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THE EVALUATION OF COSTS RELATED TO SAFETY OF MECHANICAL SYSTEMS IN DESIGN STAGES

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1. Introduction

During the last years the matters of Machine Safety have arisen to a primary importance in the European Community. In fact, in spite of the huge technical and technological progress achieved during the last 20 years, the number of accidents at work caused by malfunctioning or by a not proper use of a machine is getting higher and higher.
This new approach towards Machine Safety, which was massively afforded by the European Community throughout a series of new Directives since the beginning of the '90s, is certainly an attempt to work out this critical situation of this branch.
On the other side the always growing normative links have brought to manufacturers growing costs as well, so that it becomes a hindrance to the final pursuing of a proper level of Safety: the link between Safety and Cost seems very strong, so that it is taken into account in the new Review of the Directive "Safety of Machinery" (98/37/EC that codifies into one single text Directive 89/392/EEC, as modified by Directives 91/368/EEC, 93/44/EEC and 93/68/EEC), for what concerns the application of ERS (Essential Safety Requirements, Annex I).
The pursuance of the recent European Union Instructions regarding Safety is a very complex task which involves all the people operating in a factory, thus affecting clearly the costs that the factory itself should bear (Ashford, Hallet, Hunter, Scheel); particularly, these new standards changed widely designers' and manufacturers' role.
It is then put in evidence the necessity to find some criteria to evaluate the maximum level to which the Safety of a Machine could be increased, so to make it economically feasible at the same time.
Inside this task it comes out the great importance of Design, as found out by the main Authors in this field (Birmingham et. al.; Hundal; Main et al.; Wang & Ruxton), which allows to set the limits a designer should move within to find the optimum agreement between Safety and Cost. Such problem isn't easy to solve and puts great limits for the choices of designer and he has to make use of all his inventiveness and creativity to increase MS's safety with acceptable costs.
The aim of the present study has been the development of a Methodical Design approach to evaluate Safety Costs, according with the EC Directives Requirements in matter of risks prevention.

2. Background

The general background to the study comes from the analysis of the following aspects:

a) Analysis of the statistics on accidents at work and studies on the pursuance of the European Directives in matter of Machine Safety.
b) Analysis of safety devices and components.

c) Analysis of costs related to Safety.

a.) The study, carried out with the support of the Safety Technologies Department of the ISPESL (Italian Institute for Prevention and Safety) of Rome, not only concerned data collection and analysis on accidents at work, but also a deepened study on the problems related to the pursuance of the new laws regarding Safety.
The results of this first research phase could be summarized in the following items:

- most of the accidents are caused by the great confidence of skilled users, who steal off the safety devices and because of the lack of attention during maintenance or setup operations;
- there is still a lot of former machines in relation to the new Directive, and there are quite a lot of them in small and medium enterprises, and most of them are not even updated according to the new Directives, mainly for what concerns economical reasons;
- often a further difficulty towards a more complete introduction in companies of all the precepts and guidelines of the EC Directives is the market structure that leads to accept not complete conformity conditions to support low costs and/or a faster production.
- a not correct interpretation of the ESR, together with a not complete classification of machines in example in Annex IV, represents a huge difficulty for the correct individuation and evaluation of risks;
- the absence of "specific rules" for each kind of equipment, considering also that small companies have seldom huge mass productions: in fact they regard special and unique manufacturing or limited to few pieces (particularly in the field of wood manufacturing equipment).

b.) On the basis of the definitions of the "Machine Directive" (98/37/EC), were considered the most common safety devices, which nowadays are on the market and that have been classified as the criteria explained in the EN 954 . On the basis of the study we carried out it comes out that such classification should not be understood as hierarchical, and the designer does not choose the device belonging to the higher category class . For instance, it should be noticed that a category 4 device is not often safer than one of a lower level; moreover not all the machines are suitable with high category safety devices. In example a perfectly working mechanical safety device could be considered as belonging to category 1, and equally or even more useful than one belonging to category 3 or 4. In order to make the choice we should consider which is the result we want to achieve in relation to the type of machine we have.

c.) It is usual to divide costs related to safety into direct costs and non-direct costs. To the first class belong the costs related to safety, of which we have specific account in the budget estimation (ensurances, claims for damages, individual safety devices, workers , costs for specific safety plants, etc.), to the second class belong the costs related to the "lack of safety", which usually have not a direct relation with this budget (costs for: occurrence of an accident on work, lack of production, legal costs, overuse of energy, etc.). Data collected in different fields show that the latter cost is the most undervalued in the short time, but is the one which more affects the enterprise: in fact this cost increases vs. safety according to an exponential law.

3. Methods

Since every necessary action to increase the safety level of Mechanical Systems is strictly depending on its cost, it was deepened the study on the following Design Tools (showed in details in Figure 1):

- Design Methods for the improvement of Safety.
- Techniques and Criteria for Risk Evaluation.
- Interclasses Design Methods (Methods not directly connected to Safety and Cost, but anyway useful for the improvement of Mechanical Systems properties).
- Design Methods for Cost evaluation.
- Techniques and Criteria for Economic Evaluations of Designs.

Beside this, the study of the Standards regarding Safety was deepened, both the Directive "Safety of Machinery" (98/37/EC et al.) and the "Harmonised Standards" (EN 1050; EN 291; EN 292; etc.).

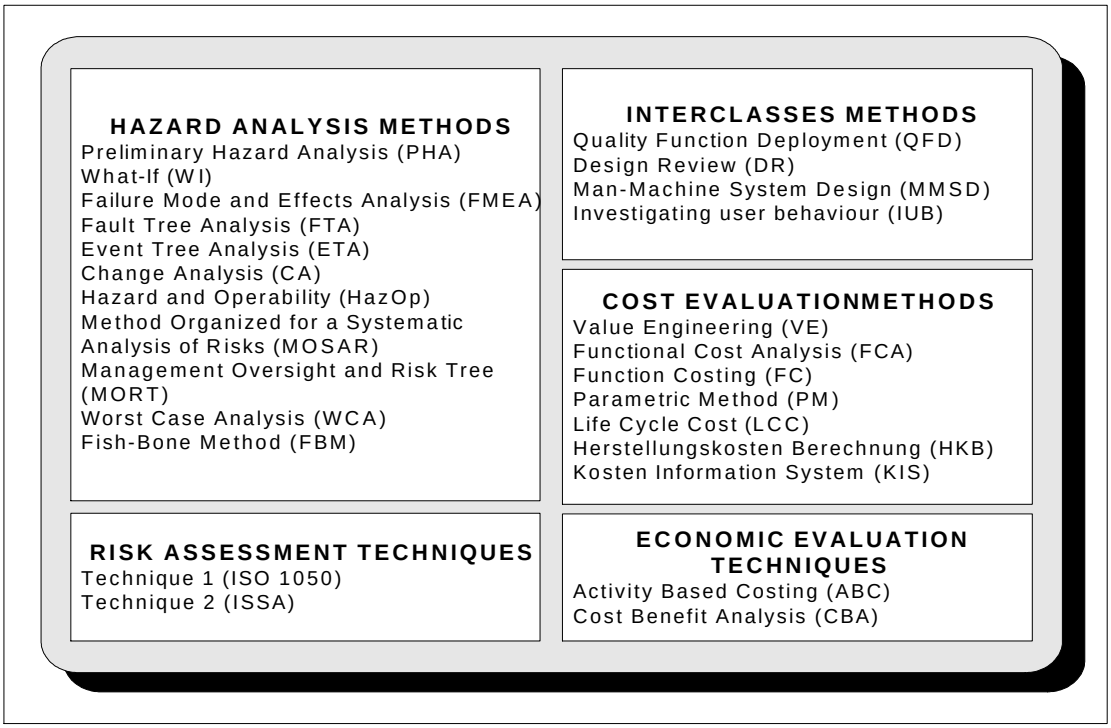

Figure 1. Design Tools

4. Results

The result of the present study was the development of a Design Methodology (SCRM - Safety/Cost Ratio Methodology), based on the Methodical Design Procedure of the School of Rome, which summarizes collected data and provides a guide for the Design Development.
For this purpose were singled out all the steps into which the Design Process is divided, and for each one of them were considered the Design Tools that can be more conveniently used, so that the designer can make the right choice in each phase of the Design Activity.
The analysis pointed out a set of criteria that should be applied during the decision making's stages of the Design Process with the aim to evaluate, for every component, part or Mechanical System, both the correct Safety level and the Cost related.

The implementation of the SCR Methodology consists of the following main steps:

a) Detecting the risks connected to the use of the machine (R_j)
b) Defining a series of feasible solutions (S_{kj}) for each detected risk
c) Valuing the cost for each of these possible solutions (C_{kj})
d) Linear combination of the feasible solutions and evaluation of the total Safety Level
e) Valuing the total cost related to any combination (Cost Level)
f) Choice of the best combination and "bottom up" control.

In Figure 2 it is showed a detail of the SCRM approach.

5. Case Study

To verify the effectiveness of the study performed, the developed Methodology was implemented to a real case, and in particular to the Re-design of a Numerically Controlled Machining Centre for the manufacture of wooden products, which includes both numerically controlled and hand controlled working phases.

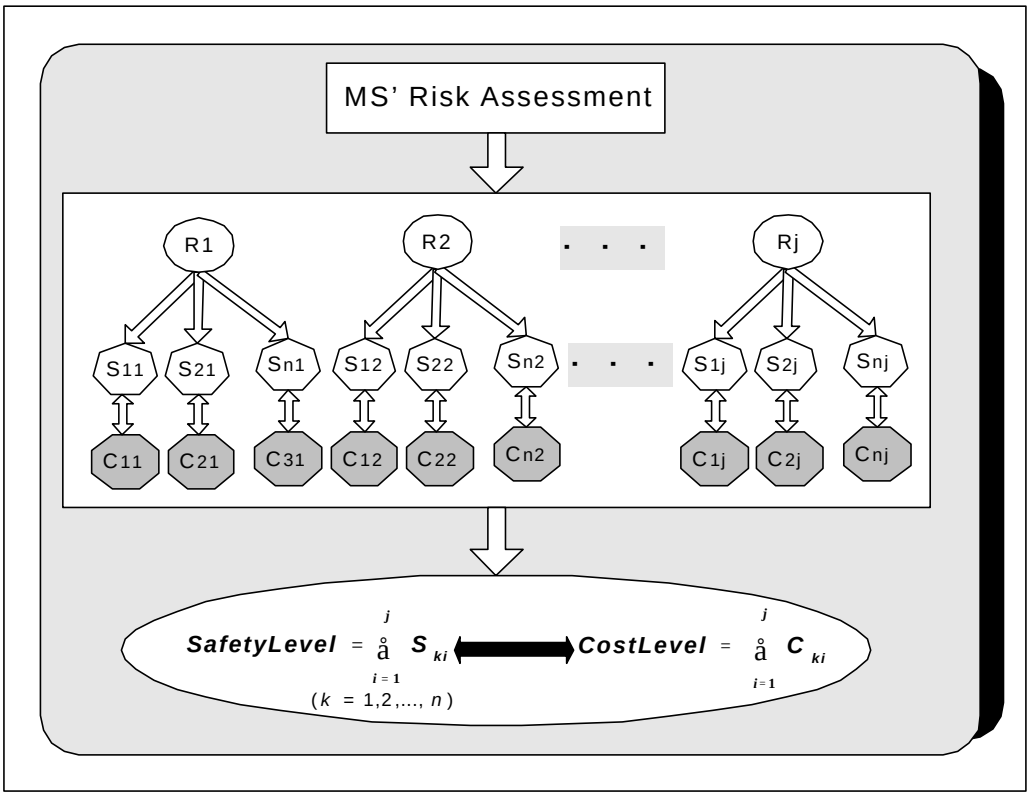

Figure 2. A detail of the SCRM approach

Phase 1. In the first phase of the Design Process , all necessary data to understand and explain the problem were collected; in particular we considered customer's requests, standards regarding safety of the machine, statistics of user incidents, characteristics and typologies of main existing safety devices. The information collected, especially those related to customer's requests, laid the basis to identify the first Design Specifications through the application of the first matrix of QFD method.
At this point, in order to improve the safety of machine from the beginning, we applied PHA method that allowed us to detect the main risks linked with all the life cycle phases of the machine and to carry out, for each risk, the evaluation of hazard level through the application of Technique 2.
The output of these analyses was used to work out in the "List of Requirements", which is the final step of this phase.

Phase 2. During the second phase the mechanical system starts to take on a more concrete shape and now it is possible to apply a lot of methods for safety and cost: in this case, we used the methods FMEA and FCA, which seemed necessary to carry out a careful technical and economic valuation of the mechanical system.
Through FMEA analysis it was possible to identify the main modes of failure of machine and to determine, for each one, the probability of occurring, the relevance and the detectability, which allow to detect the corrective measures.
On the other hand, FCA was used to determine what are the characteristics (materials, reliability, maintainability,…) that more influence cost of safety devices.
Data collected put the basis to evaluate the concepts proposed and to choose, consequently, the one presenting the best compromise between cost and technical validity.
Now, before concluding the second phase of the design process, it was carried out a further study: In fact, starting from the chosen concept, we found different solutions regarding the safety devices used. In this case also we made use of a double valuation: we in fact calculated both the safety level and the cost of its implementation.

Phase 3. During the third phase some general characteristics such as materials and dimensions were defined in order to attain a further detailed design, and it looks necessary to start to fix. Once this task was done it was possible to carry out a further analysis aiming at the improvement of the system. In this case, as the study is based on matters of Safety and Cost, we carried out a check of the main risks, and in order to make this evaluation effective, we used the evaluation Technique n.2, in order to consider not only the risk directly linked to the machine, but also the ones related to working environment and to user skills.
The results we achieved were all satisfactory (except for one of them), since the calculated values were less than the maximum acceptable limit; the only exception related to the risk of contact between operator and tool, was therefore further deepened, and this study, based, such as in the previous cases, on a cost/benefits analysis, made clear the necessity of insertion of a timer connected with the interlock of the mobile guard.
At the end we obtained a mechanical system, as shown in Figure 3 and Figure 4, characterized by:

a) a mono-radius barrier to avoid the contact between the operator and the rotative element (moving head);
b) a mobile guard equipped with the interlock device which locks the guard in order to avoid the contact between operator and tool;
c) perimetric protection panels to ensure safety of those people who may be near by the machine tool (enclosure);
d) safety stop device.

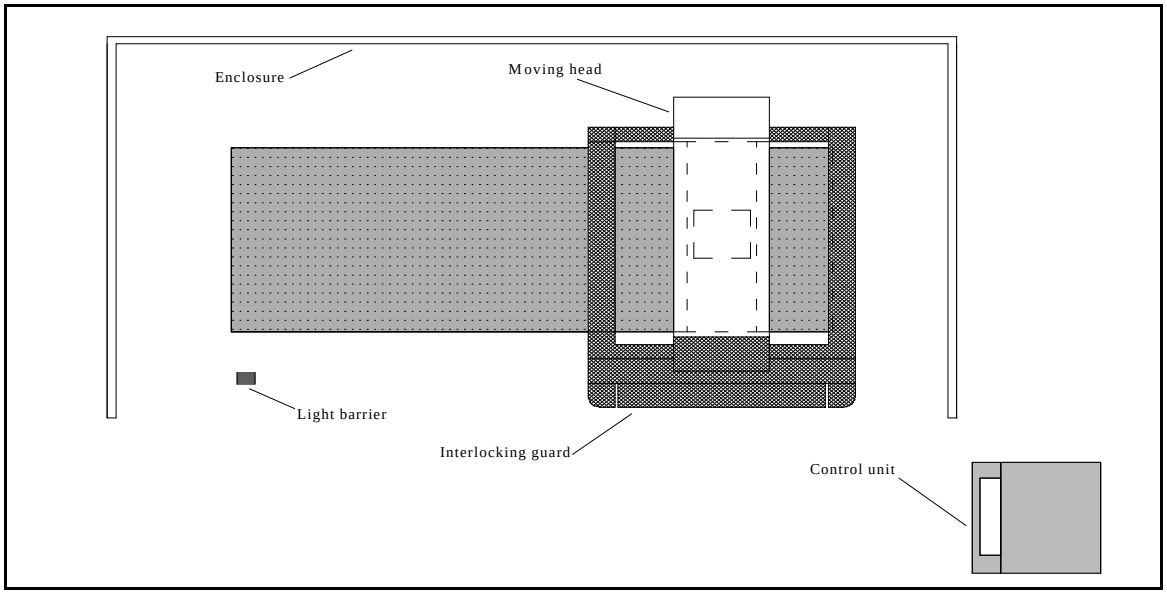

Figure 3. Top sight of the machine

6. Conclusions

The Methodology SCR allowed to single out the main risks connected to the use of this machine, and to set the interventions to execute, analyzing at once the increase of costs related to such changes.
The result achieved was a Mechanical System which satisfies the requirements given and that, in particular, gives warranty of its Safety with regards both to the operator and to other people who may be near by.
In fact the Methodology SCR allows not only a “top-down” assessment leading from hazards to components’ reliability, but also a “bottom-up” investigation of the influence of every design decision, involving both the manufacturing costs as well as the total life cycle cost.
Moreover, with the proper choice of Safety Devices, it was possible to achieve a considerable increase in Safety with a very little increase in costs.

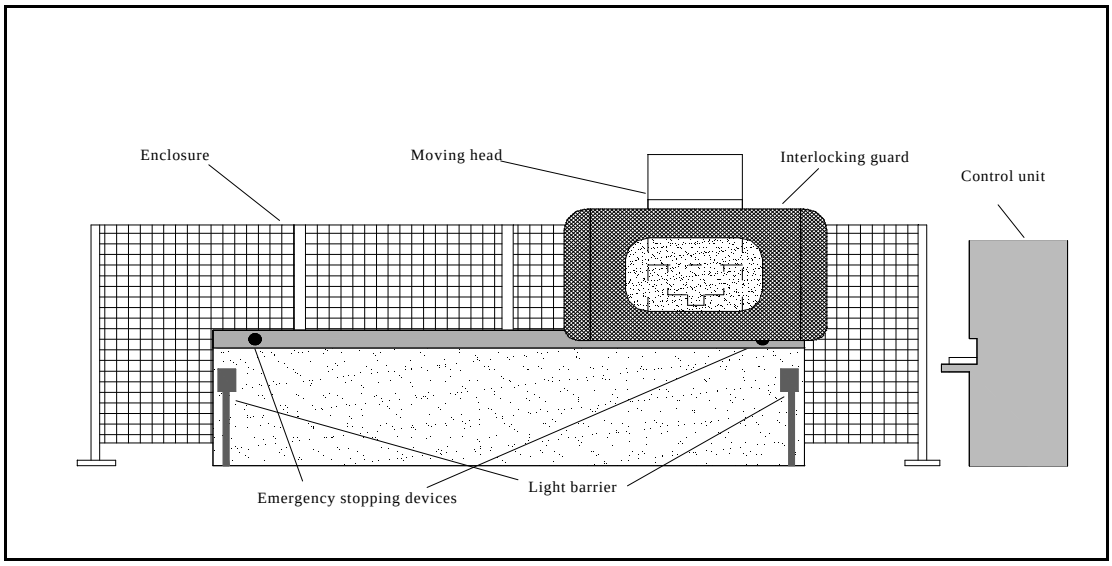

Figure 4. Lateral sight of the machine

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