

Review

A Critical Review of Pinch Technology and Other Methodologies for Designing Industrial Symbiosis

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Abstract

Creating industrial symbiosis can improve resource efficiency by creating technically feasible and economically viable exchanges of energy, water, materials, by-products, and services among firms. Pinch technology, originally developed for process integration, systematically optimizes heat, material, water, by-product, and supply-chain exchanges, as well as emissions minimization. It is also suitable for inter-firm industrial symbiosis. However, there are some other specific methodologies that are used for the design of industrial symbiosis. They are more favored than Pinch technology. This paper reviews and compares the benefits and limitations of Pinch technology with other methodologies that have already been used in industrial parks to transform them into symbiotic systems. Sources are selected based on PRISMA. Many projects used for internal process integration showed great performance with increased efficiency. But that is rare in the design of industrial symbiosis. The analysis and results of integration support the use/reuse of energy (heat exchange), materials (mass exchange), products (goods exchange), minimization of environmental footprints, and supply chains. Pinch technology offers technical solutions for designing common exchange systems between companies that want to implement industrial symbiosis. Many updates in Pinch technology, like R-curve analysis, total site integration, and exergy-based analysis, have improved its usage. Solutions can increase flexibility. This symbiosis can have a better response to fluctuations. Furthermore, we propose an algorithm for implementing Pinch technology in industrial symbiosis design. It combines different types of Pinch technologies.



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Keywords

Industrial symbiosis; Pinch technology; process integration; waste exchange; barriers

1. Introduction

In recent years, industrial symbiosis (IS) has been the focus of managing industrial parks (IPs). The main reasons for this are the high potential for reducing production expenses and improving system sustainability. IS represents a concept that involves different companies to collaborate and share resources to maximize the use of the available resources from all participants (internally) before being supplied from outside of IPs [1].

IS systems create sustainable and mutually beneficial relationships between industries. This results in increased efficiency and reduced waste generation. IS involves identifying and using one company's waste products as resources for other companies. Moreover, IS supports sustainable development by adopting circular economy principles. It minimizes the dependence on primary resources. Furthermore, it stimulates economic growth due to cost savings and better competitiveness.

IS implementation supports waste exchange programs and encourages companies to cooperate better with each other. That makes a closed-loop system where resources are continuously repurposed and recycled [2]. These closed-loop systems positively impact the environment. They reduce the carbon footprint and provide economic benefits. IS encourages sharing innovation and knowledge among other resources. These result in novel solutions and processes, improving the overall efficiency and sustainability of industrial ecosystems.

The main idea of IS is not limited to the physical exchange of raw materials. It also supports sharing infrastructure such as energy and water utilities, as well as implementing environmentally friendly practices and technologies. These strengthen symbiotic relationships between companies. Moreover, IS can be taken as a good model for sustainable industrial development. Furthermore, these can attract investments and promote a positive reputation within the industry and local community [3]. This approach maximizes the economic and environmental benefits of all its participants [4]. The concept of IS imitates natural ecosystems, where the waste of some organisms is used as feeding resources for other organisms [5]. Material flow analysis (component analysis) can be used to analyze these processes and support the creation of eco-industrial parks (EIP) or regional IS.

Business networks of interconnection employ several mechanisms, which include recycling waste, remanufacturing, and the transformation of by-products or waste into valuable resources for other industries [6]. It promotes the concept of "waste as a resource". Factors such as the complex nature of logistics, disparate industry objectives, and limits on the recycling and remanufacturing of waste become risks in investments. However, detailed planning, collective efforts, and supportive policies minimize these obstacles [5].

Successfully realized ISs are the result of using effective methodologies for their design. The approach that is used depends on the priorities of projects. Implementing ISs typically involves existing production processes and companies. It is rare to establish new IPs. That is because of the significant investment costs. Therefore, they can be either retrofit designs or completely new

designs. Retrofit designs update the current system with additional equipment to improve process efficiency. On the other hand, new designs involve developing a completely new system. Another important factor for the design of IS systems is the use of “total site” or “partial” improvements. It is important to understand the process of “total site integration”. That refers to the complete integration of systems between all interested parties. If improvements are made only on one site or a few parts of the system within a single company, this is considered partial integration.

The literature reported the following methodologies for the design of ISs: Material and Energy Flow Analysis [7], Resource Mapping and Matching [8], Industrial Ecology Tools [9], Stakeholder Engagement and Collaboration tools [10], and Pinch technology integration [11]. Unfortunately, the implementation of Pinch technology for the design and partial or total optimization of IPs in the form of IS is not widely adopted. This can be a result of many different factors. The objective of this study is the identification of the potential of Pinch technology in fostering IS within IPs, compared to other used methodologies. Moreover, it aims to detect obstacles and barriers to that condition.

The main question is why Pinch technology is not widely accepted in the design of ISs, what are the differences between currently used methodologies and Pinch technology, and what the benefits in design ISs with Pinch technology are. Furthermore, it should answer how Pinch technology can solve many technical and economic barriers to establishing IS. Besides, there are issues that Pinch integration cannot solve. Moreover, this work suggests a new approach that uses a combination of different Pinch technology types for the whole system integration.

Lawal et al. [11] made a literature review of tools that are useful for designing ISs and EIPs based on publishers and publishing years. That review mentions all possible tools at the time of its publication. It is completely different than this one in terms of aims and objectives. It summarized IS tools and showed optimal integration possibilities. Furthermore, it omits some tools.

This paper gives some basic characteristics of different types of IPs. It describes methodologies that are actively used in the design of ISs. Review different Pinch technologies and give the main possibilities in using them for IS, with their gaps compared to the other previously described methodologies.

2. Review Methodology

This review paper is based on information from peer-reviewed published literature in ScienceDirect, Scopus, Springer, and Google Scholar databases. It uses literature published in the last 10 years. The primary search for literature is made for “industrial symbiosis” (Figure 1). From that literature, sources are filtered to include those that contain a methodology used for the design of IS (“Industrial symbiosis design methodology”). Literature that describes any methodology is selected for further consideration. It is selected by the methodology that is used for design as separate filters (“MILP”, “ABM”, “MEFA”, “LCA”, “network analysis”, “emergy analysis”, and “exergy analysis”). On the other hand, Pinch technology literature is searched separately. The first filter selects sources that include known Pinch technology methodologies (Figure 1). The next filter of sources is related to containing information that describes the Pinch technology used for the design of IS, and IS case studies. This literature search includes the main principles used in different types of Pinch technology. This is used for further finding benefits and issues related to the design of ISs. Based on this information, a comparison is made between methodologies, their issues, and information about experience in real case studies for IS design. It must be mentioned that many of

the finally selected sources overlap in filter criteria (mentioning a few methodologies in the same, including Pinch technology). Some sources after the main filtration are not taken into consideration due to the fact that they did not contain relevant information for this review paper.

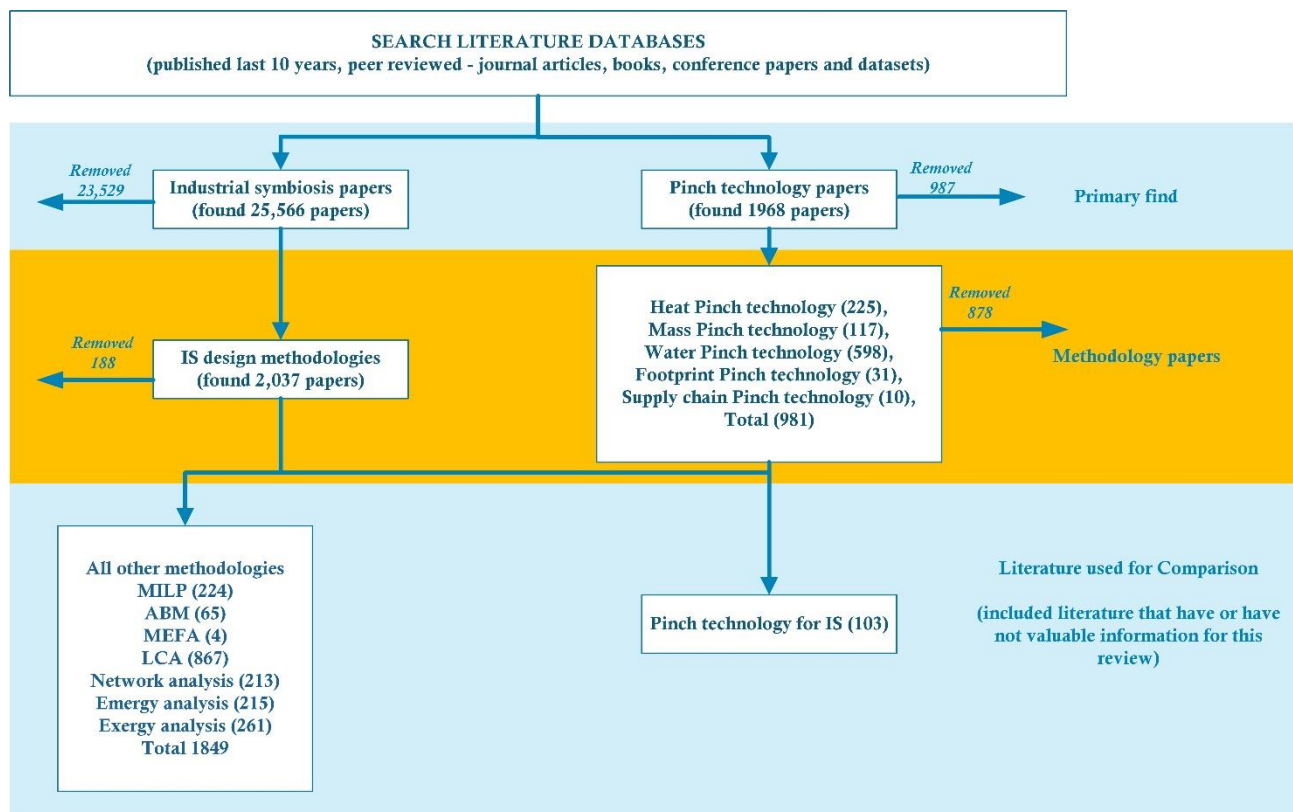


Figure 1 Search and selection of literature for review based on PRISMA.

3. Industrial Parks, Industrial Symbiosis and Barriers

IPs are specialized areas only for industrial activities. They are typically located outside of urban areas to minimize environmental and social impact. IPs are categorized by the types of industries located inside them, such as manufacturing, processing, or research & development. The organizational system of IPs can be privately owned & operated, or government-managed facilities. One of the main considerations of IPs is the minimization of ecological footprints and the promotion of environmentally friendly practices. Here are included initiatives for minimizing energy consumption, effective waste management, and emission reductions. Therefore, IPs often include green infrastructure and sustainable design principles. IPs can take the form of technological parks, EIPs, Positive Energy Industrial Parks (PEIP), special economic zones, and free-trade zones.

(1) Technological parks are areas dedicated to research and development in specific scientific fields such as biotechnology or information technology [12]. Their primary task is to facilitate the exchange of ideas, resources, equipment, and individuals. Furthermore, the credibility of these parks ensures access to reliable resources and establishes connections with domestic and international business networks [13].

(2) EIPs and PEIPs create a closed-loop system by integrating multiple industries and utilizing waste by-products as raw materials [14]. EIP consists of a group of manufacturing and service businesses that work together to improve their environmental, economic, and social performance.

The collaboration in the management of environmental and resource issues involves green design for infrastructure and plants of the park (both new and retrofitted), cleaner production and pollution prevention, energy efficiency, and cooperation between companies. EIP attempts to achieve positive impacts on neighboring communities with its own development [15]. The development of EIPs through the implementation of IS in IPs has become a standard practice [16]. According to Ernest A. Lowe [15], EIPs must have: 1. a multitude of exchanges of by-products or networks of exchanges; 2. numerous recycling business clusters; 3. a group of environmental technology companies; 4. a group of companies that manufacture environmentally friendly products; 5. an IP designed around a specific renewable source, such as solar energy; 6. a park that features environmentally friendly infrastructure or construction; 7. a mixed-use development that incorporates industrial, commercial, and residential components.

EIPs might have a higher development cost than traditional parks. That depends on the design choices made for a certain project [15]. The design of processes, site preparation, infrastructure features, construction methods, and building design elements may result in additional expenses. IS, on the other hand, refers to the collaboration and exchange of resources, materials, and by-products among industries within an IP or geographical area. PEIPs are a specific type of IP that focuses on promoting clean and renewable energy technologies, reducing carbon emissions, and achieving sustainability goals [17, 18].

Collaboration may be a challenge when an EIP consists of companies from diverse countries and cultures. The emerging sustainable economy presents several clusters that focus on significant environmental and energy industries. These clusters include Agro-EIPs, Resource Recovery Parks, Renewable Energy EIPs, and Green Petrochemical Parks.

(3) Special economic zones [19] are areas where they implement specific economic regulations to attract foreign investment and stimulate trade. These zones often require significant investment from the government. In some cases, the government may choose to manage an EIP model.

(4) Free-trade zones are places where goods can be imported, stored, manufactured, and exported without being subject to customs duties or taxes [20].

The components and infrastructure of IS can be determined by waste and material exchange infrastructure, management and service infrastructure, technology and energy components, and regulatory and standard requirements. The core requirements include exchange systems for material and energy resources (within the park and with external partners, cascade water supply systems, integrated wastewater treatment facilities for park residents, and shared utilities, including energy, water, electricity, and heat distribution systems and joint operation facilities [water treatment and gas cleaning equipment] [21]. The waste and material exchange infrastructure has waste and by-product exchanges that enable resource conservation [22], facilities for reusing waste from one industrial process as a utility for another, either in raw form or via regeneration facilities [23], and industrial recycling systems with supply chain infrastructure that allows firms to participate in material recovery [24].

The management and service infrastructure have common management systems for material and energy resources through identified focal points or anchor residents; shared services for fire safety, transportation and other supplementary activities; and infrastructure for administrative, transport, waste management, energy and water supply systems [21]. Technology and energy components support the use of renewables, water optimization, and recovery, as well as symbiotic systems for recovering waste and material flow [25]. Regulations and standards are required for ISO

management systems; land allocation for greenery, traffic works, and public utilities conforming to national construction standards; minimum number of enterprises required to participate in IS; and arrangements that facilitate symbiosis through strategic positioning and technical possibilities [24]. Based on these, the following barriers can be determined and categorized into seven dimensions: social, economic, policy, management, technological, geographical dimensions, and intermediates [26].

Economic barrier-A key economic barrier is the lack of a clear business case for IS, making it difficult for companies to justify joining resource sharing networks [27]. This is worsened by high upfront costs for infrastructure and equipment, which can be prohibitive [28]. Financial barriers concern funding and specific investments [29], as companies often struggle to secure adequate financing for high investment costs.

Regulatory barrier-Regulatory frameworks often restrict or prohibit companies from exchanging waste, wastewater, and hazardous materials, preventing IS [30]. A key challenge is the lack of specific legal provisions for IS, which makes it difficult for companies to comply with environmental regulations and implement these practices. Legal limits on waste disposal can prevent waste from being classified as by-products and reused as raw materials by other firms. Regulatory complexity hinders new processes' adoption and makes it hard for businesses to meet environmental standards.

Communication barrier-A major barrier is the lack of detailed qualitative and quantitative data on residue streams, which prevents companies from identifying symbiotic opportunities. This is worsened by the absence of information systems on material inputs and outputs. This limits the exchange of by-products between companies [31]. Communication barriers concern all issues related to the sharing of information between potential IS partners. Companies often hide or withhold information, restricting the exchange of data on the utility, origin, and availability of waste by-products [32].

Social and organizational barriers: Social and organizational barriers are focused on trust, communication, cooperation, and readiness to change. Low levels of trust, communication, and cooperation delay waste exchange initiatives and the development of symbiotic networks. A key barrier is resistance to change in organizational culture, which limits participation in collaborative relationships. Companies often struggle to modify processes and adapt them to new inputs, such as recovered waste or scraps [33]. Insufficient organizational support for integration, coordination, and communication further inhibits effective IS governance. Competition, weak commitment, low environmental awareness, and general resistance to changes often act as barriers. Many companies remain in the early stages of maturity and fail to recognize the potential benefits, with reduced participation in collaborative activities.

Deficits in administrative and governance capacity significantly slow the implementation of IS. A major governance challenge is insufficient administrative capacity, including weak organizational support for integration, coordination, and communication. This lack of institutional support is a key barrier that prevents companies from engaging in symbiotic relationships successfully [28].

Technical/technological barriers-The most important barriers that involve the physical exchange of materials, energy, and goods are technical and technological barriers. The complexity of symbiosis demands deep knowledge of material properties and cross-industrial cooperation, creating technical challenges that require more holistic thinking by regulators and industry [34]. Key barriers include the lack of suitable technology or sufficient capacity. IS projects often require technological changes that challenge participants, forcing them into transitional stages and

adaptations. In heavy industrial areas and mixed industrial parks, technical barriers have historically been among the most significant obstacles [35]. Waste exchange networks also struggled with limited technical expertise and knowledge, restricting their role largely to providing online information. The infrastructure and equipment that are needed are additional obstacles due to costs that may be unsustainable for many firms. Companies also face readiness challenges, such as difficulties in adapting processes to use recovered waste or scraps as input. The flexibility of different systems, organization of the common exchange system, maintenance, the quality and the quantity of supply/demand are very common technical barriers in IS.

Geographical barrier-Additionally, in IS, the transport of goods between companies can be a barrier by itself. That is especially notable for sensitive by-products and waste (short lifetime of source) [36]. A specific case is heat transfer. Heat can be transferred only over short distances with higher efficiency [18]. Otherwise, there is a lot of heat loss. This is a so-called geographical barrier.

4. Methodologies for Designing Industrial Symbiosis and Total Site Integration

IS design can be done using different methodologies. LIAISE COST action report summarized methodologies that can be used in the design (identification, evaluation, and selection of solutions) [36, 37]. They suggested flow analysis, emergy analysis, exergy analysis, Life Cycle Assessment (LCA), network analysis, and process integration (PI) tools. Moreover, methodologies can be divided by their purpose or step in the implementation of IS as “assessment and evaluation” methodologies [38], “optimization and mathematical modeling” [39], “design frameworks and step-by-step approach” [33], “platform and database development” [27], and “collaborative and participatory” methodologies [40]. This work focuses on technical solutions for IS. They are the basis for further calculations, agreements, regulations, and decisions in the implementation of IS. So, technical solutions can be designed using assessment and evaluation methods as well as mathematical modeling/optimization methodologies.

Evaluation and assessment methods are fundamental to IS design. They offer systematic ways to measure and analyze network performance in multiple dimensions. Practical tools include input-output matching for analysis of input types and output specifications. Furthermore, they include stakeholder analysis for understanding multi-party relationships and material and energy flow mapping. Modern comprehensive approaches integrate management and technical methods, such as environmental impact calculation, waste management accounting, and optimization assessment, to create holistic evaluation frameworks for IS networks [41]. Input-output analysis is an assessment approach that includes Ecological Input-Output Analysis (EIOA). EIOA offers a comprehensive model that captures the economic, environmental, and social behavior of industrial ecosystems and their detailed interrelationships [10]. It tracks economic, material, and energy flows for comprehensive impact analysis in all three sustainability dimensions [10]. Complementing these, Material Flow Cost Accounting (MFCA) provides an economic and ecological appraisal method that evaluates environmental efficiency and supports planning, control, and decision-making for IS design [10].

Mathematical optimization and modeling provide powerful tools for designing IS networks by systematically finding configurations that minimize waste, costs, and environmental impacts. Mixed-integer linear programming (MILP) is a core method for large and complex problems in IS and PI [39]. Modern implementations couple MILP with database frameworks and waste exchange identification algorithms to minimize non-recycled waste [10]. However, fully integrated industrial

ecosystems often exceed the capabilities of conventional optimization. Multi-objective problems can become too complex for traditional methods, prompting the use of hierarchical-Pareto and robust optimization to address both detailed technical issues and full network complexity [10]. The limits of standard MILP have also led to bilevel optimization, non-linear deterministic optimization, and stochastic methods for specific processing aspects (Table 1).

Table 1 Comparison of methodologies for the design of IS and Pinch technology: advantages and disadvantages.

Methodology	Limitations and comparison with Pinch technology
MILP	It creates a mathematical model for the analyzed system. Sometimes, they can be very complex and can show high deviations from the real system. Pinch technology partially uses MILP in economic optimization of the created HENs and MENs.
ABM	ABM enables the study of complex cooperation dynamics among firms in IS, using behavioral science theory to model the planned behavior of waste suppliers and processors across all implementation stages [42]. Its bottom-up approach, where system-level properties emerge from interactions among agents, makes ABM especially useful for analyzing complex systems that analytical models alone cannot capture [43]. This methodology is more focused on relationships between integrated companies.
MEFA	Many studies on IS tools do not define MEFA clearly nor explain its specific applications. They do not highlight the broader input-output analysis of economic or material and energy flows [44]. This indicates that MEFA is less widely understood and less widely applied than other methods. Moreover, IS research often prioritizes LCA over MEFA, suggesting that practitioners view LCA as more suitable or accessible for many evaluations [38]. Consequently, while MEFA is valuable for flow analysis, it may need to be combined with other methods to fully support the design of symbiosis.
LCA	Products based on circular economic principles do not always minimize environmental impact. LCA studies show that circular designs can have higher overall impacts than non-circular ones due to complex material recovery processes [45]. In IS, LCA limitations become sector-specific, making it less suitable for sectors [41]. The high complexity of databases and the lack of suitable interfaces for integrating LCA data into planning processes further restrict its practical use in factory planning and design [46].
Network analysis	It is limited in its generalizability. Context-specific findings may not be applicable to other regions or sectors. Poor data availability and quality can limit analytical depth. Interpretations of network dynamics, green culture, and the roles of firm size, sector, and innovation may reflect subjective bias. Network analysis offers only a static snapshot, ignoring how networks evolve over time. Complex interactions in ecological network theory risk being oversimplified [47]. Complex network analysis alone cannot yield sufficient environmental, economic, and technical performance metrics for industrial clusters, so additional indicators are needed to assess performance and improvement opportunities [48].

Emergy analysis

It faces questions of quantification, uncertainty, and sensitivity common to holistic approaches focused on industrial activity [49]. Emergy transformations of energy, materials, or capital vary by region and come from diverse sources. It carries the risk of incorrect accounting [50]. Emergy analysis assumes all inputs to be positive, but there are cases where inputs are harmful negative outputs [51]. This method poorly captures potential environmental impacts [52] and neglects pollution emissions from the system operation [53]. Boundaries may be limited to direct industrial process resources, omitting key primary energy and other resource inputs [54]. It was originally designed for ecological systems; emergy analysis requires adaptation of its indices to better fit industrial sustainability analysis. It lacks technical solutions for symbiotic systems. Footprint Pinch can be replaced or supplemented by this methodology.

Exergy analysis

Exergy analysis can reveal more potential process improvements than Pinch analysis. Many of them are not practically achievable [55]. It is heavily used in the engineering interpretation of balances. That makes it harder to apply than Pinch analysis [56]. Exergy analysis often indicates theoretical improvement potentials [57]. Pinch analysis can be applied more easily and communicated to non-technical staff [55]. However, it is limited to heat flows and temperatures. It does not integrate heat exchange networks with other process variables, such as pressure and composition. It cannot systematically identify ways to value the available energy streams for process improvement [57].

The primary advantage of exergy analysis over traditional Pinch analysis lies in its comprehensive approach to energy quality assessment [58]. The exergy method allows us to consider both quantitative and qualitative characteristics of thermal processes. The Pinch method is based on a change in enthalpy, which does not consider the qualitative characteristics of energy [59]. The method of exergy Pinch analysis allows formulation and justification of specific design measures aimed at increasing energy efficiency and can identify unused exergy and determine the part in which the loss occurs [60].

Agent-Based Models (ABM) offer well-suited analysis mechanisms such as life cycle impacts and network properties like resilience [61, 62]. They can assess geographical effects on symbiotic relationships through multi-objective optimization while validating IS performance indicators. ABM is well suited for the development of real-time “what-if” strategies [63]. These models help researchers anticipate the effects of small behavioral changes caused by agents or changes in social, natural, or economic subsystems [64]. They support the assessment of technological and organizational design choices in symbiotic networks and help identify the transition pathways that are likely under different intervention scenarios [42] (Table 1).

Flow analysis (Material and Energy Flow Analysis [MEFA]) is a systematic method used to provide detailed quantitative descriptions of material and energy flows per sector, indicating critical sectors in terms of resource consumption, waste generation, and identification of the most significant flows [65]. MEFA allows researchers to map and quantify metabolic flows in systems with their sectors, providing essential information to understand resource utilization patterns [66]. This methodology tracks the input, output, and transformation of specific material and energy resources through a

system of interest, using existing business practices, databases, inventories, and surveys as its primary source of data [67]. This approach has proven to be valuable for improving the understanding of economic dimensions and exploring opportunities for efficiency and recovery in various systems [68] (Table 1).

MEFA, combined with LCA, assesses the environmental burdens of material flows throughout life cycles, revealing net gains and shifting burdens in symbiotic relationships [69]. Network analysis with MEFA maps material, financial, and relational interactions between IS actors [67]. Input-output analysis, including Leontief matrices, is a key industrial ecology tool in computable general equilibrium models [70]. Waste flow analysis, combined with MEFA and production matrices, supports models such as the IS “system waste flow metabolism analysis” [71]. “Dynamic decision support systems” integrate Mass Flow Analysis (MFA) and LCA to track by-product flows and quantify levels of symbiosis in EIP [72] (Table 1). Substance flow analysis and ABM, often coupled with system dynamics and hybrid modeling, further extend MEFA applications [70]. The design for the environment sets MEFA together within integrated industrial ecology, promoting eco-efficiency, dematerialization, and analysis of urban/industrial metabolism [70].

Emergy analysis is a quantitative method that values resources, services, and commodities in a common unit of solar energy. It enables the comparison of all resources [49]. Moreover, emergy represents the total available (embodied) energy required directly or indirectly in a system [52]. This method calculates flows of material, energy, information, and value in natural and socio-economic systems using the value of emergy [53]. It is especially useful for evaluating the sustainability of industrial ecosystems through emergy-based indices that capture waste treatment, recovery, reuse, and recycling while accounting for all material and energy flows. These indices quantify environmental, economic, and overall sustainability performance [10]. Applications show that urban-IS systems can reduce total emergy consumption by 12% when material flow analysis is combined with emergy analysis [73] (Table 1). This method has also been used to optimize eco-industrial park operation under uncertainty, identifying Nash equilibrium solutions that balance profit and sustainability [74].

Exergy analysis defines the maximum work that is accessible when a resource becomes in thermodynamic equilibrium with its surroundings through reversible processes [57]. In industrial ecology and symbiosis, exergy analysis supports the shift from linear to closed-loop systems, turning material and energy flows once treated as waste into resources for existing or new processes. Its main strength is to express all physical phenomena in terms of a single form of energy. It is based on natural or artificial resources, processes, or emissions. They can be consistently evaluated from an exergy perspective [75]. It also assesses industrial processes through exergy balances, quantifying and tracking inefficiencies to identify improvement opportunities with all relevant variables such as temperature, pressure, and composition [57]. In IS, this is crucial, because in all material and energy transformations, exergy is lost through irreversibility [75] (Table 1).

LCA assessment is one of the most widely used tools, providing a comprehensive method for quantifying all materials and energy used in industry. It identifies IS opportunities and measures environmental impacts [41, 76]. The cradle-to-gate approach in LCA applies a life cycle perspective that looks beyond individual facilities to assess environmental impacts across all stages of the product life cycle. Since IS relies on cooperation between multiple companies, the LCA system is crucial to avoid pollution transfers between plants and the shifting of burden between impact categories [73]. LCA is widely used to confirm the environmental benefits of IS networks and to

guide the valorization of by-products [77] (Table 1). It enables a multilevel assessment of environmental performance for individual or combined waste-resource exchanges [32].

Network analysis uses quantitative methods to study the physical and social interactions between entities in a system. It is presented as a network of nodes (entities) and links (relationships). It can model links such as material and energy flows, information, financial transactions, and social interactions. In the IS field, four related methodologies are used: social network analysis, stakeholder value network approach, ecological network analysis, and food network analysis. This methodology analyzes the structural characteristics of symbiotic networks, including size (nodes and relationships), density, clustering coefficients, information transmission speed (characteristic path length), centrality, and overall complexity (Table 1). These features reveal local and global properties of symbiosis networks and guide the design and construction of effective symbiotic systems [78].

PI contains various tools based on Pinch technology (Appendix 1). Pinch analysis has been adapted for the integration of waste and energy in IS sites. It promises benefits in IS engineering design. At the operational level, simulation-based optimization uses infinitesimal perturbation analysis. It can determine optimal production policies and stock levels for IS networks [79]. Integration with Pinch technology can play a vital role in IS design by identifying opportunities for heat exchange and energy optimization between different processes and industries. Pinch technology provides a systematic approach to analyze energy flows and identify potential areas for heat recovery and optimization [11].

Continuous processes in chemical plants, refineries, and power plants can be easily integrated [80]. Pinch analysis is particularly useful because of its steady-state nature. The advantages of Pinch analysis for continuous processes include the ability to identify optimal heat integration possibilities, to minimize energy consumption, and to reduce operating costs. Additionally, Pinch analysis allows for the identification of minimal hot and cold utility requirements as well as the determination of optimal process heat exchange targets.

Pinch analysis in continuous processes effectively optimizes energy usage, minimizes waste, and improves overall process efficiency. This method is easily applicable to continuous processes because of their consistency and predictability. This allows for more accurate and reliable analysis. The first step in the integration process is data collection. In this step, values of temperatures, flows, and other parameters of interest for possible heat exchange between streams are collected. The collected data are used for the design of composite curves. The method creates a chart of hot and cold composite curves based on hot and cold streams. That chart is used to identify the Pinch temperature and the heat recovery potential. Both curves are used to create a Grand Composite Curve (GCC). The construction of a GCC is used for the analysis of overall energy integration opportunities within processes where selected streams are active. As a result of heat integration with Pinch technology is the Heat Exchanger Network (HEN). That is, a system of heat exchangers that connects selected streams for heat transfer between themselves. The design is based on mathematical optimization techniques or graphical methods. This solution maximizes heat recovery and minimizes utility consumption (fresh utility supply) [81].

On the other hand, batch processes are characterized by discrete, non-continuous operations where production occurs in batches or cycles. These processes present unique challenges for the application of Pinch analysis due to the variable nature of streams. PI of batch processes is related to time-dependent streams and the specific time of heat recovery. That is the main difference from

continuous processes. Batch processes show changeable operating conditions. That makes it difficult to use steady-state assumptions. Optimal timing for heat recovery within batch processes is crucial. That impacts the effectiveness of energy optimization and heat exchange. Very important characteristics of batch processes are repeatability or non-repeatability of streams/processes and formation of specific time slices (process sequences) [82]. HEN design for batch processes requires a dynamic approach for the time-dependent nature of these operations. The repeatable time slices refer to process steps that occur identically in each batch cycle. This allows for more consistent heat integration. Moreover, the non-repeatable time slices correspond to specific process steps that occur intermittently or with variations between batch cycles. These time slices in batch processes are prerequisites for successful Pinch analysis of the process dynamics and the identification of opportunities to capture and utilize heat across repeatable and non-repeatable time slices. Furthermore, the complexities of heat recovery based on timing within batch processes are essential to achieve effective energy optimization. Considering the evolving temperature profiles and heat transfer requirements throughout the batch cycle, engineers can strategically plan and implement heat recovery strategies to maximize the overall energy efficiency of the batch process. Solutions explore strategies for energy storage, intermediate heat exchange, and flexible utilities used to optimize energy utilization during batch operations [83-87]. The application of Pinch analysis techniques is to identify the minimum energy requirements for each batch and optimize energy usage in multiple production cycles.

Moreover, there is Pinch technology based on material recovery (mass Pinch technology), minimization of emissions (footprint Pinch technology), optimization of supply chain (supply chain Pinch technology), and optimization of water and wastewater (water Pinch technology). All these methodologies are like heat Pinch technology, and their main characteristics are explained in the table in Appendix 1.

All these developed methodologies of PI with Pinch technology have a positive impact on IS design. For a better understanding of the benefits of Pinch technology and the certain issues of other methodologies, the comparison table is prepared. Table 1 compares Pinch technology with other IS design methodologies. There are also limitations of the given methodologies and Pinch technology.

5. Pinch Technology in Industrial Symbiosis

Pinch technology was primarily invented and applied in production systems between different production processes (in the same factory). Moreover, it can be used between different factories (companies), within the IP, and even at the regional level. However, IS has different levels of application. It can be applied between companies inside the same IP, where the waste and by-products of one company are utilized as input by another company. This type of symbiosis is “on-site” IS. The wider symbiosis can integrate multiple IPs or even entire regions, where the by-products and waste streams of one industry are utilized as input by another industry, creating a closed loop of resource exchange and minimizing waste generation. And finally, IS can be applied at a national or global level, where countries or regions collaborate to optimize resource utilization and waste management on a larger scale. The last two levels are performed between companies in different places. That kind of IS can be called “virtual” because they are not visible as IS participants. Therefore, integration of the system with Pinch technology can only be performed on on-site IS,

with the exception of the supply chain Pinch technology. The implementation of Pinch technology requires a deep understanding of processes and systems involved, as well as accurate data on heat and mass flows (shared information) [88].

5.1 Realized Symbiotic Systems Based on Pinch Technology (Case Studies)

Many realized IS projects can be found worldwide. But very few IS projects use Pinch technology for design (Table 2). One of those projects is the Map Ta Phut Industrial Area, 150 km away from Bangkok. Matsuda et al. [89] describe their design using the R-curve. Utilities used in the IP are distributed mostly by distribution companies. These types of utilities come from boilers and steam turbines. The complete situation of utilities is calculated on the basis of the R-curve analysis. Furthermore, the surplus heat and cold in processes are analyzed with TSP integration. The composite curves determined surplus heat in the exhaust, low-pressure steam recovery, and a combination of very low-pressure steam with hot water. In addition, hot oil streams are included as heated by exhaust gases. In parallel with the Map Ta Phut IP analysis, they analyzed the Chiba IP in Japan [89]. Savings made on Map Ta Phut are very high. They are between 10% for integrated energy consumption and 40% more in theoretical savings with TSP or R-curve analysis. Partially, the integration between a few different sites included in the IP is realized via an extraction back-pressure turbine generator and heat recovery steam generator. The overall theoretical increase in efficiency is determined to be approximately 15.8%.

Table 2 Theoretical case studies in which Pinch technology is used for IS improvements or design.

Case/location	Evidence and method	Reported outcome	Limitation/research gap
Map Ta Phut Industrial Area, Thailand	R-curve and total-site process integration [89]	Identified surplus heat, low-pressure steam recovery, and very-low-pressure steam/hot-water integration.	Reported outcomes require consistent assumptions, economic assessment, and implementation evidence.
Chiba Industrial Park, Japan	R-curve analysis [89]	Considered a back-pressure turbine generator and heat-recovery steam generator.	More detail is needed on inter-firm ownership, operating variability, and realised savings.
Kashima chemical industrial area, Japan	Area-wide Pinch technology [90]	Reported substantial energy-saving and efficiency potential.	Distinguish target savings from verified implementation outcomes.
Union Station, Dongying, Shandong Province, China	Heat Pinch technology [91]	Reported energy-efficiency improvement.	Specify system boundary, stream data, and economic feasibility.

Another similar project is the INES project in Rotterdam Harbor (Netherlands) [92]. All 69 member companies have been clustered into industrial services, refineries, inorganic chemistry, storage and transport, mass, goods and petrochemistry. As part of the INES project, physical flows of materials and transformation flows are determined, as well as information feedback. This project had the aim of creating a cleaner production approach and to stimulate the reuse of waste streams, by-products, and energy based on the determined capabilities of involved parties. Moreover, it supported the development of required knowledge infrastructure between companies, universities, and government.

Fan et al. [12] analyzed the Hefei economic and technological development area. The main exchanged flows are steam, biomass fuel, fly ash, and slags. Moreover, system analysis is increased with the determination of emergy flows, like renewable inputs, non-renewable inputs, labor, imported inputs, services, market, and disposal. IS with emergy analysis receives the following benefits: adaptation and improvement of technologies that increase waste reuse and recycling; energy optimization with reduction of waste emissions; sustainable development of IP with restoration of the local ecosystem.

Matsuda et al. [90] use the term “area-wide Pinch technology”. It consists of R-curve analysis and Site Source Sink Profile (SSSP). It is applied to Kashima, a complex chemical industrial area in Japan. Kashima IP consists of 31 sites, where utilities are supplied by thermal power plants, and exchange is carried out through 390 heaters and 677 coolers. The case study gave results for very high energy savings and very high efficiency. They found that using Pinch technology is very appropriate for such complex systems. The theoretical increase in efficiency depends on the parts of thermal power plants and is between 22.4-28%.

The R-ratio and the R-curve are defined by Kamura and Zhu [93]. Industrial systems can convert fuel into heat and power. The ratio between generated power and generated heat is called the R-ratio (Eq. 1). The sum of heat and power generated from fuel in heat pumps is the basis for the determination of efficiency (Eq. 2). The construction of the R-curve is made as a function of the changes in efficiency and R-ratio.

$$R = \frac{Q_{power}}{Q_{heat}} \quad (1)$$

$$\eta_{cogeneration} = \frac{(Q_{heat} + Q_{power})}{Q_{fuel}} \quad (2)$$

The R-curve shows the maximum achievable efficiency. In practice, the R-curve analysis directly depends on the implementation of Pinch technology. As Pinch technology improves efficiency, the R-curve shows it. In that case, the R-ratio is increased, too. $\eta_{cogeneration}$ is also known as integrated energy efficiency.

The SSSP analysis uses data for heat exchange between heat supply and demand. The right-side SSSP curves are heat-exchange composite curves, and the left-side curves are cooling composite curves. This defines the unutilized heat and cold within the temperature ranges. Matsuda et al. [90] obtained different values for energy savings potential with the R-curve and SSSP. In total energy, SSSP has shown savings of 4%, and the R-curve has shown 24.7% of the total energy input. Therefore, it can be said that “area-wide Pinch technology” is very useful in identifying energy-saving potential even for large, complex systems.

Unfortunately, all these data on increased efficiency are theoretical projections based on calculations using Pinch technology. No information is provided on whether any of these projects have been implemented or what the actual savings or efficiency gains are.

Ruiz-Puente [62] covered mixed systems such as industry and urban areas for further urban-industrial symbiosis. The cases show the exchange of materials and energy between both systems. Mainly, donors and recipients are government, municipalities, incineration plants, cogeneration plants, power plants, and waste (liquid, solid, and exhaust) treatment plants. Municipalities and government influence through funds, changes in taxes, and policy, as well as users of generated energy (citizens).

5.2 Solutions for Industrial Symbiosis Based on Pinch Technology

Designs based on Pinch technology or Total Site Integration (TSI) depend a lot on the extracted data. When all data on existing streams from interested parties are collected, selection can be made. After the selection of the most valuable streams is done, the methodology continues with stream matching and the design of an optimal solution. Several solutions can be suggested as alternatives. But after a techno-economic evaluation of the solutions, the most optimal one is selected. Manufacturing design is focused on improving the fit between processes and products. It uses three strategies: computing in multiple dimensions, computing in multiple segments, and computing in continuous product improvement [94].

Zwolinski and Brissaud [95] analyzed the possibilities for the reduction of CO₂ emissions by using different methods. Here, PI methods have been included. Based on their research, PI can be used for the utilization of waste heat, recycling or reuse of materials, and dematerialization. Data showed that the cost of implementation of PI in waste heat recovery is between 100 and 1000 EUR/t of CO₂. The CO₂ potential in their case is between 5 and 10%. Boix et al. [96] reported the issue of using Pinch technology for water networks that happens in the presence of certain contaminants. Moreover, this can include the integration of power plants with urban or industrial sites [80].

Butturi et al. [97] focus on energy symbiosis as part of IS. Most of the cases of analysis of interplant energy flow management are based on Pinch technology or mathematical programming. This is especially related to heat integration. Chen et al. [91] analyzed and integrated the Union Station in Dongying with Pinch technology as a complex system of energy flows. Based on that analysis, they determined energy consumption bottlenecks for different temperature profiles. Many changes have been proposed to increase energy efficiency.

One of the key questions of the research of Chin et al. [98] is how Pinch technology can be used for smart contract-based transactions to optimize resource matching and maximize energy resource recycling. Their research is based on blockchains as a database system for storing various information. Each block contains specific data identified with certain numbers. They simulated a system of processing plants with selected streams of interest for heat integration. The peer-to-peer (P2P) model was monitored continuously, and the data was stored in the blockchain system. All the stored data can be analyzed to find matches for available resources in a certain period that can be used/recovered. The data analysis method is Pinch technology. The system can manage all those resources within the P2P model. Using a blockchain with the P2P model can help implement IS.

Fan et al. [12] used emergy analysis to determine the sustainability of IS in IP where the system was integrated with Pinch technology. The parameters they used are the Emergy yield ratio (EYR)

(Eq. 3) and the Energy loading ratio (ELR) (Eq. 4) as parameters for the determination of the Energy sustainability index (ESI) (Eq. 5).

$$EYR = \frac{\text{renewables} + \text{nonrenewables} + (\text{imported}_{\text{resources}} + \text{labor} + \text{services} + \text{waste})}{(\text{imported}_{\text{resources}} + \text{labor} + \text{services} + \text{waste})} \quad (3)$$

$$ELR = \frac{\text{nonrenewable} + (\text{imported}_{\text{resources}} + \text{labor} + \text{services} + \text{waste})}{\text{renewable}} \quad (4)$$

$$ESI = \frac{EYR}{ELR} \quad (5)$$

Moreover, emergy can be used for the determination of consumed resources per unit of money (Energy-to-money ratio-EMR (Eq. 6)) and money savings (MS) (Eq. 7) in symbiosis.

$$EMR = \frac{\text{Emergy}}{\text{GDP}} \quad (6)$$

$$MS = \frac{\Delta \text{Emergy}}{EMR} \quad (7)$$

Hackl et al. [99] used total site analysis (TSA) to improve collaboration between companies for energy sharing. They used different data collection for TSA: black box (process is represented only by the utility demand), gray box (heat exchange of only process utility), and white box (detailed Pinch analysis with process-to-process heat exchange).

Many authors include exergy instead of energy in the Pinch analysis [100]. This covers the total energy content of selected flows. Exergy improves the designed solutions. Ibaaz et al. [101] created a generic algorithm for the prediction and quantification of energy and exergy targets between industrial processes. It combines analysis tools such as the exergy problem table algorithm and GCC tools. Based on exergy Pinch analysis, experts and planners can be guided to make their designs and decisions in creating IS.

Kastner et al. [102] considered Pinch technology to be one of the most important quantitative tools to create symbiosis in IPs. Sinks and sources form a network, but only certain relations can be matched. TSA and R-curve analysis are included here as well.

El Massah [103] used TSI more broadly to create IS. He included energy and water, as well as products and waste. This is related to the waste-to-energy and waste-to-wealth processes. Moreover, the basic principles of the circular economy have been incorporated to realize long-term sustainability with Pinch technology as the methodology.

Lambert and Boons [104] mentioned the integration of water between industries with water Pinch technology. There, water with undesired or desired components is shared between industries, as well as treated water flows shared between plants.

Lawal et al. [11] collected a few new directions that can be used or are used for creating IS in IPs. Those methodologies related to Pinch technology are total site carbon integration (TSCI), total site waste integration (TSWI), total site power integration (TSPI), and product planning. TSCI is carbon capture in IP, its utilization, and storage [105]. It is based on the energy planning composite curve and minimizing zero-carbon energy resources. Here, generic carbon cascade analysis [106], Carbon Capture and Storage [107], as well as widely known standard Pinch technology tools can be included.

TSWI is developed for municipal solid waste, but it can also be implemented for industrial waste to apply waste management strategies [108]. TSPI is based on the methodologies developed previously for PoPA [109, 110]. This includes electricity demand for the next period (the next day) with a daily prediction of consumption. As renewables have daily variations, electricity storage is required. Rozali et al. [111] designed an electric storage framework with an AC/DC storage cascade table. Furthermore, storage can include different technologies, such as combined electricity storage and hydrogen [105, 112]. Product planning can be done with Pinch analysis of energy generation in the system that combines different sources of energy mix.

Lawal et al. [11] gave a chronological development of Pinch technology for its purpose. As a main tool for the optimization of energy in continuous and batch processes, it has been developed for mass exchange, water Pinch technology, production planning Pinch technology, materials and property Pinch technology, financial planning Pinch technology, gas Pinch analysis, CEPA, waste management Pinch technology, TSCI, supply chain Pinch technology, footprint Pinch technology, and it continues today with its use for new purposes. Yeo et al. [113] analyzed different IS tools that use input-output streams. All data that needs to be shared between companies is shared voluntarily. That means that all valuable data might not be shared. They preferred PI tools for IS design. Yong et al. [114] created a novel Pinch multi-energy grid targeting framework as part of Total Site Heat Integration. The optimization of energy goes through the trigeneration system and energy storage [105].

El-Halwagi [115] introduced a mass integration model for the EIP problem that enables the exchange of waste, by-products, and fresh resources among multiple plants through a centralized facility, which facilitates the mixing of diverse streams and interception via separation and treatment units (as depicted in Figure 2). Lovelady and El-Halwagi [116] proposed a procedure to design the EIP using the mass integration shown in Figure 3. They established the following steps: extract process data set, set of sinks for each process (with mass flow F_{sink} , and component concentration $C_{c, \text{sink}}$), set of sources (wastewater, or similar, with mass flow F_{source} , and component concentration $C_{c, \text{source}}$), interceptor design, and solving the interceptors' problems. Sets of processes and streams, such as sinks and sources, should be extracted from the process flow sheet of all involved companies. All these selected streams are connected to the interceptor. The interceptor is a system that should be designed based on the requirements of involved processes, mass exchange, or treatment systems. The design and possible alternatives of the interceptors are generated based on some questions. El-Halwagi [117] suggested the following questions as important for the design of interceptors: 1. Which streams should be recycled within the same process, and which streams should be sent to the EIP? What changes will they undergo in the EIP (e.g., mixing, separation, extent of separation)? 2. What interception technologies should be used? What are their tasks? What streams should be assigned to these interceptors? How much fresh water should be used? Where? 3. How much waste should be discharged? Where?

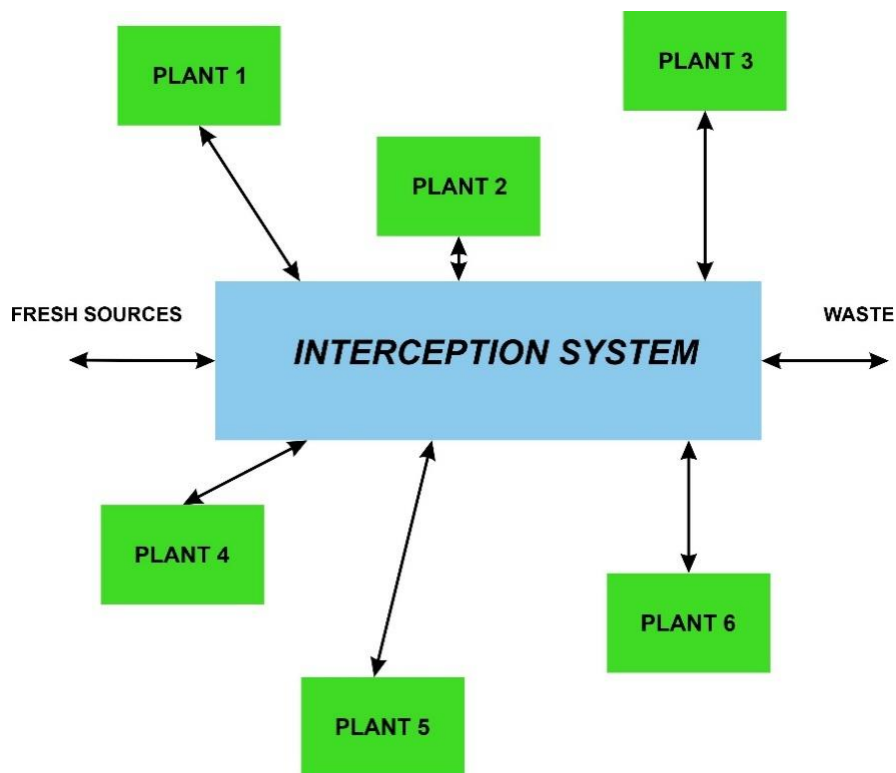


Figure 2 EIP mass integration through interception system.

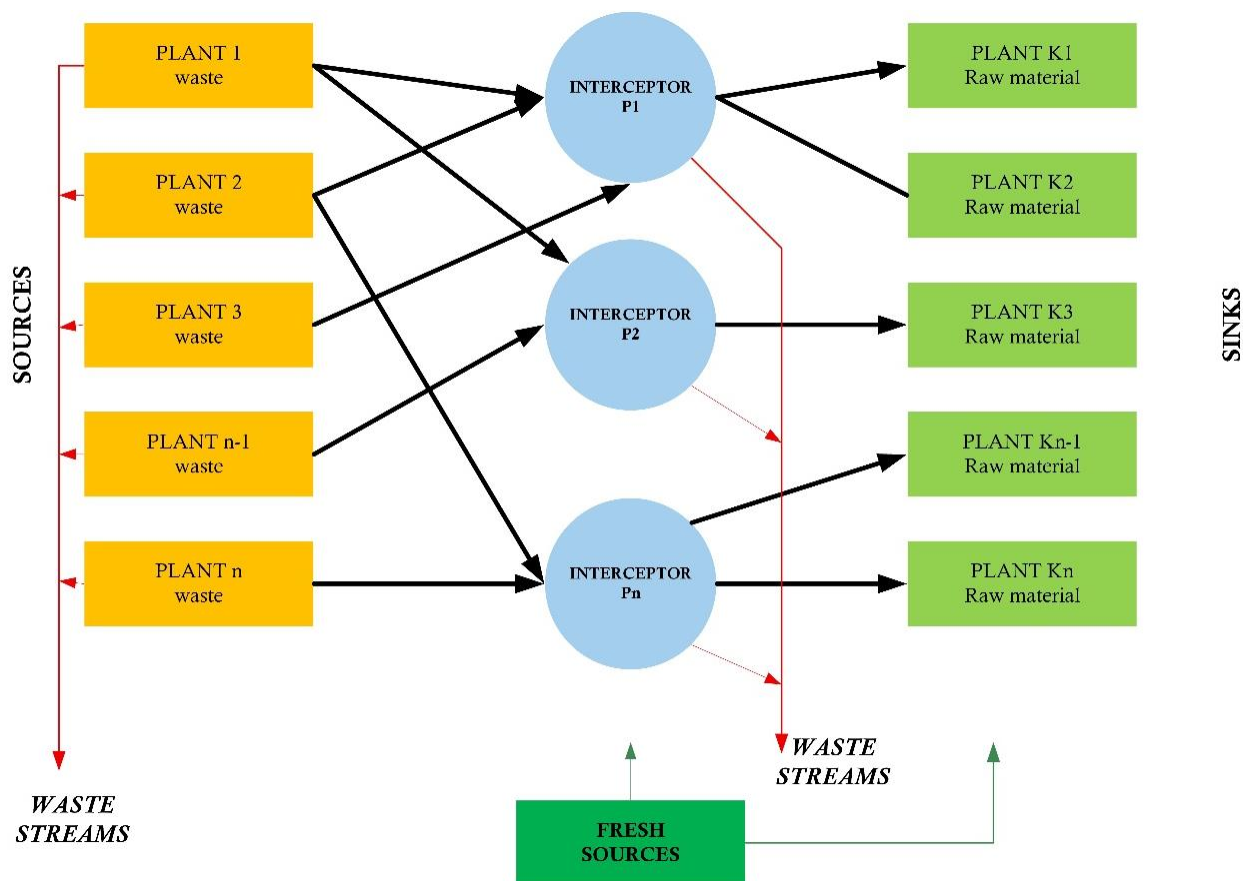


Figure 3 Interaction system between sinks, sources and interceptors for creating an EIP.

Several graphical and algorithmic PI techniques have been developed for synthesizing cost-effective EIPs based on the answers to given questions. El-Halwagi [117] suggested a graphical solution based on the material-the recycled Pinch diagram developed by El-Halwagi [117]. Algorithmic and mathematical optimization approaches are used for the synthesis of several types of EIP-design problems.

The optimization of costs for interception systems is based on Equation 8. Total Annualized Costs (TAC) depend on the number of interception units ($N_{interception}$), the amount of fresh water (sink) streams used, and the amount of generated waste.

$$TAC_{min} = \sum_{p=1}^{N_{interception}} Interception_{cost_p} Price_{fresh} \sum_{k=1}^{N_{sinks}} Fresh_k + Price_{waste} \cdot F_{waste} \quad (8)$$

The model of analysis and design developed by El-Halwagi is given in Figure 3. Furthermore, an additional method that employs chemical species as the foundation for integration involves the concept of carbon-hydrogen-oxygen symbiosis networks [115]. This was introduced by Nouredin and El-Halwagi.

Moreover, the other common organizational segments can be more easily managed than connected production processes. That is, common transportation, renewable transportation, logistics, common management, and even having a common building for the offices of administration and management with all other facilities needed for them [18].

6. Issues and Barriers in Pinch Technology Implementation

This collaborative approach can bring numerous benefits. Some critics argue that it can limit the autonomy and decision-making power of individual companies, potentially hindering innovation and progress. Positive and negative experiences can influence the way integration has been done between companies. As seen earlier, integrating different processes is easier in continuous processes. This integration can work perfectly and be synchronized. There is another question: what if a malfunction happens in one of the integrated parts? That will stop the first process, and automatically the other integrated part must be stopped. Therefore, a reserve plan must exist. In case of heat exchange, the other integrated continuous process must have active connections to hot or cold utilities. In the event of a malfunction, the production cost will increase. The integration of two continuous processes is robust and has no flexibility in realization. What should be done for better flexibility? Flexibility makes all integrated companies more independent. Therefore, flexibility can be higher if the system of integration between companies is based on batch processes or there is some storage system between connected parts [105]. Source delivery from other companies does not need to be used when supplying the system. That means that the source (heat, fuel, raw materials, water, etc.) can be delivered into storage, from which the second or third system can take without interruptions for its purposes. In this case, the optimal costs can be achieved with good design of storage systems (size, materials, connections, etc.).

Storage systems offer excellent flexibility between integrated systems. Inter-company IS is questionable when companies have different development rates [105]. When one company wants to increase production, it might need more sources delivered by symbiosis from other companies. That means other companies must increase their productivity or order the same resource from

outside the IS. From this point of view, integration, as well as the IS, interrupts or stops the independence of other companies from increasing production capacity. This can destroy the IS by breaking or canceling already signed contracts and agreements between companies.

The use of Pinch technology for IS design depends on many factors that are common to all methodologies. Those factors are barriers or limitations due to obstacles on the part of some parties in IS. Barriers can originate from companies (internal or external sources), general barriers to energy cooperation, or specific energy sharing solutions. It can be related to intra-company measures, allocation, theoretical solutions for energy cooperation, and the level of matching with designed instruments to overcome all those barriers [118].

De Canio [119] explained “the efficiency paradox” related to missing profitable energy efficiency measures. Implementing technologies (especially green technologies) that will improve efficiency can cause obstacles to sustainability and not always produce benefits or expected profits. Sometimes, investment makes a profit and improvements but might not ensure overall sustainability and resource efficiency [120]. Here, visible factors such as piping distances, flow fluctuations, and availability of utility systems influence that.

Roden and Moser [118, 121] classified barriers that influence energy integration. Some of them are barriers to the implementation of Pinch technology in the creation of ISs. The lack of knowledge directly influences the development of solutions and the use of Pinch technology. Internal competition for capital prioritization of non-energy investment, not having own funds, lack of acceptability of long payback times, retrofit design costs, fear of hidden costs, uncertainties and unknown risks, retroactive changes in renewable energy technologies, fear of unreliable business relations, and uncertainty in energy prices indirectly influence the implementation of the methodology. These are mainly economic considerations for companies that want to implement IS but have some prejudices or economic issues.

New solutions require new technology and equipment [122]. Therefore, all staff need additional training. There can be problems in adapting to new working environments, insufficient skills for non-core business issues, limited time and resources for non-core business issues, low motivation for the implementation of accepted rules for cooperation between companies, and the implementation of agreed responsibilities (for energy distribution, cross-sectional cooperation, poor work coordination of common systems, unification of implemented standards, managerial changes, and coordination bodies). Fears of business distortions, supply quality issues due to supplier changes, and behind-the-scenes maneuvering can also arise from direct market competition between companies in symbiotic systems. All of these are social and managerial barriers that also influence the choice of the solution.

Barriers that influence the framework in the implementation of designed solutions can be incomplete political strategies for energy, infrastructure uncertainties, regulations that can be obstacles for the use of certain technologies, lack of incentives, no legal solutions for pipelines that need to go through private properties, unification of local energy taxes, registered energy suppliers for managing exchanged energy, issues in case of multiple registered energy distributors, and regulations for direct exchange between two companies. Technical barriers that minimize the implementation of Pinch technology solutions could be the use of different industrial standards, lower expertise in using new technologies, waiting for the adoption of other companies for suggested designs, gaps and mistakes in matching, low technology readiness, long distances for exchange with high energy losses, having no technical solutions in managing by-products, using old

infrastructure, uncertainty in the quality of exchanged energy, limited understanding of technical options, having no technological forecasting, intermittency of supplied energy or renewables, requiring energy storage [18, 105]. The exchanged energy must be measured, controlled, and registered. These obstacles can make excellent solutions acceptable to companies. For good measurement, registration, and control, a good information system with a lot of sensors, meters, and data storage is needed. Every change or malfunction in one company can disrupt supplies for other companies. Therefore, every change must be detected and shared with others to take action to avoid bad consequences. Equipment and information systems are required, such as big data management, waste heat exchange measurement systems, implemented Internet of Things (IoT) systems, cybersecurity protocols for the privacy of data and protection of the most vulnerable points, bi-directional flow of energy and information, provision of sensitive business data, and communication between relevant people in all connected companies at different levels and times. Very important is empathy for other companies' needs in the symbiotic system and avoiding uncertainty about who manages the new exchange system between them.

7. Approach in Design of Industrial Symbiosis with Pinch Technology

Design steps for technical integration systems for IS can be determined based on all possibilities that Pinch technology can provide as a tool. Figure 4 shows different Pinch methodologies used in PI between two or more production facilities. The urban area system can be included as supply/demand points for mass or heat [123]. In addition, renewable energy sources can also be integrated [124, 125]. As with every Pinch methodology, information sharing is an important starting point. In this case, the information does not need to be detailed for the whole process of what happened in the internal systems of each company [31]. Detailed information is needed on selected streams, their quantity and quality of heat/mass/concentration, and their timelines (in case of batch processes). That starting point is enough for the design of HEN/MEN solutions, as well as possibilities in need of storage systems or additional equipment [126-128]. All of these define the exchange dynamics. When all possible solutions are generated as alternatives, they can be compared on the basis of economic optimization (as a step in the Pinch methodology) [18]. When basic technical solutions are made, the next step involves footprint Pinch technology. It optimizes environmental impact [129]. Already determined solutions must satisfy environmental regulations and laws. If that is not satisfied, it is returned for reconsideration. Solutions of footprint Pinch technology can lead to slight corrections in already generated alternative solutions. When footprint Pinch technology satisfies all rules and regulations, the technical design of integrative systems is ready for further management analysis. In this step, a common system for the transport of employees, the transport of goods, and products can be designed [31]. This can be based on supply chain Pinch technology. With this, Pinch technology can provide a whole technical solution in designing and applying IS in IPs. Exergy analysis can approve or disapprove of a potential loss of energy if the exchange is over long distances [58]. That is why the most optimal solutions require integration inside the industrial park or in nearby places that are within small distances. This is especially important for energy exchange, which can have very high transportation losses.

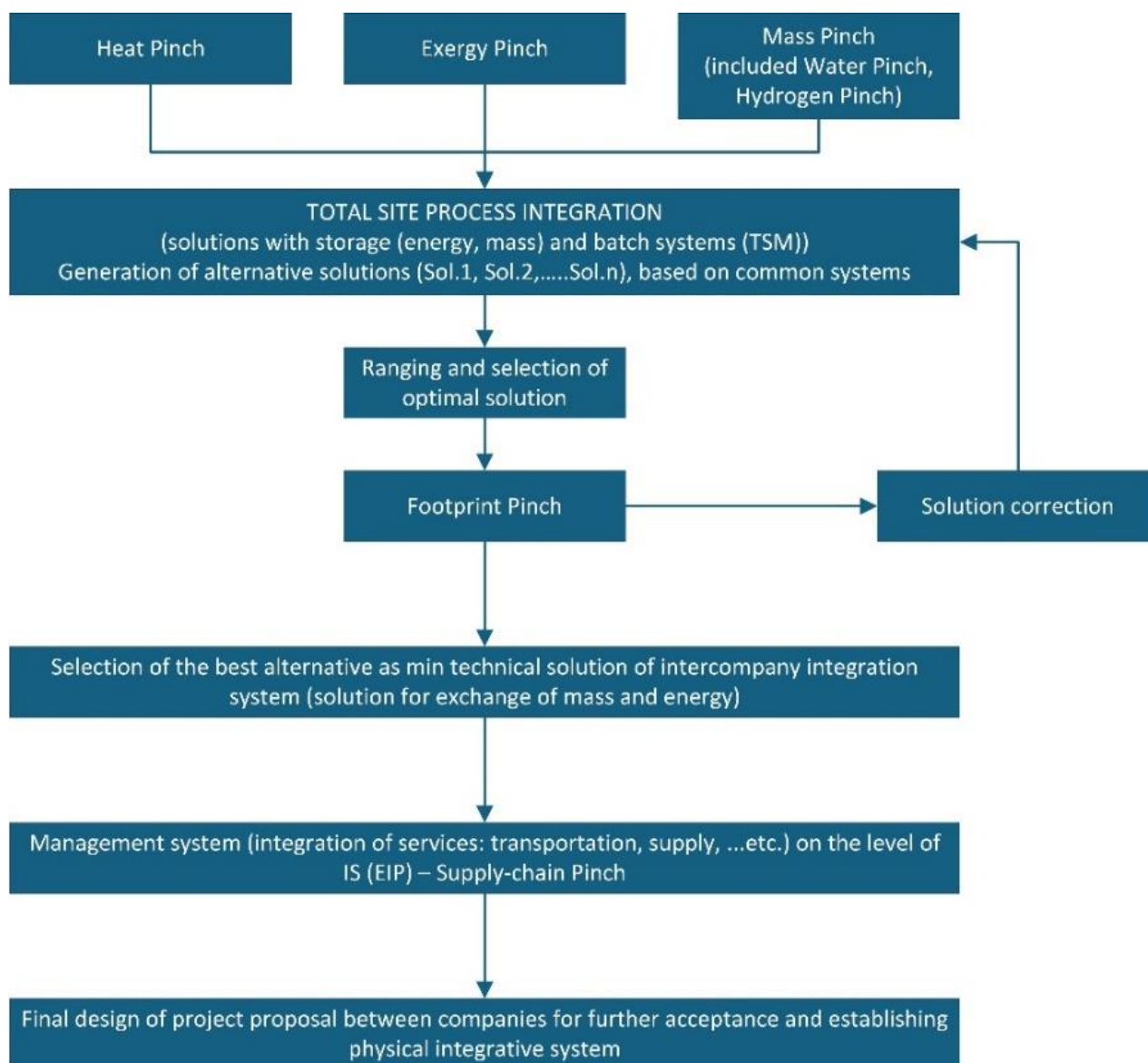


Figure 4 Steps in design of technical solution for design of IS integration system based on Pinch technology.

8. Conclusions

Pinch technology is not commonly used to create “virtual” or “on-site” information systems. There aren't many projects that use Pinch technology. Most of them are theoretical solutions. There, they show good performance in establishing symbiotic systems. In these cases, new modifications made in Pinch technology improve PI methodology. Primarily includes R-curve, TSP, and SSSP analysis. Moreover, PI methodology can be based on energy, exergy, or energy when heat and electricity are concerned for integration systems. The best results in IS design are shown only in on-site integration or in-site ISs. Additional problems appear with integration into virtual IS. Basically, distance is the main obstacle.

However, challenges persist, particularly for virtual symbiosis involving geographically dispersed sites. Technical obstacles include the need for continuous supply-demand matching, flexibility, equipment readiness, and storage solutions, which are critical to maintaining system robustness.

Non-technical barriers, such as intercompany agreements, regulatory constraints, economic considerations, education gaps, and information sharing, also significantly impact the adoption and success of Pinch-based IS designs. Awareness and knowledge dissemination among both technical and non-technical stakeholders are essential. Furthermore, developing accessible design algorithms and frameworks that can be utilized by various professionals involved in IS planning will facilitate wider implementation. Integrating Pinch technology with complementary approaches, such as supply chain optimization and environmental footprint analysis, can provide comprehensive technical solutions to foster sustainable industrial symbiosis.

Pinch technology has limitations for IS. They can be summarized as follows:

- Pinch technology is limited to steady-state conditions in case studies.
- It can be part of LCA, but PI does not include LCA.
- Material and energy losses through the exchange system are not calculated unless exergy is taken as the basis.
- It cannot be used for integration in the case of virtual IS.
- Some comparisons of material streams can hinder the use of Pinch technology.

Pinch technology offers many benefits compared to other methodologies used in IS design. They are as follows:

- Simplify the complexity of the problem.
- Determines the potential points for sources and sinks in exchange.
- Creates designs with an optimal number of exchange units.
- Solutions have optimal exchange-unit sizes.
- Solutions have minimal energy use and minimize utilities.
- Provides a clear improvement in process efficiency.
- It can be implemented for continuous, batch, and semi-continuous processes.
- It includes the determination and design of storage units and additional equipment that makes solutions flexible for all parties involved.

Pinch technology is used for IS design, but each type of Pinch technology is used separately. That makes it low impact to get a good Pinch-based solution. Therefore, all types of Pinch technology must be included, as suggested. A combination of these different types covers gaps in each separate Pinch technology solution. It can include heat, mass, and supply chain, as well as environmental influence (footprint). The suggested approach also has limitations that need to address blockchain and other economic relations, as well as areas that are not covered by technical sciences.

Overall, Pinch analysis provides a structured and potentially robust basis for the technical design and optimization of IS systems. However, its full deployment remains constrained by technical, organizational, and regulatory limitations. Mitigating these barriers through targeted capacity building, inter-organizational coordination, and continued methodological refinement is likely to be critical for enabling broader adoption and improving the effectiveness of IS implementations. The proposed multi-method toolkit is intended to support the practical enhancement and operational performance of IS systems. In the future, this algorithm needs to be more systematically developed.

Abbreviations

C	Concentration
EIP	Eco-industrial parks
ELR	Emergy loading ratio
EPoPA	Extended-power pinch analysis
ESI	Emergy sustainability index
EYR	Emergy yield ratio
F	Flow
GCC	Grand Composite Curve
GHG	Greenhouse gases
HEN	Heat Exchanger Network
IoT	Internet of Things
IP	Industrial Park
IS	Industrial symbiosis
MS	Money savings
N	Number of streams/units
PEIP	Positive Energy Industrial Parks
PI	Process Integration
SSSP	Site Source Sink Profile
TAC	Total Annualized Costs
TSA	Total site analysis
TSCI	Total site carbon integration
TSI	Total Site Integration
TSP	Total Site Process
TSPI	Total site power integration
TSWI	Total site waste integration

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The author has declared that no competing interests exist.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Appendix 1: The main types of Pinch technology and their role in PI and IS creation.

References

1. Sharpe S, Agarwal R. Strengthening Industrial Ecology's links with business studies: Insights and potential contributions from the innovation and business models literature. *Resources*. 2014; 3: 362-382.
2. Fraccascia L, Giannoccaro I. What, where, and how measuring industrial symbiosis: A reasoned taxonomy of relevant indicators. *Resour Conserv Recycl*. 2020; 157: 104799.
3. Chertow MR. "Uncovering" industrial symbiosis. *J Ind Ecol*. 2007; 11: 11-30.
4. Costa I, Ferrão P. A case study of industrial symbiosis development using a middle-out approach. *J Clean Prod*. 2010; 18: 984-892.
5. Lehtoranta S, Nissinen A, Mattila T, Melanen M. Industrial symbiosis and the policy instruments of sustainable consumption and production. *J Clean Prod*. 2011; 19: 1865-1875.
6. Neves A, Godina R, Azevedo SG, Pimentel C, Matias JCO. The potential of industrial symbiosis: Case analysis and main drivers and barriers to its implementation. *Sustainability*. 2019; 11: 7095.
7. Bao Z, Zhang S, Chen Y, Liu S, Zhang Y, Wang H. A review of material flow analysis. *Proceedings of the 2010 International Conference on Management and Service Science*; 2010 August 24-26; Wuhan, China. New York, NY: IEEE.
8. Gu C, Leveneur S, Estel L, Yassine A. Modeling and optimization of material/energy flow exchanges in an eco-industrial park. *Energy Procedia*. 2013; 36: 243-252.
9. Mattila TJ, Pakarinen S, Sokka L. Quantifying the total environmental impacts of an industrial symbiosis-a comparison of process-, hybrid and input– output life cycle assessment. *Environ Sci Technol*. 2010; 44: 4309-4314.
10. Gondkar S, Sriramagiri S, Zondervan E. Methodology for assessment and optimization of industrial eco-systems. *Challenges*. 2012; 3: 49-69.
11. Lawal M, Alwi SR, Manan ZA, Ho WS. Industrial symbiosis tools-A review. *J Clean Prod*. 2021; 280: 124327.
12. Fan Y, Qiao Q, Fang L, Yao Y. Emergy analysis on industrial symbiosis of an industrial park-a case study of Hefei economic and technological development area. *J Clean Prod*. 2017; 141: 791-798.
13. Thérin F. *Handbook of research on techno-entrepreneurship*. Cheltenham, UK: Edward Elgar Publishing; 2009.
14. Zhaohua W, Bin Z, Guilong L. Notice of retraction: Research on industrial symbiosis patterns in eco-industrial park based on industrial ecology theory. *Proceedings of the 2010 International Conference on Computer Application and System Modeling (ICCASM 2010)*; 2010 October 22-24; Shanxi, China. New York, NY: IEEE.
15. Lowe EA. *Eco-industrial park handbook for Asian developing countries*. Mandaluyong, Philippines: Asian Development Bank; 2011.
16. Ji Y, Shao Z, Wang R. Does industrial symbiosis improve carbon emission efficiency? Evidence from Chinese national demonstration eco-industrial parks. *Sustainability*. 2024; 16: 828.
17. Anastasovski A. What is needed for transformation of industrial parks into potential positive energy industrial parks? A review. *Energy Policy*. 2023; 173: 113400.
18. Anastasovski A, Rašković P, Guzović Z, Sedić A. A systematisation of methods for heat integration of solar thermal energy in production processes: A review. *J Sustain Dev Energy Water Environ Syst*. 2020; 8: 410-437.

19. UNIDO. Eco-industrial parks achievements and key insights from the global RECP programme 2012-2018. Vienna, Austria: UNIDO; 2018.
20. Chen X, Dong M, Zhang L, Luan X, Cui X, Cui Z. Comprehensive evaluation of environmental and economic benefits of industrial symbiosis in industrial parks. *J Clean Prod.* 2022; 354: 131635.
21. Liubarskaia MA, Tsurkan MV, Vorotnikov AM. Implementation of project management in eco-industrial parks development in Russian cities. *IOP Conf Ser Earth Environ Sci.* 2018; 177: 012039.
22. La Rosa AD, Ramakrishna S. Industrial symbiosis for circular economy: A possible scenario in Norway. In: *An introduction to circular economy.* Singapore: Springer Singapore; 2021. pp. 95-106.
23. Aussel D, Van KC, Salas D. Optimal design of exchange water networks with control inputs in eco-industrial parks. *Energy Econ.* 2023; 120: 106480.
24. Thanh TT, Huong DD, Long ND, Dat ND, Huyen MT, Cuong HC. Assessing the feasibility of eco-industrial parks in developing countries: A case study of Thang Long II Industrial Park in Vietnam. *Sustainability.* 2023; 15: 15602.
25. Kowalski Z, Kulczycka J, Makara A, Mondello G, Salomone R. Industrial symbiosis for sustainable management of meat waste: The case of Śmiłowo Eco-Industrial Park, Poland. *Int J Environ Res Public Health.* 2023; 20: 5162.
26. Henriques J, Ferrão P, Castro R, Azevedo J. Industrial symbiosis: A sectoral analysis on enablers and barriers. *Sustainability.* 2021; 13: 1723.
27. Pigosso DC, Schmiegelow A, Andersen MM. Measuring the readiness of SMEs for eco-innovation and industrial symbiosis: Development of a screening tool. *Sustainability.* 2018; 10: 2861.
28. Herath P, Dissanayake P, Thisakya G. The potential of industrial symbiosis: An analysis of barriers to its implementation for better waste management in industrial zones in Sri Lanka. *Proceedings of the 11th World Construction Symposium; 2023 July 21-22; Colombo, Sri Lanka.* Colombo, Sri Lanka: Ceylon Institute of Builders.
29. Kosmol L, Otto L. Implementation barriers of industrial symbiosis: A systematic review. *Proceedings of the 53rd Hawaii International Conference on System Sciences; 2020 January 07-10; Maui, HI, USA.* Honolulu, HI: University of Hawaii Press.
30. Corsini F, De Bernardi C, Frey M. Industrial symbiosis as a business strategy for the circular economy: Identifying regional firms' profiles and barriers to their adoption. *J Environ Plan Manag.* 2024; 67: 1148-1168.
31. Cavalcanti Sá de Abreu M, Mota RC, de Paula E. Identifying barriers and proposing a roadmap to develop industrial symbiosis projects. *Rev Adm UFSM.* 2020; 13: 517-534.
32. Hamam M, Spina D, Raimondo M, Di Vita G, Zanchini R, Chinnici G, et al. Industrial symbiosis and agri-food system: Themes, links, and relationships. *Front Sustain Food Syst.* 2023; 6: 1012436.
33. Scafà M, Marconi M, Germani M. A critical review of symbiosis approaches in the context of Industry 4.0. *J Comput Des Eng.* 2020; 7: 269-278.
34. Virtanen M, Manskinen K, Eerola S. Circular material library. An innovative tool to design circular economy. *Des J.* 2017; 20: S1611-S1619.
35. Corder GD, Golev A, Fyfe J, King S. The status of industrial ecology in Australia: Barriers and enablers. *Resources.* 2014; 3: 340-361.

36. Krzeminski P, Anastasovski A, Erceg A, Erceg BČ, Dosoretz CG, Borg M, et al. From theory to practice: A methodological roadmap for mapping, assessing, and implementing industrial symbiosis. *Clean Eng Technol.* 2026; 31: 101159.
37. Erceg A, Krzeminski P, Izdinsky K, Jonaitienė V, Marti MM, Dunjić B, et al. State-of-the-art report on industrial symbiosis topic and its different sub-areas (settling the basis for further improvements and their introduction in the industry) [Internet]. Yecla, Spain: Technological Centre of Furniture and Wood of the Region of Murcia; 2024. Available from: <https://doi.org/10.13140/RG.2.2.20601.58725>.
38. Ismail Y. Potential benefit of industrial symbiosis using life cycle assessment. *J Phys Conf Ser.* 2020; 1625: 012054.
39. Kantor I, Robineau JL, Bütün H, Marechal F. A mixed-integer linear programming formulation for optimizing multi-scale material and energy integration. *Front Energy Res.* 2020; 8: 49.
40. Cervo H, Ogé S, Maqbool AS, Mendez Alva F, Lessard L, Bredimas A, et al. A case study of industrial symbiosis in the Humber region using the EPOS methodology. *Sustainability.* 2019; 11: 6940.
41. Haq H, Välisuo P, Niemi S. Modelling sustainable industrial symbiosis. *Energies.* 2021; 14: 1172.
42. Lange KP, Korevaar G, Oskam IF, Herder PM. Developing and understanding design interventions in relation to industrial symbiosis dynamics. *Sustainability.* 2017; 9: 826.
43. Hua L. The impact of environmental taxation on the structure and performance of industrial symbiosis networks: An agent-based simulation study. *Heliyon.* 2024; 10: e25675.
44. Bissett CR. Mathematical models for eco-industrial networks. Kingston, RI: University of Rhode Island; 2014.
45. Kyriakopoulos GL, Kapsalis VC, Aravossis KG, Zamparas M, Mitsikas A. Evaluating circular economy under a multi-parametric approach: A technological review. *Sustainability.* 2019; 11: 6139.
46. Badenko V. Integration concept of digital shadows and BIM for a long-term optimal decision support in factory planning. *Res Sq.* 2021. doi: 10.21203/rs.3.rs-248614/v1.
47. Escandon-Barbosa D, Salas-Paramo J, Paque VC. The role of trophic, mutualistic, and competitive interactions in an industrial symbiosis process implementation: An ecological network perspective. *Environ Sci Pollut Res Int.* 2024; 31: 41905-41913.
48. Tan M, Ibarra-González P, Nikolic I, Ramírez Ramírez A. Understanding the level of integration in existing chemical clusters: Case study in the port of Rotterdam. *Circ Econ Sustain.* 2025; 5: 125-146.
49. Zhang Z, Chen X, Heck P. Emergy-based regional socio-economic metabolism analysis: An application of data envelopment analysis and decomposition analysis. *Sustainability.* 2014; 6: 8618-8638.
50. Liu W, Zhan J, Li Z, Jia S, Zhang F, Li Y. Eco-efficiency evaluation of regional circular economy: A case study in Zengcheng, Guangzhou. *Sustainability.* 2018; 10: 453.
51. Li T, Song Y, Shen J. Clean power dispatching of coal-fired power generation in China based on the production cleanliness evaluation method. *Sustainability.* 2019; 11: 6778.
52. Walzberg J, Lonca G, Hanes RJ, Eberle AL, Carpenter A, Heath GA. Do we need a new sustainability assessment method for the circular economy? A critical literature review. *Front Sustain.* 2021; 1: 620047.

53. Shen Y, Shi L, Tao Y, Wang H, Lu C, Li S, et al. Sustainability evaluation and optimization on the modern agro-pastoral circular system integrating energy analysis and life cycle assessment. *Sustainability*. 2022; 14: 4890.
54. Cano NA, Céspedes-Zuluaga S, Guerrero-Martin C, Gallego D. Exergy and emergy: Complementary tools for assessing the environmental sustainability use of biosolids generated in wastewater-treatment plant for energy-production. *Quim Nova*. 2022; 45: 4-15.
55. Svensson E, Morandin M, Harvey S. Characterization and visualization of industrial excess heat for different levels of on-site process heat recovery. *Int J Energy Res*. 2019; 43: 7988-8003.
56. Zeineb W, Zouhour K, Boulbaba L, Rachid B, Noureddine H. Exergetic analysis of bioethanol production from Tunisian waste dates. *Open Waste Manag J*. 2018; 11: 19-32.
57. Bou Malham C, Zoughaib A, Rivera Tinoco R, Schuhler T. Hybrid optimization methodology (Exergy/Pinch) and application on a simple process. *Energies*. 2019; 12: 3324.
58. Yushkova EA, Lebedev VA. Exergy Pinch analysis of the primary oil distillation unit. *J Phys Conf Ser*. 2019; 1399: 044072.
59. Lebedev V, Yushkova E. Mathematical model for optimization of heat exchange systems. *E3S Web Conf*. 2020; 164: 02011.
60. Lebedev V, Yushkova E, Churkin I. Exergy Pinch analysis of a furnace in a primary oil refining unit. *E3S Web Conf*. 2019; 124: 05088.
61. Raimbault J, Broere J, Somveille M, Serna JM, Strombom E, Moore C, et al. A spatial agent based model for simulating and optimizing networked eco-industrial systems. *Resour Conserv Recycl*. 2020; 155: 104538.
62. Ruiz-Puente C. Proposal of a conceptual model to represent urban-industrial systems from the analysis of existing worldwide experiences. *Sustainability*. 2021; 13: 9292.
63. Yazan DM, Fraccascia L. Sustainable operations of industrial symbiosis: An enterprise input-output model integrated by agent-based simulation. *Int J Prod Res*. 2020; 58: 392-414.
64. Fraccascia L, Yazdanpanah V, Van Capelleveen G, Yazan DM. A framework for industrial symbiosis systems for agent-based simulation. *Proceedings of the 2019 IEEE 21st Conference on Business Informatics (CBI); 2019 July 15-17; Moscow, Russia*. New York, NY: IEEE.
65. Papageorgiou A, Björklund A, Sinha R. Applying material and energy flow analysis to assess urban metabolism in the context of the circular economy. *J Ind Ecol*. 2024; 28: 885-900.
66. Papageorgiou A, Björklund A, Sinha R, de Almeida ML, Steubing B. Coupling material and energy flow analysis with life cycle assessment to support circular strategies at the urban level. *Int J Life Cycle Assess*. 2024; 29: 1209-1228.
67. Nogueira A, Ashton W, Teixeira C, Lyon E, Pereira J. Infrastructuring the circular economy. *Energies*. 2020; 13: 1805.
68. Pomponi F, Moncaster A. Circular economy for the built environment: A research framework. *J Clean Prod*. 2017; 143: 710-718.
69. Geetha R. Circular economy through integrated industrial ecology: Innovations in resource recovery and process re-design. *Biotechnol Notes*. 2025; 6: 245-259.
70. Kovacs E, Hoaghia MA, Senila L, Scurtu DA, Dumitras DE, Roman C. Sustainability problematization and modeling opportunities. *Sustainability*. 2020; 12: 10046.
71. Lu C, Pan X, Chen X, Mao J, Pang J, Xue B. Modeling of waste flow in industrial symbiosis system at city-region level: A case study of Jinchang, China. *Sustainability*. 2021; 13: 466.

72. Marinelli S, Butturi MA, Rimini B, Gamberini R, Sellitto MA. Estimating the circularity performance of an emerging industrial symbiosis network: The case of recycled plastic fibers in reinforced concrete. *Sustainability*. 2021; 13: 10257.
73. Marcinkowski A. The spatial limits of environmental benefit of industrial symbiosis-life cycle assessment study. *J Sustain Dev Energy Water Environ Syst*. 2019; 7: 521-538.
74. Marousi A, Charitopoulos VM. Game theoretic optimisation in process and energy systems engineering: A review. *Front Chem Eng*. 2023; 5: 1130568.
75. Valero A, Usón S, Torres C, Valero A. Application of thermoeconomics to industrial ecology. *Entropy*. 2010; 12: 591-612.
76. Cappelletti F, Germani M. Carbon reduction engineering through value chains intersection, product and process re-design, industrial processes' scraps de-manufacturing. *Int J Prod Res*. 2024; 62: 6801-6822.
77. Singh S, Babbitt C, Gaustad G, Eckelman MJ, Gregory J, Ryen E, et al. Thematic exploration of sectoral and cross-cutting challenges to circular economy implementation. *Clean Technol Environ Policy*. 2021; 23: 915-936.
78. Weng X, Lv X, Li X. Study on the implementation mechanism of symbiosis theory used in economic field. *Economics*. 2016; 5: 56-63.
79. Hennequin S, Yazdani MA, Roy D. Echelon base stock policy for symbiotic and reverse logistic flows. *IFAC-Pap*. 2022; 55: 269-274.
80. Anastasovski A. Pathways for coal-fired power plants green production process transition. *Next Sustain*. 2026; 7: 100236.
81. Perry S. 6-Total site methodology. In: *Handbook of Process Integration (PI)*. Cambridge, UK: Woodhead Publishing; 2013. pp. 217-251.
82. Krummenacher P. Contribution to the heat integration of batch processes (with or without heat storage). EPFL. 2002. doi: 10.5075/epfl-thesis-2480.
83. Knopf FC, Okos MR, Reklaitis GV. Optimal design of batch/semicontinuous processes. *Ind Eng Chem Process Des Dev*. 1982; 21: 79-86.
84. Diwekar U. *Batch processing: Modeling and design*. Boca Raton, FL: CRC Press; 2014.
85. Majozi T. *Batch chemical process integration: Analysis, synthesis and optimization*. Dordrecht, Netherlands: Springer Dordrecht; 2010.
86. Linnhoff B, Ashton GJ, Obeng ED. Process integration of batch processes. *ICHEME Symp Ser*. 1988; 109: 221-237.
87. Anastasovski A. Design of common heat exchanger network for batch processes. *Appl Therm Eng*. 2014; 65: 458-468.
88. Ebrahim M, Al-Kawari. Pinch technology: An efficient tool for chemical-plant energy and capital-cost saving. *Appl Energy*. 2000; 65: 45-49.
89. Matsuda K, Hirochi Y, Kurosaki D, Kado Y. Application of area-wide Pinch technology to a large industrial area in Thailand. *Chem Eng Trans*. 2014; 39: 1027-1032.
90. Matsuda K, Hirochi Y, Tatsumi H, Shire T. Applying heat integration total site based Pinch technology to a large industrial area in Japan to further improve performance of highly efficient process plants. *Energy*. 2009; 34: 1687-1692.
91. Chen G, Liu D, Wang Z. Research on Pinch analysis of union station a subsystem. *J Phys Conf Ser*. 2024; 2771: 012028.

92. Baas L. Industrial symbiosis in the Rotterdam harbour and industry complex: Reflections on the interconnection of the techno-sphere with the social system. *Bus Strategy Environ*. 2008; 17: 330-340.
93. Kimura H, Zhu X. R-curve concept and its application for industrial energy management. *Ind Eng Chem Res*. 2000; 39: 2315-2335.
94. Susman GI. Integrating design and manufacturing for competitive advantage. Oxford, UK: Oxford University Press; 1992.
95. Zwolinski P, Brissaud D. Designing products that are never discarded. In: *Innovation in life cycle engineering and sustainable development*. Dordrecht, Netherlands: Springer Dordrecht; 2006. pp. 225-244.
96. Boix M, Montastruc L, Azzaro-Pantel C, Domenech S. Optimization methods applied to the design of eco-industrial parks: A literature review. *J Clean Prod*. 2015; 87: 303-317.
97. Butturi MA, Lolli F, Sellitto MA, Balugani E, Gamberini R, Rimini B. Renewable energy in eco-industrial parks and urban-industrial symbiosis: A literature review and a conceptual synthesis. *Appl Energy*. 2019; 255: 113825.
98. Chin HH, Varbanov PS, Alwi SR, Manan ZA, Martincová JV. Blockchain-based concept for total site heat integration: A Pinch-based smart contract energy management in industrial symbiosis. *Energy*. 2024; 305: 132261.
99. Hackl R, Andersson E, Harvey S. Targeting for energy efficiency and improved energy collaboration between different companies using total site analysis (TSA). *Energy*. 2011; 36: 4609-4615.
100. Sharew SS, Di Pretoro A, Yimam A, Negny S, Montastruc L. Combining exergy and Pinch analysis for the operating mode optimization of a steam turbine cogeneration plant in Wonji-Shoa, Ethiopia. *Entropy*. 2024; 26: 453.
101. Ibaaz K, Oudani M, Harraki IE, Cherkaoui M, Belhadi A, Kamble S. A generic algorithm-based application for Pinch-exergy prediction in process industries: A case study. *Energy Environ*. 2024; 35: 1871-1906.
102. Kastner CA, Lau R, Kraft M. Quantitative tools for cultivating symbiosis in industrial parks; a literature review. *Appl Energy*. 2015; 155: 599-612.
103. ElMassah S. Industrial symbiosis within eco-industrial parks: Sustainable development for Borg El-Arab in Egypt. *Bus Strategy Environ*. 2018; 27: 884-892.
104. Lambert AJ, Boons FA. Eco-industrial parks: Stimulating sustainable development in mixed industrial parks. *Technovation*. 2002; 22: 471-484.
105. Anastasovski A. Is renewable energy storage sustainable? A review. *Green Technol Sustain*. 2025; 3: 100176.
106. Munir SM, Manan ZA, Alwi SR. Holistic carbon planning for industrial parks: A waste-to-resources process integration approach. *J Clean Prod*. 2012; 33: 74-85.
107. Mohd Nawi WN, Wan Alwi SR, Manan ZA, Klemeš JJ. Pinch analysis targeting for CO₂ total site planning. *Clean Technol Environ Policy*. 2016; 18: 2227-2240.
108. Ho WS, Hashim H, Lim JS, Lee CT, Sam KC, Tan ST. Waste Management Pinch Analysis (WAMPA): Application of Pinch analysis for greenhouse gas (GHG) emission reduction in municipal solid waste management. *Appl Energy*. 2017; 185: 1481-1489.
109. Bandyopadhyay S, Varghese J, Bansal V. Targeting for cogeneration potential through total site integration. *Appl Therm Eng*. 2010; 30: 6-14.

110. Alwi SR, Rozali NE, Abdul-Manan Z, Klemeš JJ. A process integration targeting method for hybrid power systems. *Energy*. 2012; 44: 6-10.
111. Mohammad Rozali NE, Wan Alwi SR, Manan ZA, Klemeš JJ, Hassan MY. A process integration approach for design of hybrid power systems with energy storage. *Clean Technol Environ Policy*. 2015; 17: 2055-2072.
112. Esfahani IJ, Lee S, Yoo C. Extended-power Pinch analysis (EPoPA) for integration of renewable energy systems with battery/hydrogen storages. *Renew Energy*. 2015; 80: 1-14.
113. Yeo Z, Masi D, Low JS, Ng YT, Tan PS, Barnes S. Tools for promoting industrial symbiosis: A systematic review. *J Ind Ecol*. 2019; 23: 1087-1108.
114. Yong WN, Liew PY, Woon KS, Alwi SR, Klemeš JJ. A Pinch-based multi-energy targeting framework for combined chilling heating power microgrid of urban-industrial symbiosis. *Renew Sustain Energy Rev*. 2021; 150: 111482.
115. El-Halwagi MM. Chapter 20-Macroscopic approaches of process integration. In: *Sustainable Design Through Process Integration*. Oxford, UK: Butterworth-Heinemann; 2017. pp. 533-565.
116. Lovelady EM, El-Halwagi MM. Design and integration of eco-industrial parks for managing water resources. *Environ Prog Sustain Energy*. 2009; 28: 265-272.
117. El-Halwagi MM, Gabriel F, Harell D. Rigorous graphical targeting for resource conservation via material recycle/reuse networks. *Ind Eng Chem Res*. 2003; 42: 4319-4328.
118. Rodin V, Moser S. The perfect match? 100 reasons why energy cooperation is not realized in industrial parks. *Energy Res Soc Sci*. 2021; 74: 101964.
119. DeCanio SJ. The efficiency paradox: Bureaucratic and organizational barriers to profitable energy-saving investments. *Energy Policy*. 1998; 26: 441-454.
120. Hiete M, Ludwig J, Schultmann F. Intercompany energy integration: Adaptation of thermal Pinch analysis and allocation of savings. *J Ind Ecol*. 2012; 16: 689-698.
121. Rodin V, Moser S. From theory to practice: Supporting industrial decarbonization and energy cooperation in Austria. *Energy Res Soc Sci*. 2022; 94: 102863.
122. Moser S, Puschnigg S, Rodin V. Designing the heat merit order to determine the value of industrial waste heat for district heating systems. *Energy*. 2020; 200: 117579.
123. Anastasovski A, Andreucci MB, Kádár J, Delli Paoli M. Energy storage in urban areas: The role of energy storage facilities, a review. *Energies*. 2024; 17: 1117.
124. Anastasovski A. *Industrial waste heat recovery techniques*. Saarbrücken, Germany: LAP LAMBERT Academic Publishing; 2020.
125. Anastasovski A. Solar heat integration in non-repeatable time slices on daily basis. *Acad Perspect Procedia*. 2019; 2: 342-350.
126. Anastasovski A. A new method for heat integration between nonrepeatable batches. *Energy Storage*. 2021; 3: e233.
127. Rašković P, Anastasovski A, Cvetković S. Process integration in bioprocess industry: Waste heat recovery in yeast and ethyl alcohol plant. *Proceedings of the International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*; 2010 June 14-17; Lausanne, Switzerland. Lausanne, Switzerland: EPFL.
128. Anastasovski A. Enthalpy Table Algorithm for design of heat exchanger network as optimal solution in Pinch technology. *Appl Therm Eng*. 2014; 73: 1113-1128.
129. Liu H, Ren L, Zhuo H, Fu S. Water footprint and water Pinch analysis in ethanol industrial production for water management. *Water*. 2019; 11: 518.