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Energy and Energy-Based GHG Emission Targeting and Optimal Pinch Identification using Constraint Logic Propagation

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In this paper an interval based constraint logic propagation (CLP) model is used for energy and energy-based emission minimum cost targeting and both optimal pinch point and process conditions identification under fuzzy process conditions. A case study to illustrate the CLP model program application using four streams problem is introduced.
Key Words: Systematic Targeting; Heat Integration; Constraint Logic Propagation; Energy-based GHG emission; Optimal Pinch Identification

1. Introduction

During the design of new processes, the process conditions are normally in their most fuzzy state. It is known for the experienced people in the filed of process integration that different sets of process conditions may render the same pinch point with constant values of energy consumption and energy-based GHG emission, same pinch point but with different values of energy consumption and energy-based GHG emission and different pinch points and, of-course, different energy consumption and energy-based GHG emission. Hence the notion of the "optimal pinch identification" for a given fuzzy process design problem is important. CLP as a technique used in constraints satisfaction is a unique problem-solving paradigm that is increasingly being used as a problem-solving tool for many engineering problems. CLP is a very efficient method for reducing the search space of combinatorial search and optimization problems and has become more important in the last two decades. The basic idea of constraint propagation methods is to detect and remove inconsistent variable(s) assignment(s) that can not participate in any feasible solution through the repeated analysis and evaluation of the variables, domains and constraints describing a specific problem instance. In this paper an interval based CLP model and a case study for energy and energy-based emissions targeting under fuzzy process conditions is introduced. The model calculates minima energy utility targets and energy-based GHG emissions under all possible combinations

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of process modifications and an interval collapsing technique is used to find optimal process conditions and in the same time the problem optimal pinch temperature.

2. Interval Constraint Logic Propagation

2.1 Constraint Satisfaction using CLP

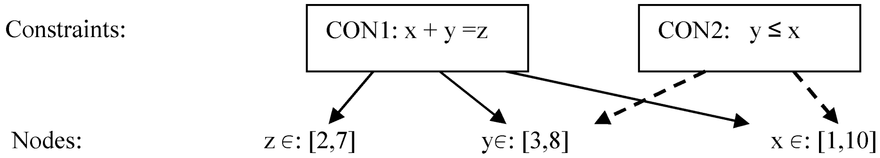
Constraint logic propagation known as CLP is a problem-solving paradigm that establishes a clear distinction between two pivotal aspects of a problem: a precise definition of the constraints that define the problem to be solved, and the algorithms and heuristics enabling selection of the decisions to solve the problem. Because of these capabilities, constraint programming is increasingly being used as a problem-solving tool for many engineering problems (M.B. Noureldin, 2001)(I. Harjunkoski, 2002). Constraint programming was originally developed for solving feasibility problems but has recently been used in optimization problems (ILOG, 1999). Although constraint programming methods are efficient in solving feasibility/targeting problems, optimization depends entirely on building the correct constrained model. To show how constraint logic propagation with interval labels works, this paper gives the earliest numerical example "Waltz" algorithm, first introduced in the mid seventies (D. Waltz, 1975).

Suppose the following relations model/define our problem:

$x+y=z$, $y \leq x$ and we can start with the following bounds:

$x \in [1,10]$, $y \in [3,8]$, $z \in [2,7]$,

This would be implemented in a data structure given by the following constraint network:



The constraint queue begins with both constraints (CON1, CON2). CON1 ($x + y = z$) is popped from the queue. Since $x \geq 1$ and $y \geq 3$, CON1 gives $z \geq 4$; therefore reset the bounds of z to 4. Since $z \leq 7$ and $y \geq 3$, CON1 gives $x \leq 4$; therefore reset the bounds of x to [1,4]. Since x and z have been changed, add CON2 to the queue. CON2 ($y \leq x$) is popped from the queue. Since $y \leq x$, CON2 gives $y \leq 4$; therefore reset the bounds of y to [3,4]. Since $y \geq 3$, CON2 gives $x \geq 3$; therefore reset the bounds of x to [3,4]. Since x and y have changed, add CON1 to the queue. CON1 ($x + y = z$) is popped from the queue. Since $x \geq 3$, $y \geq 3$, CON1 gives $z \geq 6$; therefore reset the bounds of z to [6,7].

Since only z has changed and z has no other constraints beside CON1, nothing is added

A system that includes equality, inequality, continuous and integer and logical expressions constraints can be modelled in CLP environment as below (UniCalc, 1999).

X^2 + 6.0x=y-2^k;
kx+7.7y=2.4;
(k-1)^2<4;
(ln(y+2x+12)< (k+5)) or (y>k^2) → (x<0.0) and (y<1);

Where k is integer; x, y are real and → stands for implication

The solution of the problem above exhibits several solutions that all lay in these intervals of the three variables, k = [0, 2]; x = [-6, -1e-10]; y = [0.311688, 1];

2.2 Pinch Point Multiplicity Example

Let us use the following problem to find heating and cooling energy targets, respectively, and the pinch points.

Table #1 Pinch Point Multiplicity Problem data Example (ΔT_min=10 ºK)

Stream	Ts (ºK)	Tt (ºK)	FCp(kW/ºK)
H1	522	[328:331]	15
H2	[378:383]	303	[3 : 7]
C1	[297:303]	548	17
C2	[318:321]	378	2

From the first inspection of the problem we have a set of "potential pinch points" PPP={307;308;309;310;311;312;313;328;329;330;331;378;379;380;381;382;383;522} ºK at the hot temperature scale and a subset that contains the "true pinch points", TPP={307; 308;309;310;311;312;313;383}. Multiple sets of process conditions lead to the same pinch point in this TPP sub set, rendering different energy and energy-based GHG emissions cost. For instance, pinch point 307 ºK can be obtained from tens of process condition's combinations that exhibit different energy cost targets as. follows:{1243;12},{1173;16},{1097;20},{1021;24},{960;28},{945;28},{1288;12},{1290;12},{1019;28},{1012;28},{1005;28},{998;28},{991;28},{984;28},{986;28},{988;28},{990;28},{1292,12},{939;28},{1292;12};{1294;12};{1279;12},{1264;12},{1249;12},{980;28}. Pinch point input multiplicity where multiple sets of process conditions lead to the same pinch point exhibiting different energy targets creates a situation where identifying the optimal pinch point is warranted. Identifying the optimal pinch point that renders global minimum energy cost and the optimal process conditions that lead to it is the objective of this paper.

3. Model Description and CLP Formulation

Hot streams temperatures are shifted down one-by-one by the first set of desired minimum temperature differences, $\Delta T_{min}{}^{i}$, between the hot and cold resource streams to form a set of possible discrete temperature values for a continuum of possible values for $\Delta T_{min}{}^{i}$. $\Delta T_{min}{}^{i}$ represents the ΔT_{min} of hot stream (i) which refers to the minimum temperature approach between a specific hot stream and all other cold streams, can be taken here in this paper as equal to 1ºK. The shifted supply and target temperatures of resource hot streams, and the actual supply and the target cold streams temperatures obtained through this are then sorted in a descending order, with duplicates removed, with each successive temperature pair representing the boundaries of a temperature step and defining a new temperature step “S”. Each supply temperature and target temperature input is in the form of intervals. The total number of temperature steps is “N+1,” where S varies from 0,1,2,…,N and the temperature step number ”0” represents the external energy utility temperature step. In this step, known as the external energy step, energy output, initial values: $Q_{s=0}^{low\_output} = 0.0$ in “energy units” and $Q_{s=0}^{high\_output} = 0.0$ in “energy units.” Each temperature step, ”S” greater than 0, where S =1,2,…,N, has energy surplus $Q_s^{surplus}$. Such energy surplus has two calculated values: $Q_s^{low\_surplus}$ and $Q_s^{high\_surplus}$. It also has energy output Q_s^{output} from one temperature step to another. Such energy output Q_s^{output} has also two calculated values: $Q_s^{low\_output}$ and $Q_s^{high\_output}$. These values for energy surplus $Q_s^{surplus}$ and energy output Q_s^{output} are calculated for S=1,2,…,N:

$$Q_s^{low\_surplus} = \left(\sum_{k=1}^{n_S} FCp_k^{low} - \sum_{j=1}^{m_S} FCp_j^{high}\right)(Th_s - Tc_s)$$

$$Q_s^{high\_surplus} = \left(\sum_{k=1}^{n_S} FCp_k^{high} - \sum_{j=1}^{m_S} FCp_j^{low}\right)(Th_s - Tc_s)$$

$$Q_s^{low\_output} = Q_{s-1}^{low\_output} + Q_s^{low\_Surplus}$$

$$Q_s^{high\_output} = Q_{s-1}^{high\_output} + Q_s^{high\_Surplus}$$

Where n_s and m_s are the number of the resource hot and cold streams respectively represented in the s^{th} temperature step and Th_s and Tc_s are the higher and lower shifted temperatures for the hot streams, respectively, and actual temperature of the cold streams representing the temperature boundaries. $[FCp_k]$ and $[FCp_j]$ are heat capacity flowrate intervals; defined as follows: $FCp^{low}{}_k$ is the low value of the Heat Capacity Flowrate term resulted from the multiplication of the value of the flow F lower bound by the specific heat value Cp of the hot stream number k in flow-specific heat units. $FCp^{high}{}_k$ is the high value of the Heat Capacity Flowrate term resulted from the multiplication of the value of the flow F upper bound by the specific heat value Cp of the hot stream number k in flow-specific heat units. $FCp^{low}{}_j$ is the low value of the Heat Capacity Flowrate term resulted from the multiplication of the value of the flow F lower bound by the specific heat value Cp of the cold stream number j in flow-specific heat units. $FCp^{high}{}_j$ is the high value of the Heat Capacity Flowrate term resulted from the multiplication of the value of the flow F upper bound by the specific heat value Cp of the cold stream number j in flow-specific heat units, and the CLP Model takes the following general form:

$$\sum_{k\in Hs} [FCp_k] - \sum_{j\in Cs} [FCp_j] + [Qh_s] - [Qc_s] - [Q_s^{output}] = 0.0 \qquad (1)$$

$$[M(ng)] = [Q\_consumed\ ] \div \{Hv(ng) \times \eta\} \qquad (2)$$

$$[M\_CO2] = [M(ng)] \times (wt\%\_C) \times (MW\_CO2) \div (MW\_C) \quad (3)$$

$$[Q_0^{surplus}] = 0.0; [Q_0^{output}] = 0.0; \quad (4)$$

Where, [M(ng)] is the natural gas consumption interval , [Q_consumed] is the thermal load consumed for both heating and cooling intervals , [η] is Heater/Electricity generation efficiency interval, [Hv(ng)] is heating value of fuel, [M_CO2] is carbon dioxide emissions interval (ton/year),[M(ng)] is natural gas consumption interval, wt%_C is carbon content in natural gas.

3.1 Case Study Results and Discussion

Assuming that the hot and cold utilities costs are 2.0 and 3.0 $/kW including carbon credit and different sets of process conditions has no cost impact on the process but energy cost and carbon credit. The CLP model solution results in tables # 2 and 3 below shows the energy targeting phase, under given fuzzy process conditions, and the model defuzzification step. Such step identifies both the optimal pinch point, at 307 °C hot side, and the optimal process conditions that results in global minimum energy and energy-based GHG emission cost (M. B. Noureldin, 2003, 2006 and 2007).

The CLP model calculate the heating (Qh) and cooling (Qc) energy targets inclusion intervals and define the problem pinch points inclusion interval too. It identifies the rigorous global lower bounds of both heating and cooling utilities; where the lower bound energy cost can be calculated. Global minima of heating and cooling utilities lay at their intervals lower bounds. However most of the time they are not realized simultaneously. To find the global minimum energy and energy-based emission cost (lumped here for simplicity as 2.0 and 3.0 $/kW) for heating and cooling utilities the fuzzy process conditions intervals are collapsed. Such collapsing is conducted one interval at a time. Energy cost lower bound is calculated upon each collapse. The completion of this step results in the identification of the global minimum energy cost, optimal pinch point and optimal process conditions as shown in table # 3

Table# 2 Energy Targeting under Fuzzy Conditions

ID	Stream Name	Type	Temp In (°K)		Temp Out (°K)		FCP (W/°K)		Enthalpy (W)	
			Min	Max	Min	Max	Min	Max	Min	Max
0	H1	Hot	522	522	328	331	15	15	2865	2910
1	H2	Hot	378	383	303	303	3	7	225	560
2	C1	Cold	297	303	548	548	17	17	4165	4267
3	C2	Cold	318	321	378	378	2	2	114	120

Pinch points inclusion interval on the hot side temperature scale is [307; 383] °K
Heating (Qh) and cooling (Qc) energy utilities targets inclusion intervals are [900; 1309] and [12; 91] Watts; respectively

Table# 3 Optimal Identification of Pinch Point and Process Conditions

ID	Stream Name	Type	Temp In (°K)		Temp Out (°K)		FCP (W/°K)		Enthalpy (W)	
			Min	Max	Min	Max	Min	Max	Min	Max
0	H1	Hot	522	522	328	328	15	15	2910	2910
1	H2	Hot	383	383	303	303	7	7	560	560
2	C1	Cold	297	297	548	548	17	17	4267	4267
3	C2	Cold	321	321	378	378	2	2	114	114

Optimal pinch point due to the collapsing of the inclusion intervals on the hot side temperature scale lies at 307 °K and the global minimum heating (Qh) and cooling (Qc) energy utilities are 939 and 28 Watts; respectively

Conclusion

Rigorous lower bounds on both heating and cooling utilities cost can be obtained for fuzzy process conditions at the process synthesis phase using CLP model. CLP model introduced can also identify global minimum energy and energy-based emission cost optimal process conditions and optimal pinch point, without enumeration using pinch analysis or mathematical programming techniques.

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