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Modeling and Training: How System Dynamics is Usable in OSH and MAH Frameworks

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Inail is the Italian National Institute for insurance against accidents at work, whose duties include both Occupational Safety and Health OSH, and the control of Major Accident Hazard MAH.
The objective of this research is to develop some models able to represent cause-effects links related to occupational and industrial accidents and incidents in order to get a global view of the matters concerned the industrial safety. The System Dynamics SD methodology were evaluated fit for the objective, since one of its key features is the capability to represent cause-effects links through loops instead of linear relations, offering the advantage to view the entire system all at once. The paper describes two SD models developed for training purposes.

1. Introduction

Inail is the Italian National Institute for insurance against accidents at work, a non-profit entity safe-guarding workers against physical injuries and occupational diseases. The Institute's duties include both Occupational Safety and Health OSH, as well as the control of Major Accident Hazard MAH.
A pillar of OSH activities is the recording and the analysis of serious and fatal accidents. Meanwhile, in-depth inspections at MAH establishments are a further duty in charge of Inail.
In industrial sectors, occupational safety is partially overlapping with the MAH control, indeed, both OSH and MAH activities attend to prevention. But in the first case the aim is to prevent any injury or fatality of individual worker, while in the second one the goal is to avoid major accidents involving chemicals, which might have severe consequences for workers, assets, environment and population.
MAH, despite OSH, involves just a little number of establishments and just a few industries. Occupational accidents are much more frequent than major accidents. For these reasons in MAH the study of near misses is a further pillar, as well as accident investigation.
In both OSH and MAH, Inail researchers have a special attention to small and medium companies, and devote efforts in defining methodologies and designing models and tools for supporting them.
For some years now, System Dynamics SD approach and models (SDS, 2017) have been applied for OSH purposes, including training activities and sustainability to manage the safety prevention. The SD models provide a global vision related to OSH, putting together many aspects that are often individually observed.
The paper outlines SD capabilities through the description of a model developed for training at OSH classes and one example of SD application in MAH activities.

2. Objective

The research started with some questions pointed out during the classes for training in OSH field. Firstly, how trainers make learners aware about the OSH in a company as a complex system that has a considerable amount of elements and interconnections. Next, how to show this complex system through their connections and causations, providing learners with a schematic and straightforward graphical representation. The last issue deals with MAH topics, focusing on the impact near misses analysis has on Safety Management System SMS, and hopefully providing a graphical representation to show the outcome.

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So, the objective which has been set is to develop models able to represent cause-effects links related to occupational and industrial accidents and incidents in order to facilitate a global view of the matters concerned the OSH. Their dual goal is building tools for training, related to safety and health, and acquiring information to spread to inspectors who visit companies.
Therefore, systemic approach and System Dynamics SD methodology were considered and evaluated suitable for this purpose; built models would facilitate to get a global vision related to safety issues.

3. System Dynamics

3.1 Generality

SD is a particular way to study and model reality (Senge, 1990) that allows analysis and simulation of a system moving over time. SD has been adopted in several sectors, including economic, social, and physical fields; but, there are various cases where that methodology was applied to OSH (Kontogiannis, 2012; Cooke and Rohleder, 2006; Moizer, 1999), too. However, the model is suitable for depicting the whole kind of processes or schemas, not only for a peculiar and unique event.
SD is based on Systemic Thinking ST (Forrester, 1961, Forrester, 2010): the linkages and interactions between the system components are examined and the phenomenon (or reality) is regarded as a system with feedbacks.
Over the years, ST is increasingly approaching SD (Monat and Gannon, 2015), which moves towards a more operational view consisting in computer simulation (Sterman, 2000).
The analysis of a dynamic system can be done by studying the analytical solutions of the differential equations describing the system behavior, but this approach fails if the system is complex. Hence, numerical analysis, carried out by computer simulation, overcomes that complexity.
The basic structure of a SD model is a set of non-linear first-order differential or integral equations (SDS, 2017):

$$\frac{d}{dt}\,x(t) = f(x,p) \tag{1}$$

where x is a vector of levels (stocks), p is a parameters set, and f is a nonlinear function.
Each stocks is calculated starting from its previous value and its rate of change:

$$\frac{x'(t)}{x(t)} = x(t-dt) + dt * x'(t-dt) \tag{2}$$

or more sophisticated integration scheme.
To build a SD model several aspects are taken into account, including boundaries detection, causal links between factors and, above all, the existence of feedback loops and the time lag relevance, which means to consider influences and changes over time. Stocks-and-flows mechanisms are introduced to look at filling and discharge of some system components that may be thought as reservoirs or basins, figuratively too (such as human resources, bank accounts or knowledge and skills). Feedback loops with their lags refer to causes-and-effects relations.
This research uses Vensim® software and has been turning to a teaching purpose of that kind of models.
It was Forrester himself (the discipline founder) who suggested SD models can be treated as didactical tools, too; since they are a “way of interpreting the world” and provide “a foundation underlying almost all subjects” (Forrester, 2009), making learners gain knowledge and get some practice with higher-order thinking.

3.2 System Dynamics used in OSH framework

Several studies have shown that people have difficulties to understand accumulation processes and causal feedback loops, especially in the case of time lags and space displacement (Groesser and Schaffernicht 2012).
Qualitative models are graphs representing causal loops, influence diagrams and stock-and-flow, but, of course, cannot suggest system dynamic behavior and possible scenarios, as well as the quantitative models do.
In the case of quantitative models, statistical-mathematical setting, based on both research outcomes and field experience, is followed by calibration, built on comparison with time series and peculiar analyses (for instance, in Vensim® such analyses are called “sensitivity test”, “Reality Check®” and “optimization”).
Earlier experiments findings (Dhawan et al., 2011) tell that quantitative SD models must be preferred to qualitative diagrams for facing complex tasks (e.g. laying out different scenarios for multi-factorial systems with many feedbacks), but otherwise both solutions can succeed in reaching educational advantages.

Hence, teaching and providing information by means of SD are nothing new. Besides, SD methodology has already been applied to occupational safety and health issues and is the basis of research, too.
Of course, this research relies on literature about System Dynamics regarding OSH (Leva et al., 2015), which can be split into a number of strands, including those addressing organizational factors causing accidents and lost production resulting from incidents. Moreover, they brushed up on the broadly known schemes, such as “domino theory” (Heinrich, 1932; Cooper, 2001), in order to include them in the models.

3.3 System Dynamics used in MAH framework

Industrial disasters and major accidents are particular themes this research started to address. Within major accident hazard prevention framework, there are already essays dealing with SD usage (Knegtering, 2013) and its suitability to be applied to examine weaknesses and failures (Taylor et al., 2015).
This can be obviously done by using the well-established approaches of Swiss cheese metaphor (Reason, 2000) and bowtie scheme (Bragatto et al., 2015, Alizadeh and Moshashaei, 2015). Those kinds of modeling are linear diagrams of accident causation and do not highlight the time effect and the functioning of the overall system. Major accidents have a nonlinear pattern in a dynamic complex system and, as such, can be tackled with SD methodology, especially if the target is to understand mechanism and transfer information. Salzano et al., 2014, provide a specific SD simulation of LPG tank, explaining how resilience is affected by the various aspects of the system.

4. Method

The use of SD models in training shows the feasibility to manage safety through a system-perspective approach, rather than explaining the functioning of a specific system.

4.1 MAINTsim: The maintenance model

The objective was to model the management of industrial processes of a company. MAINTsim, whose principle nodes and causal links are depicted in Figure1, is an agile model developed for representing the maintenance service, including workers’ behaviour and information flows, adopted for studying the effects of certain decisions on the likelihood of accidents and the company budget.

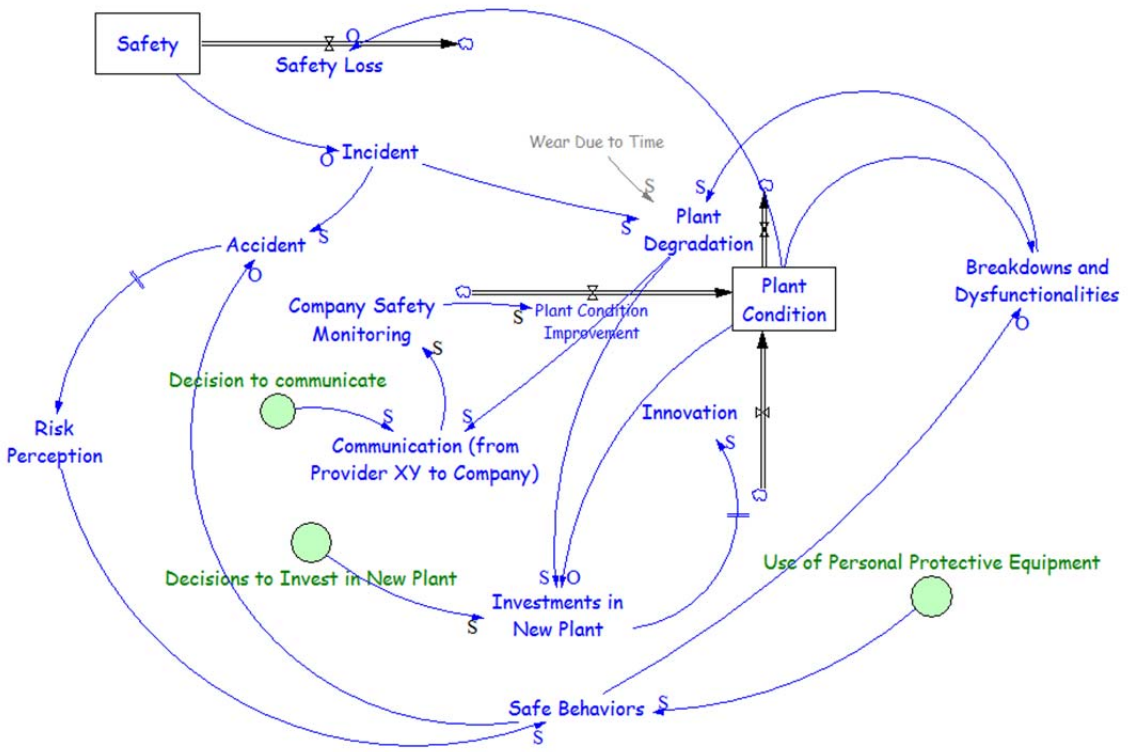

Figure 1: The principal nodes in MAINsim model and their causal relationships

It has three decisional leverage points, i.e. choices, on which the trainees could act, including the amount of investments in a new plant, the use of Personal Protective Equipment PPE, and the time dedicated to communication between the internal or external maintainer and the company.
During a simulation, the participants have to “quantify” each of the three leverage points, by guessing positive and negative impacts of their choices and considering time lags, too.
A computerized dashboard is built to make participants easily to act on the levers and control system evolution. Furthermore, to make clear that different starting scenarios lead to different effects, even with similar subsequent choices, other two leverages are provided to set preliminary circumstances in terms of company's safety culture and maintainer’s seniority. The choices have impact on the causal and stocks-and-flows diagram.
The investments on the plant affect its condition, thus safety is enhanced and likelihood of incidents and accidents decreases, and so their costs do. Nevertheless, above a certain level, investments don’t produce safety upgrading and, moreover, costs of investments themselves have to be considered, a balance has to be figured out, in which other choices come into play, too.
The second leverage point is about the time required by maintainers to comunicate with the company, notifying plant degradation and condition.
The last kind of choices, that participants have to consider, is about PPE. In the model, safe behaviour is partially related to risk perception, which in turn depends on both safety culture of maintainer and occurrences of accidents. But the amount and correct use of PPE by maintainers are emphasized as autonomous choices, in order to show the decision-making sides of the behavior issue. Views on bother of safe behaviour and work effectiveness (Shin et al, 2013) may bring the workers toward an inappropriate or even partial use of PPE, increasing the accident likelihood. On the other side, the appropriate use of PPE has both direct and indirect effect of decreasing the number of accidents and their costs.
The most significant causal feedback of MAINsim is related to incidents and accidents. Some of them are counter-intuitive balancing loops: a growth of an element causes, through a causal chain, a decrease of the same element over time (and vice versa), so triggering an ups-and-down mechanism which moves indefinitely on, if not stopped by an external-to-loop intervention. The simplest example of such a kind of loops is that more accidents give a greater risk perception and therefore a safer behaviour, which leads to less accidents.

4.2 An example of SD model in MAH framework

In the MAH establishments, the SMS represents all the safety measures, in terms of equipment, devices, operating instructions and procedures, which the owner implements in order to prevent major accidents and mitigate their consequences. The inspections are on the pillars of SMS. Bragatto et al. (2017) describe how the MAH inspections, in Italy, adopt both the systematic approach (i.e. checklist) and the risk-based approach (i.e. bow-tie). The bow-tie model is adopted to focus on the technical and organizational safeguards to prevent a Top-Event or major accident, and the means to mitigate the consequences if the event occurs.
Another pillar of SMS is the recording of the near-misses, anomalies or non-conformances, since all weak signals can be potential precursors of major accidents. Bragatto et al. (2014) show a method of near-miss discussion, using bow-tie model, for pointing out which barrier failed and which worked, and for improving the awareness of the operators and the workers to understand how the event was “far” from a real accident.
Therefore, the focus is on measuring the “proximity of an event to top-event” (PXTE variable) in drawing up the SD model that handles MAH framework.
The model deals with the load/unload activity of LPG product in a depot. It has been designed starting by the description of the physical LPG flow and the identification of the key elements involved, including equipment (road tanker, tank, small tank truck) and units (loading and unloading systems). The second step has been the inclusion of nodes representing the technical preventive and protective measures to contrast undesired events, including leakages, overflow, and overpressure, according to the available bow-ties.
Among the SMS functionalities, only the near miss management system is represented by near miss reporting and investigation nodes.
With the support of Inail’s inspectors of MAH establishments, a causal-effects model has been designed, as illustrated in Figure 2. The model is based on the main causal loop involving the PXTE variable, which assumes values in a [0, 1] range, depending on the proximity of the near miss occurred with respect to the major accident.
Increasing the value of PXTE, both activities of near miss reporting and near miss investigation increase, which positive consequences to SMS. This implies a broader application in terms of safety barriers. For the prevention, the leaks (or other failures) events decrease, while in the case of protection the consequences are limited. These loops point out and make explicit a key point in MAH framework, which is the near miss management as a method for improving safety in the plant. So far, SMS is thought as a unique block and cause-effect links between it and the other parts of the system are highlighted.

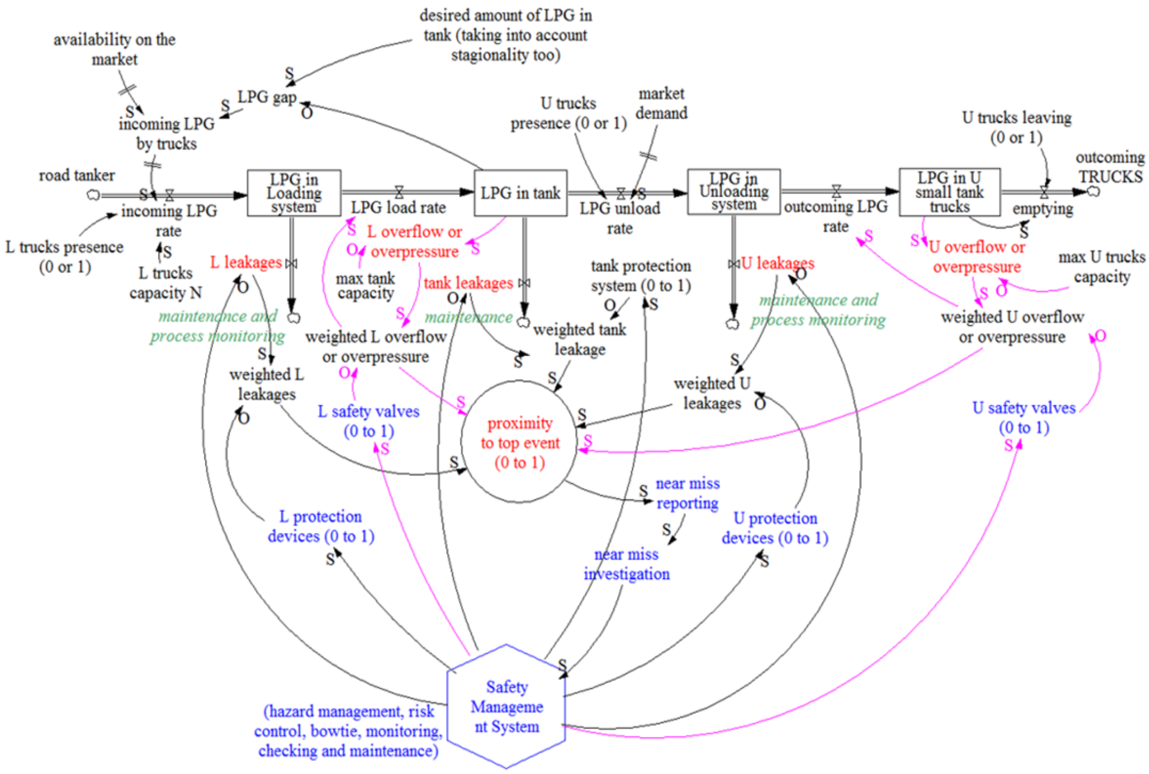

Figure 2: Causal and stocks-and-flows diagram for "MAH model"

5. Initial tests of SD models in OSH courses

The MAINTsim model is actually exploited in specific classes for test. Firstly, to check its effectiveness, a preliminary test was conducted in cooperation with four professionals, who are specialists in teaching and organizing OSH courses. The model has been evaluated for OSH trainers, where, in less than one hour, the causal relationships and their functioning are explained for making attendees able to understand the model and run some simulations.

So far, the test was applied into two separate classes of doctors and healthcare professionals. The fifteen hours courses reserved two hours for explaining the MAINTsim model and running a couple of quick simulations. The interviews of attendees, done before the courses, pointed out that part of them had expectations to acquire a wide picture of safety inside an establishment. The evaluation tests done after the courses show that the most of attendees felt the SD approach suitable for having a view of OSH issues integrated into the establishemt processes. It is under evaluation the study of a questionnaire to be filled before and after a course, in order to check how much the SD approach has improved the learning.

6. Conclusions

The MAINTsim model discussed in this paper has been mainly developed for training and informative purposes, where a more general view of safety is required. The model applies OSH principles stressing relationships between behavior and risk of injuries, but it also shows consequences of OSH-related decisions in different business areas (e.g. plant condition).

MAH model describes a physical process, its relations with respect to the SMS and development over time. Unlike MAINTsim, the development of this model is still in a preliminary phase, but the authors have already identified a possible application supported by the experts and inspectors of MAH establishments.

Both of them are aimed to provide people involved in prevention with a technique for understanding and considering links that relate the “prevention field” with other business aspects.

The systemic approach adopted in the SD models offers advantages in understanding the prospect of different scenarios and in finding the causal relationships and loops. The adoption of SD models during the training courses has pointed out another remarkable aspect that is the capability to observe the integration of different topics related to prevention, usually treated individually.

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