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Multi-Objective Optimisation of Integrated Bio-Energy Supply Chain and Heat Exchanger Network Retrofit for Multi-Period Operations Considering Economics and Environmental Impact

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This work presents a methodology for integrating bio-energy supply chain networks with combined heat and power generation networks and heat demand of industrial processes. The industrial heat demand profile investigated involves multiple periods of operations and multiple utilities in heat exchanger networks requiring retrofit. The approach adopted involves a 3-layered superstructure, with the first layer comprising the bio-energy supply chain network that provides energy sources for steam generation. The second layer comprises the energy generation hub, where the bio-energy feedstocks of the first layer are converted to heat and power. A portion of the high-pressure steam generated in the energy hub layer and the intermediate steam levels exiting the turbines are fed to the third layer as hot utilities to satisfy the hot utility demand of the multi-period heat exchanger network. The multi-period network, which is to be simultaneously retrofitted and optimised with the networks of the first and second layers of the integrated superstructure, is also fed with steam generated from fossil sources in the second layer. The overall superstructure is modelled as a multi-objective mixed integer non-linear program considering economics and environmental impact as objectives. The solution obtained for the integrated model involves the selection of certain quantities of feedstocks from all available feedstocks supply locations. The retrofitted multi-period network competes favourably in terms of investment cost with solutions of existing methods, and it uses a mix of the available renewable and non-renewable energy sources.

1. Introduction

To achieve net zero carbon emissions, process plants must be designed to be energy efficient and explore opportunities for integration with other energy and resource utilisation networks to attain optimal resource-sharing profiles. In chemical engineering process synthesis and optimisation, the synthesis of networks, such as Heat Exchanger Networks (HENs), Combined Heat and Power (CHP) networks, and bio-energy supply chain networks (SCN), have all received significant attention in the literature. Each of these networks may have surplus energy, or resources, that can be fed to one or more of the other networks to attain a more integrated and optimal resource network with better potential to achieve more realistic carbon emission reduction goals. However, the holistic integration of multiple resource networks of this nature has not been well-researched in the literature. For heat exchanger network (HEN) synthesis, which is the sub-network that has received the most attention in process optimisation, most research efforts have focused on the single-period scenario for both grassroots and retrofit networks, with less attention paid to the multi-period scenario, especially its retrofit counterpart. For the single-period scenario, Wang et al. (2022) developed the temperature versus pressure drop grid diagram approach for the retrofit of single-period HENs. For the multi-period scenario, Verheyen and Zhang (2006) adopted the maximum area sizing approach in the objective function to design exchangers that are capable of optimally transferring heat across all periods of operations. For the retrofit scenario, Isafiade (2018) extended the maximum area approach of Verheyen and Zhang (2006) using the reduced superstructure synthesis approach. In this approach, the retrofit problem is first solved as a grassroots problem. The matches selected in the optimal solution to the grassroots model are then used together with matches present in the

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original network to generate a reduced superstructure. The reduced superstructure, which is modelled as a mixed integer nonlinear program (MINLP), is then solved to obtain the optimal multi-period retrofit network with minimal investment and utility costs.

In the area of bioenergy SCN optimisation, which has also received significant attention in the scientific literature, Ganev et al. (2022) adopted a mixed integer linear programming approach for the synthesis of a sustainable biodiesel and diesel supply chain considering various scenarios of blending centre. The model, whose feedstock entails sunflower and rapeseed, was aimed at determining optimal values for key parameters such as feedstock cultivation cost, including land availability for such cultivation, size of biorefineries, including their number and locations, mode of transport, including quantities, for the feedstock and finished products. The authors evaluated their solutions using economics and environmental impact (EI). The authors found that the number of biorefineries present in a solution plays a key role in determining the optimum network. Helal et al. (2023) presented a review of studies involving supply chains of biomass to bioenergy. The authors identified six key areas that require more attention in the field. However, the authors failed to identify the benefits inherent in integrating bioenergy SCNs with other resource utilisation and heat demand networks. One of the few studies that have explored this potential is the work of Cowen et al. (2019), where a bioenergy supply chain network was integrated with the heat demand of a set of co-located process plants. In the study, the authors considered the seasonality associated with the availability of biomass feedstocks and the periodicity of the process parameters of the HENs of the plants involved. Isafiade and Short (2022) then extended the work of Cowen et al. (2019) by including a CHP network in the integrated model. However, Isafiade and Short (2022) only considered a single plant and single period HEN. To the best of the author's knowledge, no research has considered the integration and simultaneous optimisation of bioenergy SCN with CHP network and retrofit of multi-period HEN synthesis using multiple objective criteria involving economics and environmental impact, which is the goal of this paper.

2. Problem statement

Given a set of bio-based feedstocks *M* in layer 1 of the overall network and a set of transport modes *R* for shipping the feedstocks, or biogas generated from the feedstocks to a CHP plant energy hub in layer 2. Parameters associated with the bio-based feedstocks include season of availability (set *S*) and unit costs, while parameters associated with the transport modes include cost per distance travelled, tortuosity factors, the distance between feedstock locations and the energy hub in layer 2 (represented as *D*) and infrastructure costs. Given for the third layer of the overall network are periods of operations *P*, sets of hot streams *H* and cold streams *C* and their heat capacity flowrates *FCP* and heat transfer coefficients *h* for each period of operation, supply temperatures T^s for each period of operation, and target temperature T^t for each period of operation. Existing matches in the original network in the third layer are also given. Other parameters for the HEN that are given are installation costs and area costs for heat exchangers, and unit costs for cold utilities and hot utilities generated from fossil fuel. The goal is to design a network that simultaneously optimises the integration of a bioenergy SCN with a CHP network and the heat demand and investment cost required for the optimal retrofit of a multi-period HEN.

3. Methodology

An aspect of the method used in this paper is adapted from the work of Isafiade and Short (2022), who also integrated a bioenergy supply chain with a CHP generation hub and the heat demand of the HEN of a process plant. However, this paper differs from that of Isafiade and Short (2022) in that it includes the simultaneous retrofitting of multi-period HEN and additional utility generated from non-renewable sources. The proposed integrated superstructure is shown in Figure 1. In the figure, the top layer, which is represented as a mixed integer linear programming (MILP) model, is the SCN involving multiple bio-based feedstocks that can be shipped to the CHP layer through transport modes such as road (truck), rail, and pipeline. The CHP layer, which is the middle layer in the figure and modelled as a linear programming (LP) model, comprises boilers and turbines where one of the boilers receives renewable energy feedstock from the SCN layer while the other receives fuel from a non-renewable source. The turbines are required to generate a specified amount of power. The third layer entails a multiperiod HEN requiring retrofit. The HEN is modelled using the reduced superstructure synthesis method of Isafiade (2018). The layer is linked to the CHP layer through the high-pressure steam generated from any of the boilers as well as through the intermediate steam levels exiting the turbines. These steam levels serve as hot utilities in the HEN. Although the SCN and CHP layers are represented as MILP and LP models, the resulting integrated model is represented as a mixed integer non-linear programming (MINLP) model due to the presence of the multiperiod HEN. A further contribution of this work lies in the fact that the EI, through carbon emission, associated with each of the energy sources (renewables and non-renewables) are simultaneously traded-off with one another and with the economic impact of the integrated network using the goal method of multi-objective optimisation. For the sizes of the heat exchangers in the retrofitting of the multi-period model, Eq(1) illustrates the maximum area ($\mathrm{A}_{\mathrm{i,j,k}}^{\mathrm{Select}}$) in m^2 of heat exchanger that will transfer heat between hot stream i and cold stream j in interval k of the HEN superstructure that exist in multiple periods in the optimal HEN. In the equation, $q_{i,j,p,k}$ in kW is heat load exchanged between hot stream i and cold stream j in interval k and period p, $LMTD_{i,j,p,k}$ is the logarithmic mean temperature difference in the exchanger transferring heat between hot stream i and cold stream j in period p and interval k of the HEN, $U_{i,j,p}$ is overall heat transfer coefficient between hot stream i and cold stream j in period p. In Eq(2), $\mathrm{A}_{\mathrm{i,j,k}}^{\mathrm{Exist\ orig}}$ in m^2 is the area of the existing heat exchanger in the original network, while $\mathrm{A}_{\mathrm{i,j,k}}^{\mathrm{New}}$ represents the additional heat exchanger area that must be purchased, or the size of the new exchanger that must be purchased for a case where the selected exchanger did not exist in the original network. Both areas are for matches between hot stream i and cold stream j in interval k of the HEN superstructure.

$$A_{i,j,k}^{Select} \geq \frac{q_{i,j,p,k}}{U_{i,j,p} \cdot LMTD_{i,j,p,k}} \tag{1}$$

$$A_{i,j,k}^{New} = A_{i,j,k}^{Select} - A_{i,j,k}^{Exist\ orig} \tag{2}$$

In Eq(3), which is the economic component of the integrated network, the terms in the first curly bracket is the annualized capital cost of the multiperiod HEN, the terms in the second curly bracket is the annual operating cost of the multiperiod HEN, the terms in the third curly bracket (SCNCost ($/y)) is the total annual cost of the SCN while the terms in the fourth curly bracket are the annual operating cost of the CHP subnetwork. In the equation, AF is annualization factor, CF ($/$m^2$) is installation cost for new heat exchangers, $y_{i,j,k}$ is binary variable that indicates existence of a match between hot stream i and cold stream j in interval k of the HEN superstructure, AC ($/$m^2$) is the unit area cost for heat exchangers, AE is area cost exponent, DOP_p is duration of operational period p, NOP is total operational period duration in the HEN, HUC ($/(kW·y)) and CUC ($/(kW·y)) are the costs per unit of hot and cold utilities. 0.0239 $/(kW·h) (adapted from Edgar et al., 2001) is the cost per unit of power purchased PP, 0.00983 $/(kW·h) (adapted form Edgar et al., 2001) is the penalty charged per unit of excess power *EP* purchased but not used, while N_{hours} (8,160 h) is the number of operational hours in a year.

$$\begin{aligned}\mathrm{Min}\, TAC = AF &\left\{CF \sum_{i\in H}\sum_{j\in C}\sum_{k\in K} y_{i,j,k} + AC \sum_{i\in H}\sum_{j\in C}\sum_{k\in K}\left(A_{i,j,k}^{New}\right)^{AE}\right\} \\ &+ \left\{\sum_{p\in P}\left(\frac{DOP_p}{\sum_{p=1}^{NOP} DOP_p}\cdot\sum_{i\in H}\sum_{j\in C}\sum_{k\in K}\mathrm{HUC}\cdot q_{i,j,p,k}\right)\right. \\ &\left. + \sum_{p\in P}\left(\frac{DOP_p}{\sum_{p=1}^{NOP} DOP_p}\cdot\sum_{i\in H}\sum_{j\in C}\sum_{k\in K}\mathrm{CUC}\cdot q_{i,j,p,k}\right)\right\} + \left\{\sum_{m\in M}\sum_{r\in R}\sum_{s\in S} SCNCost_{m,r,s}\right\} \\ &+ \{(0.0239\cdot N_{hours}\cdot PP) + (0.00983\cdot N_{hours}\cdot EP)\}\end{aligned} \tag{3}$$

$$\begin{aligned}\min EI = &\left\{\sum_{r}\sum_{s}\left({x_{m,r,s}}/{\eta\cdot LHV_m}\right)\cdot CUA_m\cdot 3.67\cdot N_{hours}\right\} \\ &+ \left\{\sum_{p\in P}\left(\frac{DOP_p}{\sum_{p=1}^{NOP} DOP_p}\cdot\sum_{j}\sum_{k}\left({q_{HPS1,j,p,k}}/{\eta\cdot LHV_m}\right)\cdot CUA_m\cdot 3.67\cdot N_{hours}\right)\right\}\end{aligned} \tag{4}$$

$$\min Z = R_g\cdot\left(\frac{TAC}{TAC_{min}}\right) + \left(1-R_g\right)\cdot\left(\frac{EI}{EI_{min}}\right) \tag{5}$$

Eq(4), which is the EI objective function, is adapted from Shenoy (1995) and Isafiade and Short (2022). The equation is modified in this paper to capture not only the EI of the renewable energy sources (shown in the first curly bracket) as done by Isafiade and Short (2022), but that of the non-renewable as well including the associated multiperiod profile of the HEN which is shown in the second curly brackets. In Eq(4) EI (in kg/y) is the pollutant mass flowrate, $x_{m,r,s}$ (in kW) is the amount of feedstock shipped from supply m using transport mode r, in season s to the CHP subnetwork. η represents the efficiency of combustions of the feedstocks, LHV_m (in kWh/kg) represents feedstock m lower heating value, while pollutant mass percentage for feedstock m in non-oxidized form is represented by CUA_m. The values of CUA_m used in this paper for various feedstocks m are 47.4 % for corn stover (Kumar et al., 2008), 20.15 % for glycerin (Tamošiūnas et al., 2019), 53.24 % for wood (Shi et al., 2016) and 62.30 % for fossil (Babiński, et al., 2019). The 3.67 in Eq(4) was determined by dividing CO_2's molecular mass by the atomic mass of carbon. For the multi-objective optimization, shown in Eq(5) is the weighted sum method as presented by Gxavu and Smaill (2012). In the equation, z is the multi-objective variable to be minimized, TAC_{min} is the best TAC value obtained by solving the overall model with TAC as the only objective function, EI_{min} is the best EI obtained when the overall model is solved using EI as the only objective function, while R_g is the weighting factor which can vary between 0 and 1 depending on how much weight is preferred by the designer for each objective.

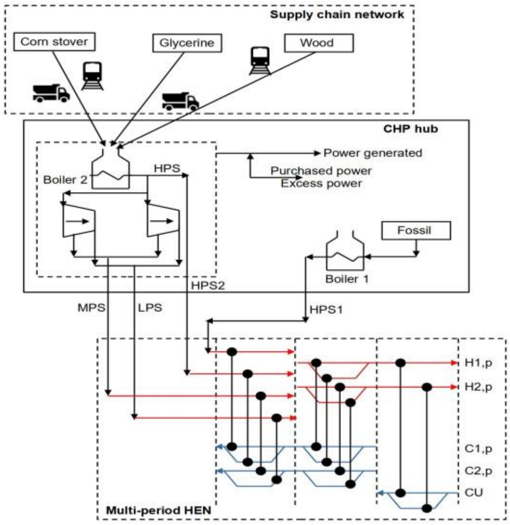

Figure 1: Superstructure representing the integrated network

4. Case study

The mathematical model and process parameters used for the CHP hub is adapted from Edgar et al. (2001) and Isafiade and Short (2022). For the CHP layer, the model of Edgar et al. (2001) and Isafiade and Short (2022) is modified in this paper to accommodate the additional non-renewable fuel source and the connection of the CHP layer with the retrofit of the multi-period HEN in the third layer. The system constraints of the CHP layer as described by Edgar et al. (2001) are also used in this paper. The constraints are that boiler 2 generates high pressure steam, HPS2, (4,378 kPa(g), 382 °C) that is then split and fed into turbines 1 and 2 which in turn both produce intermediate steam (medium pressure = 1,344 kPa(g) and low pressure = 427.5 kPa(g)). Both steam levels have 54 °C of superheat. The CHP is required to produce a minimum of 24,550 kW of electricity (Edgar et al., 2001). Considering other system constraints within the overall integrated network such as limits on supply capacity for each of the available renewable energy resources, as well as their unit costs, the CHP may or may not be able to meet the stipulated minimum power production limit of 24,550 kW. Additional electric power, with a base of 12,000 kW, can be bought from an external supplier. If the additional 12,000 kW purchased is not fully utilised, then penalty charges will be incurred. Details about the CHP constraints can be found in Edgar et al. (2001). The data for the SCN component and the CHP subnetwork of the case study investigated is taken from Isafiade and Short (2022). However, the maximum quantity of feedstock available in season 1 for glycerin used in this paper is 500,000 kg/y, which is different from that of Isafiade and Short (2022). Also, since the work of this paper includes additional energy source, the data for the supply and target temperatures of the steam generated from the non-renewable is indicated as HPS1 in Table 1. The unit cost for HPS1 is 115.2 \$/(kW·y) while that of the only available cold utility is given as 1.3 \$/(kW·y). For the multi-period HEN component, the data are shown in Table 1 while the original network which is retrofitted in this paper can be found in Isafiade (2018). The solution obtained for the integrated network using an exchanger minimum approach temperature (EMAT) of 10 °C for the HEN is shown in Figure 2. In the SCN component of the solution which has a TAC of \$ 2.318×10^7, all three renewable energy sources are selected with corn stover, and glycerin, being selected in all seasons while fuel wood is selected only in season 2. For corn stover and glycerin, the transport mode selected is rail while truck was selected for wood. In the CHP sub-network, the total power generated by the two turbines is 15,250 kW. Therefore, an additional 12,000 kW had to be purchased, of which 2,700 kW is excess power that attracted a penalty charge. Of the 46.9 kg/s of HPS2 generated by boiler 2, 15.6 kg/s and 24.3 kg/s were fed to turbines 1 and 2, while the balance of 7.12 kg/s was not used by the multi-period HEN. The multiperiod HEN received 14,395 kW of steam (HPS1) from the non-renewable source while it received 20,872.9 kW from the renewable energy source as MPS. For the multiperiod network, the retrofitted heat exchanger areas are shown below each match in Figure 2. The retrofitted HEN does not require any new exchanger which implies that no installation costs will be incurred, but it requires a total additional area of 1,320 m^2 (investment cost = 129,304 $) and a total network area requirement of 6,489 m^2. The additional area required will be added to the areas of existing units. Although the costs used for the non-renewable energy sources (including cold utility) as well as heat exchanger capital costs of this paper are denominated in US dollars, the results obtained for the retrofit multi-period HEN compares favorably with those presented in the literature denominated in Euros. In the work of Kang and Liu (2015), which investigated 4 scenarios, additional areas obtained are 1,766 m^2, 1,766 m^2, 1,219 m^2, and 1,544 m^2 for scenarios 1 to 4, while that of Isafiade (2018) was 2,969 m^2.

Table 1: Multi-period process stream data for the HEN component of the case study

Streams	Periods								
	Period 1			Period 2			Period 3		
	T^s (°C)	T^t (°C)	F (kW/°C)	T^s (°C)	T^t (°C)	F (kW/°C)	T^s (°C)	T^t (°C)	F (kW/°C)
HP1	393	60	201.6	406	60	205	420	60	208.5
HP2	160	40	185.1	160	40	198.8	160	40	175.2
HP3	354	60	137.4	362	60	136.4	360	60	134.1
CP1	72	356	209.4	72	365	210.3	72	373	211.1
CP2	62	210	141.6	62	210	141.0	62	210	140.5
CP3	220	370	176.4	220	370	175.4	220	370	174.5
CP4	253	284	294.4	250	290	318.7	249	286	271.2
HPS1	500	500	-	500	500	-	500	500	-
HPS2	372	372	-	372	372	-	372	372	-
MPS	250	250	-	250	250	-	250	250	-
LPS	180	180	-	180	180	-	180	180	-
CU1	15	25	-	15	25	-	15	25	-

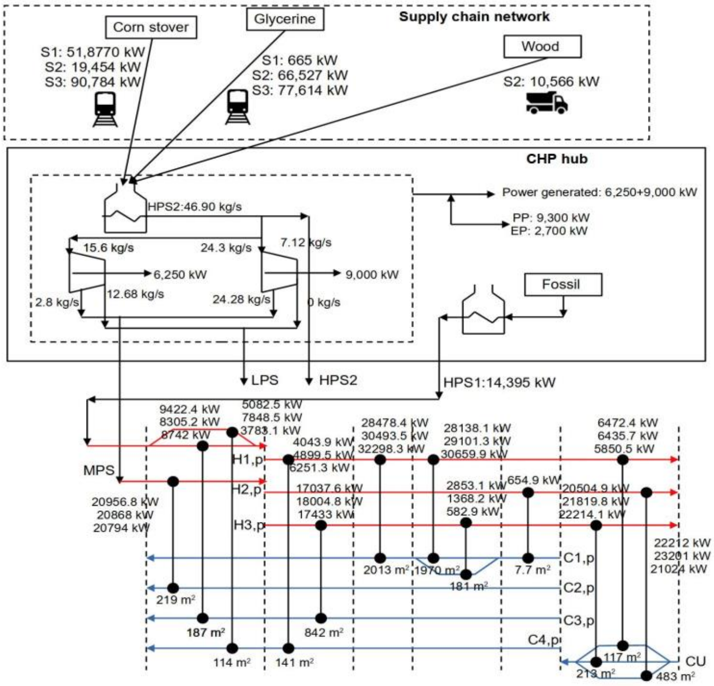

Figure 2: Optimal solution obtained for the multi-objective optimisation of the integrated network

For the multi-objective optimisation, an EMAT value of 5 °C was set for the HEN component of the integrated network and values of $ 2.1592×10^7 $/y and 2.719479×10^9 kg/y were obtained for TAC_{min} and EI_{min}. These values were then used in Equation 5, with R_g values of 0.1, 0.5, 0.7, and 0.9. For each of these R_g values, the TAC obtained are \$ 2.1864×10^7, \$ 2.1862×10^7, \$ 2.842×10^7, and \$ 2.1791×10^7, while the equivalent EI values obtained are 2.724411×10^9 kg/y, 2.724493×10^9 kg/y, 2.728530×10^9 kg/y, and 2.728530×10^9 kg/y.

5. Conclusions

An integrated resource network that systematically incorporates a SCN, a CHP and a multi-period HEN requiring retrofit, has been presented in this paper. The energy sources considered, to satisfy hot utility demand for each operational period of the multi-period network, includes renewables (from the SCN through the CHP) and non-renewable (from the CHP). Due to the inherent seasonality associated with availability of renewable energy sources as well as the periodicity associated with operations of process parameters, the integrated superstructure is systematically designed to simultaneously capture these two fluctuations at the SCN subnetwork and HEN subnetwork. The developed model further demonstrates the benefit of integrating resource networks whose design is at the grassroots level with other resource networks whose design is at the retrofit level. Such benefit includes the opportunity to systematically allocate cleaner energy sources in place of the less clean ones in the retrofit process. The trade-offs between the clean and the less clean energy sources within the integrated resource network considered in this paper is demonstrated through the weighted method of multi-objective optimisation involving economics and environmental impact. To further unpack the benefits of the developed model of this paper, other design features such as piping for fluid transport between the CHP hub and the HEN, detailed turbines, and boiler design, will be considered in future studies.

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