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Article

Modelling A Safety Management System Using System Dynamics at the Bhopal Incidental Event

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Abstract: In Safety Management System (SMS), the risk management plays a key role for the prevention of accidents. The aim of this paper is to propose a Safety Management model using a system dynamic approach to update conventional industrial safety into the new industrial safety 4.0 that is time to developed. This study analyzes some safety 4.0 aspects lacked in the Bhopal incidental event by considering different data detected in the industrial Plant. The model proposed in this paper discusses the relationships among the main causes that have contributed to the occurrence of the incidental event studied, such as broken safety devices, inadequate personnel experience, operator decisions, manager production strategy, policy decision, as deduced from the relevant literature about Bhopal incidental dynamic.

Keywords: safety management system; system dynamic; systemic approach; safety 4.0; industry 4.0

1. Introduction

In 1984, the well-known Bhopal disaster involved the chemical plant of the American multinational Union Carbide, specialized in production of pesticides. The explosion of a methyl isocyanate storage tank inside the plant caused the death of about 3000 people and poisoned tens of thousands more. The incidental event started a long process of research and investigation concerning the causes and effects [1], which led to the consideration that the accident could be avoided. In fact, a lack of maintenance and precautions in safety operations was detected. Moreover, according to these studies the large multinational Union Carbide had little concerning with safety in an emerging country where the technology used was untested and faulty. A rare incident as Bhopal is not a random event, but it is far more predictable, and the causes are accessible and the events potentially avoidable [2].

Bhopal incidental event is one of the most important examples of the lack of safety due to no maintenance policies, no human continuous training, no plan investments. For these reasons, the Bhopal accident is well suited to highlight the impact that maintenance and the human factor have on the safety management system.

In particular, if the maintenance was efficient, the extent of the accident would have been more contained [3].

The Bhopal disaster has led to regulations and awareness for process safety-related activities worldwide. The whole scientific community has moved on studies concerning the causes and consequences of the disaster, with particular attention to the topic of maintenance and safety [4].

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These studies have developed a new safety culture [5] with different proposed approaches. Yang et al proposed a Bayesian approach [6] while Garbolino [7] managed safety by using a different methodological approach based on System Dynamics (SD).

According to Lane's paradox [8] "the results of quantitative system dynamic study are qualitative insights", this paper aims to highlight, by using a quantitative model based on Bhopal accident data, that the technical, organizational and human factors could have been managed effectively with a Safety Management System (SMS).

The System Dynamics is used to highlight the interrelations among the factors that mainly affect maintenance and its effects on safety. This leads to highlighting the impact that maintenance and the human factor could have on the safety of a high-risk plant, thus being key factors in an appropriate management system. Is true that one of the key points implemented in Industry 4.0 is how to reduce environmental pollution, as shown by Abdul Moktadir and al. in a recent paper [9] but also to increase safety by receiving real time inputs about hotspots of the system; for example, in a high-risk industrial sector such as the petrochemical one, Industry 4.0 approach is used to monitor Big Data from a variety of sources, as highlighted by Hongfang Lu et al. [10].

Literature tries to support the integration among concepts and Industry 4.0 technologies, as well as PSEP (Process Safety and Environmental Protection) for sustainable production systems [11]. Undoubtedly receiving data in real time allows the optimization of the ERP [12].

The paper is organized as follows: Section 2 presents the methodological approach; in Section 3 the model is analyzed through a real case study concerning Bhopal incident; results are analyzed in Section 4. A discussion about how Industry 4.0 could reduce system failure probability is made in Section 5. Finally, conclusion of the research is summarized in Section 6.

2. Assumptions methodology description

In order to develop and implement an effective Safety Management System, many factors have to be considered to represent the whole system. Many authors in literature [13] [14] [15] have supported the effectiveness of System Dynamics as a useful tool to highlight the interrelations among the components of a system: people, things, business functions, socio-technical elements, psychophysical characteristics, etc.

The System Dynamics could be associated to a Dynamic Bayesian Network (DBN), which would allow to associate a priority scale based on the temporal evolution of faults (as if a weight factor were associated with each fault)[16].

The Causal Loop Diagram (CLD) is the graphical tool used to make cause and effect relationships among these elements immediately visible so that it is the starting point for the subsequent construction of the model.

According to the aim of this paper and starting from the literary review, a Causal Loop Diagram (CLD) was proposed. The model highlights the main aspects that influenced Bhopal incident event.

The elements of the Causal Loop Diagram and the cause–effect relations of each of them with the other elements of the system are described in Figure 1 in which it reported the following variables:

FAILURE RISK: the risk of failure/breakage is based on probability of failure of an equipment/ plant and the consequences deriving from it. This estimate will be more accurate if the information about it are more precise relatively to the type of failure/break (TYPE OF DAMAGE) [14]. This will depend on information derived from the historian of the inspections and maintenance carried out, from the planning data for inspection, from process data (temperature, pressure, etc.), from the type of

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degradation to which it is mostly subjected the construction material as well as the fault data. The risk of failure becomes the criterion of the decision-making process that leads to planning maintenance and inspection activities (PLAN). More realistic risk estimation is, more reliable the maintenance and inspection of plans will be.

TYPE OF DAMAGE: the type of damage expected to occur on an equipment/plant depends significantly on the characteristics of construction, in terms of materials used and the history of breakdowns that occurred on the same type of equipment [15]. Based on the knowledge of the type of failure that it could be demonstrated, it is possible to decide which inspection technique may be used. In this sense, the knowledge of the type of damage, that could be presented, directly affects planning, in particular, with regard to the tools and specialized personnel used in conducting particular non-destructive tests.

PLAN: in the planning phase the decision-making process is implemented which should lead to the optimal selection of interventions, considering the criteria of risk (RISK FAILURE), as well as respecting the constraints of badges, which in turn they are the result of an estimation process (COST ESTIMATION). All that is decided in this phase will affect the actual execution of what it has been planned. Being the planning, a decision-making time could not be detached from human error (HUMAN ERROR) that could affect the reliability of the maintenance plans and, therefore, its effectiveness [16].

EXECUTION: the execution of the maintenance/inspection plan is influenced by the planning (PLAN) in terms of priority of intervention and of personnel employed (COST EXIMATION), as well as the knowledge (KNOWLEDGE) of who conducts maintenance and inspection activities. Poor knowledge and experience, together with other factors such as cost reduction related to the acquisition of suitable instrumentation for conducting inspections increases the probability of human error (HUMAN ERROR).

COST ESTIMATION: the cost estimation sets constraints on planning and execution of maintenance and inspection activities. This process, if not supported by an adequate knowledge of the person who performs it, could have negative repercussions during both planning and execution. Vice versa adequate capacity in estimating costs could lead to optimal planning in terms of cost-benefit.

HUMAN ERROR: human error could materialize in routine activities that require acquisition of specific capabilities (SKILLS), or in the execution of wrong procedures (RULES) or in following a wrong reasoning. In the latter case, the error occurred at KNOWLEDGE level can undermine the planning process (PLAN) and the phase of cost estimate (COST EXTIMATION). An incidental event might derive directly from the incorrect execution of the activities of maintenance and/or inspection or to be the latent cause of the decision-making process [16].

INCIDENTAL EVENT: the incidental event is the manifestation of an occurred error or in the decision-making process or in the execution phase of the activities of maintenance/inspection. The number of incidental events as well as the arising consequences becomes the parameters with which the SAFETY MANAGMENT must measure to implement all strategies to try to avoid them [17].

SAFETY MANAGEMENT SYSTEM: the ICAO (International Civil Aviation Organization) defines the Safety Management System as an organized approach to manage safety, which includes the necessary organizational structure, the definition of the politics and procedures [18]. The deployment of a Management System requires human and financial resources, time and equipment. Top management decides the amount and allocation of these resources (COST EXIMATION). The SMS needs a series of data to be proactive in order to measure performance and make forecasts. As a result, the occurrence of an incidental event updates the knowledge of SMS and allows it to

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implement actions to prevent future accidents

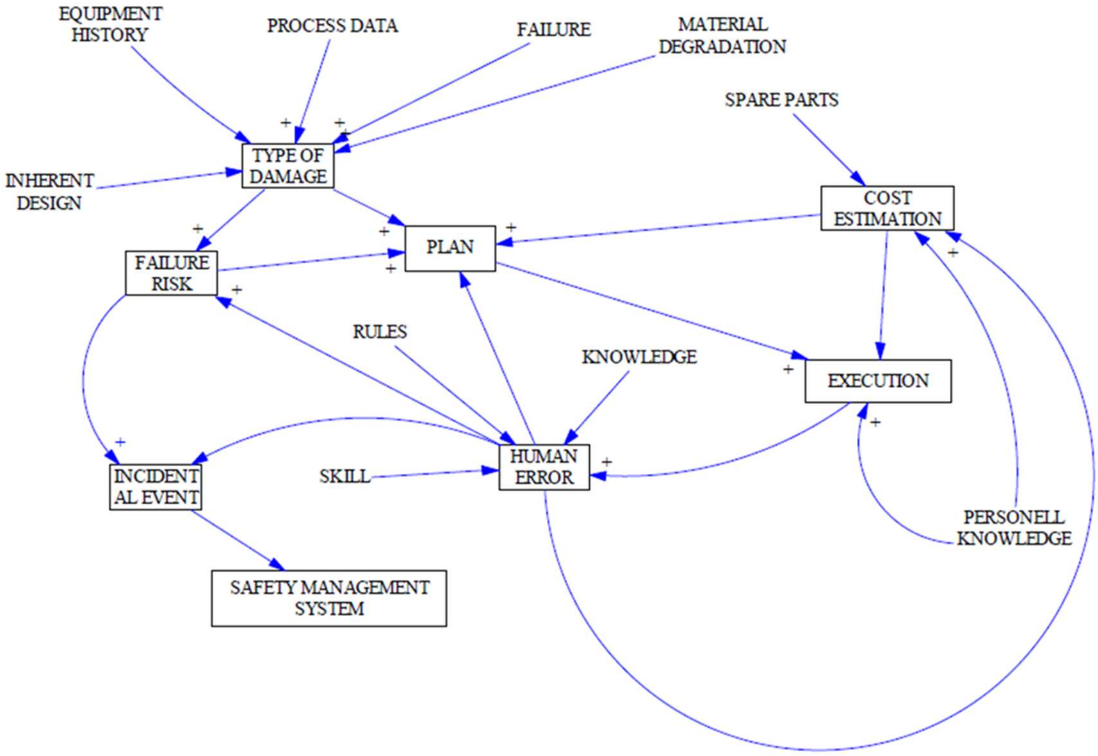

Figure 1CLD of the Bhopal plant

3. The System Dynamic applied to the Bhopal incidental event

Starting from the CLD developed above, a model in Powesim Studio is built. In order to validate the model proposed, all the data used for the simulation refer to Bhopal incident, as they are available in the literature [20, 21, 22].

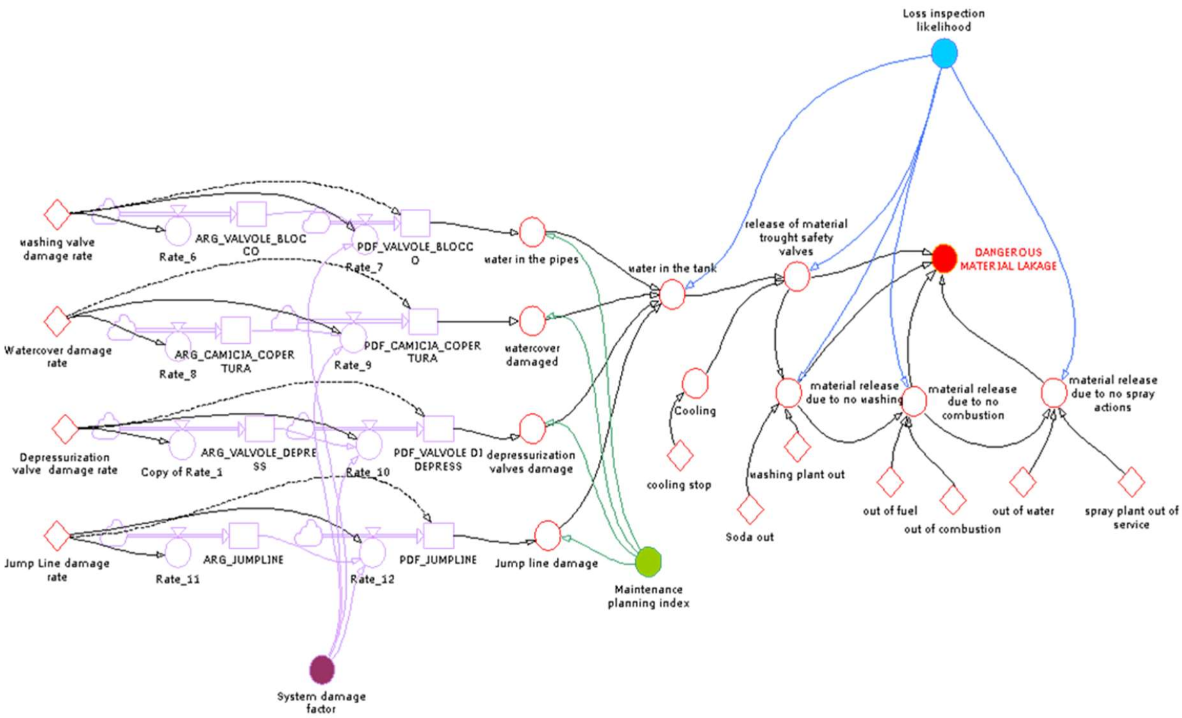

Figure 2SD diagram of mechanical system

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The probabilities of mechanic failure of the safety protection system have been expressed through appropriate aging functions, as in Figure 2. The following functions have been introduced:

1) MAINTENANCE PLANNING INDEX that considers the maintenance schedule on the plant;

2) LOSS INSPECTION LIKELIHOOD that takes into account human error in doing visual inspections. It is due to many variables (training, information…) and under certain conditions (stress, daytime, etc.) [16].

3) SYSTEM DAMAGE FACTOR that consider the impact of management on the production system.

The interaction of all these variables, above described, leads to the creation of DANGEROUS MATERIAL LAKAGE function.

The main part of the model moves to the PROBABILITY OF LOSS OF CONTAINMENT OF HAZARDOUS MATERIAL (Figure 3).

The incomingof Industry and Safety 4.0 and the development of the related technologies such as IIOT, IOT, Digital Twin, Augmented Reality and Wireless Communication Technologies, data are better collected, and in less time[9].

The model proposed describes plant comprehensive of safety prevention systems (lock valves, cover jacket, depressurization valves) which have been linked, in Figure 3, with protection measures (refrigeration, washing systems, release valves, sprinklers).

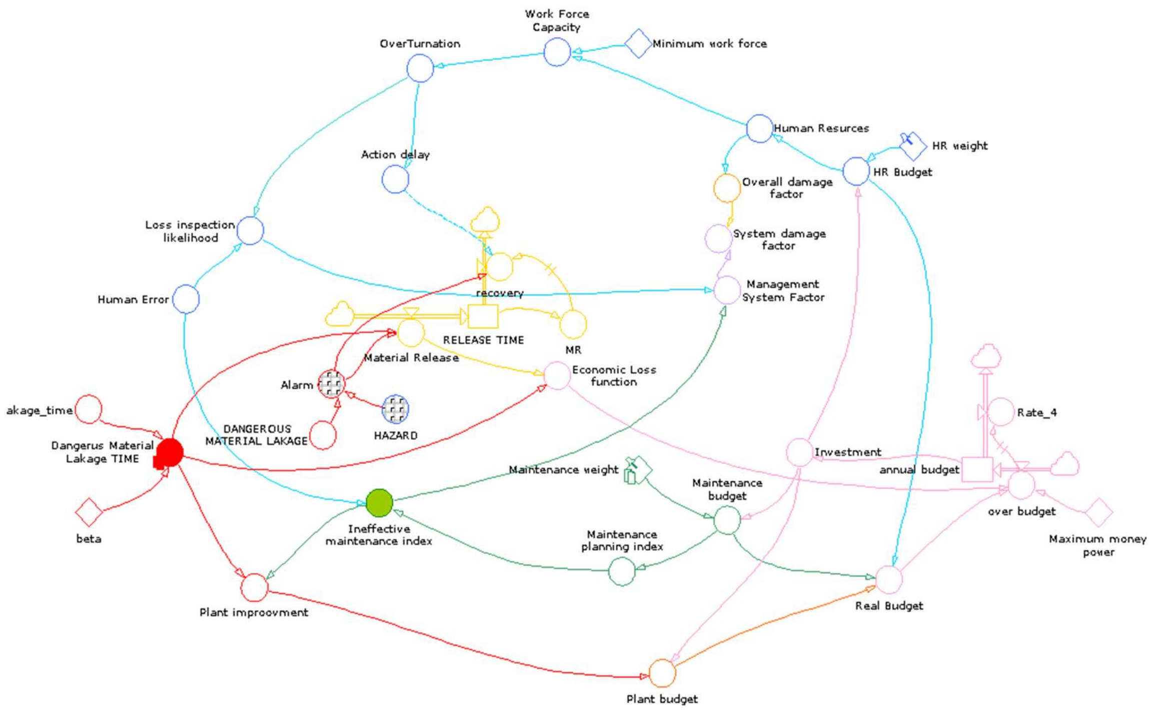

Figure 3SD diagram - management loops

According to the values considered in [21], the development of the simulation (Figure 4) shows an initial loss of about 300 minutes leading to an outlay of about $ 250,000.

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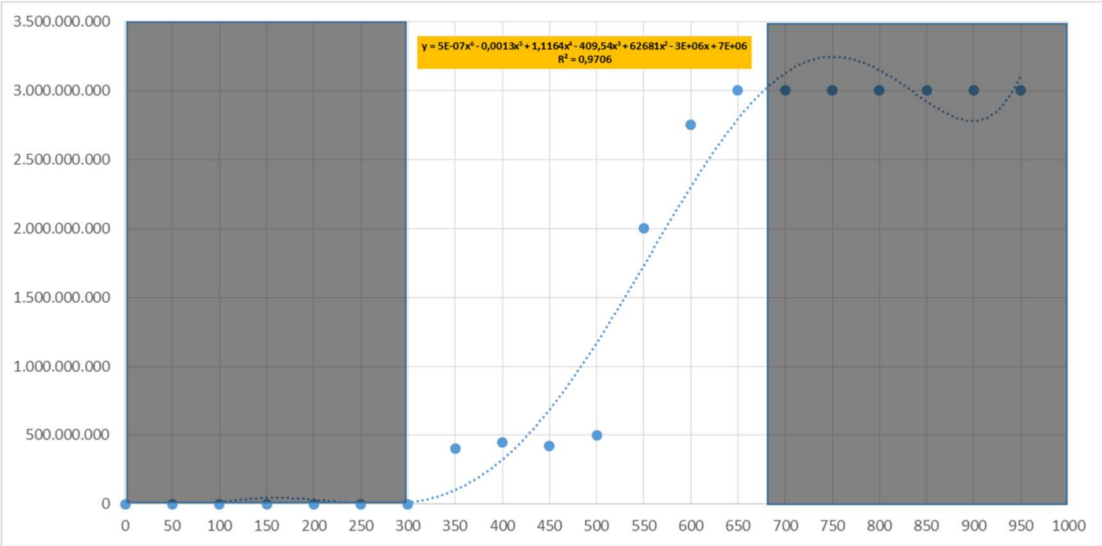

*Figure 4*Economic Loss Function

In the model, the function that links the labor force to the available capital has been obtained by interpolating available data in [20]. The Tables 1 and 2 show the human resources data in terms of operator and system safety.

OPERATORS	YEAR			1979-1980 [1]			1981-1982 [3]			1984 [5]			November 1984 [7]		
	WEIGHT	$/month	$/year	#	WF	$/year	#	WF	$/year	#	WF	$/year	#	WF	$/year
OPERATORS BSC/DIPLOMA	1	800	9600	2	2	19200	8	8	76800	2	2	16000	2	2	1600
OPERATORS HIGH SCHOOL	2	1000	12000	15	30	180000	0	0	0	6	12	60000	6	12	6000
SHIFT SUPERVISORS	3	1200	14400	3	9	43200	2	6	28800	1	3	12000	1	3	1200
MAINTENANCE SUPERVISORS	5	1600	19200	3	15	57600	2	10	38400	1	5	16000	0	0	0
PLANT SUPTD.	6	1800	211600	0	0	0	2	12	43200	1	6	18000	1	6	1800
Total Work Force				56		300000	36		187200	28		122000	23		10600
Variatio than 1979-1980				0.00%			35.71%			50.00%			58.93%		
Variatio than 1981-1982				-			0.00%			22.22%			36.11%		
Variatio than 1984				-			-			0.00%			17.86%		

*Table 1*Operators resources data

WF	$/day	System Safety	$/(WF*day)
56	821,92	0,95	14,68
36	512,88	0,70	14,25
28	401,32	0,50	14,33
23	353,33	0,30	15,36

*Table 2*System safety resources data

The relationship between the safety plant level and its workforce is shown in Figure 6. The capacity of carrying out all the ordinary tasks in time decreases while the work force goes down.

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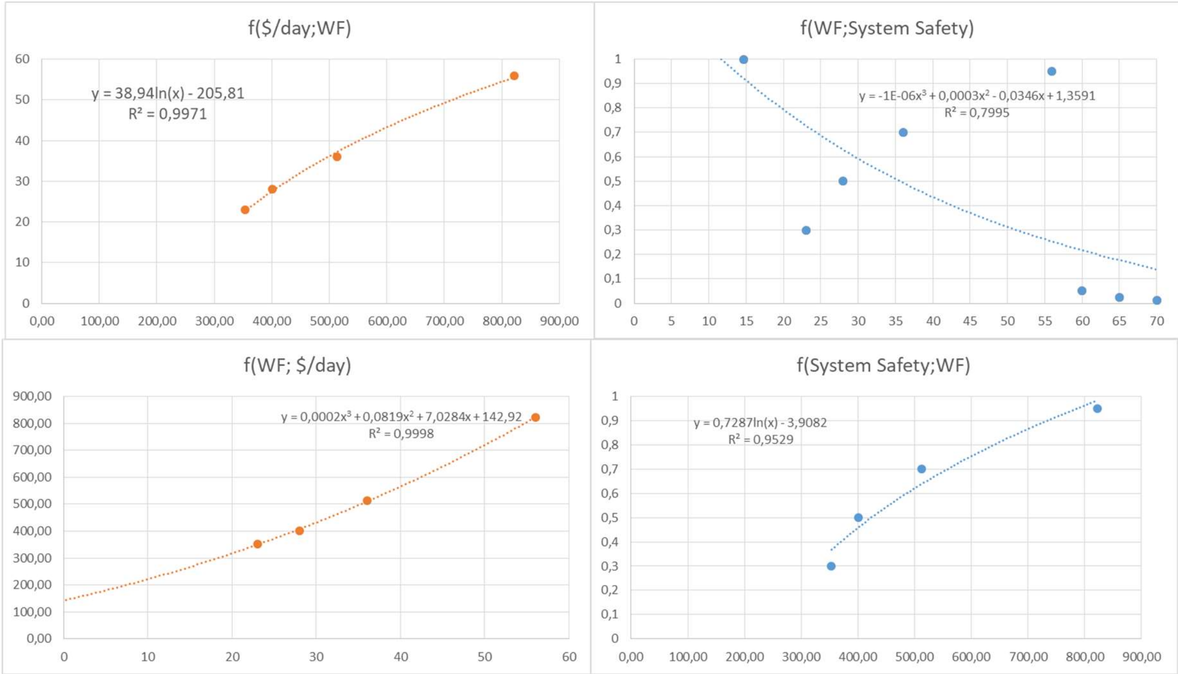

Figure 5Prediction curve related to Human Resources

In Figure 5, the value of the minimum work force required under standard conditions, in order to prevent accidents in the plant, is also shown. Based on this value function has been defined in order to prevent the possibility of non-inspection of the plant.

The function of human error has been defined separately using the HCR method (Figure 6) [24].

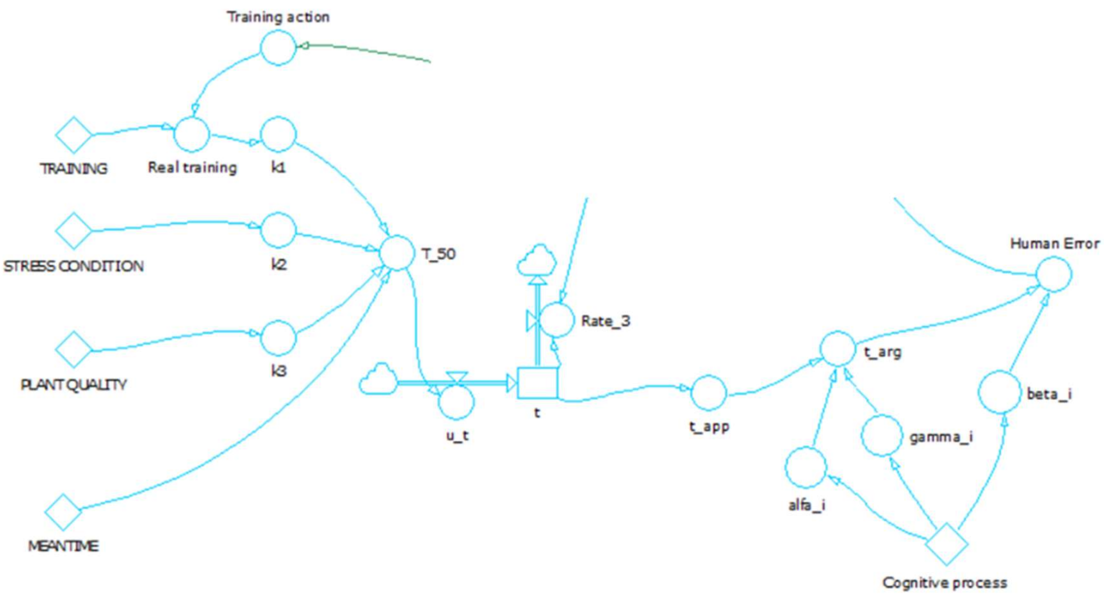

Figure 6SD diagram - HCR loop

It is necessary also to consider the effects/actions on the maintenance plan to close the loop of this subsystem. In fact, operators could make errors by carrying out

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maintenance. These errors may be reduced by improving the operators' skills (Figure 7).

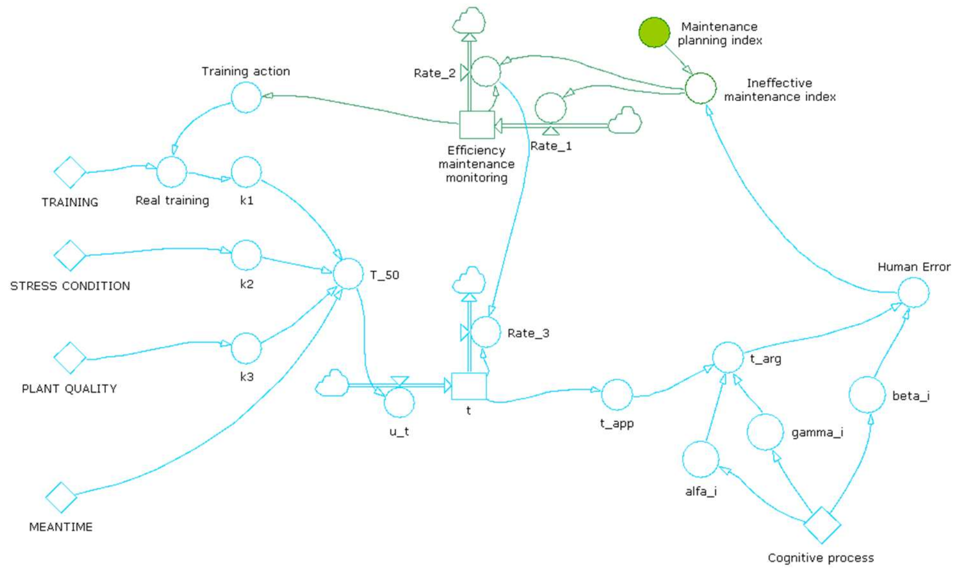

Figure 7SD diagram HCR & Maintenance variables

The introduction of the variables of HUMAN ERROR and MAINTENANCE PLANNING INDEX allows completing the SD diagram that converges in the managerial part of the system: this part of diagram represents the evaluation of all management aspects (Figure 8 and Figure 9).

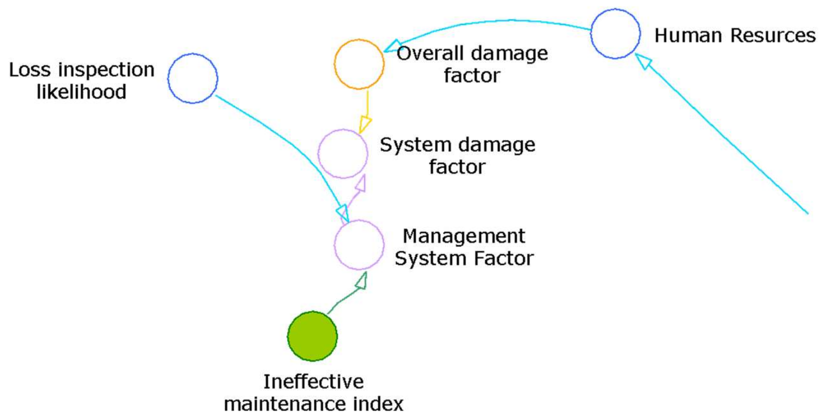

Figure 8Variables related to management

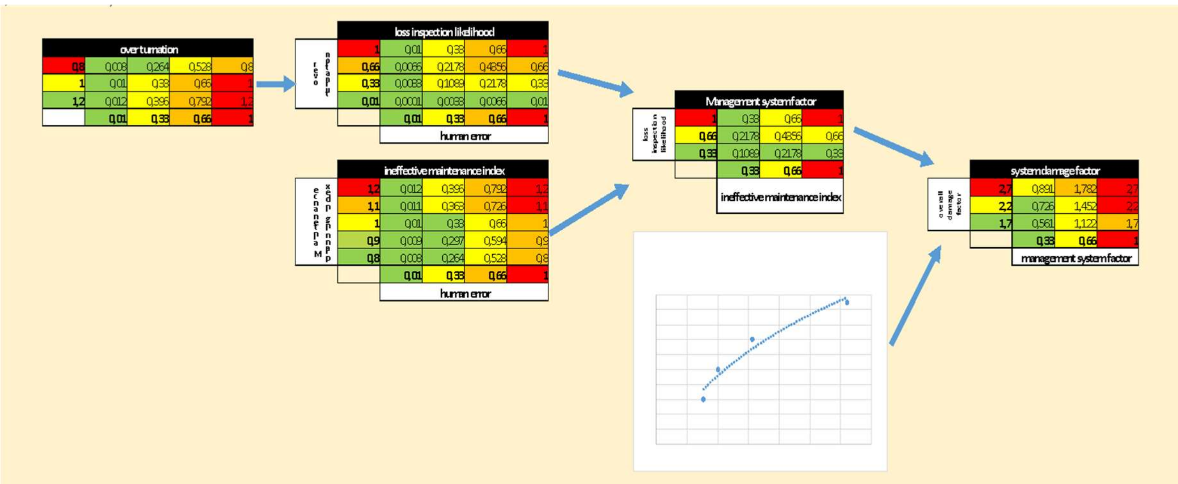

Figure 9Values referred to management variables

4. Results

The results analysis permits to focus on different aspects of the Bhopal plant: as shown in Figure 10, referred to productive plant and the mechanical part of the SD model proposed, the system breakdown probability of the prevention systems is already critical in the first days of the system operation. In fact, the Bhopal structures were very crumbling and not maintained in the months before the accident.

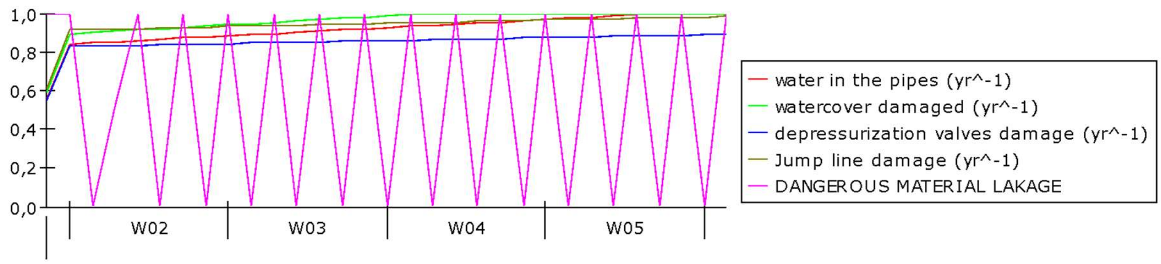

Figure 10Mechanical system result

The simulation (Figure 11) of the possible loss of containment dangerous material allows a realistic prediction of hazards (i.e. the hazard "generated randomly" actives an alarm of the loss of material).

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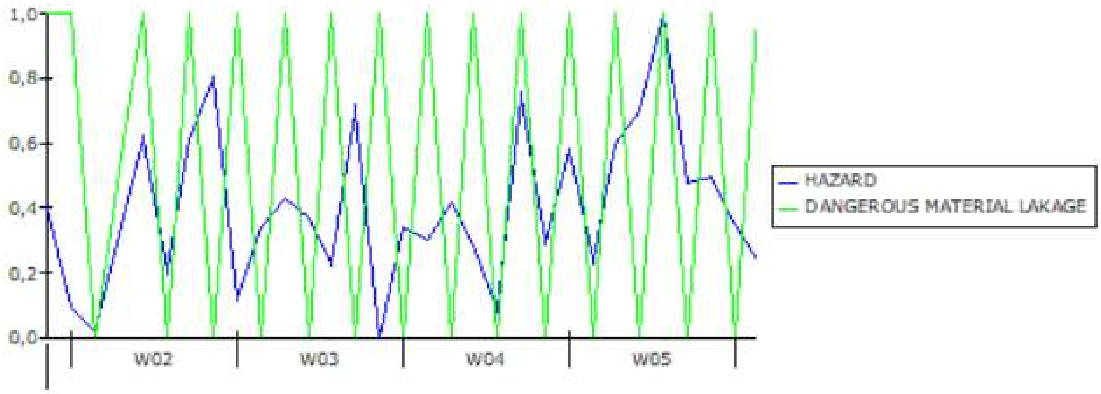

Figure 51Accident generation

The system suffers of frequent breakdowns (the blue line is often below the green line representing the probability of loss of dangerous material); moreover, the generation of random numbers of the HAZARD variable is carried out without considering the average value of accident risk at the beginning of random generation.

Obviously, the quantities released will not always be the same; the greater quantity of material will be released in the first days of activity. This leads to the greater outlay of money in order to support the costs of restoring plant, insurance and image.

As shown in Figure 12, these costs are significantly higher than the costs that the plant has normally planned to support for the standard maintenance and personal management activities.

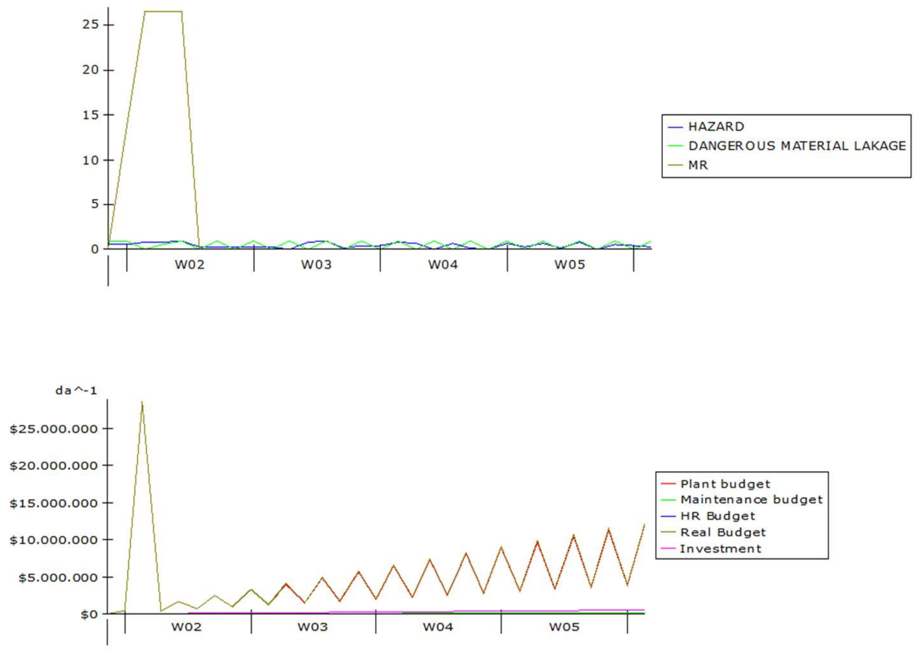

Figure 6Economic results

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On the other hand, as it is noticeable in Figure 13, the ordinary costs of the plant (maintenance, personnel) are linear and are much lower than the plant losses due to accidents of a 1:50 ratio.

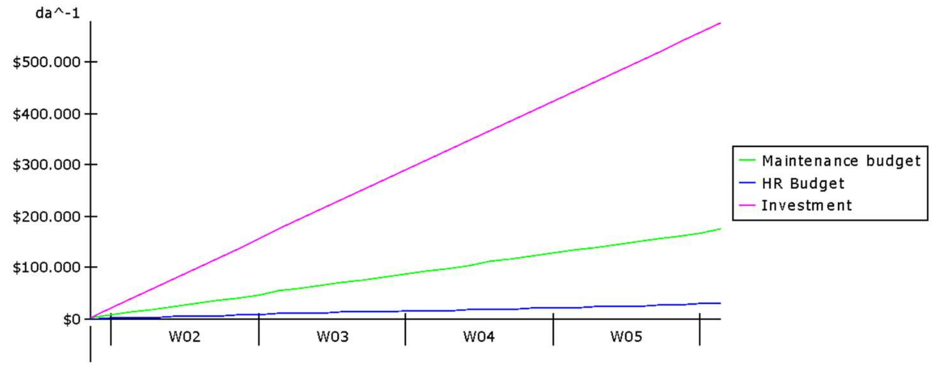

*Figure 7*Zoom on ordinary economic value

After the first major release, many micro losses generate daily costs derived from loss function that still significantly increases the costs that the plant must support with a 1:20 ratio.
While the loss function turns out to the end of the economic loop of this model, the investments in maintenance and human resources are at the starting points by influencing downstream the whole operation of the plant.
As far as human management is concerned, the total workforce is defined by the investments made for staff.
The Figure 14 shows the maintenance-planning index follows the trends of human error according to the planning.

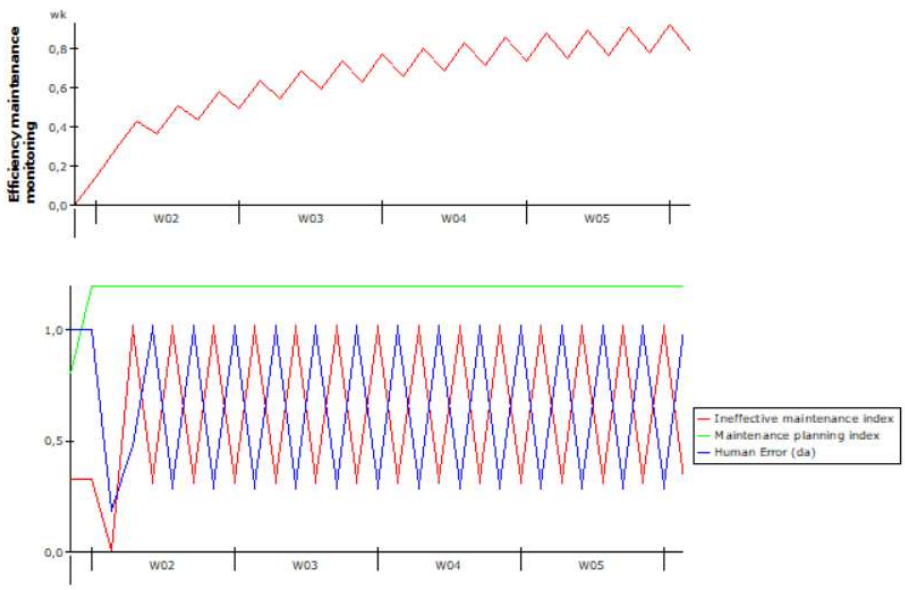

*Figure 8*HCR results

The SYSTEM DAMAGE FACTOR (Figure 15) reaches a peak value with the release of greatest quantity of material, which also corresponds to a peak of the management system factor, in which loss inspection likelihood and effectiveness maintenance index flow), while the overall damage factor immediately settles at maximum alert values even before the accident occurs.

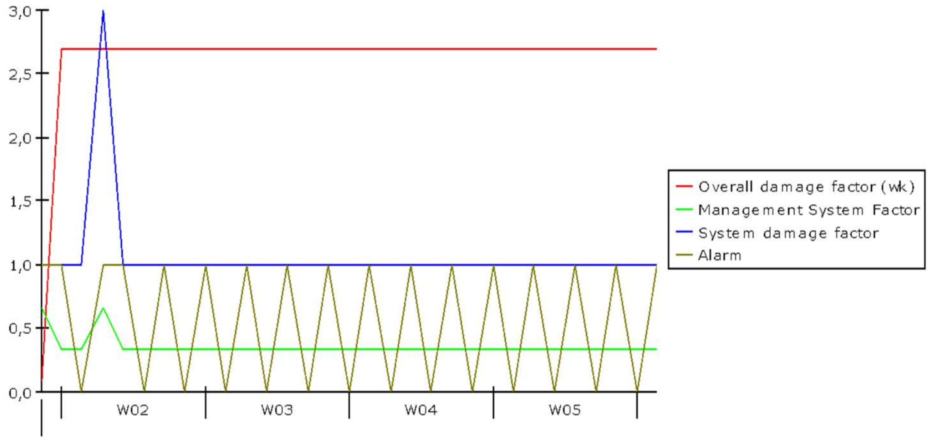

Figure 9Management results

Finally, it is possible to highlight that both factors are critical: the budget related to the maintenance and to the operators are too small. These lead to structures always in danger and to poorly trained staff, unable to carry out all the necessary interventions inside the plant.

6. Conclusion

Safety 4.0 offers a series of solutions to a great number of problems spreaded out from the Bhopal incident analysis.

In this paper a Safety Management System model is proposed by using a System Dynamics approach. This study highlights the lack and negligence of safety and maintenance in the Bhopal plant. A model has been developed and validated thanks to the well-known data in literature about the incidental event.

The casual loop diagram in section 2 has shown the interrelations between the main aspects that had influenced Bhopal incidental event. Some of these aspects can be controlled in industry 4.0 in a smarter way. FAILURE RISK can be reduced by using sensors and smart networks: oil and gas industry widely use big data analysis to realize real-time risk management [9].

It was underlined that HUMAN ERROR depends from both lack of adequate knowledge and skills: in Masoni et al. “Supporting remote maintenance in industry 4.0 through augmented reality” [25] is shown that AR visors can be used by operators to access the information necessary for performing the activities directly in the working area, without the need to refer to the printed traditional manual. The SAFETY MANAGEMENT SYSTEM can be also improved by letting different

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departments communicate each other faster and smarter, according to Taylor et al.[26].

Despite the use of Industry 4.0 concept and technology, some risks may arise from these implementations, as highlighted by Badri, Boudreau-Trudel and Souissi in a recent paper [27].

The use of System Dynamics allows to understand the importance of complex system and underlines the interactions among different management areas and can help to prevent possible critical events.

However, the proposed complex system can be face up increasing the operators' economic resources in terms of specific technical training. This bound could restrict the model application in the small industrial companies.

In future, the general model proposed could be adapted to different complex plants according to a Safety Management approach towards Safety 4.0. This will allow to detect potential hazardous situations and to control risk.

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