4.2);
- identify the risk components associated with maintenance and production interventions on the injection moulding machines and their auxiliary equipment during the eight visits to companies (section 4.4 and Appendix C). The risks inherent in both interventions were essentially similar as the problem concerned the same situation: the worker entering the mould area. In addition, the duration or frequency of exposure to the hazard in this area was high in both cases (sections 5.5 and 5.6);
- describe the maintenance and prevention intervention practices observed during the visits (section 4.4.1);
- analyze the risk reduction means used for the visited systems (chapter 5);
- ask questions, making it possible to assess the effectiveness of these risk reduction means (chapter 5);
- describe and apply the validation process for a control circuit based on NF EN ISO 13849-1:2008, albeit in a specific context, i.e. *a posteriori* and without the designer being involved (chapter 6).

The study revealed several significant points:

The risk factors are many and of both a technical and an organizational nature. The solutions appear to be known (e.g. formal work procedure, use of guards equipped with locking devices, lockout). Nonetheless, putting these solutions into practice appears to present several challenges. The circumvention of means of protection is a significant issue, as is the lack of guards, which was also observed. The operational safety of the control systems does not appear to be a major issue. When the control systems are identified as a causal agent, the deficiencies stem mainly from their not following basic, proven safety principles.

The companies that took part in the study are medium- to large-sized organizations, all of which have a safety practitioner and/or an OHS committee. Basing ourselves on the analysis of the accident and intervention reports, we can conclude that small companies are less well structured when it comes to OHS. We can therefore assume that the deficiencies observed during the visits could be more significant in small companies. However, the lack of visits to companies in that category prevents us from checking this assumption.

Lockout appears to be a risk reduction means that is accepted and practised in plants during maintenance interventions. However, the lockout practised are limited to applying a padlock on the cover of the control panel during mould cleaning and polishing and putting a padlock on an interlocked movable guard when changing the mould. For mould changing, lockout do not appear to be a means preferred by the plants for two reasons: first, heating must be maintained to keep the plastic from solidifying in the injection unit and, second, the platen has to be moved for mould adjustment purposes. The workers working in the mould area rely on the proper functioning of the movable guard on the operator side and the movable guard on the side opposite the operator. As a supplement, the emergency stop is used, which is a plus. In addition, in one case, the control panel is locked out with a transparent cover and a padlock. In another case, a padlock blocks the operator's guard in open position on its rail. In both cases, the measure is intended to prevent the unexpected start-up of the machine by a worker.

Gaining access to the mould area by climbing onto the machine remains a problem identified in our analysis of the CSST reports and observed during our visits. As we noted, using a platform above the movable platen mitigates this problem. However, to facilitate mould changing and allow the robot to pick up parts, the area under mould is not protected by a guard. It appears that safe work procedures, compliance with these procedures, training, and raising awareness of the risks present remain means to be strengthened in plants.

The use of presence detectors in the mould area is rare, despite the fact that the area is dangerous, especially when the size of the injection moulding machine and the shape of the moulds interferes with visibility.

The process described in NF EN ISO 13849-1:2008 and applied to a safety function of an injection moulding machine was presented. The feasibility of an *a posteriori* validation without support from the designer was studied for the first time. This process is necessary because the plant visits revealed that the content of this standard was unknown or poorly understood. That is unfortunate, for the standard establishes trade practices for the design and validation of safety-related control systems for all types of technology. The integrators met with during the visits found that ISO 13849-1 was difficult to apply. We hope that the process described in the report will help safety-related control system integrators in applying this standard. At the international level, machine manufacturers share the opinion of these integrators, and a process of merging the two control system design standards is under way to facilitate use of these normative documents.

Lastly, the proposed *a posteriori* validation process is transposable to safety functions for automated machines other than horizontal plastic injection moulding machine. Moreover, we believe that the grid describing the risk components and risk reduction means observed, which is presented in Appendix C, should help companies in the plastics processing industry and other industries with their risk assessment process.

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# APPENDICES

## APPENDIX A - **Final version of the data collection tool used for the visits**

# DATA COLLECTION TOOL

for the:

**Plastic Injection Moulding Machines with Peripheral Equipment – Safety During Maintenance and Production Interventions**

Research Activity

Completed by:

_____________________________

Date:

_______________

## Instructions:

To use this tool, obtain the required information by questioning your interviewees, by asking a qualified worker to perform operating tests and/or by observing the environment under study. In this document, the symbols described in the following key will indicate how to obtain the required information.

Key:

| | | | | | |
|---|---|---|---|---|---|
| ? | **Ask the question to obtain the information** | | **Ask for an operating test (demonstration) to obtain the information** | | **Observe to obtain the information** |

# ? **Part A:** Initial Contact (to be completed in the meeting room)

## Identification of the plant and interviewees:

| PLANT | INTERVIEWEE | | | |
|---|---|---|---|---|
| | First name | Last name | Title/Position in the plant* | Contact info. |
| Name: | | | | |
| | | | | |
| Number of employees: | | | | |
| Address: | | | | |
| | | | | |

*E.g.: 1. Mould changer, 2. Maintenance technician, 3. Engineer, 4. OHS officer, 5. Manager, 6. Other?

## Maintenance and production interventions in the mould area: Description

(put questions A.1 to A.5 to a technician)

| | Task | Reason for performing the task | Duration of the task | Frequency of the task | Time spent by worker in mould area | Lockout? | Other methods? Specify. |
|---|---|---|---|---|---|---|---|
| A.1 | | | | | | ☐Yes ☐No | |
| A.2 | | | | | | ☐Yes ☐No | |
| A.3 | | | | | | ☐Yes ☐No | |
| A.4 | | | | | | ☐Yes ☐No | |
| A.5 | | | | | | ☐Yes ☐No | |

## Studied IMM-auxiliary equipment system – Documentation possibly provided:

- ☐ Risk analysis (for the IMM and/or auxiliary equipment)
- ☐ Validation of control circuits by an engineer
- ☐ System plans

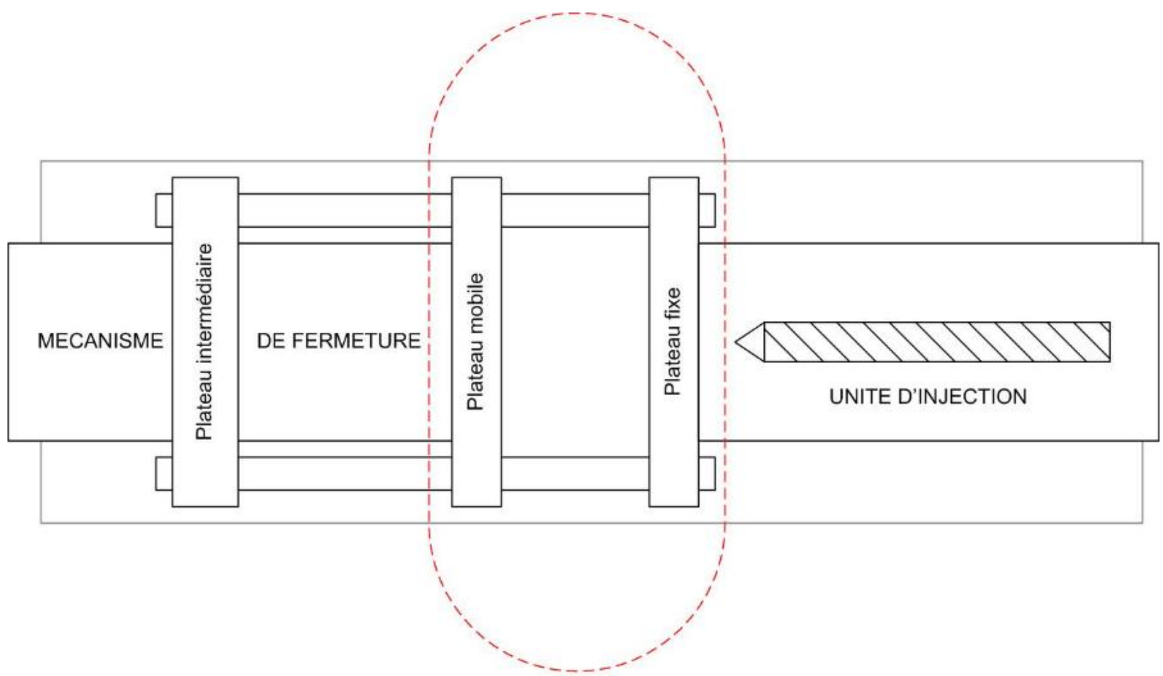
# **Part B:** Identification of the studied IMM-auxiliary equipment system

(to be completed at the studied system)

Identify and locate on the drawing the auxiliary equipment and means of protection involved in this study:

- ☐ Robot
- ☐ Conveyor
- ☐ Overhead hoist
- ☐ Granulator
- ☐ Other: _______________

- ☐ Operator guard
- ☐ Guard opposite the operator
- ☐ Guard above the mould
- ☐ Discharge guard
- ☐ Mechanical blocking system
- ☐ Sensitive mat
- ☐ Light curtain
- ☐ Cage
- ☐ Other: ______________




VUE DE DESSUS

# **Part B:** Identification of the studied IMM-auxiliary equipment system *(cont.)*

(to be completed at the studied system)

| | ? 👁 | Injection moulding machine |
|---|---|---|
| B.1 | Products made by the IMM during the visit | |
| B.2 | Make | |
| B.3 | Model/serial number | |
| B.4 | Year of manufacture | |
| B.5 | Year of installation | |
| B.6 | Identification number at the plant | |
| B.7 | Certified IMM? If yes, specify (e.g. CE). | |
| B.8 | Tonnage | |
| B.9 | Energies present in the mould area: hydraulic, electric, pneumatic (e.g. for cores), other | |

| | 👁 ? | Auxiliary 1 | Auxiliary 2 | Auxiliary 3 | Auxiliary 4 |
|---|---|---|---|---|---|
| B.10 | Type (e.g. parallel robot; conveyer) | | | | |
| B.11 | Function (e.g. recover sprue or parts; assembling) | | | | |
| B.12 | Make | | | | |
| B.13 | Model/serial number | | | | |
| B.14 | Year of manufacture | | | | |
| B.15 | Year of installation | | | | |
| B.16 | Identification number at the plant | | | | |
| B.17 | Energies present in the auxiliary equipment | | | | |

# ? **Part C:** Information on the coordination of the IMM and the auxiliary equipment

(to be completed at the studied system)

**? Put the Part C questions to a technical person (e.g. engineer) knowledgeable about the system coordination and information.**

**C.1** Describe the IMM-auxiliary equipment cycle:

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

**C.2** IMM originally designed to operate:

☐ Only with auxiliary equipment ☐ With or without auxiliary equipment ☐ Without auxiliary equipment

**C.3** Integration**:**

| Operated WITH auxiliary equipment | Operated WITHOUT auxiliary equipment |
|---|---|
| Means of protection modified: ☐ Yes ☐ No | Means of protection modified: ☐ Yes ☐ No |
| IMM program modified: ☐ Yes ☐ No | IMM program modified: ☐ Yes ☐ No |
| Justification + Description of the modifications: | Justification + Description of the modifications: |
| ______________________________________ | ______________________________________ |
| ______________________________________ | ______________________________________ |
| ______________________________________ | ______________________________________ |
| ______________________________________ | ______________________________________ |
| ______________________________________ | ______________________________________ |
| ______________________________________ | ______________________________________ |
| ______________________________________ | ______________________________________ |
| ______________________________________ | ______________________________________ |
| ______________________________________ | ______________________________________ |

**C.4** Integrator of the auxiliary equipment to the IMM control system:

☐ Qualified in-house personnel ☐ Outside organization ☐ Manufacturer ☐ Other: _____________

**C.5** Integration was based on the IMM and auxiliary equipment plans: ☐ Yes ☐ No

**C.6** Integration overseen by: ☐ Designer ☐ Manufacturer ☐ Vendor ☐ Other: ____________________

C.7 IMM-auxiliary equipment coordination:

☐ System managed by the same PLC

☐ Communication between the PLCs of each piece equipment

☐ PLC(s) dedicated to safety

Remarks:

| |
|---|
| |

**C.8** Process to switch from IMM to IMM-auxiliary equipment:

Activation conditions? Which control elements are involved?

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

What changes in the means of protection does this imply?

☐ Neutralizing of a guard or protective device (e.g. the machine “thinks” the guard is closed)

☐ Authorization to operate with an open guard (the machine “knows” the guard is open)

☐ Other: ____________________________

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

**C.9** Process to switch from auxiliary equipment to IMM-auxiliary equipment:

(e.g. Activation conditions? Which control elements are involved? Change of program or of connection? Neutralizing of means of protection?)

________________________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

## Moving parts – Control of the IMM-auxiliary equipment system by the worker in the studied area

**C.10** Measures to prevent start-up by a third-party?

________________________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

**C.11** Protection against ACCIDENTAL start-up?

________________________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

# **Part D:** Risk identification

## (to be completed at the studied IMM-auxiliary equipment system)

Hazard, hazardous events and potential harm to which the workers are exposed during their maintenance and production tasks in the system's mould area:

☐ 1. **Mould closing**

☐ 2. **Crushed** by the **ejectors**

☐ 3. **Dropping** the **mould**

☐ 4. **Struck** by the mould or hosting equipment

☐ 5. **Movement** of a **robot**

☐ 6. **Caught/jammed in** or **crushed by** a **conveyer**

☐ 7. **Electric power**

☐ 8. **Thermal** risk – burned by the mould, sprayed plastic or gas

☐ 9. Other:

The above list is used for checking the hazards found in the mould area of an IMM with auxiliary equipment. Complete it to know which sections of Part E apply to the system.

# **Part E:** Risk reduction measures

(reply to the questions at the IMM-auxiliary equipment system)

## Emergency stop and resetting

👁 ? **Type of emergency stop (ES):**

☐ **Cable** → Number: ______

Held: ☐ Yes ☐ No

Easily noticed: ☐ Yes ☐ No

☐ **Button** → Number: ______

☐ Red ☐ Not recessed ☐ Mushroom type

Easily noticed: ☐ Yes ☐ No

☐ **Pedal** → Number: ______

☐ Easily accessible (no cover)

☐ **Bar** → Number: ______

☐ **Lever** → Number: ______

? **Effect of the ES:**

$ES_{IMM}$ acts on:

☐ IMM ☐ All auxiliary equipment ☐ Some of the auxiliary equipment: ___________________________

$ES_{\text{each piece of auxiliary equipment}}$ acts on:

☐ IMM ☐ All auxiliary equipment ☐ Some of the auxiliary equipment: ___________________________

? Manual reset necessary to restart the system after ES has been activated: ☐ Yes ☐ No

? Is there a reset:

☐ For the IMM?

☐ For individual pieces of auxiliary equipment?

☐ For the entire IMM-auxiliary equipment system?

# 🛠 👁 ? E.1 Mould closing and crushing by the ejectors – Measures to protect against these hazards

**Note: Answer the 🛠 and ? questions first.**

## Identification of the protective devices:

| | Remarks: |
|---|---|
| ☐ Mechanical mould-blocking system | Bar: ☐ Yes ☐ No<br>Other: ______________________________ |
| ☐ Sensitive mat | |
| ☐ Light curtain | |
| ☐ Other: | |

## Identification of the guards:

| | 👁 Fixed | Mobile<br>? Locked out | ? Interlocked | 👁 **Number** of **position detectors** on the guard | 👁 **Type** of **position detectors** (capacitive or inductive, cam- or key-controlled electromechanical, etc.) |
|---|---|---|---|---|---|
| ☐ Operator guard | ☐ | ☐ | ☐ | | |
| ☐ Guard opposite the operator | ☐ | ☐ | ☐ | | |
| ☐ Guard above the mould | ☐ | ☐ | ☐ | | |
| ☐ Discharge guard | ☐ | ☐ | ☐ | | |
| ☐ Other: | ☐ | ☐ | ☐ | | |

Remarks:

## Effectiveness of the protective devices

**🛠 Do the tests in manual mode!**
**🛠 Do not enter the mould area to carry out tests!**

| | | Mechanical mould-blocking system | Sensitive mat | Light curtain |
|---|---|---|---|---|
| | Engage the mechanical blocking, press on the mat or obstruct the curtain: | | | |
| 🛠 | →**prevents** the mobile platen **from closing** | ☐ Y<br>☐ N | ☐ Y<br>☐ N | ☐ Y<br>☐ N |
| 🛠 | →**prevents** the **ejectors** from moving | ☐ Y<br>☐ N | ☐ Y<br>☐ N | ☐ Y<br>☐ N |
| 🛠 | → **prevents which other moving parts** of the system from moving? | | | |
| ? | In which **modes**? | ☐ Automatic<br>☐ Semi-automatic<br>☐ Manual | ☐ Automatic<br>☐ Semi-automatic<br>☐ Manual | ☐ Automatic<br>☐ Semi-automatic<br>☐ Manual |
| 🛠 | →**allows which moving parts** to move? | | | |
| ? | In which **modes**? | ☐ Automatic<br>☐ Semi-automatic<br>☐ Manual | ☐ Automatic<br>☐ Semi- automatic<br>☐ Manual | ☐ Automatic<br>☐ Semi- automatic<br>☐ Manual |
| 🛠 | **Intentional restart required** to make the system's moving parts move after the curtains are no longer obstructed or the mats no longer pressed | Not applicable | ☐ Y<br>☐ N | ☐ Y<br>☐ N |

Remarks:

## Effectiveness of the guards

| 🛠 **Do the tests in manual mode!** | Operator guard | Guard opposite operator | Guard above mould area | Discharge guard |
|---|---|---|---|---|
| **Opening** a guard: | | | | |
| 🛠 →**instantly stops** the mobile platen or **prevents** it from **closing** | ☐ Y<br>☐ N | ☐ Y<br>☐ N | ☐ Y<br>☐ N | ☐ Y<br>☐ N |
| 🛠 →**instant stops** the **ejectors** or **prevents** them from moving | ☐ Y<br>☐ N | ☐ Y<br>☐ N | ☐ Y<br>☐ N | ☐ Y<br>☐ N |
| 🛠 →**stops** or **prevents** movement of **which other moving parts** of the system? | | | | |
| ? In which **modes**? | ☐ Auto.<br>☐ Semi-auto.<br>☐ Manual | ☐ Auto.<br>☐ Semi-auto.<br>☐ Manual | ☐ Auto.<br>☐ Semi-auto.<br>☐ Manual | ☐ Auto.<br>☐ Semi-auto.<br>☐ Manual |
| 🛠 →**allows which moving parts** of the system to move? | | | | |
| ? In which **modes**? | ☐ Auto.<br>☐ Semi-auto.<br>☐ Manual | ☐ Auto.<br>☐ Semi-auto.<br>☐ Manual | ☐ Auto.<br>☐ Semi-auto.<br>☐ Manual | ☐ Auto.<br>☐ Semi-auto.<br>☐ Manual |
| 🛠 **Intentional restart required** to make the system's moving parts move after a guard has been closed | ☐ Y<br>☐ N | ☐ Y<br>☐ N | ☐ Y<br>☐ N | ☐ Y<br>☐ N |

👁 Diagram the position detectors on the means of protection by showing whether they are the normally closed (⊝) or positive actuation type (⊕)

| Operator guard | Guard opposite operator | Guard above mould area | Discharge guard |
|---|---|---|---|
| | | | |

## Overall effectiveness of the guards and protective devices

| Area between the platens accessible despite the protections in place? |
|---|
| ☐ No<br><br>☐ Yes. Explain: |

Remarks:

| |
|---|
| |

## ? E.2 Dropping the mould – Means to protect against this hazard

Hoisting equipment used to lift the mould: ____________________________________________

/ ? Maximum load the hoisting equipment can carry: ____________________________________________

? Weight of the heaviest mould ever installed on this IMM: ____________________________________________

? How often the hoisting equipment is inspected: ____________________________________________

? Checks made before using a lifting eye:

- ☐ Safe working load
- ☐ Condition of the eye
- ☐ Other: ____________________________________________

? Checks made before using the clamps:

- ☐ Condition of the clamps
- ☐ Other: ____________________________________________

Remarks/Other risk reduction means:

## ? 👁 E.3 Struck by the mould or hoisting equipment – Means to protect against this hazard

Risk reduction means for this hazard:

## ? 👁 E.4 Movement of a robot – Means to protect against this hazard

👁 Caged robot: ☐ Yes ☐ No ☐ Other: ____________________

👁 Robot enclosure accessible despite the cage:

☐ No

☐ Yes. Explain:

? **Opening** the cage **prevents which parts** of the system from moving?

______________________________________________________________

______________________________________________________________

? **Opening** the cage **allows which parts** of the system to move?

______________________________________________________________

______________________________________________________________

? Enabling switch or pendant**:** ☐ Yes ☐ No

Diagram of the cage with its gates and the gate position switches (➔, ⊕):

## E.5 Caught/jammed in or crushed by a conveyor – Means to protect against this hazard

In-running nip guard: ☐ Yes ☐ No

Crush zone guard: ☐ Yes ☐ No

Remarks/Other risk reduction means for this hazard:

## E.6 Electric power – Means to protect against this hazard

Electric power at play: ________________. Where: _____________________________

Remarks/Other risk reduction means for this hazard:

# E.7 Thermal risk – Means to protect against this hazard

Means of protection: see the IMM guards mentioned in section E.1

PPE worn while the studied system was observed:

☐ Gloves ☐ Safety goggles ☐ Hood ☐ Other: ______________________________

Measure the temperature of the mould during the observed operation: $T_{mould}$ = _________°C

Operation performed while the mould temperature was being taken: _________________________________________________

# Operation observed:

## Note how the observed operation is performed and any hazardous situations.

# APPENDIX B - Steps observed for tasks performed during plant visits

**Mould disassembly** (task performed by one mould assembler-fitter at plant A and two mould assembler-fitters at plant E):

At the start of the disassembly process, the mould and operator guard are both open. The following steps to disassemble the mould were observed:

- empty the mould;
- move the mobile part of the mould onto the fixed part by activating the switch to close the mobile platen;
- insert the hook(s) of the overhead crane into the eyelet(s) of the mould;
- detach the mould's flexible tubing;
- remove the clamps or bolts that attach the mould to the movable platen;
- remove the clamps or bolts that attach the mould to the fixed platen;
- raise the mould with the overhead crane;
- arrange, on the mould, the flexible tubing specific to it;
- gently set the mould on the ground.

→ duration of the task: $T_{visit\ A}$ = 45 min.; $T_{visit\ E}$ = 20 min.

**Mould assembly** (task performed by one to four workers: set-up technicians and mould assembler-fitters at plants A, B, C and E)

At the start, the fixed and mobile parts of the mould are generally clamped together and the operator guard is open. It should be noted that in plant C, the mould's weight exceeded the maximum load of the overhead crane. Out of safety concerns, mould assembly took place in two stages: installation of the mould's fixed part, then of its mobile part, both of which parts weighed less than the overhead crane's maximum load. On our arrival in the plant, the mould's fixed part was already bolted to the fixed platen. We therefore observed that installation of the mould's mobile part and the remainder of the assembly process. Generally speaking, during the visits, mould assembly proceeded as follows:

- if there is a robot, position it at its initial position (home) and switch it off or unplug it without lockout. Robot lockout is not required because of the trust in the safety of the control system;
- insert the hook(s) of the overhead crane into the eyelet(s) of the mould;
- move the mould to the mould area by operating the overhead crane using its pendant;
- position the mould so that its sprue bushing is aligned with the nozzle of the injection barrel;
- install the clamps and bolts to attach the fixed part of the mould to the fixed platen;

- install the injectors on the mobile part of the mould so they are aligned with the IMM's ejection mechanism;
- activate the movable platen clamping mechanism so that it rests against the mobile part of the mould;
- install the clamps and bolts to attach the mobile part of the mould to the movable platen;
- remove the overhead crane's hook from the mould's eyelet;
- disconnect the fixed part of the mould from the mobile part (a clamp holds them together);
- connect, if applicable, the electric sensors to the mould (the sensors inform the PLCs of the position of the moving parts in the mould area: movable platen, ejectors, cores);
- install the mould's flexible tubing for hot and cold water;
- install, if applicable, the mould's flexible hydraulic tubing (may be required for the hydraulic valves that drive the mould's cores);
- if there is a robot, return it to service;
- Adjust the IMM's settings for the type of part to be made.

→ duration of the task: $T_{visit\ A}$ = 45 min.; $T_{visit\ B}$ = 20 min.; $T_{visit\ C}$ = 8 h.; $T_{visit\ E}$ = 40 min.

**Production tests** (task performed by one client (mould manufacturer) and two workers: mould assembler-fitters and set-up technicians at plant C)

During production tests, the IMM operates in semi-automatic mode: after each cycle, the worker recovers the part made. Production tests are carried out as follows:

- adjust the IMM's settings from its console;
- check the movable platen opening and closing speeds, the clamping pressure and the locking of the mould after clamping (these tests frequently alternate with adjustment setting);
- check that the plastic is being injected correctly (the plastic is injected into the fixed part of the open mould and comes out through the gates in the cavity);
- enter the mould area to remove, using compressed air, the ejected plastic (the compressed air is used to dry the hot plastic so it is completely free of the cavity and cavity gates);
- the client checks whether, after the plastic has been removed from the cavity, the cavity is damaged. He inspects the cavity's gates with a flashlight;
- carry out production tests of the first two parts;
- connect the ejector position sensors (this is to ensure safety, as the mould will not close if the ejectors are extended);
- continue part production testing (most of the part production tests alternate with inspection of the cavity);

- if, between two tests, the IMM has not injected anything for five minutes, purge the mould to empty it of any partially hardened plastic. Then re-enter the mould area to dry the plastic ejected from the mould with compressed air and remove it;
- after each part is produced, go down into the mould area to recover the part so it can be checked with the client;
- during the tests, the client noted that several parts were difficult to remove because of their sprue, which remained stuck to the mobile part of the mould. In the event a robot was to recover the parts, it would have difficulty freeing the parts and the IMM would risk being subject to frequent stoppages. The client and his assistant consequently used a portable electric grinder to remove part of the material of the sprue ejector so it would hold back the part less and facilitate its removal;
- after milling, the client cleaned the cavity of the mobile part of the mould and its gates with compressed air;
- as the milling took longer than five minutes, the fixed part of the mould had to be purged to free any partially solidified plastic.

→ duration of the task: $T_{visit\ C} > 4$ h.

**Installation of mould inserts** (task performed by one worker: mould-change, adjustment and start-up technician at plant D)

This task is performed on the mould installed against the fixed and movable platens. Here are the related steps:

- switch off the hydraulic motor before opening the cage;
- open the cage (red light goes on);
- maintain electric power to the IMM;
- place the inserts on the fixed and mobile parts of the mould;
- bolt the inserts to the mould;
- leave the IMM and the cage;
- return the robot to service.

→ duration of the task: $T_{visit\ D} = 45$ min.

**Inspection, polishing and cleaning of the mould cavity** (task performed by two clients and 1 worker: the polisher at plant C)

This maintenance operation is performed as follows:

- the client inspects the mould (he is standing in the mould area on sensitive mats);
- the client cleans various parts of the mould cavity using a cotton cloth (the client then leaves the mould area);

- at the client's request, a polisher cleans the cavity (with a cotton cloth) and polishes it in places (with a portable electric grinder);
- the polisher fills any cracks in the cavity with paste;
- the client inspects the mould a final time.

→ duration of the task: $T_{visit\ C}$ = 40 min.

<u>**Mould polishing and cleaning** (tasks performed by one worker at plant F)</u>

The polishing is of the mould cavity (correction of flaws due to wear and tear, for example), while the cleaning involves everything else (to remove any early signs of rust formation). The two tasks are performed simultaneously:

- the various workers involved prevent use of the control panel by installing a Plexiglas cover to block access to all controls except the emergency stop button. The cover is padlocked and the padlock's only key is locked in a lockout box onto which each worker has attached his personal padlock;
- the workers clean and polish using cloths and pneumatic tools. The user of the pneumatic tools wears a protective mask;
- as the mould is very large, the workers use a stepladder and a table as means of access. The polisher even has to completely enter the mould cavity;
- when the polishing and cleaning tasks are completed, each worker removes his padlock from the lockout box.

→ duration of all maintenance operations: $T_{visit\ F}$ = 4 h.

# APPENDIX C - **Observed Risk Components and Risk Reductions Means: Analysis Grid**

In this grid:

- the risks have only been identified, without respect to probability;
- "near" means located close to the danger zone and having access to it;
- the acronym ES means emergency switch;
- the observed risk reduction means (RRMs) concern only the machine-auxiliary equipment configuration seen during the various tasks studied in the plants;
- the references M and P in the leftmost column refer to the observed type of intervention concerned by the hazardous phenomenon (M = maintenance, P = production);
- the following figures are used to illustrate proper examples of a stepladder, step, platform and ladder to which the grid refers;
- in the table, each risk reduction means is accompanied by a number enclosed in parentheses. The number refers to the risk component against which the risk reduction means acts.

**Figure 29 – Example of a stepladder (left) and step (right).**

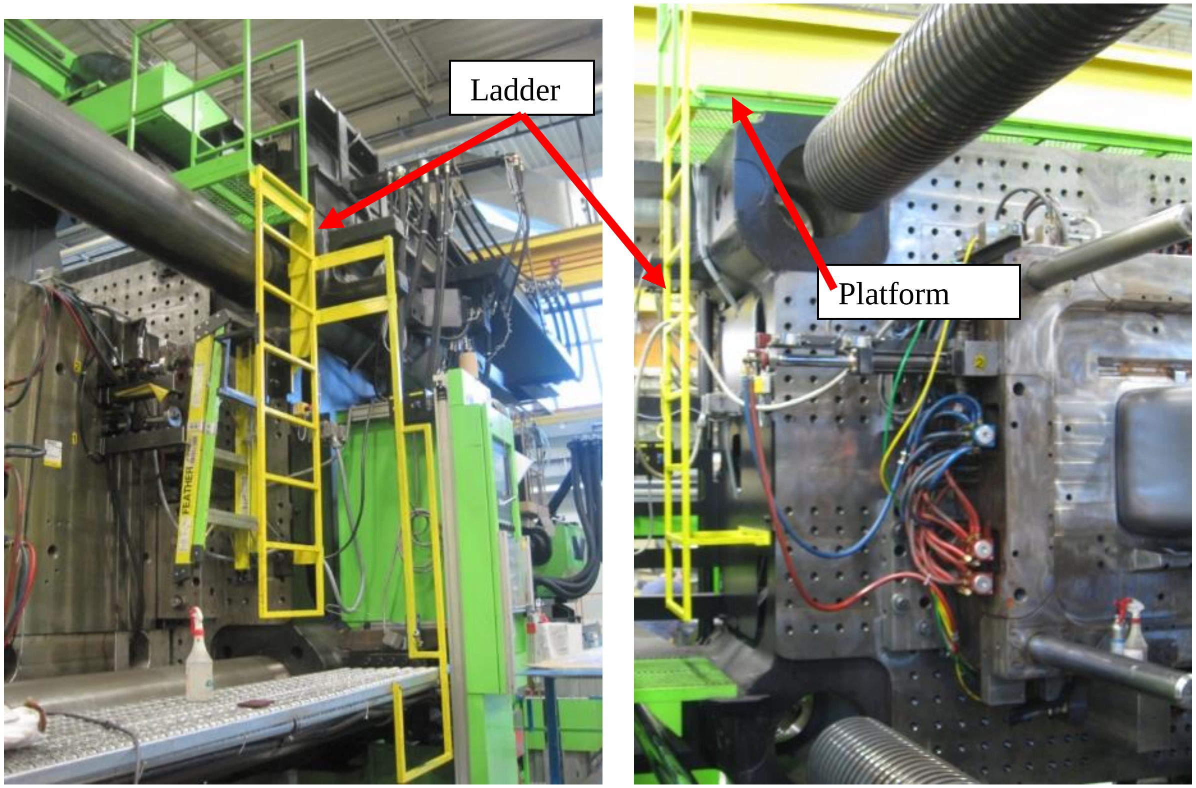



**Figure 30 – Use of a platform equipped with ladders to avoid having to climb on the mould.**

| Visits concerned with risk | RISK COMPONENTS OBSERVED | | | | Visits concerned with RRMs | RISK REDUCTION MEANS (RRMS) OBSERVED |
|---|---|---|---|---|---|---|
| | **Hazardous phenomenon (1)** | **Hazardous situation (2)** | **Hazardous event (3)** | **Possible damage (4)** | | |
| ABCDEF1 F2 (M and P) | Clamping movement of the fixed movable platen results in the creation of a crush zone (Figure 22, p. 45) | Being near the movable platen during its movement | Entering in the path of the movable platen during its movement (e.g. loss of balance) | Cutting, crushing, severing, amputation, death | ABC EF1F2 | Operator-side (locked movable) guard (2, 3), provided it is closed |
| | | | | | AB DEF1 | Opposite operator-side (locked movable) guard (2, 3), provided it is closed |
| | | | | | CD F1F2 | Robot enclosure with locked access gate (operator side or opposite operator side) (2, 3), provided worker is outside the enclosure, gates closed |
| | | | | | A CDEF1F2 | Fixed discharge guard, operator side (2,3) |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2,3) |
| | | | | | BCDEF1F2 | Using a parts recovery robot to reduce production-related risks (2, 3) |
| | | | | | A | Recovery of parts by gravity on a conveyor to reduce production-related risks (2, 3) |
| | | | | | ABCDE | Emergency stop device used in combination with a locked, movable guard (1) |
| | | | | | ABC EF1F2 | Mechanical blocking system for the movable platen (1) |
| | | A part of the body (e.g. arm, leg, head) located in the path of the stopped movable platen | Unplanned start-up of the movable platen caused by (I) a failure in the standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | | ABC EF1F2 | Operator-side (locked movable) guard (3; I and II), provided it is open |
| | | | | | AB DEF1 | Opposite operator-side (locked movable) guard (3; I and II), provided it is open |
| | | | | | CD F1F2 | Robot enclosure with locked access gate (operator side or opposite operator side) (3; I and II), provided at least one access gate is open |
| | | | | | A CDEF1F2 | Fixed discharge guard, operator side (2) |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2) |
| | | | | | BCDEF1F2 | Using a parts recovery robot to reduce production-related risks (2) |
| | | | | | A | Recovery of parts by gravity on a conveyor to reduce production-related risks (2) |
| | | | | | ABCDEF1F2 | Voluntary manual action required to start all or part of the system (3; II.) |
| | | | | | F1F2 | Blocking of the control panel (except the ES) (3; II and III) |
| | | | | | C F1 | Sensitive mat in the mould area (3; II and III) |
| | | | | | ABCDE | Emergency stop device used in combination with a locked, movable guard (1,3) |
| | | | | | ABC EF1F2 | Mechanical blocking system for the movable platen (1, 3) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Body located in the path of the stopped movable platen | | | ABC EF1F2 | Operator-side (locked movable) guard (3), provided the guard is not closed |
| | | | | | AB DEF1 | Opposite operator-side (locked movable) guard (3), provided the guard is not closed |
| | | | | | CD F1F2 | Robot enclosure with locked access gate (operator side or opposite operator side) (2), provided at least one access gate is open |
| | | | | | A DEF1F2 | Fixed discharge guard, operator side (2) |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2) |
| | | | | | BCDEF1F2 | Using a parts recovery robot to reduce production-related risks (2) |
| | | | | | A | Recovery of parts by gravity on a conveyor to reduce production-related risks (2) |
| | | | | | ABCDEF1F2 | Voluntary manual action required to start all or part of the system (3; II) |
| | | | | | F1F2 | Blocking of the control panel (except the ES) (3; II and III) |
| | | | | | C F1 | Sensitive mat in the mould area (3; II and III) |
| | | | | | ABCDE | Emergency stop device used in combination with a locked, movable guard (1) |
| | | | | | ABC EF1F2 | Mechanical blocking system for the movable platen (1) |
| ABCDEF2 (M and P) | Movable platen's opening movement results in the creation of a crush zone behind the platen (Figure 11, p. 28) | Being near the movable platen during the movement | Entering in the path of movable platen during the movement | Clipping, cutting, crushing, severing, amputation, death | AB E F2 | Operator-side (locked movable) guard (2, 3), provided the guard is not closed<br>Note: not for visits C and F1, because the fixed guard prevented access from the operator side and the opposition side. |
| | | | | | AB DE | Opposite operator-side (locked movable) guard (2, 3), provided the guard is not closed |
| | | | | | CD F2 | Robot enclosure with locked access gate (operator side or opposite operator side) (2, 3), provided worker is outside the enclosure, gates closed |
| | | | | | ABCDE | Emergency stop device used in combination with a locked, movable guard (1) |
| | | Body part (e.g. arm, leg, head) located in the path of the stopped movable platen | Unplanned start-up of the movable platen caused by (I) a failure in the standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | | AB E F2 | Operator-side (locked movable) guard (3; I and II), provided the guard is not closed |
| | | | | | AB DE | Opposite operator-side (locked movable) guard (3; I and II), provided the guard is not closed |
| | | | | | CD F2 | Robot enclosure with locked access gate (operator side or opposite operator side) (3; I and II), provided at least one access gate is open |
| | | | | | ABCDE F2 | Voluntary manual action required to start all or part of the system (3; II) |
| | | | | | F2 | Blocking of the control panel (except the ES) (3; II and III) |
| | | | | | C | Sensitive mat in the mould area (3; II and III) |
| | | | | | ABCDE | Emergency stop device used in combination with a locked, movable guard (1,3) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | The body part located in the path of the stopped moveable platen | | | AB E F2 | Operator-side (locked movable) guard (3; I and II), provided the guard is not closed |
| | | | | | AB DE | Opposite operator-side (locked movable) guard (3; I and II), provided the guard is not closed |
| | | | | | CD F2 | Robot enclosure with locked access gate (operator side or opposite operator side) (3; I and II), provided at least one access gate is open |
| | | | | | ABCDE F2 | Voluntary manual action required to start all or part of the system (3; II) |
| | | | | | F2 | Blocking of the control panel (except the ES) (3; II and III) |
| | | | | | C | Sensitive mat in the mould area (3; II and III) |
| | | | | | ABCDE | Emergency stop device used in combination with a locked, movable guard (1) |
| ABCDEF1 F2 (M and P) | Back and forth movement of the ejectors and their mechanism | Being near the ejectors or their mechanism during the movement | Entering into the path of the ejectors or their mechanism during the movement | Depending on the shape of the ejector: fracture, crushing, amputation, bruising, contusion, eye injury | ABC EF1F2 | Operator-side (locked movable) guard (2, 3), provided the guard is not closed |
| | | | | | AB DEF1 | Opposite operator-side (locked movable) guard (2, 3), provided the guard is not closed |
| | | | | | CD F1F2 | Robot enclosure with locked access gate (operator side or opposite operator side), provided worker is outside the enclosure, gates closed |
| | | | | | A CDEF1F2 | Fixed discharge guard, operator side (2, 3) |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2, 3) |
| | | | | | BCDEF1F2 | Using a parts recovery robot to reduce production-related risks (2, 3) |
| | | | | | A | Recovery of parts by gravity on a conveyor to reduce production-related risks (2, 3) |
| | | | | | ABCDE | Emergency stop device used in combination with a locked, movable guard (1) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Being located in the path of the stopped ejectors or their mechanism | Unplanned start-up of the ejectors caused by (I) a failure in the standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | | ABC EF1F2<br>AB DEF1F2<br>CD F1F2<br>A CDEF1F2<br>C EF1F2<br>BCDEF1F2<br>A<br>ABCDEF1F2<br>C F1<br>ABCDE | Operator-side (locked movable) guard (3; I and II), provided the guard is not closed<br>Opposite operator-side (locked movable) guard (3; I and II), provided the guard is not closed<br>Robot enclosure with locked access gate (operator side or opposite operator side) (3; I and II), provided at least one access gate is open<br>Fixed discharge guard, operator side (2)<br>Fixed discharge guard, side opposite operator (2)<br>Using a parts recovery robot to reduce production-related risks (2)<br>Recovery of parts by gravity on a conveyor to reduce production-related risks (2)<br>Voluntary manual action required to start all or part of the system (3; II)<br>Sensitive mat in the mould area (3; II and III)<br>Emergency stop device used in combination with a locked, movable guard (1, 3) |
| A C EF1F2 (M and P) | Movement of the cores and their mechanism | Being near the cores or their mechanisms during the movement | Entering into the path of the cores and their mechanism during the movement | Depending on the shape of the core: fracture, crushing, amputation, bruising, contusion | A C EF1F2<br>A EF1<br>C F1F2<br>A C EF1F2<br>C EF1F2<br>C EF1F2<br>A<br>A C E | Operator-side (locked movable) guard (2, 3), provided the guard is not closed<br>Opposite operator-side (locked movable) guard (2, 3), provided the guard is not closed<br>Robot enclosure with locked access gate (operator side or opposite operator side), provided worker is outside the enclosure, gates closed<br>Fixed discharge guard, operator side (2, 3)<br>Fixed discharge guard, side opposite operator (2, 3)<br>Using a parts recovery robot to reduce production-related risks (2, 3)<br>Recovery of parts by gravity on a conveyor to reduce production-related risks (2, 3)<br>Emergency stop device used in combination with a locked, movable guard (1) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Being located in the path of the stopped cores or their mechanism | Unplanned start-up of the cores and their mechanisms caused by (I) a failure in the standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | | A C EF1F2 | Operator-side (locked movable) guard (3; I and II), provided the guard is not closed |
| | | | | | A EF1 | Opposite operator-side (locked movable) guard (3; I and II), provided the guard is not closed |
| | | | | | C F1F2 | Robot enclosure with locked access gate (operator side or opposite operator side) (3; I and II), provided at least one access gate is open |
| | | | | | A C EF1F2 | Fixed discharge guard, operator side (2) |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2) |
| | | | | | C EF1F2 | Using a parts recovery robot to reduce production-related risks (2) |
| | | | | | A | Recovery of parts by gravity on a conveyor to reduce production-related risks (2) |
| | | | | | A C EF1F2 | Voluntary manual action required to start all or part of the system (3; II) |
| | | | | | F1F2 | Blocking of the control panel (except the ES) (3; II and III) |
| | | | | | C F1 | Sensitive mat in the mould area (3; II and III) |
| | | | | | ABCDE | Emergency stop device used in combination with a locked, movable guard (1, 3) |
| ABCDEF1 F2 (M and P) | Cutting or sharp shaped part: mould, ejectors, cores or inserts | Being near the part | Coming into contact with a sharp edge of the part | Cut, stab, eye injury | ABC EF1F2 | Operator-side (locked movable) guard (2, 3), provided the guard is closed |
| | | | | | ABC EF1 | Opposite operator-side (locked movable) guard (2, 3), provided the guard is closed |
| | | | | | BCDEF1F2 | Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed |
| | | | | | A CDEF1F2 | Fixed discharge guard, operator side (2, 3) |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2, 3) |
| | | | | | BCDEF1F2 | Using a parts recovery robot to reduce production-related risks (2, 3) |
| | | | | | A | Recovery of parts by gravity on a conveyor to reduce production-related risks (2, 3) |
| | | | | | A DE | Job-specific gloves (3, 4) |
| | | | | | A DEF1F2 | Safety goggles (3, 4) |
| | | Handling the part | | | A DE | Job-specific gloves (3, 4) |
| | | | | | A DEF1F2 | **Safety googles** (3, 4) |

| | | | | | | |
|---|---|---|---|---|---|---|
| C E (M and P) | High temperature of the mould | Being near a hot mould | Coming into contract with a hot mould | Burn | C E | Operator-side (locked movable) guard (2, 3), provided the guard is closed |
| | | | | | E | Opposite operator-side (locked movable) guard (2, 3), provided the guard is closed |
| | | | | | C E | Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed |
| | | | | | C E | Fixed discharge guard, operator side (2, 3) |
| | | | | | C E | Fixed discharge guard, side opposite operator (2, 3) |
| | | | | | C E | Using a parts recovery robot to reduce production-related risks (2, 3) |
| | | | | | E | Job-specific gloves (3, 4) |
| | | | | | E | Circulating water to lower the mould’s temperature to 80°C before performing the task (1) |
| ABCDEF1 F2 (M and P) | High temperature of the plastic | Being near the mould where the hot plastic is found | Coming into contact with hot plastic | Burn | ABC EF1F2 | Operator-side (locked movable) guard (2, 3), provided the guard is closed |
| | | | | | AB DEF1 | Opposite operator-side (locked movable) guard (2, 3), provided the guard is closed |
| | | | | | BCDEF1F2 | Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed |
| | | | | | A CDEF1F2 | Fixed discharge guard, operator side (2, 3) |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2, 3) |
| | | | | | BCDEF1F2 | Using a parts recovery robot to reduce production-related risks (2, 3) |
| | | | | | A | Recovery of parts by gravity on a conveyor to reduce production-related risks (2, 3) |
| | | | | | E | Job-specific gloves (3, 4) |
| | | Being in the path of projected hot plastic | Unexpected projection of hot plastic | | ABC EF1F2 | Operator-side (locked movable) guard (2), provided the guard is closed |
| | | | | | AB DEF1 | Opposite operator-side (locked movable) guard (2), provided the guard is closed |
| | | | | | BC EF1 | Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed, and it is not wire mesh |
| | | | | | A C EF1F2 | Fixed discharge guard, operator side (2), provided it is not wire mesh |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2), provided it is not wire mesh |
| | | | | | E | Job-specific gloves (4) |
| | | | | | A DEF1F2 | Safety goggles (4) |
| | | | | | F1F2 | Visor (4) |
| ABCDEF1 F2 (M and P) | Release of hot or burning gas | Being in the path of projected hot or burning gas | Unexpected projection of hot or burning gas | Burn | E | Job-specific gloves (4) |
| | | | | | F1F2 | Visor (4) |
| ABCDEF1 F2 (M and P) | Release of gas that may be toxic | Being near the released gas | Inhalation of gas that could be toxic | Irritation of respiratory passages | C | Capture-at-source ventilation system (3) |

| | | | | | | |
|---|---|---|---|---|---|---|
| ABCDEF1 F2 (M and P) | Whipping movement of the cooling system's flexible water tubing | Being in the path of the flexible tubing when the mould's cooling circuit disconnects or breaks | Disconnection or break of the flexible tubing, causing a whipping movement | Bruise, fracture, eye injury | ABC EF1F2 | Operator-side (locked movable) guard (2), provided the guard is closed and presents an obstacle to the whipping of the tubing inside the mould area |
| | | | | | AB DEF1 | Opposite operator-side (locked movable) guard (2), provided the guard is closed and presents an obstacle to the whipping of the tubing inside the mould area |
| | | | | | BCDEF1F2 | Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed |
| | | | | | A CDEF1F2 | Fixed discharge guard, operator side (2) |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2) |
| | | | | | A DEF1F2 | Safety goggles (4) |
| ABCDEF1 F2 (M and P) | High temperature of the water in the mould | Being in the path of hot water sprayed from the mould | Disconnection or break of a connector or flexible tubing, spraying hot water | Hot water burn | ABC EF1F2 | Operator-side (locked movable) guard (2), provided the guard is closed and presents an obstacle to the spray of hot water inside the mould area |
| | | | | | AB DEF1 | Opposite operator-side (locked movable) guard (2), provided the guard is closed and presents an obstacle to the spray of hot water inside the mould area |
| | | | | | BC EF1 | Robot enclosure (operator side or opposite operator side), provided the worker is outside the enclosure, gates closed, and the enclosure is not wire mesh |
| | | | | | A C EF1F2 | Fixed discharge guard, operator side (2), provided it is not wire mesh |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2), provided it is not wire mesh |
| ABCDEF1 F2 (M and P) | Whipping movement of the hydraulic system's flexible tubing | Being in the path of the flexible tubing when the mould's hydraulic circuit is disconnected or breaks | Disconnection or break of a connector or flexible tubing, causing a whipping movement | Contusion, fracture, eye injury | ABC EF1F2 | Operator-side (locked movable) guard (2), provided the guard is closed and presents an obstacle to the whipping of the tubing inside the mould area |
| | | | | | AB DEF1 | Opposite operator-side (locked movable) guard (2), provided the guard is closed and presents an obstacle to the whipping of the tubing inside the mould area |
| | | | | | BCDEF1F2 | Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed |
| | | | | | A CDEF1F2 | Fixed discharge guard, operator side (2) |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2) |
| | | | | | A DEF1F2 | Safety goggles (4) |

| | | | | | | |
|---|---|---|---|---|---|---|
| ABCDEF1 F2 (M and P) | Spraying of pressurized oil | Being in the path of the spayed oil | Disconnection or break of a connector or tubing, resulting in a leak | Necrosis, serious puncturing of the skin, eye injury | ABC EF1F2 | Operator-side (locked movable) guard (2), provided the guard is closed and presents an obstacle to the spraying of oil inside the mould area |
| | | | | | AB DEF1 | Opposite operator-side (locked movable) guard (2), provided the guard is closed and presents an obstacle to the spraying of oil inside the mould area |
| | | | | | BC EF1 | Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed, and it is not wire mesh |
| | | | | | A CDEF1F2 | Fixed discharge guard, operator side (2), provided it is not wire mesh |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2), provided it is not wire mesh |
| | | | | | A DEF1F2 | Safety goggles (4) |
| ABCDEF1 F2 (M and P) | Hot oil | Being in the path sprayed oil | Disconnection or break of a connector or flexible tubing, causing hot oil to be sprayed | Hot oil burn | ABC EF1F2 | Operator-side (locked movable) guard (2), provided the guard is closed and presents an obstacle to the spraying of oil inside the mould area |
| | | | | | AB DEF1 | Opposite operator-side (locked movable) guard (2), provided the guard is closed and presents an obstacle to the spraying of oil inside the mould area |
| | | | | | BC EF1 | Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed, and it is not wire mesh |
| | | | | | A CDEF1F2 | Fixed discharge guard, operator side (2), provided it is not wire mesh |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2), provided it is not wire mesh |
| ABCDEF1 F2 (M and P) | Gravity (falling object) | Being in the object's path (e.g. mould, clamps, accessories) | Improperly adapted hoisting accessory | Depending on mass, shape, speed: getting struck, fracture, bruising, crushing, death | | Note: the operator-side guard, the guard opposite the operator and the robot enclosure are not mentioned here because the operations concerned require access to the mould area and the guards are therefore open. |
| | | | | | A CDEF1F2 | Training on the proper use of hoisting devices and accessories (3) |
| | | | | | ABCDEF1F2 | Protective footwear (4) |
| | | | Breakdown of the hoisting equipment | | ABCDEF1F2 | Checking the hoisting accessories (3) |
| | | | | | A CDEF1F2 | Regular inspection and maintenance of the hoisting devices (3) |
| | | | | | ABCDEF1F2 | Protective footwear (4) |
| | | | Object lost by the operator (e.g. clamps, eyelets, tools, accessories, accidentally making a tool fall from a height) | | ABCDEF1F2 | Protective footwear (4) |

| | | | | | | |
|---|---|---|---|---|---|---|
| ABCDEF1 F2 (p) | Movement of the mould during handling | Being in the path of the movement | Movement due to the improper use of the hoisting equipment (e.g. mould dangling, inertia or rotation) | Depending on mass, shape, speed: getting struck, crushing, death | A CDEF1F2 | Training on the proper use of hoisting devices and accessories (3) |
| | | | Unplanned start-up of the hoisting device caused by (I) a failure in the standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | | | No RAM observed. |
| | | Being near the path of the moving mould | Coming into the mould's path (e.g. jostling, inattention) | Depending on mass, shape, speed: getting struck, crushing, death | A CDEF1F2 | Training on the proper use of hoisting devices and accessories (3) |
| ABCDEF1 F2 (M and P) | Gravity (fall of a person) | Working at heights (e.g. working on a stepladder, step, or gangway) (Figure 21, p. 44) | Losing one's balance | Depending on the height, contact surface: fracture, bruising, death | ABCDEF1F2<br>C F1 | Non-slip surfaces (3)<br>Guard rail/ramp for staircases and the gangway (3, 4) |
| | | | Unstable equipment | | F1 | Addition of platforms on the fixed and movable platens and fixed ladders to access them (3) (Figure 29, p. 95) |
| | | Balancing on a fixed part of the IMM not designed for the purpose (e.g. slide bar or piece of equipment) (Figure 30, p. 96) | Losing one's balance | | ABC E<br>F1 | Small non-slip platform installed on the IMM (2, 3)<br>Addition of platforms on the fixed and movable platens and fixed ladders to access them (2) (Figure 29, p. 95) |
| | | Being on a part of the IMM that could start moving (e.g. mould in the IMM) or a piece of equipment (e.g. conveyor) (Figure 9, p. 26) | Unplanned start-up causing one to lose one's balance | | ABC EF1F2<br>AB DEF1<br>CD F1F2<br>ABCDEF1F2<br>F1F2 | Operator-side (locked movable) guard (3), provided the guard is open<br>Opposite operator-side (locked movable) guard (3), provided the guard is open<br>Robot enclosure with locked access gate (operator side or opposite operator side) (3), provided at least one access gate is open<br>Voluntary manual action required to start all or part of the system (3)<br>Blocking of the control panel (except the ES) (3) |
| | | | Losing one's balance | | ABCDEF1F2<br>ABCDEF1F2 | Non-slip surfaces (2, 3)<br>Protective footwear (3) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Situation conducive to same-level falls (e.g. slippery or cluttered floor, uneven ground) (Figure 20, p. 43) | Losing one's balance | Depending on the height, contact surface: fracture, bruising, death | ABCDEF1F2<br>ABCDEF1F2<br>CD | Non-slip surfaces (2, 3)<br>Protective footwear (3)<br>Keep the ground clear (person assigned this task or task shared by all) (2) |
| ABCDEF1 F2 (p) | Movement of an ejected part | Being in the path of the ejection | Closing of the mould resulting in the ejection of an object (e.g. a tool inadvertently left behind, debris, mould fragment) | Contusion, puncturing, fracture, death, eye injury | ABC EF1F2<br>AB DEF1<br>BCDEF1F2<br>A CDEF1F2<br>C EF1F2<br>BC<br>BC<br>A DEF1F2 | Operator-side (locked movable) guard (2), provided the guard is closed, depending on the ejected part's direction<br>Opposite operator-side (locked movable) guard (2), provided the guard is closed, depending on the ejected part's direction<br>Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed and depending on the size of the openings in the mesh<br>Fixed discharge guard, operator side (2), depending on the size of the openings in the mesh<br>Fixed discharge guard, side opposite operator (2) depending on the size of the openings in the mesh<br>Mould-clamping movement conditional upon the robot's position (3)<br>Robot's movement conditional on the platen's movement (3)<br>Safety goggles (4, for small parts) |
| ABCDEF1 F2 (M and P) | Hard surface* | Being near a hard surface and working while bending over | Hit the hard surface when raising head | Contusion | BCDEF1F2<br>A | Using a parts recovery robot to reduce production-related risks (2)<br>Recovery of parts by gravity on a conveyor to reduce production-related risks (2)<br>*Hard surfaces located in the mould area |
| A CDEF1 (M and P) | Conveyor nip points | Body part, clothing or worn tool located near an in-running nip point of a conveyor | Access to the nip point, resulting in being pulled in | Jamming, crushing, amputation, friction burn | C F1<br>A D<br>A CDE<br>F1<br>C<br>A F1 | Robot enclosure (operator side or opposite operator side) for nip points located inside the enclosure (Figure 24, p. 53)<br>Fixed discharge guard, operator side (2, 3) for the nip points located in the mould area<br>"Rollerless" belt conveyor (1)<br>Addition of in-running nip guards (Figure 25, p. 54) (3)<br>Emergency stop device for the IMM-auxiliary equipment system in automatic mode (1)<br>The conveyor's emergency stop device (1) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Body part, clothing or worn tool in a nip point of a stopped conveyor | Unplanned start-up of the conveyor caused by (I) a failure in the standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | | C<br>A D<br>A CDE<br>C<br>F1<br>C<br>A F1 | Robot enclosure with locked access gate (operator side or opposite operator side) (3; I and II), provided at least one access gate is open<br>Fixed discharge guard, operator side (2) for the nip points located under the mould area<br>"Rollerless" belt conveyor (1)<br>Voluntary manual action required to start up all or part of the system (3; II)<br>Addition of in-running nip guards (Figure 25, p. 54) (2)<br>Emergency stop device for the IMM-auxiliary equipment system in automatic mode (1, 3)<br>The conveyor's emergency stop device (1, 3) |
| A CDEF1 (M and P) | Movement of the conveyor belt (Figure 9, p. 26) | Being on the belt of the stopped conveyor | Unplanned start-up of the movable platen caused by (I) a failure in the standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | Fracture, bruising, laceration | C<br>A D<br>C<br>C<br>A F1 | Robot enclosure with locked access gate (operator side or opposite operator side), provided at least one access gate is open<br>Fixed discharge guard, operator side (2) for the part of the conveyor located under the mould area<br>Voluntary manual action required to start up all or part of the system (3; II)<br>Emergency stop device for the IMM-auxiliary equipment system in automatic mode (1, 3)<br>The conveyor's emergency stop device (1, 3) |
| | | Body part, clothing or worn tool located near a running belt with irregularities (e.g. mechanical splices, tears, cleats, conveyed parts) | Getting caught on the belt's irregularity, resulting in being pulled in | Fracture, bruising, laceration, stab | C EF1<br>A D<br>C<br>A F1 | Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed<br>Fixed discharge guard, operator side (2, 3) for the part of the conveyor located under the mould area<br>Emergency stop device for the IMM-auxiliary equipment system in automatic mode (1)<br>The conveyor's emergency stop device (1) |
| | | Body part, clothing or worn tool located near a stopped belt with irregularities | Unplanned start-up of the conveyor caused by (I) a failure in the standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | | C<br>A D<br>C<br>C<br>A F1 | Robot enclosure with locked access gate (operator side or opposite operator side), provided at least one access gate is open<br>Fixed discharge guard, operator side (2) for the part of the conveyor located under the mould area<br>Voluntary manual action required to start up all or part of the system (3; II)<br>Emergency stop device for the IMM-auxiliary equipment system in automatic mode (1, 3)<br>The conveyor's emergency stop device (1, 3) |

| | | | | | | |
|---|---|---|---|---|---|---|
| BCDEF1F2<br>(M and P) | Movements of the robot's arm (including the gripper and the load carried) | Being near the robot's path during movement | Coming into the robot's path during the movement | Depending on the configuration: bruising, fracture, jamming, death, perforation, eye injury | BCDEF1F2<br>BC EF1F2<br>D F1<br>BCDE<br>DEF1F2 | Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed (3)<br>Operator-side (locked movable) guard (3), provided it is closed<br>Opposite operator-side (locked movable) guard (3), provided it is closed<br>Emergency stop device used in combination with a locked, movable guard (1)<br>Safety goggles (4) |
| | | Being located in the path of the stopped robot | Unplanned start-up of the robot caused by (I) a failure in the standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | | CD F1F2<br>BC EF1F2<br>D F1<br>BCDEF1F2<br>C F1<br>BCDE<br>BCDEF1F2<br>DEF1F2 | Robot enclosure with locked access gate (operator side or opposite operator side) (3; II), provided at least one access gate is open<br>Operator-side (locked movable) guard (3; II), provided it is open<br>Opposite operator-side (locked movable) guard (3; II), provided it is open<br>Voluntary manual action required to start up all or part of the system (3; II)<br>Sensitive mat in the mould area (3; II and III), preventing the system's moving parts from moving, including the motorized operator guard<br>Emergency stop device used in combination with a locked, movable guard (1, 3)<br>Enabling device for robot programming pendant (3; II)<br>Safety goggles (4) |
| | | Being located in the maximum robot motion space | Technical failure resulting in the path's going outside the restricted area | | CD F1F2<br>BC EF1F2<br>D F1<br>DEF1F2 | Robot enclosure with locked access gate (operator side or opposite operator side), provided at least one access gate is open (2)<br>Operator-side (locked movable) guard (3), provided it is open<br>Opposite operator-side (locked movable) guard (3), provided it is open<br>Safety goggles (4) |
| BCDEF1F2<br>(M and P) | Movements of the grippers (hands) alone | Being in the motion space of the stopped gripper | Unplanned start-up of the gripper caused by (I) a failure in the standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | Fracture, bruising, severing, eye injury | CD F1F2<br>BC EF1F2<br>D F1<br>BCDE<br>BCDEF1F2<br>DEF1F2 | Robot enclosure with locked access gate (operator side or opposite operator side) (2), provided at least one access gate is open<br>Operator-side (locked movable) guard (3; II), provided it is open<br>Opposite operator-side (locked movable) guard (3; II), provided it is open<br>Emergency stop device used in combination with a locked, movable guard (1, 3)<br>Enabling device for robot programming pendant (3; II)<br>Safety goggles (4) |

| | | | | | | |
|---|---|---|---|---|---|---|
| |  | Being near the gripper motion space during the movement | Entering the gripper motions space | | CD F1F2 | Robot enclosure with locked access gate (operator side or opposite operator side) (3), provided at least one access gate is open |
| | | | | | BC EF1F2 | Operator-side (locked movable) guard (3), provided it is open |
| | | | | | D F1 | Opposite operator-side (locked movable) guard (3), provided it is open |
| | | | | | BCDE | Emergency stop device used in combination with a locked, movable guard (1, 3) |
| | | | | | DEF1F2 | Safety goggles (4) |
| BCDEF1F2 (p) | Gravity (dropping of the robot's load) | Being in the path of the load | Unsuitable gripper | Depending on the height of the fall and the load's mass and shape: getting hit, fracture, bruising, crushing | BCDEF1F2 | Robot enclosure (operator side or opposite operator side), provided worker is outside the enclosure, gates closed (2) |
| | | | | | BC EF1F2 | Operator-side (locked movable) guard (2), provided it is closed and the load falls within the mould area |
| | | | | | B DEF1 | Opposite operator-side (locked movable) guard (2), provided it is closed and the load falls within the mould area |
| | | | | | CDEF1F2 | Fixed discharge guard, operator side (2), provided the load falls within the mould area |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2), provided the load falls within the mould area |
| | | | | | BCDEF1F2 | Protective footwear (4) |
| | | | Breakage of the gripper or load | | BCDEF1F2 | Robot enclosure (operator side or opposite operator side) (2), provided worker is outside the enclosure, gates closed |
| | | | | | BC EF1F2 | Operator-side (locked movable) guard (2), provided it is closed and the load falls within the mould area |
| | | | | | B DEF1 | Opposite operator-side (locked movable) guard (2), provided it is closed and the load falls within the mould area |
| | | | | | CDEF1F2 | Fixed discharge guard, operator side (2), provided the load falls within the mould area |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2), provided the load falls within the mould area |
| | | | | | BCDEF1F2 | Protective footwear (4) |
| | | | Unplanned start-up of the gripper caused by (I) a failure in the standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | | BCDEF1F2 | Robot enclosure (operator side or opposite operator side) (2), provided worker is outside the enclosure, gates closed |
| | | | | | BC EF1F2 | Operator-side (locked movable) guard (2), provided it is closed and the load falls within the mould area |
| | | | | | B DEF1 | Opposite operator-side (locked movable) guard (2), provided it is closed and the load falls within the mould area |
| | | | | | CDEF1F2 | Fixed discharge guard, operator side (2), provided the load falls within the mould area |
| | | | | | C EF1F2 | Fixed discharge guard, side opposite operator (2), provided the load falls within the mould area |
| | | | | | BCDEF1F2 | Enabling device for robot programming pendant (3; II) |
| | | | | | BCDEF1F2 | Protective footwear (4) |

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|---|---|---|---|---|---|---|
| BCDEF1F2<br>(p) | Movement of a load thrown by the robot | Being in the path of the thrown load | Unsuitable gripper resulting in the release of load while the robot is moving | Depending on the robot's speed and the mass and shape of the load: getting hit, fracture, bruising, eye injury | BCDEF1F2<br>BC EF1F2<br>D F1<br>CDEF1F2<br>C EF1F2<br>DEF1F2 | Robot enclosure (operator side or opposite operator side) (2), provided worker is outside the enclosure, gates closed<br>Operator-side (locked movable) guard (2), provided it is closed<br>Opposite operator-side (locked movable) guard (2), provided it is closed<br>Fixed discharge guard, operator side (2), provided the load falls within the mould area<br>Fixed discharge guard, side opposite operator (2), provided the load falls within the mould area<br>Safety goggles (4, for small parts) |
| | | | Breakage of the gripper or load resulting in the release of the load while the robot is moving | | BCDEF1F2<br>BC EF1F2<br>D F1<br>CDEF1F2<br>C EF1F2<br>DEF1F2 | Robot enclosure (operator side or opposite operator side) (2), provided worker is outside the enclosure, gates closed<br>Operator-side (locked movable) guard (2), provided it is closed<br>Opposite operator-side (locked movable) guard (2), provided it is closed<br>Fixed discharge guard, operator side (2), provided the load falls within the mould area<br>Fixed discharge guard, side opposite operator (2), provided the load falls within the mould area<br>Safety goggles (4, for small parts) |
| | | | Unplanned release of the load caused by (I) a failure of the gripper's standard control system or a loss of power (e.g. pneumatic), (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party while the robot is moving | | BCDEF1F2<br>BC EF1F2<br>D F1<br>CDEF1F2<br>C EF1F2<br>BCDEF1F2<br>DEF1F2 | Robot enclosure (operator side or opposite operator side) (2), provided worker is outside the enclosure, gates closed<br>Operator-side (locked movable) guard (2), provided it is closed<br>Opposite operator-side (locked movable) guard (2), provided it is closed<br>Fixed discharge guard, operator side (2), provided the load falls within the mould area<br>Fixed discharge guard, side opposite operator (2), provided the load falls within the mould area<br>Enabling device for robot programming pendant (3; II)<br>Safety goggles (4, for small parts) |
| ABCDEF1F2<br>(M and P) | Electric power | Coming into contact with part of a piece of equipment that is normally live but that is not (e.g. touching a bare wire while doing repair work) | Accidental powering on (e.g. by a third party or due to a failure) | Electric shock, electrocution | A | Low voltage (1) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Being near an energized part, which is intended to be so (e.g. measure the mould's tensile strength, disconnecting the mould's electric circuit without knowing whether it is live) | Coming into contact with the energized part of a piece of equipment | | A | Low voltage (1) |
| | | Being in contact with part of a piece of equipment that is not intended to be energized (e.g. machine stand) and that is not | Accidental powering on (e.g. due to a failure) | | A | Low voltage (1) |
| | | Being near part of a piece of equipment not intended to be energized (e.g. machine stand) but that actually is | Coming into contact with the accidentally energized part | | A | Low voltage (1) |
| ABCDEF1 F2 (M and P) | Ambient noise | Exposure to noise | Unusually intense exposure | Tinnitus, deafness, deterioration in auditory acuity or balance, fatigue, stress, decreased attentiveness | A D | Hearing protector (3, 4) |
| BC EF1 (M and P) | Closing movement of the motorized operator-side guard | Body part in the path of the stopped motorized guard | Unplanned start-up of the guard caused by (I) a failure of the guard's standard control system, (II) accidentally (e.g. by a third party or the operator), or (III) voluntarily by a third party | Jamming, bruising | BC EF1<br>B EF1<br>C F1<br>BC EF1 | Intentional manual actin necessary to return to movement all or part of the system (3; II)<br>Slower motorized guard closing speed (4)<br>Sensitive mat in the mould area (3; II and III)<br>Emergency stop device used in combination with a locked, movable guard (1, 3) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Being near motorized guard during the movement | Coming into the path of the motorized guard while it is moving (e.g. loss of balance) | | BC EF1<br>BC EF1 | Sensitive edge (4)<br>Emergency stop device used in combination with a locked, movable guard (1, 3) |
| C F1 (m) | Projection of metal shavings | Being near the projection of metal shavings | Coming into the path of the projected metal shavings | Eye injuries | C F1 | Job-specific safety goggles (4) |
| C F1 (m) | Cleaning liquid | Using the cleaning liquid | Coming into contact with the cleaning liquid | Skin irritation, necrosis | C F1 | Job-specific gloves (4) |
| ABCDEF1 F2 (M and P) | Non-compliance with ergonomic principles | Bending into the mould area | Awkward posture<br>Repetitive movements | Musculoskeletal disorder (MSD) | BCDEF1F2<br>A | Using a parts recovery robot to reduce production-related risks (2, 3)<br>Recovery of parts by gravity on a conveyor to reduce production-related risks (2, 3) |
| | | Manually opening the mould area guard | Excessive exertion<br>Repetitive movements | | BCDEF1F2<br>A<br>BC EF1 | Using a parts recovery robot to reduce production-related risks (2, 3)<br>Recovery of parts by gravity on a conveyor to reduce production-related risks (2)<br>Installing a motorized guard (2, 3) |
| | | Handling heavy objects (e.g. portable tools, core mechanisms) | Excessive exertion<br>Repetitive movements<br>Awkward posture | | ABCDEF1F2 | Arranging heavy objects near the mould area (e.g. in mobile work benches with drawers, on a retractable table installed on the gangway guard rail) (3) |
| | | Accessing a lower-level workspace | Impact of the jump | | AB DEF1F2 | Using a stepladder that is sufficiently high and has a sufficient number of steps to avoid jumping (3) |
| | | Accessing a higher-level workspace | Large steps and frequent climbing | | AB DEF1F2<br>C F1 | Using a job-specific stepladder or step to reduce access efforts (3)<br>Using a gangway (3) |

# APPENDIX D - *A posteriori* Validation: contexts of the study

Formulas 1 to 4 presented in section 6.3.3 of this report use the following as parameters: the $MTTF_d$ for each of the components of the safety function and their own DCs. The $MTTF_d$ for each component may be found in the manufacturer's manual or in ISO 13849-1. If the component concerned does not have a predetermined $MTTF_d$, it can be calculated using the annual average number of uses of the safety function (see parameter $n_{op}$ below) and parameter $B_{10d}$, which corresponds to the number of cycles until 10% of the components fail dangerously. Parameter $n_{op}$ depends on the context in which the safety function is used. For this study, the $n_{op}$ was calculated for two contexts: "Plant" (see table 13 and table 14). As for the DC of each component, it can be found in ISO 13849-1. The components' technical characteristics make it possible to select their respective DC and $MTTF_d$ or $B_{10d}$ when using ISO 13849-1.

Parameter $n_{op}$ is calculated using the following formula from NF EN ISO 13849-1:2008:

$$n_{op} = \frac{d_{op} \times h_{op} \times 3600 s/h}{t_{cycle}} \qquad \text{Eq. (D. 1)}$$

Parameters $d_{op}$, $h_{op}$, and $t_{cycle}$ are described in table 13 and table 14. These parameters depend on the context of use.

The $n_{op}$ allows us to determine the $MTTF_d$ for each component using the following formula from NF EN ISO 13849-1:2008:

$$\boldsymbol{MTTF_d = \frac{B_{10d}}{0,1 \times n_{op}}} \qquad \textbf{Eq. (D. 2)}$$

**Table 13 – Definition of the "Plant" context.**

| Parameters | | S151A | K01, K02 |
|---|---|---|---|
| Average number of hours of use per day | $h_{op}$ **(h)** | 20 | 20 |
| Average number of days of use per year | $d_{op}$ **(day)** | 350 | 350 |
| Average time between the start of two successive cycles of the component, in seconds per cycle | $t_{cycle}$ **(s/cycle)** | 6 | 6 |
| Average annual number of uses | $n_{op}$ **(cycles/year)** | 4,200,000 | 4,200,000 |

**Table 14 – Definition of the "Laboratory" context.**

| Parameters | | S151A | K01, K02 |
|---|---|---|---|
| Mean operation, in hours per day | **$h_{op}$ (h)** | 2 | 2 |
| Mean operation, in days per year | **$d_{op}$ (day)** | 5 | 5 |
| Mean time between the between of two successive cycles of the component, in seconds per cycle | **$t_{cycle}$ (s/cycle)** | 6 | 6 |
| Mean annual operation | **$n_{op}$ (cycles/year)** | 6,000 | 6,000 |

## APPENDIX E - **Component Characteristics – “Industrial” Context.**

Appendix E presents the characteristics of the safety function components that have made it possible to calculate their $MTTF_d$ and to select their DC form the “industrial” context.

For the tables in appendices E and F, the headings of certain columns are explained as follows:

- “Actual characteristics”: characteristics taken from the component’s technical data or the IMM manufacturer’s manual.
- “Hypothetical characteristics”: default value of parameters taken from table C.1 of NF EN ISO 13849-1:2008. To apply these values to the studied components, we had to hypothesize that the components were designed according to the criteria found in section C.2 and C.3 of the standard.
- “DC”: default value of the diagnostic coverage proposed in table E.1 of the standard.

**Table 15 – “Industrial” context: characteristics of the channel 1 components (N/A = not applicable)**

| Identification | Number | Actual characteristics | Hypothetical characteristics | | $MTTF_d$ per component (years) | DC |
|---|---|---|---|---|---|---|
| Switches | **S151A** | Direct opening action<br>Diagnosed by relay KO3 with mechanical linked contacts | $B_{10d}$ (cycles) | 2,000,000 | 4.76 | 0.99 |
| | **S151B** | Direct opening action<br>Switch with positive mechanical action Diagnosed by relay KO3 with mechanical linked contacts | N/A, because fault exclusion | | N/A, because fault exclusion | N/A, because fault exclusion |
| Relays | **K01** | Relay with mechanical linked contacts<br>Diagnosed by relay KO3 with mechanical linked contacts | $B_{10d}$ (cycles) | 400,000 | 0.95 | 0.99 |
| | **K02** | Relay with mechanical linked contacts<br>Diagnosed by relay KO3 with mechanical linked contacts | $B_{10d}$ (cycles) | 400,000 | 0.95 | 0.99 |
| Valve D1 | **Y101** | Diagnosed by a programmable electronic card whose operation is unknown. The worst case is chosen: DC = 0 | $MTTF_d$ (years) | 150 | 150 | 0.00 |

| | | | | | |
|---|---|---|---|---|---|
| Relay | **K03** | Relay with mechanically linked contacts | N/A | N/A | N/A |

**Table 16 – "Industrial" context: characteristics of the channel 2 components (N/A = not applicable).**

| Identification | Number | Actual characteristics | Hypothetical characteristics | $MTTF_d$ per component (years) | DC |
|---|---|---|---|---|---|
| Switch | **S175** | Direct opening action<br>Switch with positive mechanical action | N/A | N/A, because fault exclusion | N/A, because fault exclusion |
| Valve D2 | **Y171** | N/A | $MTTF_d$ 150 (years) | 150 | 0,00 |
| Programmable electronic card | **N/A** | N/A | N/A | N/A | N/A |

# APPENDIX F - Component Characteristics – "Laboratory" Context

Appendix F presents the characteristics of the safety function components that have made it possible to calculated their MTTFd and to select their DC for the "Laboratory" context.

**Table 17 – "Laboratory" context: characteristics of the channel 1 components (N/A = not applicable).**

| Identification | Number | Actual characteristics | Hypothetical characteristics | | $MTTF_d$ per component (years) | DC |
|---|---|---|---|---|---|---|
| Switches | **S151A** | Direct opening action<br>Diagnosed by relay KO3 with mechanical linked contacts | $B_{10d}$ (cycles) | 2,000,000 | 3,333.33 | 0.99 |
| | **S151B** | Direct opening action<br>Switch with positive mechanical action Diagnosed by relay KO3 with mechanical linked contacts | N/A, because fault exclusion | | N/A, because fault exclusion | N/A, because fault exclusion |
| Relays | **K01** | Relay with mechanical linked contacts<br>Diagnosed by relay KO3 with mechanical linked contacts | $B_{10d}$ (cycles) | 400,000 | 666.67 | 0.99 |
| | **K02** | Relay with mechanical linked contacts<br>Diagnosed by relay KO3 with mechanical linked contacts | $B_{10d}$ (cycles) | 400,000 | 666.67 | 0.99 |
| Distributor D1 | **Y101** | Diagnosed by a programmable electronic card whose operation is unknown. The worst case is chosen: DC = 0 | $MTTF_d$ (years) | 150 | 150.00 | 0.00 |
| Relay | **K03** | Relay with mechanically linked contacts | N/A | | N/A | N/A |

**Table 18 – "Laboratory" context: characteristics of the channel 2 components 2 (N/A = not applicable).**

| Identification | Number | Actual characteristics | Hypothetical characteristics | $MTTF_d$ per component (years) | DC |
|---|---|---|---|---|---|
| Switch | **S175** | Direct opening action<br>Switch with positive mechanical action | N/A | N/A, as defaults are excluded | N/A, as defaults are excluded |
| Valve D2 | **Y171** | N/A | $MTTF_d$ (years) 150 | 150.00 | 0.00 |
| Programmable electronic card | **N/A** | N/A | N/A | N/A | N/A |