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Process Integration Contribution to Safety and Related Financial Management Issues

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Total Site Heat Integration (TSHI) has been established as an extension of Pinch Technology and well implemented in industry. It was initially developed as a procedure for targeting energy performance of sites using the central utility system for inter-process heat recovery. Beside the thermodynamics, other critical issues, such as safety, and related financial management also have to be considered as that can influence the implementation of TSHI on industrial sites. The presented work analyses aspects related to safety on Total Sites including Data Extraction, constraints introduced by safety requirements and investment prioritisation for safety improvement. A case study based on the Bhopal incident data is used to illustrate the proposed method.

1. Introduction

TSHI is a tool for targeting energy site-wide and has been well implemented in the industry (Klemeš et al., 2013). The methodology was introduced by Dhole and Linnhoff (1993) and has been established as an extension of Pinch Technology (PT). Hu and Ahmad (1994) developed a graphical procedure using the utility system. TSHI has been even further extended. Klemeš et al. (1997) added targeting of power co-generation. Perry et al. (2008) enhanced TSHI by integrating waste and renewable energy to reduce the GHG (greenhouse gas) footprint. Matsuda et al. (2009) applied TSHI to large industrial areas in Japan, identifying considerable energy saving potential. Klemeš and Varbanov (2010) summarised a 20 steps guideline to achieve a credible solution on TSHI and presented data extraction rules. Chew et al. (2013) investigated the main issues that can influence the implementation of TSHI on the industrial sites. Several key issues have been identified as being of vital importance for the industries: design, operation, reliability, regulatory policy and economics. Chew et al. (2015) extended process modifications of individual processes and the Plus-Minus principle has been adapted to enable the beneficial process modification options to be selected in order to maximise energy savings in TSHI. Heat Integration (HI) focuses mainly on the thermal properties of plant streams, performing Data Extraction and energy targeting. In an early stage of HI design, the limited information on equipment makes it difficult to fully account for safety on the site. However, safety is a key concern for industrial plants to implement sustainable development and has serious implications on the TSHI procedure. Safety assessment is needed to undertake in the concept stage of the proposed TSHI scenario. Tan et al. (2016) presented an innovative study for targeting safety and environmental performance improvements for a process. They have combined key concepts such as the criticality of the expected failure modes or environmental impacts on the one hand, with the possibility or willingness of the company management to pay for such improvements. This is an interesting approach identifying the trade-off between the necessary improvements and funds made available as a bottleneck – a Pinch Point between the two curves. However, this work is only a first step and does not account for further key concepts in investment planning and safety improvement. The most important ones in this regard are that the investment limits are usually provided per periods and rarely made as one-off payments. The targeting and optimisation should be considered for campaigns rather than for single actions. From the analysis a number of issues can be identified that are still open and pending investigation, see e.g. (Liu et al., 2015). They include the identification of correct data for TSHI projects as well as revealing further limitations on the integration efforts posed by safety and maintainability concerns. An important task is to provide adequate tools to company

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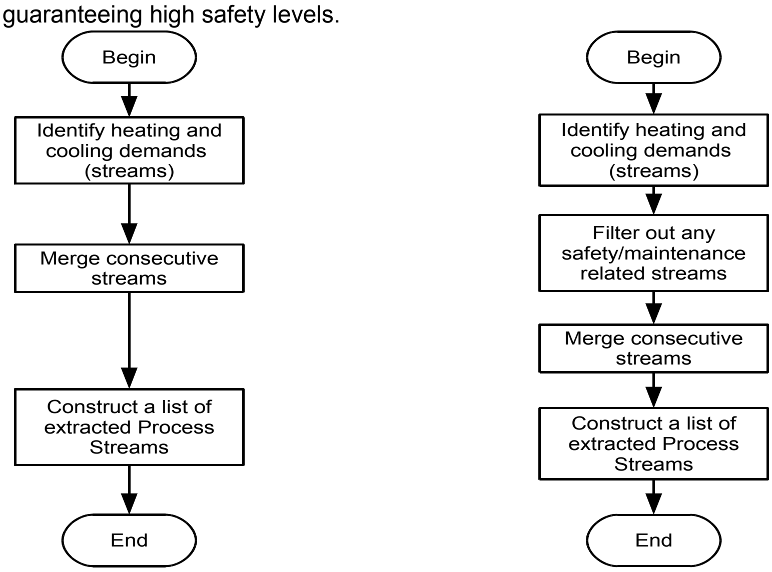
managers that would feature the necessary simplicity and yet to still contain the information necessary for making the investment decisions. The current paper investigates initial attempts on resolving these issues.

2. Safety and maintenance issues during Data Extraction

Data Extraction (DE) is a fundamental activity in Process Integration (PI). It takes as input the flowsheet with measured (and reconciled) data of a process and extracts only those data items relevant to the specific PI variant applied. For HI and TSHI the relevant data items include Heat Capacity Flowrate (CP) and temperatures of the Process Streams. Since DE and the overall process of targeting and network optimisation are very time-consuming, it is essential to filter out any data that cannot or should not be used in the integration procedure. The possible DE procedures are shown in Figure 1. Following the algorithm in Figure 1a is adequate for simple processes with no significant issues raised by site engineers – for instance from food processing or hotel service activities. However, proceeding to refineries and chemical plants, certain issues arise with possibilities for integration, related to the possible risks of undesired or dangerous events taking place: explosion, stream or environment contamination, excessive scaling, etc. Some examples are:

- The risk of explosion from hydrogen leaking. This would necessitate preventing integration of the related streams for the purpose of tighter monitoring and control using higher than normal standards of safety.
- The risk of contamination of product streams when integrated with oil, oily products or waste streams. This would require excluding integration of the involved dangerous streams or at least forbidding integration of those streams with the ones requiring guaranteed high purity.
- The risk of failure to deliver heating or cooling when integrating crude oil or related streams. This can be caused by pipes clogging inside heat exchangers and stopping those devices for cleaning and maintenance.

Clearly such risks and maintenance needs impose certain constraints to the HI procedures. One constraint type excludes any integration whatsoever as in the case with hydrogen production. In such cases, the modified procedure from Figure 1b should be applied, to exclude any high-risk streams from further consideration and guaranteeing high safety levels.



(a) Plain steps (b) Accounting for safety or maintenance constraints

Figure 1: Procedures for DE from a process

Other possible constraints can be imposed at the stage of synthesis of the Heat Exchanger Network (HEN) and Total Site Heat Integration Network (TSHIN). This can take the form of forbidden matches, where matching certain pairs of hot and cold streams are forbidden as part of the data input to the synthesis procedure.

3. Safety and costing target issues to be considered for Process Integration

3.1 Safety issues

Safety is key for industrial plants to implement sustainable development policies and actions. It should be considered as the most critical step in the TSHI procedure. The safety assessment is needed to undertake at the concept stage of the proposed TSHI scenario. Authors' previous work (Liu et al., 2015) presented safety assessment for TSHI. The safety assessment guideline consists of five steps, designed to help engineers in decision making on site-level safety. The severity identification and assessment are TS-specific and should be extended/amended accordingly. As a result of the safety assessment, the principles of risk reduction and process control in TS should be applied. If the risks associated with the proposed TS scenarios, which are unacceptable, the alternative route should be considered with specified control measures and safety procedures.

3.2 Efficiency and safety improvement

Another key aspect of reliability which relates to Process Integration is prioritisation of investments. Usually, measures for improving plant performance fall into several dimensions:

- Safety, reliability, maintenance/maintainability
- Utilisation efficiency of energy, water and other resources
- Minimisation of the site impact on the environment or society via emissions and other mechanisms

PI projects are interrelated with the ones for improving safety and environmental impact. When one of these dimensions dominates in a project, it is categorised as belonging to that. Safety dimension is given highest priority, as the prospect of having a failure can result in injuries and losses, which may severely damage all aspects of the enterprise work. It is important to ensure that the projects involving any of the main dimensions are prioritised and balanced, to minimise the potential losses and maximise the benefit from the investments.

3.3 Tool for investment targeting

Prioritising investments can be performed in several contexts. The most immediate context is to consider a number of measures for improving site and process safety and quantify the necessary investments against quantitative indications of the potential safety improvements. This would allow mapping potential spending against potential benefits, as any safety improvement, besides humanitarian and societal aspects also can be quantified in terms of saved costs or avoided profit losses. The proposed tool involves ordering the safety improvement measures by ascending Cost-Benefit Ratio (CBR) and plotting curves of cumulative investment on the Y-axis vs. cumulative safety improvement on the X-axis. The safety improvement can be expressed in various ways. Here it has been selected to represent it as "avoided criticality" following Tan et al. (2016).
The procedure for safety investment planning follows the construction of the Safety Investment Requirement Composite Curve (SIRCC) and then the Safety Investment Plan Composite Curve (SIPCC) for safety improvement. The former is referred to as the "Source" Composite Curve in (Tan et al., 2016). The latter corresponds to the "Sink" Composite Curve for the "management willingness to pay". However, in the current method it is built in a different way, providing appropriate meaning to both curves and mapping them to investment planning concepts. While the SIRCC reflects the necessary safety improvement measures with their criticality and cost values, the SIPCC refers to investment planning concepts: investment period, budgetary limit for each period, acceptable criticality avoidance.

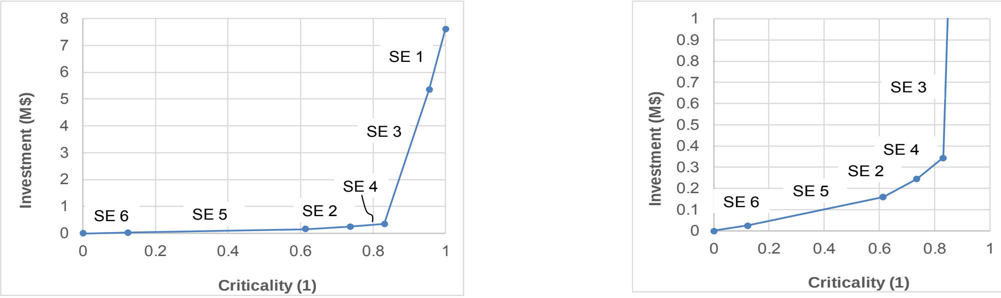
4. Case Study illustration

4.1 Problem formulation

The proposed improvement to the investment targeting tool is illustrated with a case study derived from the Bhopal accident (Ishizaka and Labib, 2014). The risk of toxic gas release due to the poor plant design can be described by six potential sub-events, as shown in Table 1.

Table 1: Safety problems and cost of reducing risk

Sub-Event (SE) No.	Sub-event	Criticality (1)	Improvement cost (M$)	CBR (M$/(1))
6	Ineffective water sprays system	0.1230	0.0250	0.203
5	Ineffective vent gas scrubber	0.4900	0.1350	0.276
2	Ineffective flare tower	0.1230	0.0850	0.691
4	No unit tank storage	0.0950	0.9500	1.053
3	No computerised warning	0.1230	5.0000	40.650
1	Stainless steel pipes replaced by carbon steel	0.0450	2.2500	50.000



(a) The complete SIRCC *(b) Zoom in up to 1 M$ investment*

Figure 2: Safety Investment Requirement Composite Curve

The events with higher priority have higher criticality and higher risk probability. In order to avoid the accident, a number of safety improvement measures can be performed. Corresponding to each of the sub-events. There are 6 sub-events that contributed the plant design susceptibility to the accident. Hence, the repair measures for risk reduction on these sub-events could improve the safety of the plant design. The cost of preventing sub-events varies with the appropriate measures. The entries in Table 1 have been sorted by the (CBR) values for the potential risk reduction measures. Following Tan et al. (2016), a curve has been constructed of cumulative investment on the Y-axis vs. cumulative criticality avoided of the X-axis (Figure 2). Unlike the cited previous work, here this is termed Safety Investment Requirement Composite Curve (SIRCC) to reflect its fundamental meaning and context. This curve represents an assessment of the potential risks within a process plant in terms of the criticality and cost for elimination or reduction to acceptable levels.
The next step is to consider the possibilities for satisfying the identified requirements. Providing an evaluation of the possible investment as a one-off payment (Tan et al., 2016) is a good first step. To bring the consideration closer to solving practical problems it is necessary to account for the development of the process in time. Usually, there are time frames for implementing the safety measures. The enterprise management usually plans investments by regular time periods. This applies also to investments into safety, where the emergency measures can be considered as an extreme case with a very short time frame.
In the current work, it is proposed to consider investment budgeting within the framework defined by

- The time period for implementing actions and providing the investment. The period duration is a user-defined parameter. In this case study, it is assumed that this is 1 month, the investment limit is monthly and the risk reduction measures also take place in monthly batches.
- The investment provision is considered to be an upper limit, not an exact sum to be spent.
- The assumption that the measures cannot be implemented partially (Tan et al., 2016) is unnecessary and in practice can be too restrictive. An example would be such a measure as changing the pipes in the plant back from such of carbon to stainless steel. This is obviously a costly investment and the corresponding operation may take also a significant time to be implemented. This step may be eventually implemented in partial steps. This assumption is relaxed.
  The same value as in (Tan et al., 2016) is also adopted in the current work: 250,000 $. However, here it is treated as a monthly upper limit, not as a one-off budget allowance. The investment limit for the first period (month) is illustrated in Figure 3. It can be seen that this would intersect with the SIRCC within the mitigation measure for SE 4. This means that there would be sufficient funds for implementing measures for SE 6, SE 5 and SE 2, leaving the measures for SE 4 and the remaining sub-events for future periods (months).

4.2 Construction of the SIPCC

Connecting the initial point (0,0) with the intersection point (0.7408, 0.25) provides the first segment of the investment plan. It is assumed that the funds for each period are provided at the start. The second segment of the plan starts from the latter point (0.7408, 0.25) and finishes at the investment limit for the second period: 0.50 M$, touching the SIRCC after the beginning of the SE 3 segment. From this point until (0.9517, 5.25) just before the end of the SE 3 segment are 19 investment periods, but the SIPCC does not change slope, following the SE 3 segment of the SIRCC. The investment period immediately after that overlaps partly the SIPCC segments for SE 3 and SE 1, and the last period follows the SIPCC segment for SE 1 until the end. The resulting Composite Curves are shown in Figure 4: the overall curve (a) and (b) the investment slice of up to 0.5 M$.

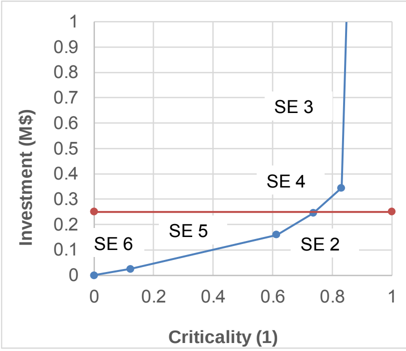
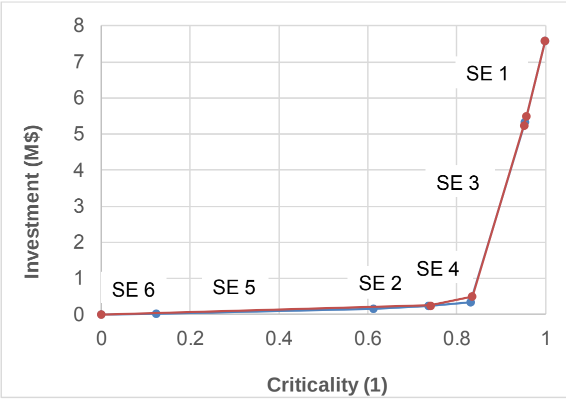
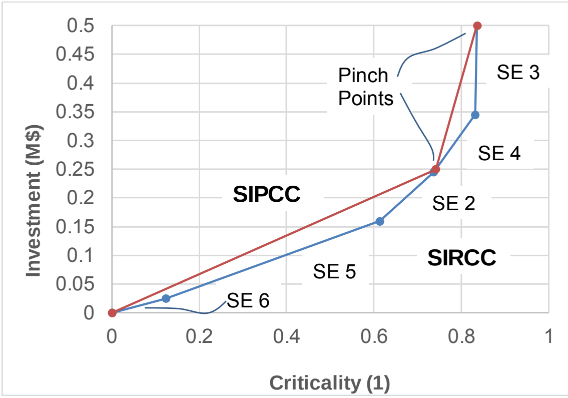


Figure 3: Superimposing the investment limit for the first year on the SIRCC



(a) The complete view



(b) The investment slice up to 0.5 M$

Figure 4: Safety Investment Composite Curves

4.3 Discussion

The safety investment targeting picture (Figure 4) provides a basis for several important observations– conceptual insights and specific to the case study. The conceptual insights can be formulated as follows:

- The introduction of the concept of investment periods provides a semantically rich and appropriate meaning for the second Composite Curve. The pair of curves is mapped to represent what measures are necessary to implement (SIRCC) and how much can be invested, within how many investment periods (SIPCC). The presented improvement eliminates the need to shift the SIRCC, in turn eliminating the unexplained criticality gap in the plots from Tan et al. (2016).
- At the end of each investment period the two curves touch, featuring Pinch Points. These can be clearly mapped to milestones in terms of investment, defining which safety improvement measures it is feasible to implement within the current period and how much finds can be transferred for use in the following periods.

The issues specific to the case study involve the urgency of the necessary actions and whether the improvements can stop before implementing all measures, leading to important generalisations.

Regarding the extent to which to keep applying the measures. it can be observed that most of the improvements can be performed within the first two investment periods and that removes most of the risk represented by the criticality of the sub-events: 0.8348 – i.e. 83 % of the overall risk exposure. In this context arises the question whether this is an acceptable level of risk reduction? There is the need for finding ways of defining the threshold of acceptable risk reduction level within the overall set of possible measures.

Comparing these results with those in (Tan et al., 2016), there have been identified the identical improvement target for the specified one-off limit of $ 250,000: 0.736 criticality reduction costing $ 245,000 and leaving $ 5,000 unspent. It can be seen that the proposed method improvement provides an appropriate extension, allowing to explore the problem on a wider scope. The remainder of the first investment period is transferred to the second period. If the corresponding measure allows partial implementation, this transfer can be used immediately after the follow-up investment period starts. The second issue deals with the potential urgency of the measures. The plant on which the case study is based has suffered the accident 2 y after an inspection has recommended a number of safety improvement measures. Within this time frame, how fast should the measures be implemented, in order to ensure safe plant operation – would this be 6, 12 or 18 months? It can be observed that implementing all measures would take 30 investment periods. Taking the specified 1-month duration per period this translates into 2.5 y. If all measures are necessary to implement, this means that a disaster would take place as the risks would not be eliminated on time. If the acceptable level of residual risk for safe operation is up to 0.264 (i.e. the residual criticality after one investment period), or if it is up to 0.1652 (residual criticality after two investment periods), then the disaster would be prevented within sufficient time.

5. Conclusions and future work

This contribution has analysed key issues concerning safety and maintenance within the context of TSHI. They can be grouped into the derivation of constraints for the energy integration activities and investment planning. The constraint derivation part is important for preventing unnecessary data collection and processing for process units which have to be isolated from the rest of the site for improved control and safety implementation, as well as for identifying key forbidden matches for HI. The paper presented the development of an investment planning tool. Its implications are deeper. The tool provides a simple single-view plot for decision makers for planning their investments in safety improvement. It is possible to make the decisions accounting for the time as the factor –when certain safety improvement actions should be made and how much this would cost, compared with the investment limits available to the company. The latter defines a triple trade-off between safety improvement measures vs. investment, vs. time for achieving the desired safety levels. Important directions for future work in this regard would be to investigate

- Accounting for the time dimension more thoroughly – i.e. the urgency of the safety measures;
- Definition of acceptable residual criticality and providing means of computing it;
- Combining safety improvement measures with the resource efficiency and environmental impact reduction measures into a uniform framework for site sustainability improvement;
- Identification of clusters of actions and measures that have to be implemented together, in order to minimise unnecessary spending and losses.

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