Propelling beyond the Bow Tie: an emergent dynamic risk – resilience model

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Abstract: The Bow Tie is a well known model in risk analysis and is widely used in crises and emergency management. It shows where LOD's can be introduced to either prevent a LOC or contain the consequences. On the other hand organizational resilience is of major importance for emergency response organizations to be ready for a LOC. A major disadvantage of the Bow Tie model is its one way approach: the model contains no feedback loop to learn from previous incidents. It is postulated a feedback loop should be part of a Bow Tie Model. As this feedback loop is described by the ***Unique Dynamic Operational Resilience*** $f(R_{ero})_{UV}$ factor a model is postulated to describe the dynamic interaction between risk and resilience. It shows how identified risks and organizational resilience influence the striking capabilities of emergency response organizations in relation to the emergence of a crises.
This model is called: "Propeller" and is mathematically described by $(x^2 + y^2)^2 = f(R_{ero})_{max}{}^2 . (x^2 - y^2)$.

Keywords: Model, Propeller, Resilience, Risks.

1. INTRODUCTION

Within risk analysis the concept of the Bow Tie is very well known and widely used. This concept is a combination of a Fault Tree and an Event Tree coupled around a Loss of Containment (LOC). As far as we know this Bow Tie model was first introduced by the hazard analysis department of ICI in 1979 (Ale, 2009a).

The main characteristic of this Bow Tie model is the application of Lines of Defense (LOD's) that are placed either in the left part where the Fault Tree is located or in the right part where the Event Tree is located. Those Lines of Defense are stopping barriers where the natural propagation of the fault or event is halted. It is this aspect that is used to mitigate the consequences for instance by Emergency Response Organizations either by preventive measures of by crises and disaster response. Many varieties of the Bow Tie model have been developed but they have all one thing in common: it is a one way concept. This one way concept suggests that after the Loss of Containment the following event stand on itself without changing the character of possible faults in the future. In reality there is always a feedback as it is a habit to investigate any accident or Loss of Containment and make recommendations to avoid the same LOC in the future (Boin *et al*, 2005; Deverell & Olsson, 2009; Deverell, 2010; Elliot & Macpherson, 2010). Hence, there must be at least a learning loop or feedback loop involved which is not part of the Bow Tie model.

Van Trijp *et al* (2011, 2012) present an in depth description of the ***Unique Dynamic Operational Resilience*** $f(R_{ero})_{UV}$ factor for a Dutch Emergency Response Organization (Safety Region). In these papers it is concluded $f(R_{ero})_{UV}$ factor is the result of equation (1):

$$f(R_{ero})_{UV} = (R_{ero})_{UV} (R_{awa} + R_{kv} + R_{ac} + R_q + \varepsilon)_{UV} \quad (1)$$

where R_{ero} = Resilience of Dutch Emergency Response Safety Region; R_{awa} = Resilience is a function of Awareness; R_{kv} = Resilience is a function of Keystone Vulnerabilities; R_{ac} = Resilience is a function of Adaptive Capacity; R_q = Resilience is a function of Quality; ε = unspecified data and items which are also a function of Resilience and UV = Utility Value. $f(R_{ero})$ is defined as Dynamic Operational Resilience as it dynamically describes the actual state of resilience of the organization. When ε is nullified the maximum value in arbitrary Resilience Units (RU) is (2) (Van Trijp *et al*, 2011, 2012):

$$f(R_{ero})_{max} = 22.54\ RU \quad (2)$$

where $f(R_{ero})_{max}$ = Maximum Achievable Dynamic Operational Resilience.

In this paper a theoretical dynamic risk – resilience model will be postulated that shows the interdependence of risk and resilience.

2. RISK – RESILIENCE MODEL

2.1. Conceptual model

Figure 1 shows a classical Bow Tie model where from left to right events lead to a Loss of Containment followed by the events occurring from the Loss of Containment (LOC). Clearly visible are the Lines of Defense (LOD). In this model it is assumed no LOC can occur as the LOD's function at 100%. In case the middle left LOD functions at < 100%, the top right events at the upper right quadrant will occur in due time given an LOC takes place as no LOD are present.

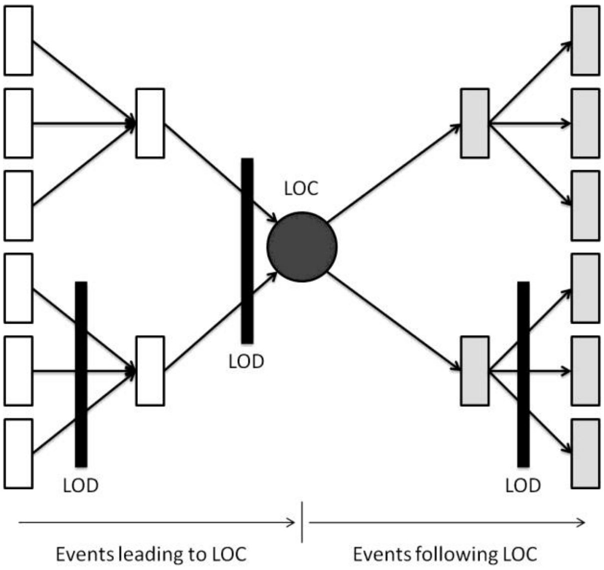

Figure 1. Bow Tie model. LOD = Line of Defence, LOC = Loss of Containment (Source: author)

From occurred LOC's and subsequent events, it is more than plausible to assume society as a whole and an emergency response organization in particular will try to prevent the same chain of reactions again. There is a feedback loop involved which has to be added to the Bow Tie model, see figure 2.

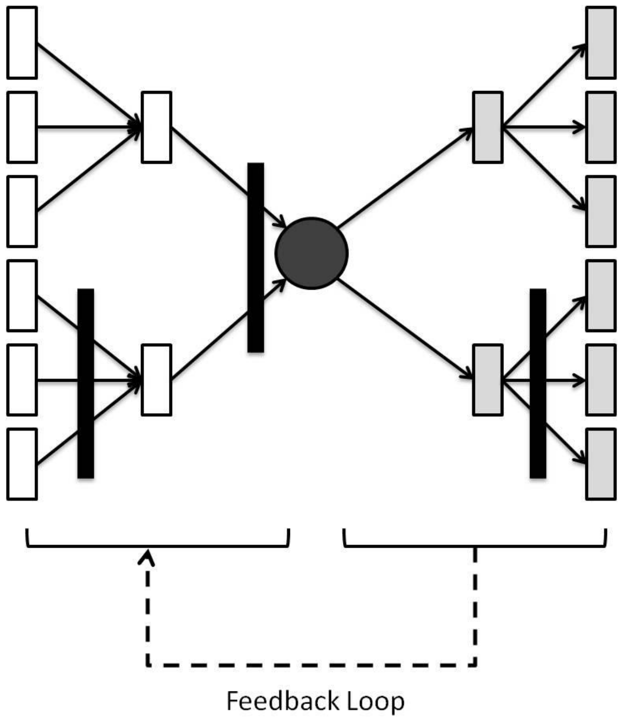

Figure 2. Bow Tie model with Feedback Loop (Source: author)

This feedback loop symbolizes any input generated by the event trees on the right to the fault trees on the left in order to correct or replace the LOD's. Hence, generating a new type of Bow Tie. This advances the one dimensional Bow Tie into a two dimensional Bow Tie model capable of change.

Furthermore it may be recognized the left and the right sides of the Bow Tie model are each based on the well known concept of:

$$\sum(\textit{Probability} * \textit{Consequence}) \Rightarrow \sum(\textit{Risks}) \quad (3)$$

According to a common definition of Risk (Ale, 2009b); Risk consists of two dimensions which cover the extent of consequence and the probability of occurrence. Both are present in an event tree and a fault tree. Hence, it is concluded this definition is applicable for the left and right side of the Bow Tie model.
See the respective clouds in figure 3.

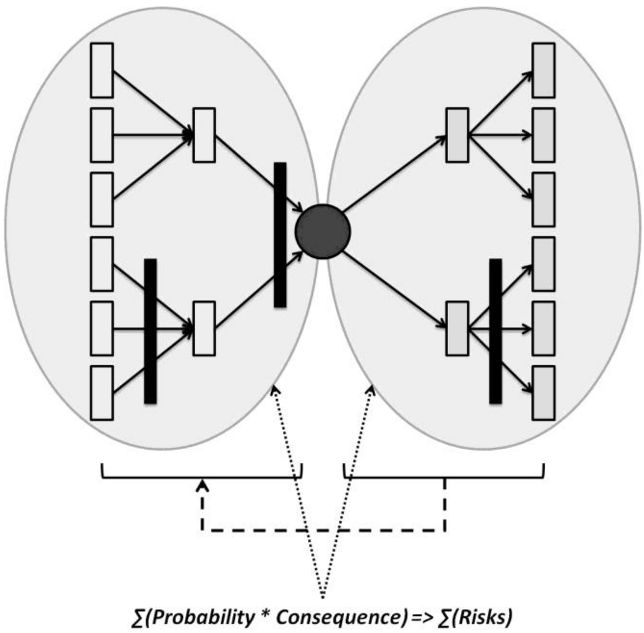

Figure 3. Bow Tie model with two Risks clouds (Source: author)

As this feedback loop is described by the Unique Dynamic Operational Resilience factor (1) or Dynamic Operational Resilience $\boldsymbol{f(R_{ero})}$ when the Utility Values ***UV*** equal 1, figure 3 may be transformed into figure 4 where the left and right side of the Bow Tie model showing $\boldsymbol{\sum(Risks)}$ are combined into one Risks cloud. A similar Resilience cloud can be drawn around the feedback loop to show $\boldsymbol{f(R_{ero})}$.

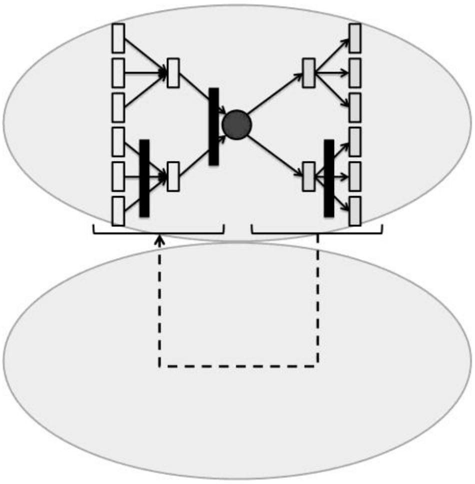

Figure 4, Model with Risk and Resilience cloud (Source: author)

At the point in figure 4 where the Risks cloud and the Resilience Cloud touch each other a special situation occurs:

$$\boldsymbol{Resilience = Risks \Leftrightarrow f(R_{ero}) = \sum(Risks)} \tag{4}$$

When combining the two clouds a lemniscate like model (Propeller) is formed (figure 5).

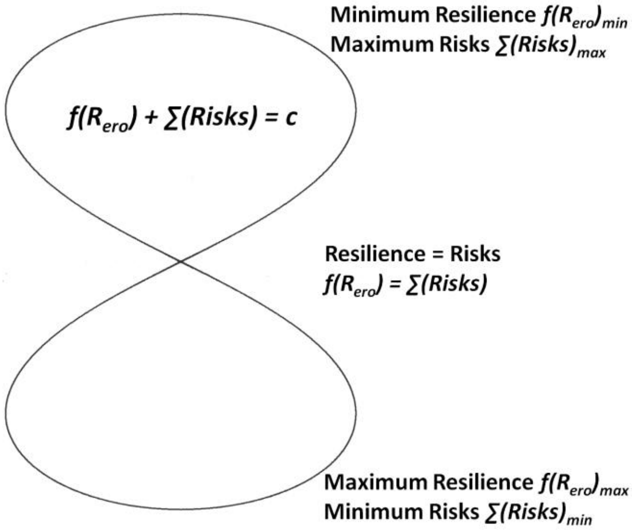

Figure 5, Propeller model showing relationship between Risks and Resilience

The shown Propeller model where the Risks and the Resilience cloud are equal is based on the following equation (5):

$$\boldsymbol{f(R_{ero}) + \sum(Risks) = c} \tag{5}$$

Where $\boldsymbol{c = 22.54}$ **RU**. At the top of the Propeller model the following situation is valid: Minimum Resilience $\boldsymbol{f(R_{ero})_{min}}$ and Maximum Risks $\boldsymbol{\sum(Risks)_{max}}$.

At the bottom on the other hand the situation is *vice versa*: Maximum Resilience $f(R_{ero})_{max}$ and Minimum Risks $\sum(Risks)_{min}$.

Taken into account $f(R_{ero})_{max}$ **= 22.54 RU** (2) and equation (5): $\sum(Risks)_{max}$ **= 22.54 RU**.

This shows in a balanced and optimal situation the maximum amount of Risks with which the system can cope is defined by the maximum Dynamic Operational Resilience $f(R_{ero})$ factor which this system possesses.

Every single point at the Propeller model is according to equation (5) always the sum of Resilience and Risks and is governed by the Cartesian equation which describes the Lemniscate of Bernouilli (Farréol & Mandonnet, 2011) (6):

$$(x^2 + y^2)^2 = a^2(x^2 - y^2),\ a > 0 \tag{6}$$

In case for the Propeller model $a = f(R_{ero})_{max} = \sum(Risks)_{max} = 22.54$ equation (6) transforms into equations (7) and (8)

$$(x^2 + y^2)^2 = 22.54^2 .(x^2 - y^2) \tag{7}$$

$$=> (x^2 + y^2)^2 \approx 508.05\ (x^2 - y^2) \tag{8}$$

Which mathematically describes the dynamic relationship between Risks and Resilience in the case of a Dutch Emergency Response Organization or in general terms (9):

$$(x^2 + y^2)^2 = f(R_{ero})_{max}{}^2 .(x^2 - y^2) \tag{9}$$

In figure 6 this dynamic relationship is represented by the orbs traveling the lemniscate trajectory.

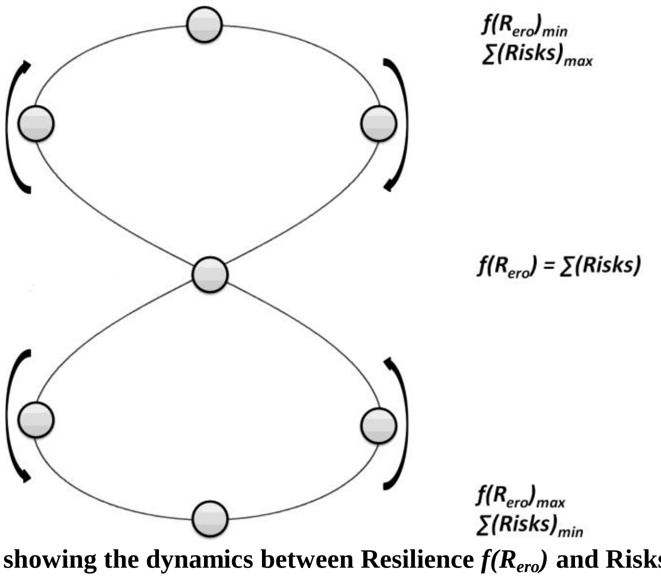

Figure 6, Propeller model showing the dynamics between Resilience $f(R_{ero})$ and Risks $\sum(Risks)$ (Source: author)

The speed the orbs travel the trajectory is governed by the dynamic relationship between Resilience and Risks of the Emergency Response Organization. A fast Resilience response of the Emergency Response Organization to minimize identified Risks causes a high orb frequency. Accordingly, a slow Resilience response to identified Risks causes a low orb frequency. The orb frequency or Propeller resonance is defined by the length in ***RU*** of the lemniscate divided by the velocity $\bar{v}$ ($RU.s^{-1}$) at which an orb travels the lemniscate. According to (Farréol & Mandonnet, 2011) the length of a lemniscate can be estimated to be ≈ 5.224 ***a***.

As $\boldsymbol{a} = \boldsymbol{f(R_{ero})_{max}} = \sum \boldsymbol{(Risks)_{max}} = \boldsymbol{22.54}$ **RU** the length of the lemniscate is ≈ 117.75 **RU**.
Hence, the resonance $\boldsymbol{v_{propeller}}$ is defined by equation (10):

$$v_{propeller} = 117.75 \,.\, (\bar{v})^{-1} \tag{10}$$

in cycles per second, dimension $\boldsymbol{t^{-1}}$; $\bar{v}$ = velocity in $\mathbf{RU.s^{-1}}$.

It is postulated a high resonance or a high value for $\boldsymbol{v_{propeller}}$ is needed to create a highly adaptive system (i.e. a Dutch Safety Region) to cope with emerging risks.

2.2. Imbalance between Risks and Resilience

In paragraph 2.1 it is assumed $\boldsymbol{f(R_{ero})_{max}}$ **= 22.54 RU** (2) and: $\sum \boldsymbol{(Risks)_{max}}$ **= 22.54 RU** (5). What does the model look like in case this is not true?
Let us observe the situation where $\boldsymbol{f(R_{ero})_{max}} < \sum \boldsymbol{(Risks)_{max}}$, see figure 7.

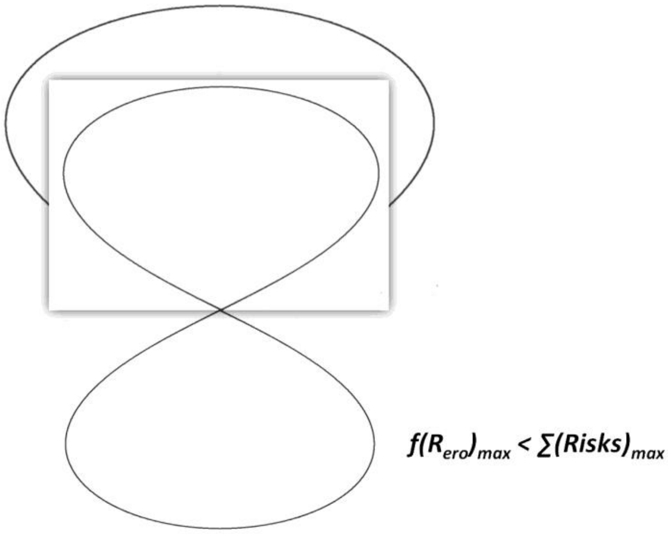

Figure 7, Maximum sum of Risks > maximum sum of Resilience (Source: author)

It is clear from figure 7 in order to balance Resilience with Risks again it is necessary either to increase $\boldsymbol{f(R_{ero})_{max}}$ and / or to decrease $\sum \boldsymbol{(Risks)_{max}}$. The difference between the two upper Risk clouds is the total amount that needs to be adjusted. A cost benefit analysis should provide the answer what is the most beneficial approach for and Emergence Response Organization to balance out Risks and Resilience.

3. DISCUSSION

The use of a lemniscate model in case of resilience was introduced by Holling (2001) where the dynamics of four ecosystem functions and the flow of events were clarified. The use of Propeller may be seen as an extended and enhanced version of the model originally proposed by Holling (2001). Based on the Bow Tie model and the introduced feedback loop for resilience, it may be clear resilience is no static characteristic. From daily observation in society a similar observation about risks may be performed: they are dynamic and not static. This is why the Propeller model has been introduced to show the dynamic relationship between risks and resilience.
Propeller helps to understand when the amount of risks can outweigh the ***Unique Dynamic Operational Resilience*** $\boldsymbol{f(R_{ero})_{UV}}$ factor and as such influence the striking capability of an emergency response organization. The model also shows the faster an emergency response organization adjusts its resilience to shifting and changing risks the more in phase the emergency response organization is. Hence, creating higher striking capability at an elevated frequency it may even become more aware of emerging risks before they actually happen. This is also suggested by Allen & Holling (2010): novelty and innovation are required for

systems to remain functional. In this case changing risks ask for the need of novelty and innovation for resilience in order to act as a coping mechanism. Stephenson *et al* (2010) describe this as the organizations' ability to survive and potentially thrive in case of a crisis. Silveira dos Santos *et al* (2010) suggest the coping mechanism should consist of sense making processes during a crisis event as they act as a great opportunity for organizational learning: the feedback loop in Propeller.

As stated in this paper the two clouds in the Propeller model do not need to have an identical size. An identical size shall only be present during optimal circumstances, reality is different. This model possesses the possibility to show what can be the optimal size of the cloud, where the largest of the two also sets the maximum to be achieved. In general an emergency response organization will use a dual approach, minimizing one and at the same time maximizing the other until a balance is reached. Any emergency response organization will try to maximize its ***Unique Dynamic Operational Resilience*** $\boldsymbol{f(R_{ero})_{UV}}$ while society looks at minimizing risks and decision makers try to minimize the cost involved. Propeller will act in such a case as a decision support tool as it also takes into account the possibility of minimizing the risks involved. A careful cost-benefit analysis will show the most optimum sizes of the cloud and the resonance needed.

A current example where high resonance is involved is presented by the Israeli project "Sensors for Safety" funded under the FP& specific program Cooperation under the theme Security (Anonymous, 2011). This Emergency Support System is a system of fixed or mobile sensors to capture information from audio, video to radioactive and biochemical information. This information will be easily accessible to crisis managers through an online portal, connecting emergency response services enhancing efficiency and ultimately saving lives. Thus enabling quick response to any occurring risk. In case of Propeller this can be translated into a high resonance system where emergency response services adapt at a high rate to emerging risks. Similar approaches are envisaged in the near future in crisis and emergency management where high resonances are needed.

4. CONCLUSION

This paper proposes a model (Propeller) that shows the dynamic relationship between Risks and Resilience which is an enhanced model of the well known Bow Tie model. Propeller uses an introduced feedback loop in the Bow Tie model that interconnects with the ***Dynamic Operational Resilience*** $\boldsymbol{f(R_{ero})}$ factor. From the two clouds described (Risks and Resilience) and equations (4), (5) and (6) it is shown that the mathematical description of the dynamic relationship between Risks and Resilience in the case of a Dutch Emergency Response Organization is described by equation (7) in particular and equation (9) in general.
It is also postulated the resonance of Propeller (10) can be used to identify fast resilience response of an Emergency Response Organization.
Finally it is concluded Propeller may show any imbalance between Risks and Resilience leading to a cost benefit analysis in order to mitigate the optimal balance between Risks and Resilience.
An example of a project where high resonance is involved is briefly addressed.

Acknowledgement

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