WATER AND ENERGY INTEGRATION: A COMPREHENSIVE LITERATURE REVIEW OF NON-ISOTHERMAL WATER NETWORK SYNTHESIS

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Abstract

Syntheses of non-isothermal water networks consisting of water-usages, wastewater treatment, and heat exchanger networks has been recognised as an active research field in Process Systems Engineering. However, only brief overviews of this important field have so far been provided within the literature. This work presents a systematic and comprehensive review of papers published over the last two decades and highlights possible future directions within this field. This review can be useful for researchers and engineers interested in water and energy integration within process water networks using systematic methods based on pinch analysis, mathematical programming, and their combination. We believe that this research field will continue to be active in the near future due to the importance of simultaneous optimising processes, water and energy integration for achieving profitability and sustainability within process industries.

Key words: water networks, non-isothermal water networks, combined water and energy networks, water and energy integration, pinch analysis, mathematical programming, review.

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CONTENTS

1. INTRODUCTION

1.1. Sustainable water and energy management within the industries

A typical chemical process consists of several subsystems, namely a reaction network, a separation network, a utility plant, a heat exchanger network, a water network, and a wastewater network. These subsystems are interconnected by different streams, e.g. process streams, water streams, hot and cold utilities, etc., within and between industrial processes, and also within the environment (see Figure 1). The main goal of a chemical process is to transform raw materials into the finally desired products, thus enabling profitable and sustainable production and minimisation of water and energy consumption and waste generation into the environment.

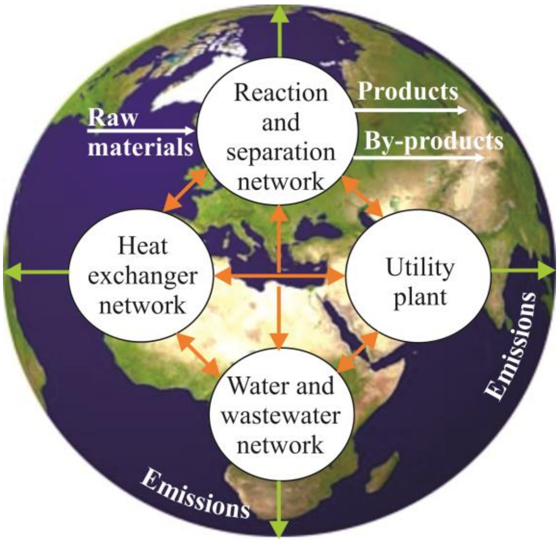


Figure 1. The interconnections between the subsystems of a chemical process and the environment.

Given the growths in global economies and populations, the global consumption of water and energy is increasing and this trend is going to continue in the future [1]. In addition, Chemical Process Industries (CPIs) use large amounts of water and energy, and generate waste streams that are discharged into the environment. Pulp, paper and petroleum refining processes are amongst the larger users of water and energy within the manufacturing sector [2]. Water and energy are usually linked within a process, e.g., water is used for energy or utility production, and energy produced from water is used for heating, transportation of water within a process, and purification of wastewater via treatment operations. Minimisation of water usage results in minimisation of wastewater generation as well as energy usage for heating and cooling within a process, and vice versa. Accordingly, water and energy consumption, and wastewater generation should therefore be minimised simultaneously. Discovering the better alternatives for minimising water and energy usage, and waste generation whilst satisfying environmental constraints is a global challenge for engineers and researchers [3], who search for efficient solutions for successfully addressing this important problem. There are some excellent handbooks/books and review papers covering these issues related to CPI applying Process Integration (PI) and Process Synthesis (PS). Recently, Klemeš [4] edited the Handbook of

Process integration, which addresses the minimisation of energy and water usages, waste, and emissions within chemical processes. A book, relating to sustainable design through process integration, was written by El-Halwagi [5], process Integration for resource conservation by Foo [6], sustainability in process industry by Klemeš [7], chemical process design and integration by Smith [8], and systematic methods of chemical process design by Biegler et al. [9]. Also, the reader is referred to studies on process integration [10], recent developments in process integration and synthesis [11] and process synthesis [12]. Systematic methods based on mathematical programming (MP) and pinch analysis (PA) have been applied over more than 40 years in order to achieve improved energy and water integration in CPI [13]. For further details of these topics the reader is referred to comprehensive review papers relating to recent advances in chemical process optimisation [14], mixed-integer nonlinear and general disjunctive programming solution methods [15], heat exchanger network synthesis [16, 17] and retrofit [18], optimal design of sustainable chemical processes and supply chains [19], water network design methods using mathematical programming [20], pinch analysis [21], and pinch analysis and mathematical programming [22, 23]. Over the last two decades a considerable attention has been devoted to the synthesis problem of heat integration within water networks and it is going to be an active research direction in a near future. The main goal of this synthesis problem is to perform simultaneous water and heat integration, and design an optimum combined network consisting of a water network (including water-using units and/or wastewater treatment units) and heat exchanger network. This research field is known in the literature as the syntheses of non-isothermal water networks (heat-integrated water networks (HIWNs), water allocation and heat exchange networks (WAHENs), combined water and energy networks, heat-integrated water-using and wastewater treatment networks (HIWTNs) or heat-integrated resource conservation networks (HIRCNs)). In the following section we first provide a short discussion about previous studies, in which brief overviews of contributions in non-isothermal water network synthesis are given, and then highlight the goal and purpose of this review.

1.2. Previous brief literature overviews on water and energy integration

The first comprehensive review papers on the topic of water network synthesis using pinch analysis and mathematical programming were provided by Bagajewicz [22], Jeżowski [20], and Foo [21]. The main focus of those papers was on studies in which water integration was considered without heat integration. However, the importance of simultaneously considering water and energy integration was highlighted as an important further direction in this field. In later review papers [23-26] only brief overviews were presented for some contributions on water and energy integration and the syntheses of non-isothermal water networks (see Table 1). In addition, two excellent overviews of process integration concepts and novel methods for combined energy and water integration were provided in the book's chapters [27, 28].

Table 1. Review papers providing brief overviews of non-isothermal water networks.

Author (s)	Year	Journal	Remarks/Features/Notes	Ref.
Jeżowski	2010	Industrial & Engineering Chemistry Research	In this paper a review was presented on the WN synthesis (including isothermal and non-isothermal water networks) with literature annotations. More than 260 contributions over the period 1998-2009 were devoted to water network synthesis problems, whilst less than 20 contributions to non-isothermal water networks. However, this research field was recognised as being the directions of further investigations.	[23]
Chen and Wang	2012	Frontiers of Chemical Science and Engineering	This paper provided a review on the synthesis of heat, mass, and work exchange networks, and highlighted that future research directions could be focused on multi-objective optimisation of those networks. However, the challenge is how to combine networks into a single one. In addition, a part of this review is devoted to a brief discussion of 21 contributions related to non-isothermal water networks as an important research field.	[24]
Klemeš	2012	Current Opinion in Chemical Engineering	This paper provided an overview of the topics on water footprint and life cycle analysis, water and wastewater minimisation, and combined water and energy minimisation. The advantages of methods based on pinch analysis and mathematical programming were shown on cases in which the significant improvements in water and energy minimisation were obtained. Also, a very brief overview was given for less than 10 papers on the syntheses of non-isothermal water networks.	[25]
Grossmann et al.	2014	Current Opinion in Chemical Engineering	In this paper a review of optimisation models for integrated process water networks was presented as well as their application to biofuel processes, which consume large amounts of water. In addition, a discussion about the importance of simultaneous flow sheet optimisation, heat and water integration was pointed out. However, only a short overview of several papers devoted to non-isothermal water networks was presented.	[26]

1.3. The purpose of the paper

Over the last two decades the synthesis of non-isothermal water networks has attracted the attention of many researchers. Developments within this research field, especially over the last five years, and the need for updating current overviews and providing possible future directions regarding this topic have motivated the writing this review. Moreover, to the best of our knowledge there has been no comprehensive literature review of this field to date. The purpose of this paper is thus to provide such a comprehensive literature review of contributions over the last two decades within the field of synthesising non-isothermal water networks, and to highlight possible future directions. This review is mainly limited to journal and conference papers written in English but other works are also commented on and discussed such as books and book chapters, etc. It is hoped that this review will be useful for researchers as well as engineers in order to be up-to-date as to what is currently being done in this field, and have an overview of possible future challenges.

1.4. The structure of the paper

The paper is organised as follows. The second section of the paper presents the classifying of the water network synthesis problem into isothermal and non-isothermal water networks. As the main focus of this review is on non-isothermal water networks, a synthesis analysis of this research field is provided highlighting the importance of considering simultaneous water and energy integration within a network consisting of water-using units, wastewater treatment units, and heat exchangers. The third section provides classifications of systematic methods for synthesising non-isothermal water networks into pinch analysis, mathematical programming, and hybrid (combined) methods. Moreover, brief overviews of methods are provided highlighting their advantages and disadvantages. A comprehensive and systematic literature review covering the period 1997-2014 is presented in the fourth section of the paper in order to bring the readers up-to-date with the state-of-the-art and progress within this field. This section discusses different concepts and synthesis methods applied in this field. The fifth section of the paper presents the classifications and the overall analysis of the published papers. Different types of diagrams are created in order to show the chronological trend of the published papers by year and different time periods, distribution of papers published in different journals and conference proceedings, the number of papers published by authors from different countries and universities. Finally, the last section of the paper summarises the main conclusions and provides future directions and challenges in this field.

2. CLASSIFICATIONS OF WATER NETWORK SYNTHESIS PROBLEMS

The syntheses of water networks (WNs) has been an important research area over the last few decades [25]. Water network synthesis problems can be classified as isothermal and non-isothermal (see Figure 2). In an isothermal network's synthesis problem it is assumed that the temperatures of all streams are constant and are not taken into account during the water network synthesis and design. However, in non-isothermal water network synthesis problems temperatures are not constant because it is necessary to heat and/or cool water streams in order to satisfy different temperature constraints within the network (i.e. operating temperatures of process and/or treatment units, temperature of wastewater stream discharged into the environment, etc.). According to this, temperatures are taken into account during non-isothermal network synthesis and design. Non-isothermal water networks are more realistic problems compared to isothermal water networks and this paper provides a review on this topic. A brief description and classifications of water network synthesis problems are presented in the following part of the paper.

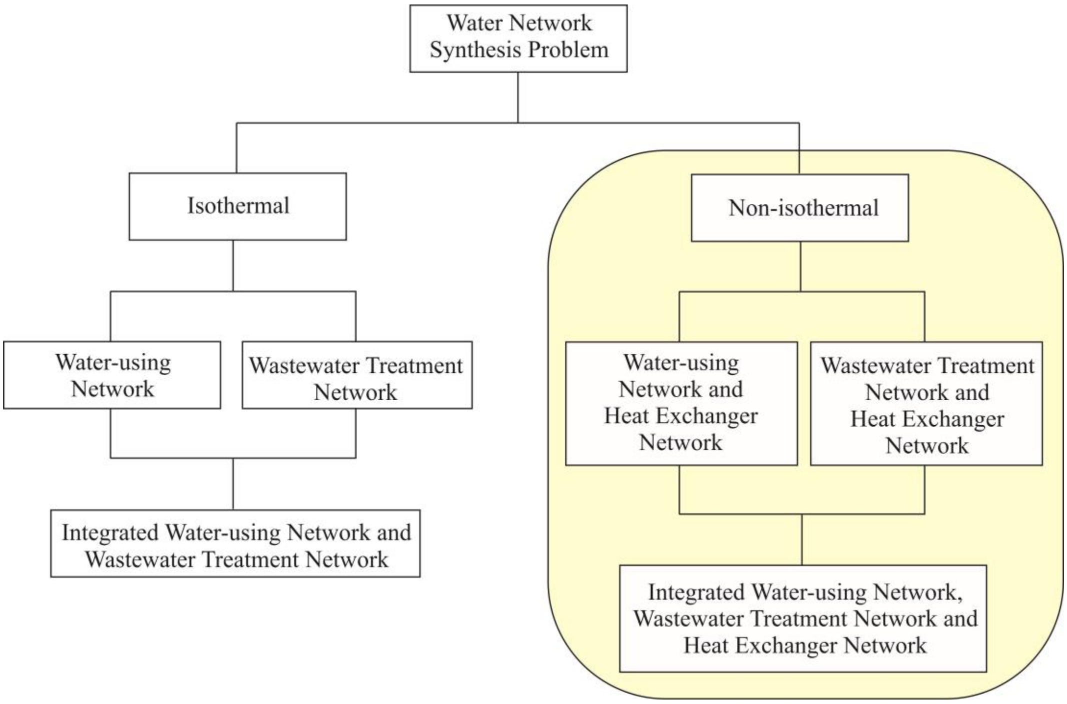


Figure 2. Classifications of water network synthesis problems.

2.1. Isothermal water network synthesis problems

Water network synthesis for isothermal networks can be performed for water-using units (process units), wastewater treatment units (regeneration units) or as integrated networks consisting of water-using and wastewater treatment units (see Figure 2). Within an integrated water network the following water minimisation options are considered: water reuse, regeneration reuse, and regeneration recycling. The aim is to obtain a network design that exhibits minimum freshwater consumption and minimum wastewater generation. A water network problem as a special case regarding a mass exchanger network problem was proposed by El-Halwagi and Manousiouthakis [29]. The first contributions to isothermal WN synthesis were presented by Takama et al. [30, 31], who used a mathematical programming approach for synthesising WN design. Later, Wang and Smith [32, 33] used the pinch analysis method for addressing the syntheses of WNs. Later studies considered an isothermal water network consisting of water-using units and/or wastewater treatment units and the main goal was to simultaneously minimise freshwater consumption and wastewater generation. Several studies have used the mathematical programming approach and global optimisation for the syntheses of integrated water networks including multiple contaminants [34, 35] In general, water-using networks and/or wastewater treatment networks are considered within the same plant but over recent years inter-plant water networks with direct and indirect integration (via utility hub) have been studied, in which water integration is considered between different plants [36-39] involving continuous and batch units [39] or considering retrofitting of water networks from different plants within the same industrial zone [40]. As isothermal water networks are not the focus of this paper the reader is referred to excellent review papers by Bagajewicz [22], Foo [21], Jeżowski [23], and books by Mann and Liu [41], Smith [8], Klemeš et al. [7], El-Halwagi [5], and Klemeš [4] for further details and recent developments within this research field.

2.2. Non-isothermal water network synthesis problems

In isothermal water networks water integration is considered as being isolated from energy integration. However, energy and water integration within water network synthesis problems should be considered together in order to simultaneously minimise energy and water consumption. Water and energy network synthesis problems represent special cases of mass and heat exchange network synthesis problems. The reader is referred to the work by El-Halwagi and Manousiouthakis [29] and Srinivas and El-Halwagi [42] for more details about the syntheses of mass exchange networks and combined heat and reactive-mass exchange networks, and a study by Papalexandri and Pistikopoulos [43], who addressed the synthesis of heat and mass transfer operations. The important issue when considering energy and water interactions regarding industrial implications has also been recently highlighted by Varbanov [44]. A fast development has been noticed in this area over the last two decades, especially over recent years [25] thus providing the driving force for updating literature overviews of this field. The focus of this paper is on a review regarding the combined synthesis of energy and water networks or non-isothermal water network synthesis (see the marked part in Figure 2).

2.2.1. General representation of the non-isothermal water network synthesis problem

Figure 3 shows a general representation of a non-isothermal water network including process units, treatment units and heat transfer units, which is an extension of the problem formulation for simultaneous energy and water minimisation proposed by Savulescu and Smith [45]. Freshwater and utilities (hot and cold) with specified temperatures and contaminant concentrations (freshwater) have been supplied to this network in order to satisfy the demands, contaminant concentrations and temperature constraints of process units (water-using units). Wastewater generated within process units can be reused in process units and/or regenerated in treatment units in order to enable reuse and/or recycling of water within the network. Part of the wastewater is discharged from the network into the environment and must satisfy the constraints regarding the maximum temperature and contaminant concentrations.

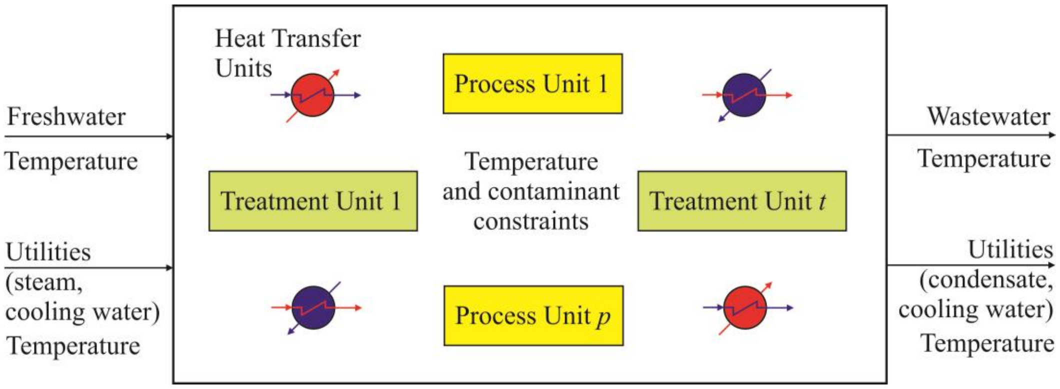


Figure 3. A general representation of non-isothermal water network synthesis problems including process units, treatment units and heat transfer units [46].

Heating and cooling within the network can be performed in heat transfer units or by direct mixing of water streams. Direct heat exchange can be performed by the isothermal and non-isothermal mixing of streams. Non-isothermal mixing can reduce the number of heat exchanger units but it can cause the degradation of energy and temperature driving forces for heat recovery [47]. However, this option should be considered if this option produces a final network design with a fewer number of heat exchangers but without degradation of energy. On the other hand, an indirect heat transfer between hot and cold streams is enabled through a heat exchanger area. In this case heat recovery can be improved but the network design with an increased number of heat exchangers can be obtained within a final network design. All these heat integrations as well as water integration possibilities (water-reuse, wastewater regeneration, regeneration reuse, and regeneration recycling) should be considered during simultaneous optimisation of water and heat integration in order to determine an optimal network design. However, this is a complex task that must be solved systematically and simultaneously in order to explore all water and heat integration opportunities and obtain an appropriate trade-off between investment and operating cost.

The synthesis problems of non-isothermal water networks can be threshold, in which only one type of utility (hot or cold utility) is required or pinched which requires both hot and cold utilities. In threshold problems [47, 48] the temperature of the freshwater is less than the temperature of the wastewater discharged into the environment as well as the maximum temperature of the water-using units. However, in cases in which the temperature of freshwater is greater than the temperature of wastewater discharged into the environment [49], or where multiple sources of freshwater with different temperatures [50] exist in the network as well as in different scenarios of water heating followed by cooling [51] problems are usually pinched requiring both hot and cold utilities.

A general problem formulation regarding non-isothermal water networks can be stated as follows. Given are:

- A set of freshwater sources with different temperatures and qualities
- A set of process units or water-using units with specified operating temperatures and maximum concentrations of contaminants for the inlet and outlet water streams, and contaminants' mass load transferred from process streams to water streams within water-using units. Water-using units can operate isothermally (temperatures at the inlets and outlets of water-using units are the same) and/or non-isothermally (temperatures at the inlets and outlets of the water-using units are different) so in these cases heat losses and gains exist within the water-using units. Water-using units can operate without and/or with water flow rate gains or losses.
- A set of wastewater treatment units (regeneration units) with specified removal ratios of contaminants or fixed contaminant concentrations at the outlets of the wastewater treatment units. The investment and operating cost data are also given.
- A set of hot and cold external utilities with specified temperatures, heat-transfer coefficients, and cost data
- Heat capacities and heat transfer coefficients of the water streams
- Temperature of the wastewater stream discharged into the environment (in the case of a combined water-using and heat exchanger network), or temperature and maximum

concentration of contaminants within a wastewater stream discharged into the environment (in the case of a combined water-using, wastewater treatment and heat exchanger network)

- Hours of a network plant operation per year
- The problem involves only water streams that can be split and mixed within a network.

The goal of this non-isothermal water network synthesis problem is to design a combined water network (consisting of water-using units and/or wastewater treatment units) and a heat exchanger network for a specified objective function (e.g. minimum total annual cost in the mathematical programming approach or minimum water and utility consumption in the pinch analysis approach) and find the connections between freshwater sources, water-using units and/or wastewater treatment units, and the wastewater discharge point, as well as the placement of heat transfer units (heat exchangers, heaters, coolers) on water streams within the overall network.

The synthesis problem of non-isothermal water networks presented in this section can be formulated for a combined water-using network and heat exchanger network, and also extended by considering an additional wastewater treatment network. The vast majority of published papers have considered only combined water-using network and heat exchanger networks without a wastewater treatment network using pinch analysis and mathematical programming. In contrast, only several papers [46, 49, 52-54] have studied combined water-using networks, wastewater treatment networks and heat exchanger networks involving multiple contaminants within water streams. In these studies the mathematical programming approach was applied.

Figure 4 shows the conventional water network design for the most studied example [45, 47, 48] in the literature, which involves four process units and a single contaminant. In this network freshwater is used in all process units and wastewater is discharged into the environment. Note that there is no water reuse and heat integration in this case. Freshwater usage is 112.5kg/s, total consumption of hot and cold utilities 27772.5 and 23047.5kW, and total annual cost 22,078,445 $/y. By applying systematic methods, which are described later in this paper, it is possible to reduce water usage and utility consumption by producing a more profitable and sustainable solution. Figure 5 represents an optimal solution of heat-integrated water-using network design [55]. This network design exhibits the minimum freshwater usage (90kg/s), and the minimum hot (3780kW) and cold (0kW) utility consumption. It consists of three exchange units (two heat exchangers and one heater). The minimum total annual cost of the network is 2,652,959 $/y. Note that there is a significant decrease in hot (3780 vs. 27772.5 kW) and cold (0 vs. 23047.5kW) utilities consumption, freshwater usage (90 vs. 112.5kg/s), and total annual cost (2,652,959 vs. 22,078,445 $/y).

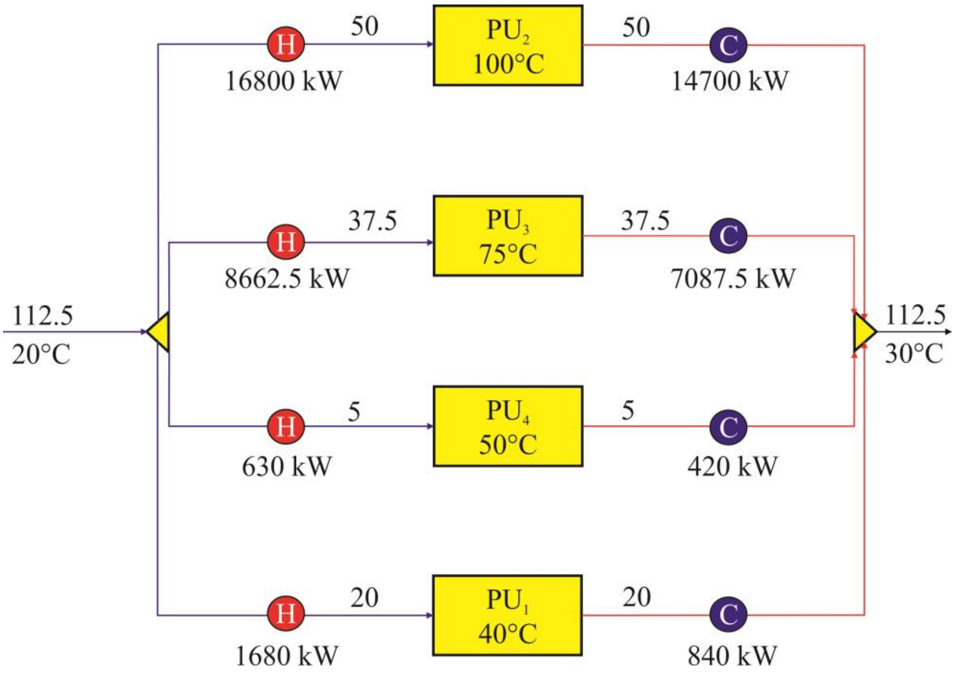


Figure 4. Conventional design of water-using network.

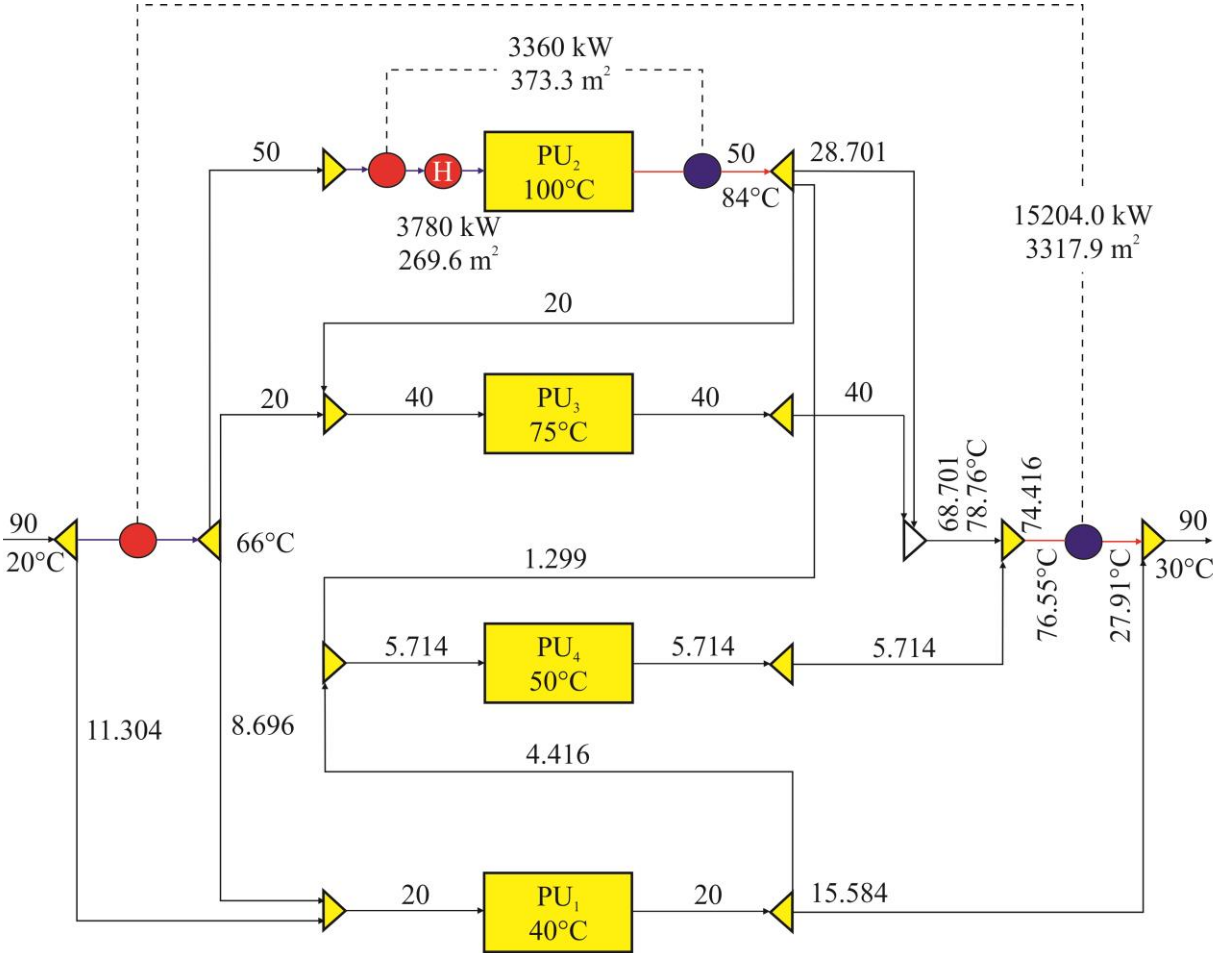


Figure 5. Optimal design of a heat-integrated water-using network.

2.2.2. Brief analysis of previous works on the topic of non-isothermal water networks

In the initial studies on non-isothermal water networks synthesis, the importance of simultaneously considering water and energy interactions within a water network was highlighted and the first conference contribution using pinch analysis within this field appeared in the late 1990s [45]. Several years later the first journal papers were published in the field of water and energy integration within water networks using pinch analysis [47, 48] and mathematical programming [51]. However, in these and many later studies combined water-using network and heat exchanger network were considered but without wastewater treatment networks. Also only single contaminant water network problems were analysed during most studies. It is worth pointing out that an overall non-isothermal water network should be a combination of a water-using network, wastewater network, and heat exchanger network in order to enable simultaneous water integration (water reuse, regeneration reuse and regeneration recycling) and heat integration (direct and indirect heat transfer) (see Figure 3 and 6). The strong and important two-way interactions within, as well as between, these networks must be systematically and simultaneously explored in order to achieve improved results regarding freshwater and utility consumption, wastewater generation, and investment cost.

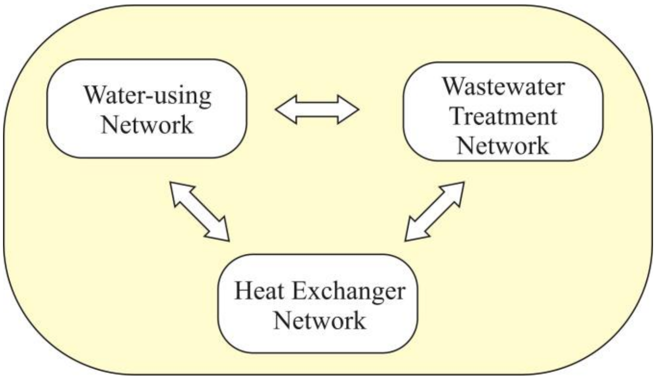


Figure 6. Interactions within an integrated non-isothermal water network.

Additionally, multiple contaminants should be considered within water streams in the network in order to represent more realistic cases. However, this synthesis problem of non-isothermal water networks comprised of water-using network, wastewater treatment network and heat exchanger network, whilst dealing with multiple contaminant systems is a challenging and complex task requiring special solution strategies. It should be mentioned that only several solution strategies have been proposed in order to solve the overall synthesis problem simultaneously. In the following parts of this paper classifications of systematic methods for a combined water and energy integration are presented as well as a comprehensive and critical review of the published works in this field.

3. CLASSIFICATIONS OF SYSTEMATIC METHODS AND STRATEGIES FOR WATER AND ENERGY INTEGRATION

Systematic methods, based on pinch analysis, mathematical programming and their combination (hybrid method) as well as sequential and simultaneous solution strategies have been used for water and energy integration in order to synthesize non-isothermal water networks (combined water and energy networks) (Figure 7). A brief overview of these methods and strategies is given in the following part of the paper.

3.1. Sequential and simultaneous solution methods and strategies

Systematic methods can be a sequential or simultaneous in nature. Pinch analysis represents a sequential solution method whilst mathematical programming problem can be solved using a sequential or a simultaneous approach. In the sequential approach the overall synthesis problem of a non-isothermal water network is decomposed within a sequence of smaller problems, namely, water networks and heat exchanger networks that are easier to solve. However, this approach cannot explore the interactions between sub-systems (water network and heat exchanger network) in order to obtain the improved solution, Also, an appropriate trade-off between investments and operating cost cannot be simultaneously established.

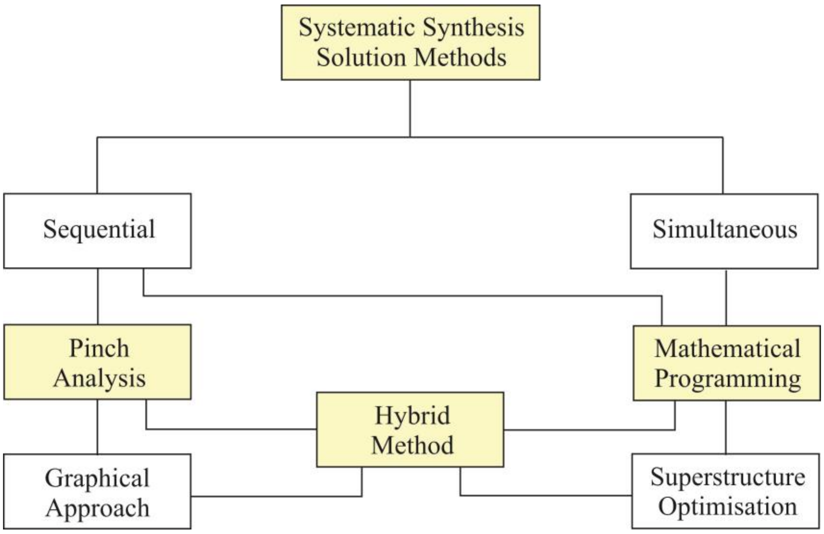


Figure 7. Classifications of systematic methods and strategies for water and energy integration and non-isothermal water network synthesis.

However, in the simultaneous solution approach the interactions between, as well as within, the subsystems of an overall network combining water network and heat exchanger network are fully and systematically explored producing improved solutions with an appropriate trade-off between investment and operating cost [56]. The simultaneous approach has advantages compared to the sequential one, especially in those cases when complex interactions between subsystems and, hence, complex trade-offs between operation and investment costs exist. However, the overall synthesis problem is more difficult to solve due to the complexity of the problem and many interactions. Also, in the simultaneous solution approach applied to combined water and energy networks' temperatures of hot and cold streams as well as their heat capacity flow rates are optimisation variables and thus unknown, in comparison with the sequential approach and the classical HEN synthesis problem, in which they are fixed. Consequently, water streams from the water network must be recognised by the heat exchanger model as hot or cold streams in order to perform simultaneous water and heat integration. In regard to this a set of constraints should be formulated in order to identify hot and cold streams explicitly within the overall network. Recently, different mathematical formulations [54, 55] and strategies [57] have been proposed in order to address this issue.

3.2. Pinch analysis

Pinch analysis represents a conceptual and graphical approach based on physical insights, engineering experience and heuristics. In this approach pinch analysis for heat integration and pinch analysis for water integration are combined in order to address the overall problem of energy and water minimisation. Pinch analysis consists of two phases, namely, targeting and design. The main goals of these phases are to first determine water (e.g. minimum flow rate of freshwater and wastewater) and energy targets (e.g. minimum utility consumption or maximum heat recovery, minimum number of heat transfer units) and then design a water and energy network. Pinch analysis enables better graphical visualisation than mathematical programming. However, this approach is sequential in nature and cannot easily deal with multiple contaminants, practical constraints, and appropriate trade-offs between operational and capital costs cannot be obtained simultaneously. Consequently, the solutions obtained are sub-optimal.

3.3. Mathematical programming

Mathematical programming is based on superstructure optimisation and consists of three main steps, namely, the synthesis of a superstructure, model development, and model solving [9]. According to this approach a superstructure of water and energy networks is first synthesised followed by a mathematical model's development and its solution in order to produce an optimal water and energy network design. The mathematical programming approach can handle the previously mentioned difficulties of pinch analysis (multiple contaminants, practical constraints, simultaneous trade-offs between operation and capital costs). However, the overall synthesis model, especially for larger-scale problems, can be complex (e.g. highly non-linear and non-convex) requiring special solution strategies to be applied in order to obtain an optimal solution. A challenging task for the process systems engineering (PSE) community is to solve the synthesis problems by mathematical programming in order to obtain a global optimum solution or even a good local optimum, and practical solutions, especially for moderate and large-scale synthesis problems.

3.4. Hybrid method combining pinch analysis and mathematical programming

It is important to mention that the advantages of process insights from pinch analysis can be combined with the advantages of numerical and mathematical programming methods in order to successfully address the overall problem [58]. The reader is referred to Ref. [13] for more details about the opportunities of using pinch and mathematical programming methods, as well as their combination, in the heat integration of chemical processes, and retrofit of heat exchanger networks [18]. This hybrid or combined method could be a useful approach for solving the overall synthesis problems, especially large-scale problems. For example, process insights obtained from pinch analysis (water and/or energy targets) can be combined with numerical and mathematical programming methods in order to more easily address and solve the overall synthesis problem. Recently, Manan et al. [59] proposed a new approach for simultaneous water and energy minimisation combining numerical and graphical methods, which was applied to a paper mill plant.

Finally, it can be concluded that the methods presented in the previous sections play important roles in solving the synthesis and retrofit problems within the process industries. Significant savings in energy and water consumption have been achieved over the last few decades by applying these methods within different manufacturing processes (e.g. pulp and paper, oil refining, chemicals, iron and steel, petrochemicals, and food & drink) [60, 61].

4. COMPREHENSIVE AND SYSTEMATIC LITERATURE REVIEW

This section presents a comprehensive and systematic literature review of the published papers in the field of non-isothermal water network synthesis within different time periods (before 2000, 2000-2004, 2005-2009, and 2010-2014). Firstly, the review is provided of those studies based on pinch analysis, mathematical programming, and their combination during overall network synthesis. Then, a systematic and critical review is presented of the main features of the studied problems within the literature. A brief discussion of the batch processes is provided including wastewater minimisation and heat integration. Finally, a brief overview is given of several industrial case studies resulting in minimised water and utility consumption.

4.1. Studies of non-isothermal water network synthesis within different time periods

Table 2 presents the synthesis solution methods (pinch analysis, mathematical programming, and their combination (hybrid or combined method)), and a comprehensive and systematic literature review and analyses of the published papers in peer-reviewed journals and at conference proceedings on the topic of non-isothermal water-usage, and wastewater treatment networks within different time intervals.

Table 2. Systematic overviews of published papers on the topic of non-isothermal water network synthesis within different time periods.

Method	Before 2000	2000-2004	2005-2009	2010-2014	Total
Pinch analysis	[45]	[50], [62]	[47], [48], [59], [63], [64]	[65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76]	
Total:	1	2	5	12	20
Mathematical programming	[77]	[22], [51], [78], [79], [80], [81]	[49], [82], [83], [52], [84], [85], [86], [87]	[46], [53], [56], [55], [54], [57], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110]	
Total:	1	6	8	29	44
Hybrid (combined)		[111], [112]	[113], [114], [115]	[116], [117], [118], [119], [120], [121], [122], [123], [124], [125]	
Total:		2	3	10	15
TOTAL:	2	10	16	51	79

This table only presents those papers strictly addressing continuous non-isothermal water using and wastewater treatment networks. Seid and Majozi [126] recently provided an overview of the published papers considering scheduling of batch plants, energy integration, and wastewater minimisation in these plants, so those papers are excluded from Table 2. It is also important to point out that over the last decade different studies considering water and heat integration within industrial processes (e.g. pulp and paper, biofuels, chemical, food, etc.) have been performed by using pinch analysis, mathematical programming or their combination. However, these works are also excluded from Table 2 because they are not in the category of those papers strictly considering water and heat integration within non-isothermal water networks. However, the final part of this chapter does provide a brief description of the papers considering batch processes and industrial processes including water and heat integration during these processes. As can be seen from Table 2, the first two contributions in the field of non-isothermal water networks appeared before 2000, and after 2000 significant progress has been achieved in this field resulting in an increasing number of contributions. The total number of published papers within the period 1997-2014 was 79. It is interesting to note that over the last five-year period (2009-2014) twice as many papers have been published than within the earlier twelve-year period (1997-2009) (51 vs. 28). Also, the number of published papers using the mathematical programming approach doubled when compared to the studies based on pinch analysis within the period 1997-2009 (47 vs. 20). Finally, it should be mentioned that some studies (12 papers) used a combined approach to address the syntheses problems of non-isothermal water networks.

4.2. Studies of non-isothermal water network synthesis by pinch analysis

This section presents a brief description of the first important works in the field of non-isothermal water networks using pinch analysis, followed by systematic overview of the published contributions within different time periods (see Table 3). The first work considering simultaneous optimisation of energy and water using pinch analysis was provided by Savulescu and Smith [45]. In 1998 they presented work entitled “Simultaneous energy and water minimisation” at the AIChE Annual meeting. They introduced the Two Dimensional Grid Diagram (TDGD) in order to simultaneously consider re-use of water and heat recovery in design. One of the main messages of this study was that a systematic method is required in order to address the problem of simultaneous energy and water minimisation due to complex trade-offs between water consumption, energy requirements, and design complexity. Several years later, the authors extended their previous research and contributed with two journal papers in the field of simultaneous energy and water minimisation by considering systems with no water re-use [48] and with maximum re-use of water [47]. They presented a methodology consisting of targeting and design phases which simultaneously minimise the requirements for water and energy within a water network. Direct and indirect heat recoveries were studied within a network. They highlighted that direct heat recovery (mixing of water streams) requires fewer heat exchangers but it can result in a sacrificing of energy consumption. In contrast, indirect heat recovery can recover the maximum amount of heat but it can result in an increased number of heat exchangers in the overall network. The next part of this section presents a systematic review of those studies based on pinch analysis and corresponding tools and solution strategies (see Table 3) for synthesising an overall non-isothermal water network.

Concept of non-isothermal water-using network

As can be seen from Table 3, the concept of a non-isothermal water-using network is considered in all papers using the pinch analysis method. However, this network should be combined with a wastewater treatment network in order to enable wastewater regeneration reuse and regeneration recycling within the network. Consequently, the freshwater usage, wastewater generation, and utility consumption can be minimised thus achieving a more profitable and sustainable solution. This could be a possible future further research direction.

Tools and solution strategies for freshwater and energy targeting, and the designing of water and heat exchanger networks

The synthesis and designing of non-isothermal water networks consisting of water-using units and heat exchangers has been performed by using different systematic procedures and tools, and solution strategies for water and energy targeting and the design of water-using network as well as heat exchanger network (see Table 3). Generally speaking, the overall system of a non-isothermal water-using network is divided into two parts, namely water-using network and heat exchanger network, and solved sequentially. The water composite curve (concentration vs. mass load diagram) is used in order to minimise the freshwater usage and determine the freshwater target, followed by the water network design, which satisfies the freshwater target. On the basis of the water network design determined during the first step, the water hot and cold streams and their corresponding inlet and outlet temperatures and heat capacity flow rates can be extracted in order to perform heat integration and the designing of a heat exchanger network. Heat composite curves (temperature vs. heat load) are used for heat integration and the hot and cold utility targeting (minimum consumption of utilities). However, the strong interactions between water and energy as well as water and heat exchange networks cannot be systematically explored in this sequential solution. Therefore, sub-optimal solutions can only be obtained. Other tools and solution strategies (e.g. the Two Dimensional Grid Diagram) combines the principles of water and energy pinch analysis in order to simultaneously explore water-reuse and heat recovery opportunities and determine the freshwater and hot and cold utilities targets before the overall network design (see Table 3). In general, in these solution strategies water and energy targeting is performed simultaneously producing the water network design of the first step, followed by heat exchanger network design during the second step. However, the overall synthesis problem and network design is again solved sequentially in two-step procedures. The reader is referred to Table 3 in which a systematic review is provided for the tools and solution strategies in order to perform freshwater and energy targeting as well as water and heat exchanger network design. Finally, it is important to mention that the pinch tools and solution strategies are proposed only for non-isothermal water-using networks without considering a wastewater treatment network. In reality an integrated water network consists of an integrated non-isothermal water-using and wastewater treatment. As this integrated network enables additional opportunities for water integration (wastewater regeneration reuse and regeneration recycling) and heat recovery (direct and indirect heat transfer) possible future research could be expected in this direction in order to develop novel tools and solution strategies by addressing an integrated non-isothermal water-using and wastewater treatment network.

Studies on the effect of non-isothermal mixing

Different studies have been presented in the literature that have investigated the influence of non-isothermally mixing water streams within the water network on hot and cold utility targets and some rules are proposed in order to avoid any energy penalties (see Table 3). The studies on the effect of non-isothermal mixing are important because they provide rules that can be useful for mathematical programming in order to develop simplified and more efficient models, thus avoiding energy penalties during simultaneous optimisation of water and energy integration.

Table 3. Synthetic overview of concepts, pinch analysis tools, and solution strategies used for solving the studied problems.

Pinch Analysis	**Before 2000**	**2000-2004**	**2005-2009**	**2010-2014**
Synthesis concepts				
Heat-integrated (non-isothermal) water-using networks (HIWNs)	[45]	[50], [62],	[47], [48], [59], [63], [64]	[65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76]
Tools and Solution Strategies				
Water Targeting				
Water Cascade Analysis (WCA) [127]			[59]	
Water Pinch				[68]
Energy Targeting				
Energy Composite Curve (T-Q)		[62]		[68], [70], [71], [74], [75]
Problem Table for heat integration [9]				[67], [72]
Source-Demand Energy Composite Curve		[50]		
WN Design				
Cleanest and Cleanest Rule [128]			[59]	
Pinch Design Method [129]			[63]	[66]
HEN Design				
Separate Systems/sub-Systems		[50], [62]		[67]
Pinch Design Method			[59]	
Process insights and heuristics			[63]	[66]
Grid Diagram Representation				[70]
Simultaneous water and energy targeting and WN Design				
Two Dimensional Grid Diagram	[45]		[47]	

Table 3 (continued)

Water Energy Balance Diagram		[64]	
Energy Composite Curves		[48]	
Temperature vs. Concentration Diagram			[69], [73]
Superimposed Mass and Energy Curves (SMEC)			[70]
Temperature and Concentration Order Composite Curves (TCOCC)			[76]
HEN Design			
Heuristic Approach			[76]
Composite Curves			[69], [73]
Separate Systems/sub-Systems	[45]	[48], [47], [64]	
Studies on the effect of non-isothermal mixing			[67], [71], [72], [74], [75]

4.3. Studies of non-isothermal water network synthesis by mathematical programming

The goal of this section is to first present a brief description of the initial important works in the field of non-isothermal water networks using mathematical programming, and then summarise, systemise, and analyse all published contributions in this field during different time periods (see Table 4). The first comprehensive review in the field of water network synthesis using pinch analysis and mathematical programming was given by Bagajewicz [22]. Mainly those studies relating to isothermal water network synthesis have been analysed and discussed in this review paper. However, simultaneous water minimisation and heat integration within non-isothermal water networks has also been highlighted as an important issue within chemical process plants [77]. Using an illustrative single contaminant problem a discussion between pinch analysis and mathematical programming is provided showing that mathematical programming can better address simultaneous water and energy integration compared to pinch analysis (e.g. those cases when heating is required in process-to-process streams, multiple contaminants, etc.) [22]. Also, it has been highlighted that network design consisting of water and heat exchanger network involving the splitting of freshwater streams and the merging of the wastewater streams cannot be obtained automatically, and that further progress in this field is required. The first comprehensive journal paper related to simultaneous minimisation of freshwater and energy consumption within water networks using mathematical programming was the study by Bagajewicz et al. [51]. They presented models for minimum freshwater and utility targeting, and used state-space representation of the synthesis problem. In their approach hot utility is minimised for a fixed amount of freshwater determined during the freshwater targeting step followed by creating a heat exchanger network design. The merging procedure presented is not systematic although it produces a structure of less complexity than the structure given by Savulescu and Smith [45]. The approach used is sequential in nature to that applied to a single contaminant problem. However, an automated simultaneous approach is required for simultaneously considering and solving the overall water and energy problem by exploring the complex trade-off between operational and investment costs. Table 4 shows a summarised and systematic review of the contributions on non-isothermal water networks during different time intervals highlighting the main synthesis concepts, mathematical modelling formulations and solution strategies, as well as other important issues in this field.

Synthesis concepts

Different synthesis concepts were used in order to address the synthesis problem of non-isothermal water networks (see Table 4). The first studies considered a network consisting of a non-isothermal water-using network and a heat exchanger network or heat-integrated water-using network (HIWN). In order to easily solve the overall problem, the network was divided in two parts, water using network and heat exchanger network, and solved sequentially. This approach was used in many of the published studies. Later, the overall combined network (non-isothermal water-using network and a heat exchanger network) was solved simultaneously, and improved results were obtained compared to the sequential solution of the synthesis problem. In order to enable wastewater treatment and reuse and the recycling of wastewater, the synthesis concept was extended in order to incorporate wastewater treatment. The resulting combined network consisting of water-using network, wastewater treatment network, and heat exchanger network (HIWTN) enabled exploring additional water and heat integration opportunities within the network, thus minimising freshwater usage, wastewater generation, and utility consumption. However, the complexity of the overall synthesis problem was increased due to the increased number of constraints, optimisation variables and bilinear terms of the mathematical model, and special solution strategies were required in order to solve this problem. The authors proposed different initial superstructures to address these syntheses problems. In general, a superstructure included water-using units (process units), wastewater treatment units, heat transfer units, splitters, and mixers. Freshwater source (s), hot and cold utilities are supplied to this superstructure and wastewater effluent is discharged from the superstructure into the environment. Also, the authors considered different options for heat transfer (direct and indirect), and the splitting and mixing of water streams within water and wastewater networks, as well as within heat exchanger networks. The superstructure optimisation approach enables consideration of simultaneously multiple contaminants, required/forbidden matches, additional heat integration opportunities (e.g. indirect heat transfer between water-reuse streams and other hot streams in the network), heat and flow rate losses and gains. Moreover, appropriate trade-offs between fresh water usage, utility consumption and investment can be obtained simultaneously.

In addition, in order to address the synthesis problem of non-isothermal water networks, the authors have used different network representations, namely, state-space, source-demand or source-sink, and considered the same or similar issues previously presented for the superstructure synthesis representation (see Table 4). In recent studies the synthesis concept of multi-scale state-space representation is used in order to synthesise interplant water-allocation and heat exchange networks (IWAHENs) with direct and indirect integration schemes, while the synthesis concept of source-sink representation is used for the synthesis of concentration and property-based heat-integrated resource conservation networks (HIRCNs). The concept of an eco-industrial park and the global equivalent cost of fresh water are used in order to consider the water and energy management within the network consisting of several processes that share common infrastructure.

Mathematical Models and Solution Strategies

The authors have proposed different mathematical models and solution strategies, namely sequential and simultaneous in order to solve the synthesis problems of non-isothermal water networks (see Table 4). Generally speaking, in sequential solution strategy a water network design is solved first followed by solving a heat exchanger network design. Finally, solutions of the water and heat exchanger network designs are joined in order to represent the overall non-isothermal water network. In simultaneous solution strategy, most mathematical models of the overall synthesis problems are usually formulated as MINLPs but due to their complexities and non-convexities, especially for moderate and large-scale problems, they cannot be solved directly by available global optimisation solvers. Consequently, a good initialisation point is required for solving MINLPs by local optimisation solvers. It is important to point out that obtaining near global or good locally optimal solutions for these types of problems is still a challenge for chemical engineers and researchers. The initialisation point for MINLPs of non-isothermal water networks is provided using different approaches, for example, stochastic perturbation procedures, water and energy targeting models, combined water network and heat integration models, etc. In some cases an MINLP is solved within iterations of the NLP as a sub-problem and MILP master problem before identifying the optimal solution. It is important to highlight that the authors developed different models (see Table 4), for example, water and heat targeting models for simultaneous flow sheet optimisation, simultaneous minimisation of water and energy, identification of hot and cold streams within the network for heat integration, and used epsilon constraint strategy and bi-objective optimisation in order to address the synthesis problems of non-isothermal water networks. The objective functions used in mathematical programming approaches minimise freshwater usage and utility consumption or total annual cost (TAC) including investment (e.g. for heat exchangers, wastewater treatment units, piping, etc.) and operating costs (e.g. freshwater and utility cost). Finally, it should be highlighted that the simultaneous mathematical programming approach enables the obtaining of trade-offs between the investment and operating costs of the overall network.

Table 4. Systematic overview of concepts, mathematical programming models, and solution strategies.

Mathematical programming	**Before 2000**	**2000-2004**	**2005-2009**	**2010-2014**
Synthesis concepts				
Heat-integrated (non-isothermal) water-using networks (HIWNs)	[77]	[22], [51], [78] [79], [80], [81]	[49], [52], [82], [83], [84], [85], [86], [87]	[56], [55], [57], [88], [89], [90], [91], [92],[93], [96], [97], [98], [99], [101], [102], [103], [104], [105], [106], [109]
Heat-integrated water-using, and wastewater treatments networks (HIWTNs)			[49], [52] , [54]	[46], [53], [90], [100], [101], [108]
Interplant water-allocation and heat-exchange networks (IWAHENs)				[94], [95]
Heat-integrated resource conservation networks (HIRCNs)				[107]
Eco-industrial parks				[88]
State-space representation		[22], [51]	[49]	[106]
Multi-scale state-space representation				[94], [95]
Source-demand or source-sink representation				[103], [104]
Mathematical Models and Solution Strategies				
Sequential: WN design → HEN design				
NLP → MINLP		[79]	[52], [83], [84]	[56], [97]
MILP → MINLP				[57], [93]
MINLP → MINLP		[80]	[54]	[92]
MINLP (MILP → NLP)			[82]	
LP [130] → MILP [130] + constraints [85] → Trans-shipment model [131] → MILP				[105]

Table 4 (continued)

Water and energy targeting models → MINLP	[81]		[106]
Water and energy targeting models (LP) → MILP	[22], [51]		
Stochastic perturbation procedure → MINLP		[49]	
WN targeting-Minimum number of temperature local fluctuations (MINLP)		[85]	
Two-stage MINLP		[86]	
MILP/Integer cut constraint (ICC)			[103]
Simultaneous: Initialisation → WN+HEN design			
MINLP (ASAGA algorithm)	[80]		
MINLP (WN model) → MINLP			[46], [56], [55], [91], [96], [102], [109]
NLP (WN+HI models) → MINLP			[53], [98], [99], [108]
MILP → MINLP	[78]		
MINLP (WN+HI models) MINLP			[53], [100]
Initial guesses and random perturbations → MINLP (MILPs → NLPs)			[94], [95]
The bounds of some variables are determined in advance → MINLP		[86]	
Other mathematical models			
Water and heat targeting models for simultaneous flow sheet optimisation			[90], [101]
Simultaneous minimisation of water and energy			[104]
Minimizing energy consumption and global equivalent cost			[88]
Bi-objective optimisation			[89]
Identification of hot and cold streams for HEN		[52]	[55], [57], [98], [106]

4.4. Studies of non-isothermal water network synthesis by the combined approach

A combined (hybrid) approach based on using pinch analysis and mathematical programming can be applied in order to address the synthesis problem of non-isothermal water networks. This approach can be useful in solving the synthesis problems both sequentially and simultaneously. In a sequential strategy it is possible, for example, to first solve the water network design problem by pinch analysis and then the heat exchanger network design problem by mathematical programming, and vice versa. Moreover, in simultaneous solution strategy the solution obtained by pinch analysis can be used in order to provide good bounds for the overall synthesis problem solved by mathematical programming.

Table 5 presents a systematic overview of synthesis concepts, models/tools, and solution strategies of a combined approach used in the studies on non-isothermal water networks, as published in the literature.

Synthesis concepts

A combined approach is used in order to mainly address the synthesis problems of non-isothermal water-using networks (see Table 5). Only in one study has non-isothermal water-using network been considered that included wastewater regeneration. Also, the synthesis concepts of source-demand and multiple water allocation networks have been used in order to address the problem of non-isothermal water networks including water and heat integration.

Mathematical Models and Solution Strategies

A combined approach based on a sequential solutions strategy is applied in the studies presented in Table 5. In this approach the water network design problem is solved first (by pinch analysis or mathematical programming) followed by solving the heat exchanger design problem (by mathematical programming or pinch analysis). In order to design water networks, the following proposed methods and models are used: non-isothermal mixing point identification (MILP), non-isothermal mixing (NLP), Modified Problem Table Algorithm (MPTA), a combination of LP/Trans-shipment model/DNLP, and Tableau-based procedure, whilst for designing heat exchanger networks New separate system generation, Separate systems generation, and Pinch Design method have been used (see Table 5).

Table 5. Systematic overview of the concepts, models/tools, and solution strategies of a combined approach.

Combined approach (PA+MP)	**2000-2004**	**2005-2009**	**2010-2014**
Synthesis concepts			
Heat-integrated (non-isothermal) water-using networks (HIWNs)	[111], [112]	[113], [115]	[119], [120], [121], [122], [123], [124], [125]
Heat-integrated water-using, and wastewater treatments networks (HIWTNs)		[114]	
Multiple water allocation networks (WANs)			[124], [125]
Heat-integrated resource conservation networks (HIRCNs)			[116], [117], [118]
Source-demand or source-sink representation			[119], [121]
Mathematical Models and Solution Strategies			
WN design → HEN design			
Water pinch (or MP) → Pinch Design method (or MILP)	[111]		
Non-isothermal mixing point identification (MILP) → New separate system generation	[112]		
Non-isothermal mixing (NLP) → Separate systems generation (PA)		[114], [115]	[120]
Discretized MINLP (MILP) → Pinch Design method [132]			[117]
MINLP Water and energy targeting model → Pinch Design method [132]			[116], [118]
Modified Problem Table Algorithm (MPTA) → Pinch Design method			[119]
LP → Trans-shipment (isothermal mixing)/ DNLP (non-isothermal mixing) → Pinch Design method			[121]
Trans-shipment model [131] → Pinch Design method			[122]
Tableau-based procedure, Energy recovery algorithm (ERA) and Grand Composite Curves (GCC)			[123], [124], [125]

4.5. The main features of the studied non-isothermal water network problems

The studied problems of non-isothermal water networks in the literature using synthesis solution methods based on pinch analysis, mathematical programming or their combination have different features, as shown in Table 6. The synthesis problems including single and multiple contaminants as well as negligible contaminants are considered where the vast majority of studies considered single contaminant problems. It was discovered that only one recent study [76] has considered multiple contaminant problems using a graphical approach, denoted as temperature and concentration order composite curves (TCOCC), whist in four studies multiple contaminant problems have been solved by combined approaches. Note that there are numerous studies in which multiple contaminant problems were solved by using mathematical programming approaches. In addition, the authors considered problems with multiple properties (i.e. concentration, temperature, pH, density, toxicity, etc.) using mathematical programming approaches. In several studies multiple sources of freshwater have been considered. The studied problems included different types of problems, namely, fixed flow rate, fixed load, or their combination. Non-mass transfer-based operations were considered by pinch analysis, and flow rate loss/gain by a combined approach. Also, heat losses and gains, isothermal and non-isothermal mixing, pinch and threshold problems were considered in the studied examples using all approaches. Finally, note that only two papers have considered non-isothermal water-using network problems including wastewater regeneration using a combined approach, and ten studies using mathematical programming (see Table 6).

Table 6. Main features of the studied non-isothermal water network problems.

Features of the Studied Problems	**Pinch Analysis**	**Mathematical Programming**	**Combined Approach**
Single contaminant	[45], [47], [48], [59], [63], [64], [65], [66],[67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [133]	[22], [46], [49], [51], [52], [53], [54], [55], [57] [78], [82], [83], [84], [85], [88], [89], [91], [92], [93], [94], [95], [98], [99], [100], [101], [102], [103], [105], [106], [109]	[56], [104], [111], [115], [116], [117], [118], [119], [121], [122], [123], [124]
Multiple contaminants	[76]	[46], [49], [52], [53], [55], [79], [80], [86], [92], [94], [95], [96], [97], [98], [99], [101], [102], [103], [108], [109]	[119], [120], [121]
Negligible contaminants	[50], [62]		[125]
Multiple properties			[116]
Multiple freshwater sources	[50], [62]	[53], [82], [101]	[118]
Fixed contaminant mass load	[45], [47], [48], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [76]	[22], [46], [49], [51], [52], [53], [54], [55], [57], [78], [79], [80], [83], [84], [85], [86], [88], [89], [91], [92], [93], [95], [96], [98], [99], [100], [102], [103], [105], [106], [108], [109]	[56], [113], [114], [115], [120], [122]
Fixed flow rate	[50], [59], [62], [74], [75], [133]	[82], [94], [95], [101]	[104], [116], [117], [118], [119], [121], [123], [124], [125]
Combination of fixed flow rate and fixed contaminant mass load		[95]	
Non-mass transfer based operations	[70]		
Flow rate losses and/or gains			[119]

Table 6 (continued)

Heat losses and/or gains	[47]	[46], [52], [53], [108]	[114], [115], [120]
Isothermal mixing	[47], [48], [50], [59], [62], [63], [66], [76]	[79], [80]	[56], [119], [121], [123], [124], [125]
Non-isothermal mixing	[45], [47], [48], [50], [59], [62], [64], [67], [68], [69], [71], [72], [73], [74], [75]	[22], [46], [49], [51], [52], [53], [54], [55], [57], [78], [82], [83], [84], [85], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [108], [109]	[56], [104], [111], [113], [114], [115], [116], [117], [119], [120], [121], [122], [124], [125]
Fixed removal ratio in treatment units		[46], [49], [52], [53], [94], [95], [100], [101], [108]	
Fixed contaminant concentration at the outlet of treatment unit		[54]	[114]
Threshold	[45], [47], [48], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [76]	[22], [49], [51], [52], [53], [55], [57], [78], [79], [80], [83], [84], [85], [86], [89], [91], [92], [93], [94], [95], [98], [99], [100], [101], [102], [103], [106], [109]	[56], [111], [104], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [125]
Pinched	[50], [59], [62], [74], [75]	[46], [49], [52], [53], [54], [82], [94], [95], [96], [98], [100], [101], [103], [105], [106], [108]	[117], [118], [119], [121], [123], [124], [125]

4.6. Studies of water and energy optimisation in batch plants

The synthesis problems of water and energy integration within continuous processes have been widely studied in the literature compared to water and energy integration within batch processes. Batch processes have received relatively little attention in the literature. In these problems the additional time dimension is taken into account. One of the first studies considering water management and optimisation of water use in batch processes was work by Almato et al. [134], who developed a mathematical model describing water reuse through a storage tank. One of the model's objectives was to minimise water, utility (hot and cold) and network investment costs. They presented results for two industrial case studies, namely, a brewery and a fruit juice production plant showing water reduction of up to 50%. Over the last couple of years several interesting studies have considered water and energy issues within batch process scheduling where the main goal was to develop a methodology that could be applied for solving the overall problem including scheduling, and heat and water minimisation. Following this research direction, Halim and Srinivasan [135] proposed a sequential approach in order to address water and energy optimisation during batch process scheduling, and later Adekola et al. [136, 137] presented a unified framework for the simultaneous optimisation of water and energy in multipurpose batch processes by considering direct and indirect heat integration. Finally, Seid and Majozi [126, 138] presented an improved model for water and energy optimisation within a multipurpose batch plant. They showed that improved results in terms of cost could be achieved of about 35% by applying water and heat integration embedded within the scheduling frameworks and solved simultaneously. Finally, it is important to highlight that Seid and Majozi [126] also presented a comprehensive literature review regarding this research field.

4.7. Industrial case studies considering water and heat integration within a process

Table 7 presents industrial case studies in which water and energy were optimised within different processes (pulp and paper, bio-fuels, methanol, petroleum refinery) but a concept of non-isothermal water networks was unconsidered and not applied in these cases. In addition, Table 7 shows some industrial case studies in which non-isothermal water networks were optimised. In most of the industrial applications presented in Table 7 optimisation was performed in order to obtain process design but is some cases the goal was to perform process retrofitting.

Table 7. Industrial case studies in which water and energy integration is considered.

Synthesis Studies	Water and energy optimisation*	Non-isothermal water networks
Pulp and paper	[59], [65], [139], [140], [141], [142], [133], [143], [144], [145], [146], [147], [148], [149]	[93], [104]
Biofuels	[101], [150], [151], [152], [153]	
Methanol	[101]	
Petroleum refinery	[154]	
Vinyl acetate monomer		[117]
Vinyl chloride monomer		[106]
Vinyl chloride polymerisation		[57]
Retrofit Studies	[139], [140]	[65]

*A concept of non-isothermal water networks is not applied in these studies

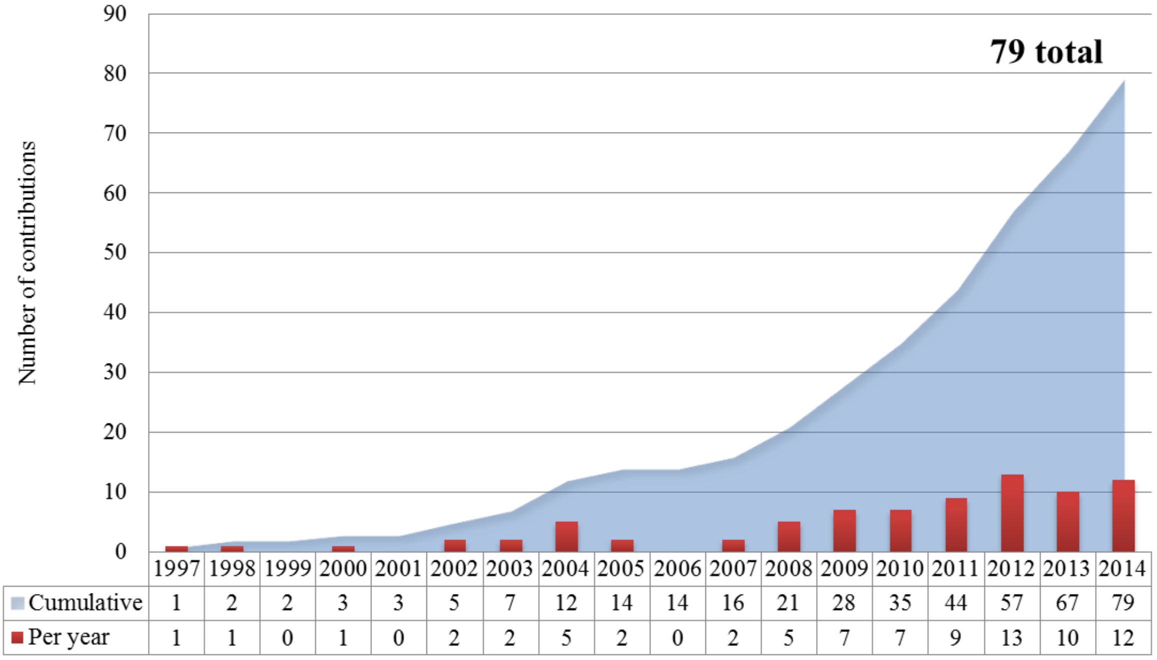
5. ANALYSIS AND STATISTICS OF THE PUBLISHED PAPERS

5.1. Scope of the analysis in this review

This section presents a comprehensive analysis of the published contributions including peer-reviewed journal papers and conference papers (presented and published at conference proceedings) using pinch analysis (PA), mathematical programming (MP), and a combined approach (PA-MP). Some of these conference studies have been substantially extended later and published as peer-reviewed journal papers. Analyses and statistics were performed for 79 contributions within the field of continuous heat-integrated (non-isothermal) water networks during different time periods, similarly as given by Furman and Sahinidis [16] for heat exchanger network synthesis. Contributions related to batch scheduling processes and specific processes (e.g. pulp and paper, biofuels, refineries etc.) in which water and heat integration are not performed by applications of non-isothermal water networks are excluded from this analysis.

5.2. Number of contributions by year and their cumulative number

Figure 8 shows a number of contributions by year and their cumulative number at the end of each year starting from 1997, when the first contribution related to the synthesis of heat-integrated water networks was presented by Savelski and Bagajewicz [77], including 2014. It is important to point out that the number of contributions until 2009 did not exceeded 5 per year, and after that period this number is increased (up to 13 contributions per year in 2012) resulting in 58 contributions published within the last five-year period (2009-2014, including 2009) which is more than two-fold (58 vs. 21) compared to the eleven-year period (1997-2008, including 2008).

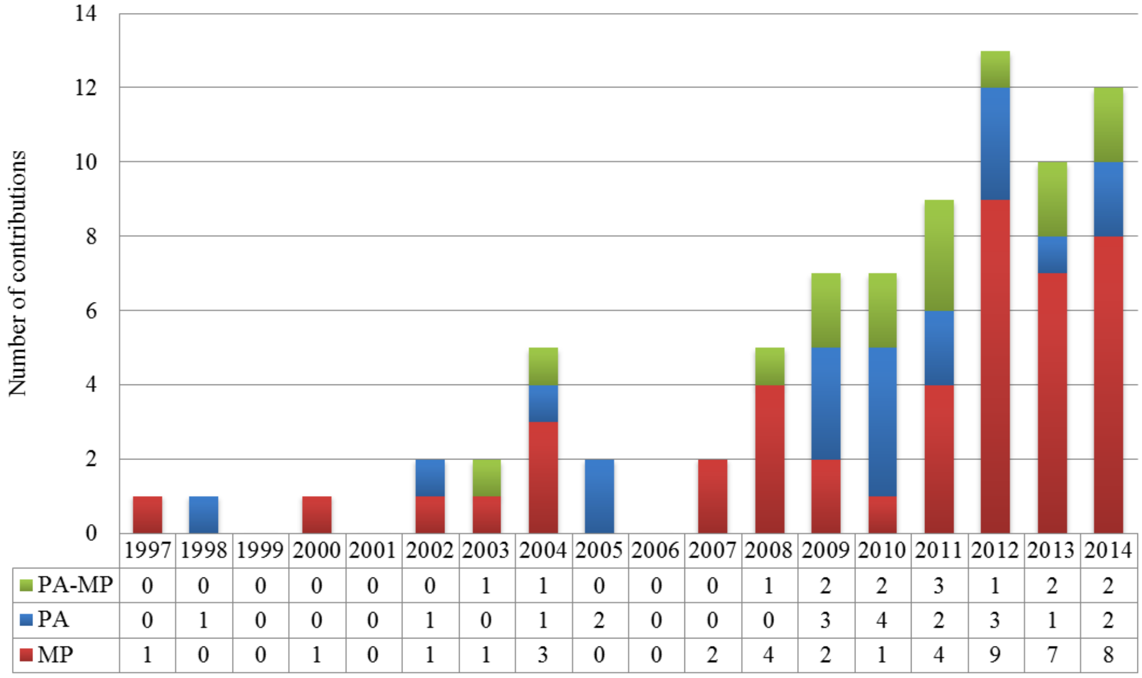


	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
■ Cumulative	1	2	2	3	3	5	7	12	14	14	16	21	28	35	44	57	67	79
■ Per year	1	1	0	1	0	2	2	5	2	0	2	5	7	7	9	13	10	12

Figure 8. Number of contributions per year and their cumulative number.

5.3. Distribution of contributions by year using different synthesis solution methods

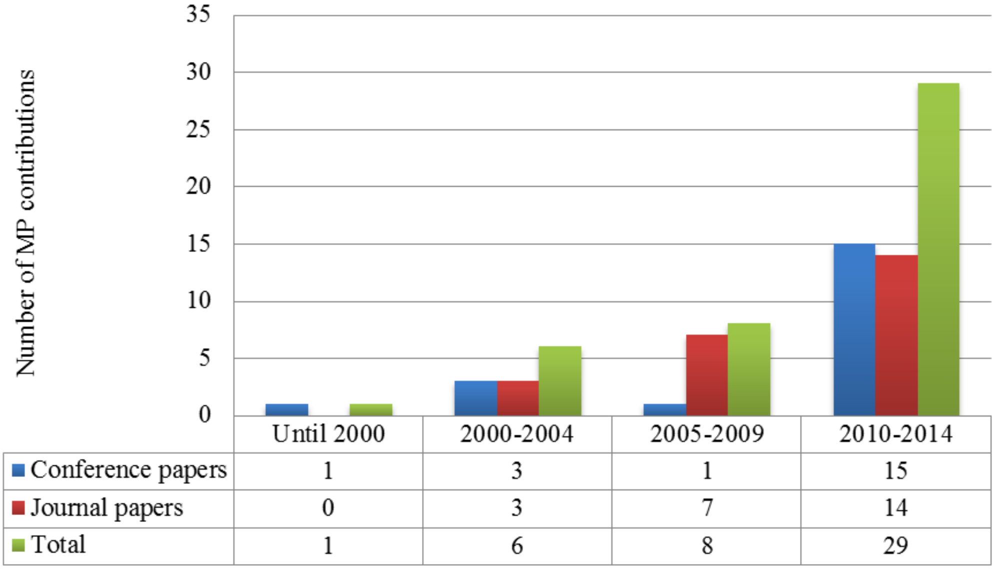
Figure 9 shows the distribution of contributions using different methods by year. In 44 contributions the mathematical programming method was used, in 20 pinch analysis method, and in 15 contributions a combined method is applied. It can be clearly seen that there has been an increasing number of contributions, especially within the last period (2010-2014). Also, note that within this period the number of contributions were as follows: 29 (mathematical programming), 12 (pinch analysis), and 10 (combined approach).



	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
🟩 PA-MP	0	0	0	0	0	0	1	1	0	0	0	1	2	2	3	1	2	2
🟦 PA	0	1	0	0	0	1	0	1	2	0	0	0	3	4	2	3	1	2
🟥 MP	1	0	0	1	0	1	1	3	0	0	2	4	2	1	4	9	7	8

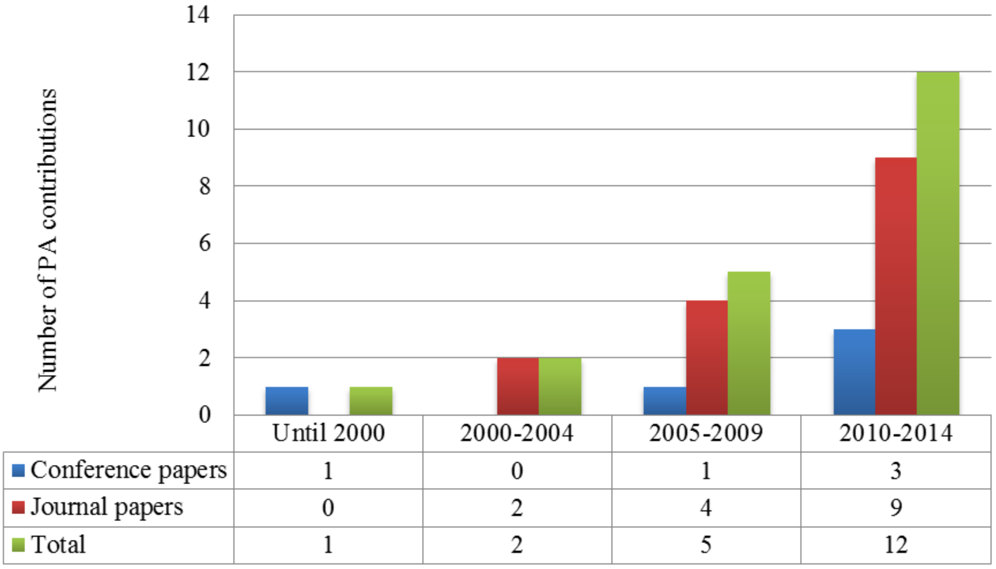
Figure 9. Distribution of contributions by year using different synthesis solution methods.

In addition, an analysis relating to the specific methods applied in the peer-reviewed journal and conference papers is given in Figures 10-12.



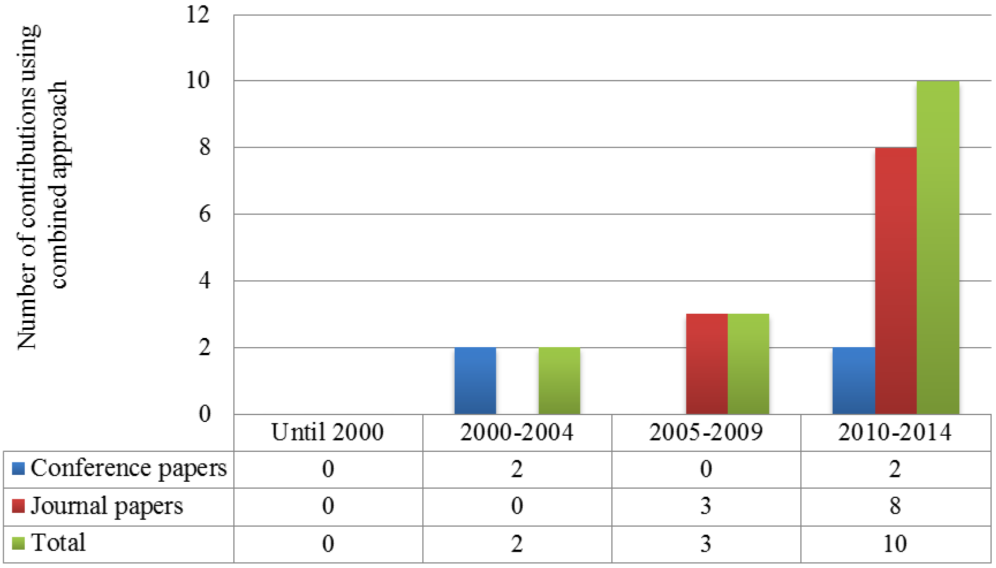
	Until 2000	2000-2004	2005-2009	2010-2014
🟦 Conference papers	1	3	1	15
🟥 Journal papers	0	3	7	14
🟩 Total	1	6	8	29

Figure 10. Number of mathematical programming contributions within different time periods.



	Until 2000	2000-2004	2005-2009	2010-2014
🟦 Conference papers	1	0	1	3
🟥 Journal papers	0	2	4	9
🟩 Total	1	2	5	12

Figure 11. Number of pinch analysis contributions within different time periods.



	Until 2000	2000-2004	2005-2009	2010-2014
🟦 Conference papers	0	2	0	2
🟥 Journal papers	0	0	3	8
🟩 Total	0	2	3	10

Figure 12. Number of combined approach contributions within different time periods.

5.4. Distribution between (and within) peer-reviewed journal and conference papers

Figure 13 shows the distributions of the published peer-reviewed journal and conference papers, where 63% of the contributions (50) have been published in the journals and 37% (29) in conference proceedings.

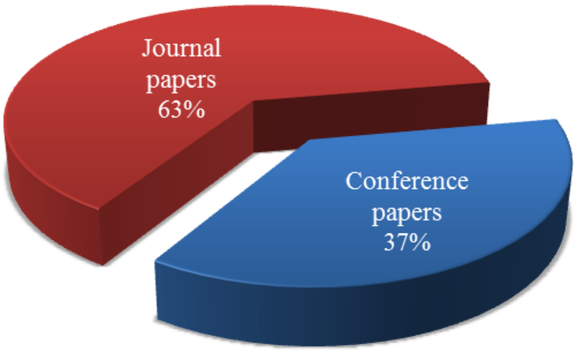


Figure 13. Distribution between peer-reviewed journal and conference papers.

Figure 14 presents a distribution of peer-reviewed journal papers within different journals. It can be clearly seen that Applied Thermal Engineering (ATE) had the largest number of publications (8), whilst the Computers & Chemical Engineering (C&CE), Chemical Engineering Science (CES) and Industrial and Engineering Chemistry Research (IECR) journals each had 6 publications. The right hand side of Figure 14 present the distribution of two or less publications within different journals.

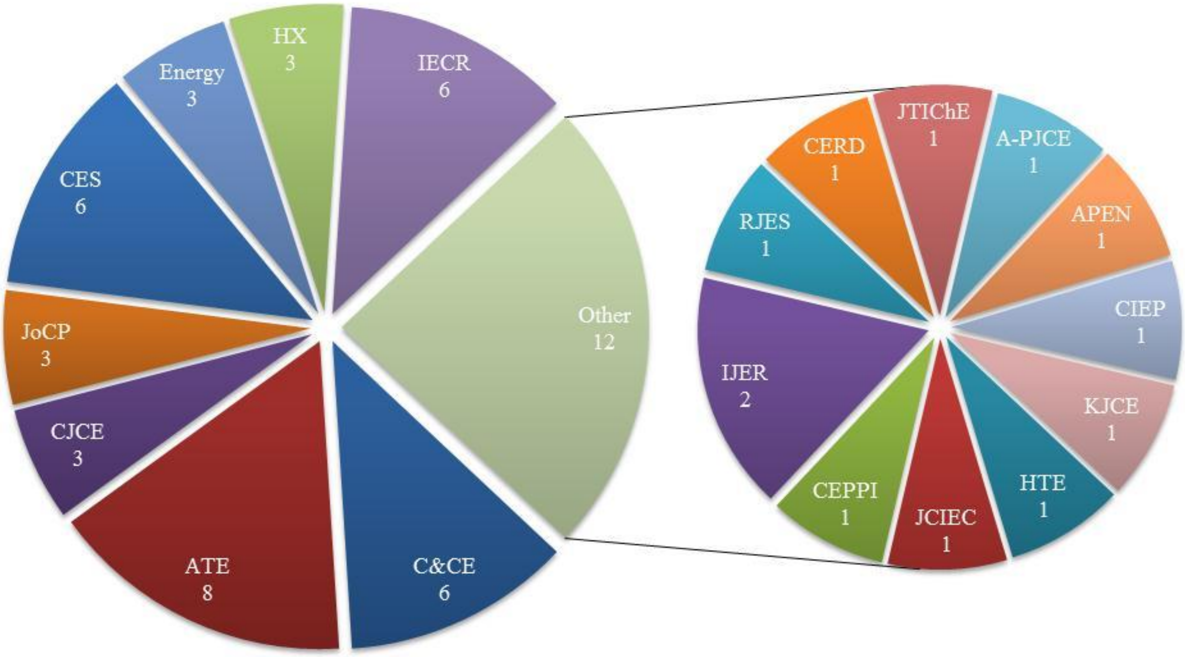


Figure 14. Distribution of peer-reviewed journal papers within different journals.

Figure 15 shows the distributions of 29 conference papers within different conference proceedings. The conference papers were published in Computer-Aided Chemical Engineering (CACE) proceedings (24%) as special issues of European Symposium on Computer Aided Chemical Engineering (CACE-ESCAPE), and International Conference on Process Systems Engineering (CACE-PSE) (17%). Note that 21% papers are published in conference proceedings Chemical Engineering Transactions (CET) related to Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES), and AIChE Annual Meeting conference proceedings (21%). Conferences on the Sustainable Development of Energy, Water and Environment Systems (SDEWES), Slovenian Chemical Days (SKD) and International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS) are also recognised as important international conferences within the field of PSE and sustainable development.

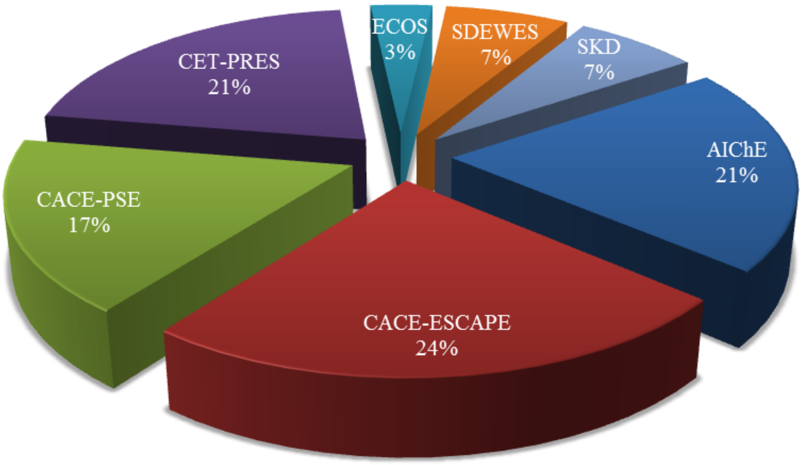


Figure 15. Distributions of conference papers within different conference proceedings.

5.5. Distributions of contributions between regions, countries and institutions

Figure 16 shows the regions where the research works were carried out (based on the authors' affiliations). As it can be seen from this the figures' works were approximately equally distributed between the Americas, Europe and Asia. Also, we provide an analysis of the number of contributions by regions as well as the methods used for solving the synthesis problems (Figure 17).

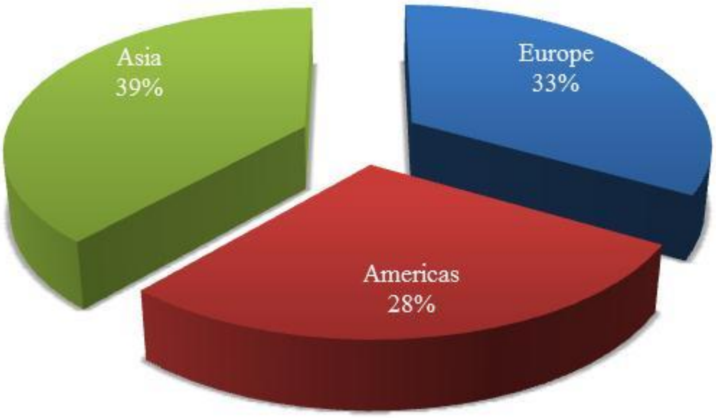
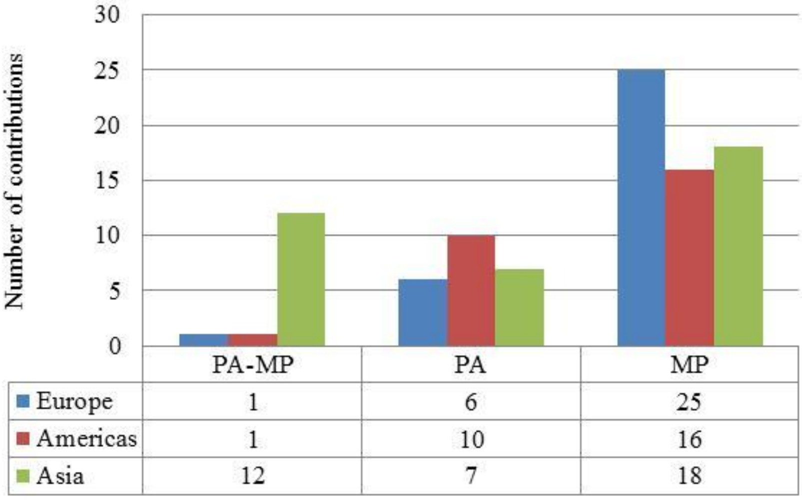


Figure 16. Distributions of contributions by regions.



	PA-MP	PA	MP
🟦 Europe	1	6	25
🟥 Americas	1	10	16
🟩 Asia	12	7	18

Figure 17. Number of contributions by regions and methods used when solving the problem.

Figure 18 shows the numbers of contributions from 17 countries, whilst Figure 19 presents contributions from 37 Universities and Research Institutions. It should be mentioned that several contributions considered in this analysis, for which abstracts in English are provided, were published in Chinese journals [67, 74, 122, 155]. This also contributes to the total number of contributions in China (22) as shown in Figure 18. More than 10 contributions were provided by researchers from Slovenia, USA, Bosnia and Herzegovina (B&H) and UK. It should be noted that the numbers of contributions related to countries usually depended on research groups from corresponding universities and research institutions. However, in some cases publications from different institutions belonged to the same research group.

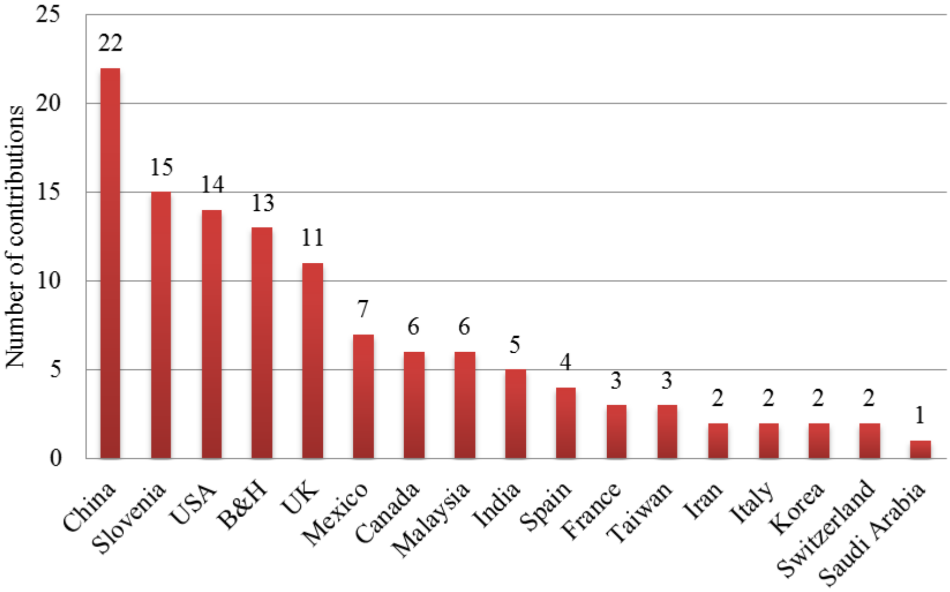


Figure 18. Number of contributions by countries.

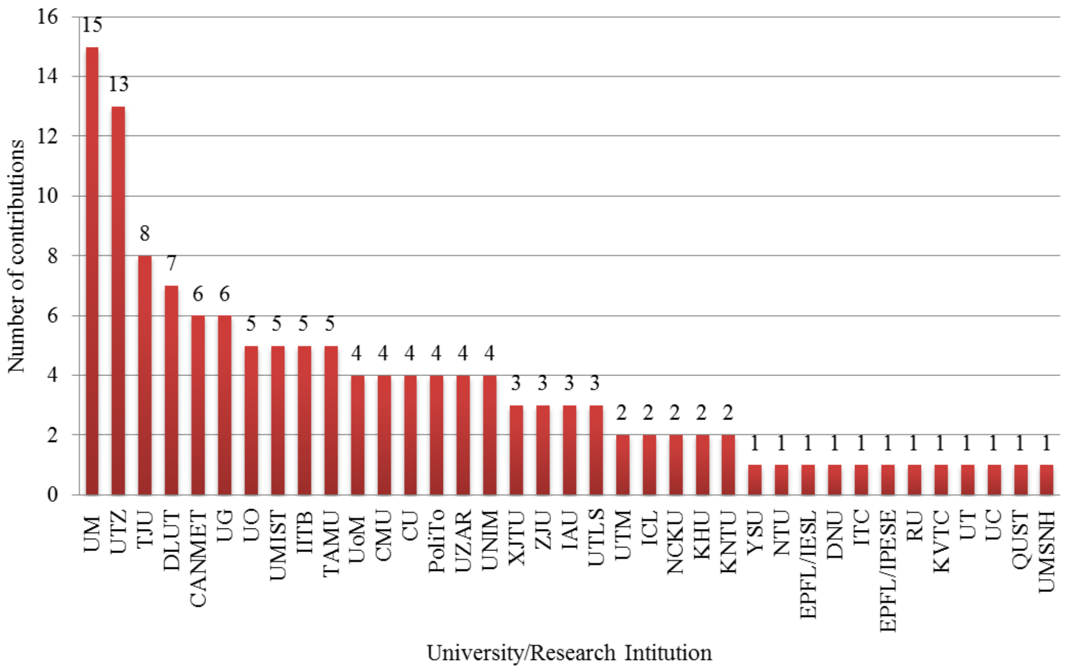


Figure 19. Number of contributions by Universities and Research Institutions.

Table 8. Abbreviations used for Universities.

University name	**Abbreviations**
Carnegie Mellon University	CMU
Curtin University	CU
Dalian Nationalities University	DNU
Dalian University of Technology	DLUT
EPFL/Industrial Energy Systems Laboratory	EPFL/IESL
EPFL/Industrial Processes & Energy Systems Engineering Group (IPESE)	EPFL/IPESE
Imperial College London	ICL
Indian Institute of Technology Bombay	IITB
Instituto Tecnólogo de Celaya	ITC
Islamic Azad University	IAU
K. N. Toosi University of Technology	KNTU
Kalamay Vocational & Technical College	KVTC
Kyung Hee University	KHU
National Cheng Kung University	NCKU
National Taiwan University	NTU
Natural Resources Canada, CANMET Energy Technology Center	CANMET
Politecnico di Torino	PoliTo
Qingdao University of Science and Technology	QUST
Rowan University	RU
Texas A & M University	TAMU
Tianjin University	TJU
UMIST	UMIST
Universidad Michoacana de San Nicolás de Hidalgo	UMSNH
Université de Toulouse	UTLS
Universiti Teknologi Malaysia	UTM
University of Calgary	UC

Table 8 (continued)

University of Guanajuato	UG
University of Manchester	UoM
University of Maribor	UM
University of Nottingham Malaysia	UNIM
University of Oklahoma	UO
University of Tehran	UT
University of Tuzla	UTZ
University of Zaragoza	UZAR
Xi'an Jiaotong University	XJTU
Yonsei University	YSU
Zhejiang University	ZJU

5.6. Visual representations for some interesting issues of non-isothermal water networks

Finally, in order to enable visual representations for some interesting issues related to the non-isothermal water networks, we have used a tag cloud or word cloud (http://www.wordle.net/) to show the importance of each word with font size. According to this, Figure 20 shows 20 key words by their frequencies of appearing within the journal articles or conference proceedings titles (the larger the word font size-the more frequent the appearances). Also, we provided word clouds for all Journals (see Figure 21 and Table 9), and conferences (Figure 22).

Figure 20. Word cloud for the contribution titles (79 papers, limit 20 words).

Figure 21. Word cloud for all Journals.

Table 9. Abbreviations used for Journals.

Journal name	**Abbreviations**
Applied Energy	APEN
Applied Thermal Engineering	ATE
Asia-Pacific Journal of Chemical Engineering	A-PJCE
Chemical Engineering and Processing: Process Intensification	CEPPI
Chemical Engineering Research and Design	CERD
Chemical Engineering Science	CES
Chemical Industry and Engineering Progress	CIEP
Chinese Journal of Chemical Engineering	CJCE
Computers & Chemical Engineering	CCE
Energy	Energy
Heat Transfer Engineering	HTE
Huagong Xuebao	HX
Industrial & Engineering Chemistry Research	IECR
International Journal of Environmental Research	IJER
Journal of Chemical Industry and Engineering (China)	JCIEC
Journal of Cleaner Production	JoCP
Journal of the Taiwan Institute of Chemical Engineers	JTIChE
Korean Journal of Chemical Engineering	KJCE
Research Journal of Environmental Sciences	RJES

Figure 22. Word cloud for all conference proceedings and names.

Table 10. Abbreviations used for Conference proceedings and names.

Conference Proceeding and Conference Name	**Abbreviations**
American Institute of Chemical Engineers - Annual Meeting	AIChE
Chemical Engineering Transactions - Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction	CET-PRES
Computer Aided Chemical Engineering - European Symposium on Computer Aided Process Engineering	CACE-ESCAPE
Computer Aided Chemical Engineering - Symposium on Process Systems Engineering	CACE-PSE
Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems	ECOS
Slovenian Chemical Days	SKD
Sustainable Development of Energy, Water and Environment Systems	SDEWES

6. CONCLUSIONS AND FUTURE DIRECTIONS

This paper presented a comprehensive and synthetic overview of non-isothermal water network synthesis. This research field has received considerable attention throughout academia and industry over the last two decades. An increasing number of papers and industrial applications have been published, especially over the last five years. It is important to point out that about twice the number of papers have been published during the last five years (2010-2014, including 2010) compared to the ten-year period before (1997-2009, including 2009). This trend could be similar in the near future because the issue of water and energy minimisation is one of the top priorities for the process industries (e.g. pulp and paper, chemical, food, etc.), which are large consumers of natural resources.

Non-isothermal water-using and wastewater treatment networks

The vast majority of the published papers considered single contaminant problems and heat integration within water-using networks, in which water reuse and local water recycling around water-using units could be enabled in order to minimise freshwater usage and wastewater generation. However, heat integration should be performed within an integrated network consisting of water-using network and wastewater treatment. In this network wastewater regeneration, regeneration reuse, and regeneration recycling is enabled, resulting in an additional minimisation of freshwater usage and wastewater generation. Additionally, multiple contaminant problems should be considered for having more realistic cases. Several papers [46, 49, 52-54] published in the literature had addressed these issues but the small and medium size problems were only solved due to the complexities of the overall synthesis problem. New solution strategies and tools are required for solving large-scale water, wastewater, and heat exchanger networks simultaneously due to expensive computational costs, which could be a possible future direction in this field. Also, more realistic equations for investment cost (i.e. heat transfer units, treatment units, piping), and operating cost (i.e. pumping of water, wastewater treatment) should be considered within models in order to represent more realistic cases. The vast majority of the published studies considered the designs of non-isothermal water networks, whilst only certain papers addressed the retrofit cases of non-isothermal water networks. This could also be a possible future research direction.

Combined process, non-isothermal water-using and wastewater treatment networks

An integrated non-isothermal water-using and wastewater treatment network should be combined with a process network consisting of, for example, reaction and separation units in order perform simultaneous optimisation of the process flow sheet, water and heat integration. In these cases the additional interactions could be enabled within, as well as between, the overall network (see Figure 23), and better trade-offs between the costs of raw material, freshwater usage, utility consumption and the investment could be obtained, and the income from products Consequently, lower consumption of natural resources within a process could be achieved as well as a reduction in waste emissions into the environment leading to a sustainable and profitable solution. However, this issue is also a big challenge for the process systems engineering community and the possible future research direction in order to obtain the improved energy and water efficient, sustainable, and profitable solutions. Recently, important progress in this direction has been made by Yang and Grossmann [101], who performed simultaneous optimisation of water and heat integration for a process flow sheet. In addition, research progress has been identified over recent years within the synthesis of heat-integrated resource conservation networks [117, 118], and interplant non-isothermal water-using and wastewater treatment networks [94, 95]. Possible further research directions in these research fields can be expected in order to obtain improved and more realistic results.

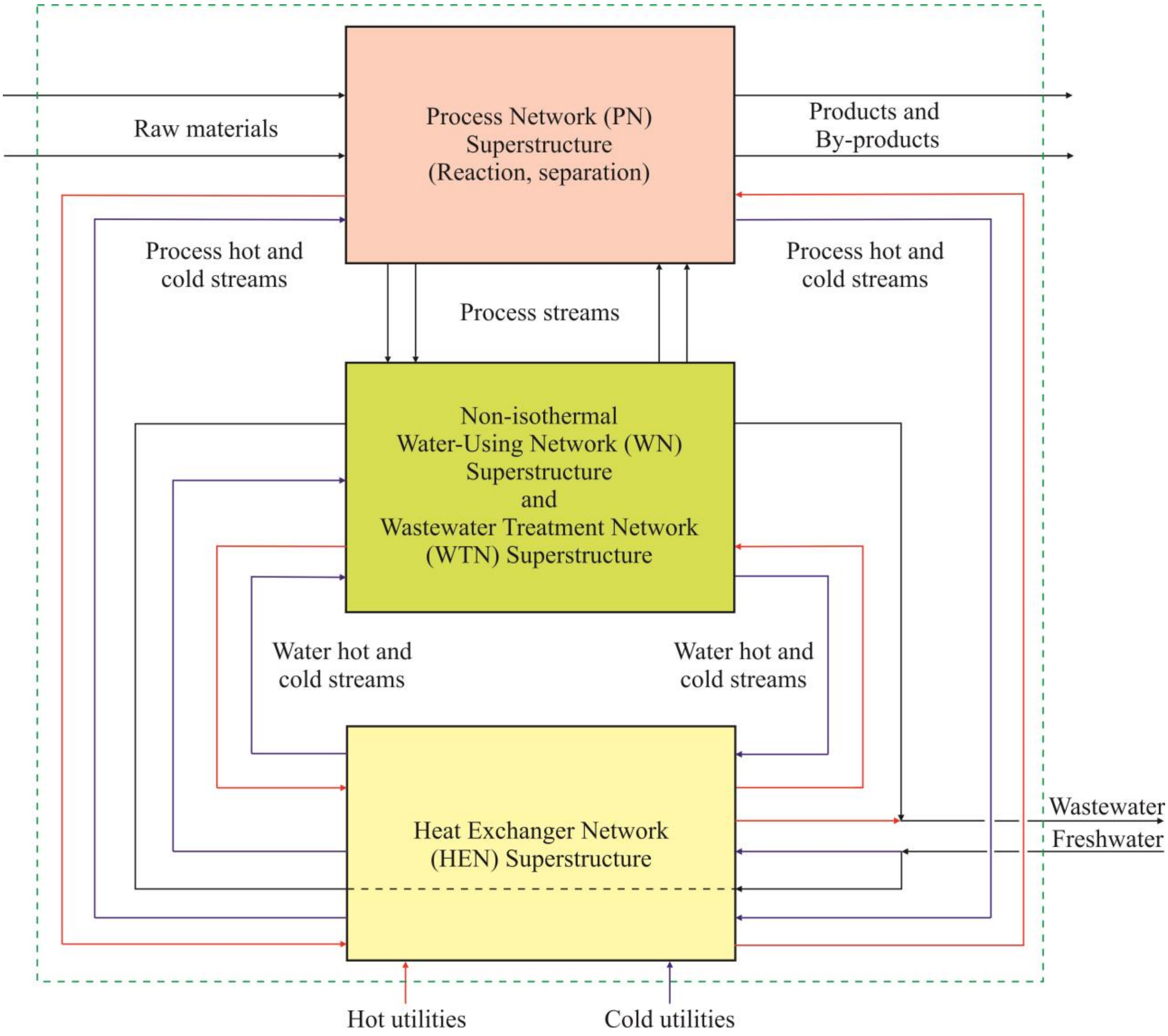


Figure 23. Combined process network, water-using, wastewater treatment and heat exchanger networks.

Batch networks

The synthesis problems of water and energy integration within continuous processes have been widely studied in the literature compared to batch processes which have received relatively little attention in the literature due to their complexities. However, over the last couple of years several excellent studies have been published in this field for considering water and energy integration within a batch process scheduling framework. Further research direction in this field could be expected in the near future.

7. ACKNOWLEDGMENTS

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