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Safety of Manufacturing Equipment: Methodology Based on a Work Situation Model and Need Functional Analysis

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Abstract: The aim of “integrated prevention” is to conduct a preliminary risk analysis in order to achieve a lower level of risk in the design of future work equipment. Despite the many safety documents that exist, many companies, particularly SME/SMIs, do not yet apply these safe design principles. Integration of safety in the design process is mainly based on the individual knowledge or experience of the designers and is not conducted in any formalized way. In order to answer to this problem, this paper presents a methodology to involve engaging stakeholders in dynamic dialogue and a framework so that they may together define the information necessary for implementing safe design principles during the functional specification. The proposed methodology has been validated to industrial case.

Keywords: work situation, integrated prevention, requirement specification, need functional analysis, safe design

1. Introduction

The concept of “integrated prevention” has been widely shared by European countries since the 1990s (Figure 1). It consists of applying safe design principles as early as possible in the design process. The aim is to conduct a preliminary risk analysis in order to achieve a lower level of risk in the design of future work equipment.

Despite that many safety documents that exist (e.g., design instructions, guides and standards), many companies, particularly SME/SMIs, do not yet apply these safe design principles correctly. This is largely because the different participants in the design process (engineers, technicians, project leaders) are not prevention specialists and lack of appropriate methods and tools. As a result, it is difficult for them to make the correct choices in a timely manner without penalizing the project cost or delaying project completion. Consequently, integration of safety in the design process is mainly based on the individual knowledge or experience of the designers and is not conducted in any formalized way [2]. Safety requirements are usually addressed in formulaic sentences such as “the equipment should respect regulations and standards” or “should be safe, ergonomic and easy to use” etc. As a result, prevention issues and technical requirements are often handled separately and the safety problems are often dealt with at the end of the project once the concepts and technical solutions have already been defined. At this point, the measures implemented are mainly corrective, merely to satisfy the regulations. This cannot be considered to constitute true safety integration, which takes into account the future activity of the operators, including “reasonably foreseeable misuse” [3].

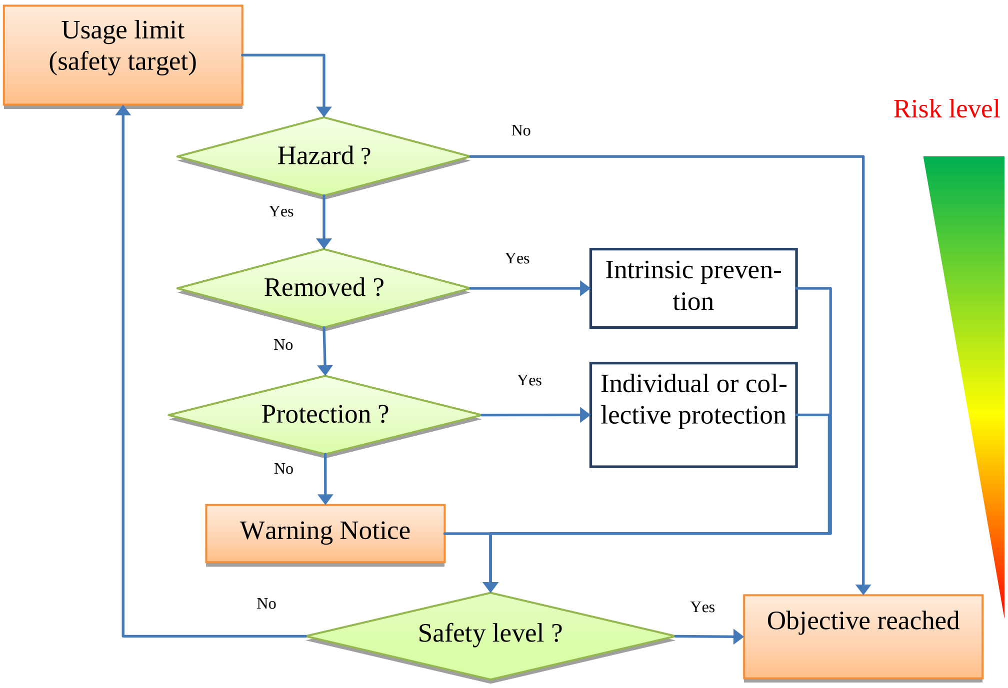

Figure 1. Risk reduction process according to NF EN ISO 12100 [1]

In response to this problem, the following methodology involves engaging stakeholders in dynamic dialogue so that they may together define the information necessary for implementing safe design principles during the functional specification.

2. State of the art

A number of publications concerning safety integration at the specification stage recommend considering health, safety and ergonomics as design objectives that should be specified in the requirement document. To do so, specifications should go beyond safety recommendations contained in standards and take into account predictable use of the work equipment, for instance by analyzing the activities of the operators of similar machinery [4] to [8].

Need Functional Analysis (NFA) is a well-known methodological tool standardized [9] that can support the specification stage. While a number of studies have highlighted the benefits of functional analysis in the prevention of risks because of its pluridisciplinary approach [10], others have described its limitations in regard to its ability to specify different contexts of use and future user activities [11].

MOSTRA (Work situation model) resulted from previous INRS research on safety integration in design [12]. The specific objective of this model is to help designers to take into account different contexts of use and future user activities. MOSTRA is based on the concept of work situations according to a systemic model described by Guillevic [13], and uses the entities involved in safe working practices. Figure 2 shows the different concepts that designers typically deal with (e.g., system, function, technical solution, consumables) and MOSTRA allows them to consider those concepts that mainly concern the users, the tasks to be performed, and the associated risks (for example, dangerous zones, hazards, dangerous events, or safety measures).

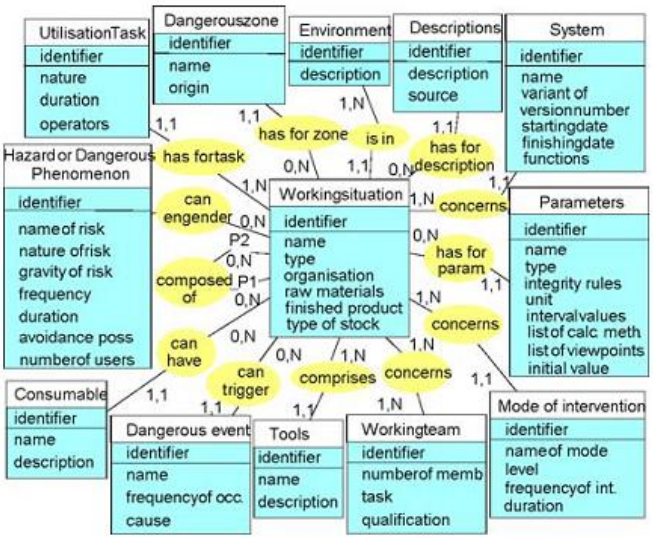

Figure 2 Simplified view of MOSTRA [13]

The model cannot manage the design process by itself but, in order to exploit it, it is necessary to use it in conjunction with traditional design tools. Through such a combined approach, the methodology relevance is assured by the logical use of the traditional tools and the data consistency is provided by MOSTRA.

3. Specification methodology for safe design

In order to achieve our goal, we decided to use the "MOSTRA" model to form a link between the functions identified with NFA and the work-situation parameters needed for the risk assessment.

3.1. NFA and safety requirements

Safety requirements may be integrated in the functional analysis at three possible levels, the choice of which can lead to different results:

- General constraints: as enacted by EN 1325-1 [9], however, although this is necessary, it is not sufficiently detailed and may lead to the designer developing the prevention apart from the technical and functional requirements,
- Function: this approach is relevant only when the objective is to design a safety-related system. However, integration at the functional level leads designers to specify the prevention separately from the functional requirement.
- Function performance criteria: the goal is to identify all parameters which have a direct impact on safety. The functional decomposition of the system is then used to define the future user tasks on the work equipment.

We will continue with this last approach in our methodology. The "user/designer" should be guided to obtain a complete picture of a design task. Although they naturally provide the foundation on which to focus design efforts, there are other important criteria that the user may not even perceive, such as safety issues. Otto and Wood [14] define these as latent specifications (needed, but not always expressed by the customer). To do this, it is necessary to ask what the possible work situations are and which entities are involved for each function. The second stage of NFA method therefore needs to be divided into two different phases: description and characterization.

3.2. Description step

The description phase should be carried out by a work team (designers, users, project leader), with the help of a structured and easy-to-use questionnaire which collects all information, including latent information. At this point it is necessary to decide whether it is better to:

- Directly use MOSTRA links to build the questionnaire and gather information about work situations such as "Environment", "User task", "Work team", etc.
- Use a tool such as "5Ws and an H", which is often used in industrial problem solving [15]. The work team must answer "What", "Who", "Where", "When", "Why" and "How" the function is accomplished. This tool uses an intuitive, descriptive and imaginative way to describe the work situation because it uses basic

question prompts thereby generating answers in natural language. Firstly an exploratory test was conducted so that these two approaches could be compared. A case study of band saw machines for the food industry was chosen, and two study groups were formed. Each group was composed of two technical designers and an ergonomist, who each had the same level of knowledge of the case study. In both questionnaires the participants were asked to specify four functions (F1: set-up the blade, F2: remove the blade, F3: cutting meat, F4: cleaning the machine). The first team started with functional analysis and the "5Ws and an H" questionnaire, while the second started with the MOSTRA-based questionnaire.

Table 1. Functional chart – Industrial application

Function : To receive and to place parts to manufacture from uphill machine line to the milling unit		
Criteria	**Value**	**MOSTRA Object**
WHAT	Geometry : deformable and non rectilinear part	C
	Maximum dimensions : (2x200) x 20 x 12000 (Width, Thickness, Length)	C
	Minimum dimension : compatibility with the existing conveyor and clamping system	S, C
	Maximum weight : about 750 kg (62kg/m)	C
	Surface finition : no slippery parts for good grip	C
	Stability of parts : homogeneous part with easily identifiable center of gravity	C
	Room temperature	EV
	Initial state : parts positioned on the conveyor	C, S
	Final state : machining position	C
	Precision of the placement +/- 2 mm	C
WHO	Machine : long parts (automatic configuration)	S, C, FM
	Operator : short parts (manual command configuration)	WT, C, FM
	Operator : short and long parts for the clamping system	WT, C, UT
WHERE	From the uphill conveyor to the manufacturing area of the milling machine	S
WHEN	Before the milling cycle	UT
HOW	Machine: long parts: automatically positioned by the uphill conveyor according to the entered command.	S, C, FM
	Operator: short parts: manually positioned by the operator (on sight) on the conveyor up to the position of the laser dead stop and the clamping system.	WT, C, UT, S
	Need visibility from the milling control panel while positioning manually to see the parts through the conveyor of uphill machine line and the laser dead stop	UT, FM, S
	Accessibility of the operator to the milling control panel during manual operations	UT, S
	Operator position : standing in front of the control panel with visibility for the positioning	WT, IM, UT
	Automatic mode : 1m/s	FM, UT
	Manual mode : <0.5 m/s	FM, UT
	No handling from the operator	S, UT

Legend: Consumable (C), System (S), Work Team (WT), Environment (EV), User Task (UT), Tool (T), Intervention Mode (IM), Functioning Mode (FM)

This test shows that the "5Ws and an H" questionnaire overlap those of the MOSTRA. We therefore recommend using the "5Ws and an H" questionnaire for the description step. The MOSTRA-based questionnaire will be used during the characterization step. A chart was created to orientate the group discussion towards achieving our objectives. Then an industrial case study: company that designs and manufactures both specialized and standard machines with several optional functions (drilling, stamping, and sawing machining transfer line) for working with steel beams, was performed (Table 1).

3.3. Characterization step

The objective of the characterization step is to define the performance criteria that characterize each previously identified entity. Each performance criterion, specially health, safety and ergonomic aspects, should be measurable, testable or verifiable at each successive step in the development process [14]. To achieve this, it is necessary to first associate one or several MOSTRA objects with each description according to what it characterizes. To do this the "5Ws and an H" were mapped with MOSTRA objects and then MOSTRA-based questionnaire allows completion and verification of the data coherence with regard to the function concerned. These associations allow identification of the main working situations in which the function is effective. The structure used to define the working situations is illustrated in Table 2.

Table 2 - Data structure of main work situations – industrial case

F: Receive and place parts to manufacture from uphill machining transfer line to the milling unit.

<table>
<tr>
<td>|_ WS1: Automatic positioning for long parts
|_ UT1: Placing parts
|_ C1: Long parts
|_ S4: Conveyor of the line
|_ FM2: Automatic mode

|_ WS2: Manual positioning for short parts
|_ UT1: Placing parts
|_ WT: Operator
|_ IM1: Standing posture
|_ C2: Short parts
|_ FM1: Manual mode</td>
<td>|_ WS3: Manual command of the clamping
|_ UT5: Clamping the parts
|_ C1: Short parts
|_ C2: Long parts
|_ S2: Clamping system</td>
</tr>
</table>

The final step is to add a quantitative or qualitative value to each criterion. These can be either predefined attributes of the Mostra UML model (task name, duration, work team, intervention mode) or specific parameters (initial/final state, speed …). This step facilitates and enhances the risk analysis, which should be carried out iteratively according to NFA progress. Within the framework of this study we used the IDAR® method developed by CETIM [16]. Based on the EN12100 standard approach, this method has a specifically user- centered and human-safety oriented analysis, which matches our objectives.

3.4. Discussion

We describe the solutions implemented with regard to the following function: to receive and to place parts to manufacture from uphill machining transfer line to the milling unit (Table 1). According to the part length, two operating modes were initially defined by the industrial partner: manual and automatic. In answering the “5Ws and an H” questions, the designers realized that the technical solutions retained for these two operating modes were not entirely satisfactory from a safety point of view. For the short part, the operator needs to control and simultaneously visualize the part’s positioning. The current location of the control panel leads to an uncomfortable position for the operator. In addition, the transferring wheels were designed for parts longer than 300 mm, but when answering the “What” question, it was stated that some customers produced shorter parts (250mm). In these situations, the operator has to handle the parts manually, risking a hand being crushed between the part (25 kg) and the transferring wheels.

Another safety issue highlighted by the proposed methodology concerned the possible interactions during the loading/unloading phase. It quickly became apparent that the end-user would perform this operation during the production time, when the machine was operating in an automatic mode for a period of several minutes and did not require the intervention of the operator. This working practice comes under the definition of “reasonably foreseeable misuse” in the Machinery Directive and must also be taken into account by the designer; this was not the case in the initial design. As the preparation area was located close to the conveyor, its access was also prevented by the safety device. However, it seems highly likely that it will be bypassed at some time in the future due to productivity constraints.

4. Conclusion

The aim of this research work is to use the “user/designer” pair to define the information necessary (intermediary objects [17]) for integrating safety requirements at the specification stage. Our hypothesis is to integrate safety requirements as performance criteria for each function and not as specific functions or general requirements, in other words, to specify that each function should be safe. We suggest using:

1. Need Functional Analysis, which is used to identify all functions of a future product (work equipment in our case).
2. An intuitive and descriptive tool such as “5Ws and an H” to define, for each function, the usage-based criteria including safety criteria.
3. The MOSTRA working situation model to organize and capitalize these data. This model was specifically developed to support safety integration at the design stage.

In addition to the specific benefits of traditional functional analysis (e.g., saving time in the subsequent design-process steps, possibility of capitalizing the results of the analysis etc.), the proposed approach creates a common basis for both NFA and risk analysis. The first industrial application yielded relevant results: unsafe work situations were identified that had not been detected in the original design by the industrial partner. However, this case study only allowed validation of the potential benefits from a designer's point of view. Data was mainly provided by the designers and few data were supplied by the final user.

This work has been performed in the frame of the dual laboratory between INRS and ENSAM/ LCFC (safety design of working situation: functional requirements, equipment design, working place management).

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