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INTEGRATION OF BOUNDARY SITUATIONS TOLERATED IN OPERATION IN INDUSTRIAL RISK ANALYSIS

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ABSTRACT: *This paper proposes an operational definition of Boundary Situations Tolerated in Operation (BSTO) and highlights indicators that can allow comparison of prescribed task to the effectively performed task, in the context of human-machine system's safety. Risk analysis should identify the points where safety-related functions are not separated from other functions of the machine and the extent to which access to these locations is possible. This is important especially when remote access is necessary for diagnosis and correction process. The second part of the paper summarizes the results of risk analysis in two industrial units, taking into account BSTO's and the bypass of safety measures. The analysis carried out in printing shops allowed the incorporation of BSTO's and concluded in proposing a systematic approach that allows the integration of these undesirable situations into industrial risk analysis processes.*
KEYWORDS: *Boundary Situations Tolerated in Operation, risk, analysis, human-machine system*

INTRODUCTION

Increasing any system's safety involves risk analysis and establishing means of prevention and protection for risk control. Moreover, the key problem of access to optimize human integration in the system of professional requirements, involves the conservation and efficient use of its creative potential, being today a multidisciplinary field that integrates conjugated concerns of technical and human sciences, both interested in finding the most appropriate means of the functioning of human – machine system [8].

Industrial risk analysis represents a systematic and planned work and voluntary action, performed even in early stages of conception and design of a system or technology. Contrary to the accident investigation and analysis, industrial and occupational risk analysis is "a priori" a preventive and not curative approach, so that conditions favorable to dialogue to be met. This analysis, though it seems difficult at first, allows the definition of complex industrial situations, which is to interfere with technical equipment, products, people and other relevant factors [6, 9].

THE CONCEPT OF RISK WITHIN THE HUMAN – MACHINE SYSTEM

Framing the notion of risk for the human – machine system into a general pattern that would express its fullest and most concentrated essence required the exploit of the lexical field of the word and definition of risk has taken various formulations. Thus risk is defined "as a potential hazard, more or less predictable" [1] and can be interpreted as a potential level of insecurity. Favaro & Monteau [2] states that the risk is:

- *a sense, felt by the individual (in a subjective approach);*
- *a way, that a situation or a work that will be considered safe if there is no unwanted phenomena a long period of time;*
- *an object or purpose for individuals, organizations or society (overall safety is a goal towards which it tends and which should be considered in making decisions).*

Undesired state of human-machine system leads to negative internal consequences, when they relate to the system, or external nature when they relate to the external environment of the system [18, 19] (see Figure 1). Villemeur [24], defines the measure of risk as "the size of a hazard which associates a measure of the likelihood of an undesired event and a measure of effects or consequences".

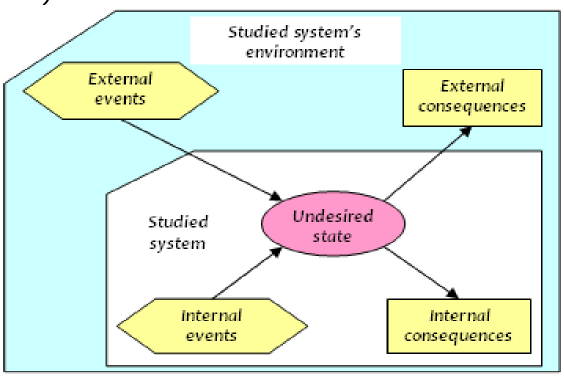

Figure 1. The generic causal field of „triggering events-consequences" set

The nature of consequences varies significantly and creates difficulties in analyzing the consequences [4, 23]. Analysis of probability of occurrence and severity of the consequences is the risk assessment foundation [11, 14]. Assessing the consequences can be expressed in number of lost working days of, disability, number of people affected or associated costs of accidents and failures (see Table 1).

Table 1. Ways of expressing the probability and consequences

Occurrence measure	Occurrence probability evaluation	Nature of consequences	Consequence gravity evaluation
Probability	On elementary operation	Physical	Unavailability duration
Frequency	On request (occasion)	Physical	Number of
Percentage,	On time unit	Financial	machines/humans affected
ratio	On life-cycle	Political	Losses magnitude
Qualitative	On a certain time lapse	Temporal	Losses cost
expression	On a certain distance etc	Qualitative expression	

Decision on risk can be represented as a decision tree with two possibilities: a gain with probability P, or a loss with probability 1 - P (see Figure 2) [13, 17].

This decision model is specific to the economic risk, where risk is regarded from the perspective of a cost – benefit analysis. Thus, in decision theory, the consequence occurrence (V) of the alternative B is expressed by equation (1):

$$EV(B) = p \cdot G + (1 - p) \cdot P \quad (1)$$

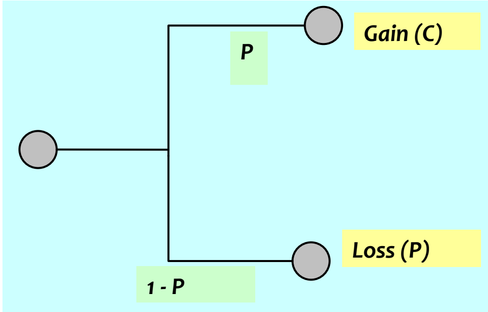

Figure 2. Risk-based decision-making criteria

Therefore, risk assessment is a tool for substantiating the decision. Decision may relate to the choice of several variants of a certain action to be taken. Decision maker must choose one of the "m" alternatives. Often, an alternative's outcome is uncertain and for each alternative can be examined several consequences. Assuming the existence of "n" potential consequences, the risk R can be defined as a set of couples (2):

$$R_i \equiv \{(P_{i.i}, C_{i.i}) \ldots (P_{j,n}, C_{j,n})\} \quad (2)$$

where: Rj is the risk associated with alternative "j";

$P_{j,i}$- the measure of event „i" occurrence, for „j" alternative;

$C_{i.n}$ – the measure of consequences gravity of event „i", for „j" alternative.

Since it is not possible to define an ordering relationship of couples, aggregate measure is necessary to measure the probability of occurrence and consequences. For this purpose, one performs generally the product of the two quantities as given below in Eq. (3)

$$R_{i,i} = P_i \cdot C_i \quad (3)$$

If Pi represents the probability of occurrence is required to report the severity of consequences by weighting it with probability. Thus, for the same value of gravity we would prefer a situation for which the measure the probability of occurrence is low. It is defined, therefore, the average severity by Eq. (4):

$$G_j = \sum_{i=1}^{n} R_{j,i} = \sum_{i=1}^{n} (P_i \cdot C_i) \quad (4)$$

The previous definition is used in operational safety, since the numerical evaluation allows easier comparison of different configurations. To evaluate the risk in the system human - machine is necessary to take into consideration all the technical and human components.

RISK ANALYSIS AND OPERATION ALSAFETY IN HUMAN - MACHINE SYSTEMS

Risk analysis involves identifying the causes that generate an unwanted event and its consequences, ie the origin of risk and his "target". The presence of the human operator should be considered at both levels. Integrating the human operator into risk analysis is indispensable. The human - machine system corresponds to a socio - technical system – which consists of a human operator in interaction with a technical system. Hence, the importance of functional and structural analysis, that defines the organization of human - machine system's components. In normal operation, human operators are only involved in higher organization levels, while in fault situations operators can intervene only at lower levels of command.

An entity is considered "safe operation" or „fail-safe" if it has the ability to satisfy one or more functions in given conditions [10]. Failures are considered as obstacles to reliability. An undesired event is a situation that deviates enough against a baseline to be relevant in the analysis of reliability and safety. Therefore, a failure is a particular event leading to termination of an entity's ability to perform functions (see Figure 3). We can say that systems safety represents, through his four specific components (safety, availability, reliability and maintenance), a component of different phases of existence of a system. Operational safety allows the assessment of the degree of trust (reliability) in the outputs of a system. The confidence can be addressed according to different aspects (Figure 4) interdependently and complementary [20] such as reliability, availability, maintainability and safety, defined as it follows:

- *reliability: the ability of a machine to perform a required function in given conditions, in a given time;*

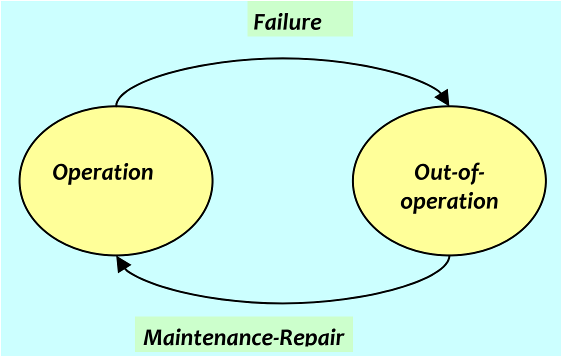

Figure 3. The bi-univocal link operation-failure

Operational safety analysis is aimed at identify and quantify the barriers that prevent abnormal functioning of a system [12]. Laprie [7] classified these obstacles, as follows:

- *fault, corresponding to a deviation from normal operation;*
- *error, representing a part of the system's state likely to cause a failure;*
- *failure, representing the cause of an error.*

- *availability: the ability of machines to be able to perform a required function in given conditions at a given time; availability depends on the reliability and maintainability;*
- *maintainability: ability of machines to be maintained or restored to a state in which they that can perform a required function, when maintenance is performed in given conditions, based on prescribed procedures and resources.*
- *safety: the ability of a machine to avoid, in given conditions, a critical, undesired or catastrophic event.*

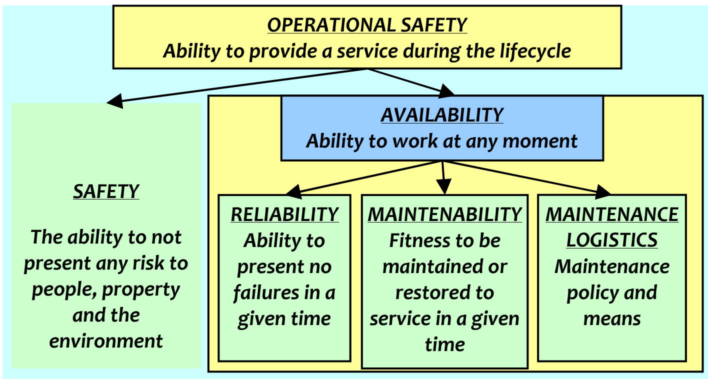

Figure 4. Structure of a machine's operational safety components

The notions of fault, error and failure depend decisively on the point of view adopted: system's dynamic, system status and operation performed (Figure 5). Concerning the terms for the human operator, existing confusion hinders the homogenization of definitions. Thus, in the literature on human reliability, failure and human error terms are often confused. The definition of human error proposed by Villemeur [24] is very similar to the failure of an entity: "the difference between the human operator behavior and its imposed behavior when the difference exceeds the limit of acceptability in given conditions." Human error, consisting in operator's failure, is manifested by a behavior other than the preset one. This definition is however simplified, since the operator is not limited to performing certain actions. He is primarily a decision-maker, and other authors, of which we mention Fadier [3], are taking into account all human activity. As a result, human error can be defined as "unacceptable result (outside tolerance borders) of human action and / or action without an operator and / or a team, action that should be undertaken to achieve a specific purpose in given conditions and in a period of time "[5].

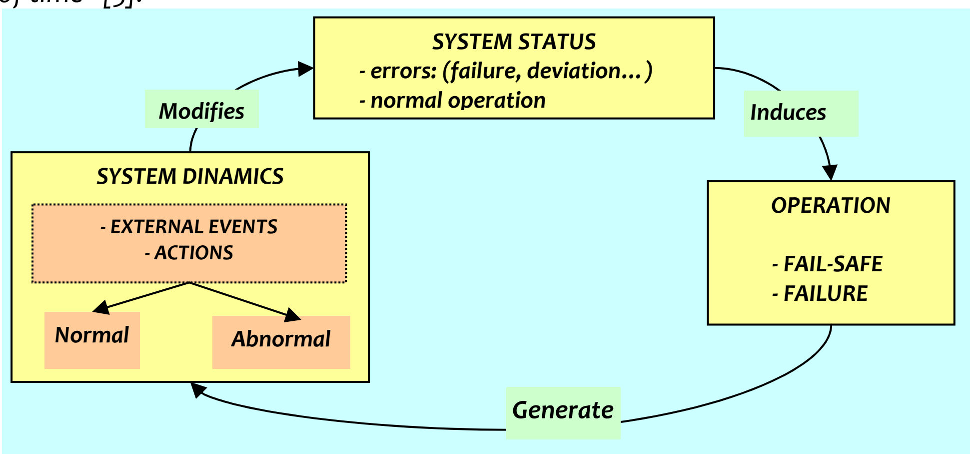

Figure 5. Approaching deviation, error, failure

It comes, that human error is defined as the unacceptable interval between what was prescribed (in terms of actions and outcomes) and what has been done practically. We speak about the difference or deviation between the charge prescribed and effective load observed by means of human activity analysis.

BOUNDARY SITUATIONS TOLERATED IN OPERATION: CONCEPTUAL FRAME

Comparing the prescribed and actual situations working tasks observed, important differences are generally resulting, differences which have the effect of changing the system. From structural point of view, these differences appear after each stage of a product's life: design, integration and operation.

On the other hand, it is known that most prescriptions are determined at conception – design stage. Operator's decision in relation to requirements can diverge, due to different perceptions of a situation or because of different objectives [15].

The acknowledged existence of Boundary Situations Tolerated in Operation (BSTO) rise a challenge for current methods of risk analysis, methods that consider only prescribed operating conditions. Considering the BSTO's the spectrum of risk analysis broadens, adding to prescribed operating situations all the risks associated with BSTO's. For our case study in printing facilities, we selected for performance criteria to be analyzed with regard to operator's behavior:

- ***productivity**: which refers to the number of copies printed; this criterion is mainly determined by the availability of production equipment; the main objective of the task is the number of copies to be printed;*
- ***quality**: the samples must meet specific requirements for absence of defects of printing, the color (as close to the model), the correct folding, etc;*
- ***safety**: this criterion is retained as operators are at risk of burns, bruises, handling toxic and flammable dryer; handling errors can lead to explosions;*
- ***the working task**: this criterion, which refers to operations is retained in order to integrate specific aspects of individual operators.*

Consequently, given the above observations can be expressed the following definitions, in terms of Boundary Situations Tolerated in Operation typology [16, 25].

***Definition 1: Boundary Situations in Operation.** Let gi(tj) be the severity assessment relative to criteria i. To severity it can be associated an acceptability level for the designer $S_{i,C}$, and, C, and one for the user operating the equipment, $S_{i,E}$. A case can be considered a Boundary Situation in Operation (SL) if at least one criterion exists for whom the associated severity exceeds the acceptability threshold of the designer:*

$$SL = \left\{ s_j / \exists i / g_i\left(t_j\right) > S_{i,C} \right\} \tag{5}$$

***Definition 2: Situation Tolerated in Operation.** A case can be considered as Situation Tolerated in Operation (SAE) if, regardless of the criteria considered, gravity does not exceed the associated acceptability threshold set by user (equation 6).*

$$SAE = \left\{ s_j / \forall i,\ g_i\left(t_j\right) < S_{i,E} \right\} \tag{6}$$

***Definition 3: Boundary Situations Tolerated in Operation (BSTO).** The set of BSTO's is established according to equation (7) as the intersection of the sets of Situation Tolerated in Operation (S.A.E.) and Boundary Situations in Operation (S.L.).*

$$SLAE = \left\{ s_j / s_j \in \left(SL \cap SAE\right) \right\} \tag{7}$$

Two operating modes are characterized by the designer: normal operation (Mn) and nominal operating mode (Mo). We consider three additional modes that can be observed in practical situations, namely: (i) a voluntary deviation, called a deviated mode (M_d); (ii) an added mode(M_a); (iii) an incorrect utilization mode(M_i). The algorithm shown in Figure 6 allows the determination of different cases depending on the viewpoint of the designer and operator.

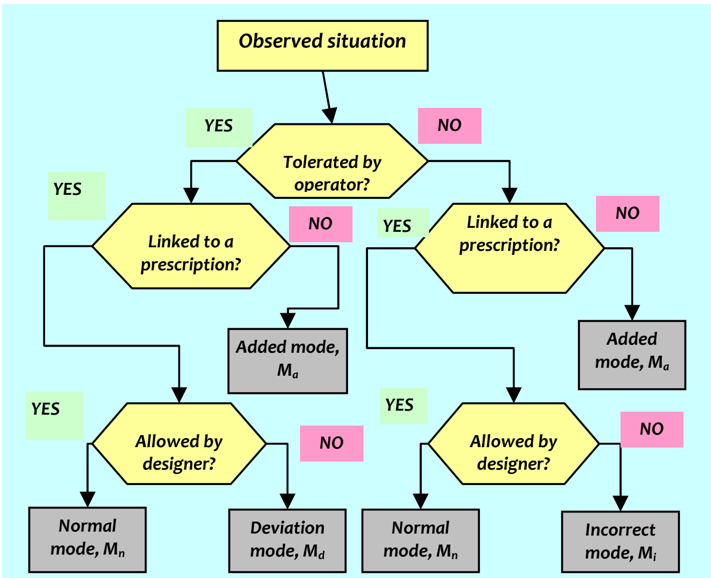

Figure 6. Operating modes determination

***Definition 4: Normal operating mode (M_n).** It is the operation mode guaranteed by the designer. This does not necessarily coincide with the prescribed task quality achieved, but safety criteria are met.*

***Definition 5: Nominal operating mode (M_o).** Nominal mode is "in principle, in perfect adequacy with the quality of mission" corresponding to "meet the specification set in the conditions of production".*

$$M_o \subset M_n$$

Definition 6: Incorrect mode (M_i). *Is the operation mode for which the designer requirements are not met, but without intent.*

Definition 7: Voluntary deviation mode (M_d). *Is the operation mode for which the designer requirements are not met, but with intent, on purpose.*

Definition 8: Added operating mode (M_a). *Is a mode that does not fit either set of prescribed modes by the designer, nor the set of incorrect or diverted modes.*

Examining all the previous definitions it can be inferred that only deviation and added operating modes are generating Boundary Situations Tolerated in Operation.

CASE STUDY IN TWO PRINTING FACILITIES

The analysis of results obtained in S.C. TIPARG S.A. Piteşti and S.C. GIG S.R.L. Câmpulung printing facilities [21], along a few weeks of systematic observations guided through APRECIH method [22], allowed us to identify 32 BSTO's, which were grouped into 6 categories. The results obtained are summarized in Table 2. Almost 61% of BSTO's are related to barriers removal or circumvention of safety measures. In this context there are to be mentioned: the failure to respect procedures (immaterial safety measures), unauthorized interference with operating machines (immaterial safety measures), removal of physical safety barriers, catachresis allowing operator access in areas normally inaccessible (measures of operational safety).

Table 2. Categories of BSTO's recorded in analyzed printing units

BSTO type	Identified BSTO's
Failure to follow procedures	8
Removal of physical safety means	6
Problems related to employment and training	7
Interventions on the machine in operation	4
Maintenance	3
Catachresis * misuse and abuse of a word (here as "bad communication"	4

To study the benefit, cost and potential deficit, for each of the four criteria of defining the severity a multi-criteria analysis was performed for the identified BSTO's. The results obtained are shown in Table 3. For each criterion was accounted the BSTO number for which has been found that there is a benefit, cost or deficit, given that some BSTO have multiple effects on multiple criteria.

Table 3. Multiple criteria analysis of BSTO's in terms of benefit, cost and potential deficit

Immediate benefit		Immediate cost		Potential deficit	
Criteria	BSTO number	Criteria	BSTO number	Criteria	BSTO number
Productivity	20	Productivity	6	Productivity	6
Quality	5	Quality	12	Quality	8
Working task	7	Working task	8	Working task	2
Safety	0	Safety	6	Safety	16

Table 4. Comparative description of studied printing facilities

CARACTHERISTICS	PRINTING UNIT NO. 1	PRINTING UNIT NO. 2
Ownership	Private property	Private property
Economic situation	Relatively stable, with real development possibilities	Oscillating, with risk of bankruptcy
Work organization	2 x 8 hours; 5 days/week	1 x 8 hours; 5 days/week
The average age of operators	35 years	32 years
Level of education	Medium level	Medium level
Team organization	A supervisor machinist, two machinists, 2 auxiliaries, 2 receptionists, a winder	
Training	Training initially made by the manufacturer; Training in the workplace, according to legislation.	Training in the workplace, according to legislation.
Operator's role	Clearly defined	Clearly defined
Products	Various catalogues; Newspapers; Magazines.	Magazines (80 %); Miscellaneous printings (20 %).
Configuration	Possibility of simultaneous production of two products	One product at a time
Maintenance	Curative	In principle curative with re-evaluation intended by the manufacturer-imposed periodicity
Machines line age	> 15 years	> 20 years
Configuration of production systems	2 lines juxtaposed dependently and / or independently	Overlapping dependent lines
Workstation	Completely enclosed system in an enclosure anti-noise, protecting all machine operators	System equipped with a cockpit protecting the operator from noise

Analysis of data contained in Table 3 shows that most BSTO's bring an immediate benefit in terms of production (≈ 62%) allowing a time gain in performing operations and limiting the production interruptions. The potential deficit refers in 50% of BSTO cases to the safety level. Although rarely materializes, safety deficit is a consequence of voluntary exposure of operators to dangerous areas and embrittlement of protective systems in series. Basically, the cost is expressed in terms of work load (25%), resulting in additional work for operators to annihilate or bypass safety measures. Because protection systems are not put back into operation after operation, this cost becomes negligible. Such multi-criteria view and analyze the benefits, costs and potential scarcity, allows identification of causes and effects of BSTO. During the survey there was the possibility of confrontation results of the observations made in the two printing units that differs by type of production, economic and psychosocial environment. Table 4 shows the comparison between the two printing units, according to certain characteristics.

In spite of significant differences between the two units and that observations were made on different time periods, 46% of BSTO observed are common to the two production units. A number of 3 BSTO's were observed only in unit no. 1, while 5 were recorded only in unit no. 2.

This result highlights the generic nature of BSTO. They are not isolated cases, but recorded in different production units. In consequence, one can accept that the solutions chosen at design stages can lead to BSTO's. Their generic character is an argument in support of forecasting BSTO test, since the design phase. Field analysis indicates the importance BSTO, which is reflected by annihilation or removal of safety measures, consistent with the response of operators.

RESULTS INTERPRETATION AND DISCUSSION

Multiple criteria analysis of the benefit, cost and potential deficit illustrates the reason of which BSTO must be considered in industrial risk analysis. But, combining BSTO with normal operating conditions is not rational and can cause errors. Therefore, the risk analysis approach requires a new perspective. Thus, we developed fault tree for the top event „operator's presence inside the beading press", resulting that the tree is not the same for prescribed operating situations (see Figure 7) and BSTO-case (see Figure 8). In the first case no voluntary deviations are considered and therefore no effect on the working situation. In normal operation the operator will not make any intervention, if the machine is running. Switching is possible only in case of failure of the indicator "open door". In BSTO-case, the indicator is off, the operator voluntarily agrees to intervene during the operation of the machine.

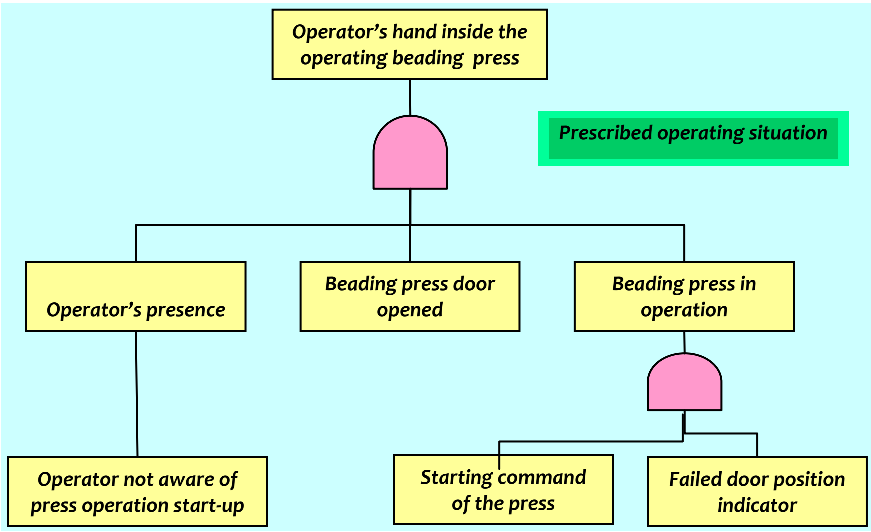

Figure 7. Fault tree for the top event „operator's presence inside the beading press" in prescribed operating situation

It follows that, in prescribed circumstances only a section of order 4 leads to unwanted event, while for BSTO-case there are recorded four sections of order 3 that lead to the same event. This simple example confirms that the causes of an event are not the same in prescribed operating situations and in BSTO- cases. Furthermore, it is important to note that it is not possible to associate to the root causes of the first fault tree, the causes of the second one.

In the considered example the machine is in operation following a prescribed command, and the operator, compliant to requirements, will not interfere as long as the machine is running. In the BSTO-case the operator will intervene even if the machine is in operation. Thus, the qualitative exploitation of the fault tree (determination of minimal sections) rises the validation question. The same problem occurs for quantitative exploitation of the tree (estimate probability of occurrence of undesirable event).

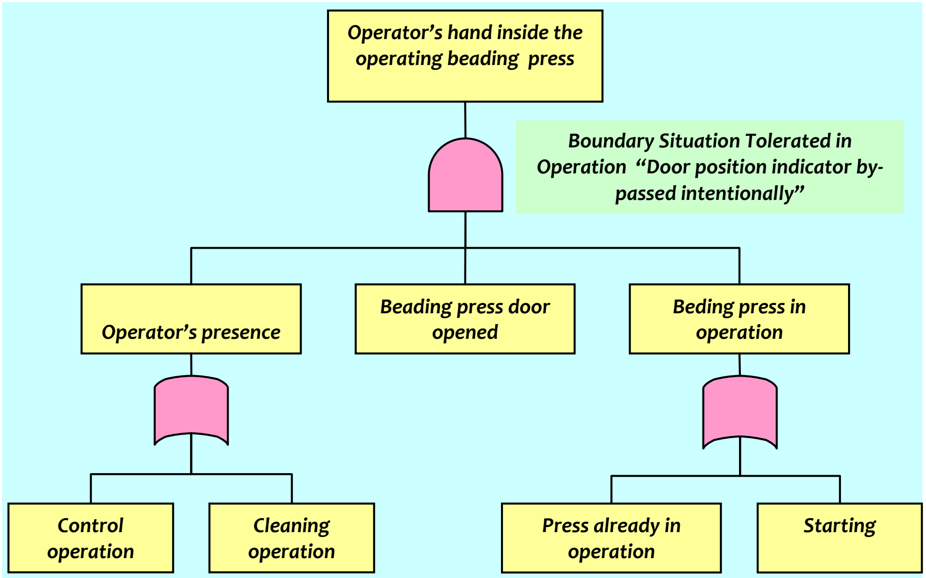

Figure 8. Fault tree for the top event „operator's presence inside the beading press" in Boundary Situation Tolerated in Operation

Moreover, BSTO's exposes operator to new risks. Failure of the cleaning rubber rollers procedure leads to operator exposure to the risk of crushing and chemical aggression. It thus highlights the limited risk analysis taking into account only the prescribed circumstances. Study of the failure modes of technical components and human error must be completed by studying the ways to suppress or bypass the security measures that lead to BSTO. For consideration of BSTO in a priori analysis, in risk analysis approaches stages should be added to identify BSTO's.

After Preliminary Risk Analysis, which identifies sources of hazard, should follow the analysis of safety measures applied. In this respect, it will be studied the precise function of each particular safety measure and restrictions introduced regarding human operator's behavior. This set of steps for the identification of operational situations/modes, represented in Figure 9, can be facilitated through operational analysis and lessons learned.

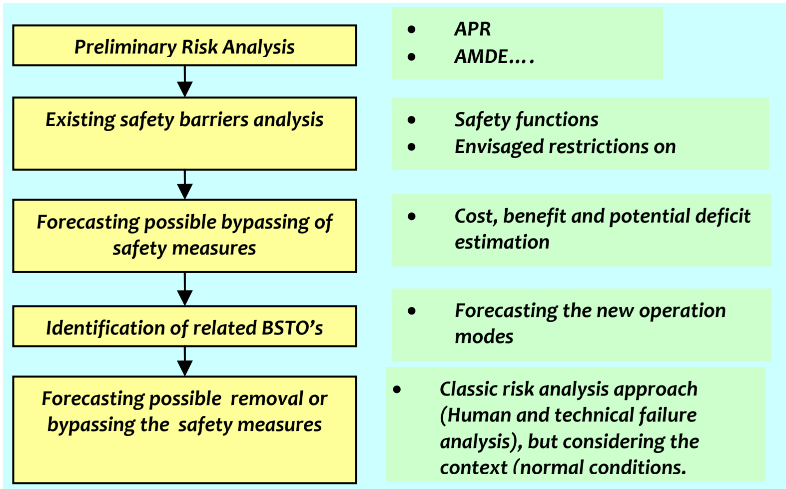

Figure 9. Proposed structure for integrating BSTO's in industrial risk analysis

This analysis should be the bases of forecasting safety measures annihilation or bypass, by estimating the costs, benefits and potential deficit. It is also possible to analyze and forecast the associated operating modes and foreseeing the resulting BSTO's. Finally, risk analysis can be performed for each operating situation

CONCLUSIONS

We introduced the concept of Boundary Situation Tolerated in Operation, as the situation accepted by the machine user, but undesired and unsupported by the manufacturer or designer. BSTO do manifest through voluntary deviations from procedures and added operating modes. So far, these types of violations were not considered in risk analysis and, in consequence-the spectrum of operational risk is not entirely covered by a priori analysis. BSTO is a compromise due to deviation from the requirements of the designer and / or manufacturer in order to improve the performance of the human - machine. Highlighting this compromise is facilitated by multi-criteria analysis. To optimize performance against a criterion (e.g. productivity), BSTO's are leading to the degradation of performance in relation to other criteria (e.g. safety).

Safety measures implemented by various stakeholders involved are designed to prevent (reduce the probability of occurrence) and / or protection (minimizing severity of consequences) risk of injury. They operate through restrictions on human operator's behavior. Annihilation or temporary removal of security barriers is a way of voluntary deviation. The analysis in printing units, guided by the APRECIH *method, allowed the identification BSTO's, most of these situations having correspondence with annihilation or bypassing the safety measures. Finally, it was proposed a risk analysis approach that allows integration of these situations.*

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