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# Prospects for Novel Pinch Analysis Application Domains in the 21st Century

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Pinch Analysis was originally developed as a thermodynamically-based methodology for targeting and design of industrial heat recovery systems. Subsequent extensions of pinch analysis have since been developed; for example, mass pinch analysis is derived directly from analogies between heat and mass transfer, and has led to application for the efficient use of mass separating agents (MSAs) in process plants. More recent literature shows Pinch extensions for numerous applications, including energy sector planning using diverse quality measures. Other Pinch techniques have also been developed using time as the quality index, for applications such as production planning, financial analysis, supply chain management, isolated energy system design, batch process scheduling, carbon dioxide sequestration, and human resource allocation. These applications demonstrate how common problem structures allow an elegant solution approach to be developed for seemingly diverse applications. In this paper, past applications of Pinch Analysis are reviewed, and its further prospective extensions that may be developed, based on similar analogies, for non-conventional problem domains are discussed.

## 1. Introduction

The increasing global awareness regarding the limitations of the natural environmental to absorb pressure caused by human activities has led to widespread research interest in finding sustainable engineering solutions (Rockström et al., 2009). As a result, there has been significant activity in the development of numerical footprint metrics for measuring sustainability, as documented in a recent review by Čuček et al. (2012). In addition, there have been attempts at aggregating inherently multi-dimensional sustainability aspects into a unified composite index (De Benedetto and Klemeš, 2009). Such methodologies have enabled rigorous benchmarking of environmental performance of sustainable technological systems. At the same time, over time Process Integration (PI) techniques have also evolved to enable gains in sustainability to be achieved via system-level interventions (Klemeš et al., 2011).
Within the general framework of PI, Pinch Analysis was originally developed as a thermodynamically-founded, insight-based methodology for targeting and design of industrial heat recovery systems (Linnhoff et al., 1978). Mathematical Programming techniques have also been developed in parallel as a complementary approach (Klemeš and Kravanja, 2013). The insight-based strategy underlying Pinch analysis allows targets to be determined prior to detailed system design, and also enables problem decomposition to facilitate process engineering decisions. This feature is especially useful for complex industrial problems that need to be addressed by professional engineers. Thermal Pinch Analysis is based on the use of temperature as an indicator of quality of heat, which thus defines the driving force, or direction of heat flows, within the system. Over the past four decades, this methodology has become widely used in industry as an effective means of implementing heat recovery for reducing fuel consumption, operating costs, and emissions (Linnhoff, 1993). As a result, basic principles and detailed

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steps of Pinch Analysis for thermal systems can now be found in modern textbooks, e.g., (Smith, 2005) and reference books, e.g., (Klemeš et al., 2011), and thus need not be repeated here.

This paper focuses on Pinch Analysis extensions that have emerged, or which are expected to emerge in the near future, out of the exploitation of analogous underlying problem structures. A clear example is the well-documented case of Mass Pinch techniques, which were developed directly out of mathematical and conceptual analogies between heat and mass transfer (El-Halwagi and Manousiouthakis, 1989). However, in the past twenty years numerous diverse extensions have been proposed in the literature via similar analogies. In particular, these structural analogies were noted by Shenoy (2011) for resource conservation network problems and by Tan and Foo (2013) for energy allocation problems. The rest of this paper is organized as follows. Section 2 briefly discusses common Pinch principles that underline all these variants. Next, Section 3 discusses the historical evolution of non-thermal Pinch Analysis literature. Section 4 then discusses ideas currently under development, as well as possibilities that to date have not yet been explored. Concluding remarks are then given in Section 5.

## 2. General Principles of Pinch Analysis

In all Pinch Analysis methods, it is necessary that streams be characterized by both quantity and quality measures. In the case of thermal pinch analysis, for example, energy streams are quantified in terms of enthalpy and temperature, with the latter providing the directional quality index. Next, problem components are grouped into sources and demands (or sinks). The fundamental problem involves optimizing the matches of source and sink streams, subject to quality constraints, such that the demand for an externally-sourced, high-value resource (e.g., hot utilities in the case of thermal systems) is minimized. A direct consequence of such optimization is that the discharge of unusable waste streams (e.g., rejected heat in thermal systems) is also minimized. Optimization can be facilitated using a graphical approach known as the Composite Curves as shown in Figure 1, which are based on the conventional mapping of quantities in heat and mass Pinch applications.

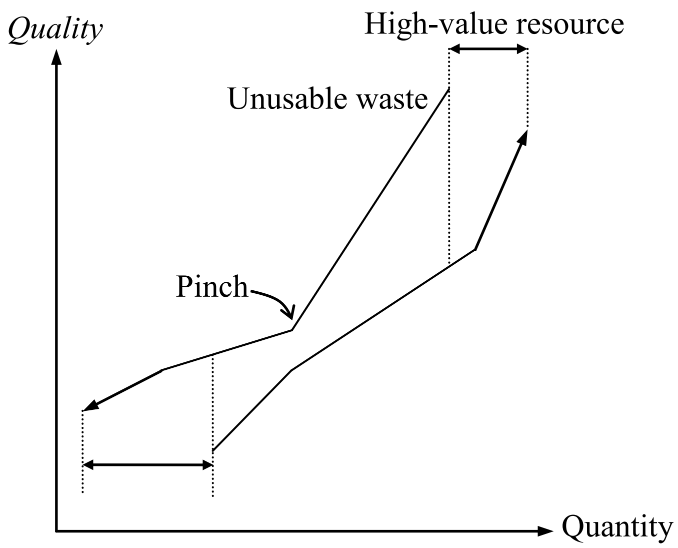


*Figure 1: Composite Curves for Heat/Mass Pinch Analysis*

Although the approach used in Figure 1 is well-established for Heat and Mass Pinch applications, alternative graphical representations have been proposed. A graphical method was developed by El-Halwagi et al. (2003) using flow rate as the x-axis and mass load as the y-axis. The same method was also independently developed by Prakash and Shenoy (2005). A different graphical tool for the same problem structure was also proposed by Hallale (2002) using stream purity as the y-axis instead. This approach was later modified and improved by Saw et al. (2010). On the other hand, Bandyopadhyay (2006) proposed an equivalent technique using an alternative mapping using mass load as the x-axis and concentration as the y-axis to give a waste composite curve. In addition, algorithmic approaches have also been proposed, such as the well-known Problem Table Algorithm (PTA) described by Linnhoff et al. (1982), and more recently, the cascade technique of Manan et al. (2004). All these techniques enable targets and Pinch Points to be identified. Subsequent problem decomposition is possible since, according to the **Golden Rule of Pinch Analysis**, areas above and below the Pinch Point can be solved separately as independent sub-problems. Detailed network design for allocation of streams can then be accomplished through related techniques, such as the **nearest neighbour algorithm** (NNA) developed by Prakash and Shenoy (2005).

## 3. Beyond Heat Pinch

Subsequent extensions of Pinch Analysis have since been developed using analogous quality indicators; in the same manner that mass Pinch Analysis is derived directly via analogies between heat and mass transfer. Due to space constraints, this paper does not attempt to do a comprehensive review of such extensions. Instead, Table 1 simply serves to illustrate the scope of possible Pinch Analysis extensions for a wide variety of problems (other than the conventional Thermal Pinch application).

*Table 1: Various non-conventional problems addressed with Pinch Analysis*

| Quantity | Quality | Problem | Reference |
|---|---|---|---|
| Mass | Concentration | Mass separating agent (MSA) reuse | El-Halwagi and Manousiouthakis (1989) |
| Mass | Concentration | Refinery hydrogen allocation | Alves and Towler (2002) |
| Mass | Concentration | Water reuse/recycle | Wang and Smith (1994) |
| Mass | Property | Property integration | Kazantzi and El-Halwagi (2005) |
| Mass | Concentration | Biorefinery design | Shenoy and Shenoy (2014) |
| Energy | $CO_2$ intensity | Energy sector planning | Tan and Foo (2007) |
| Energy | Water footprint | Energy sector planning | Tan et al. (2009) |
| Energy | Land footprint | Energy sector planning | Foo et al. (2008) |
| Energy | Transformity | Energy sector planning | Bandyopadhyay et al. (2010) |
| Energy | Inoperability risk | Energy sector planning | Tan and Foo (2013) |
| Energy | Energy return on investment (EROI) | Energy sector planning | Walmsley et al. (2014) |
| Money | Time | Financial planning | Zhelev (2005) |
| Product units | Time | Supply chain planning | Singhvi and Shenoy (2002) |
| Mass | Time | Biomass supply chain management | Ludwig et al. (2009) |
| Process units | Time | Batch production scheduling | Foo et al. (2007) |
| Workers | Time | Task scheduling | Foo et al. (2010) |
| Process units | Time | Production planning in small and medium industries (SMIs) | Lim et al. (2014) |
| $CO_2$ | Time | Carbon capture and storage (CCS) planning | Ooi et al. (2013) |
| Electricity | Time | Stand-alone energy system design | Mohammad Rozali et al. (2013) |

The examples listed are grouped based on the driving force. In addition to chemical engineering applications such as mass integration (El-Halwagi and Manousiothakis, 1989), water integration (Wang and Smith, 1994), property integration (Kazantzi and El-Halwagi, 2005), refinery hydrogen integration (Alves and Towler, 2002) and ethanol integration (Shenoy and Shenoy, 2014), other novel applications have emerged in allied fields. In particular, it can also be seen that many recent variants belong to two main groups of applications:

- Energy planning problems using various quality measures

- Problems with time as the quality index to define directionality in the system

Literature trends suggest possible further developments in these areas in coming years.

## 4. Emerging Applications of Pinch Analysis

Different emerging applications of Pinch Analysis as well as new domain for potential applications are discussed in this section. Promising areas include as follows.

### 4.1 Multiple-Objective Pinch Analysis

Pinch Analysis was originally developed for single objective optimization problems. However, in many fields, this is important to consider multiple objective functions or to take decision under multiple criteria. It is important to extend existing methodologies to handle multiple objectives in pinch analysis frame work. Preliminary work in this area has been attempted by Geldermann et al. (2006), but no major breakthrough has been reported to date.

### 4.2 Cost optimal design on isolated energy systems and subsidy planning

Isolated energy systems are extremely important to evolve localised sustainable energy systems. There are numerous methods proposed in the literature to design isolated energy systems. Recently, techniques of pinch analysis are extended to address design issues of isolated energy systems. This approach is limited to physical sizing of various components. However, it is important to consider economic aspects as well as issues related to providing subsidy for design and operation of isolated energy systems. In addition, design methodologies to account for cyclic load fluctuations may be developed further, based on such initial work as the Electric Systems Cascade Analysis (ESCA) technique (Ho et al., 2014) and Power Pinch Analysis (PoPA) technique (Mohammad Rozali et al., 2013).

### 4.3 Incorporation of uncertainty in production planning

Optimization under uncertainty has been recognized for many years as an essential aspect for practical problems (Sahinidis, 2004). Techniques of Pinch Analysis have been extended to address various production planning problems, for example, supply chain management, process scheduling, human resource planning, isolated power system, etc. (see Table 1). These techniques are applicable for deterministic problems. However, in reality, these problems are stochastic in nature. It is important to develop techniques to consider uncertainties and reliability in pinch analysis frame work. One possible direction is the development of a comprehensive sensitivity analysis framework based on pinch analysis, which can be analogous to sensitivity analysis techniques used in conjunction with mathematical programming (Seferlis and Hrymak, 1996). The work of Diamante et al. (2013) on CCS planning provides some insights on potential developments in this direction.

### 4.4 Resource conservation networks with different quality indicators

As apparent from Table 1, that recent efforts are directed towards extending pinch analysis methodologies for problems with multiple qualities. For example, resource conservations in batch processes consider time as a directional quality along with temperature (for energy conservation), concentration (for conservation of MSAs), or properties (for material recycling), etc. Similarly, concentration and pressure are two qualities for optimal design of hydrogen conservation network in refineries. Such problems with multiple qualities cannot usually be solved using sequential approaches. In general, different qualities are to be accounted for simultaneously.

### 4.5 Pinch Analysis for Risk and Safety Management

Aside from the risk pinch approach using inoperability that was proposed by Tan and Foo (2013), a recent Mathematical Programming formulation for selection of safety measures in process industries has been proposed (Ishizaka and Labib, 2011). The latter work, coupled with the aforementioned equivalence of such models with pinch analysis, strongly suggests the potential for a pinch-based approach to selecting safety measures for process plants under budget constraints.

### 4.6 Hybrid Methods

It is notable that pinch analysis and mathematical programming methods have evolved into complementary approaches to problem-solving for thermal integration applications (Klemeš and Kravanja, 2013). The trend suggests promising directions in the development of hybrid techniques that utilize the relative advantages of both approaches. In addition, there is some potential in use of pinch analysis in conjunction with P-graph methodology, which is based on a series of papers outlining fundamental axioms (Friedler et al., 1992a), solution algorithms (Friedler et al., 1992b) and maximal structure generation

(Friedler et al., 1993). A recent review by Lam (2013) likewise highlights the diversity of recent applications of P-graph methodology, which seems to parallel the diversity of recent Pinch literature.

## 5. Conclusions

This paper has described prospects for the extension of the Pinch Analysis methodology to new problem domains relevant to contemporary sustainability issues. Such problems present rich opportunities for the diversification of process integration research into non-conventional areas. Nevertheless, these potential applications are all unified by a common underlying principle, whose roots date back to the earliest thermal pinch works. In all cases, flows must be subject to a quality metric that provides a “driving force” within the system. In addition to those domains described here, further opportunities will inevitably arise as researchers uncover analogous problem structures that allow pinch analysis principles to be employed. Promising directions include methodological extensions, such as multiple-objective and multiple-quality index Pinch Analysis, as well as hybridization of Pinch Analysis with allied optimization techniques. On the other hand, there are also potentially novel applications of Pinch Analysis, such as optimal planning of stand-alone energy systems, production planning under uncertainty, and risk and safety management.

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