ARTICLE IN PRESS

Safety Science xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

The bowtie method: A review

A. de Ruijter [a,b,*], F. Guldenmund [b]

[a] CGE Risk Management Solutions, Vlietweg 17v, 2266KA Leidschendam, The Netherlands
[b] Safety Science Group, Delft University of Technology, The Netherlands

ARTICLE INFO

Article history:
Received 11 April 2015
Received in revised form 1 March 2016
Accepted 1 March 2016
Available online xxxx

Keywords:
Bowtie
Qualitative risk assessment
Quantitative risk assessment
Risk analysis

ABSTRACT

The bowtie method is becoming more popular, but it lacks a consistent approach. This article reviews the available literature and identifies the different approaches that are taken. There are two main types of bowties. Quantitative bowties and Qualitative bowties. Most Quantitative bowties use a fault tree together with an event tree and barriers to calculate risk. The ORM bowtie can also be considered a Quantitative bowtie, although its structure is different from a fault and event tree. Qualitative bowties use simpler cause–effect scenarios with barriers to communicate the risk to an audience. It is proposed to allow these variations of the method to exist and be used when applicable. It is also proposed that people using the bowtie method give an additional qualification as to whether they're using a qualitative or quantitative variant.

1. Introduction

Organisations in all industries strive to understand and control the risks inherent to operating a business. Attempts to gain insight into, and manage risk have resulted in a lot of methodologies available to systematically analyse and assess risk. The bowtie method is one of the methods that has become popular in high hazard industries like oil & gas, aviation and mining.

However, there is no consensus on the exact definition of the bowtie method besides superficial characteristics like the shape of the diagram (which looks like a bow-tie). This can be partly attributed to the fragmented history and development of the bowtie, which has led to multiple interpretations.

There are four historical developments that preceded the bowtie: Fault trees, Event trees, Cause Consequence Diagrams and Barrier thinking. We'll discuss these to more fully understand how the method has developed.

1.1. Fault Tree Analysis (FTA)

The fault tree method was invented in 1961 at Bell laboratories to visualise the failure mechanisms of a system in a diagram (Ericson, 1999). It uses boolean logic to construct a tree of possible failure paths leading to a single top event at the end (usually a critical failure or loss of control). On top of the value it has to understand failure paths in detail, the boolean logic allows the diagram to be quantified. Events in the tree will receive a probability of occurrence after which, based on the logic between the events, those probabilities can be used to calculate the probability of the top event occurring. Fault trees are often used to build the left side of the bowtie diagram (Markowski et al., 2009; Targoutzidis, 2010; de Dianous and Fiévez, 2006; Delvosalle et al., 2006; Chevreau et al., 2006; Badreddine and Amor, 2010; Franks et al., 2002; Bellamy et al., 2007; Ale et al., 2008a; Zuijderduijn, 1999; Jacinto and Silva, 2010).

1.2. Event Tree Analysis (ETA)

The fault tree is complemented by the event tree method, which often represents the right side of the bowtie. To create an event tree, a single event is chosen as the initiating event. Further possible events or system failures are then identified. These can either happen or not, which creates a range of possibilities and eventual outcomes. The major difference between fault trees and event trees is that the former traces a causal path from a single event backwards, while the latter starts from a single event and explores the possibilities afterwards. Both methods can be used to quantify the probability of the end event (in the case of a fault tree that is the top event, in the event tree it is the different outcomes). Ericson (2005) states that:

"ETA appears to have been developed during the WASH-1400 nuclear power plant safety study (circa 1974). The WASH-1400

* Corresponding author at: CGE Risk Management Solutions, Vlietweg 17v, 2266KA Leidschendam, The Netherlands.

E-mail addresses: a.de.ruijter@cgerisk.com (A. de Ruijter), F.W.Guldenmund@tudelft.nl (F. Guldenmund).

http://dx.doi.org/10.1016/j.ssci.2016.03.001
0925-7535/

Please cite this article in press as: de Ruijter, A., Guldenmund, F. The bowtie method: A review. Safety Sci. (2016), http://dx.doi.org/10.1016/j.ssci.2016.03.001

team realized that a nuclear power plant probabilistic risk assessment could be achieved by FTA; however, the resulting fault trees (FTs) would be very large and cumbersome, and they therefore established ETA to condense the analysis into a more manageable picture, while still utilizing FTA. Event trees use binary logic (events or failures either take place or they don't) to create a range of possible consequences."

Both event trees and fault trees are still widely used in a number of sectors.

1.3. Cause Consequence Diagram

Another important model, which includes a fault tree and an early version of an event tree was invented by Nielsen (1971). He developed the Cause Consequence Diagram, which can be regarded as the earliest bowtie. These diagrams start with a fault tree and then move into an event tree through what he calls a 'critical event'. He defines a critical event as a 'transgression of the safety limit of a vital reactor parameter'.

1.4. Barrier thinking

While Cause Consequence Diagrams only try to model the failure of a system, there are also models that make an additional distinction between negative events and control mechanisms. This is done by categorising certain systems or human interventions as controls or barriers[1] (these terms are used interchangeably here).

Barriers are those parts of a system that prevent deviations from occurring. There are often multiple barriers such that if a single one fails, there is a contingency. This concept is often applied to areas such as quality, safety, security and health, but any area that is involved in keeping normal processes running consistently can use a barrier model.

Trying to control a process is not new, but is often done implicitly. We want to restrict our review to the explicit, and structured analysis techniques that have been developed to think about unwanted events and ways to control them.

Haddon (1973) is among the first to think about barriers in a systematic way using the Hazard-Barrier-Target model. The idea being there are energy sources (hazards), and multiple barriers put in place to keep hazards from impacting a target (e.g. a person or asset). He described 10 different strategies or types of barriers that can be used to control hazards. Haddon's ideas were also used in the Management Oversight and Risk Tree (MORT) (Johnson, 1973) in which barriers are an important concept.

After that, Reason (1990) formulated his Swiss Cheese metaphor in the early nineties. The powerful image of a barrier depicted as a layer of cheese with inherent and temporary weaknesses represented by holes, is still very popular and propelled the barrier concept into the mainstream of organisations.

In the last decade, Sklet (2006) brought together a lot of the work on safety barriers and consolidated it in a review article and a definition of barriers which is now widely used. He defines safety barriers as:

> "... physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents."

de Dianous and Fiévez (2006) identify three reasons for formally identifying barriers:

- Encourage more investments in safety by making safety elements explicit.
- Increase knowledge about which pieces in an installation have a safety function.
- Help to identify areas that are not sufficiently controlled yet.

1.5. Combining these methods

These methods created the context that allowed the bowtie diagram to emerge. A bowtie combines a Cause Consequence Diagram and merges it with barriers into a single diagram. Although it seems straightforward, there are differences in how this diagram has been put together. This article provides an overview of the different variations of the method, and discusses advantages and disadvantages. Each variation will also be discussed separately in more detail.

2. Method

This article tries to answer the following questions:

- How is the bowtie method defined?
- Why is the bowtie used?

To answer these questions, a systematic review was done by combining Sciencedirect (http://www.sciencedirect.com/) with some well known grey literature from the Health & Safety Executive UK (HSE UK), the International Organisation for Standardization (ISO) and the International Association of Drilling Contractors (IADC) on the bowtie. The following search query was run:

> *(bow-tie OR bow-ties OR bow tie OR bow ties OR bowtie OR bow-ties) AND (risk analysis OR risk assessment OR safety OR safety barrier OR safety barriers OR safety control OR safety controls OR diagram OR diagrams OR model OR analysis)*

Major safety journals were then selected. This resulted in a list of 199 articles. These were first scanned by title. Articles that were obviously not applicable were excluded. This was mostly done by looking at the application area. Medical or mathematical papers using the word bowtie for something different were excluded based on title. Of the remaining articles, the abstracts were read and a quick search for the word 'bow' was done. Articles were excluded if they turned out not to contain relevant information or only a brief mention of the bowtie. The remaining articles were read in full and used in the review if they adhered to the article criteria.

2.1. Article criteria

To be eligible for inclusion, a couple of criteria were set. An article should have a stated goal for the bowtie method. It should provide a general description of the bowtie method and preferably use that description in a consistent way in the article. Optional criteria that made articles more likely to be discussed in more detail were also described. A graphic representation, detailed description of each component in the bowtie and a worked-out example were all preferred.

3. Variations of the bowtie method

Several authors have used the bowtie method and have given definitions of its structure. We'll start by examining the common elements, before turning to the differences. The word bowtie refers to the characteristic shape of the diagram, which looks like a men's

[1] Nielsen (1971) did talk about the concept of barriers. He made the point that categorising systems or behaviour as barriers can be difficult because some things that are regarded as part of the primary structure or process can also have a positive effect on safety, without being classified as a safety system.

Please cite this article in press as: de Ruijter, A., Guldenmund, F. The bowtie method: A review. Safety Sci. (2016), http://dx.doi.org/10.1016/j.ssci.2016.03.001