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Pinch Analysis Based Approach to Safety Risk Management in the Process Industries

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Pinch Analysis is an established method for enhancing the sustainability of industrial processes via efficient use of various resources. It is based on the principle of target identification followed by subsequent system design aided by a problem decomposition strategy using the Pinch Point. This approach has recently been extended to a broad range of structurally analogous problems in various domains, such as financial management, carbon-constrained energy planning, etc. In this work, a novel graphical methodology for risk management in the process industries is proposed. In this approach, it is assumed that there a set of risk reduction measures is available, and that each measure is characterized by its implementation cost and the degree of risk criticality that it addresses. These data are then used to generate a Source Composite Curve. Targeting can then be achieved by shifting this curve relative to a pre-defined Sink Composite Curve, which represents the locus of the plant management's "willingness to pay", or budget relative to risk criticality. The methodology is then demonstrated on a case study based on the well-known Bhopal incident.

1. Introduction

Pinch Analysis originally emerged as a systematic approach to achieving heat recovery and energy conservation in industrial thermal systems (Linnhoff et al., 1982). It is based on the principle of identifying thermodynamically feasible system-level targets, followed by detailed system design with the aid of a decomposition strategy. The latter strategy is based on the so-called golden rule of Pinch Analysis, which allows sub-problems above and below the Pinch point (i.e., system bottleneck) to be optimally solved independently. Pinch analysis has become sufficiently established over the past four decades, as a complementary approach to other techniques such as mathematical programming (Klemeš and Kravanja, 2013). Fundamentals of Pinch Analysis are now described in modern textbooks (e.g., Smith, 2005) and handbooks (e.g., Klemeš, 2013). Furthermore, in other textbooks focusing on Mass Integration (El-Halwagi, 2012) and resource conservation (Foo, 2012) extensions of Pinch Analysis have been published to give detailed accounts of recent developments.
Pinch Analysis extensions have emerged mainly as a result of the recognition of analogous problem structures. For example, transport phenomenon analogies between heat and mass transfer led to the emergence of Mass Integration (El-Halwagi and Manousiothakis, 1989). Various applications have been reported, such as water reuse/recycle (Wang and Smith, 1994), Hydrogen Integration (Alves and Towler, 2002), carbon-constrained energy planning (Tan and Foo, 2007), emergy-based planning (Bandyopadhyay et al., 2010), industrial production planning (Lim et al., 2013), financial planning (Zhelev, 2005), smart grid operation (Giaouris et al., 2014) and many other applications. In all cases, the key is to identify quantity (analogous to enthalpy) and quality (analogous to temperature) parameters for all system flows. The quality metric acts as a "driving force" that imposes unidirectional constraints on system flows. Unifying principles for Pinch approaches to resource conservation have been noted by Shenoy (2011), while Tan and Foo (2013) have noted the common underlying principles for general allocation problems.

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The equivalence to mathematical programming models has also been noted by numerous authors. For example, El-Halwagi et al. (2003) used a dynamic programming (DP) approach to prove optimality, while Prakash and Shenoy (2005) explained the similarity to linear programming (LP). Bandyopadhyay et al. (2010) then described an extension to segregated targeting problems. Finally, Tan and Foo (2013) noted that the Pinch Method can be viewed as a special case of a multiple-component LP problem.

Systematic risk analysis in the process industries is an important aspect to ensure safe and sustainable operations. According to Kaplan and Garrick (1981), proper risk analysis entails identifying:

- What can go wrong?
- What is the likelihood of each adverse event?
- What are the consequences of each adverse event?

Such analysis should be able to provide insights on how to mitigate risks via appropriate countermeasures, even in the face of significant uncertainties associated with rare events (Cox, 2012). The infamous Bhopal industrial accident is a clear example of failure of risk management, as a recent work suggests from ex post analysis that the event could have been prevented (Ishizaka and Labib, 2014) without undue investment. To date, the only risk-based application of Pinch Analysis has been reported by Tan and Foo (2013), where the dimensionless metric of “inoperability” was used as a quality index for energy streams. Inoperability was proposed by Haimes and Jiang (2001) as a linear risk indicator, whose value ranges from 0 (to indicate a system in normal state) to 1 (to indicate a system in a state of complete failure). Intermediate values indicate partial failure in physical terms (Haimes and Jiang, 2001). Nevertheless, even the Inoperability Pinch of Tan and Foo (2013) does not directly address issues pertaining to safety in process plants. Use of Pinch Analysis for safety risks have not been reported to date, although risk curves such as those described by Kaplan and Garrick (1981) suggest the possibility. In a recent paper, Ishizaka and Labib (2014) defined, within the crisis tree analysis (CTA) framework, the concept of criticality to signify the extent to which a sub-event contributes to a major disaster. This quantitative index measures the extent to which a component event contributes to the escalation of a crisis, and accounts for physical and subjective factors simultaneously. Note that the criticality of all contributing sub-events will, by definition, sum up to unity.

In this paper, a graphical Pinch-Based Methodology for safety risk management in the process industries is developed. The graphical approach is based on the targeting technique known as the Material Recovery Pinch Diagram, developed independently and simultaneously by El-Halwagi et al. (2003) and later by Prakash and Shenoy (2005). This paper is organized as follows. Section 2 gives a formal problem statement, followed by a brief description of the methodology in Section 3. Then, a case study based on an *ex post* analysis of the Bhopal industrial accident is shown in Section 4 to illustrate the methodology. Finally, concluding remarks are then given in Section 5.

2. Problem Statement

The formal problem statement is as follows:

- Given N sub-events that potentially contribute to a disastrous failure
- Given the criticality of each of the N sub-events
- Given the projected cost to prevent each of the N sub-events using countermeasures
- Given a threshold curve that signifies the decision maker’s “willingness to pay” to avert the disastrous event
- The objective is to determine the optimal mix of prevention strategies via systematic Pinch Analysis

3. Methodology

The main steps in the methodology are as follows:

- Identify sub-events that potentially contribute to a disastrous failure
- Determine the criticality and projected cost of prevention, or countermeasure, of each sub-event
- Arrange the sub-events based on ascending order of the ratio between countermeasure cost to criticality
- Generate the Source Composite Curve by plotting each sub-event in sequence, using the cost of prevention as the y-axis and criticality as the x-axis. This step is accomplished in the same manner as the composite curves as described by both El-Halwagi et al. (2003) and later by Prakash and Shenoy (2005).

- Define the Sink Composite Curve based on the decision-maker's locus of "willingness to pay" or "budget for process safety". The curve may be determined from a psychological threshold, or may be based on benchmarks with historical or industry average data.
- Superimpose the Composite Curves and determine if the Source Composite Curve lies entirely beneath and to the right of the Sink Composite Curve. If so, all countermeasures should be selected for implementation. The solution corresponds to a threshold problem in conventional pinch applications.
- If an infeasible orientation exists in the previous step, it is necessary to shift the Source Composite Curve to the right, until the two curves are tangent to each other. The point of tangency is the Pinch Point, and represents the bottleneck of the system. The Pinch Point coordinates represent the overall budget and criticality reduction for the system.
- All countermeasures below the Pinch Point are to be selected for implementation.
- Pinch-Based sensitivity analysis may then be done to further aid in decision-making (e.g., whether additional effort will be invested in revising criticality estimates, or whether countermeasure cost reductions will significantly change priorities).

4. Case Study

This case study serves to illustrate the Pinch-Based approach to safety risk management in the process industries. This example is based on the ex post analysis by Ishizaka and Labib (2014) of the Bhopal industrial accident. Based on CTA, the process data for this example are specified in Table 1. Each sub-event represents a failure or deficiency which contributed to the disaster; hence, in hindsight, corrective measures for each of these would have reduced the risk of such a catastrophic failure of the facility. Note that the sub-events have been arranged in ascending order of ratio between countermeasure cost to criticality.

Table 1: Countermeasure cost and criticality data for sub-events (Ishizaka and Labib, 2014)

Sub-event (SE)	Countermeasure cost (in M$US)	Criticality
Ineffective water spray system (SE1)	0.025	0.123
Ineffective VGS (SE2)	0.135	0.490
Ineffective flare tower (SE3)	0.085	0.123
No unit tank storage (SE4)	0.1	0.095
No computerized warning system (SE5)	5	0.123
Stainless steel piping replaced with carbon steel (SE6)	2.25	0.045

Based on this data, it is possible to construct the Source Composite Curve, following the steps outlined in Section 3. The resulting Composite Curve is shown in Figure 1. Next, this curve is superimposed on the decision-maker's "willingness to pay" Sink Curve (see Figure 2). Note that, in this case, the latter curve is a straight line, indicating a linear correlation between cumulative countermeasure cost and criticality reduction; in this case, it is assumed that the overall budget is US$ 250,000. However, in general, some curvature may be exhibited by the Sink Curve to signify diminishing returns in risk mitigation measures. Similar inflections may be observed in empirical curves used in risk analysis (Kaplan and Garrick, 1981). Note that the initial orientation shows an infeasible system.

Next, the Source Composite Curve is shifted until a feasible solution is found, as shown in Figure 3. Note that the Source Composite Curve has shifted by a distance of 0.264 from the origin; this distance signifies the residual criticality (i.e., all the countermeasures to be adopted contribute a combined criticality reduction of 0.736 (= 0-123 + 0.490 + 0.123).

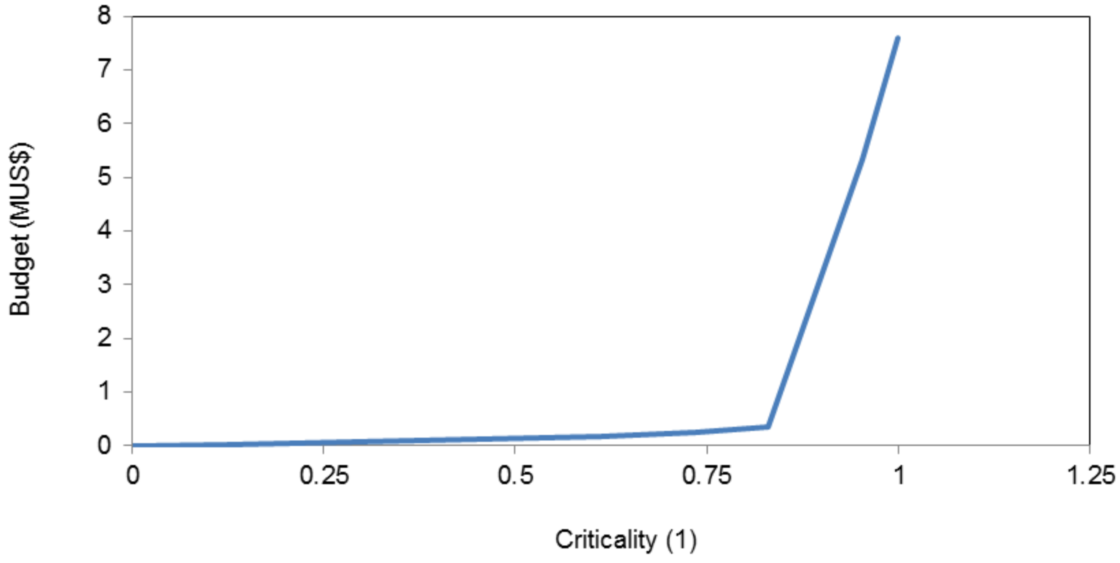

Figure 1: Generating the Source Composite Curve

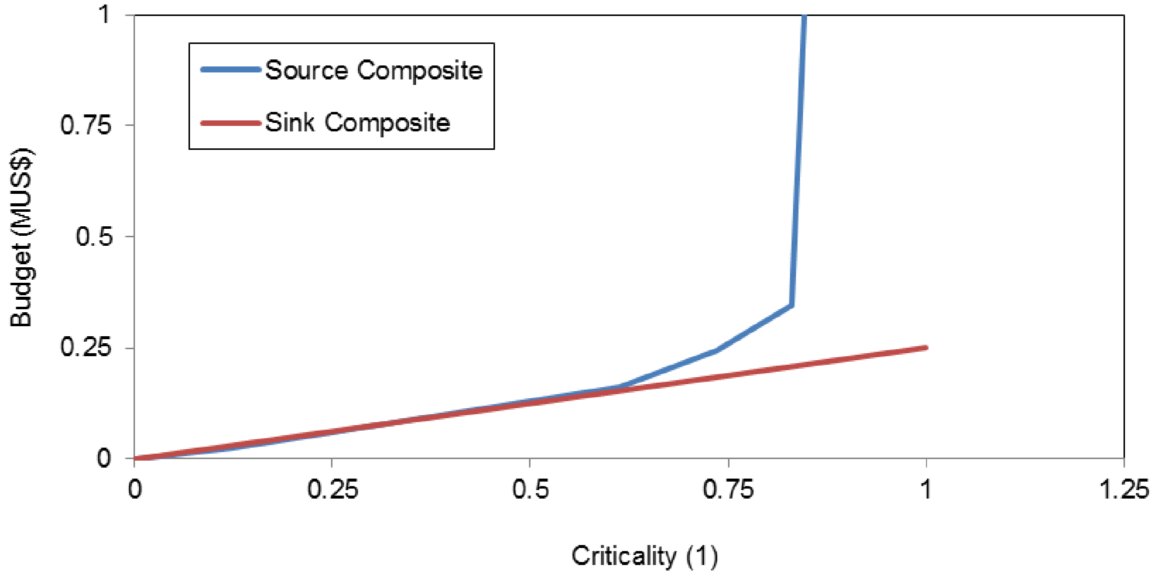

Figure 2: Infeasible orientation of the Composite Curves

The Pinch Point is located so as to signify an optimal projected budget for countermeasures amounting to a maximum of US$ 250,000, with a corresponding reduction in criticality of 0.75. Note that the location of the Pinch Point also signifies that the solution is insensitive to any changes occurring above and to the right of the Pinch. Furthermore, the solution needs to be rounded off since the countermeasures are either completely selected or not selected for implementation; partial implementation is not possible. Since the Pinch Point in Figure 3 touches the Source Composite Curve at SE4, only SE1, SE2 and SE3 are actually selected in the final solution. It can be seen that this solution requires the implementation of countermeasures 1, 2 and 3, with an exact cost of US$ 245,000 (= M$US 0.025 + 0.135 + 0.085). This solution matches the one reported by Ishizaka and Labib (2014), which was determined via a 0-1 mathematical programming model. However, the graphical display is useful for facilitating decision-making with respect to practical applications (Ahmad et al., 2013).

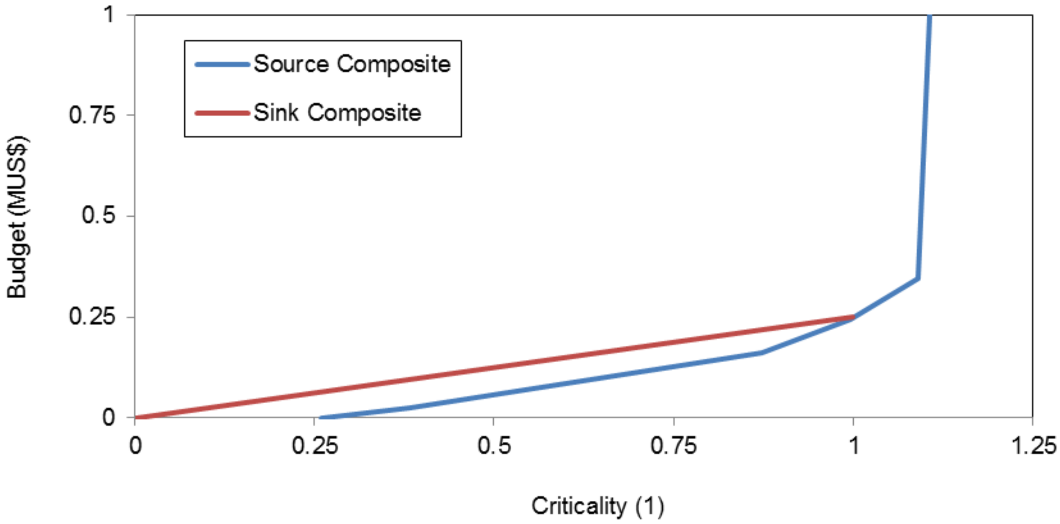

Figure 3: Optimal orientation of Composite Curves showing Pinch Point

5. Conclusions

A novel Pinch-Based Methodology for risk management in the process industries has been proposed in this work. This technique enables Pinch Analysis philosophy to be applied to the problem of allocating resources to mitigate risks in industrial processes. The graphical Pinch approach used here facilitates decision-making, while remaining consistent with conventional data displays used in risk analysis. A case study based on the infamous Bhopal incident has been solved to illustrate this approach. The solution determined is identical to that reported in literature using 0-1 programming models. This work contributes a novel approach to risk management which can be used as an alternative or supplement to mathematical programming. Future work will focus on extending this methodology further, using equivalent numerical (i.e., tabular) Pinch Techniques. Further applications to industrial problems should also be explored. Furthermore, it is necessary to do additional work on how to establish “willingness to pay” thresholds for decision makers.

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