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Research article

Urban and industrial symbiosis for circular economy: Total EcoSite Integration

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ABSTRACT

The paper presents an extension of Pinch Analysis and namely, Total Site Process Integration. It benefits from up to date developments and introduction of Total EcoSite Integration for urban and industrial symbiosis. An important development is Pinch Analysis for Solid Waste Integration which is a crucial step for the symbiosis in a circular economy. As the potential EcoSites are usually extensive and cover various units, a methodology based on clusters has been used. The solution has been supported by graphical tools using the analogy with already implemented extensions of Pinch Analysis. The results of a demonstration case study revealed the potential of the novel approach. The identified integrated design increased the energy recovered from the solid waste by 11.39 MWh/d and diverted 2 t/d of the waste from the landfill, benefiting both the urban and industrial site. The proposed approach is also capable of minimising the requirement of energy-intensive thermal drying for waste whenever the process allowed, subsequently offer a solution with lower environmental footprint and cost. For future work, a even more comprehensive case study can be conducted by considering the other forms of the waste, recovery process and drying approaches.

1. Introduction

Sustainable development has set off various models or system design, aiming to meets the current need without compromising the environmental, economic as well as the social aspects. Fig. 1 illustrates the relationship between the various models or system design. The circular economy is among the broader concept covers from production and consumption to waste management and the market of secondary raw materials (Polverini and Miretti, 2019). The initiatives or measures could reduce environmental burden, improve the security of the supply of raw materials, stimulate innovation, growth, and job creation (EC, 2020a). Industrial ecology and industrial symbiosis, on the other hand, having more focus on the industrial processes in production stages allows entities and companies that traditionally be separated, to cooperate among them in the sharing of resources (Neves et al., 2020). Although various definitions have been proposed, it remains inconsistent. Li (2018) states that industrial symbiosis cannot exist without the presence of industrial ecology, serving as support in achieving industrial ecology. The difference between industrial symbiosis and industrial ecology lies in the focus instead of the scale of the economy. Walmsley et al. (2019) state that the concepts of a circular economy, industrial ecology and Process Integration (Klemeš and Kravanja, 2013) are in line and equally important. However, the emphasis is slightly different, originating from other disciplines (e.g., chemical engineering, ecology, business) and viewing the same "problem" exists at different scales (e.g., processes, industrial, urban, regions).

Methods to facilitate the planning and execute the design of these sustainable development thinking are essential to prevent ending up at conceptual deadlock. They can generally divide into two categories, assessment, and optimisation. Assessment/analysis is mainly to measure the system performance, identify the potential unintended consequences for further improvement. Life cycle assessment (LCA) is among the widely applied method where environmental impacts (Klemeš, 2015) and environmental footprints (Čuček et al., 2012) are serving as indicators. Different economic indicators, circularity indicators (Moraga et al., 2019) and thermodynamics indicators (exergy, emergy)

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(Huysman et al., 2017) have also been proposed to be applied in LCA. For example, Mesa et al. (2020) proposed material durability indicators, offering a balanced measurement of durability and environmental burdens to facilitate the appropriate material selection in a circular economy. They are important to inform the performance of an existing design and identify the potential design through a scenario or comparative analysis. Other available measurements and quantification analyses than LCA are flow analysis (material flow analysis, Input-Output approach), and network analysis (Fraccascia and Giannoccaro, 2020). Different circular economy performance assessment methods have also been summarised by Sassanelli et al. (2019), grouped in a more detailed classification.

Optimisation, on the other hand, focuses on identifying an optimal design under a defined objective function according to different priorities and constraints. It is usually serving as a basis to support the decision making for developing a system design rather than informing the performance of a system design. Mathematical programming is the main optimisation method, capable of solving complex model and considering different parameters. Boix et al. (2015) review the optimisation method to design eco-industrial parks and summarise the objectives as societal/managerial, economic, topological, environmental objectives.

The advantages of mathematical programming, however, could also turn into the limitation in an application. The creation and the development of a superstructure is a key issue, and even one missing node can move the optimisation of the reality into the optimisation of just a model. The model could fail to embrace many real-world constraints if the understanding of the problem is insufficient. In most real-life optimisation problems, it usually does not come with a neat problem description or well-defined technical problem (Marchau et al., 2019). Efficient collaboration with the decision-makers that are experienced in the application area is required. However, there is a challenge in communicating with the decision-makers. To find a commonly understandable language on how the model works and how to incorporate the model into the workflow of the technical experts (people who will apply the results), not to mention personally adapting the model based on the changing need. There are more and more studies which attempting to bridge this gap (Hassan and Rashid, 2020) to ensure the optimised solution is feasible.

1.1. Process integration: Pinch analysis and total site integration

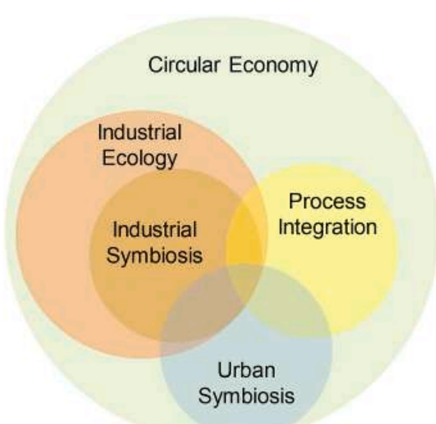
As shown in Fig. 1, other than simultaneous methods by mathematical programming, there is a sequential/targeting method to facilitate the planning and system design. One of the well-established targeting methods in an industrial application (Klemeš et al., 2018a) is Pinch Analysis. It is an effective targeting tool for early-stage as well as retrofit design (Lai et al., 2020) communication with decision-maker (Klemeš et al., 2018b), due to its clear graphical illustration. Total Site Integration (TSI) is a framework, and a method extended based on Pinch Analysis – first developed for heat recovery (Dhole and Linnhoff, 1993) and after extended to Combined Heat and Power Integration (Klemeš et al., 1997). It is based on the idea that processes are rarely operating in isolation and considering the complete site as an integrated system could further optimise the resources use and recovery.

Pinch Analysis is started from Process Integration, see e.g. (Klemeš, 2013), of a single process (production unit), while TSI is having an emphasised for application in an entire processing site covering various production as well as supporting units (as, e.g. utility providers). For example, in this study, different sites in urban and industrial are referred to as the Total Site. Fig. 2 summarises the Pinch Analysis for complex Integration and Total Site planning. They are originated from Pinch Analysis for Heat Integration (Linnhoff et al., 1994) to identify the energy-saving potential (target) through the determination of possible interchange of heat flows, subsequently facilitating the design of heat exchanger network design.

Based on the Heat Integration Pinch Analysis, it has been later extended and modified to resolving various contemporary issues in planning, as in Fig. 2. Another type of extended Pinch Analysis which is not classified in the figure is by Lam et al. (2010) where the y-axis = energy, x-axis = area for regional biomass supply chains planning. Water Scarcity Pinch Analysis is proposed by Jia et al. (2020) with water categories as y-axis and volume as the x-axis. The working principles of extended Pinch Analysis evolved in some variations, as e.g. Carbon Emission Pinch Analysis introduced by Tan and Foo (2007), as discussed in Klemeš et al. (2018a). The spirit of setting targets, using the targets for problem decomposition through the identification of sub-regions and solving the resulting smaller problem has been a strong connecting base of the methodology.

Pinch Analysis for Heat and Water Integration has been established; however, the development for Solid Waste Integration is still at the earlier stage. Ho et al. (2017) proposed Waste Management Pinch Analysis, later applied by Jia et al. (2018) and modified by Fan et al. (2019) to different implementations illustrated by case studies (city-level and regional level). The Waste Management Pinch Analysis (Ho et al., 2017) is mainly to accomplish a targeted GHG emission by allocating waste to different treatments without fully considering the characteristics of waste (e.g. the moisture content) and existing treatment capacity. The y-axis is cumulative GHG emission, and the x-axis is the waste amount, fall into the category of Pinch Analysis for environmental sustainability planning as Carbon Emission Pinch Analysis, see Fig. 2.

Solid waste management plays a critical role in implementing the



Optimisation/design methods:
- Sequential methods (Pinch Analysis/ Total Site Integration method, heuristic method)
- Simultaneous methods (Mathematical programming)

Other design methods:
- Scenario/comparative analysis – LCA (environmental impacts, environmental footprint, economic feasibility and other circularity indicators assessment)

Fig. 1. The relationship between concepts including the circular economy (Ellen Macarthur Foundation, 2012), industrial ecology (Frosh and Gallopoulous, 1989), industrial (Jelinski et al., 1992) and urban symbiosis and Process/Total Site Integration.

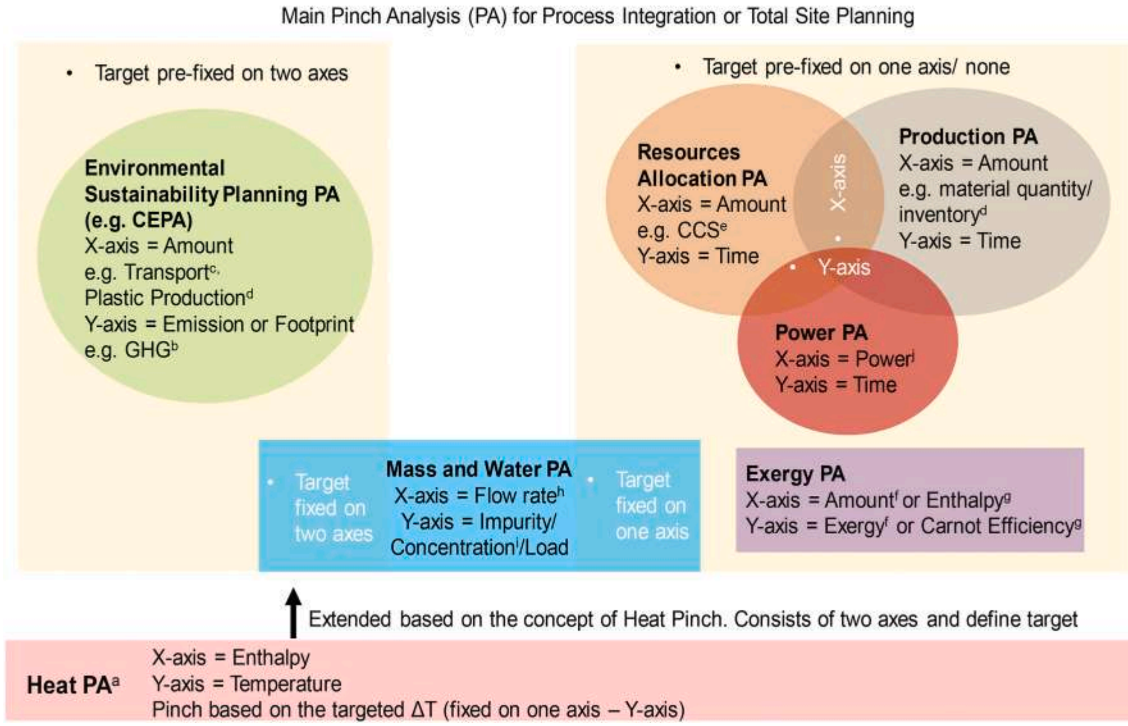


Fig. 2. Summary of the main Pinch Analysis and its example extension. An example is given to each extended Pinch Analysis, refer to Klemeš et al. (2018a) for more information on the comprehensive development (Linnhoff et al., 1994).[a] (Kim et al., 2016),[b] (Walmsley et al., 2015),[c] (Abdul-Latif et al., 2020),[d] (Ooi et al., 2013),[e] (Singhvi and Shenoy, 2002),[f] (Rozali et al., 2015),[g] (Manan et al., 2004),[h] (Wang and Smith, 1994),[I] (Varbanov et al., 2020),[j] (Marmolejo-Correa and Gundersen, 2013),[k].

circular economy. It remains one of the biggest challenges from an economic, environmental, and social perspective. An integrated management system utilising waste and excess resources from one process for another process as secondary resources could minimise the environmental footprints and production cost. It mitigates the issues such as waste fluctuation, the uneven spatial distribution of waste and recovery plants, waste to landfill and construction of new waste treatment plants which against the priorities of circular economy (EC, 2020b), achieving a symbiosis relationship. Solid Waste Integration at Total Site using Pinch Analysis method deserves still further development. Fig. 3 shows the TSI design considering heat recovery (Klemeš et al., 1997), which was extended in Varbanov and Klemeš (2011) to handle targeting for variable supply and demand flows. An alternative procedure for Total Site Heat Integration data extraction can be seen in Pouransari et al. (2014) which is trying to reveal the heat sources and sinks that the processes can offer to the site utility system based on practical considerations.

The other TSI is Total Site Water Integration (Ahmad Fadzil et al., 2018) and Total Site Carbon Emissions Integration (Nawi et al., 2016). There have been since then several developments extending the TSI. Fig. 4 shows the concept of Locally Integrated Energy Sectors (Perry et al., 2008) – an extension of the work based on Klemeš et al. (1997) considering both heat and power integration. This has been further employed for targeting energy planning scenarios (Liew et al., 2017).

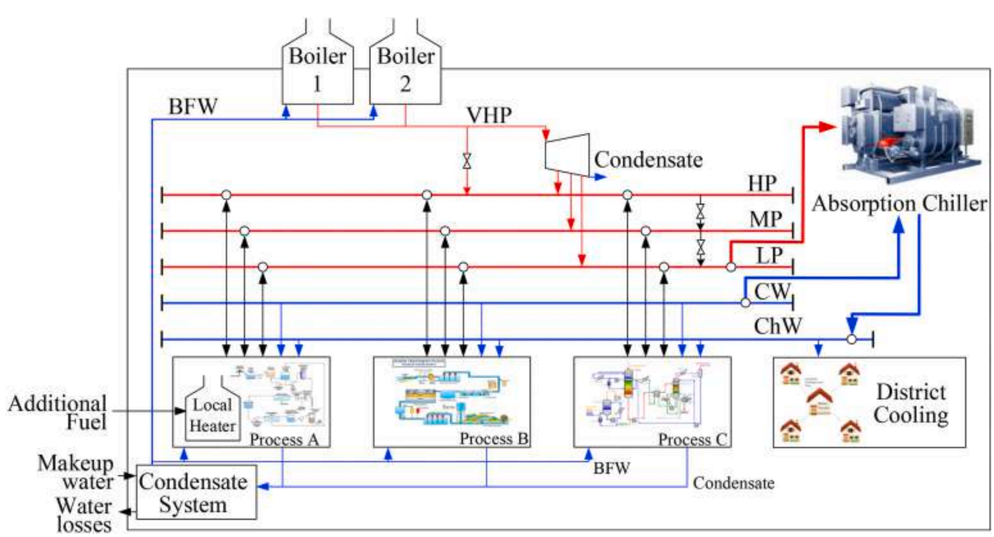


Fig. 3. Industrial Total Site for heat recovery, adapted from Klemeš et al. (2018b), introduced in (Klemeš et al., 1997).

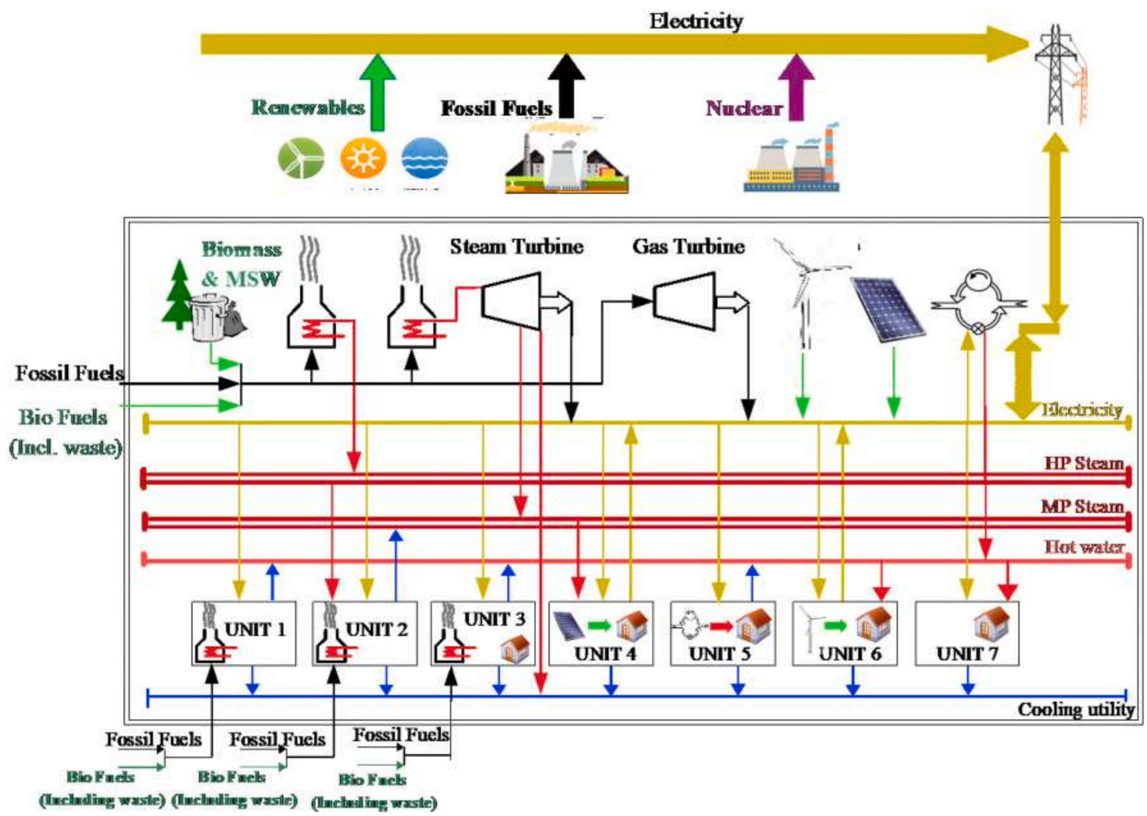


Fig. 4. Locally integrated Energy Sector, further adapted from Klemeš et al. (2018a), introduced by Perry et al. (2008).

Solid waste has been proposed as part of the energy input (Fig. 4 – energy flow), however not yet integrated as material flow (all converted to energy). The idea of Solid Waste Integration at a Total Site, for matching, allocation (supply and demand) and recovery are not new. For example, Ong et al. (2017) developed a method for Total Site Mass, Heat and Power Integration in biorefinery plant where solid waste material is integrated using P-graph superstructure. However, in many cases, mathematical programming is applied as an alternative to the TSI method as the Pinch Analysis for Solid Waste Integration is not sufficiently studied.

1.2. Aim and novel contribution of the presented study

The TSI based on Pinch Analysis could offer superiority in term of interpretability and intuitive decision support for an integrated system design. Combination of industrial and urban as a Total Site plays a significant role in a sustainable circular economy. This study aims to extend the TSI method by including Solid Waste Integration to facilitate the planning of urban and industrial symbiosis. It could enhance the environmental and economic feasibility by reducing the dependency on utility (e.g. steam, hot water, cool water, fresh water, waste drying) through recovered resources.

The novel contributions of this paper include.

(i) Extension of Pinch Analysis methodology to facilitate the Solid Waste Integration, considering moisture content of waste in the recovery processes
(ii) Development of Grand TSI model, integrating solid waste, water and energy recovery, for a Total EcoSite Integration (TESI) design in achieving urban and industrial symbiosis.

These contributions are demonstrated by a case study to illustrate the potential recovery and reduction in resources use.

2. TESI framework for urban and industrial symbiosis

Process Integration is one of the useful tools to facilitate industrial symbiosis planning, as discussed in Lawal et al. (2020). This section introduces the extended TSI framework in Process Integration for industrial and urban symbiosis by taking waste integration into consideration, namely TESI. Energy, including Power and Heat Integration, as well as water integration by Pinch Analysis, are well developed. However, solid waste integration is still underexplored, as discussed in Section 1. Fig. 5 shows the general idea of the assessed integration, where the resources (Energy, water and waste) within the industrial and urban cluster are first integrated discretely and later among the clusters to achieve a symbiotic relationship.

2.1. General framework and method

Fig. 6 shows the research framework for TESI and the method applied in this study. The newly developed Solid Waste Integration within the own cluster (e.g. urban and industrial) is first presented (Step 1, Fig. 6), followed by Total Site application to integrate the resources among the different clusters (Step 2, Fig. 6). Solid waste integration is a

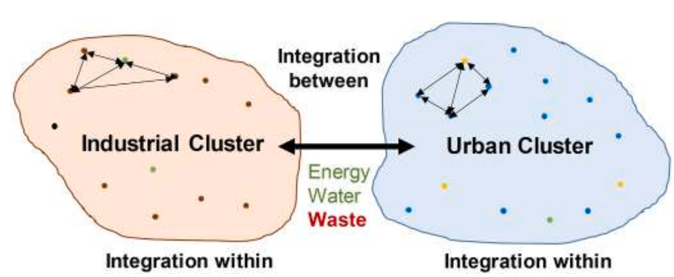


Fig. 5. The assessed integration in this study with a particular focus on waste integration.

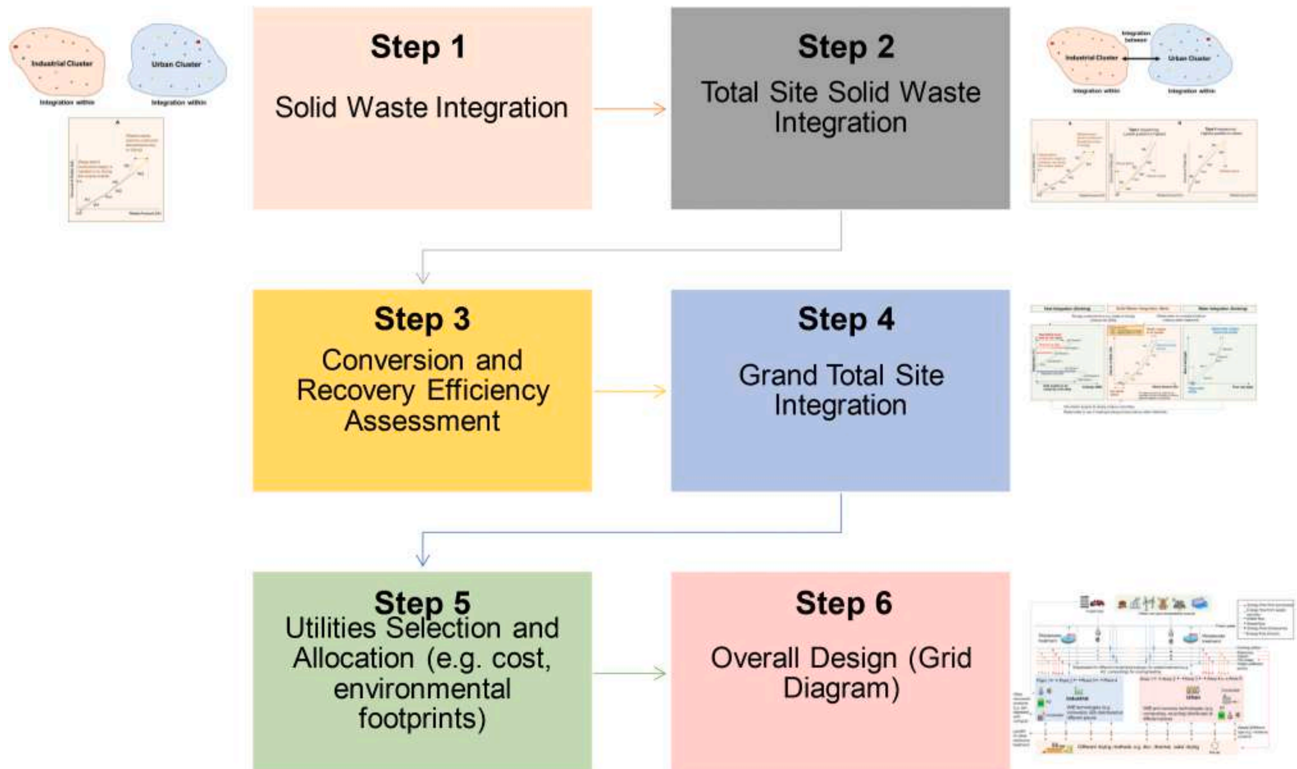


Fig. 6. The general framework of industrial and urban symbiosis by TESI.

tool to facilitate the matching of waste source and waste sink (treatment type and available capacity) by maximising the recovered resources and lowering the utility usage (e.g. energy required for pre-treatment - drying). The constraints are the moisture condition or specification and the capacity for waste recovery treatment.

Energy balance and recovered products from Solid Waste Integration are then estimated (Step 3, Fig. 6) for further Grand TSI. Grand TSI is defined as the integration that consists of a combination of several Process Integrations, e.g. Heat, Water, Power or other Integration (Step 4, Fig. 6). For example, wastewater surplus in Water Integration can be utilised in Solid Waste Integration to adjust the moisture content; recovered energy in Solid Waste Integration can be used to reduce the required utility in Heat Integration or Power Integration. The identified matching/targets through Solid Waste Integration can then be evaluated in term of the cost, environmental performance and available infrastructure/facility (Step 5, Fig. 6) for an overall feasible design (Step 6, Fig. 6), refer to TESI.

2.1.1. Solid waste integration model: Pinch Analysis and Total Site

Fig. 7 shows the developed Pinch Analysis for Solid Waste Integration. It consists of two axes as for Heat Integration. It comprises of two curves: one is for the Cumulative Waste Recovery/Treatment (Sink), and another is the Cumulative Waste Supply (Source). Different waste recovery processes are having a different requirement on the moisture content specification. Each of the waste supply is having a different moisture content. The y-axis represents the amount of water; the x-axis represents the waste amount, and the gradient represents the moisture content.

The cumulative curves are plotted by stacking all the different sink and source starts from zero, forming Waste Recovery Curve (WRC) (green) and Waste Supply Curve (WSC) (brown/yellow). For example, by referring to Fig. 7, R1 to Rn are the different recovery processes with different degree of acceptance to the moisture content of waste to be treated. W1 to Wn (in Fig. 7) comprises the WSC are the waste source with different moisture content. The WSC (brown/yellow) is shifted in the direction to the right, along the x-axis from zero. Before shifting (zero), it shows the original or unintegrated design, where after shifting is the suggested optimised allocation. The shifting is complete when none of the WSC curves crossed over or behind the WRC, forming a Pinch Point. The shifted magnitude before the Pinch Point indicates the amount of dried waste required (waste deficit – to be imported from other clusters) to adjust the moisture content meeting the requirement of recovery processes. The magnitude differences between the WRC and WSC after Pinch Point represents the waste surplus. The waste surplus is due to the insufficient handling capacity, and the waste has to be treated or recovered outsource (e.g. outside A, see Fig. 7(a)).

The stacking sequence (e.g. W1, W2, W3 …) is based on the quality of the waste type, from the highest quality to the lowest quality. For example, in Pinch Analysis for Water Integration, it arranges by water with the lowest contaminant to highest (El-Halwagi et al., 2003). Shifting the curve in this arrangement could make sure the required utility (e.g. clean water) can be minimised. The definition of "quality" for water is rather direct, where low contaminant represents high quality. However, the "high quality" waste can be diverse, for example, based on the moisture content requirement and specification of the waste recovery/treatment process. In general, waste with lower moisture content (dried) is preferable for waste to energy processes due to a higher low heating value (LHV) and waste with higher moisture content is preferable for biological treatment, e.g. composting.

The identified waste surplus in a cluster (e.g. Cluster A, Fig. 7) can be a resource in another cluster (e.g. Cluster B, Fig. 7), forming a Total Site Solid Waste Integration. Two scenarios are illustrated to explicit stacking sequencing. Scenario 1 (Fig. 7(a)) shows the situation where the waste to be transferred from A (Yellow Curve) to B is at the lowest moisture content compared to the waste source in B. Scenario 2 (Fig. 7(b)) shows the circumstances where the waste transferred from A (Yellow Curve) to B is with the highest moisture content.

As mentioned earlier, stacking sequencing is according to the definition of "high quality". Type I shows the arrangement where "high quality" is referred to the drier waste (from the lowest gradient to the

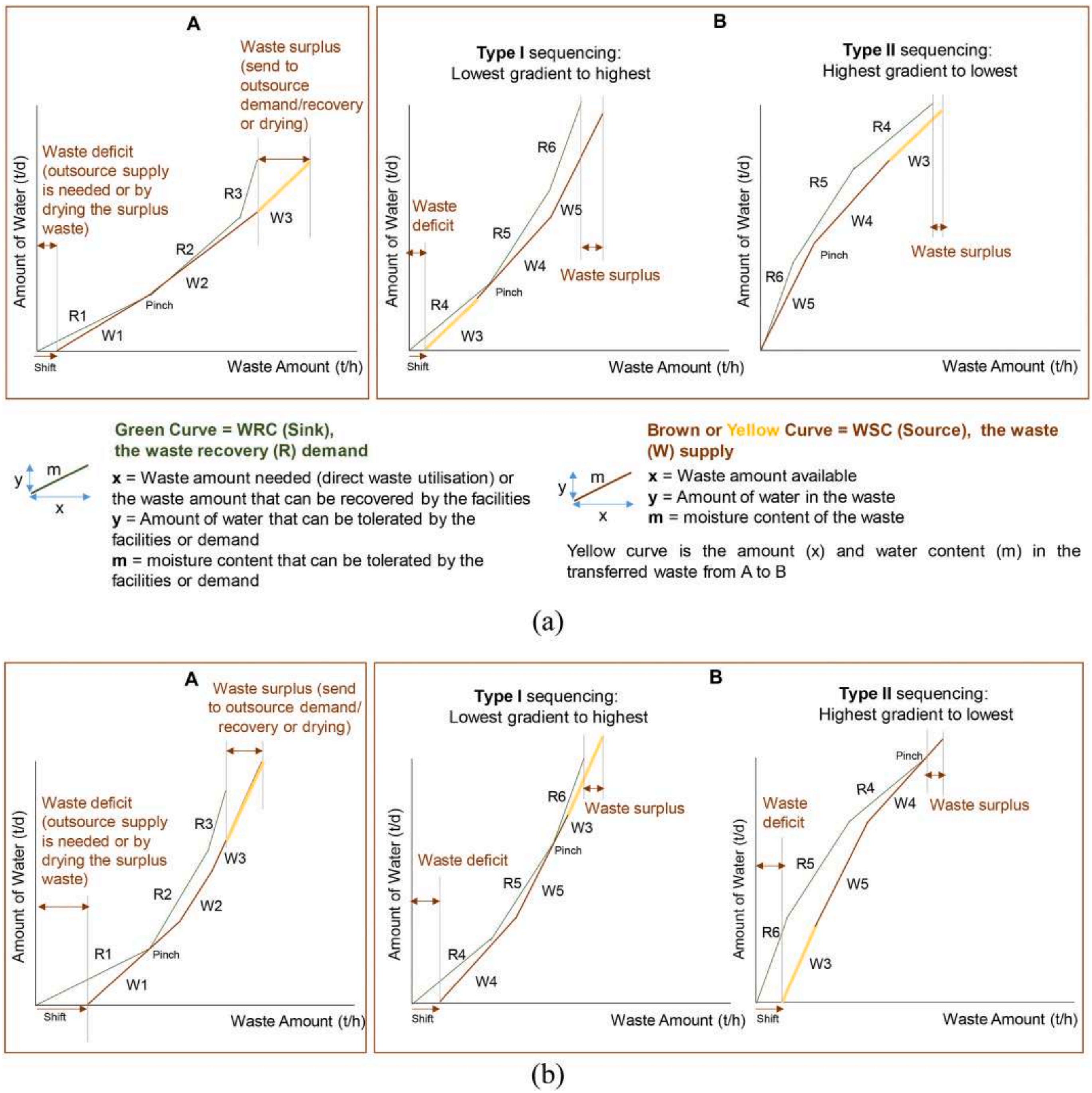


Fig. 7. Solid Waste Integration by Pinch Analysis (a) Scenario 1: The identified waste surplus in A is having the lowest moisture content (gradient) in B, and (b) Scenario 2: The identified waste surplus in A is having the highest moisture content (gradient) in B.

highest). Type II shows the arrangement where "high quality" refers to the damper waste (from highest gradient to lowest gradient). This sequencing aims to maximise the use of damper waste (e.g. for biological treatment), and the drier waste can be recovered for other purposes. This targeting approach maximises the value of waste by diverting from landfill through TSI and minimise the need for outsourcing dried waste without compromise the recovery processes. This is critical as drying process consumes energy and dried waste usually can have a better utilisation (e.g. recycling) than for incineration and having a less challenging in transporting.

2.1.2. Identification of recovered utilities and products in Solid Waste Integration

The identified waste allocation and targets (waste surplus, deficit) are then applied to estimate the recovered utility or product as in Eqs (1) and (2).

$$TE = \sum_{s,r} W_s \times LHV_s \times Ce_r \tag{1}$$

$$TP = \sum_{s,r} W_s \times Cp_r \tag{2}$$

Where TE is the total recovered utility/energy (MWh or MJ), W is the waste amount (t), LHV is the low heating value (MWh/t or MJ/t), Ce is the conversion efficiency to energy, e.g. heat of electricity (%). The symbol s is an index of different waste source/type. r is an index of different waste recovery processes. TP is the total recovered products (e. g. compost, digestate or ash) (t). Cp is the conversion efficiency (%) to the respective products.

To summarise, the simplified steps for Solid Waste Integration are as stated below:

- **Step 1.1:** Construct the x-axis (quantity) and y-axis (quality) representing waste amount and water content
- **Step 1.2:** Plot the WSC (waste supplies) and WRC (waste recoveries)
- **Step 1.3:** Select the stacking sequencing by defining "quality". Start with high-quality waste (e.g. lowest moisture content) to low quality (e.g. highest moisture content).
- **Step 1.4:** Shift the WSC along the x-axis until one of the points meet the WRC, and the others are in front of it.
- **Step 1.5:** Identify the targets (e.g. surplus, deficits, pinch point) and allocation by referring to the differences between the shifted WSC and WRC
- Step 2 (Fig. 6): Repeat step 1.1–1.5 by including the waste surplus, which has to transfer to another site (e.g. from A to B, see Fig. 7) for recovery.
- Step 3 (Fig. 6): Identify the recovered products and utilities for Grand TSI

2.1.3. *Grand TSI: the economic and environmental sustainability towards TESI*

Grand TSI is conducted to further reduce the required utilities in Heat Integration, Power Integration, Water Integration etc. by utilising the recovered and/or surplus utilities through Solid Waste Integration, see Fig. 8. For example, the heat deficit in Heat Integration (Klemeš et al., 2018b) can be partially fulfilled by integrating the heat recovered from Solid Waste Integration. The heat surplus can be utilised for pre-drying. The wastewater surplus which supposed to send for treatment in Water Integration can be utilised in waste recovery process e.g. anaerobic digestion as inoculants. However, it is important to ensure the sustainability of the integration towards industrial or urban symbiosis.

Eq (3) shows the estimation of the total cost, including the operating cost and environmental price. To achieve a symbiosis, the parties/clusters involved in the integration needs to have a mutually beneficial relationship. The integrated design needs to offer a higher benefit than the original design (without integration) for both parties (e.g. the supply and the receiver or the urban cluster and industrial cluster), as presented in Eq (4), forming TESI.

$$TC_{o,i} = TOC_{o,i} - \sum_{o,i,k} RP_{o,i,k} \cdot SP_k + \sum_{o,i,e} EFR_{o,i,e} \cdot EP_e - \sum_{o,i,e} EFA_{o,i} \cdot EP_e \quad (3)$$

$$TC_o \geq TC_i \quad (4)$$

Where TC is the total cost (€). TOC is the total operating cost (€) including transporting (collection, distribution), pre-treatment (drying), recovery processes etc. RP is the amount of recovered products/utilities (t). SP is the respective selling price of utilities or product (€/t). EFR is the environmental footprint (e.g. t of CO_2 emission). EP is the environmental price (e.g. €/t CO_2). EFA is the avoided environmental footprint through recovered utilities or product. o is the index for different original design (baseline scenario). i is the index for different integrated design. k is the index for different recovered utilities (e.g. heat, electricity, compost). e is the index for different environmental footprint or impacts.

Fig. 9 illustrates the design of Grand TSI using a Grid Diagram, firstly developed by Linnhoff and Hindmarsh (1983), later several times extended, e.g. by (Yong et al., 2015) up to Advanced Shifted Retrofit Thermodynamic Grid Diagram (Wang et al., 2020). The potential integration is demonstrated, including the energy (heat or electricity) from different processes and clusters, water flow and the solid waste flow with the principle of minimising the raw materials and resources. It is an extended Total Site design on the basis of Figs. 1 and 2 introduced by the other researchers, highlighting the novel inclusion of Solid Waste Integration.

3. Illustrated case study for Total Site Solid Waste Integration

The illustrated case study is to demonstrate the applicability of the developed Solid Waste Integration (Fig. 7) representing the main novelty of this study. Two clusters, industrial and urban, are assessed based

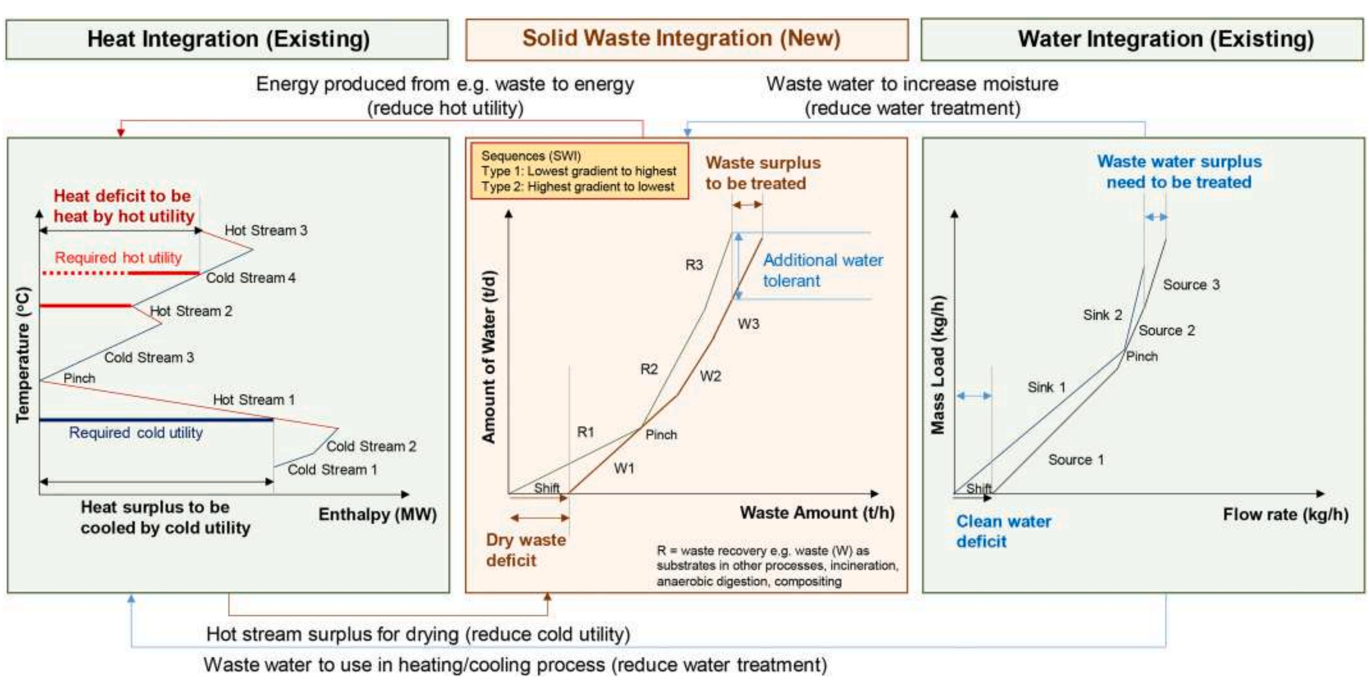


Fig. 8. The Grand TSI, can e.g. consist of Heat Integration (Klemeš, 2018b), Solid Waste Integration (novel development) and Water Integration (El-Halwagi et al., 2003).

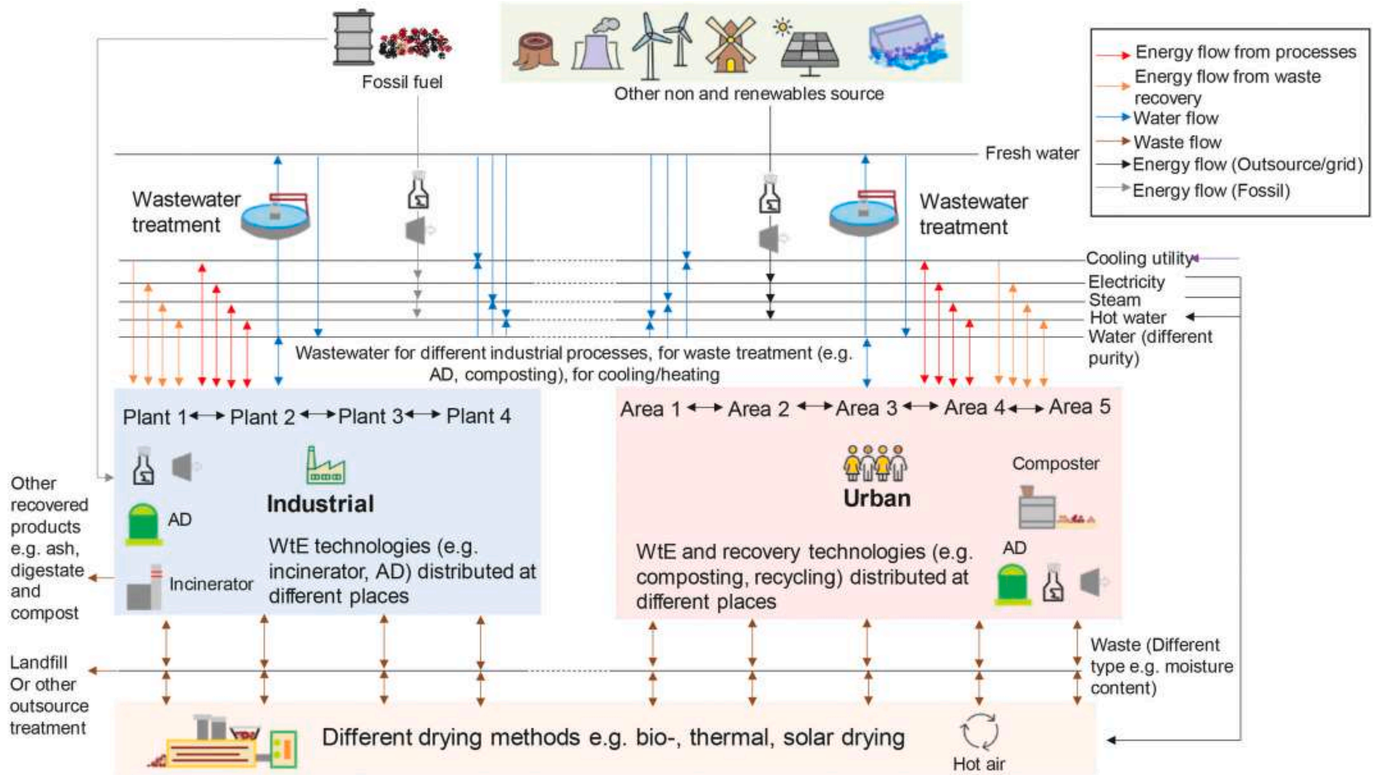


Fig. 9. The extended Grand TSI model considering the Solid Waste Integration of Urban and Industrial Symbiosis towards TESI. WtE = Waste to Energy. AD = Anaerobic Digestion.

on the assumed datasets and conversion efficiency. Table 1 shows the data input for the Source (waste supply) and Sink (waste recovery) in the industrial and urban cluster. R1 – R3 represents different thermal treatment. R4 - R5 represent different biological treatment (e.g. anaerobic digestion), and R6 represents composting. The Grand TSI that performed is focused on Solid Waste and Heat Integration. Table 2 shows

Table 1a
Data input of source and sink for industrial cluster.

Industrial Cluster	Waste Amount (t/d)	Water Amount (t/d)	Moisture content (%)	LHV (MJ/kg)	Conversion Efficiency
Waste supply 1 (W1)	12	1.56	13	15	–
Waste supply 2 (W2)	3	0.6	20	13	–
Waste supply 3 (W3)	4	1	25	10	–
Waste supply 4 (W4)	3	2.1	70	7	–
Waste recovery demand (R1)	20	2	10	–	2 MWh heat, 2 MWh electricity/t of waste (with LHV of 10 MJ/kg)
Waste recovery demand (R2)	3	0.9	30	–	4 MWh heat/t of waste (with LHV of 10 MJ/kg), ash (25% of its weight of input)
Waste recovery demand (R3)	3	1.5	50	–	5 MWh heat/t of waste (with LHV of 10 MJ/kg), ash (25% of its weight of input)

Note: The basis of estimation for the conversion efficiency is by referring to Gross et al. (2010). LHV = Low heating value.

Table 1b
Data Input of Source and Sink for Urban Cluster

Urban Cluster	Waste Amount (t/d)	Water Amount (t/d)	Moisture content (%)	LHV (MJ/kg)	Conversion Efficiency
Waste supply 5 (W5)	3	0.6	20	10	–
Waste supply 6 (W6)	5	1.5	30	9	–
Waste supply 7 (W7)	5	1.75	35	7	–
Waste supply 8 (W8)	7	4.55	65	6	–
Waste recovery demand (R4)	15	4.5	30	–	4.5 MWh heat/t of waste (with LHV of 10 MJ/kg), 0.7 t digestate/t waste
Waste recovery demand (R5)	10	5	50	–	4.0 MWh heat/t of waste (with LHV of 10 MJ/kg), 0.7 t digestate/t waste
Waste recovery demand (R6)	5	3	60	–	600 kg compost/t

Note: The basis of estimation for the conversion efficiency is by referring to Fan et al. (2020) for R4 and R5; Fan et al. (2018) for R6. LHV = Low heating value.

Table 2
Data set for the heat integration analysis (Klemeš et al., 2018b) of industrial process.

Stream	Type	Ts (°C)	Tt (°C)	CP (kW/°C)
H1	Hot	180	80	20
H2	Hot	130	40	40
C1	Cold	60	100	80
C2	Cold	30	120	36

H = Hot stream; C = Cold stream; Ts = Supply temperature; Tt = Targeted temperature; CP = Heat capacity flowrate.

the data sets for Heat Integration which later integrated with the energy recovered from Solid Waste Integration. The required hot utility, cold utility and recovered heat will be determined by well-established Heat Pinch Analysis (Klemeš et al., 2018b). The minimum permissible temperature difference between hot and cold streams entering and exiting an individual heat exchanger is 10 °C. Detailed instruction of constructing the Composite and Grand Composite Curves is available in (Klemeš et al., 2018b).

4. Results and discussion

Fig. 10 shows the Solid Waste Integration constructed based on the described method in Section 3, and dataset as in Tables 1 and 2 Fig. 10 (a) and (b) are for the industrial cluster. Fig. 10(a) shows the original cumulative plots before shifting. The Source Curve (brown) is located behind the Sink Curve (Green), suggesting the moisture content of the waste exceeding the processing specification of R1, R2 and R3 despite the recovery capacity is sufficient. Drying or mixing (co-substrate) with dried waste is required to lower the moisture content. Pinch Analysis identified the following targets (Fig. 10(b)) and suggested (i) 20 t/d of waste can be recovered or integrated within its own cluster. (ii) an additional of 6 t/d dried waste is required (deficit) and (iii) 2 t/d of waste has to be dried or send to the other cluster for recovery processes with a higher tolerance to moisture content.

The waste recovery infrastructure in the urban cluster generally has a higher acceptance to wet waste, as shown in the gradient of Green Curves, in Fig. 10(c) and (d). The waste surplus after integrating with the industrial cluster can be transferred to the urban cluster. Different type of sequencing would propose different targets or allocation. Fig. 10(c) and (d) show the type I and II sequencing. In general, type II (Fig. 10(d)) is preferable as the dried waste deficit is lower (3.5 t/d) compared to 5 t/d in type I (Fig. 10(c)). The concept is similar to Heat and Water Pinch Analysis where minimising the requirement of resources, e.g. outsource heat utility and clean water, is the aim. Dried waste offers a wider range of application (various recycling and recovery), safe waste storage, microbiological inactivation, and lower transporting. Drying is generally regarded as an energy-intensive process (Perazzini et al., 2016). Motavali et al. (2020) reported that the energy consumption ranges from 3.182 kWh/kg_{water} (hybrid microwave/hot air dryer) to 306.977

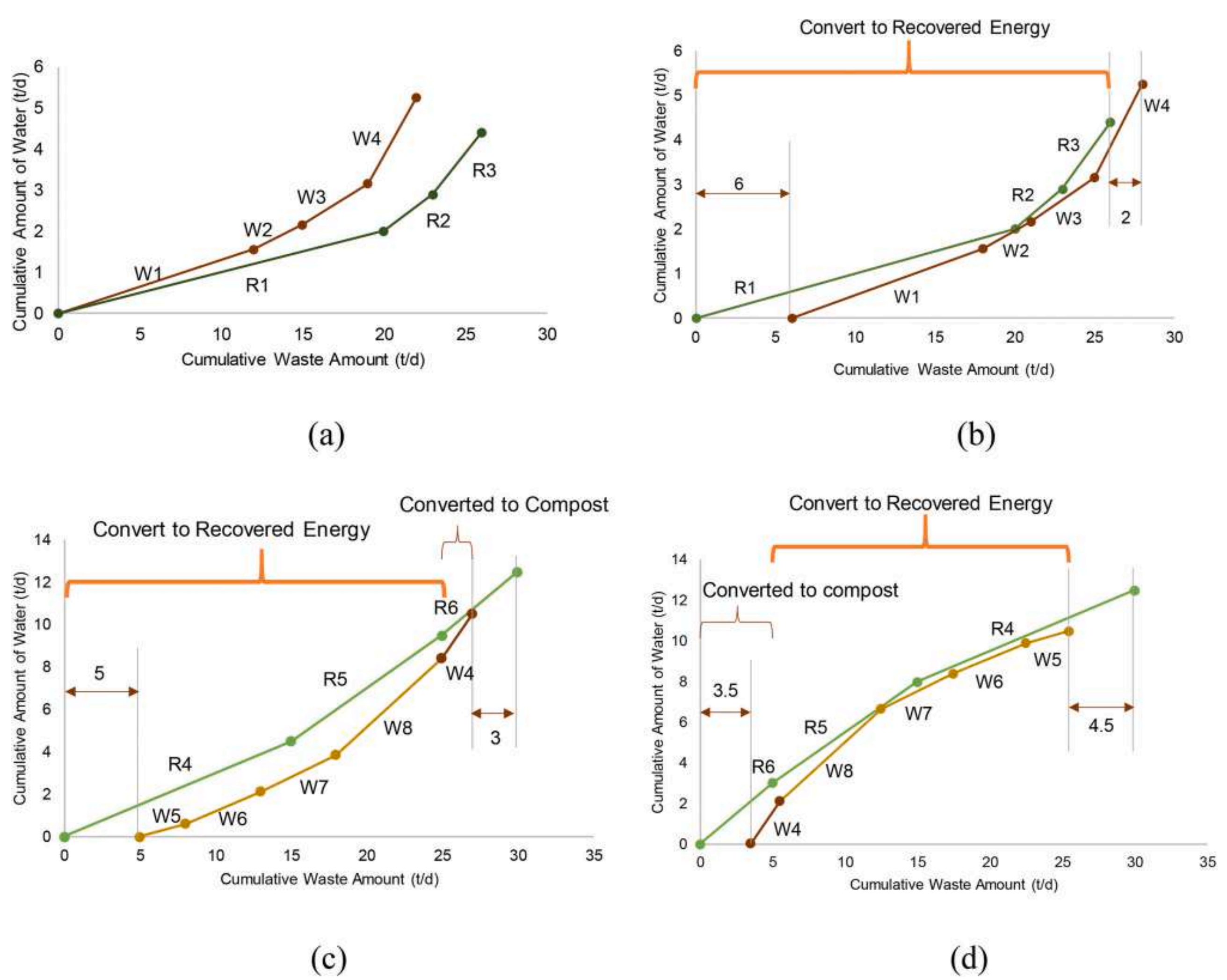


Fig. 10. Solid Waste Integration by Pinch Analysis (a) Industrial Cluster (Before shifting) (b) Industrial Cluster (after shifting - optimised) (c) Urban Cluster (optimised integrated design - Type I) and (d) Urban Cluster (optimised integrated design - Type II).

kWh/kg_{water} (fluidised bed), depending on the technologies as well as the drying time (Tun and Juchelková, 2018). Motevali et al. (2011) highlighted that drying time increased with air velocity and resulted in increased energy consumption. Minimise the dried waste deficit in waste treatment within the same cluster by prioritising the treatment of wet waste as much as possible, whenever the process allowed, could minimise the overall environmental footprints and cost.

Table 3 shows the extracted results based on Fig. 10, where the recovered utilities and products are also identified. The total heat can be recovered in the industrial cluster is 67.9 MWh/d, and urban cluster (Type II) is 65.43 MWh/d, slightly higher than the urban cluster Type I sequencing. In addition, the urban cluster (Type II) has a spare capacity of 4.5 t/d, which enable the handling of additional waste from the other urban cluster. The identified integrated design (65.43 MWh/d) increased the energy recovered from the solid waste by 11.39 MWh/d in the urban cluster compared to the unintegrated design (54.04 MWh/d). 2 t/d of waste in the industrial cluster is diverted from the landfill. At the local level, both parties (urban and industrial cluster) gain from the recovered energy, avoided landfill disposal fees, drying cost or carbon tax, if applied. In the national or global level, GHG saving is achieved. The benefit of integrating industrial and urban cluster is not firstly reported. Ohnishi et al. (2017) evaluate the environmental saving of industrial and urban symbiosis by material flow analysis and suggesting a 6.4% reduction in material used can be achieved. A similar approach has been applied to a case study in China, where 6.6 Mt/y cuts in solid waste can be achieved (Sun et al., 2017). The proposed TESI in this study could facilitate the urban and industrial symbiosis planning beyond as an assessment framework but a tool in identifying the integrated design.

Table 3
Summarised results - Total Site Solid Waste Integration.

Industrial Cluster	Amount (t/d)	Recovered Product
W1→R1	12	36 MWh/d (Heat); 36 MWh/d (Electricity); 3 t/d ash
W2→R1	2	5.2 MWh/d (Heat); 5.2 MWh/d (Electricity; 0.5 t/d ash
W2→R2	1	5.2 MWh/d (Heat); 0.25 t/d ash
W3→R2	2	8 MWh/d (Heat); 0.5 t/d ash
W3→R3	2	10 MWh/d (Heat); 0.5 t/d ash
W4→R3	1	3.5 MWh/d (Heat); 0.25 t/d ash
Remarks: Total recovered heat = 67.9 MWh/d (2.83 MW) Total recovered electricity = 41.20 MWh/d Total recovered product = 1.5 t/d ash Deficit dried waste = 6 t/d Surplus treatment = 0 Surplus waste = 2 t/d (W4)		
Urban Cluster (Type 1)	**Amount (t/d)**	**Recovered Product**
W5→R4	3	13.5 MWh/d (Heat); 2.1 t/d digestate
W6→R4	5	20.25 MWh/d (Heat); 3.5 t/d digestate
W7→R4	2	6.3 MWh/d (Heat); 1.4 t/d digestate
W7→R5	3	8.4 MWh/d (Heat); 2.1 t/d digestate
W8→R5	7	16.8 MWh/d (Heat); 4.9 t/d digestate
W4→R6	2	1.2 t/d compost
Remarks: Total recovered heat = 65.25 MWh/d (2.72 MW) Total recovered product = 12.8 t/d digestate; 1.2 t/d compost Deficit dried waste = 5 t/d Surplus treatment = 3 t/d (R4)		
Urban Cluster (Type 2)	**Amount (t/d)**	**Recovered Product**
W5→R4	3	13.5 MWh/d (Heat); 2.1 t/d digestate
W6→R4	5	20.25 MWh/d (Heat); 3.5 t/d digestate
W7→R4	2.5	7.88 MWh/d (Heat); 1.75 t/d digestate
W7→R5	2.5	7 MWh/d (Heat); 1.75 t/d digestate
W8→R5	7	16.8 MWh/d (Heat); 4.9 t/d digestate
W4→R6	2	1.2 t/d compost
Remarks: Total recovered heat = 65.43 MWh/d (2.73 MW) Total recovered product = 12.8 t/d digestate; 1.2 t/d compost Deficit dried waste = 3.5 t/d Surplus treatment = 4.5 t/d (R4)		

Based on the dataset in Table 2, a Grand Composite Curve of Heat Integration is constructed (Fig. 11(b)) following the Composite Curve (Fig. 11(a)). 5,480 kW of heat can be recovered internally by a heat exchanger, identified through the Heat Pinch Analysis. However, an additional 960 kW of hot utility and 120 kW of cold utility are required. The same interpretation can be obtained in both the Composite Curve and Grand Composite Curve. The main advantage of Grand Composite Curve is enhancing the derived information, allowing a better illustration of utility placement (Klemeš et al., 2018). The required hot utility (e.g. steam, hot oil) can be further reduced by the converted heat in Total Site Solid Waste Integration. It is feasible as the generated heat is sufficient in term of both quantity and quality, where the temperature of the heat from, e.g. incineration is higher than 100 °C (Planete Energies, 2015). The hot stream (source 1 – low-grade heat) that has to be cooled by 120 kW of cold utility (e.g. cooling water, chilled water, refrigerant) can be utilised in Solid Waste Integration for pre-drying (Arsenyeva et al., 2016). The utilisation of waste heat from the industrial process as the heat source for drying is deemed as feasible by Li et al., (2012), however sensitive to the selling value of the recovered material or energy.

Fig. 12 shows the overall potential integrated design. For example, in the industrial cluster, 2 t/d of solid waste (W3) and 1 t/d of solid waste (W4) are allocated to R3. 13.5 MWh/d of heat can be recovered from the conversion (R3). Another 2 t/d of solid waste (W4) is not qualified to be treated in the industrial cluster due to the insufficient capacity and/or high moisture content. It is transferred to the solid waste network. The 2 t/d of W4 can be either treated in R6 (urban cluster) or go through drying for R1. The decision is related to net energy consumption, in drying (dry W4 or other waste), transporting (distance to R1 vs R6) as well as the potentially recovered utilities (R6 vs R1). The original moisture content of the compared waste and the drying approaches (technologies and the energy source) play the critical roles for the sustainable selection. This case study illustrates the potential alternatives supported by Fig. 12. The final preference is based on the allocated budgets, available infrastructures, distance within clusters, environmental concern, and priorities of stakeholders. An integrated design, with the support of an intuitive approach, converting waste at a place to resources in another place, could facilitate the decision-maker toward sustainable and symbiotic management. However, as discussed by Dong et al. (2016), regulations, policies and financial incentives play an important role in the implementation of urban and industrial symbiosis. It is critical to initiate more capacity building in improving the awareness and understanding of innovative symbiosis, applying economic instruments, and developing the regulation that considers the demands of different parties. One crucial feature of TESI is the scale and resulting multi-agency that involve various players including government, firms and cooperatives. A future study for the establishment of cooperation (e.g. information sharing), trust and regulation (economic and environmental) towards the realisation of TESI is required.

5. Conclusion

A novel Pinch Analysis based method for Solid Waste Integration at a Total Site has been developed in this study. The incorporation of other Process Integration (e.g. Heat Integration, Water Integration) with consideration of environmental and economic feasibility forming a TESI. It could facilitate the design of industrial and urban symbiosis and especially crucial in the transition of a circular economy which stressing on waste minimisation and recovery at the end of life. The advantages of this approach lie at the graphical, transparent, and coherent algorithm, enabling accessible communication with decision-makers. It is capable of minimising the requirement for waste drying (dried waste). If drying is unavoidable due to the recovery performance, the utilisation of low-

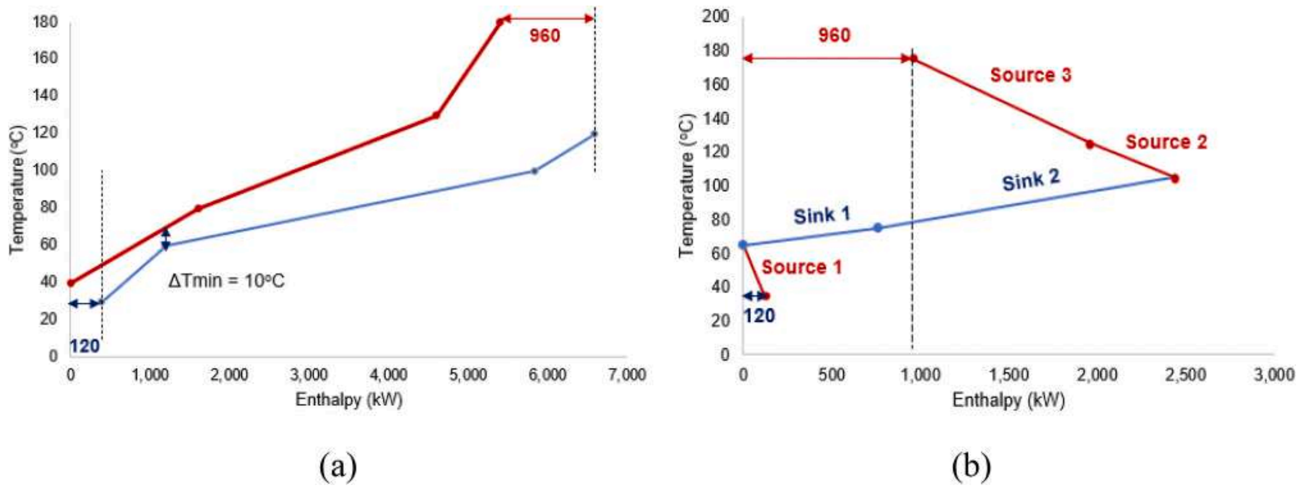


Fig. 11. (a) Composite Curves and (b) Grand Composite Curve of Heat Integration (industrial process) in the industrial cluster. Based on the dataset from Klemeš et al. (2018b).

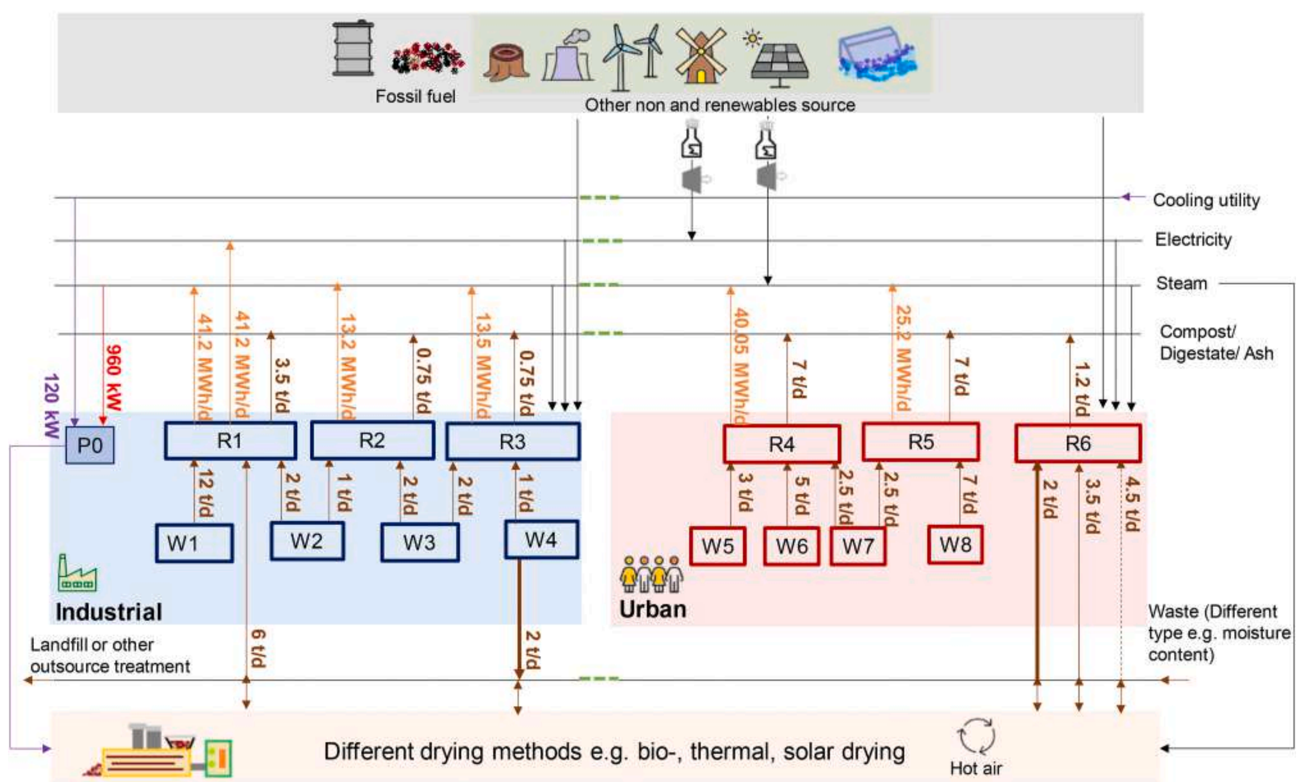


Fig. 12. The TESI considering the Solid Waste Integration. The colour code of arrows can be interpreted as red = flow of hot utility; orange = flow of energy recovered from waste; brown = flow of waste and recovered waste; purple = flow of cooling utility and waste heat for drying. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

grade heat is first considered supported by other hot utilities. The illustrative case study suggested that the identified integrated design could increase the recovered heat from the solid waste in the urban cluster by 20% (11.39 MWh/d). The unmanageable solid waste (2 t/d) in the industrial cluster, destined to the landfill, is diverted and a total of 960 kW hot utility (e.g. hot water) in the industrial cluster could be avoided by utilising the recovered heat. The value of the solid waste has been maximised through the resulting solution where waste matching/allocation is conducted, considering the quality of waste (e.g. moisture content), supply, demand, and recovery capacity. The case study assessed in this study is mainly to demonstrate the applicability of the proposed method, particularly the newly developed method for Solid Waste Integration. Future work could focus on extending the assessed scope and detail of the case study, for example, by increasing the number of clusters (e.g. agriculture), type of waste and recovery options (e.g. recycling). More importantly, a comprehensive economic feasibility analysis under different scenarios, as proposed in the methodology, have to be conducted. There have been various energy sources (renewable and non-renewable) and drying approaches (e.g. thermal drying, bio drying, solar drying) with different efficiency, economic and environmental performance. A different set up of comparative basis or alternatives inclusion could lead to a disparate integrated design.

Credit author statement

Yee Van Fan: Conceptualisation, Data curation, Formal analysis, Methodology, Visualisation, Writing – original draft; Petar Sabev Varbanov: Supervision, Writing – review & editing, Validation, Proofreading; Jiří Jaromír Klemeš; : Conceptualisation, Supervision, Funding acquisition, Writing – review & editing; Proofreading; Sergey Vladimirovich Romanenko: Funding acquisition, Reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Glossary

GHG: Greenhouse gas
LCA: Life Cycle Assessment
LHV: Low Heating Value
TESI: Total EcoSite Integration
TSI: Total Site Integration
WRC: Waste Recovery Curve
WSC: Waste Supply Curve
Ce: Conversing efficiency to energy (%)
Cp: Conversion efficiency to products (%)
e: Index for different environmental footprints
EFA: Avoided environmental footprint (e.g. tCO_2)
EFR: Environmental footprint (e.g. tCO_2)
EP: Environmental price (e.g. €/tCO_2)
i: Index for different integrated design
k: Index for different recovered utilities
o: Index for different baseline scenario
r: Index of waste recovery
RP: Recovered products/utilities (t)
s: Index of waste source
SP: Selling price (€/t)
TC: Total Cost (€)
TE: Total recovered utility/energy (MWh or MJ)
TOC: Total Operating Cost (€)
TP: Total recovered products (t)
W: Waste amount (t)