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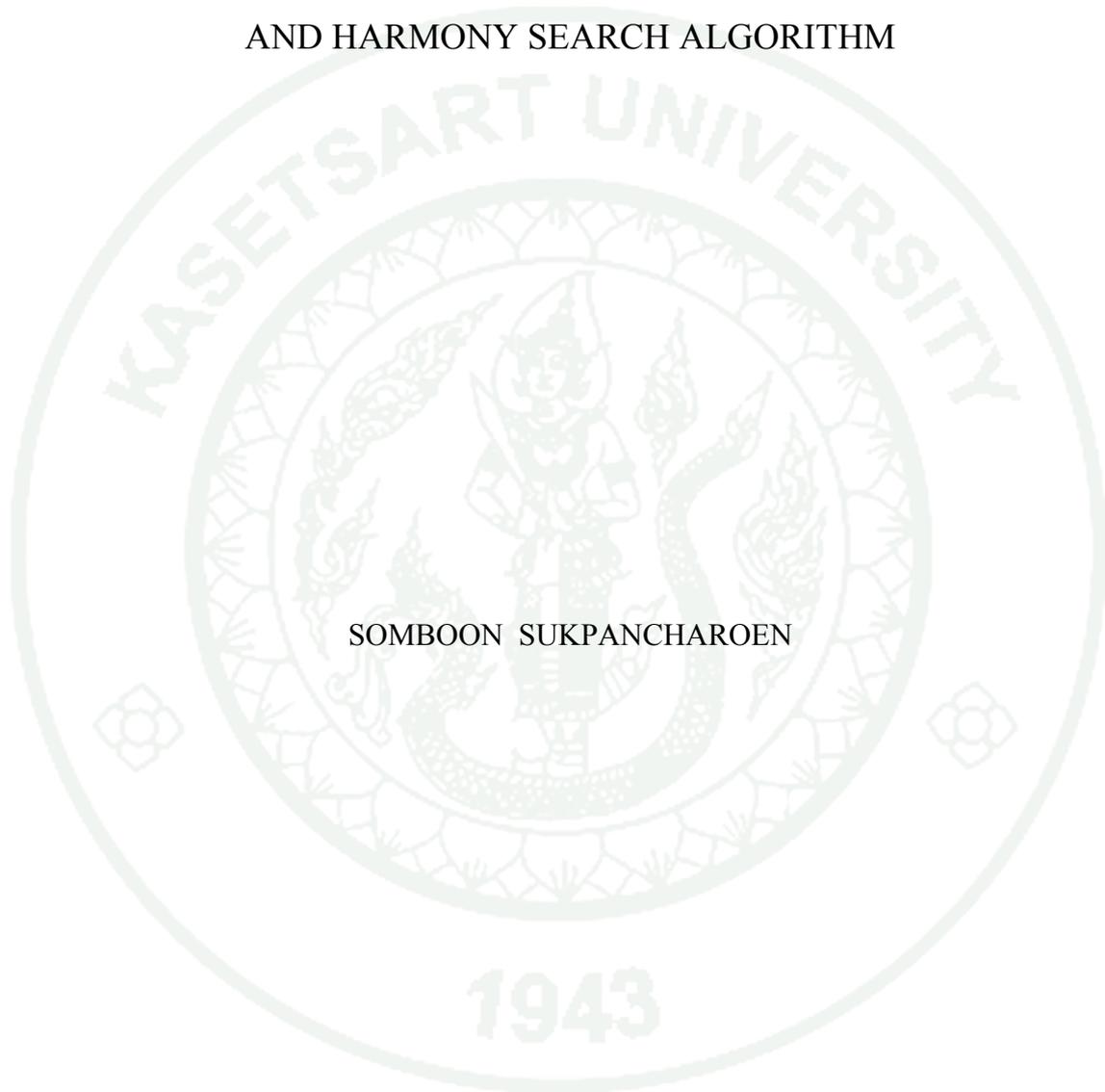
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THESIS

OPTIMIZATION OF HEAT-INTEGRATED DISTILLATION
SEQUENCES SYNTHESIS USING ANT COLONY ALGORITHM
AND HARMONY SEARCH ALGORITHM



SOMBOON SUKPANCHAROEN

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The proper rearrangement of distillation sequences can approach the most suitable structure of the chemical separation process according to considerations of cost. This study suggests two meta-heuristic techniques: Ant colony algorithm and Harmony search algorithm. The overall synthesis problem is formulated as an implicit mixed-integer linear programming (MILP) problem. Four cases including 3-components case, 4-components case, 5-components case and 6-components case for separation are illustrated. The shortcut model DSTWU was simulated. Percents of light key and heavy key are determined. Ninety-eight percent pure substrate can be obtained for these optimizations. Either Ant colony algorithm or Harmony search algorithm can address at the exact optimum point but Ant colony algorithm proposes the better value and is more robust than Harmony search algorithm. As a result, it was found that the system of 3-components can separate at 97.02-99.45% purity, 4-components at 95.46-99.96%, 5-components at 91.96-99.19%, and 6-components at 92.88-99.26% purity; respectively. After application of heat-integrated distillation sequences, the system of 3-components can reduce the cost at 0.1772%, 4-components at 0.5068%, 5-components at 0.4255% and 6-components at 0.3310%; respectively.

Student's signature

Thesis Advisor's signature

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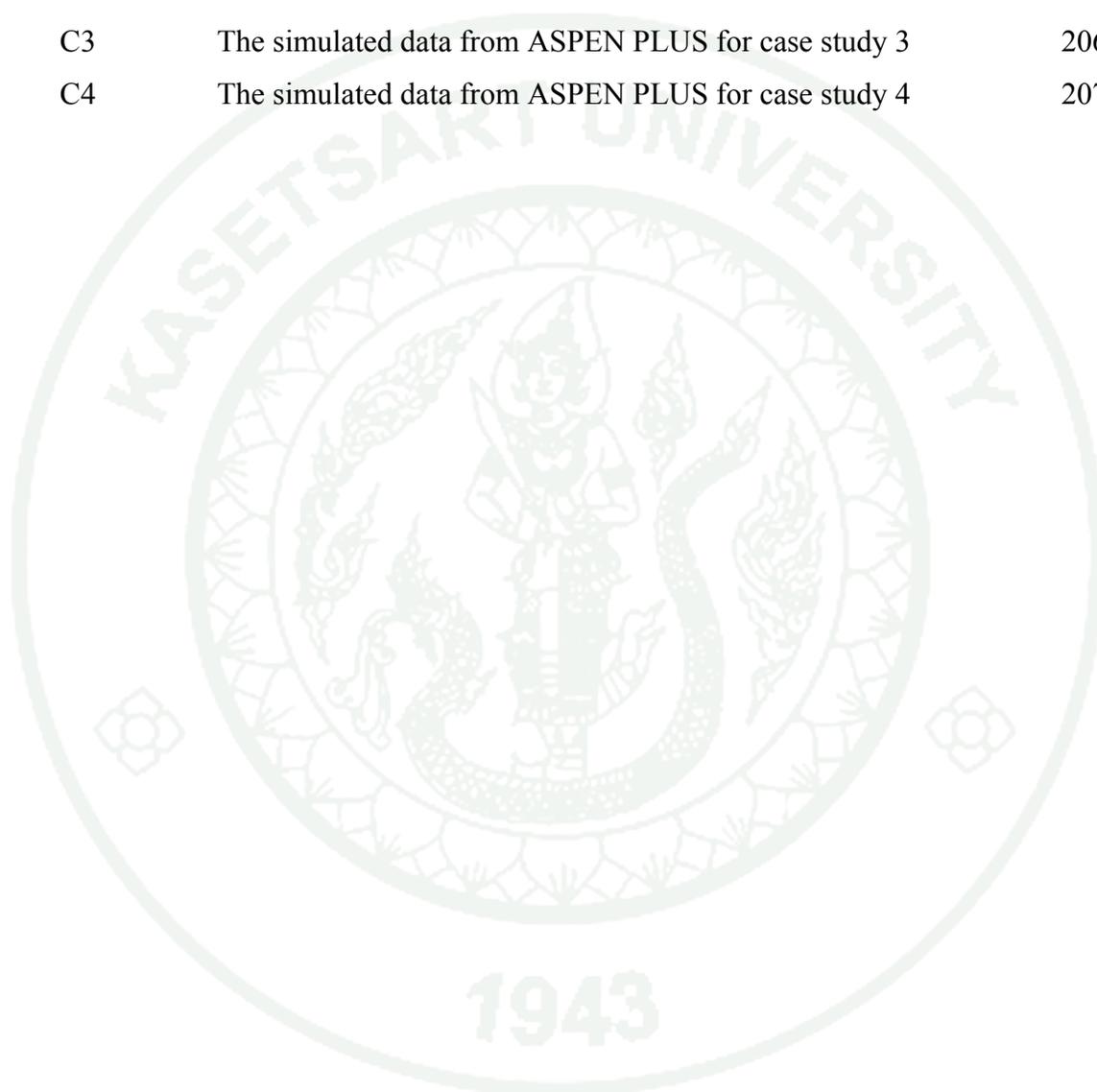
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LIST OF ABBREVIATIONS

Heat-integrated Distillation Sequences

α	=	payout time for capital investment
A_{ij}	=	heat exchanger area for heat transfer from heat source j to heat sink i
A_{ref}	=	reference heat exchanger area
B_k	=	flow of bottoms product from column k
$C_{CU,i}$	=	annual cost per unit of heat flow to a cold utility for the cold utility i
$C_{HU,j}$	=	annual cost per unit of heat flow from a hot utility for the hot utility j
$C_{HX,ij}$	=	cost of heat exchanger area per unit of heat transfer for heat transfer from heat source j to heat sink i
$C_{HX,ref}$	=	reference heat exchanger cost
CAC	=	installed capital cost for a process
CAC_{HX}	=	installed capital cost for all heat exchangers
$COLS$	=	index set of all columns in a superstructure
$Cost$	=	annualized cost for a column
CS	=	index set of heat sinks
CU	=	index set of all cold utilities
D_k	=	flow of distillate product from column k
F_k	=	feed flow to column k
$F_{ref,k}$	=	reference feed flow to column k
F_{TOT}	=	total feed to process
$FM_{i,\bullet}$	=	index set of all feasible matches between all heat sources and heat sink i

LIST OF ABBREVIATIONS (Continued)

$FM_{\bullet,j}$	=	index set of all feasible matches between hot source j and all heat sinks
FS_m	=	index set of all columns having (intermediate)
HS	=	index set of all hot heat sources
HU	=	index set of all hot utilities
I	=	integer variable
IP	=	index set of all intermediate products
OPC	=	annual operating cost for a process
PS_m	=	index set of all columns producing intermediate product m as either distillate or bottoms
Q	=	rate of heat flow
$Q_C(i)$	=	rate of heat flow into cold sink i from a column condenser
$Q_H(j)$	=	rate of heat flow from hot source j into a column reboiler i
q_{ij}	=	rate of heat transfer from heat source j to heat sink i
Q_k	=	heat flow for column
$Q_{ref,k}$	=	reference heat duty for column k
U	=	heat transfer coefficient
U_k	=	upper bound on the feed flow to column k
V_k	=	coefficient for estimating variable cost for column
VC	=	annualized cost for a process
y_k	=	binary variable (value 0 or 1 only)

LIST OF ABBREVIATIONS (Continued)

Ant Colony Algorithm

β	=	constant to convert annual operating cost to an annualize cost (to account for income tax) for a process
ΔT_{LM}	=	log mean temperature difference for heat exchange
ξ_B	=	fraction of feed to column which exits in the bottoms product
ξ_D	=	fraction of feed to column which exits in the distillate product
p_{ij}^k	=	the probability of choosing
α	=	the relative influence of the pheromone trail
β	=	the relative influence of the heuristic information
N_i^k	=	the feasible neighborhood of ant k
k	=	number of ants
τ_{ij}	=	the value of the associated pheromone trail
η_{ij}	=	the heuristic information value
j	=	city choose to go to city
ρ	=	the pheromone evaporation rate
$\Delta \tau_{ij}^k$	=	is the amount of pheromone ant k deposits on the arcs it has visited
C^k	=	the length of the tour
T^k	=	computed as the sum of the lengths of the arcs belonging
T^{bs}	=	this tour is denoted as best so far
C^{ib}	=	is the length of the iteration – base tour
τ_{\min}	=	lower of pheromone trail limits
τ_{\max}	=	upper of pheromone trail limits

LIST OF ABBREVIATIONS (Continued)

C^*	=	the length of the optimal tour
τ_0	=	set to be the same as the initial value for the pheromone trails
C^m	=	the length of a nearest – neighbor tour

Harmony Search Algorithm

X_i	=	the set of the possible range of values for each design variable
N	=	the number of design variables
x'_1	=	the value of the first design variable
HMCR	=	the probability of choosing one value from the historic values stored in the HM
PAR	=	pitch adjusting rate process
bw	=	an arbitrary distance bandwidth for the continuous design variable

OPTIMIZATION OF HEAT-INTEGRATED DISTILLATION SEQUENCES SYNTHESIS USING ANT COLONY ALGORITHM AND HARMONY SEARCH ALGORITHM

INTRODUCTION

Separation of multi-component mixtures into individual or multiple components is a frequently occurring need in the chemical process industry. Distillation is the most commonly used separation operation and is a very energy intensive operation. The objective of synthesis of multi-component distillation systems is to find the separation sequence and the heat integration structure that give the best behavior in terms of investment and operating costs of the system.

The designer's task in multi-component separation is the selection of the separation sequence, followed by optimization of the column design and heat integration of the system. For the four component system, A, B, C, D, the possible sequences when simple columns and sharp splits. The 5 distinct sequences for the four-component system and 14 sequences in a five-component system and 42 sequences for a six-component system. As the number of components increases, the problem of determination of the optimal sequence becomes highly combinatorial even without considering heat integration between columns.

The attractiveness of heat integration between columns of a separation sequence stems from the fact that heat rejected in the condenser of one column can potentially be utilized in the reboiler of another column. The integration requires the condenser temperature of the heat-source column to be higher than the reboiler temperature of the heat-sink column. This can sometimes be achieved by manipulating the pressure in the columns. The heat rejected in the condenser of one column is utilized in the reboiler of the other. In practice, an auxiliary heater or cooler will

usually be required at one of the matched ends, unless the heat duties in both columns happen to be the same.

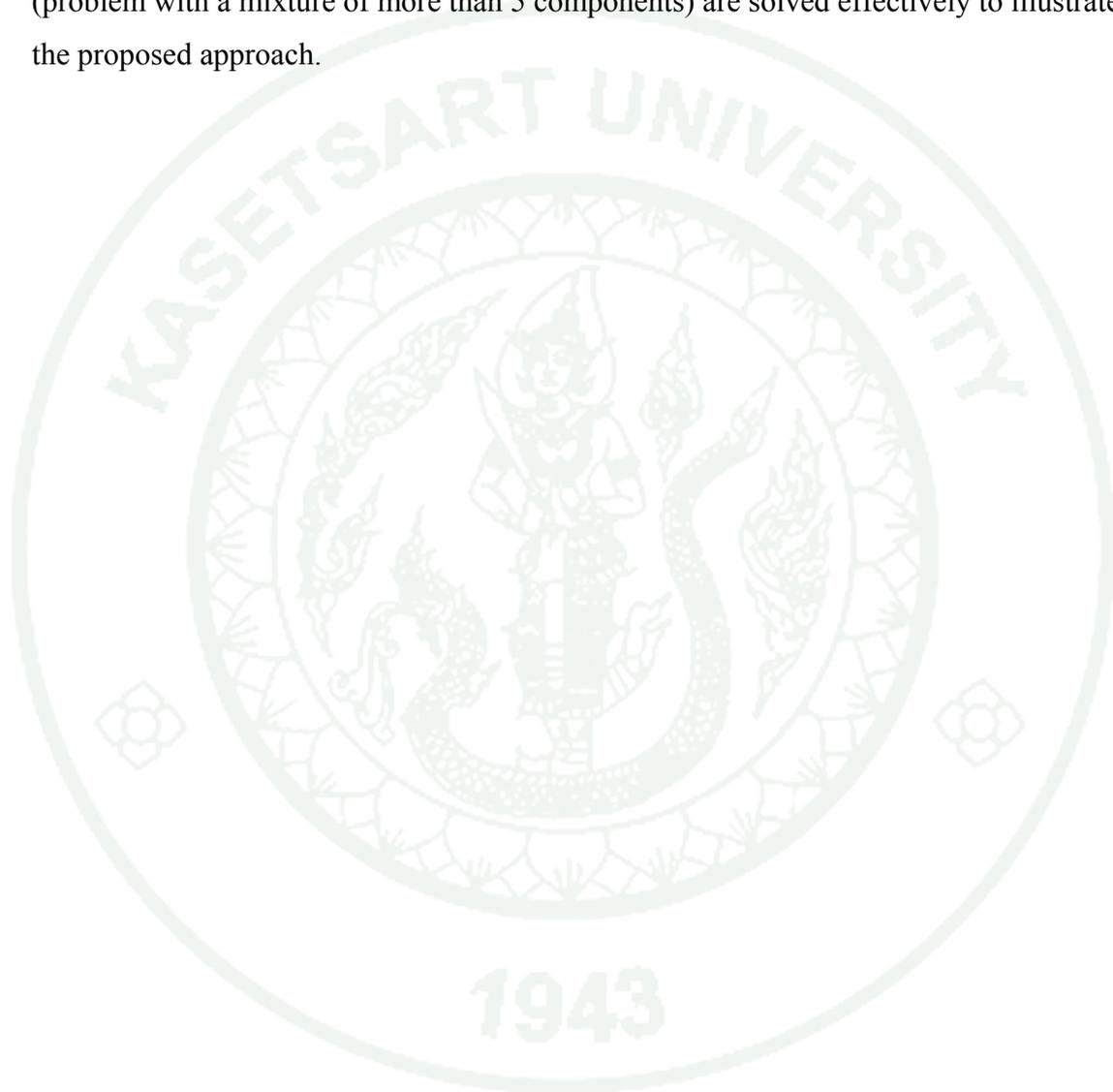
Integration introduces an energy feed-back into the separation sequence. While the cost of performing a separation sequence depends on the cost of utilities required for the separation, the cost of the utilities will not be known until the complete separation sequence is synthesized and its energy sources and sinks are integrated.

In the last couple of decades, a number of approaches have been proposed for systematic solutions to the problems of synthesis of distillation sequences, including heuristic methods (Seader and Westerberg, 1977), evolutionary techniques, hierarchical decomposition (Douglas, 1988), superstructure optimization (Andrecovich and Westerberg, 1985; Floudas and Paules, 1988; Yeomans and Grossmann, 1999), and stochastic methods (Chen *et al.*, 1997; Floquet *et al.*, 1994; Marcoulaki *et al.*, 2001; Wang *et al.*, 1998), etc. Reviews on distillation system synthesis can be found in Westerberg (1985), Wang *et al.* (1998), and Yeomans and Grossmann (1999).

The goal of this work is to develop a stochastic search algorithm to find the optimal or nearly optimal separation sequences which include heat integration between the columns in the sequence. Optimality is defined as minimization of the total venture cost of separating a multi-component product into individual components. The venture cost was defined as the sum of the annual operating and capital costs. The annual capital costs were equal to the product of the total installed cost for the equipment and a factor for depreciation. The capital costs considered in this work include the costs for the distillation columns, trays and heat exchangers. The annual operating costs were equal to the product of the total utility cost and a factor to allow for taxes. The utilities include the hot and cold utilities for heating and cooling.

The present work is to develop a robust Ant colony optimization (ACO) and Harmony search (HS) approach to the synthesis of distillation systems with heat integration. To achieve this, an encoding procedure for representing and manipulating

separation sequence as well as heat integration configuration structures is developed based on binary sort tree principle. Based on the coding representation, an ACO and HS based method for solving the overall MILP (Andrecovich and Westerberg, 1985) optimization problem is developed. Example problems of moderate and large scale (problem with a mixture of more than 5 components) are solved effectively to illustrate the proposed approach.



OBJECTIVES

1. To study and simulate heat-integrated distillation sequences synthesis.
2. To apply of optimal heat-integrated distillation sequences or near the most optimal sequences using Ant colony algorithm and Harmony search algorithm technique.
3. To study the cost during the first year of distillation sequences with heat integration and without heat integration.

Scopes of work

1. A tool to optimize the problem solving heat-integrated distillation sequences using Ant colony algorithm and Harmony search algorithm.
2. Factors for each parameter of the Ant colony algorithm and Harmony search algorithm that minimize cost.
3. Process synthesis of optimal distillation sequences and heat-integrated distillation sequences of the four case studies.

LITERATURE REVIEW

1. Metaheuristic Algorithm

Heuristic algorithms typically intend to find a good solution to an optimization problem by “trial-and-error” in a reasonable amount of computing time. Here “heuristic” means to “find” or “search” by trials and errors. There is no guarantee to find the best or optimal solution, though it might find a better or improved solution than an educated guess. Broadly speaking, heuristic methods are local search methods because their searches focus on the local variations, and the optimal or best solution can locate outside of this local region. However, a high-quality feasible solution in the local region of interest is usually accepted as a good solution in many optimization problems in practice if time is the major constraint.

Metaheuristic algorithms are advanced heuristic algorithms. Because “*meta-*” means “beyond” or “higher-level”, metaheuristic literally means to find the solution using higher-level techniques, though certain trial-and-error processes are still used. Broadly speaking, metaheuristics are considered as higher-level techniques or strategies that intend to combine lower-level techniques and tactics for exploration and exploitation of the huge solution space. In recent years, the word “*metaheuristics*” refers to all modern higher-level algorithms, including Evolutionary Algorithms (EA) including Genetic Algorithms (GA), Simulated Annealing (SA), Tabu Search (TS), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Bee Algorithms (BA), Firefly Algorithms (FA), and certainly Harmony Search (HS).

2. Ant colony optimization (ACO)

Ant colony optimization (ACO) is a metaheuristic inspired by the foraging behavior of real ant colonies (Dorigo *et al.*, 1996). In many ant species, ants walking to and from a food source deposit on the ground a substance called pheromone. Other ants perceive the presence of pheromone, and tend to follow paths where pheromone

concentration is higher. Through this mechanism, ants are able to transport food to their nest in an extremely effective way. In this example, ants coordinate their activities via stigmergy, a form of indirect communication mediated by modifications of the environment. The ant algorithm uses this idea to form the artificial stigmergy to coordinate societies of artificial ants (Dorigo and Stutzle, 2004).

The ACO algorithms are essentially construction algorithms. For each iteration, every ant constructs a solution to the problem by traveling on a construction graph. Each edge of the graph, representing the possible steps the ant can make, has associated two kinds of information that guide the ant movement. The other is artificial pheromone trail information, which measures the “learned desirability” of the movement and mimics the real pheromone that natural ants deposit. This information is modified during the process depending on the solutions found by the ants. It is denoted by τ_{ij} .

Several researchers have further developed different ACO algorithms such as the Ant System (Dorigo *et al.*, 1996), the ant colony system (Dorigo and Gambardella, 1997), the Max–Min ant system (Stutzle and Hoos, 1997), the rank-based ant system (Bullnheimer *et al.*, 1999), and the best–worst ant system (Cordon *et al.*, 2000). The two basic ant algorithms are briefly reviewed as follows.

Table 1 ACO algorithms according to chronological order of appearance

ACO algorithm	Main references
Ant system (AS)	Dorigo, <i>et al.</i> (1991)
Elitist ant system (EAS)	Dorigo, <i>et al.</i> (1992)
Rank – Based ant system (AS-rank)	Bullnheimer, <i>et al.</i> (1997)
Max-Min ant system (MMAS)	Stutzle and Hoos (1997)
Ant colony system (ACS)	Dorigo and Gambardella (1997)

2.1 Ant System

Initially, three different versions of AS were proposed (Dorigo *et al.*, 1991). These were called ant-density, ant-quantity, and ant-cycle. Whereas in the ant-density and ant-quantity versions the ants updated the pheromone directly after a move from one city to an adjacent city, in the ant-cycle versions the pheromone update was only done after all the ants had constructed the tours quality. Nowadays, when referring to AS, one actually refers to ant-cycle since the two other variants were abandoned because of their inferior performance.

2.1.1 Tour Construction

In AS, m (artificial) ants concurrently build a tour of the TSP. Initially, ant are put on randomly chosen cities. At each construction step, ant k applies a probabilistic action choice rule, called random proportional rule, to decide which city to visit next. In particular, the probability with which and k , currently at city choose to go to city j is

$$p_{ij}^k = \frac{[\tau_{ij}]^\alpha [\eta_{ij}]^\beta}{\sum_{l \in N_i^k} [\tau_{il}]^\alpha [\eta_{il}]^\beta}, \quad \text{if } j \in N_i^k \quad (1)$$

Where $\eta_{ij} = 1/d_{ij}$ is a heuristic that is available a priori, α and β are two parameters which determine the relative influence of the pheromone trail and the heuristic information, and N_i^k is the feasible neighborhood of ant k when being at city i , that is, the set of cities ant k has visited yet (the probability of choosing a city outside N_i^k is 0). By this probabilistic rule, the probability of choosing a particular are (i, j) increases with the value of the associated pheromone trail τ_{ij} and of the heuristic information value η_{ij} . The role of the parameters α and β is the following. If $\alpha = 0$ the closest cities are more likely to be selected: this corresponds to a classic

stochastic greedy algorithm (with multiple starting points since ants are initially randomly distributed over the cities). If $\beta = 0$ only pheromone amplification is at work, that is, only pheromone is used, without and heuristic bias. This generally leads to rather poor results and, in particular, for value of $\alpha > 1$ it leads to the rapid emergence of a *stagnation situation*, that is, a situation in which all the ants follow the same path and construct the same tour, which, in general, is strongly suboptimal (Dorigo, 1992 ; Dorigo *et al.*, 1996).

Each ant k maintains a memory M^k which contains the cities already visited, in the order they were visited. This memory is used to define the feasible neighborhood N_i^k in the construction rule given by Equation (1). In addition, the memory M^k allows ant k both to compute the length of the tour T^k it generated and to retrace the path to deposit pheromone.

There are two different ways of implementing it: parallel and sequential solution construction. In the parallel implementation, at each construction step all the ants move from their current city to the next one, while in the sequential implementation an ant builds a complete tour before the next one starts to build another one. In the AS case, both choices for the implementation of the tour construction are equivalent in the sense that they do not significantly influence the algorithm's behavior. As we will see, this is not the case for other ACO algorithm such as ACS.

2.1.2 Update of Pheromone Trails

After all the ants have constructed their tours, the pheromone trails are updated. This is done by first lowering the pheromone value on all arcs by a constant factor, and then adding pheromone on the arcs the ants have crossed in their tours. Pheromone evaporation is implemented by

$$\tau_{ij} \leftarrow (1 - \rho)\tau_{ij}, \quad \forall (i, j) \in L, \quad (2)$$

where $0 < \rho \leq 1$ is the pheromone evaporation rate. The parameter ρ is use to avoid unlimited accumulation of the pheromone trails and it enables the algorithm to “forget” bad decisions previously taken. In fact, if an arc is not chosen by the ants, its associated pheromone value decreases exponentially in the number of iterations. After evaporation, all ants deposit pheromone on the are they have crossed in their tour.

$$\tau_{ij} \leftarrow \tau_{ij} + \sum_{k=1}^m \Delta\tau_{ij}^k, \quad \forall (i, j) \in L \quad (3)$$

where $\Delta\tau_{ij}^k$ is the amount of pheromone ant k deposits on the arcs it has visited. It is defined as follows:

$$\Delta\tau_{ij}^k = \begin{cases} 1/C^k, & \text{if } \text{arc}(i, j) \text{ belongs to } T^k \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where C^k the length of the tour T^k built by the k -th ant, is computed as the sum of the lengths of the arcs belonging to T^k . By means of Equation (4), the better an Ant's tour is, the more pheromone the arcs belonging to this tour receive. In general, arc that are used by many ants and which are part of short tour, receive more pheromone and are therefore more likely to be chosen by ants in future iterations of the algorithm.

As we said, the relative performance of AS when compared to other metaheuristics tends to decrease dramatically a the size of the test-instance increases. Therefore, a substantial amount of research on ACO has focused on how to improve AS.

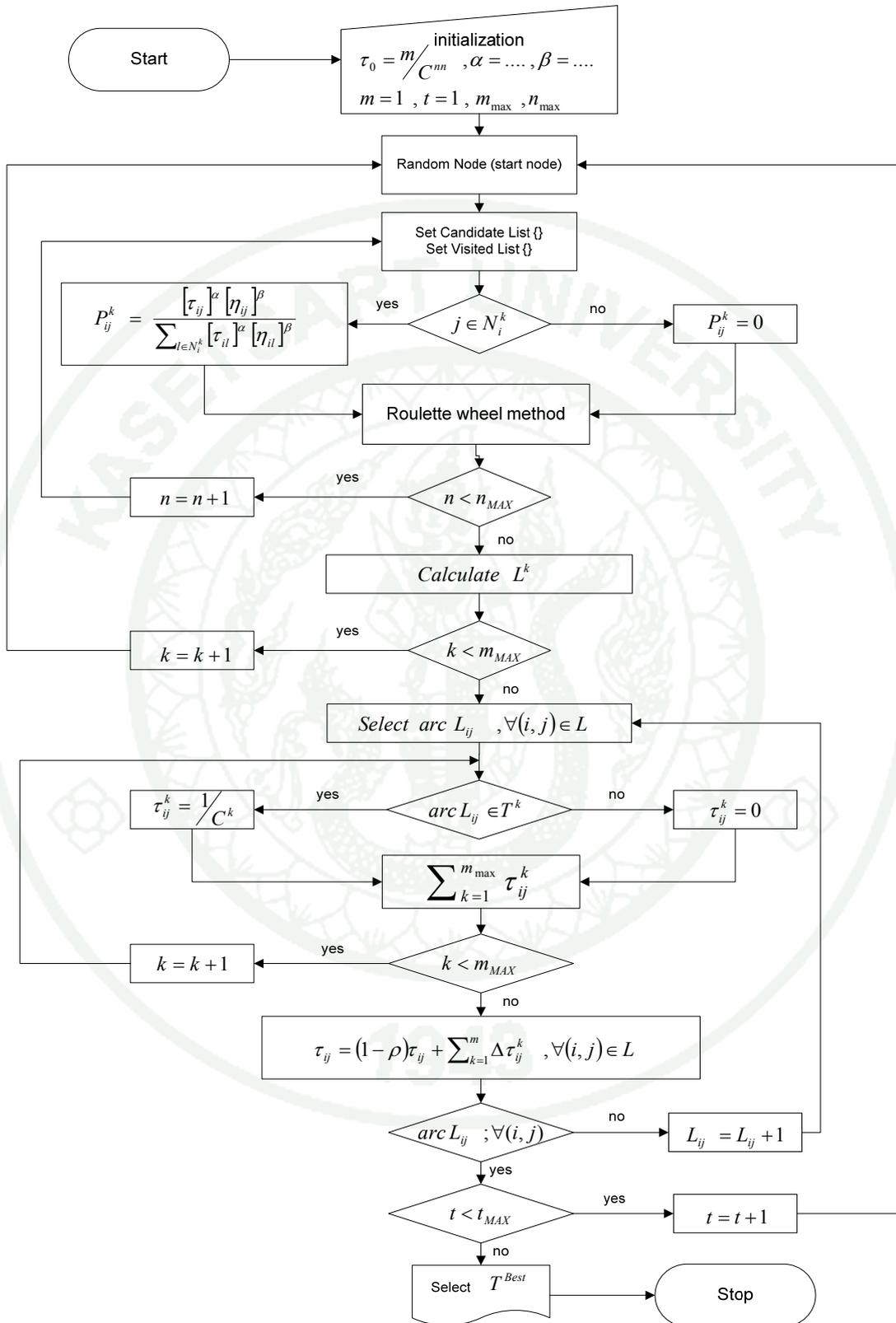


Figure 1 Flow chart of Ant system

Source: Lutuksin (2007)

2.2 Elitist Ant System

A first improvement on the initial AS, called the *elitist strategy* for Ant System (EAS), was introduced in Dorigo (1992) and Dorigo *et al.* (1991a,1996). The idea is to provide strong additional reinforcement to the arcs belonging to the best tour found since the start of the algorithm ; this tour is denoted as T^{bs} (*best-so-far*) in the following. Note that this additional feedback on the best-so-far tour (which can be viewed as additional pheromone deposited by an additional ant called *best so-far ant*) is another example of a daemon action of the ACO metaheuristic.

2.2.1 Update of Pheromone Trails

The additional reinforcement of tour T^{bs} is achieved by adding a quantity e/C^{bs} to its arcs , where e is a parameter that defines the weight given to the best- so-far tour T^{bs} , and C^{bs} is its length. Thus, Equation (3) for the pheromone deposit becomes

$$\tau_{ij} \leftarrow \tau_{ij} + \sum_{k=1}^m \Delta\tau_{ij}^k + e\Delta\tau_{ij}^{bs} \quad (5)$$

Where $\Delta\tau_{ij}^k$ is defined as in Equation (4) and $\Delta\tau_{ij}^{bs}$ is defined as follows:

$$\Delta\tau_{ij}^{bs} = \begin{cases} 1/C^{bs}, & \text{if } arc(i, j) \text{ belongs to } T^{bs} \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

Note that in EAS, as well as in all other all other algorithms presented in pheromone evaporation is implemented as in AS.

Computational results presented in Dorigo (1991,1996) suggest that the use of the elitist strategy with an appropriate value for parameter e allows AS to both find better tours and find them in a lower number of iterations.

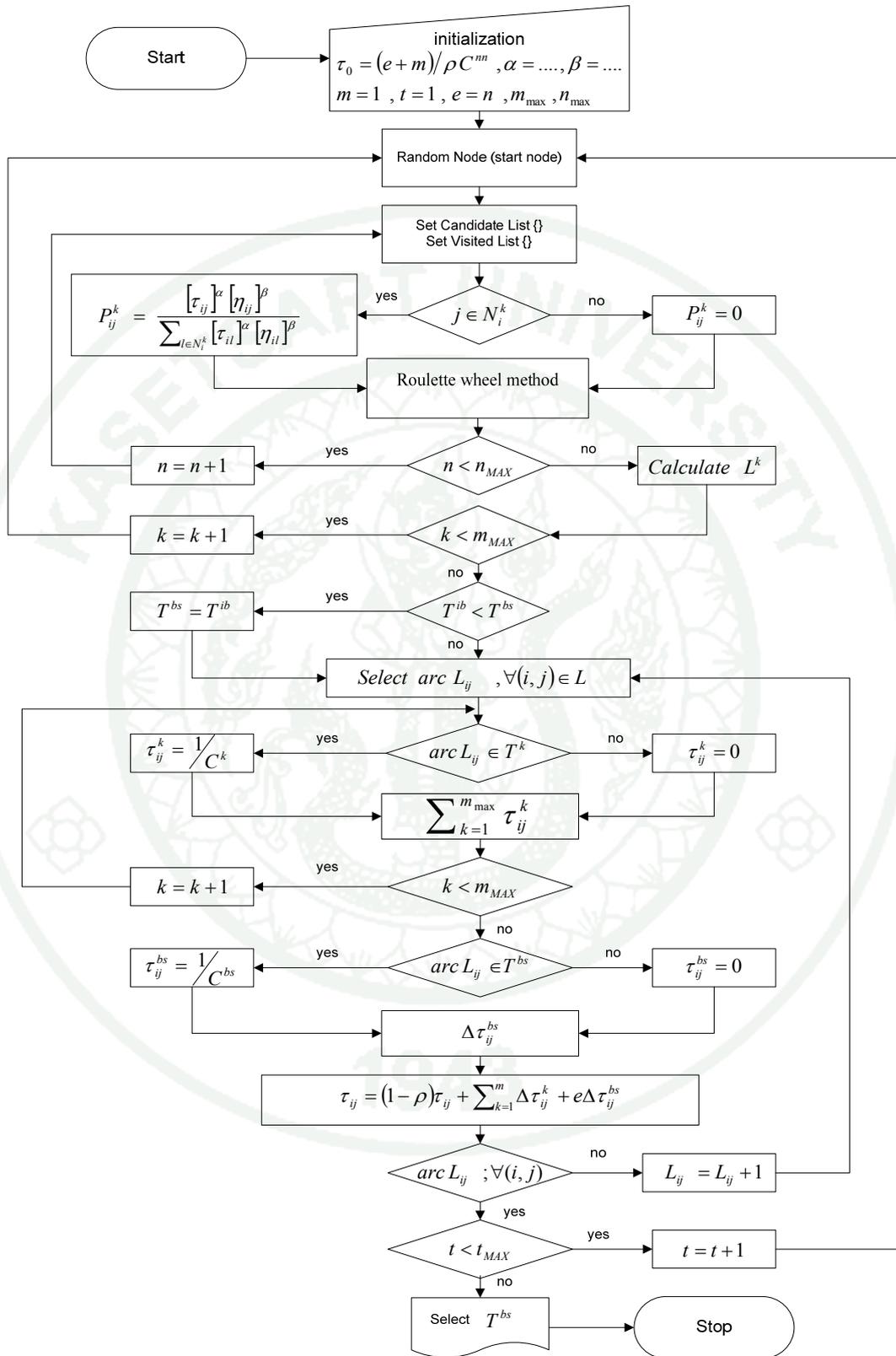


Figure 2 Flow chart of Elitist ant system

Source: Lutuksin (2007)

2.3 Rank-Based Ant System

Another improvement over AS is the rank-based version of AS (AS_{rank}), proposed by Bullnheimer *et al.* (1999c). In AS_{rank} each ant deposits an amount of pheromone that Decreases with its rank. Additionally, as in EAS, the best-so-far ant always deposits the largest of pheromone in each iteration.

2.3.1 Update of pheromone trial

Before updating the pheromone trials, the ants are sorted by increasing tour length and the quantity of pheromone an ant deposits is weighted according to the rank r of the ant. Ties can be solved randomly (in our implementation they are solved by lexicographic ordering on the ant name k .) In each iteration only the $(w-1)$ best-ranked ants and the ant that produced the best-so-far tour (this ant does not necessarily belong to the set of ants of the currents algorithm iteration) are allowed to deposit pheromone . The best-so-far tour gives the strongest feedback, with weight (i.e., its contribution $1/C^{bs}$ is multiplied by w); the r -th best ant of the current iteration contributes to pheromone updating with the value $1/C^r$ multiplied by a weight given by $\max\{0, w-r\}$. Thus, the AS_{rank} pheromone update rule is

$$\tau_{ij} \leftarrow \tau_{ij} + \sum_{r=1}^{w-1} (w-r)\Delta\tau_{ij}^r + w\Delta\tau_{ij}^{bs} \quad (7)$$

where $\Delta\tau_{ij}^r = 1/C^r$ and $\Delta\tau_{ij}^{bs} = 1/C^{bs}$. The results of an experimental evaluation by Bullnheimer *et al.* (1999c) suggest that AS_{rank} performs slightly better than EAS and significantly better than AS.

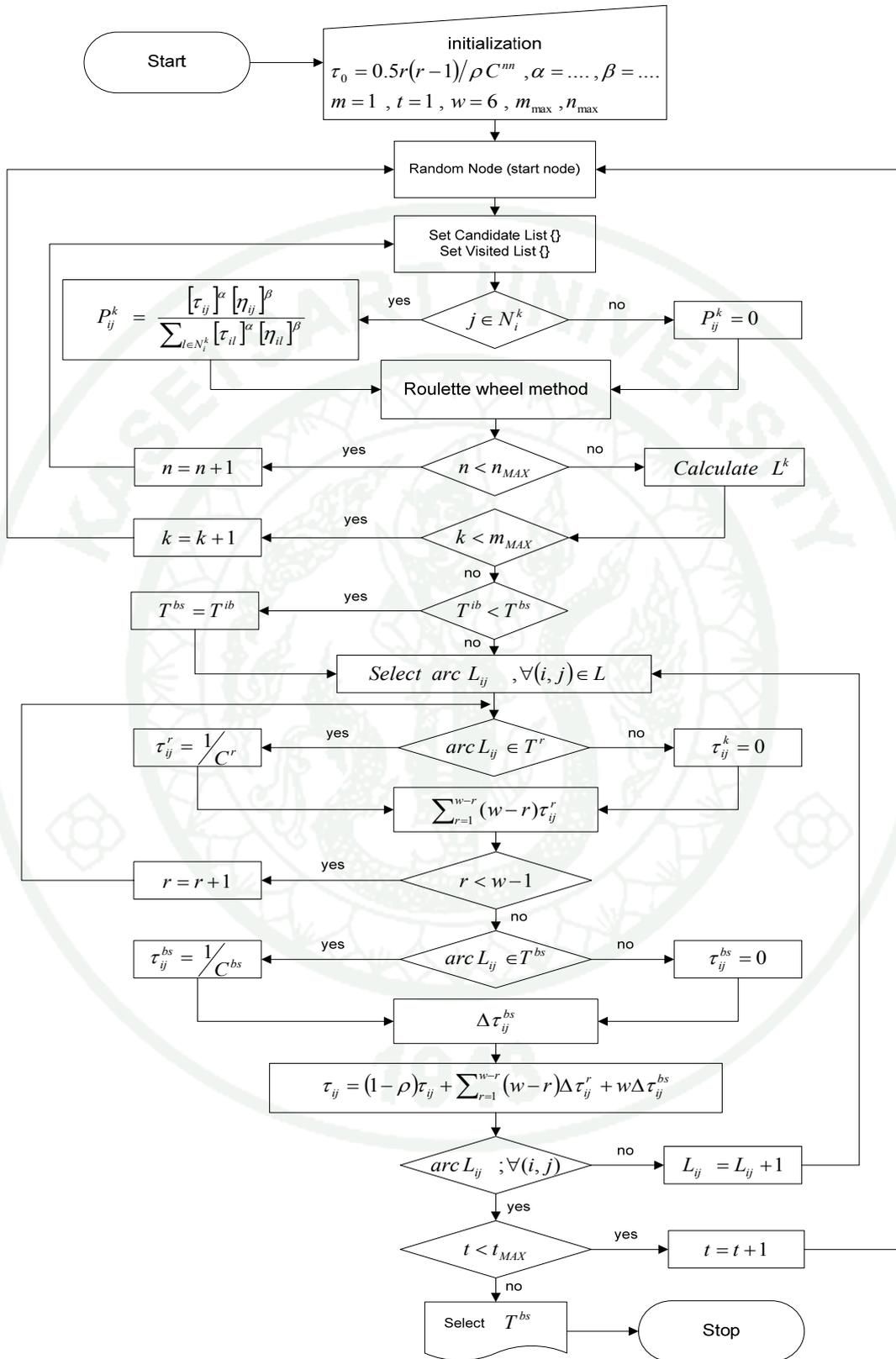


Figure 3 Flow chart of Rank-based ant system

Source: Lutuksin (2007)

2.4 *MAX – MIN* Ant system

MAX – MIN Ant system (*MMAS*) (Stutzle and Hoos, 1997,2000; Stutzle, 1999) introduces four main modification with respect to AS. First. It Strongly exploits the best tours found: only either the iteration –best ant, that is the ant that produced the best tour in the current iteration, or the best-so-far ants is allowed to deposit pheromone . Unfortunately, such a strategy may lead to a stagnation situation in which all the ant follow the same tour, because of the excessive growth of pheromone trails on arcs of a good, although suboptimal, tour. To counteract this effect, a second modification introduced by *MMAS* is that limits the possible range of pheromone trail values to the interval $[\tau_{\min}, \tau_{\max}]$. Third, the pheromone trail are initialized to the upper pheromone trail limit, which, together with a small pheromone evaporation rate, increases the exploration of tour at the start of the search. Finally, in *MMAS* , pheromone trails are initialized each time the system approaches stagnation or when no improved tour has been generated for a certain number of consecutive iteration.

2.4.1 Update of pheromone Trails

After all ants have constructed tour, pheromone are updated by applying evaporation as in AS [Equation (2)], followed by the deposit of new pheromone as follows:

$$\tau_{ij} \leftarrow \tau_{ij} + \Delta\tau_{ij}^{best} \quad (8)$$

where $\Delta\tau_{ij}^{best} = 1/C^{best}$. The ant is which is allowed to add pheromone may be either the best-so-far , in which case $\Delta\tau_{ij}^{best} = 1/C^{bs}$ or the iteration – best, in which case $\Delta\tau_{ij}^{best} = 1/C^{ib}$, where C^{ib} is the length of the iteration – base tour . In general, in *MMAS* implementations both the iteration – best and the best-so-far update rules are use . in an alternate way. Obviously , the choice of the relative frequency with which the two pheromone update rules are applied has an influence on how greedy the search

is : When pheromone updates are always performed by the best-so-far ant the search focus very quickly around T^{bs} , whereas when it is the iteration-best ant that updates pheromone, then the number of arcs that receive pheromone is larger and the search is less directed.

Experimental results indicate that for small TSP instances it may be best to use only iteration – best pheromone updates, while for large TSPs with several hundreds of cities the best performance is obtained by giving an increasing stronger emphasis to the best – so – far tour. This can be achieved, for example. By gradually increasing the frequency with which the best-so-far tour T^{bs} is chosen for the update (Stützle,1999).

2.4.2 Pheromone Trail Limits

In *MMAS*, lower and upper limits τ_{\min} and τ_{\max} on the possible pheromone values on any arc are imposed in order to avoid search stagnation particular, the imposed pheromone trail limit have the effect of limiting the probability p_{ij} of selecting a city j when an ant is in city i to the interval $[p_{\min}, p_{\max}]$, with $0 < p_{\min} \leq p_{ij} \leq p_{\max} \leq 1$. Only when an ant k has just one single possible choice for the next city, that is $|N_i^k|=1$, we have $p_{\min} = p_{\max} = 1$.

It is easy to show that, in the long run, the upper pheromone trail limit on any arc is bounded by $1/\rho C^*$, where C^* is the length of the optimal tour. Based on this result, *MMAS* uses an estimate of this value, $1/\rho C^{bs}$, to define τ_{\max} : each time a new best-so-far tour is found, the value of τ_{\max} is updated. The lower pheromone trail limit is set to $\tau_{\min} = \tau_{\max} / a$, where a is a parameter (Atutzle, 1999; Stutzle and Hoos, 2000). Experimental results (Stutzle,1999) suggest that, in order to avoid stagnation, the pheromone trail limits play a more important role than τ_{\max} . On the other hand, τ_{\max} remains useful for setting the pheromone values during the occasional trail reinitializations.

2.4.3 Pheromone Trail Initialization

At the start of the algorithm, the initial pheromone trails are set to an estimate of the upper pheromone trail limit. This way of initializing the pheromone trails, in combination with a small pheromone evaporation parameter, causes a slow increase in the relative difference in the pheromone trail levels, so that the initial search phase of *MMAS* is very explorative.

As a further means of increasing the exploration of paths that have only a small probability of being chosen, in *MMAS* pheromone trails are occasionally reinitialized. Pheromone trail reinitialization is typically triggered when the algorithm approaches the stagnation behavior (as measured by some statistics on the pheromone trails) or if for a given number of algorithm iterations no improved tour is found.

MMAS is one of the most studied ACO algorithms and it has been extended in many ways. In one of these extensions, the pheromone update rule occasionally uses the best tour found since the most recent reinitialization of the pheromone trails instead of the best-so-fat tour (Stutzle, 1999; Stutzle and Hoos, 2000). Another variant (Stutzle, 1999; Stutzle and Hoos, 1999) exploits the same pseudorandom proportional action choice rule as introduced by ACS.

2.5 Ant Colony System

ACS (Dorigo and Gambardella, 1997a,b) differs from AS in three main points. First, it exploits the search experience accumulated by the ants more strongly than AS does through the use of a more aggressive action choice rule. Second, pheromone evaporation and pheromone deposit take place only on the arcs belonging to the best-so-far tour. Third, each time an ant arc (i, j) to move from city i to city j , it removes some pheromone from the arc to increase the exploration of alternative path. In the following. We present these innovations in more detail.

2.5.1 Tour construction

In ACS, when located at city i , and k moves to a city j chosen according to the so called pseudorandom proportional rule, given by

$$j = \begin{cases} \arg \max_{l \in N_i^k} \{ \tau_{il} [\eta_{il}]^\beta \} & \text{if } q \leq q_0; \\ J. & \text{otherwise} \end{cases} \quad (9)$$

where q is a random variable uniformly distributed in $[0,1]$, q_0 ($0 \leq q_0 \leq 1$) is a parameter, and J is a random Variable selected according to the probability distribution given by Equation (1) (with $\alpha = 1$).

In other words, with probability q_0 the ant makes the best possible move as indicated by the learned pheromone trails and the heuristic information (in this case, the ant is exploiting the learned knowledge), while with probability $(1 - q_0)$ it performs a biased exploration of the arcs. Tuning the parameter q_0 allows modulation of the degree of exploration and the choice of whether to concentrate the search of the system around the best-so-far solution or to explore other tours.

2.4.4 Global Pheromone Trail Update

In ACS only one ant (the best-so-far ant) is allowed to add pheromone after each iteration. Thus, the update in ACS is implemented by the following Equation 10.

$$\tau_{ij} \leftarrow (1 - \rho)\tau_{ij} + \rho\Delta\tau_{ij}^{bs} \quad \forall (i, j) \in T^{bs} \quad (10)$$

where $\Delta\tau_{ij}^{bs} = 1/C^{bs}$. It is important to note that in ACS the pheromone trail update, both evaporation and new pheromone deposit, only applies to the arcs of T^{bs} , not to all the arcs as in AS. This is important, because in this way the computational complexity of the pheromone update at each iteration is reduced from $O(n^2)$ to $O(n)$, where n is the size of the instance being solved. As usual, the parameter ρ represents pheromone evaporation: unlike AS's Equations (2) and (3), in Equation (10) the deposited pheromone is discounted by a factor $(1 - \rho)$; this results in the new pheromone trail being a weighted average between the old pheromone value and the amount of pheromone deposited.

In initial experiments, the use of the iteration – best tour was also considered for the pheromone updates. Although for small TSP instances the differences in the final tour quality obtained by updating the pheromones using the best – so – far or the iteration – best tour was found to be minimal, for instances with more than 100 cities the use of the use of the best – so – far tour gave far better results.

2.5.3 Local Pheromone Trail Update

In addition to the global pheromone trail updating rule, in ACS the ants use a local pheromone update rule that they apply immediately after having crossed an arc (i, j) during the tour construction:

$$\tau_{ij} \leftarrow (1 - \xi)\tau_{ij} + \xi\tau_0 \quad (11)$$

where ξ , $0 < \xi < 1$ and τ_0 are two parameters. The value of τ_0 is set to be the same as the initial value for the pheromone trails. Experimentally, a good value for ξ was found to be 0.1, while a good value for τ_0 was found to be $1/nC^m$, where n is the number of cities of cities in the TSP instance and C^m , is the length of a nearest – neighbor tour. The effect of the local updating rule is that each time an ant uses an arc (i, j) its pheromone trail τ_{ij} is reduced, so that the arc becomes less desirable for the following ants. In other words, this allows an increase in the exploration of arcs that have not been visited yet and. In practice, has the effect that the algorithm does not show a stagnation behavior (i.e., ants do not converge to the generation of a common path) (Dorigo and Gambardella, 1997b). it is important to note that, while for the previously discussed AS variants it does not matter whether the ants construct the tours in parallel or sequentially, this makes a difference in ACS because of the local pheromone update rule. In most ACS implementations the choice has been to let all the ants move in parallel, although there is at the moment, no experimental evidence in favor of one choice or the other.

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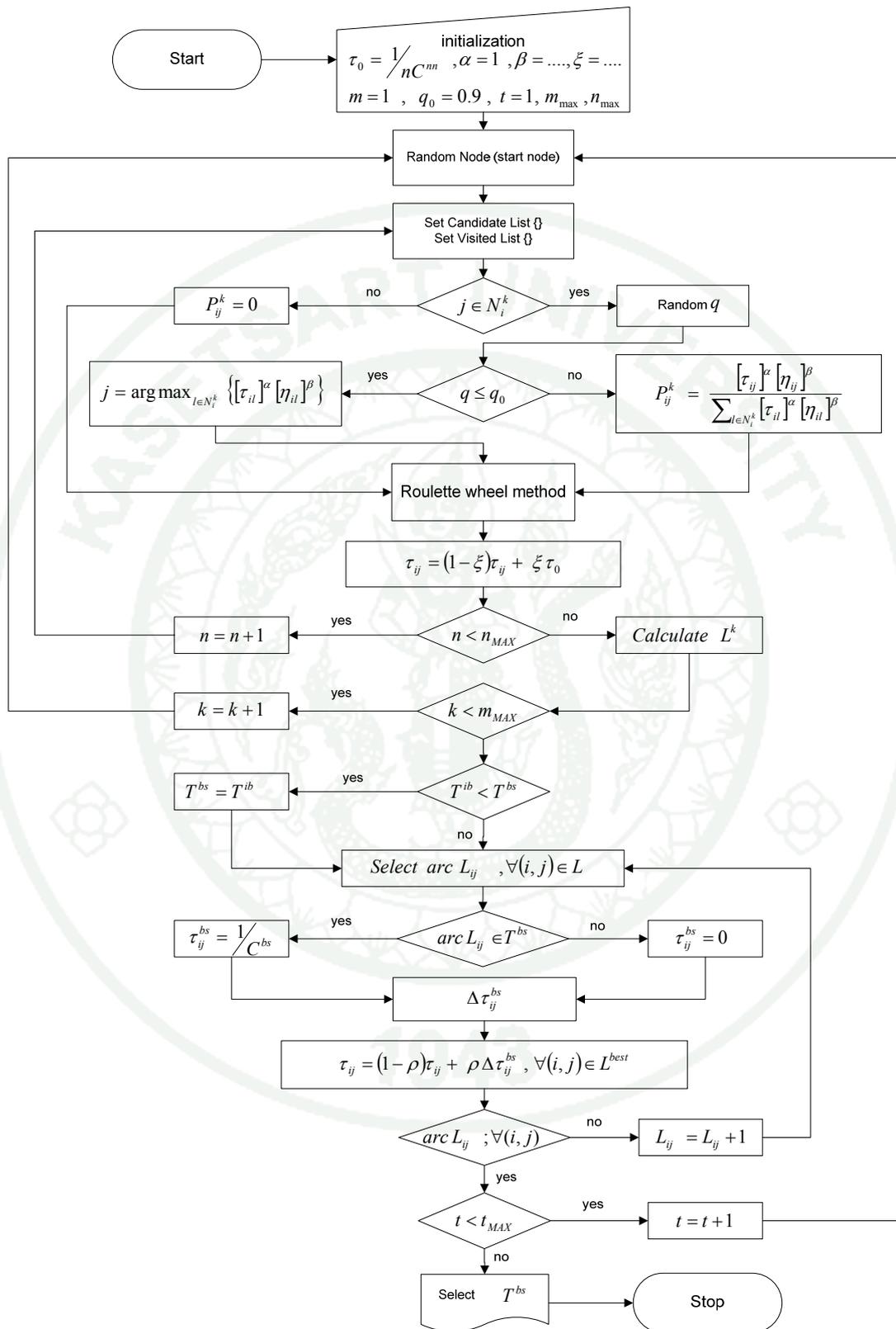


Figure 5 Flow chart of Ant colony system

Source: Lutuksin (2007)

Stützle and Hoos (2000) presented Ant System, the first Ant Colony Optimization algorithm, showed to be a viable method for attacking hard combinatorial optimization problems. Yet, its performance, when compared to more fine-tuned algorithms, was rather poor for large instances of traditional benchmark problems like the Traveling Salesman Problem. To show that Ant Colony Optimization algorithms could be good alternatives to existing algorithms for hard combinatorial optimization problems, recent research in this area has mainly focused on the development of algorithmic variants which achieve better performance than Ant System. In this paper, we present *MAX-MIN* Ant System (*MMAS*), an Ant Colony Optimization algorithm derived from Ant System. *MMAS* differs from Ant System in several important aspects, whose usefulness we demonstrate by means of an experimental study. Additionally, we relate one of the characteristics specific to *MMAS* that of using a greedier search than Ant System—to results from the search space analysis of the combinatorial optimization problems attacked in this paper. Our computational results on the Traveling Salesman Problem and the Quadratic Assignment Problem show that *MMAS* is currently among the best performing algorithms for these problems.

Shelokar and Jayaraman (2004) presented recently developed ant colony optimization meta-heuristic procedure has been recast as a rule based machine learning method, called as *ant colony classifier* system, and applied to three process engineering examples. The learning algorithm addresses the problem of knowledge acquisition in terms of rules from example cases by developing and maintaining the knowledge base through the use of simple mechanism, pheromone trail information matrix and use of available heuristic information. The performance of an ant colony classifier is compared with the well-known decision tree based C4.5 algorithm in terms of the predictive accuracy on test cases and the simplicity of rules discovered. The results indicate that the ant classifier is able to discover rules in the data sets with better predictive accuracy than the C4.5 algorithm.

Zhang and Chen (2005) study For solving dynamic optimization problems of chemical process with numerical methods, a novel algorithm named iterative ant-

colony algorithm (IACA), the main idea of which was to iteratively execute ant-colony algorithm and gradually approximate the optimal control profile, was developed in this paper. The first step of IACA was to discretize time interval and control region to make the continuous dynamic optimization problem be a discrete problem. Ant-colony algorithm was then used to seek the best control profile of the discrete dynamic system. At last, the iteration based on region reduction strategy was employed to get more accurate results and enhance robustness of this algorithm. Iterative ant-colony algorithm is easy to implement. The results of the case studies demonstrated the feasibility and robustness of this novel method. IACA approach can be regarded as a reliable and useful optimization tool when gradient is not available.

3. Harmony Search Algorithm (HS)

Since the initial development of the Harmony Search (HS) algorithm by Geem in 2000. Current meta-heuristic algorithms imitate natural phenomena, i.e., physical annealing in simulated annealing, human memory in tabu search, and evolution in evolutionary algorithms. A new HS meta-heuristic algorithm was conceptualized using the musical process of searching for a perfect state of harmony. Musical performances seek to find pleasing harmony (a perfect state) as determined by an aesthetic standard, just as the optimization process seeks to find a global solution (a perfect state) as determined by an objective function. The pitch of each musical instrument determines the aesthetic quality, just as the objective function value is determined by the set of values assigned to each decision variable. The new HS meta-heuristic algorithm was derived based on natural musical performance processes that occur when a musician searches for a better state of harmony, such as during jazz improvisation.

Figure 6 shows the details of the analogy between music improvisation and engineering optimization. In music improvisation, each player sounds any pitch within the possible range, together making one harmony vector. If all the pitches make a good harmony, that experience is stored in each players memory, and the possibility to make a good harmony is increased next time. Similarly in engineering optimization, each decision variable initially chooses any value within the possible range, together

making one solution vector. If all the values of decision variables make a good solution, that experience is stored in each variables memory, and the possibility to make a good solution is also increased next time.

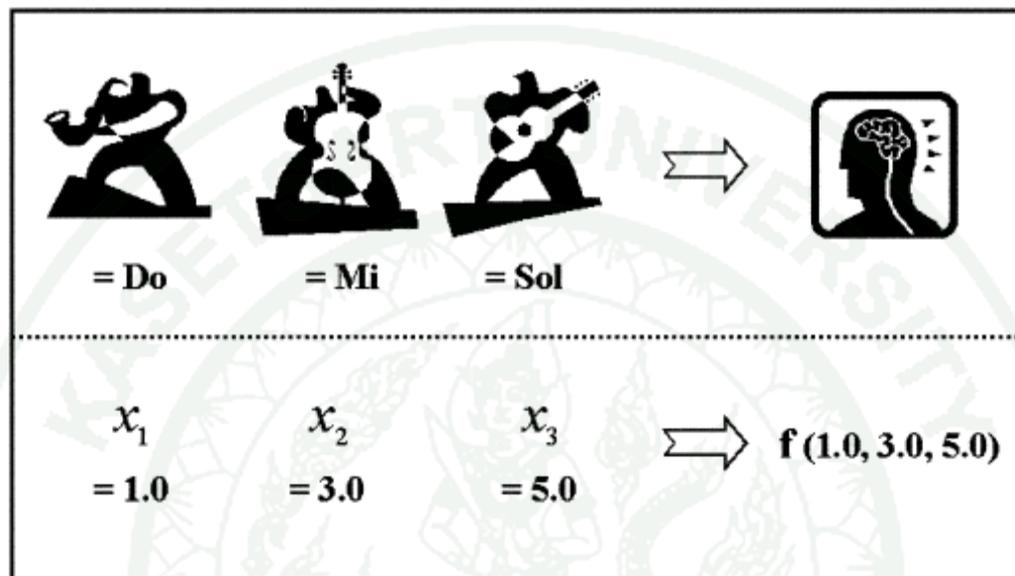


Figure 6 Analogy between music improvisation and engineering optimization

Source: Ayvaz (2009)

Figure 7 shows the structure of the harmony memory (HM) that is the core part of the HS. Consider a jazztrio composed of saxophone, double bass, and guitar. There exist certain amount of preferable pitches in each musician_s memory: saxophonist, {Do, Mi, Sol}; double bassist, {Si, Sol, Re}; and guitarist, {La, Fa, Do}. If saxophonist randomly plays {Sol} out of its memory {Do, Mi, Sol}, double bassist {Si} out of {Si, Sol, Re}, and guitarist {Do} out of {La, Fa, Do}, that harmony (Sol, Si, Do) makes another harmony (musically C-7 chord). And if this new harmony is better than existing worst harmony in the HM, the new harmony is included in the HM and the worst harmony is excluded from the HM. This procedure is repeated until fantastic harmony is found.

In real optimization, each musician can be replaced with each decision variable, and its preferred sound pitches can be replaced with each variables preferred

values. If each decision variable represents pipe diameter of an arc between two nodes, it has certain number of preferred diameters. And if first variable chooses {100mm} out of {100mm, 300mm, 500mm}, second {500mm} out of {700mm, 500mm, 200mm}, and third {400mm} out of {600mm, 400mm, 100mm}, those values (100mm, 500mm, 400mm) make another solution vector. And if this new vector is better than existing worst vector in the HM, the new vector is included in the HM and the worst vector is excluded from the HM. This procedure is repeated until certain termination criterion is satisfied

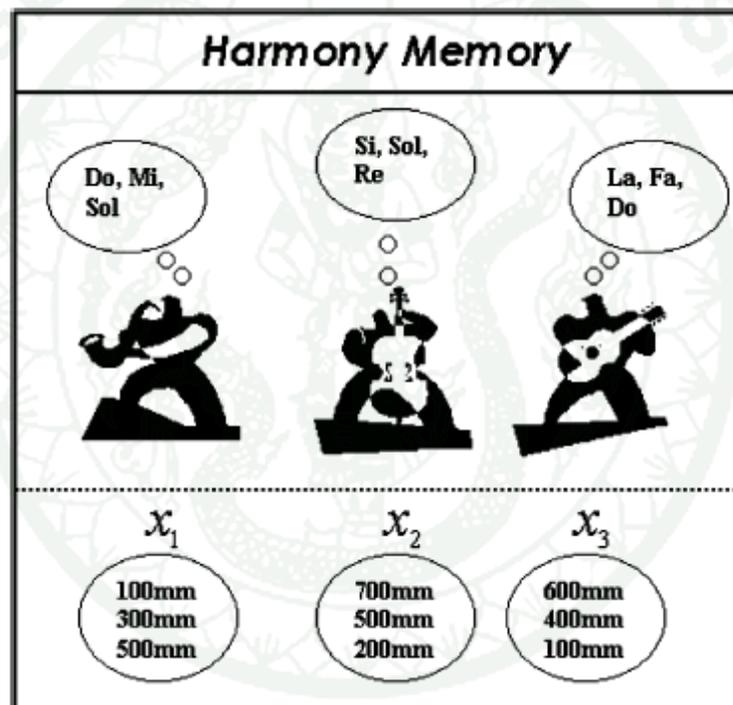


Figure 7 Structure of harmony memory

Source: Geem (2005)

When a musician improvises one pitch, usually he (or she) follows any one of three rules:

- (1) playing any one pitch from his (or her) memory,
- (2) playing an adjacent pitch of one pitch from his (or her) memory,
- (3) playing totally random pitch from the possible sound range.

Similarly, when each decision variable chooses one value in the HS algorithm, it follows any one of three rules:

(1) choosing any one value from the HS memory (defined as memory considerations),

(2) choosing an adjacent value of one value from the HS memory (defined as pitch adjustments), and

(3) choosing totally random value from the possible value range (defined as randomization). The three rules in HS algorithm are effectively directed using two parameters, i.e., harmony memory considering rate (HMCR) and pitch adjusting rate (PAR), as stated later.

Figures 8 and 9 represents the optimization procedure of the HS meta-heuristic algorithm, which consists of steps 1–5, as follows:

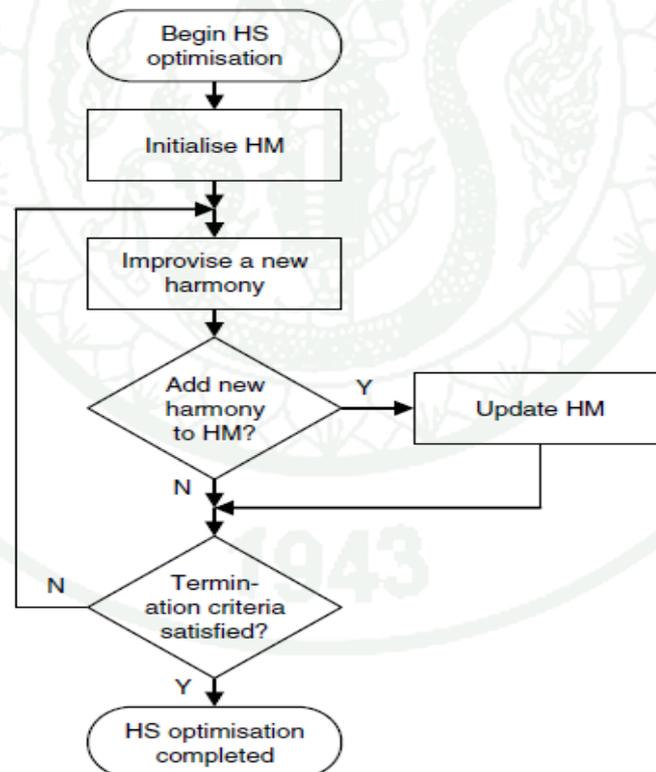


Figure 8 Flowchart for the original HS algorithm

Source: Ingram and Zhang (2009)

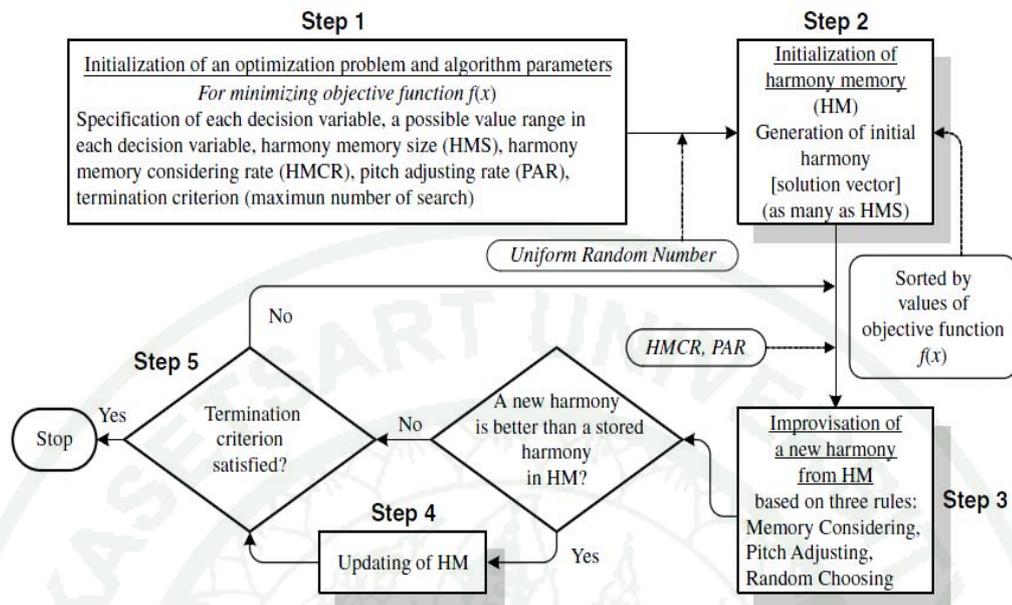


Figure 9 Optimization procedure of the harmony search algorithm

Source: Geem (2005)

Step 1. Initialize the optimization problem and algorithm parameters.

First, the optimization problem is specified as follows:

$$\text{Minimize } f(x) \text{ s.t. } x_i \in X_i, \quad i=1,2,\dots,N, \quad (12)$$

where $f(x)$ is the objective function.

x is the set of each design variable (x_i).

X_i is the set of the possible range of values for each design variable (continuous design variables), that is, ${}_L x_i \leq X_i \leq {}_u x_i$

N is the number of design variables.

The HS algorithm parameters that are required to solve the optimization problem in Equation 12 are also specified in this step: the harmony memory size (number of solution vectors in harmony memory, HMS), harmony memory considering rate (HMCR), pitch adjusting rate (PAR), and termination criterion

(maximum number of searches). Here, HMCR and PAR are parameters that are used to improve the solution vector. Both are defined in Step 3.

Step 2. Initialize the harmony memory (HM). In Step 2, the “harmony memory” (HM) matrix, shown in Equation (13), is filled with randomly generated solution vectors and sorted by the values of the objective function, $f(x)$.

$$HM = \begin{bmatrix} x^1 \\ x^2 \\ \cdot \\ \cdot \\ \cdot \\ x^{HMS} \end{bmatrix} \quad (13)$$

Step 3. Improvise a new harmony from the HM. In Step 3, a new harmony vector, $x' = (x'_1, x'_2, \dots, x'_n)$ is generated from the HM based on memory considerations, pitch adjustments, and randomization, as shown in Figure 10. For instance, the value of the first design variable (x'_1) for the new vector can be chosen from any value in the specified HM range ($x'_1 - x_1^{HMS}$). Values of the other design variables (x'_i) can be chosen in the same manner. Here, it is possible to choose the new value using the HMCR parameter, which varies between 0 and 1 as follows:

$$x'_i \leftarrow \begin{cases} x'_i \in \{x_i^1, x_i^2, \dots, x_i^{HMS}\} & \text{with probability } y \text{ HMCR,} \\ x'_i \in X_i & \text{with probability } y \text{ (1 - HMCR).} \end{cases} \quad (14)$$

The HMCR is the probability of choosing one value from the historic values stored in the HM, and (1-HMCR) is the probability of randomly choosing one feasible value not limited to those stored in the HM. For example, an HMCR of 0.95 indicates that the HS algorithm will choose the design variable value from historically stored values in the HM with a 95% probability, and from the entire feasible range with a 5% probability. An HMCR value of 1.0 is not recommended because of the possibility that

the solution may be improved by values not stored in the HM. This is similar to the reason why the genetic algorithm uses a mutation rate in the selection process.

Every component of the new harmony vector, $x' = (x'_1, x'_2, \dots, x'_n)$ is examined to determine whether it should be pitch-adjusted. This procedure uses the PAR parameter that sets the rate of adjustment for the pitch chosen from the HM as follows:

$$\text{Pitch adjusting decision for } x'_i \leftarrow \begin{cases} \text{Yes with propability } PAR, \\ \text{No with propability } (1 - PAR). \end{cases} \quad (15)$$

The Pitch adjusting process is performed only after a value is chosen from the HM. The value (1-PAR) sets the rate of doing nothing. A PAR of 0.3 indicates that the algorithm will choose a neighboring value with $30\% \cdot \text{HMCR}$ probability. If the pitch adjustment decision for x'_i is Yes, and x'_i is assumed to be $x_i(k)$, i.e., the k th element in x'_i , the pitch-adjusted value of $x_i(k)$ is:

$$x'_i \leftarrow x'_i + \alpha \quad (16)$$

where α is the value of $bwxu(-1,1)$,

bw is an arbitrary distance bandwidth for the continuous design variable, and $u(-1,1)$ is a uniform distribution between -1 and 1.

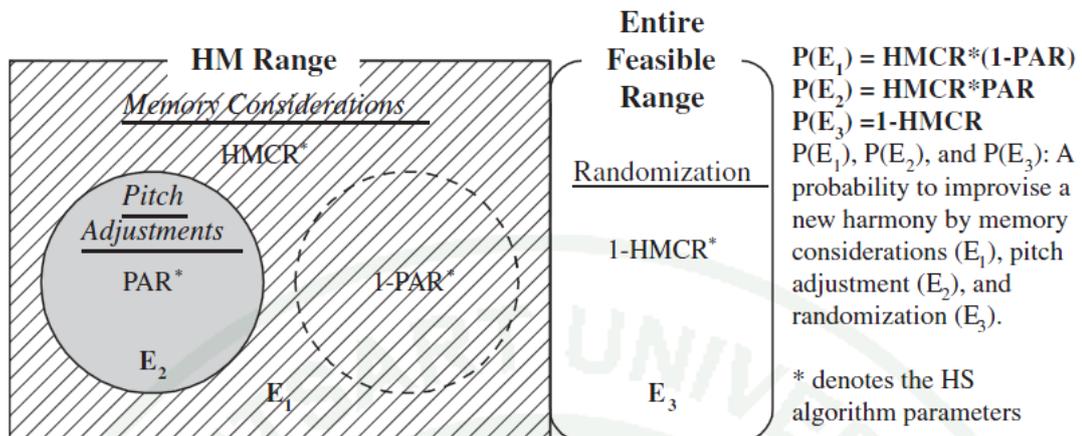


Figure 10 New harmony improvisation concept (Step 3)

Source: Geem (2005)

Step 4. Update the HM. In Step 4, if the new harmony vector is better than the worst harmony in the HM in terms of the objective function value, the new harmony is included in the HM and the existing worst harmony is excluded from the HM. The HM is then sorted by the objective function value.

Step 5. Repeat Steps 3 and 4 until the termination criterion is satisfied. In Step 5, the computations are terminated when the termination criterion is satisfied. If not, Steps 3 and 4 are repeated.

Geem (2000) presented a cost minimization model for the design of water distribution networks. The model uses a recently developed harmony search optimization algorithm while satisfying all the design constraints. The harmony search algorithm mimics a jazz improvisation process in order to find better design solutions, in this case pipe diameters in a water distribution network. The model also interfaces with a popular hydraulic simulator, EPANET, to check the hydraulic constraints. If the design solution vector violates the hydraulic constraints, the amount of violation is considered in the cost function as a penalty. The model was applied to five water distribution networks, and obtained designs that were either the same or cost 0.28 - 10.26% less than those of competitive meta-heuristic algorithms, such as the genetic

algorithm, simulated annealing, and tabu search under the similar or less favorable conditions. The results show that the harmony search-based model is suitable for water network design.

Fesanghary and Damangir (2009) study explores the use of global sensitivity analysis (GSA) and harmony search algorithm (HSA) for design optimization of shell and tube heat exchangers (STHXs) from the economic viewpoint. To reduce the size of the optimization problem, non-influential geometrical parameters which have the least effect on total cost of STHXs are identified using GSA. The HSA which is a meta-heuristic based algorithm is then applied to optimize the influential geometrical parameters. To demonstrate the effectiveness and accuracy of the proposed algorithm, an illustrative example is studied. Comparing the HSA results with those obtained using genetic algorithm (GA) reveals that the HSA can converge to optimum solution with higher accuracy.

Mohammadhasani and Fesanghary (2009) study presents a new hybrid methodology for synthesis of cost-optimal heat exchanger networks (HENs). The problem is solved in a two-level approach. The upper level generates the structure of HENs using harmony search (HS) algorithm. To evaluate the minimum cost of each structure, it is sent to the lower level in which the heat load of units and stream-split fractions are optimized by a combination of the HS and sequential quadratic programming (SQP). Based on the cost obtained for each structure HS ranks the HENs and produces new structures until algorithm converges to optimal solution. For validation purpose, three benchmark problems are examined and also a real-world industrial-sized problem is solved to demonstrate the applicability of this method for large-sized problems. The results of this study show that the new approach is able to find more economical networks than those generated by other methods.

3. Distillation sequences

3.1 Abstraction of Data Structure of Distillation Separation Sequence

There are analogous structure shared in distillation separation sequences and binary trees, the binary tree is the most reasonable data structure that describes the distillation separation sequences. A binary tree that describes a distillation separation sequence can be organized as follows: separation points correspond to the internal nodes of a binary tree, while pure components correspond to the leaf nodes of a binary tree, as a result, a kind of complete mode that expresses a feasible separation sequence is formed. If leaf nodes, corresponding to pure components, are deleted from a binary tree of the complete mode, and yet the root node and internal nodes that correspond to separation points are still reserved, another kind of shortcut mode, that expresses a feasible separation sequence, is obtained. It is obvious to see that a binary tree of complete mode is a regular binary tree, while a binary tree of shortcut mode is a general binary tree.

A binary search tree is defined as follows: a binary tree where every node's left subtree has values less than the node's value, and every right subtree has values greater. Evidently a binary tree of the shortcut mode corresponds to its preorder or post order traversal that is namely a numeric sequence, so a binary tree of the shortcut mode can be described by a numeric sequence, while a binary tree of the complete mode can be described by a nested parenthesis. Thereby, a distillation separation sequence can be described properly by a nested parenthesis that corresponds to a binary tree of the complete mode and a preorder or post order traversal that corresponds to a binary tree of the shortcut mode. As the post order traversal of a binary tree of the shortcut mode can reflect the hierarchy that a distillation separation sequence implicates, the separation cost that evaluates the corresponding distillation separation process can be calculated by gradual recursion according to the post order traversal.

For five-component distillation separation sequence synthesis problem is instanced. The initial component group is arrayed according to the order list, and all possible separation points are shown as follows



A regular binary tree of the complete mode and a general binary tree of the shortcut mode that respectively express a distillation separation sequence are shown in Fig.3.

In fact, for tree superstructures of distillation separation sequences, a single regular binary tree that has R leaf nodes corresponds to a single general binary tree that has $R-1$ nodes. According to the enumerative theory of the binary tree, the number of all distinct regular binary trees that are possessed of R leaf nodes and of all distinct general binary trees that possess $R-1$ nodes both are equal to $b = \frac{1}{R} C_{2(R-1)}^{R-1}$. Apparently, the number b of all distinct binary trees and the number S_R of all feasible separation sequences both are equal to the Catalan number of the problem size $R-1$. Hence, the feasible solution region that all distillation separation sequences forms is mapped to the space that all distinct binary trees form.

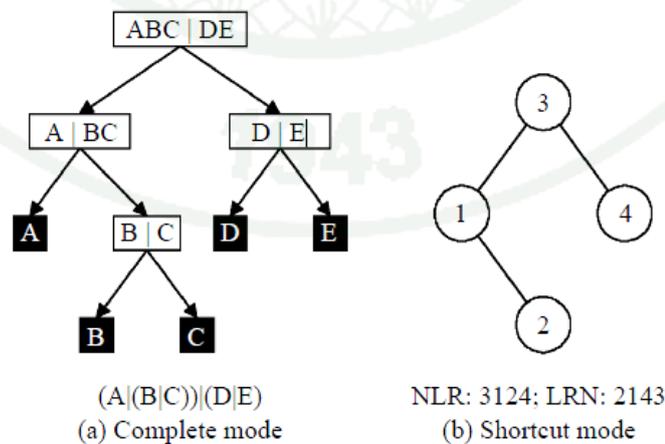


Figure 11 Representation of a distillation separation sequence

Source: Dong (2005)

3.2 Coding approach for separation sequence representation

Consider an N -component mixture, and the components $\{C_1, C_2, C_i, C_{i+1}, \dots, C_N\}$ are ordered according to their volatilities (i.e. C_1 is the most volatile and C_N the least). We use nature numbers $1, 2, \dots, N-1$ as the codes to name the cuts between each pair of adjacent components, as shown in Figure 12.

Typically, code i indicates the split between components C_i and C_{i+1} , and its value is identical to the order of the light-key component C_i for the split. Thus, an ordered $(N-1)$ code sequence $\{s_i\} = (i = 1, 2, \dots, N-1)$ can be used to denote a separation sequence. For example, for a mixture of $N=6$, the sequence $\{s_i\} = \{2, 4, 5, 1, 3\}$ can represent the separation sequence $C_1C_2 | C_3C_4C_5C_6 \rightarrow C_3C_4 | C_5C_6 \rightarrow C_5 | C_6 \rightarrow C_1 | C_2 \rightarrow C_3 | C_4$.

This example indicates that, a code (a cutting position) in Figure 12 can be used to denote anyone in the family of separation tasks that have the same pair of light and heavy key components. For example code “2” in Figure 12 can be used to represent the separation tasks $C_2 | C_3, C_1C_2 | C_3, C_1C_2 | C_3C_4$, or $C_1C_2 | C_3, \dots, C_N$, etc. The separation task represented by a code can be identified in sequence $\{s_i\}$ according to its position in the sequence. For example, the element “2” in sequence $\{s_i\}$ denotes the separation task $C_1C_2 | C_3, \dots, C_N$, as it is the first element in $\{s_i\}$. To manipulate code sequence $\{s_i\}$ to generate separation sequences, a sorting procedure is needed to identify systematically the separation tasks denoted by the elements in $\{s_i\}$. In this work a binary sort tree approach is developed for this purpose.

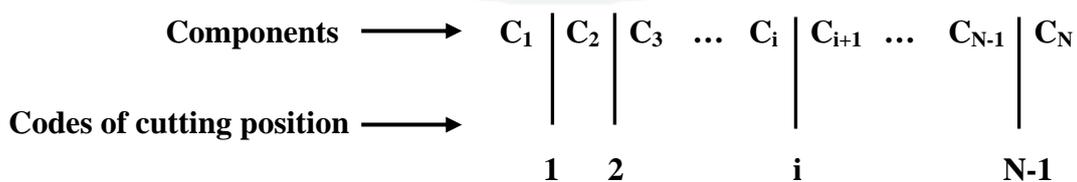


Figure 12 Codes for naming the cutting position

Source: zhong and Gang (2009)

3.3 Design of Neighborhood Structure Based on the Binary Tree

The key of realizing the neighborhood search algorithm lies in the evolution of the binary tree structure. This paper proposes a kind of evolutionary method through node operations. That is, the change mechanism of neighborhood separation points based on the binary trees is built, and then an effective evolutionary neighborhood structure is constructed. Detailed steps are as follows

- a. A possible separation point sequence is randomly generated, and then an initial binary tree is built according to it.
- b. Two neighborhood separation points are randomly selected from the separation point sequence, and then their positions in the corresponding binary tree are found. In this way, the phenomenon of direct search only towards some goal can be avoided.
- c. The node key in the higher layer (more close to leaf nodes) takes the place of the node key in the lower layer (more close to the root node).
- d. The node in the higher layer is deleted. If its left subtree or right subtree exists, its subsequent nodes are appended to its grandparent at the proper location.
- e. When the displaced node key is bigger than the replaced node key, the replaced node is inserted into the left subtree of the displaced node and becomes its left child; when the displaced node key is smaller than the replaced node, the replaced node is inserted into the right subtree of the displaced node and becomes its right child.

If n components are to be separated into n single component products, one requires $(n - 1)$ distillation columns, each receiving a feed and producing two products. Two-component system requires a single column. Ternary mixture requires two columns in series, either direct or indirect sequence. Four component system requires

three columns in series, either direct sequence or indirect sequence or other combinations, resulting in five sequences (Figure 12). In general, the number of column sequences, S_n for separating n components into n single component products can be found from

$$S_n = \sum_{j=1}^{n-1} S_j S_{n-j} \quad (17)$$

where S_j represents the sequences by which the J overhead components from the first column can be separated in subsequent distillations and S_{n-j} is the number of sequences by which the bottom components from first column can be separated in subsequent distillations.

A more generalized Equation to find the number of sequences to separate a multi-component mixture is given by

$$S_n = \frac{[2(n-1)]!}{[n!(n-1)!]} \quad (18)$$

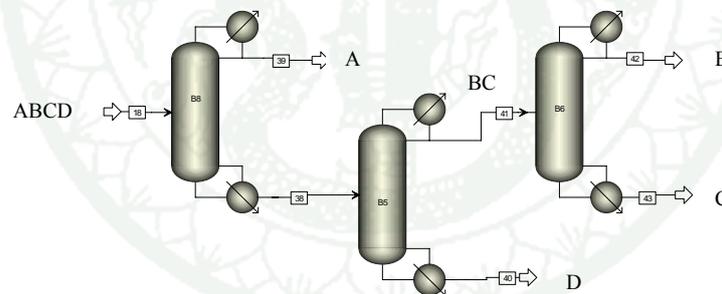
Table 2 gives the number of sequences required. Comparison of different sequences can be made by estimating the marginal vapour flows for each separator and then for the complete sequence considered.

Table 2 Number of sequences required to separate a multi-component mixture

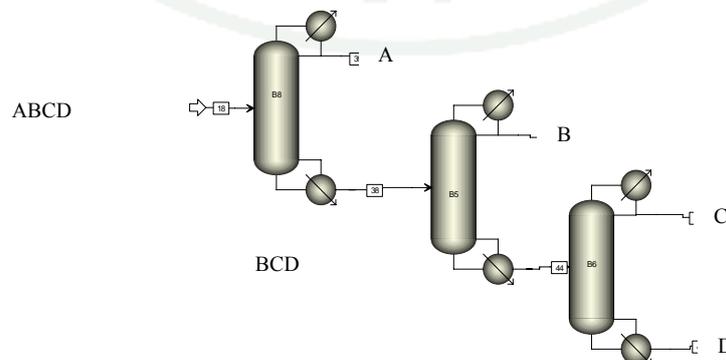
Number of Components (n)	Number of column sequences (S_n)
2	1
3	2
4	5
5	14
6	42
7	132
8	429
9	1430
10	4862

For separation of distillation sequences for a four component system

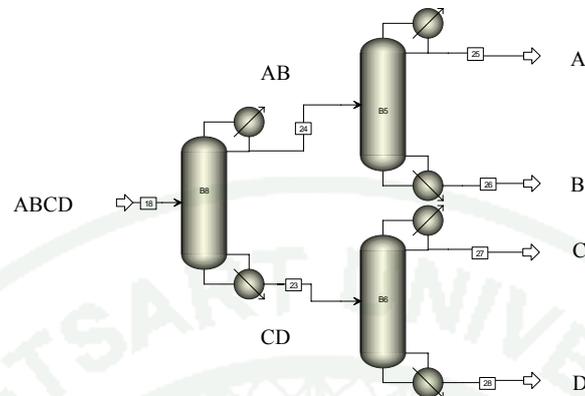
1. A/BCD, BC/D, B/C



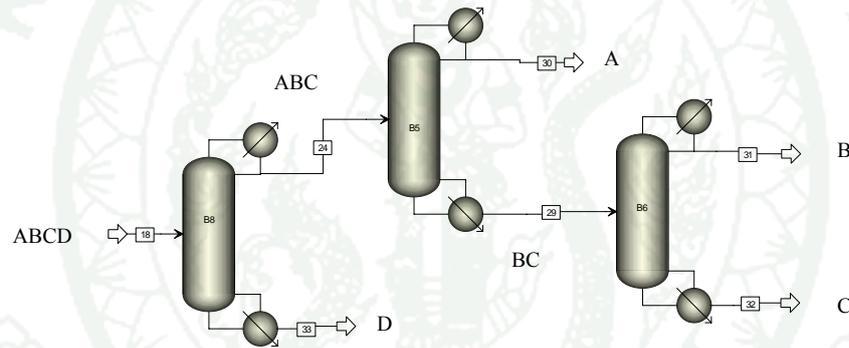
2. A/BCD, B/CD, C/D



3. AB/CD, A/B, C/D



4. ABC/D, A/BC, B/C



5. ABC/D, AB/C, A/B

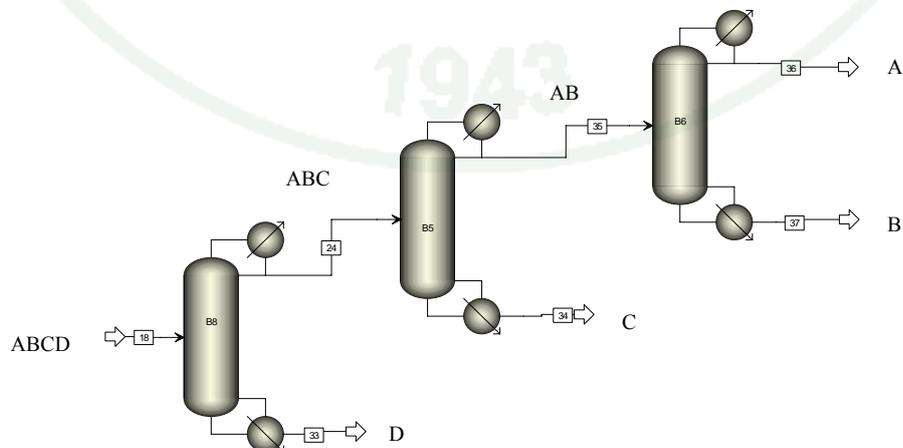


Figure 13 Distillation sequences for a four component system

Piumsomboon and Thitiprayoonwongse presented (2001) Optimal distillation sequencing is a method for obtaining the best structure of multicomponent separation processes. Due to the significant contribution of the distillation sequences to the capital and operating costs for the whole chemical process, the development of a systematic framework that will select the optimal distillation sequences becomes an important research issue. Since distillation sequencing is a combinatorial problem, this paper elaborates an algorithm to handle the problem and explains how to employ a Genetic Algorithm (GA) to solve the problem. GA is an optimization technique imitating the biological process of natural selection (Darwin's rule) and natural genetics by which only the fit can survive. The distillation sequences were coded into the chromosome structure. A set of initial chromosomes was generated. The fitness values were computed considering all the constraints. The highest fitness values were given the highest probability to be selected in the next generation. The new population was generated by the processes of reproduction, which were duplication, cross linking and mutation. The effects of GA parameters such as the population size and the probabilities of reproduction, crossover, and mutation on the convergence rate were studied.

Dong and Qin (2005) presented distillation separation sequences can be described as binary tree data structures, because of the analogous structures of distillation separation sequences and binary trees, and then by applying graph theory, the change mechanism of neighborhood separation points based on binary trees is built, correspondingly a kind of highly effective, evolutionary neighborhood structure is constructed. For the purpose of researching further tabu search algorithms, adaptive mechanisms and parallel techniques are introduced. That is, according to memory frequency information, the tabu length and the number of candidates are adaptively adjusted, and multitask parallel technology is realized through the arrangement of the search assignments. The example shows that adaptive parallel tabu searches can solve, successfully, large-scale distillation separation sequence synthesis problems.

4. Heat-Integration distillation sequences

The direct heat integration of independent processes was proposed by Xiao *et al.* (2004). To determine whether the direct heat integration is feasible or not, the distance between integrated processes, the properties of matched streams and the simultaneous operation time are considered as the key factors. The study is performed by comparing a simple independent separation process with the synthetic heat integration process. The mathematical formulation for the separate integration is established. From the results, the direct heat integration is feasible only when: there is no degradation of the products quality of each process due to the leakage between matched streams, the integrated processes have the simultaneous operating hours beyond certain hours, and the distance between the integrated processes has a certain radius.

4.1 Coding approach for heat integration configuration representation

For dealing with heat integration simultaneously, the following coding procedure is proposed to represent the heat integration structure, i.e. condenser-reboiler matches.

For the separation of an N -component mixture with $N-1$ separators, the maximum number of possible matches is M

$$M = \frac{(N-1)}{2} \quad (19)$$

when N is odd, and

$$M = \left(\frac{N}{2}\right) - 1 \quad (20)$$

when N is even. Thus, a $2M$ -element sequence $\{h_k\}$, $k=1, 2, \dots, 2M$ can be used as the code sequence to represent possible condenser-reboiler matches. In series $\{h_k\}$, the

value of a code, which represents a column, is the order number of the code representing the same column in $\{s_i\}$. For the separation of a five-component mixture, the maximal number of heat matches is two. If the sequence is given by $\{s_i\} = \{2, 1, 4, 3\}$, then $\{h_k\} = \{[4, 2], [1, 3]\}$ denotes that one match takes place between the condenser of the column represented by s_4 (code 3) and the reboiler of the column represented by s_2 (code 1) in $\{s_i\}$, and another takes place between the condenser of column s_1 and the reboiler of column s_3 . It should be pointed out that the given encoded matches, which are generated randomly, denote merely the possibility of matches because a real heat match must satisfy the basic conditions of heat exchange (for example the minimum temperature difference ΔT_{\min} allowed) for a given separation flow sheet and the corresponding operating parameters.

Zhong and Gang (2009) presented a simulated annealing-based approach to synthesis of multi-component distillation systems is developed. An encoding procedure that makes use of an integer number series is developed to represent and manipulate the flow sheet structure of the system. With the representation procedure, the overall synthesis problem is formulated as an implicit mixed-integer nonlinear programming (MINLP) problem. A simulated annealing approach suitable for MINLP optimization is adopted and improved to solve the problem.

Wang and Li (2010) presented Genetic programming (GP) is used to solve the synthesis problem of heat integration nonsharp distillation sequences and the optimization objective of it is to seek the optimal heat integration nonsharp flow based on minimizing the annually total cost. Meanwhile, the major technological parameters for these important equipments are given. Combining with the domain knowledge of chemical engineering, some evolutionary factors are improved, and a set of special encoding method and heat integration strategy is proposed to deal with this kind of problem. The system structural variable is optimized by GP and the continuous variable is optimized by the complex algorithm simultaneously. Because GP has the automatically searching function, the optimal heat integration solution can be found

automatically without any superstructures of nonsharp distillation sequences. Four case studies are presented in the next chapter.



MATERIALS AND METHODS

Materials

1. Personal Computer (PC)
 - CPU [Intel(R) Core(TM)2 Duo 2.00 GHz]
 - 2.00 GB of RAM
 - 320 GB of hard disk
2. Operating System: Microsoft Window 7 Professional
3. Software
 - Aspen Plus V. 7
 - Aspen Process Economic Analyzer V.7
 - Microsoft Visual Studio V.2008
 - Minitab V.14

Methods

In this work, the study of all case study can be divided into 6 steps. These steps are :

1. Applications of heat integrated distillation sequences.
2. Process synthesis of all case study.
3. Optimization using Ant colony algorithm for heat-integrated distillation sequences
 - 3.1 Pseudo code of Ant colony algorithm for heat-integrated distillation sequences
 - 3.2 Find the optimal parameters by statistical analysis.

4. Optimization using Harmony search algorithm for heat-integrated distillation sequences

4.1 Pseudo code of Harmony search algorithm for heat-integrated distillation sequences

4.2 Find the optimal parameters by statistical analysis.

5. Comparison optimal technical between Ant colony algorithm and Harmony search algorithm.

6. Steady-state process of all case study.

The methodology of each step is as the following shown in Figure 14.

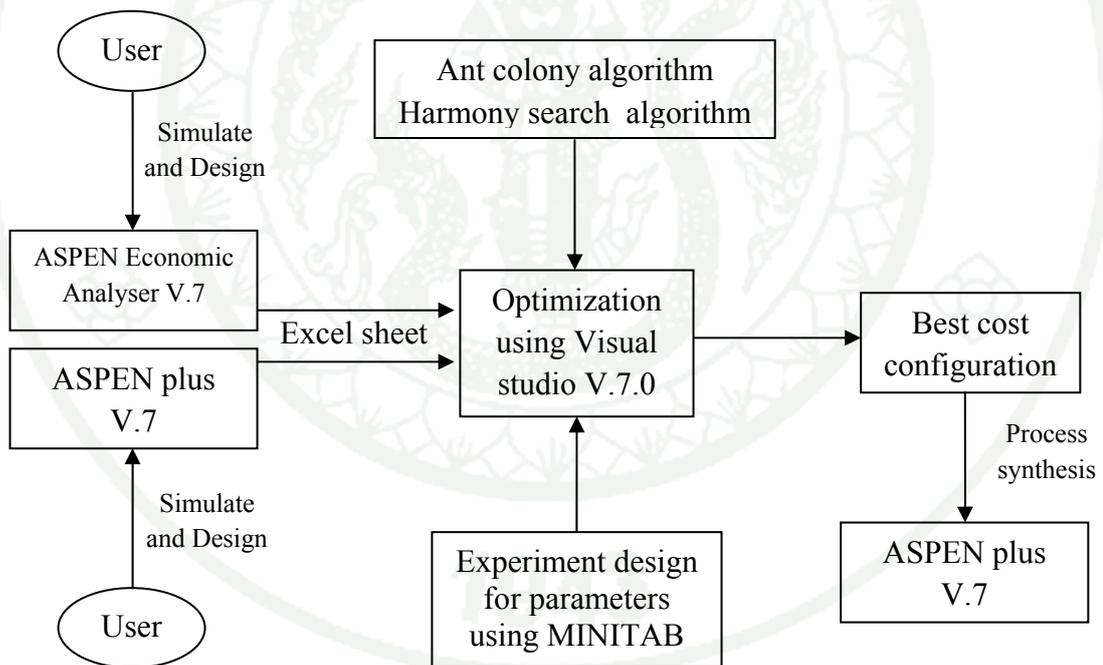


Figure 14 Flow chart for in this work

1. Applications of heat integrated distillation sequences.

1.1 Problem statement

The problem addressed in this paper can be stated as: Given N -component mixture of known conditions: composition, flowrate, temperature and pressure. To find a distillation system for separating the mixture into N products corresponding to the components, with a flowsheet structure including separation sequence and heat integration and operating parameters that give the lowest total annual cost.

The assumptions made for the problem are as follows:

- 1) All separations are considered to be sharp splits of the light and heavy keys with no distribution of components in both the distillate and the bottoms.
- 2) Mixture to be separated does not form azeotropes.
- 3) The feed is assumed to be saturated liquid and the products are removed at their bubble point temperatures for all columns. The thermodynamic state (e.g. saturated liquid, saturated vapor) the thermodynamic state of the distillate and bottoms products are also known.
- 4) Operating pressures of the columns are allowed to vary within a feasible range for heat integrations.
- 5) The reflux ratio for any individual distillation column is set to the value of 1.2 times the minimum reflux ratio for that column.
- 6) The condenser type of each column is known.
- 7) Heat integrations occur only between the condensers (heat source) and the reboiler (heat sink) of different distillation columns. No heat match is considered with a third column when a column has heat match with another. Heat transfer coefficients are held constant in all heat exchangers.
- 8) Available to each column is a set of constant temperature hot and cold utilities. Each column may exchange heat with any number of utilities. Each column

condenser or reboiler may also exchange heat with as many reboiler and condensers in the superstructure as desired as well as with the set of utilities.

1.2 Formulation and solution of the mixed integer linear program (MILP)

In the previous section two methods have been described for generating superstructures for the problem of heat integrated distillation sequence synthesis. This section describes the formulation of a mixed integer linear program which represents this superstructure and the heat integration possibilities within it.

1.2.1 The MILP Objective Function

The first step in formulating a mixed integer linear program for this problem is devising an objective function which can be used to compare different alternatives. An obvious choice for the objective function is the project cost, which is made up of equipment costs and operating costs. The major equipment costs in a distillation system are those of the distillation columns themselves and of the heat exchangers used as condensers and reboiler. The major operating cost is the cost of the utilities used. The objective function should account for both of these costs.

The cost of a distillation column is a function of many variables. Among these are the feed flow rate to the column, the reflux ratio, the number of trays, the column temperature, the column pressure, and the physical properties of the feed components. Most of these parameters are fixed implicitly or explicitly by the superstructure generating algorithms of the previous section. The pressures and temperatures of each column are specified by these algorithms, and from them the minimum reflux ratio and minimum number of trays can be calculated (Fenske, 1932; Underwood, 1946,1948)

The operating reflux ratio is chosen to be 1.2 times the minimum as discussed earlier. This also determines the number of trays for a specified product purity (Gilliland, 1940; Erbar and Maddox,1961). The only unspecified variable is the feed flow rate, which depends on the distillation system.

The objective function for the mixed integer linear program can be formulated as

$$VC = (CAC/\alpha) + \beta(OPC) \quad (21)$$

where CAC is the installed capital cost.

OPC is the annual operating cost.

The parameter α is the payout time for capital investment and β corrects the operating costs for the income tax rate. In this paper, unless otherwise noted the payout time is assumed to be 2.5 years and β is 0.52.

The venture cost for a distillation superstructure can be formulated as

$$VC = \frac{1}{\alpha} \sum_{k \in COLS} [FC_k + V_k F_K] + \beta \sum_{j \in HU} C_{HU,j} Q_H(j) + \beta \sum_{i \in CU} C_{CU,i} Q_C(i) \quad (22)$$

where $COLS$ is the set of all columns in the superstructure.

HU is the set of all hot utilities.

CU is the set of all cold utilities.

The first term is the capital cost of the distillation columns and the other terms are the costs of the hot and cold utilities which are required.

This objective function is subject to constraints of three types. Material balance constraints describe the permissible routes by which material may flow from one column in the superstructure to another. Some heat integration constraints describe the amount of heat associated with each reboiler and condenser while others describe the feasible heat exchange possibilities. The third type of constraints, which will be called integrality constraints, insure consistency between the continuous and integer variables.

1.2.2 Material Balance Constraints

Material balance constraints relate material flows into and out of columns in the superstructure. Each column separates its feed into two product streams whose amounts are related to the feed flow by

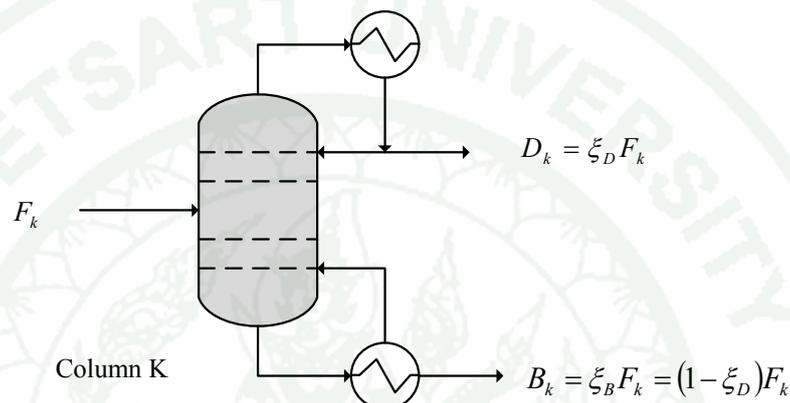


Figure 15 Mass balances for separated of component mixture.

$$D_k = \xi_D F_k \quad (23)$$

$$B_k = \xi_B F_k = (1 - \xi_D) F_k \quad (24)$$

where ξ_D is the fraction of the feed to column k which leaves in the distillate

ξ_B is the fraction which leaves in the bottoms. Interconnections between distillation columns are also described by material balance constraints. Consider the structure shown in Figure 15. The feed streams to many columns in this structure are product streams from other columns. For each intermediate product of two or more components in this structure, a constraint is written which states that the amount of each intermediate product produced by columns in the structure must equal the amount of that intermediate product fed to columns which further separate the product. That is

$$\sum_{i \in PS_m} \xi_i F_i - \sum_{j \in FS_m} F_j = 0 \quad m \in IP \quad (25)$$

where PS_m is the set of all columns which produce a given intermediate product m as distillate or bottoms.

FS_m is the set of all columns having intermediate product m as feed.

F is the total flow rate to a column.

IP is the set of all intermediate products.

ξ is the split fraction relating distillate or bottoms flows to feed flows.

This constraint is written for each intermediate product. A similar expression is necessary for the feed to the distillation system.

1.2.3 Energy Balance Constraints

Once a superstructure has been developed the problem of heat integration within that superstructure is very similar to the heat exchanger network synthesis problem. The hot and cold streams are the condenser streams, reboiler streams, and the utilities. The temperature levels for the reboiler and condenser streams are fixed by specifying the column pressures, and the temperature level of each utility is given in the problem specification. The amount of heat associated with each reboiler and condenser however, is not known. Since all other column operating conditions are fixed in the development of the superstructure, the heat duty in each condenser and reboiler is only a function of the column feed flow rate. These duties are directly proportional to the feed flow.

$$Q_k = Q_{ref,k} \frac{F_k}{F_{ref,k}} \quad (26)$$

where $Q_{ref,k}$ is the condenser or reboiler duty of column k with a feed flow rate of $F_{ref,k}$.

Q_k is the reboiler or condenser duty for that column with a feed flow rate of F_k .

In this study the maximum possible feed flow in a particular column is used to evaluate the reference heat duty for that column.

It is also assumed in this study that the heat duties in the condenser and reboiler of each column are equal. This assumption can be justified by considering an energy balance around a single distillation column. Heat enters the column in the reboiler and with the feed stream; heat leaves in the condenser and with the distillate and bottoms products. The distillate and bottoms products are normally saturated liquids. If it is further assumed that the feed stream is also a saturated liquid (as is the case in this study), the net effect of these streams on the overall energy balance is only the difference in sensible heat between the product streams and the feed streams. The reboiler and condenser heat loads involve latent heat effects which are much larger than the sensible heat effects, particularly at high reflux ratios. If the sensible heat effects are ignored entirely, the energy balance states that the condenser and reboiler duties must be equal.

The feasible heat exchange possibilities within the superstructure for heat integrated distillation sequence synthesis can be described using methods developed for heat exchanger network synthesis: formulation as a transportation problem in linear programming (Cerda *et al.*, 1983) or as a transshipment problem in linear programming (Papoulias, 1982).

1.2.4 Heat Exchanges

The transportation formulation for describing the feasible heat exchanges within a superstructure for heat-integrated distillation sequence synthesis is quite simple. The problem can be represented using the stream matrix developed by Pho and Lapidus (1973). All of the condensers and hot utilities are listed across the top of the matrix and reboiler and cold utilities are listed along the side. Each row of the matrix is associated with a single reboiler or cold utility and each column is associated with a single condenser or hot utility. This is a simplification of the partitioning procedure developed by Cerda *et al.* (1983) which is made possible by the assumption

that the condenser and reboiler streams exchange heat at a single temperature rather than over a temperature range as is usually the *case* in heat exchanger network synthesis. This assumption is certainly true for condensing or reboiling single-component product streams but is not true for multicomponent product streams. The boiling range of multicomponent product streams is neglected in this study and such streams are assumed to receive or transfer heat at their bubble point temperature. This temperature is chosen because all the heat rejected in a condenser is rejected at or above the bubble point temperature, and because in a kettle type reboiler all the heat is absorbed near the bubble temperature of the bottoms.

For each condenser or reboiler the amount of heat transferred must equal the amount of heat which is available. These criteria can be written as:

$$\sum_{i \in FM_{\bullet, j}} q(ij) = Q_H(j) \quad j \in HS \quad (27)$$

$$\sum_{j \in FM_{i, \bullet}} q(ij) = Q_C(j) \quad i \in CS \quad (28)$$

where $q(ij)$ is the amount of heat transferred from condenser or hot utility j to reboiler or cold utility i .

$FM_{\bullet, j}$ is the set of feasible matches between reboiler or cold utilities and condenser or hot utility j .

$FM_{i, \bullet}$ is the set of feasible matches between condensers or hot utilities and reboiler or cold utility i .

$Q_C(i)$ or $Q_H(i)$ is the amount of heat associated with each reboiler, condenser, or utility stream

HS is the set of all hot streams, process or utility.

CS is the set of all cold streams, process or utility.

The amount of cold utility i which is required can be obtained from

$$Q_C(i) = \sum_{j \in FM_i} q(ij) \quad i \in CU \quad (29)$$

and the amount of hot utility j from

$$Q_H(j) = \sum_{i \in FM_j} q(ij) \quad i \in HU \quad (30)$$

These expressions for $Q_C(i)$ and $Q_H(i)$ can be substituted for the energy use terms in the objective function in Equation 22.

Heat exchanger costs can also be included with the transportation formulation of the heat integration. This is done by relating the cost of the heat exchanger for each feasible match in Equation 27 and Equation 28 to the amount of heat exchanged in that match. The area is calculated from

$$A = \frac{Q}{U \Delta T_{LM}} \quad (31)$$

where Q is the amount of heat transferred

U is the heat transfer coefficient for the match, and

ΔT_{LM} is the log mean temperature difference between the streams in the match.

The heat transfer coefficient can be estimated for each match, and ΔT_{LM} can be determined for each match from the temperatures in the superstructure. The heat exchanger area is then only a function of the amount of heat transferred in a particular match. The relation between the cost and the area is actually nonlinear, but in this analysis it is assumed that cost is directly proportional to area

$$C_{HX,ij} = \frac{A_{ij}}{A_{ref}} C_{HX,ref} \quad (32)$$

where $C_{HX,ref}$ is the cost of a heat exchanger of area A_{ref} . The cost of a heat exchanger in this method is

$$Cost = C_{HX,ij} q(ij) = \frac{C_{HX,ref}}{A_{ref} U \Delta T_{LM}} q(ij) \quad (33)$$

All of the heat exchanger costs can be included in the formulation by adding the following terms to the objective function

$$CAC_{HX} = \frac{1}{\alpha} \sum_{i \in CS} \sum_{j \in FM_i} C_{HX,ij} q(ij) \quad (34)$$

1.2.5 Integrality Constraints

Neither the material balance nor the heat integration constraints account for the fact that each alternative distillation system consists of only a few distillation columns in the superstructure. Integer variables and constraints must be added to account for this. A binary variable is associated with each column in the superstructure. These variables indicate which columns are present in a particular distillation system. A binary variable with a value of one indicates that the column associated with that variable appears in the solution, a binary variable with a value of zero indicates that it does not.

$$F_k - U_k y_k \leq 0 \quad (35)$$

where U_k is an upper bound on the feed flow rate to column k. If the binary variable y_k is set to one, this constraint becomes

$$F_k \leq U_k \quad (36)$$

If the binary variable is set to zero, the feed flow rate will be set to zero. If the feed flow is zero, the heat duty will also be zero since the duty is proportional to the feed flow rate.

The complete MILP formulation

A complete mixed integer linear program can now be formulated for the problem of distillation sequence synthesis with heat integration. Two versions are possible; one uses the transportation problem model for the heat integration, the other uses the transshipment model. These two formulations will now be presented.

- MILP formulation with the transportation model for heat integration

$$\begin{aligned} \text{MINIMIZE COST} = & \frac{1}{\alpha} \sum_{k \in \text{COLS}} [FC_k y_k + V_k F_k] + \frac{1}{\alpha} \sum_{i \in \text{CS}} \sum_{j \in \text{FM}_i} C_{HX,ij} q(ij) \\ & + \beta \sum_{i \in \text{CU}} C_{CU,i} \sum_{j \in \text{FM}_i} q(ij) + \beta \sum_{j \in \text{HU}} C_{HU,j} \sum_{i \in \text{FM}_j} q(ij) \end{aligned} \quad (37)$$

The decision variables in this formulation are the binary variables, y_k , the flow rates to each column, F_k , and the amount of heat transferred between each hot and cold stream, $q(ij)$.

In this research, heat integrated distillation sequences is synthesized by using Visual Studio V.7.0 ; industrial standard optimization tool, to find the optimal solution according to Andrecovich and Westerberg (1985)'s research. The optimization can be formulated in the form of mixed-integer linear programming (MILP) problem which was proposed by Andrecovich and Westerberg (1985). During the synthesis of heat integrated distillation, the following information is needed:

(1) Split fraction of each columns in superstructure

In material balance constraint, split fraction for specified intermediate product from each columns are required to create the logical linking of columns in superstructure. Split fraction is calculated by assuming that this process performs sharp separation. Intermediate components and split fraction of each column.

(2) Columns and heat exchanger investment cost

The investment cost of each distillation column is expressed as a linear fixed charge cost according to Equation 38. A Column cost data is the result from performing regression analysis on the simulation data taken by varying column condenser temperature and column feed flowrate. First the short cut model, DSTWU, in ASPEN PLUS simulator is used to simulate a column of the superstructure at a condenser temperature and feed flowrate. Next, this simulation results is exported to evaluate the process investment cost in Aspen Process Economic Analyzer. At this step, one data point for the relation between column condenser and column feed flowrate with column investment cost is obtained. Then this column is simulated again by varying column temperatures or feed flowrate in order to obtain another data points. Finally, the regression analysis is done for these simulation data points. From the regression analysis, fixed charge and variable charge for each column of the superstructure will be obtained.

$$Cost = FC + V \cdot F \quad (38)$$

where FC is a fixed cost associated with the column

V is the slope of the line relating the column cost to the feed flow rate.

There are many values of FC and V which could adequately describe the actual linear cost function.

(3) Columns heat duty

Equation 39 is a constraint of this optimization problem which provides the relation of column i reboiler duty of this column.

$$Q_R = K_R F_K \quad (39)$$

where K_R is a constant of reboiler which can be obtained from Equation 39.

Equation 40 is a constraint of this optimization problem which provides the relation of column i condenser duty of this column.

$$Q_C = K_C F_K \quad (40)$$

where K_C is a constant of condenser which can be obtained from Equation 40.

(4) Allowable matches of heat integration for superstructure

As mentioned before, there are three types of heat integration in a heat integrated distillation sequence including column-column, hot utility-column reboiler and column condenser-cold utility heat exchange. For heat integration between columns, heat can be exchanged between condenser cold utility outlet of the column and reboiler of other column. This type of heat integration only permits heat exchange between columns in the same sequence.

3. Optimization using Ant colony algorithm for heat-integrated distillation sequences

3.1 Pseudo code of Ant colony algorithm for heat-integrated distillation sequences

```

1   Start
2   Define original pheromone (WOP)
3   Set parameter of max-min ant system
4   For iteration = 1 to i (NOI)
5       For ant = 1 to i (NOA)
6           Random start node
7           Do while node < i
8               Select next node
9           Loop
10      Calculate objective function
11      End loop ant
12      Update pheromone
13      End loop iteration

```

Figure 16 Pseudo code of Max-Min Ant System (MMAS)

From shown in Figure 16 is pseudo code which can be described as a 13 step.

Step 1 : This step is the beginning of work. We will use the Max-Min ant system (MMAS) algorithm to create a problem to solve heat-integrated distillation sequences.

Step 2 : The second step is a set amount of pheromone begin to select routes for ants. In this section we use the initial amount of pheromone equal to 1 in every way that occasion the ant to walk.

Step 3 : This step is a step the parameters of the Max-Min ant system by which we determine the parameters is number of iterations (NOI) /number of ants (NOA), weight of heuristic information (WOH), evaporation rate (ER)

Step 4 : This step is a step to obtain the number of iterations (NOI) from the parameters of the NOI to the loop condition.

Step 5 : This step is a step to obtain the number of ant (NOA) from the parameters of the NOA to the loop condition.

Step 6-9 : This step is the process of random node to cut the key components. By looking at examples of random node from the examples below.

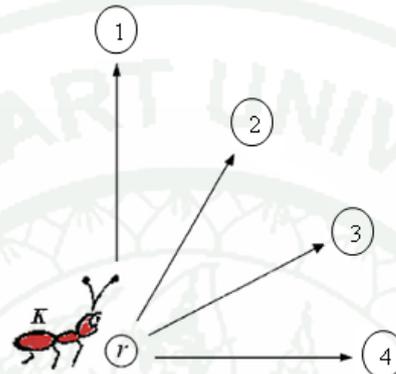


Figure 17 Ants to the city will choose a path r to the city of 1,2,3,4

For 5 components

A₁ B₂ C₃ D₄ E

Begin the first ants randomly where to cut. The chance to sample the ant to cut the 4 position, suppose that the ants make a cut at position 2.



After the first ant randomly cut to structure of possible distillation sequences are two structures shown below.

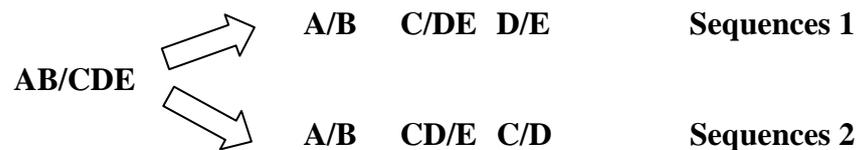


Figure 18 Sequences that ants will choose the path walked

Figure 18 can be explained that there are two paths that ants choose to walk. The ant will choose a path sequences 1 or sequences 2 is determined from the Equation 1, the probability that ants will choose to walk the following in Equation 1. Be the probability to calculated from sequences 1 and sequences 2 through the process of roulette wheel selection rule shown in Figure 17 for the probability of each of the sequences to be divided. Then randomly selected a fall in value if any. Ant, it will choose to walk that path.

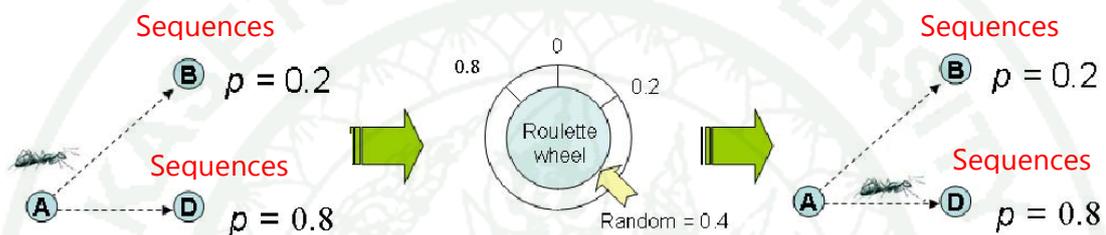


Figure 19 Roulette wheel selection rule

Assumed if the probability of choosing a path of sequences at 0.8. Therefore, the two sequences is the probability to choose path = 0.2. Then the value would be divided over the wheel. Randomly to the 0.4, so ants will choose the second path or sequences second.

Step 10 : This procedure will be calculated objective function of ants choose to walk the path.

Step 11 : Ants will choose to walk this repeatedly until the terms of the NOA has stopped working.

Step 12 : After all the ants choose to walk conditionally until the end. While walking ants will release pheromones. Update pheromone, which we need to make the Equation 8.

Step 13 : The last step is. NOI a complete loop around the if condition is false, it will stop a round. If it does not meet the conditions will be repeated by the NOI.

3.2 Find the optimal parameters by statistical analysis.

Designed in this research will use the design of trials of real factory 3 levels is high level, Medium level and low level with 4 variables is

- Number of iterations (NOI) /Number of ants (NOA)
- Weight of pheromone (WOP)
- Weight of heuristic information (WOH)
- Evaporation rate (ER)

The details shown in the following Table 3.

Table 3 Level factors and parameters for Ant colony algorithm

Factors	Level Factors		
	Low	Medium	High
Number of iterations (NOI) /Number of ants (NOA)	5/20	10/10	20/5
Weight of pheromone (WOP)	0.5	1.5	2.5
Weight of heuristic information (WOH)	1	2.5	5
Evaporation rate (ER)	0.2	0.55	0.9

In the experimental design for how the Ant colony algorithm. To model the foraging behavior of ants a Max-Min ant system. We will design this experiment to determine the optimal parameters for distillation sequences and heat-integrated distillation sequences. In our example, all problems will be studied six case studies. By each of the second cycle will be repeated, so the number of results is 162 order of each size of the problem in that the ants is shown in Appendix A. The analysis we will use the software package Minitab V.14 is shown in Figure 20.

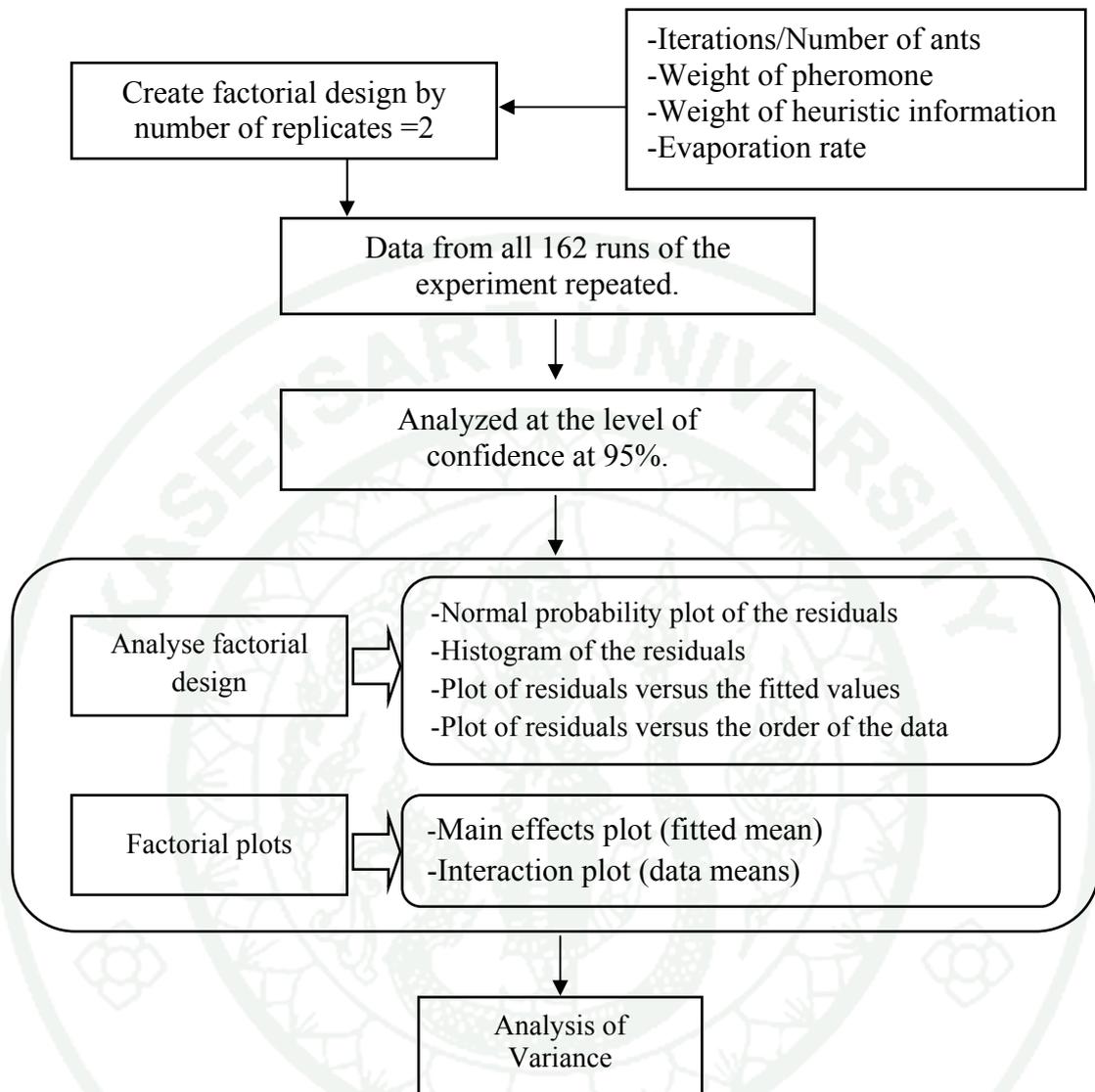


Figure 20 Analysis of variance of Ant colony algorithm

4. Optimization using Harmony search algorithm a for heat-integrated distillation sequences

4.1 Pseudo code of harmony colony algorithm for heat-integrated distillation sequences.

```

1   Start
2   For iteration = 1 to n (Number of iteration)
3       If i=1
4           Create harmony size by random
5           Check condition for harmony memory consider rate
6           Check condition for pitch adjustment rate
7           Calculate objective compare with harmony size
8           If better = choose
9           Else if No better = cancel
10  End Iteration

```

Figure 21 Pseudo code of Harmony search algorithm

From shown in Figure 21 is pseudo code which can be described as a 10 step.

Step 1 : This step is the beginning of work. We will use the Harmony search algorithm to create a problem to solve heat-integrated distillation sequences.

Step 2 : This step is for the number of iteration of the command.

Step 3 : This step will be run to start the first iteration.

Step 4 : This step will create harmony size.

For 5 components

$A_1 B_2 C_3 D_4 E$

Is the intersection point is 4 points 1,2,3 and 4 which took off at each point put in the array. The array will be equal to the number of harmony size (HS). It will be random. Assume that the harmony size = 3 will be as follows;

2	1	4	3
2	3	1	4
4	2	1	3

Figure 22 Array based on the number of harmony size (HS)

Calculate the objective function of each array and then be sorted in ascending order.

Step 5 : Check condition for harmony memory consider rate (HMCR). Is the random value from 1-100. If it is greater than Harmony memory considering rate (HMCR) through this process without having to step 6 improved array. If the random is less than the harmony memory considering rate (HMCR) to make a point, new crop increased the global harmony size has started to come to calculate of cost, then the array created to include the array have it all at 6 array, as shown in Figure 23 and then calculate the objective function will cost. Would need to sort ascending.

2	1	4	3
2	3	1	4
4	2	1	3
1	2	3	4
3	4	1	2
2	3	4	1

Figure 23 Array of new developments by conditional harmony memory consider rate

Step 6 : Check condition for pitch adjustment rate. If the random number between 1-100. If the value is greater than the random Pitch adjustment rate to jump to step7. If the random is less than Pitch adjustment rate for the conditions by select a value from step 5 minimal cost as shown in Figure 24.

1	2	3	4
---	---	---	---

Figure 24 Array of calculated for minimum cost in step 5

Figure 25 is assumed that the array at the lowest cost. Next to a random value to assume that the random number will be 2.

1	2	3	4
2	1	3	4
1	2	4	3

Figure 25 Array of alternating left to right through the pitch adjustment rate

Step 7-9 : The array shown in Figure 25. This combined with the array caused by harmony size in Figure 23 then sort. Then cut out the best array of Harmony size was specified in the equal 3, so here are the best array which only 3 per 1 iteration.

Step 10 : Exit at the first iteration.

4.2 Find the optimal parameters by statistical analysis.

Designed in this research will use the design of trials of real factory 3 levels is high level, Medium level and low level with 3 variables is

- Number of iterations (NOI) /Harmony size (HS)
- Harmony memory considering rate (HMCR)
- Pitch adjustment rate (PAR)

The details shown in the following Table 4

Table 4 Level factors and parameters for Harmony search algorithm

Factors	Level Factors		
	Low	Medium	High
Number of iterations (NOI) / Harmony size (HS)	5/20	10/10	20/5
Harmony memory considering rate (HMCR)	70	80	90
Pitch adjustment rate (PAR)	15	30	45

In the experimental design for how the Harmony search algorithm. We will design this experiment to determine the optimal parameters for distillation sequences and heat-integrated distillation sequences. In our example, all problems will be studied six case studies. By each of the second cycle will be repeated, so the number of results is 81 order of each size of the problem in that the harmony is shown in Appendix A. The analysis we will use the software package Minitab V.14 is shown in Figure 26.

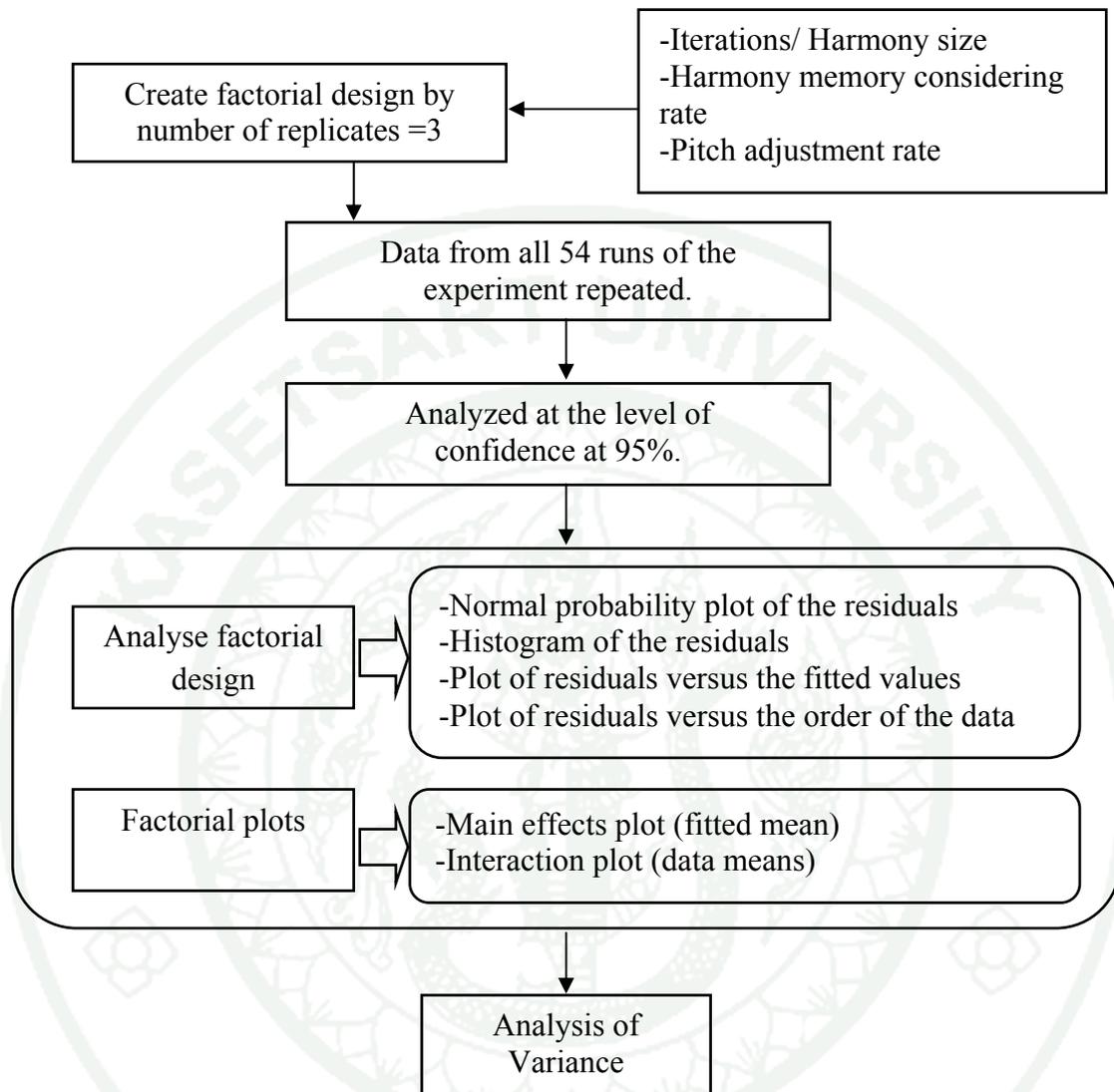


Figure 26 Analysis of variance of Harmony search algorithm

5. Comparison optimal technical between Ant colony algorithm and Harmony search algorithm and with alternative of proposed

After the optimal parameters of the Ant colony algorithm and Harmony search algorithm using Microsoft Visual Studio 2007 for configuration to minimize cost (\$), including analysis by heat integration and without heat integration. Each case study will compare and with alternative of proposed.

6. Steady-state processes of all case study

Radfrac model is used as the distillation column. Number of stages, condenser and reboiler type, valid phase, distillate rate, reflux ratio, feed stage and the operating pressure for each column must be specified. Where, column operating pressure is obtained from optimal results. The rests is obtained from the simulation by using short cut model DSTWU by input light key and heavy key components for each distillation task. Then the simulation for each configuration is performed in ASPEN PLUS simulator. The desire purity of product is 98%. When focus on energy consumption, the comparison between process with and without heat integration is done by comparing the hot utility usage of columns reboiler.

RESULT AND DISCUSSION

Four case study were studied in this work. The systems were modeled using the short-cut method in the process simulator. All the possible sequences for case study 1-4 were costed without and with heat integration and the set of “optimal” sequences was identified. Values from the literature for the costs of the sequences and also whether or not a particular sequence has been classified as optimal are noted.

The method developed in this work was applied to each of the four problems. The sequences identified by this method as being competitive are compared with the comprehensive list of costed values and with available literature results. The competitive sequences suggested by other meta-heuristic methods are compared with sequences selected by this method.

1. Case study 1

Component	n-Hexane	Benzene	n-Heptane
Mole fraction	0.8	0.1	0.1

2. Case study 2

Component	iso-Butane	n-Butane	iso-Pentane	n-Pentane
Mole fraction	0.157	0.263	0.212	0.368

3. Case study 3

Component	Propane	iso-Butane	n-Butane
Mole fraction	0.05	0.15	0.25
Component	iso-Pentane	n-Pentane	
Mole fraction	0.2	0.35	

4. Case study 4

Component	iso-Butane	n-Butane	neo-Pentane	n-Pentane
Mole fraction	0.05	0.05	0.10	0.15
Component	n-Hexane	n-Heptane		
Mole fraction	0.25	0.40		

1. Case study 1

This is a three-component separation problem taken from An Wei zhong (2009) and used to demonstrate the solution of a small example. The problem data is given in Table 5.

Table 5 Components and mole fractions of the feed of case study 1

Key Component	Component	Formula	Mole fraction	Boiling Temperature
A	n-Hexane	C ₆ H ₁₄ -1	0.80	341.88 K
B	Benzene	C ₆ H ₆	0.10	353.00 K
C	n-Heptane	C ₇ H ₁₆ -1	0.10	371.58 K

Data simulation for process

- Property method & models

Process type : Common

Base method : BK 10

- Feed state variables

Feed flow rate : 396 kmol/h

Temperature : 300 K

Pressure : 1 atm

- Heat transfer parameters

Overall heat transfer : 300 Watt/m²K

Log mean temperature : 10 K

Cost equations for heat exchanger network : $2143A^{0.514}$

Table 6 The best run of distillation sequences for case study 1 using low-level parameters (3-DS)

K	Distillation sequences (DS)			
	Ant colony algorithm		Harmony search algorithm	
	Code Sequences (s_k)	Minimum Cost (\$)	Code Sequences (s_k)	Minimum Cost (\$)
1	{2,1}	62,730,109	{2,1}	62,730,109
2	{2,1}	62,730,109	{2,1}	62,730,109
3	{2,1}	62,730,109	{2,1}	62,730,109
4	{2,1}	62,730,109	{2,1}	62,730,109
5	{2,1}	62,730,109	{2,1}	62,730,109
6	{2,1}	62,730,109	{2,1}	62,730,109
7	{2,1}	62,730,109	{2,1}	62,730,109
8	{2,1}	62,730,109	{2,1}	62,730,109
9	{2,1}	62,730,109	{2,1}	62,730,109
10	{2,1}	62,730,109	{2,1}	62,730,109
11	{2,1}	62,730,109	{2,1}	62,730,109
12	{2,1}	62,730,109	{2,1}	62,730,109
13	{2,1}	62,730,109	{2,1}	62,730,109
14	{2,1}	62,730,109	{2,1}	62,730,109
15	{2,1}	62,730,109	{2,1}	62,730,109
16	{2,1}	62,730,109	{2,1}	62,730,109
17	{2,1}	62,730,109	{2,1}	62,730,109
18	{2,1}	62,730,109	{2,1}	62,730,109
19	{2,1}	62,730,109	{2,1}	62,730,109
20	{2,1}	62,730,109	{2,1}	62,730,109
Best cost(\$)	{2,1}	62,730,109	{2,1}	62,730,109
Average		62,730,109		62,730,109
St.Dev		0.0000		0.0000

Table 6 shows results of the run to solve distillation sequences (DS) using low-level parameters of the Ant colony algorithm and the Harmony search algorithm is the same value is code sequences {2,1}, cost is 62,730,109 USD/year.

Table 7 The best run of distillation sequences for case study 1 using medium-level parameters (3-DS)

K	Distillation sequences (DS)			
	Ant colony algorithm		Harmony search algorithm	
	Code Sequences (s_k)	Minimum Cost (\$)	Code Sequences (s_k)	Minimum Cost (\$)
1	{2,1}	62,730,109	{2,1}	62,730,109
2	{2,1}	62,730,109	{2,1}	62,730,109
3	{2,1}	62,730,109	{2,1}	62,730,109
4	{2,1}	62,730,109	{2,1}	62,730,109
5	{2,1}	62,730,109	{2,1}	62,730,109
6	{2,1}	62,730,109	{2,1}	62,730,109
7	{2,1}	62,730,109	{2,1}	62,730,109
8	{2,1}	62,730,109	{2,1}	62,730,109
9	{2,1}	62,730,109	{2,1}	62,730,109
10	{2,1}	62,730,109	{2,1}	62,730,109
11	{2,1}	62,730,109	{2,1}	62,730,109
12	{2,1}	62,730,109	{2,1}	62,730,109
13	{2,1}	62,730,109	{2,1}	62,730,109
14	{2,1}	62,730,109	{2,1}	62,730,109
15	{2,1}	62,730,109	{2,1}	62,730,109
16	{2,1}	62,730,109	{2,1}	62,730,109
17	{2,1}	62,730,109	{2,1}	62,730,109
18	{2,1}	62,730,109	{2,1}	62,730,109
19	{2,1}	62,730,109	{2,1}	62,730,109
20	{2,1}	62,730,109	{2,1}	62,730,109
Best cost(\$)	{2,1}	62,730,109	{2,1}	62,730,109
Average		62,730,109		62,730,109
St.Dev		0.0000		0.0000

Table 7 shows results of the run to solve distillation sequences (DS) using medium-level parameters of the Ant colony algorithm and the Harmony search algorithm is the same value is code sequences {2,1}, cost is 62,730,109 USD/year.

Table 8 The best run of distillation sequences for case study 1 using high-level parameters (3-DS)

K	Distillation sequences (DS)			
	Ant colony algorithm		Harmony search algorithm	
	Code Sequences (s_k)	Minimum Cost (\$)	Code Sequences (s_k)	Minimum Cost (\$)
1	{2,1}	62,730,109	{2,1}	62,730,109
2	{2,1}	62,730,109	{2,1}	62,730,109
3	{2,1}	62,730,109	{2,1}	62,730,109
4	{2,1}	62,730,109	{2,1}	62,730,109
5	{2,1}	62,730,109	{2,1}	62,730,109
6	{2,1}	62,730,109	{2,1}	62,730,109
7	{2,1}	62,730,109	{2,1}	62,730,109
8	{2,1}	62,730,109	{2,1}	62,730,109
9	{2,1}	62,730,109	{2,1}	62,730,109
10	{2,1}	62,730,109	{2,1}	62,730,109
11	{2,1}	62,730,109	{2,1}	62,730,109
12	{2,1}	62,730,109	{2,1}	62,730,109
13	{2,1}	62,730,109	{2,1}	62,730,109
14	{2,1}	62,730,109	{2,1}	62,730,109
15	{2,1}	62,730,109	{2,1}	62,730,109
16	{2,1}	62,730,109	{2,1}	62,730,109
17	{2,1}	62,730,109	{2,1}	62,730,109
18	{2,1}	62,730,109	{2,1}	62,730,109
19	{2,1}	62,730,109	{2,1}	62,730,109
20	{2,1}	62,730,109	{2,1}	62,730,109
Best cost(\$)	{2,1}	62,730,109	{2,1}	62,730,109
Average		62,730,109		62,730,109
St.Dev		0.0000		0.0000

Table 8 shows results of the run to solve distillation sequences (DS) using high-level parameters of the Ant colony algorithm and the Harmony search algorithm is the same value is code sequences {2,1}, cost is 62,730,109 USD/year.

Table 9 The best run of heat-integrated distillation sequences for case study 1 using low- level parameters (3-HIDS)

K	Heat-integration distillation sequences (HIDS)					
	Ant colony algorithm			Harmony search algorithm		
	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)
1	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
2	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
3	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
4	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
5	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
6	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
7	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
8	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
9	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
10	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
11	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
12	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
13	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
14	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
15	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
16	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
17	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
18	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
19	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
20	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
Best cost(\$)	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
Average			62,618,957			62,618,957
St.Dev			0.0000			0.0000

Table 9 shows results of the run to solve heat-integrated distillation sequences (HIDS) using low-level parameters of the Ant colony algorithm and the Harmony search algorithm is the same value is code sequences {2,1} and code match condenser-reboiler {2,1}, cost is 62,618,957 USD/year.

Table 10 The best run of heat-integrated distillation sequences for case study 1 using medium-level parameters (3-HIDS)

K	Heat-integration distillation sequences (HIDS)					
	Ant colony algorithm			Harmony search algorithm		
	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)
1	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
2	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
3	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
4	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
5	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
6	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
7	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
8	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
9	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
10	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
11	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
12	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
13	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
14	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
15	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
16	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
17	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
18	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
19	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
20	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
Best cost(\$)	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
Average			62,618,957			62,618,957
St.Dev			0.0000			0.0000

Table 10 shows results of the run to solve heat-integrated distillation sequences (HIDS) using medium-level parameters of the Ant colony algorithm and the Harmony search algorithm is the same value is code sequences {2,1} and code match condenser-reboiler {2,1}, cost is 62,618,957 USD/year.

Table 11 The best run of heat-integrated distillation sequences for case study 1 using high-level parameters (3-HIDS)

K	Heat-integration distillation sequences (HIDS)					
	Ant colony algorithm			Harmony search algorithm		
	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)
1	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
2	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
3	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
4	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
5	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
6	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
7	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
8	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
9	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
10	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
11	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
12	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
13	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
14	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
15	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
16	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
17	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
18	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
19	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
20	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
Best cost(\$)	{2,1}	{2,1}	62,618,957	{2,1}	{2,1}	62,618,957
Average			62,618,957			62,618,957
St.Dev			0.0000			0.0000

Table 11 shows results of the run to solve heat-integrated distillation sequences (HIDS) using low-level parameters of the Ant colony algorithm and the Harmony search algorithm is the same value is code sequences {2,1} and code match condenser-reboiler {2,1}, cost is 62,618,957 USD/year.

Table 12 The selected answers and costs of each configuration for case study 1 using low-level parameters

Configurations			Distillation Sequences				Heat-integrated distillation sequences					
#	Column 1	Column 2	AC	Cost in (\$10,000)	HS	Cost in (\$10,000)	AC	Cost in (\$10,000)	Code Match	HS	Cost in (\$10,000)	Code Match
1	A/BC	B/C	18	6,866	55	6,866	14	6,881	{2,1}	58	6,881	{2,1}
2	AB/C	A/B	82	6,273*	45	6,273*	86	6,261*	{2,1}	42	6,261*	{2,1}

Table 13 The selected answers and costs of each configuration for case study 1 using medium-level parameters

Configurations			Distillation Sequences				Heat-integrated distillation sequences					
#	Column 1	Column 2	AC	Cost in (\$10,000)	HS	Cost in (\$10,000)	AC	Cost in (\$10,000)	Code Match	HS	Cost in (\$10,000)	Code Match
1	A/BC	B/C	15	6,866	52	6,866	17	6,881	{2,1}	51	6,881	{2,1}
2	AB/C	A/B	85	6,273*	48	6,273*	83	6,261*	{2,1}	49	6,261*	{2,1}

Table 14 The selected answers and costs of each configuration for case study 1 using high-level parameters

Configurations			Distillation Sequences				Heat-integrated distillation sequences					
#	Column 1	Column 2	AC	Cost in (\$10,000)	HS	Cost in (\$10,000)	AC	Cost in (\$10,000)	Code Match	HS	Cost in (\$10,000)	Code Match
1	A/BC	B/C	15	6,866	61	6,866	20	6,881	{2,1}	59	6,881	{2,1}
2	AB/C	A/B	85	6,273*	39	6,273*	80	6,261*	{2,1}	41	6,261*	{2,1}

* Best investment costs (USD/year)

Table 12 shows the selection by the answers of the two methods by using:

Ant colony algorithm for solving the problem of case study 1 (DS) using low-level parameters. Select the configuration number 2 which was selected the most. And, for solving the problem of case study 1 (HIDS). Select the configuration number 2 which was selected the most.

Harmony search algorithm for solving the problem of case study 1 (DS) using low-level parameters. Select the configuration number 1 which was selected the most. And, for solving the problem of case study 1 (HIDS). Select the configuration number 1 which was selected the most.

Table 13 shows the selection by the answers of the two methods by using:

Ant colony algorithm for solving the problem of case study 1 (DS) using medium-level parameters. Select the configuration number 2 which was selected the most. And, for solving the problem of case study 1 (HIDS). Select the configuration number 2 which was selected the most.

Harmony search algorithm for solving the problem of case study 1 (DS) using medium-level parameters. Select the configuration number 1 which was selected the most. And, for solving the problem of case study 1 (HIDS). Select the configuration number 1 which was selected the most.

Table 14 shows the selection by the answers of the two methods by using:

Ant colony algorithm for solving the problem of case study 1 (DS) using high-level parameters. Select the configuration number 2 which was selected the most. And, for solving the problem of case study 1 (HIDS). Select the configuration number 2 which was selected the most.

Harmony search algorithm for solving the problem of case study 1 (DS) using high-level parameters. Select the configuration number 1 which was selected the most. And, for solving the problem of case study 1 (HIDS). Select the configuration number 1 which was selected the most.

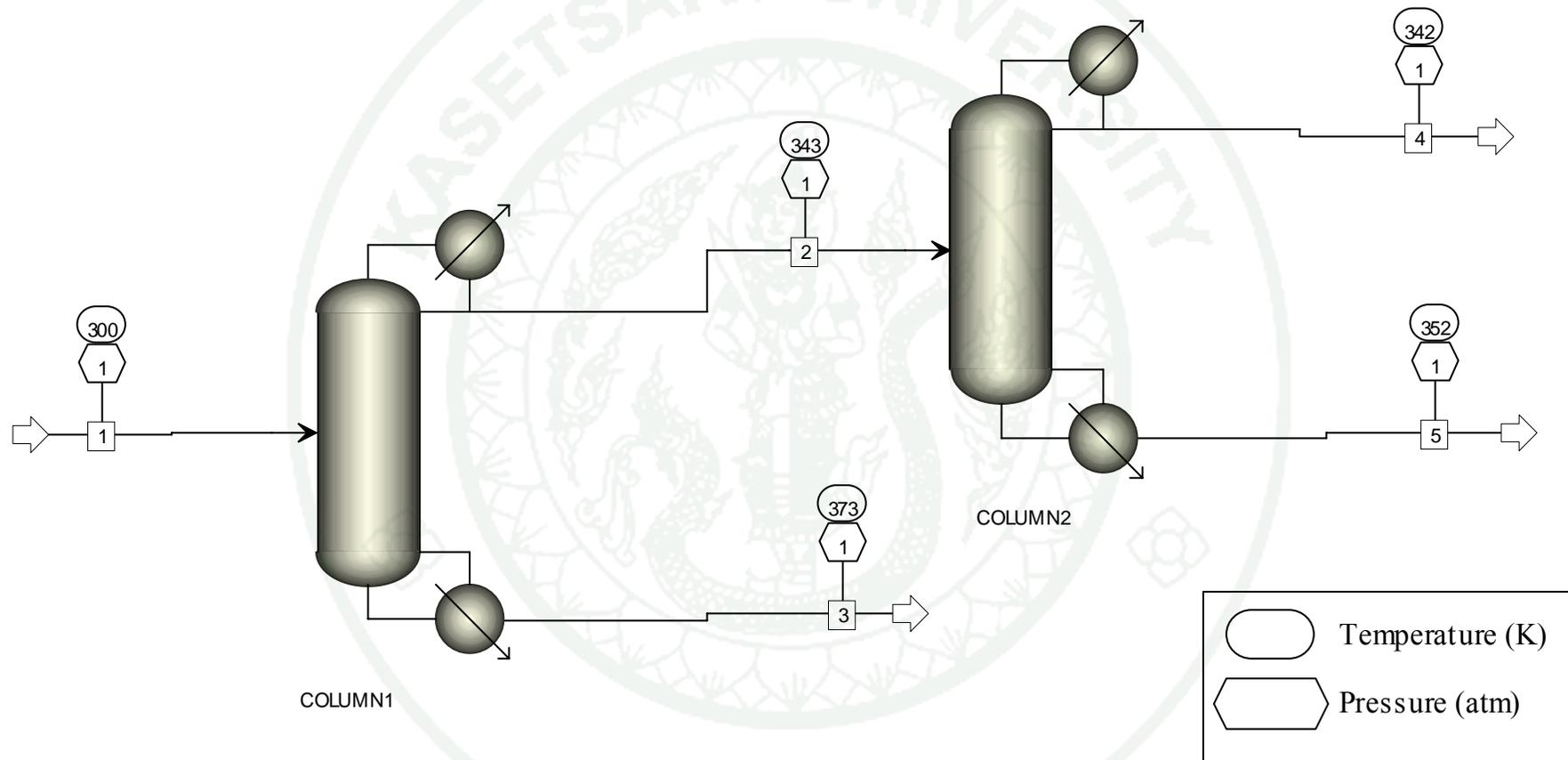


Figure 27 The optimal configuration number 1- Optimal of distillation sequences(without heat-integrated) for case study1,
 Cost=62,730,109 USD/year

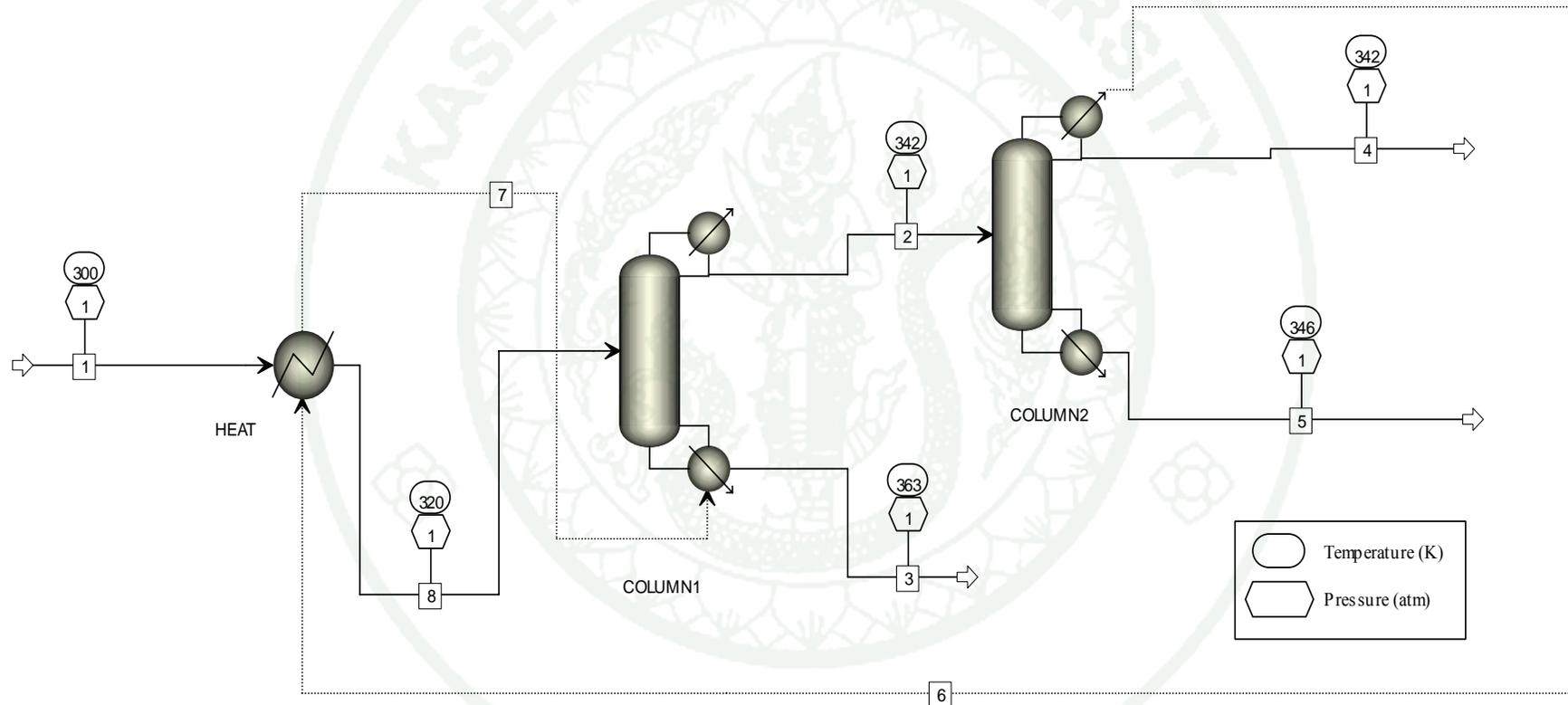


Figure 28 The optimal Configuration number 2- Optimal of heat-integrated distillation sequences(with heat-integrated) for case study1,
 Cost=62,618,957 USD/year

In configuration number 1 (Figure 27), process distillation sequences synthesis section is the optimal sequence solution. There are two distillation columns in this sequence, which is column 1, and column 2,. First, stream 1 is fed to column 1 to be separated n-Hexane and Benzene as a distillate intermediate stream (stream 2) and bottom product stream (stream 3) is n-Heptane. Stream 2 is become a feed stream of column 2 in order to separate benzene out as a bottom product stream (stream 5). This column separate n-Hexane as a distillate product stream (stream 4). These two columns are Radfrac model. The operating condition of each column is shown in Table 15. The simulation result for configuration number 1 is shown in Table 16. All simulation using DSTWU result is shown in Appendix C1.

Table 15 Operating condition of each column in the optimal heat integrated distillation sequences for case study 1

Operating condition	Column 1	Column 2
Number of stages	32	59
Feed stage	17	29
Distillate to feed ratio (kmol/h)	356.27	315.84
Reflux ratio	1.092	3.87
Condenser heat duty (GJ/h)	22.02	45.06
Reboiler heat duty (GJ/h)	25.54	45.15
Condenser type	Total	Total
Reboiler type	Kettle	Kettle

Table 16 Stream result of steady-state for case study 1

Component	Mole flowrate (Kmol/h) (Steam 1)	Separated		%Purity
		Stream	Separated (Kmol/h)	
(A) n-Hexane	316.80	4	310.97	99.45%
(B) Benzene	39.60	5	38.48	97.02%
(C) n-Heptane	39.60	3	39.35	99.37%

For configuration number 2 (Figure 28), sources and sinks of each heat integrate are showed in Table 17. The comparison of cost between process with and without heat integration is showed in Table 18. And the comparative study using various methods of case study1 are showed in Table 19.

Table 17 Source and sink of each heat integration match for configuration number 2 of case study1

Heat stream	Source-Sink
6-7	Column 2 - Column 1

Table 18 The comparison of costs between process with and without heat integration of each column in the optimal configuration of case study 1

Configuration	Best cost (\$)	
	With heat integration	Without heat integration
The optimal configuration	62,618,957	62,730,109
Reduce the costs (%)	0.1772%	

Table 19 Comparative study using various methods of case study 1

Method	Ant colony algorithm	Harmony search algorithm	Simulated annealing	General Algebraic
Authors	This work	This work	zhong	Floudast and Paules
Optimal configuration for distillation sequences	$S_k = \{2,1\}$	$S_k = \{2,1\}$	$S_k = \{2,1\}$	$S_k = \{2,1\}$
The total annual cost (\$) (without heat-integration)	62,730,109	62,730,109	-	-
Optimal configuration for heat-integrated distillation sequences	$S_k = \{2,1\}$ $H_k = \{2,1\}$			
The total annual cost (\$) (with heat-integration)	62,618,957	62,618,957	-	-

2. Case study 2

This is a four-component mixture separation problem solved firstly by Floudast and Paules (1988). The problem data is given in Table 20. The costs of the 5 possible sequences without and with heat-integration are shown in Table 25.

Table 20 Components and mole fractions of the feed of case study 2

Key Component	Component	Formula	Mole fraction	Boiling Temperature
A	iso-Butane	C ₄ H ₁₀ -2	0.157	261.0 K
B	n-Butane	C ₄ H ₁₀ -1	0.263	272.6 K
C	iso-Pentane	C ₅ H ₁₂ -2	0.212	300.9 K
D	n-Pentane	C ₅ H ₁₂ -1	0.368	308.0 K

Data simulation for process

- Property method & models

Process type : Common
Base method : CHAO-SEA

- Feed state variables

Feed flow rate : 865 kmol/h
Temperature : 280 K
Pressure : 1 atm

- Heat transfer parameters

Overall heat transfer : 800 Watt/m²K
Log mean temperature : 10 K
Cost equations for heat exchanger network : $2143A^{0.514}$

2.1 Ant colony algorithm for distillation sequences (DS) (without heat-integrated distillation sequences)

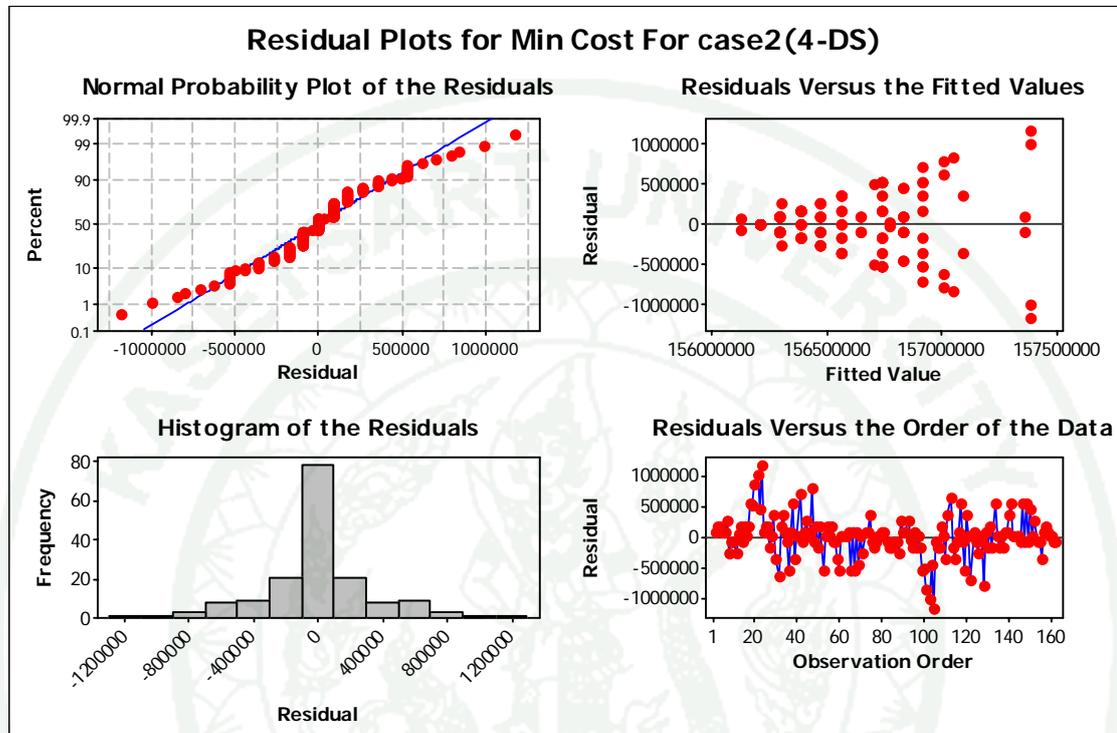


Figure 29 Hypothesis testing of Ant colony algorithm for case study 2 (4-DS)

Figure 29 show of testing the hypothesis of the Ant colony algorithm for case study 2 (4-DS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For case2(4-DS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/Ants	2	9.56793E+11	9.56793E+11	4.78396E+11
Weight of pheromone	2	5.28393E+11	5.28393E+11	2.64196E+11
Weight of heuristic information	2	1.62987E+12	1.62987E+12	8.14936E+11
Evaporation rate	2	22888623085	22888623085	11444311543
Source		F	P	
Iteration/Ants		2.14	0.124	
Weight of pheromone		1.18	0.312	
Weight of heuristic information		3.64	0.031	
Evaporation rate		0.05	0.950	

Figure 30 Analysis of variance of the Ant colony algorithm for case study 2 (4-DS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 31 was iteration / ants (I/A) to the P-value = 0.124, weight of pheromone (WOP) to the P-value = 0.312, weight of heuristic information (WOH) for the P-value = 0.031 and evaporation rate (ER) to the P-value. = 0.950 shows that the factors is weight of heuristic information (WOH) as the impact Ant colony algorithm to find the answer for 4-DS which is determined by the P-value is less than 0.05. In contrast, three factors have no effect on finding answers to the iteration / ants (I/A) , weight of pheromone (WOP) and weight of pheromone (WOP), because the P-value is greater than 0.5.

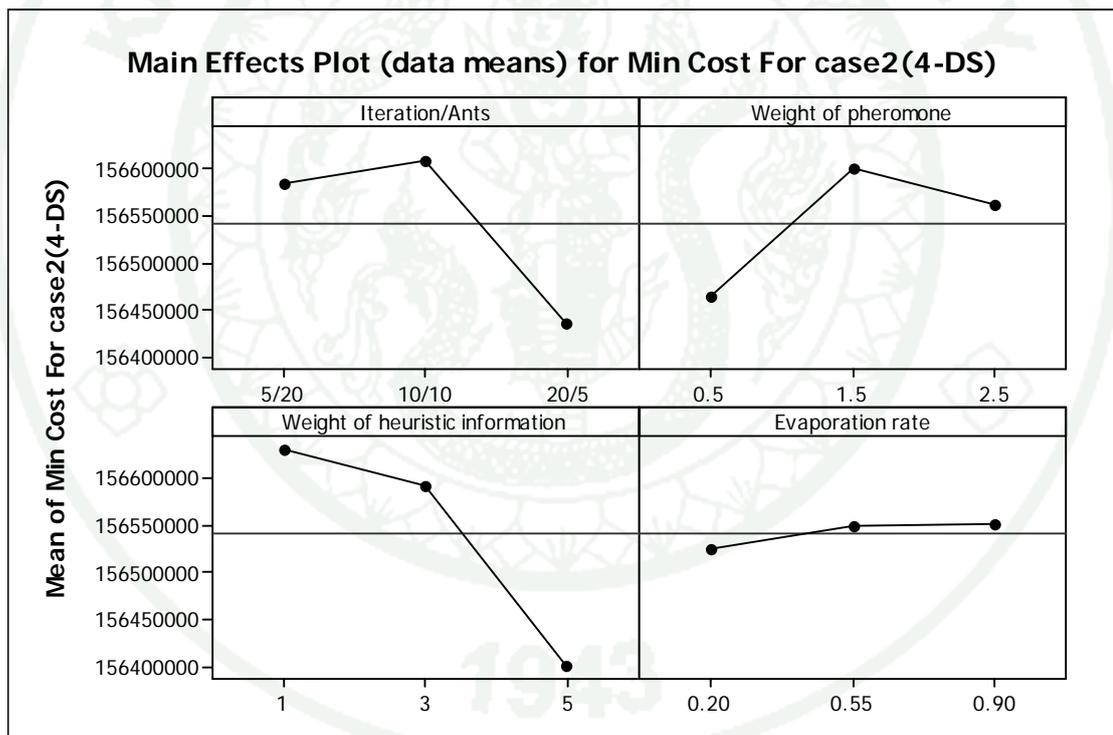


Figure 31 Impact that occurs on the main factors of Ant colony algorithm for case study 2 (4-DS)

Main effects plot caused major problems of case study 2 (4-DS) for the Ant colony algorithm was the iteration / ants (I/A) at 20 / 5, weight of pheromone (WOP) at 0.5, weight of heuristic information (WOH) at 5 and evaporation rate (ER) at 0.20.

All this resulted in answers to the most valuable minimum cost. It can be summarized in Table 21.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 32.

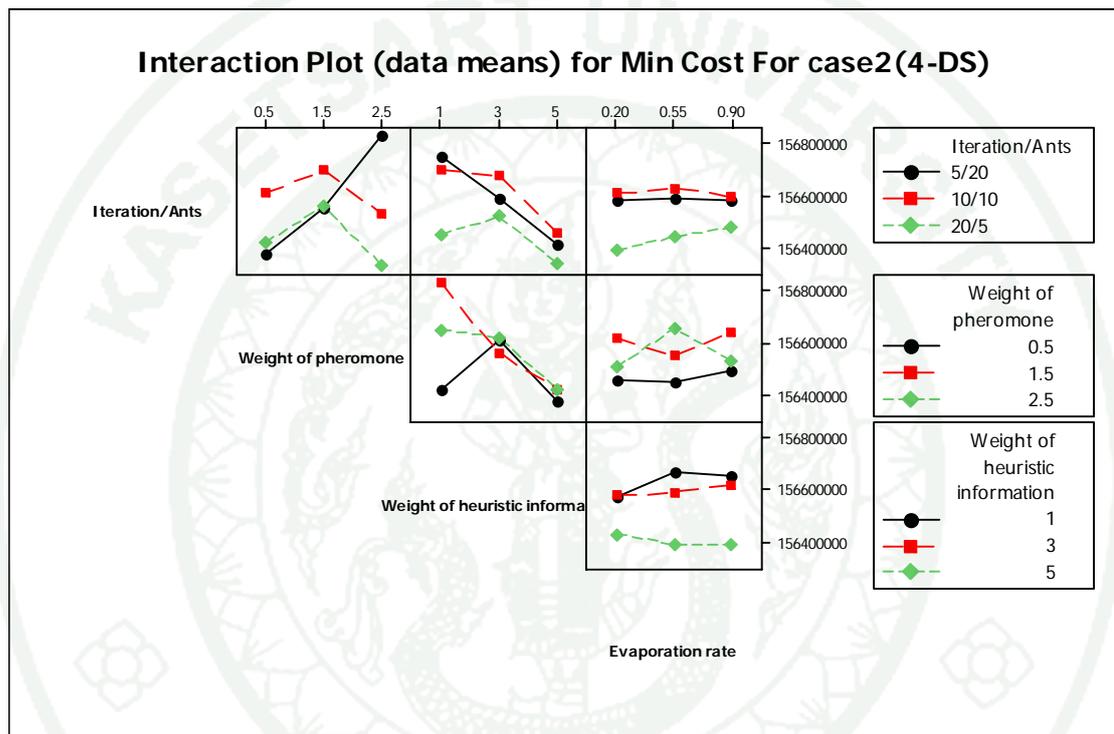


Figure 32 Interaction plot between the Ant colony algorithm for case study 2 (4-DS)

2.2 Ant colony algorithm for heat-integrated distillation sequences (HIDS) (with heat-integrated distillation sequences)

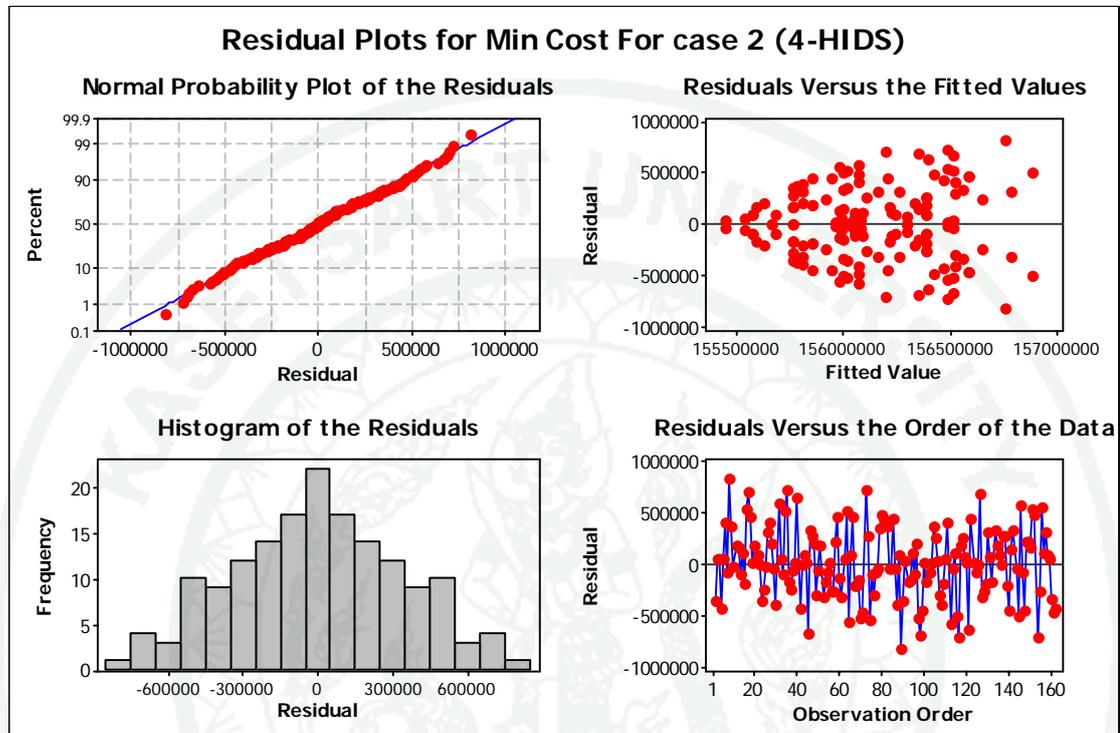


Figure 33 Hypothesis testing of Ant colony algorithm for case study 2 (4-HIDS)

Figure 33 show of testing the hypothesis of the Ant colony algorithm for case study 2 (4-HIDS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For case 2 (4-HIDS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/Ants	2	61911180952	61911180952	30955590476
Weight of pheromone	2	1.96960E+11	1.96960E+11	98480170478
Weight of heuristic information	2	1.64088E+12	1.64088E+12	8.20439E+11
Evaporation rate	2	4.23533E+11	4.23533E+11	2.11767E+11
Source	F	P		
Iteration/Ants	0.13	0.874		
Weight of pheromone	0.43	0.654		
Weight of heuristic information	3.56	0.033		
Evaporation rate	0.92	0.403		

Figure 34 Analysis of variance of the Ant colony algorithm for case study 2 (4-HIDS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 35 was iteration / ant (I/A) to the P-value = 0.874, weight of pheromone (WOP) to the P-value = 0.654, weight of heuristic information (WOH) for the P-value = 0.033 and evaporation rate (ER) to the P-value. = 0.403 shows that the factors is weight of heuristic information (WOH) as the impact Ant colony algorithm to find the answer for 4-HIDS which is determined by the P-value is less than 0.05. In contrast, three factors have no effect on finding answers to the iteration / ant (I/A), weight of pheromone (WOP) and evaporation rate (ER), because the P-value is greater than 0.5.

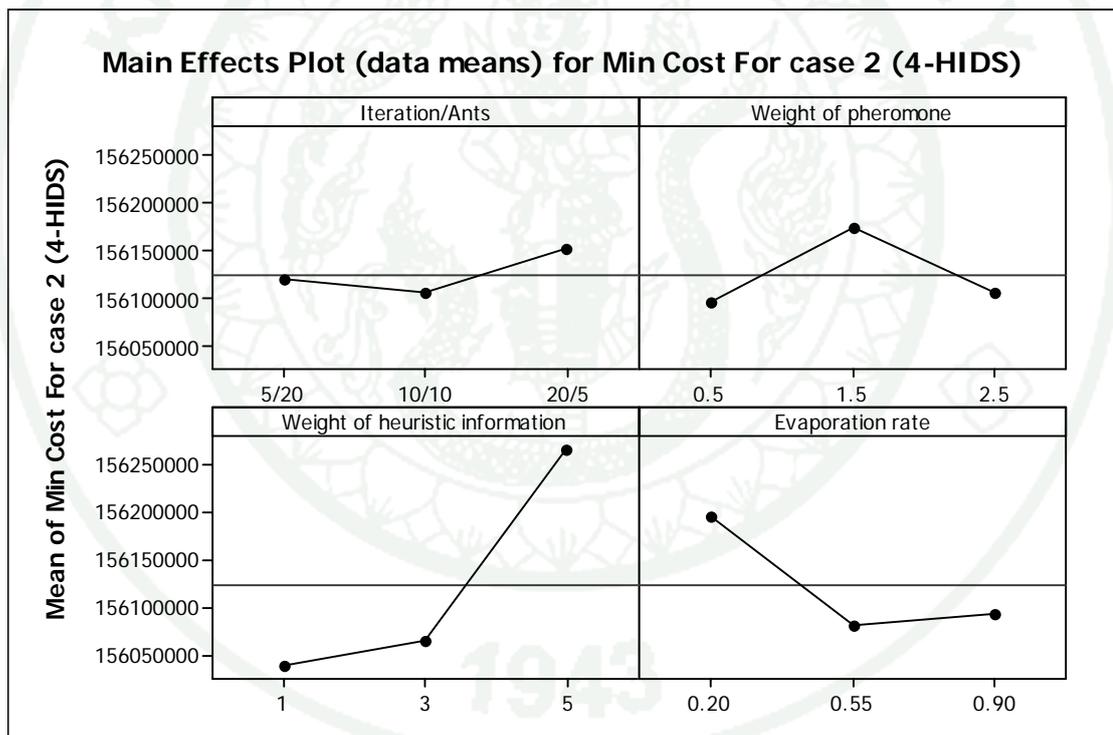


Figure 35 Impact that occurs on the main factors of Ant colony algorithm for case study 2 (4-HIDS)

Main effects plot caused major problems of case study 2 (4-HIDS) for the Ant colony algorithm was the iteration / ant (I/A) at 10 / 10, weight of pheromone (WOP) at 0.5, weight of heuristic information (WOH) at 1 and evaporation rate (ER) at 0.55.

All this resulted in answers to the most valuable minimum cost. It can be summarized in Table 21.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 36.

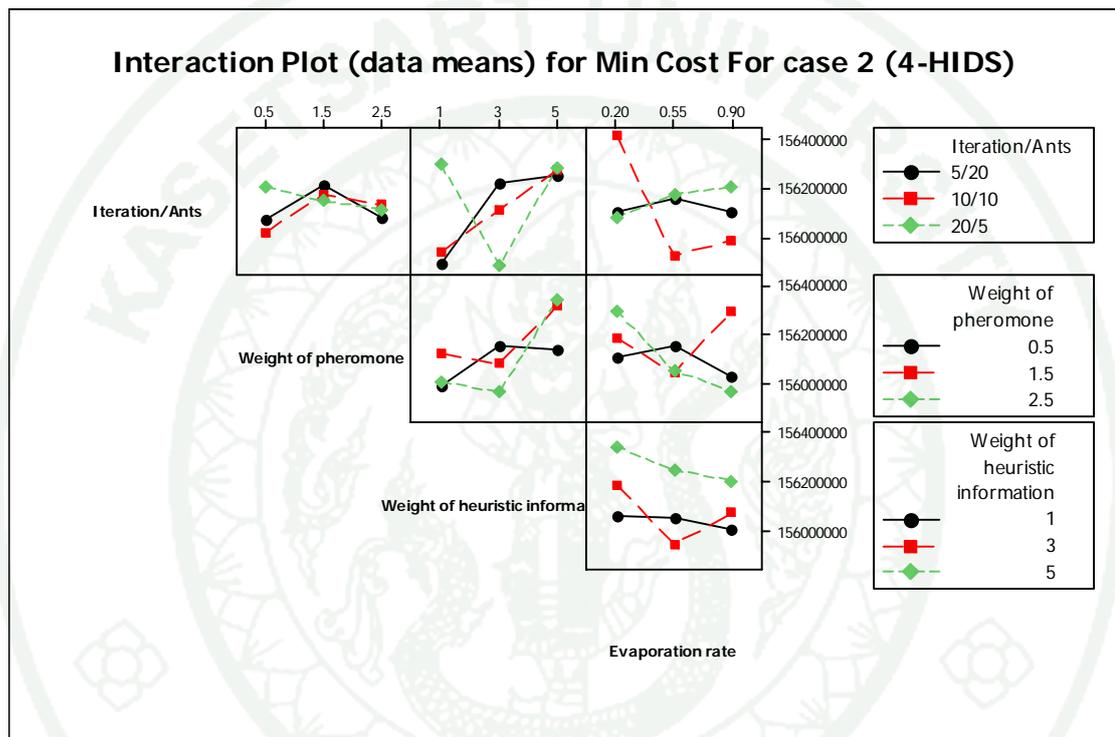


Figure 36 Interaction plot between the Ant colony algorithm for case study 2 (4- HIDS)

2.3 Harmony search algorithm for distillation sequences (DS) (without heat-integrated distillation sequences)

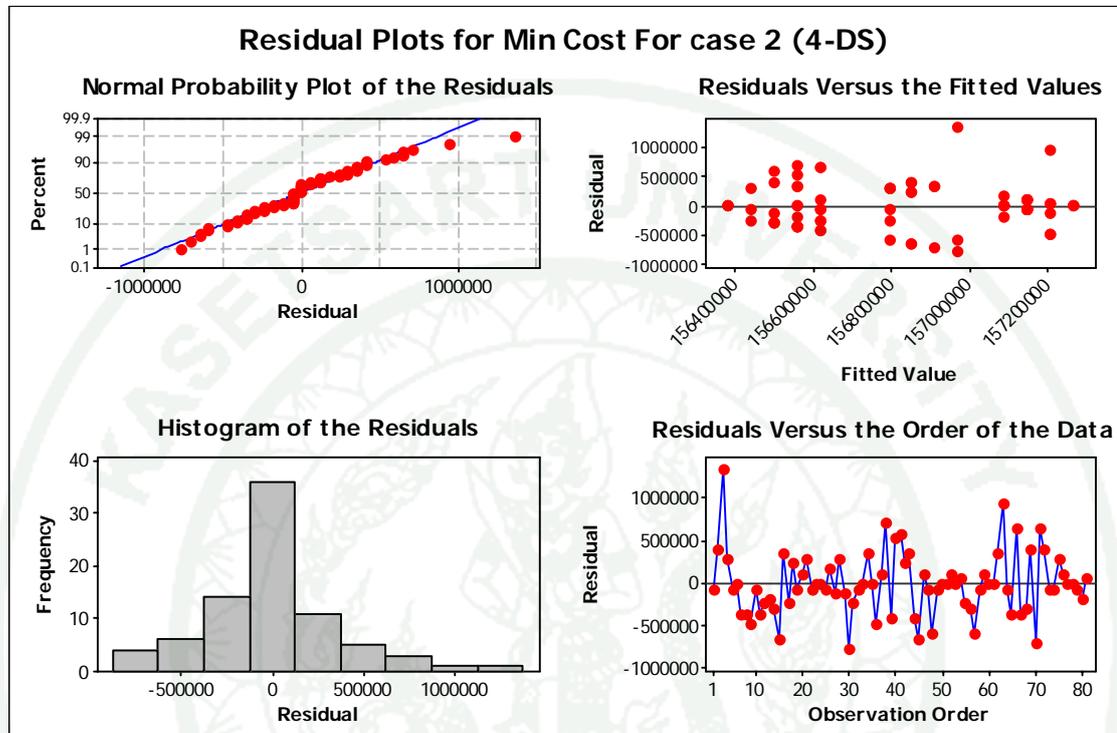


Figure 37 Hypothesis testing of Harmony search algorithm for case study 2 (4-DS)

Figure 37 show of testing the hypothesis of the Harmony search algorithm for case study 2 (4-DS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For case 2 (4-DS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/Harmony size	2	3.15367E+12	3.15367E+12	1.57684E+12
Harmony Memory Considering Rate	2	1.77803E+11	1.77803E+11	88901732636
Pitch Adjustment Rate	2	2.55008E+11	2.55008E+11	1.27504E+11
Source	F	P		
Iteration/Harmony size	7.70	0.001		
Harmony Memory Considering Rate	0.43	0.650		
Pitch Adjustment Rate	0.62	0.540		

Figure 38 Analysis of variance of the Harmony search algorithm for case study 2 (4-DS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 39 was iteration / Harmony size (I/H) to the P-value = 0.001, harmony memory considering rate (HMCR) to the P-value = 0.650, and pitch adjustment rate (PAR) to the P-value. = 0.540 shows that the factors is iteration / harmony size (I/H) as the impact Harmony search algorithm to find the answer for case study 2 (4-DS) which is determined by the P-value is less than 0.05. In contrast, two factors have no effect on finding answers to the harmony memory considering rate (HMCR) and pitch adjustment rate (PAR) , because the P-value is greater than 0.5.

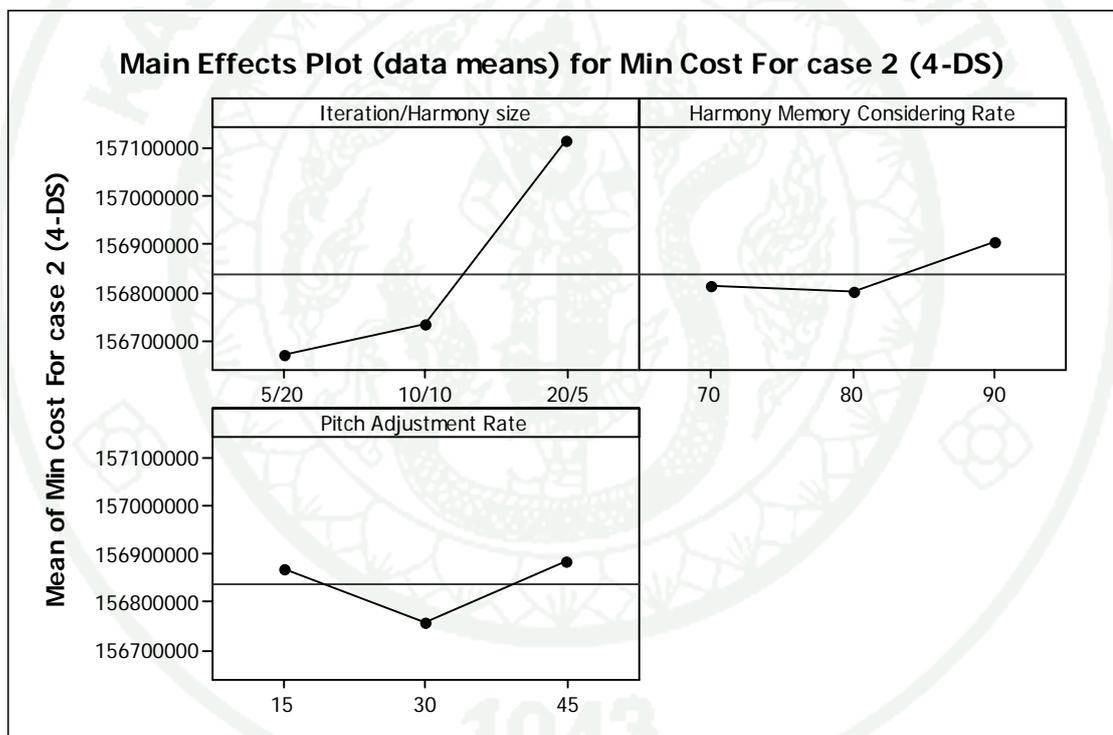


Figure 39 Impact that occurs on the main factors of Harmony search algorithm for case study 2 (4-DS)

Main effects plot caused major problems of case study 2 (4-DS) for the Harmony search algorithm was the iteration / harmony size (I/H) at 5 / 20, harmony memory considering rate (HMCR) at 70, and pitch adjustment rate at 30. All this

resulted in answers to the most valuable minimum cost. It can be summarized in Table 22.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 40.

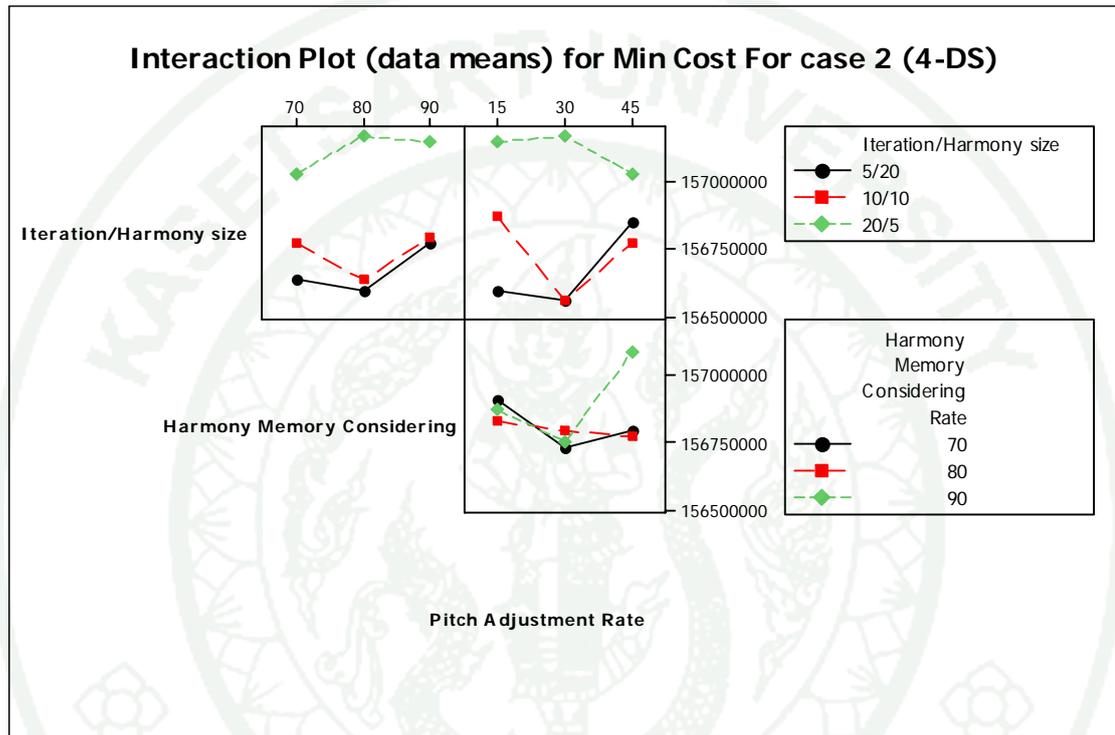


Figure 40 Interaction plot between the Harmony search algorithm for case study 2 (4-DS)

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2.4 Harmony search algorithm for heat-integrated distillation sequences (HIDS) (with heat-integrated distillation sequences)

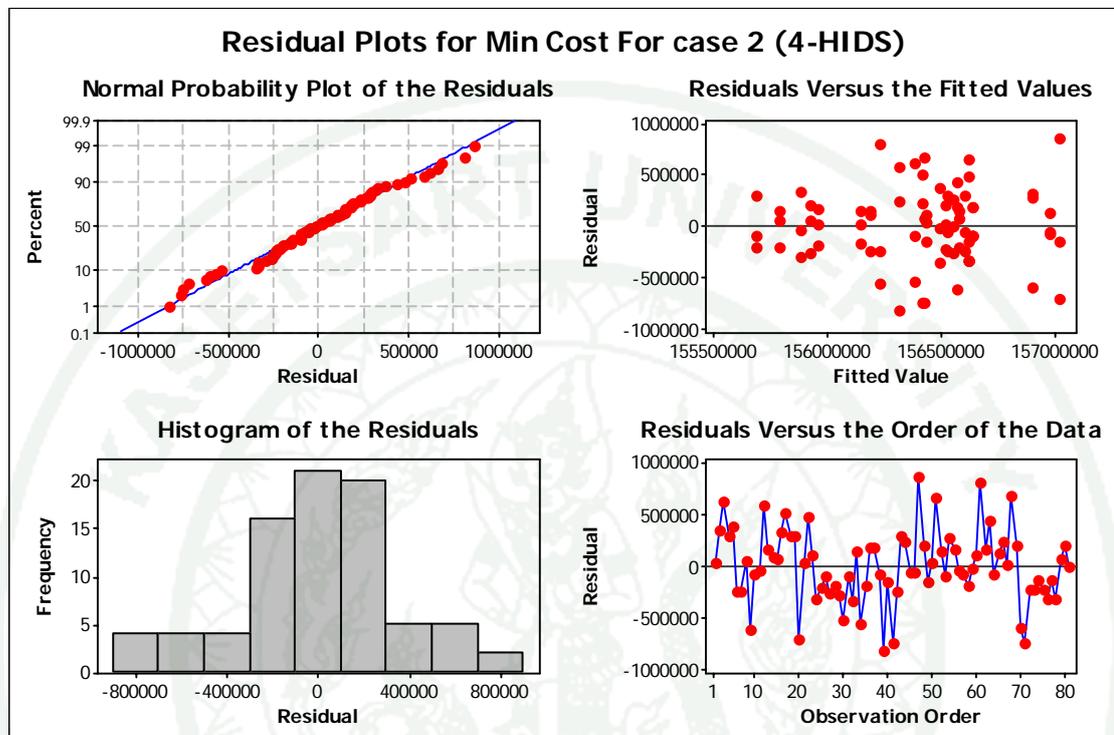


Figure 41 Hypothesis testing of Harmony search algorithm for case study 2 (4-HIDS)

Figure 41 show of testing the hypothesis of the Harmony search algorithm for case study 2 (4-HIDS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For case 2 (4-HIDS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/Harmony size	2	3.38490E+12	3.38490E+12	1.69245E+12
Harmony Memory Considering Rate	2	6.45253E+11	6.45253E+11	3.22627E+11
Pitch Adjustment Rate	2	1.03735E+11	1.03735E+11	51867655240
Source		F	P	
Iteration/Harmony size		9.15	0.000	
Harmony Memory Considering Rate		1.74	0.184	
Pitch Adjustment Rate		0.28	0.756	

Figure 42 Analysis of variance of the Harmony search algorithm for case study 2 (4-HIDS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 43 was iteration / Harmony size (I/H) to the P-value = 0.000, harmony memory considering rate (HMCR) to the P-value = 0.184, and pitch adjustment rate (PAR) to the P-value. = 0.756 shows that the factors is iteration / harmony size (I/H) as the impact Harmony search algorithm to find the answer for 4-HIDS which is determined by the P-value is less than 0.05. In contrast, two factors have no effect on finding answers to the harmony memory considering rate (HMCR) and pitch adjustment rate (PAR) , because the P-value is greater than 0.5.

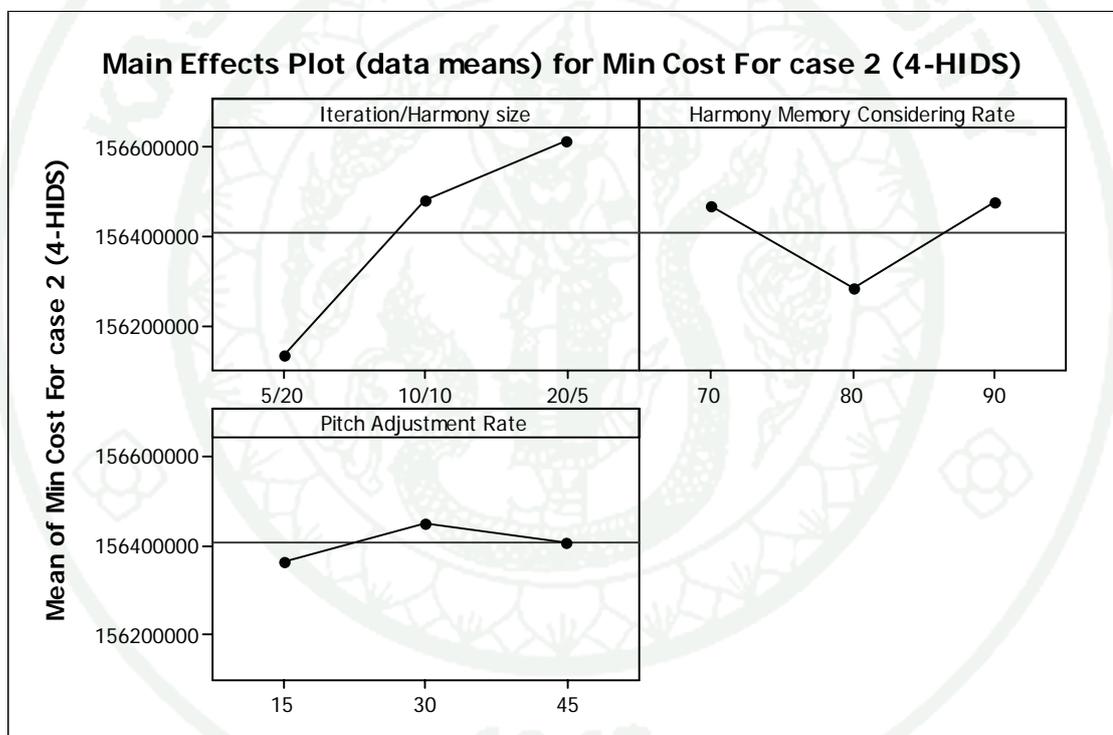


Figure 43 Impact that occurs on the main factors of Harmony search algorithm for case study 2 (4-HIDS)

Main effects plot caused major problems of case study 2 (4-HIDS) for the Harmony search algorithm was the iteration / harmony size (I/H) at 5 / 20, harmony memory considering rate (HMCR) at 80, and pitch adjustment rate at 15. All this

resulted in answers to the most valuable minimum cost. It can be summarized in Table 22.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 44.

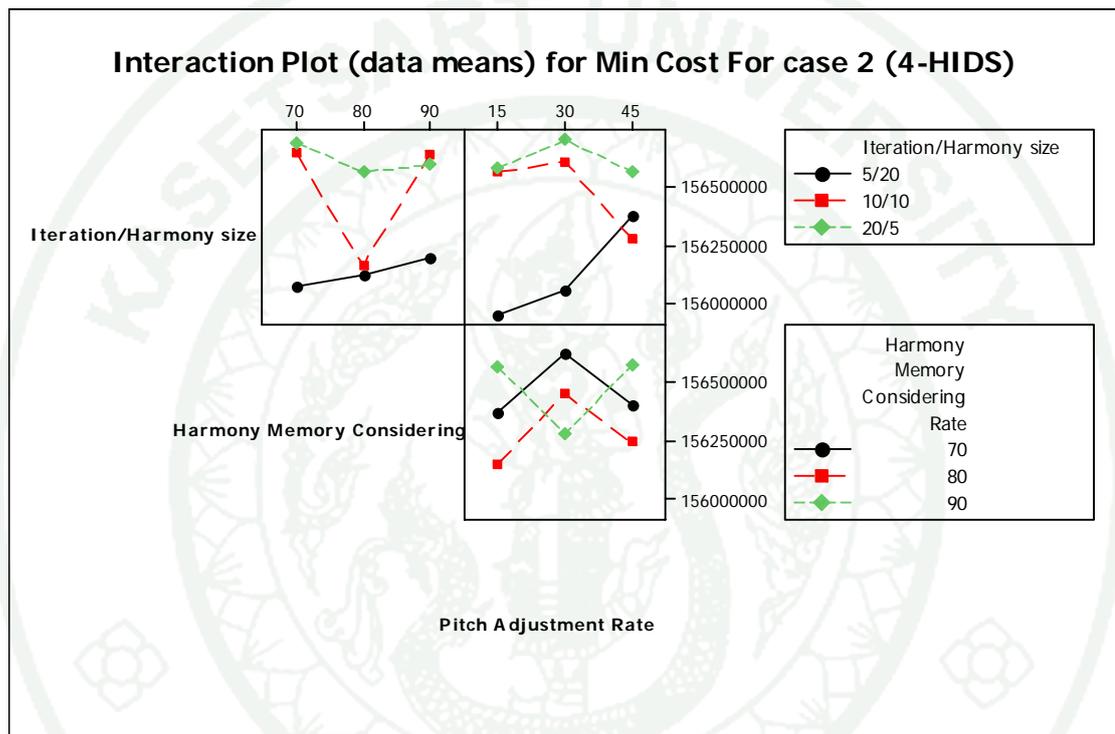


Figure 44 Interaction plot between the Harmony search algorithm for case study 2 (4-HIDS)

2.5 Comparison of results between the two methods and process synthesis.

After these parameters at optimal way Ant colony algorithm are shown in Table 21 and the parameters are the optimal way Harmony search algorithm are shown in Table 22 is important for them each how to enter the program Visual Studio V.8.0 to make. Run each of 20 values are shown in Table 23 and Table 24 of the two processes is to compare the distillation sequences (DS) or without heat-integrated and the heat-integrated distillation sequences (HIDS) or with heat-integrated to find a way to provide the best solution.

Table 21 Optimization of levels and factors of Ant colony algorithm for case study 2

Factors	Distillation sequences (DS)	Heat-integrated distillation sequences (HIDS)
Iteration/Ants (I/A)	20/5 (High)	10/10 (Medium)
Weight of pheromone (WOP)	0.5 (Low)	0.5 (Low)
Weight of heuristic information (WOH)	5 (High)	1 (Low)
Evaporation rate (ER)	0.2 (Low)	0.55 (Medium)

Table 22 Optimization of levels and factors of Harmony search algorithm for case study 2

Factors	Distillation sequences (DS)	Heat-integrated distillation sequences (HIDS)
Iteration/Harmony size (I/H)	5/20 (Low)	5/20 (Low)
Harmony memory considering rate (HMCR)	70 (Low)	80 (Medium)
Pitch adjustment rate (PAR)	30 (Medium)	15 (Low)

Table 23 The best run of distillation sequences for case study 2 (4-DS)

K	Distillation sequences (DS)			
	Ant colony algorithm		Harmony search algorithm	
	Code Sequences (s_k)	Minimum Cost (\$)	Code Sequences (s_k)	Minimum Cost (\$)
1	{2,1,3}	159,274,858	{2,1,3}	159,274,858
2	{2,1,3}	159,274,858	{2,1,3}	159,274,858
3	{2,1,3}	159,274,858	{2,1,3}	159,274,858
4	{2,1,3}	159,274,858	{2,1,3}	159,274,858
5	{2,1,3}	159,274,858	{2,1,3}	159,274,858
6	{2,1,3}	159,274,858	{2,1,3}	159,274,858
7	{2,1,3}	159,274,858	{2,1,3}	159,274,858
8	{2,1,3}	159,274,858	{2,1,3}	159,274,858
9	{2,1,3}	159,274,858	{2,1,3}	159,274,858
10	{2,1,3}	159,274,858	{2,1,3}	159,274,858
11	{2,1,3}	159,274,858	{2,1,3}	159,274,858
12	{2,1,3}	159,274,858	{2,1,3}	159,274,858
13	{2,1,3}	159,274,858	{2,1,3}	159,274,858
14	{2,1,3}	159,274,858	{2,1,3}	159,274,858
15	{2,1,3}	159,274,858	{2,1,3}	159,274,858
16	{2,1,3}	159,274,858	{2,1,3}	159,274,858
17	{2,1,3}	159,274,858	{2,1,3}	159,274,858
18	{2,1,3}	159,274,858	{2,1,3}	159,274,858
19	{2,1,3}	159,274,858	{2,1,3}	159,274,858
20	{2,1,3}	159,274,858	{2,1,3}	159,274,858
Best cost(\$)	{2,1,3}	159,274,858	{2,1,3}	159,274,858
Average		159,274,858		159,274,858
St.Dev		0.0000		0.0000

Table 23 concluded that a solution distillation sequences (DS), using Ant colony algorithm and Harmony search algorithm gives the same run 20 times by optimal distillation sequences is {2,1,3} or AB / CD, A / B, C / D with investment cost is 159, 274,858 USD/ year.

Table 24 The best run of heat-integrated distillation sequences for case study 2 (4-HIDS)

K	Heat-integration distillation sequences (HIDS)					
	Ant colony algorithm			Harmony search algorithm		
	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)
1	{2,1,3}	{3,1}	159,049,959	{2,1,3}	{3,2}	158,545,348
2	{2,1,3}	{3,2}	158,545,348	{2,1,3}	{3,2}	158,545,348
3	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{3,2}	158,545,348
4	{2,1,3}	{3,2}	158,545,348	{2,1,3}	{1,2}	158,467,709
5	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
6	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
7	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
8	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
9	{2,1,3}	{1,3}	159,009,357	{2,1,3}	{1,2}	158,467,709
10	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
11	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
12	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
13	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
14	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,3}	159,009,357
15	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,3}	159,009,357
16	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
17	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
18	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
19	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{3,2}	158,545,348
20	{2,1,3}	{3,2}	158,545,348	{2,1,3}	{1,2}	158,467,709
Best cost(\$)	{2,1,3}	{1,2}	158,467,709	{2,1,3}	{1,2}	158,467,709
Average			158,535,550			158,537,402
St.Dev			171,438.759			164,434.469

Table 24 concluded that a solution heat-integrated distillation sequences (HIDS), using Ant colony algorithm and Harmony search algorithm run 20 times for the same. The optimal of heat-integrated distillation sequences (HIDS) that is $s_k = \{2,1,3\}$ or AB / CD, A / B, C / D, $h_k = \{1,2\}$ or condenser at column 1 match steam reboiler at column 2 , with investment costs 158,467,709 USD/ year. The Ant

colony algorithm is more robust Harmony search algorithm seen from the average of the Ant colony algorithm using the average is 158,535,550 USD/year was lower cost than the Harmony search algorithm is the average is 158,537,402 USD/year, but both can provide the best cost the same configuration.



Table 25 The selected answers and costs of each configuration for case study 2

#	Configurations			Distillation Sequences				Heat-integrated distillation sequences					
	Column 1	Column 2	Column 3	AC	Cost in (\$) 10,000	HS	Cost in (\$) 10,000	AC	Cost in (\$) 10,000	Code Match	HS	Cost in (\$) 10,000	Code Match
1	A/BCD	B/CD	C/D	0	-	17	19,253	2	19,169	{2,1}	3	19,212	{1,3}
2	A/BCD	BC/D	B/C	0	-	10	18,202	4	18,164	{1,2}	19	18,130	{1,3}
3	AB/CD	A/B	C/D	7	15,927*	23	15,927*	1	15,846*	{1,2}	28	15,846*	{1,2}
4	ABC/D	A/BC	B/C	42	16,848	30	16,848	35	16,814	{2,1}	15	16,822	{3,2}
5	ABC/D	AB/C	A/B	51	16,506	20	16,506	58	16,431	{2,3}	35	16,431	{2,3}

* Best investment costs (USD/year)

Table 25 shows the selection by the answers of the two methods by using:

Ant colony algorithm for solving the problem of case study 2 (DS). Select the configuration number 5 which was selected the most followed by the configuration number 4 , configuration number 3 respectively. And, for solving the problem of case study 2 (HIDS). Select the configuration number 5 which was selected the most followed by the configuration number 4, configuration number 2 respectively.

Harmony search algorithm for solving the problem of case study 2 (DS). Select the configuration number 4 which was selected the most followed by the configuration number 3, configuration number 5 respectively. And, for solving the problem of case study 2 (HIDS). Select the configuration number 5 which was selected the most followed by the configuration number 3 , configuration number 2 respectively.

2.6 Process synthesis at steady-state process

Distillation is an energy consuming process that is used for about 95% of all fluid separation in the chemical industry and accounts for an estimated 3% of the world energy consumption, Hewitt et al. (1999). The calculation of the minimum heating and cooling requirements reveal significant energy saving. Heat-integrated distillation sequence takes an advantage of a minimum external utility usage, so plant operating costs can be saved. In the previous part, the optimal heat integrated distillation sequences have been acquired, So there are two configurations for this process that are:

- 1) Configuration number 1-process synthesis with the optimal distillation sequence.
- 2) Configuration number 2 - process synthesis with the optimal heat-integrated distillation sequence.

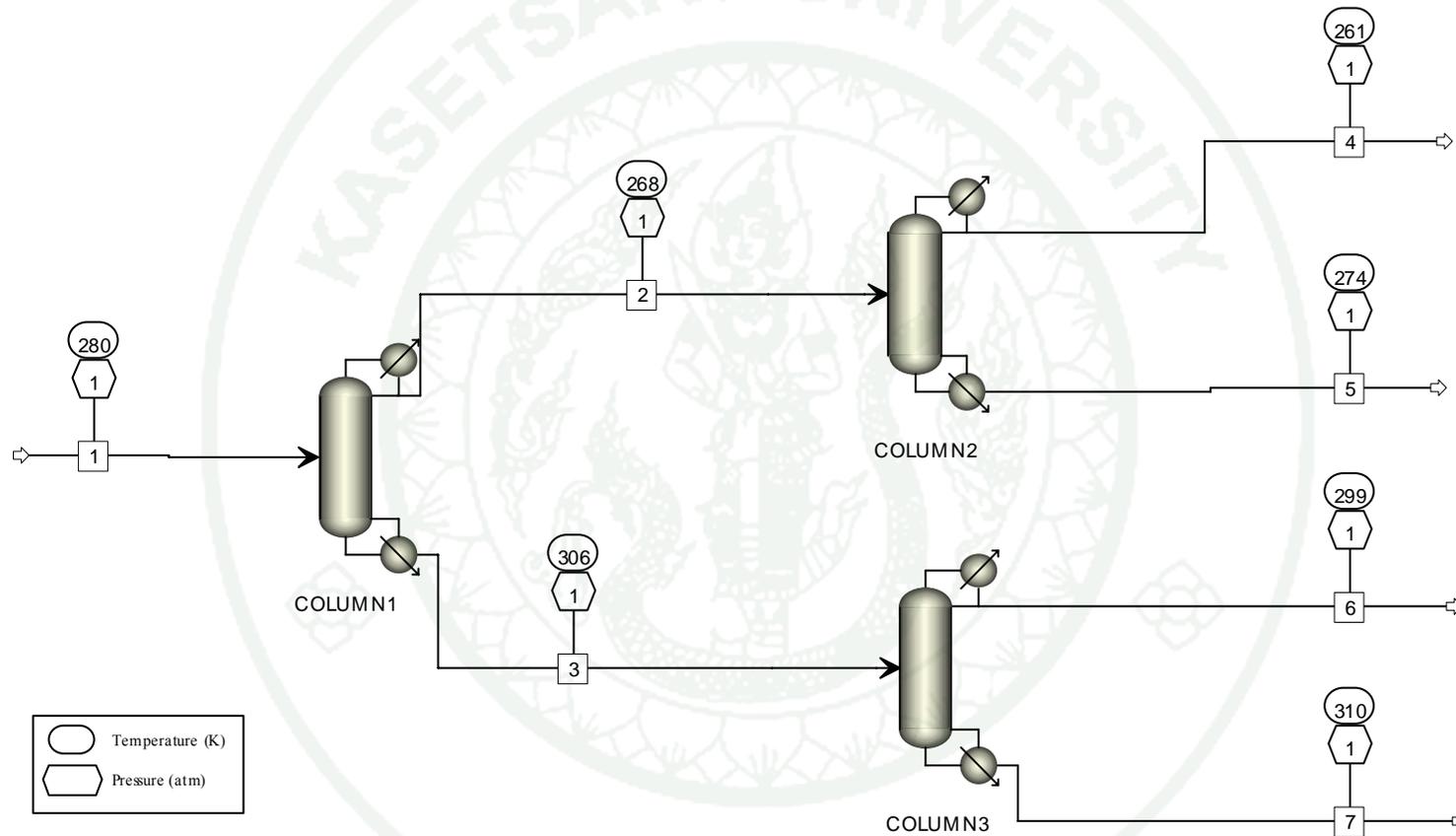


Figure 45 The optimal configuration number 1- Optimal of distillation sequences(without heat-integrated) for case study 2,
 Cost=159,274,858 USD/year

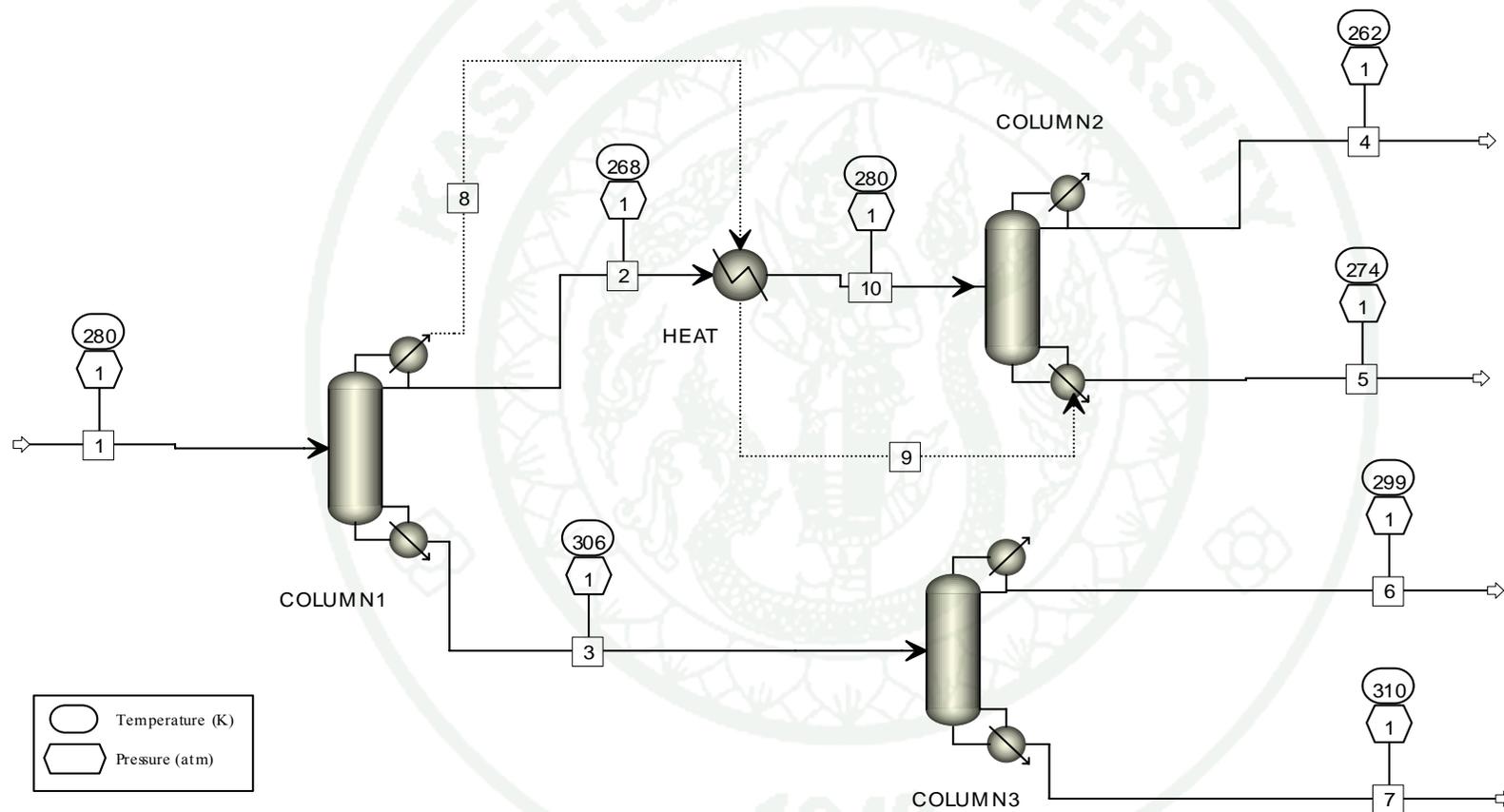


Figure 46 The optimal configuration number 2 - Optimal of heat-integrated distillation sequences (with heat-integrated) for case study 2, Cost=158,467,709 USD/year

In configuration number 1(Figure 45), process synthesis section is the optimal sequence solution. There are three distillation columns in this sequence, which is column number 1, 2 and 3. First, stream 1 is fed to column 1 to be separated iso-Butane and n-Butane as a distillate intermediate stream (stream 2) and other components is iso-Pentane and n-Pentane become a bottom intermediate stream (stream 3). Then, stream 2 is fed to column 2 to separate iso-Butane as a distillate product stream (stream 4) and n-Butane as a bottom product stream (stream 5). Stream 3 is become a feed stream of column 3 in order to separate n-Pentane out as a bottom product stream (stream 7) and iso-Pentane separate as a distillate product stream (stream 6) and These three columns are Radfrac model. The operating condition of each column is shown in Table 26. The simulation result for configuration number 1 is shown in Table 27. All simulation using DSTWU result for this configuration is shown in Appendix C2.

Table 26 Operating condition of each column in the optimal heat integrated distillation sequences for case study 2

Operating condition	Optimal configuration		
	Column 1	Column 2	Column 3
Number of stages	21	42	60
Feed stage	11	22	31
Distillate to feed ratio (kmol/h)	362.99	136.37	180.06
Reflux ratio	1.06	6.144	9.828
Condenser heat duty (GJ/h)	16.68	20.67	48.54
Reboiler heat duty (GJ/h)	18.29	20.74	48.52
Condenser type	Total	Total	Total
Reboiler type	Kettle	Kettle	Kettle

Table 27 Stream result of steady-state for case study 2

Component	Mole flowrate (Kmol/h) (Steam 1)	Separated		%Purity
		Stream	Separated (Kmol/h)	
(A) iso-Butene	135.81	4	133.69	98.44%
(B) n-Butane	227.49	5	217.17	95.46%
(C) iso-Pentane	183.38	6	183.31	99.96%
(D) n-Pentane	318.32	7	315.02	98.96%

For configuration number 2 (Figure 47), sources and sinks of each heat integrate are showed in Table 28, occur of heat duty of condenser for column2 to put the heater preheat of stream 1 until the temperature increases until the cause of stream 8 reboiler duty reduction. The comparison of costs between process with and without heat integration is showed in Table 29. Stream result of steady-state of configuration number 1(Figure 46) for case study is showed in Table 27. And the comparative study using various methods of case study 2 are showed in Table 30.

Table 28 Source and sink of each heat integration match for configuration number 2 of case study 2

Heat stream	Source-Sink
8-9	Column 1 - Column 2

Table 29 The comparison of costs between process with and without heat integration of each column of case study 2

Format	Best cost (\$)	
	With heat integration	Without heat integration
Optimal configuration	158,467,709	159,274,858
Reduce the costs (%)	0.5068%	

Table 30 Comparative study using various methods of case study 2

Method	Ant colony algorithm	Harmony search algorithm	Genetic algorithm	General Algebraic
Authors	This work	This work	Piumsomboon	Floudast
Optimal configuration for distillation sequences	$S_k = \{2,1,3\}$	$S_k = \{2,1,3\}$	$S_k = \{2,1,3\}$	$S_k = \{2,1,3\}$
The total annual cost (\$) (without heat-integration)	159,274,858	159,274,858	-	-
Optimal configuration for heat-integrated distillation sequences	$S_k = \{2,1,3\}$ $H_k = \{1,2\}$	$S_k = \{2,1,3\}$ $H_k = \{1,2\}$	-	$S_k = \{2,1,3\}$ $H_k = \{1,2\}$
The total annual cost (\$) (with heat-integration)	158,467,709	158,467,709	-	-

3. Case study 3

This is a five-component mixture separation problem solved firstly by Rathore, Van Wormer, and Powers (1974). The problem data is given in Table 31. The costs of the 14 possible sequences without and with integration are shown in Table 36.

Table 31 Components and mole fractions of the feed of case study 3

Key Component	Component	Formula	Mole fraction	Boiling Temperature
A	Propane	C ₃ H ₈	0.05	231.11 K
B	iso-Butane	C ₄ H ₁₀₋₂	0.15	261.43 K
C	n-Butane	C ₄ H ₁₀₋₁	0.25	272.65 K
D	iso-Pentane	C ₅ H ₁₂₋₂	0.20	300.99 K
E	n-Pentane	C ₅ H ₁₂₋₁	0.35	309.22 K

Data simulation for process

- Property method & models

Process type : Common
Base method : BK 10

- Feed state variables

Feed flow rate : 910 kmol/h
Temperature : 275 K
Pressure : 1 atm

- Heat transfer parameters

Overall heat transfer : 1000 Watt/m²K
Log mean temperature : 10 K
Cost equations for heat exchanger network : 2143A^{0.514}

3.1 Ant colony algorithm for distillation sequences (DS) (without heat-integrated distillation sequences)

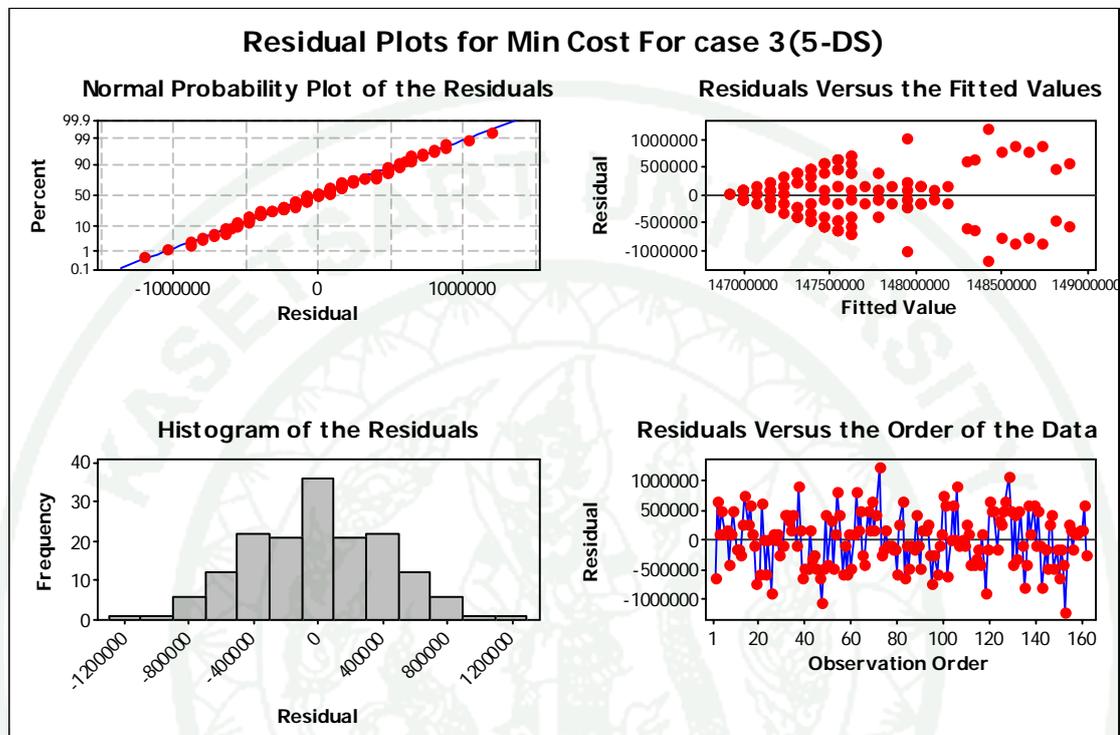


Figure 47 Hypothesis testing of Ant colony algorithm for case study 3 (5-DS)

Figure 47 show of testing the hypothesis of the Ant colony algorithm for case study 3 (5-DS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For case 3(5-DS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/Ants	2	1.14245E+12	1.14245E+12	5.71227E+11
Weight of pheromone	2	5.55026E+11	5.55026E+11	2.77513E+11
Weight of heuristic information	2	2.52025E+12	2.52025E+12	1.26013E+12
Evaporation rate	2	1.57100E+12	1.57100E+12	7.85499E+11
Source	F	P		
Iteration/Ants	1.48	0.233		
Weight of pheromone	0.72	0.489		
Weight of heuristic information	3.28	0.043		
Evaporation rate	2.04	0.136		

Figure 48 Analysis of variance of the Ant colony algorithm for case study 3 (5-DS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 49 was iteration / ant (I/A) to the P-value = 0.233, weight of pheromone (WOP) to the P-value = 0.489, weight of heuristic information (WOH) for the P-value = 0.043 and evaporation rate (ER) to the P-value. = 0.136 shows that the factors is weight of heuristic information (WOH) as the impact Ant colony algorithm to find the answer for 5-DS which is determined by the P-value is less than 0.05. In contrast, three factors have no effect on finding answers to the iteration / ant (I / A), weight of pheromone (WOP) and evaporation rate (ER), because the P-value is greater than 0.5.

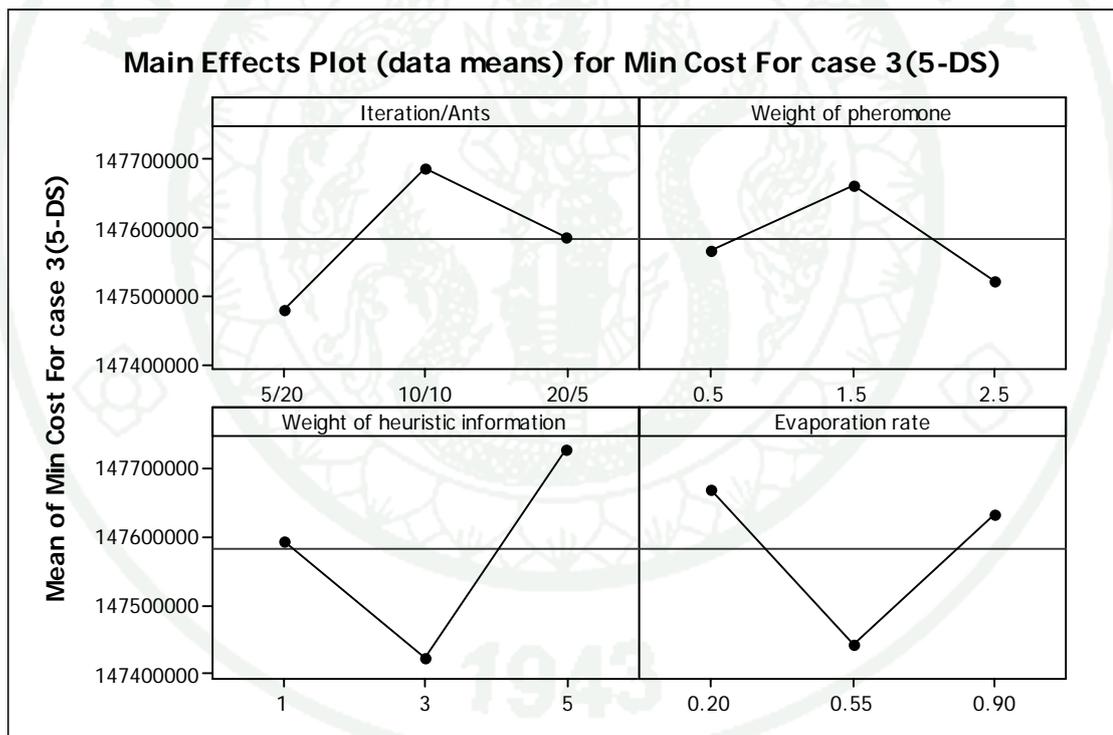


Figure 49 Impact that occurs on the main factors of Ant colony algorithm for case study 3 (5-DS)

Main effects plot caused major problems of case study 3 (5-DS) for the Ant colony algorithm was the iteration / ant (I/A) at 5 / 20, weight of pheromone (WOP) at 2.5, weight of heuristic information (WOH) at 3 and evaporation rate (ER) at 0.55. All

this resulted in answers to the most valuable minimum cost. It can be summarized in Table 32.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 50.

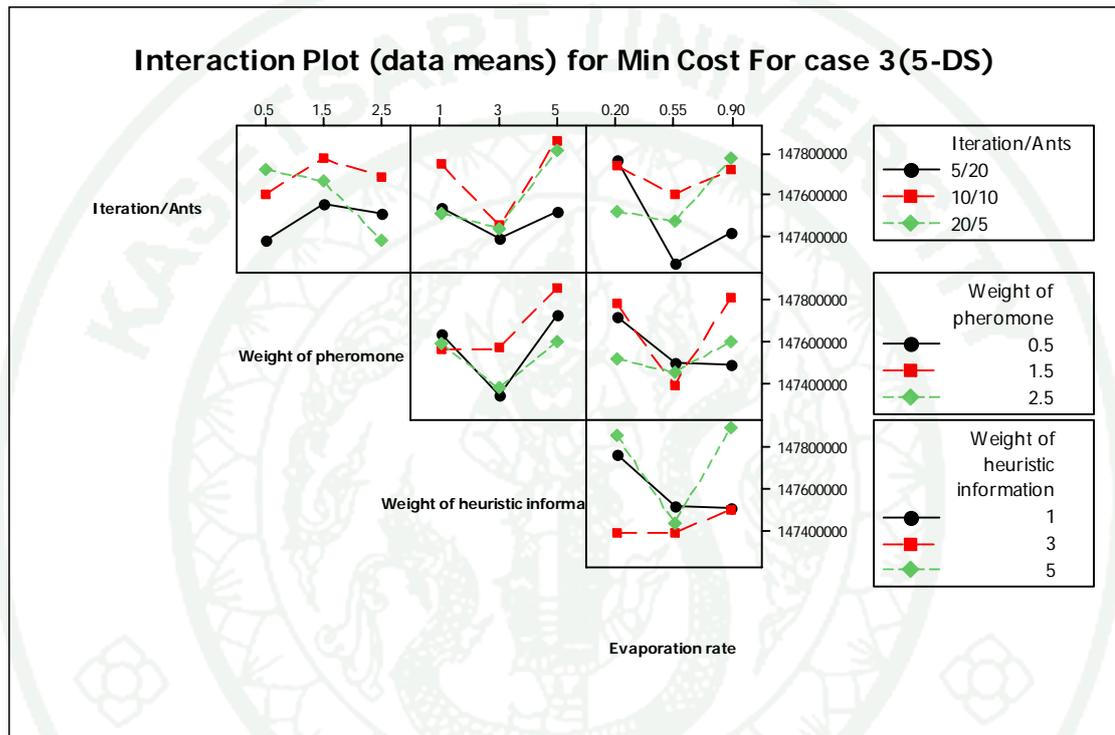


Figure 50 Interaction plot between the Ant colony algorithm for case study 3 (5-DS)

3.2 Ant colony algorithm for heat-integrated distillation sequences (HIDS) (with heat-integrated distillation sequences)

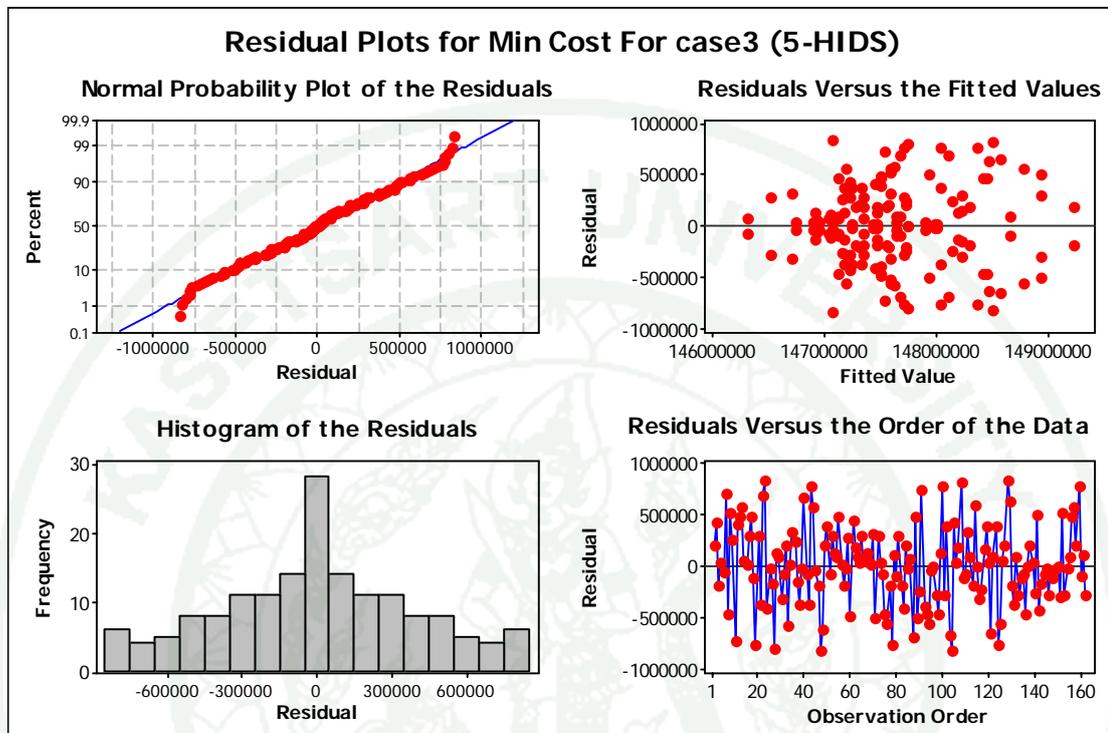


Figure 51 Hypothesis testing of Ant colony algorithm for case study 3 (5-HIDS)

Figure 51 show of testing the hypothesis of the Ant colony algorithm for case study 3 (5-HIDS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For case3 (5-HIDS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/Ants	2	4.65039E+11	4.65039E+11	2.32520E+11
Weight of pheromone	2	1.04282E+12	1.04282E+12	5.21410E+11
Weight of heuristic information	2	2.29631E+12	2.29631E+12	1.14816E+12
Evaporation rate	2	7.83525E+11	7.83525E+11	3.91763E+11
Source		F	P	
Iteration/Ants		0.78	0.464	
Weight of pheromone		1.74	0.182	
Weight of heuristic information		3.83	0.026	
Evaporation rate		1.31	0.277	

Figure 52 Analysis of variance of the Ant colony algorithm for case study 3 (5-HIDS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 53 was iteration / ant (I/A) to the P-value = 0.464, weight of pheromone (WOP) to the P-value = 0.182, weight of heuristic information (WOH) for the P-value = 0.026 and Evaporation rate (ER) to the P-value. = 0.277 shows that the factors is weight of heuristic information (WOH) as the impact Ant colony algorithm to find the answer for 5-HIDS which is determined by the P-value is less than 0.05. In contrast, three factors have no effect on finding answers to the iteration / ant (I / A), weight of pheromone (WOP) and evaporation rate (ER), because the P-value is greater than 0.5.

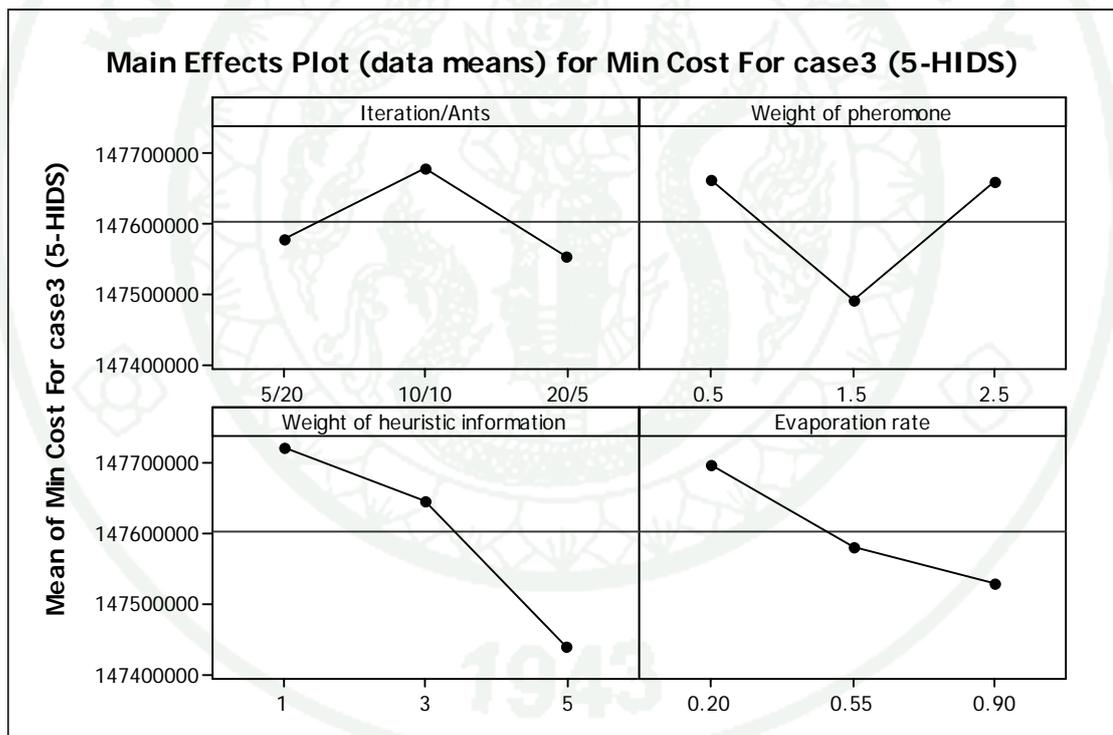


Figure 53 Impact that occurs on the main factors of Ant colony algorithm for case study3 (5-HIDS)

Main effects plot caused major problems of case study 3 (5-DS) for the Ant colony algorithm was the iteration / ants (I/A) at 20 / 5, weight of pheromone (WOP) at 1.5, weight of heuristic information (WOH) at 5 and evaporation rate (ER) at 0.90.

All this resulted in answers to the most valuable minimum cost. It can be summarized in Table 32.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 54.

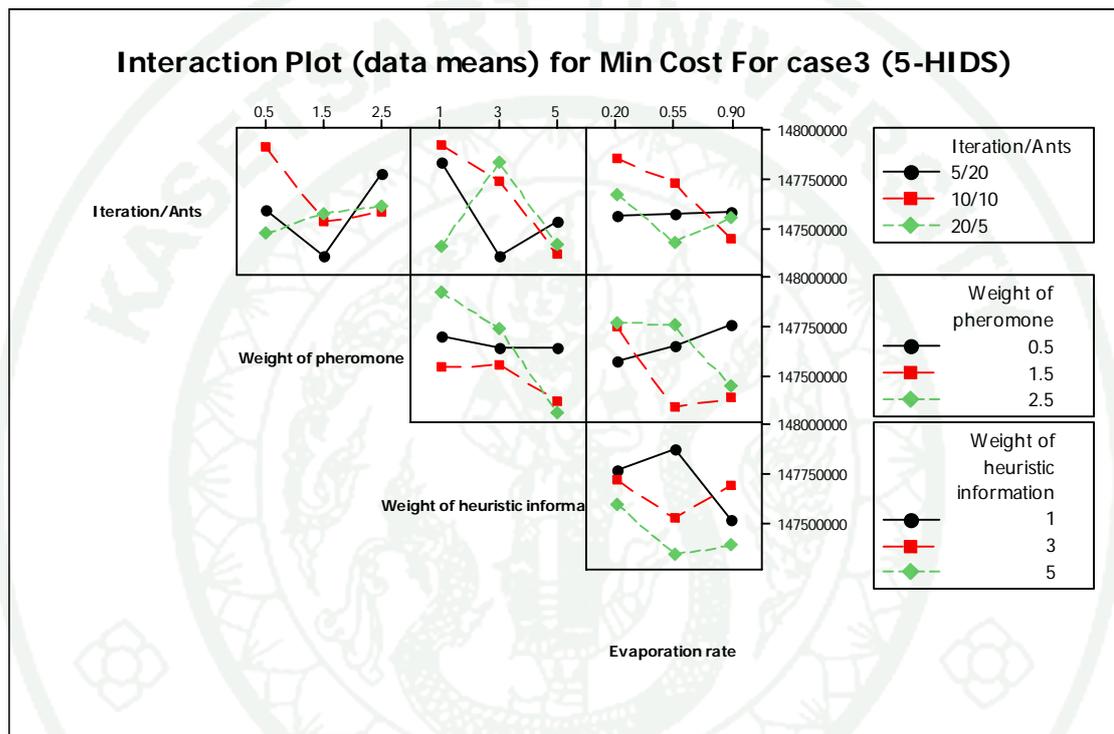


Figure 54 Interaction plot between the Ant colony algorithm for case study 3 (5-HIDS)

3.3 Harmony search algorithm for distillation sequences (DS) (without heat-integrated distillation sequences)

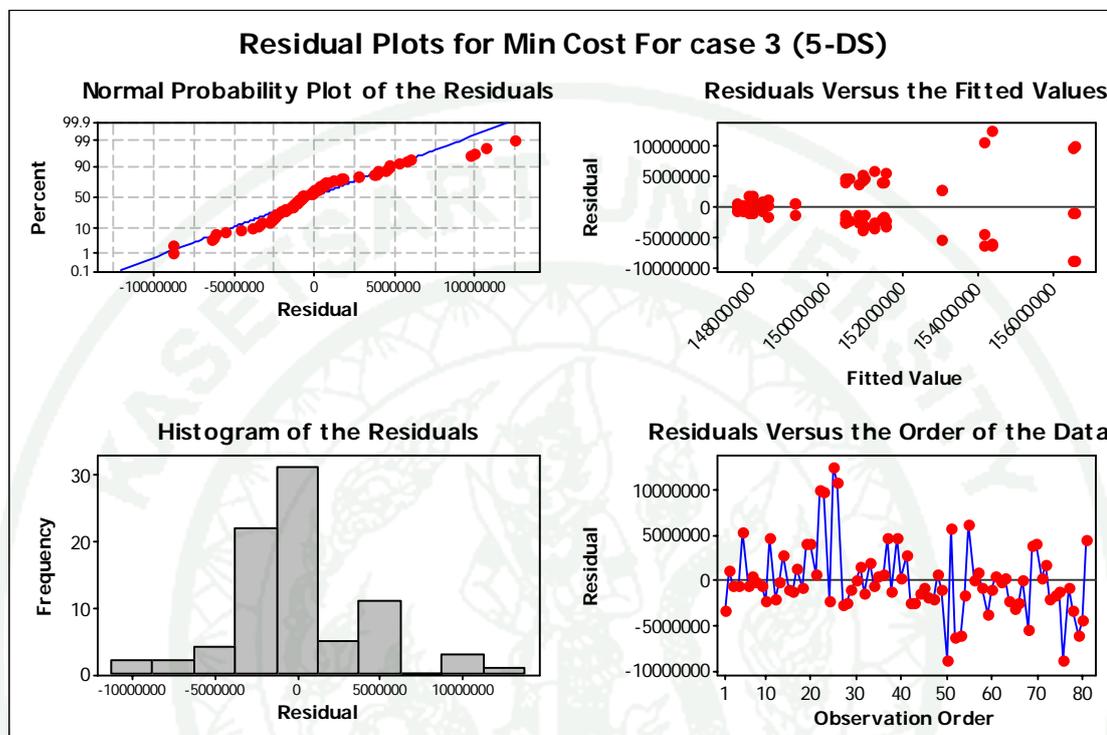


Figure 55 Hypothesis testing of Harmony search algorithm for case study 3 (5-DS)

Figure 55 show of testing the hypothesis of the Harmony search algorithm for case study 3 (5-DS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For case 3 (5-DS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/Harmony size	2	2.58754E+14	2.58754E+14	1.29377E+14
Harmony Memory Considering Rate	2	3.74224E+13	3.74224E+13	1.87112E+13
Pitch Adjustment Rate	2	5.34578E+13	5.34578E+13	2.67289E+13
Source	F	P		
Iteration/Harmony size	5.78	0.005		
Harmony Memory Considering Rate	0.84	0.439		
Pitch Adjustment Rate	1.19	0.311		

Figure 56 Analysis of variance of the Harmony search algorithm for case study 3 (5-DS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 57 was iteration / Harmony size (I/H) to the P-value = 0.005, harmony memory considering rate (HMCR) to the P-value = 0.439, and pitch adjustment rate (PAR) to the P-value. = 0.311 shows that the factors is iteration / Harmony size (I/H) as the impact Harmony search algorithm to find the answer for 5-DS which is determined by the P-value is less than 0.05. In contrast, two factors have no effect on finding answers to the harmony memory considering rate (HMCR) and pitch adjustment rate (PAR) , because the P-value is greater than 0.5.

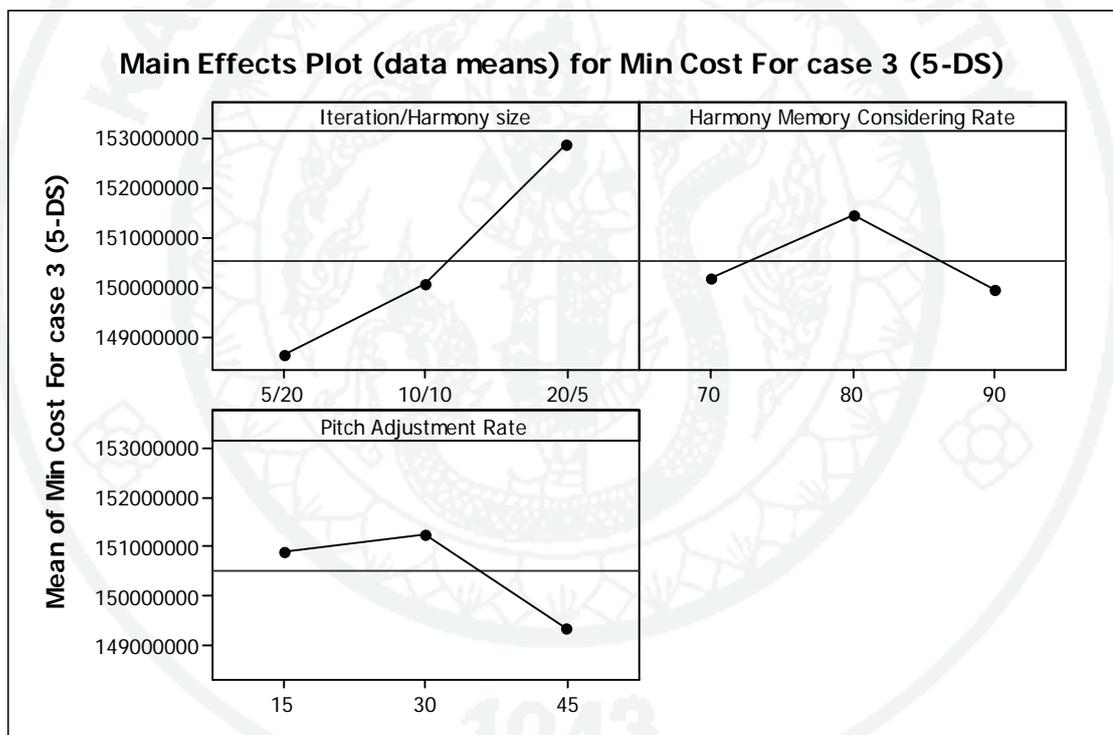


Figure 57 Impact that occurs on the main factors of Harmony search algorithm for case study 3 (5-DS)

Main effects plot caused major problems of case study 3 (5-DS) for the Harmony search algorithm was the iteration / harmony size (I/H) at 5 / 20, harmony memory considering rate (HMCR) at 90, and pitch adjustment rate at 45. All this

resulted in answers to the most valuable minimum cost. It can be summarized in Table 33.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 58.

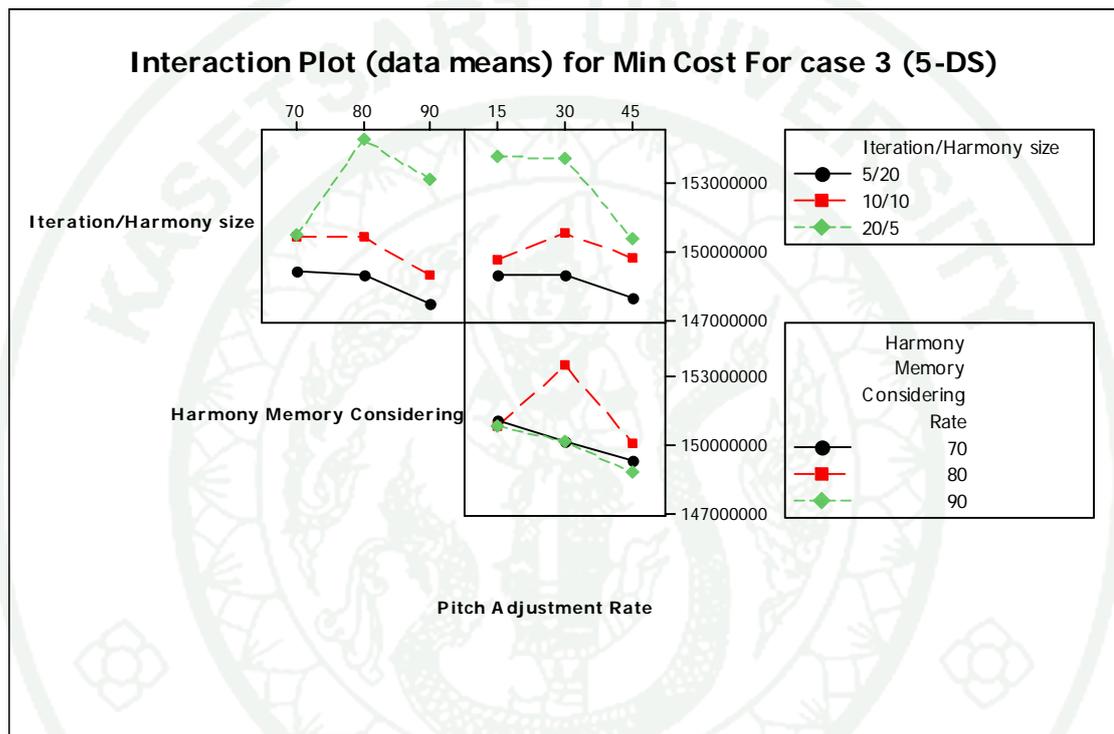


Figure 58 Interaction plot between the Harmony search algorithm for case study 3 (5-DS)

3.4 Harmony search algorithm for heat-integrated distillation sequences (HIDS) (with heat-integrated distillation sequences)

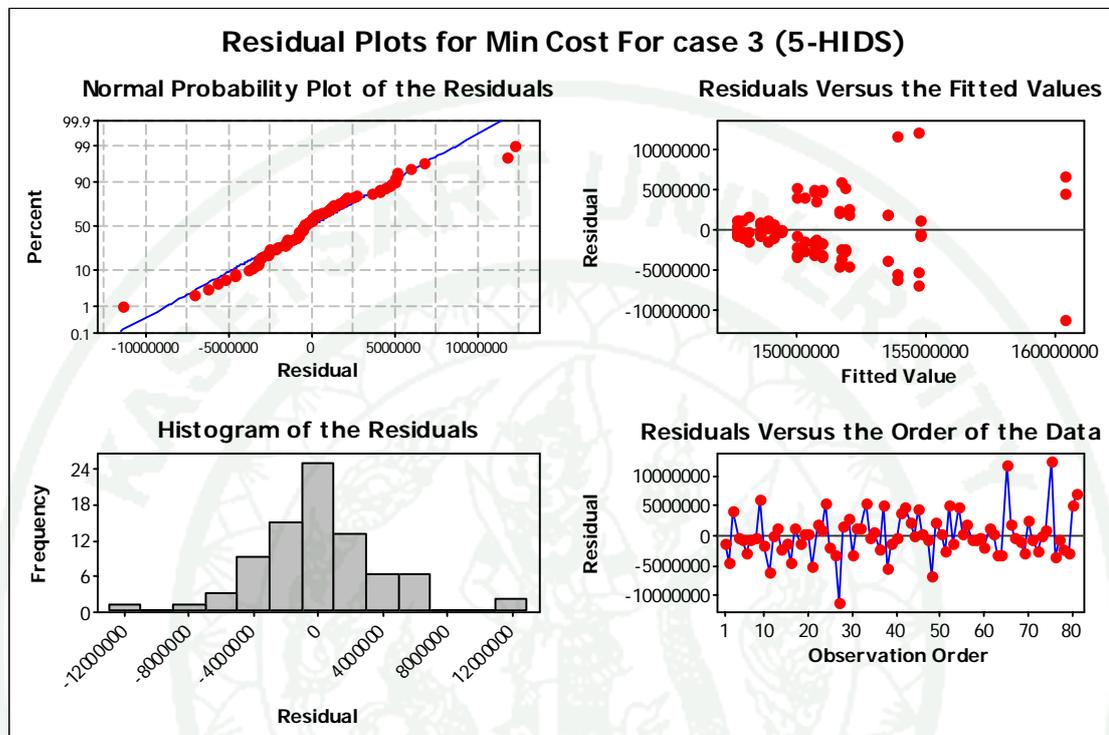


Figure 59 Hypothesis testing of Harmony search algorithm for case study 3
(5-HIDS)

Figure 59 show of testing the hypothesis of the Harmony search algorithm for case study 3 (5-HIDS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For case 3 (5-HIDS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/Harmony size	2	1.28031E+14	1.28031E+14	6.40156E+13
Harmony Memory Considering Rate	2	5.35017E+13	5.35017E+13	2.67508E+13
Pitch Adjustment Rate	2	3.80512E+13	3.80512E+13	1.90256E+13
Source	F	P		
Iteration/Harmony size	3.21	0.048		
Harmony Memory Considering Rate	1.34	0.270		
Pitch Adjustment Rate	0.95	0.392		

Figure 60 Analysis of variance of the Harmony search algorithm for case study 3
(5-HIDS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 61 was iteration / Harmony size (I/H) to the P-value = 0.048, harmony memory considering rate (HMCR) to the P-value = 0.270, and pitch adjustment rate (PAR) to the P-value. = 0.392 shows that the factors is iteration / Harmony size (I/H) as the impact Harmony search algorithm to find the answer for 5-DS which is determined by the P-value is less than 0.05. In contrast, two factors have no effect on finding answers to the harmony memory considering rate (HMCR) and pitch adjustment rate (PAR) , because the P-value is greater than 0.5.

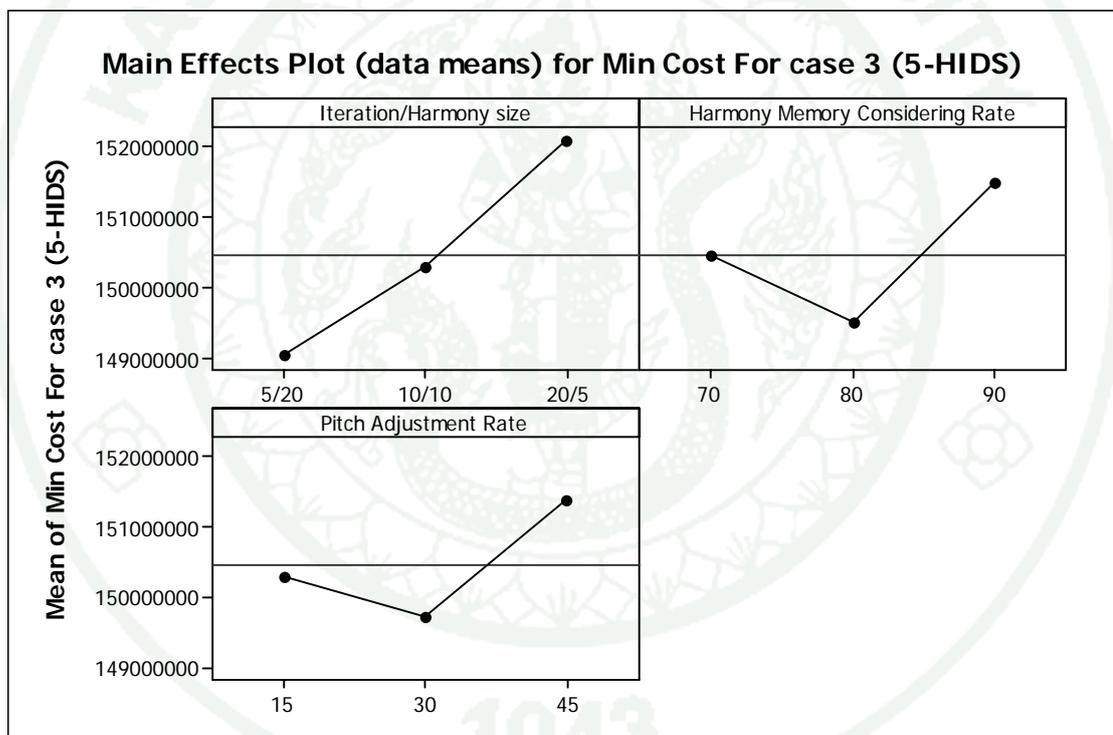


Figure 61 Impact that occurs on the main factors of Harmony search algorithm for case study 3 (5-HIDS)

Main effects plot caused major problems of case study 3 (5-HIDS) for the Harmony search algorithm was the iteration / harmony size (I/H) at 5 / 20, harmony memory considering rate (HMCR) at 80, and Pitch adjustment rate at 30. All this

resulted in answers to the most valuable minimum cost. It can be summarized in Table 33.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 62.

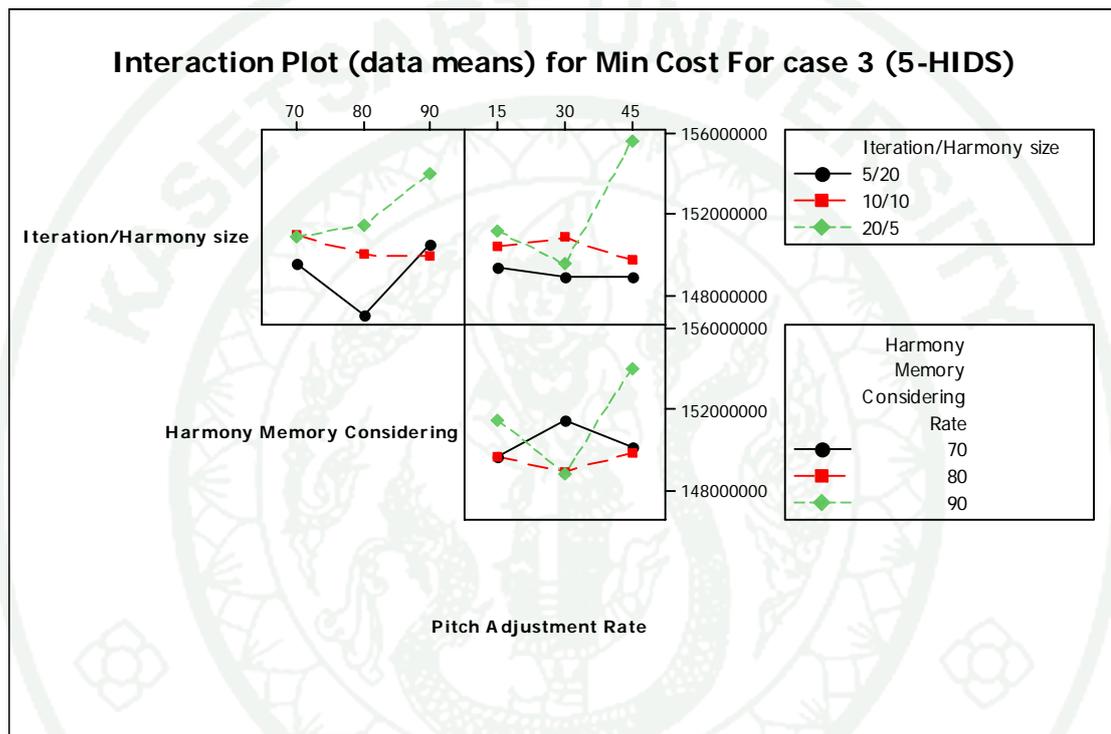


Figure 62 Interaction plot between the Harmony search algorithm for case study 3 (5-HIDS)

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3.5 Comparison of results between the two methods.

After these parameters at optimal way Ant colony algorithm are shown in Table 32 and the parameters are the optimal way Harmony search algorithm are shown in Table 33 is important for them each how to enter the program Visual Studio V.8.0 to make. Run each of 20 values are shown in Table 34 and Table 35 of the two processes is to compare the distillation sequences (DS) or without heat-integrated and the heat-integrated distillation sequences (HIDS) or with heat-integrated to find a way to provide the best solution.

Table 32 Optimization of levels and factors of Ant colony algorithm for case study 3

Factors	Distillation sequences (DS)	Heat-integrated distillation sequences (HIDS)
Iteration/Ants (I/A)	5/20 (Low)	20/5 (High)
Weight of pheromone (WOP)	2.5 (High)	1.5 (Medium)
Weight of heuristic information (WOH)	3 (Medium)	5 (High)
Evaporation rate (ER)	0.55 (Medium)	0.90 (High)

Table 33 Optimization of levels and factors of Harmony search algorithm for case study 3

Factors	Distillation sequences (DS)	Heat-integrated distillation sequences (HIDS)
Iteration/Harmony size (I/H)	5/20 (Low)	5/20 (Low)
Harmony memory considering rate (HMCR)	90 (High)	80 (Medium)
Pitch adjustment rate (PAR)	45 (High)	30 (Medium)

Table 34 The best run of distillation sequences for case study 3(5-DS)

K	Distillation sequences (DS)			
	Ant colony algorithm		Harmony search algorithm	
	Code Sequences (s_k)	Minimum Cost (\$)	Code Sequences (s_k)	Minimum Cost (\$)
1	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
2	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
3	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
4	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
5	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
6	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
7	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
8	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
9	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
10	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
11	{3,4,2,1}	149,809,030	{4,2,1,3}	157,295,890
12	{3,4,2,1}	149,809,030	{4,2,1,3}	157,295,890
13	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
14	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
15	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
16	{3,4,2,1}	149,809,030	{4,2,1,3}	157,295,890
17	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
18	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
19	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
20	{3,4,2,1}	149,809,030	{4,2,1,3}	157,295,890
Best cost(\$)	{3,4,2,1}	149,809,030	{3,4,2,1}	149,809,030
Average		149,809,030		151,306,402
St.Dev		0.0000		3,072,542

Table 34 concluded that a solution distillation sequences (DS), using Ant colony algorithm and Harmony search algorithm gives the same run 20 times by optimal distillation sequences is {3,4,2,1} or ABC/DE, D/E, AB/C, A/B with investment cost is 149,809,030 USD/ year.

Table 35 The best run of heat-integrated distillation sequences for case study 3
(5-HIDS)

K	Heat-integration distillation sequences (HIDS)					
	Ant colony algorithm			Harmony search algorithm		
	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)
1	{3,4,2,1}	{3,1},{4,2}	149,171,538	{4,2,1,3}	{3,4},{2,1}	156,945,187
2	{3,4,2,1}	{4,1},{2,3}	149,702,074	{3,4,2,1}	{3,4},{2,1}	149,789,791
3	{3,4,2,1}	{4,3},{2,1}	149,683,009	{3,4,2,1}	{3,1},{2,4}	149,829,073
4	{3,4,2,1}	{3,1},{2,4}	149,829,073	{4,2,1,3}	{4,2},{1,3}	157,499,410
5	{3,4,2,1}	{4,2},{3,1}	149,171,538	{4,2,1,3}	{3,4},{1,2}	156,928,100
6	{3,4,2,1}	{4,3},{2,1}	149,683,009	{4,2,1,3}	{4,3},{1,2}	156,922,471
7	{3,4,2,1}	{3,1},{2,4}	149,829,073	{3,4,2,1}	{1,4},{2,3}	149,768,233
8	{3,4,2,1}	{4,2},{3,1}	149,171,538	{3,4,2,1}	{3,4},{2,1}	149,789,791
9	{3,4,2,1}	{3,2},{4,1}	149,858,531	{3,4,2,1}	{1,4},{3,2}	149,870,564
10	{3,4,2,1}	{4,3},{2,1}	149,683,009	{3,4,2,1}	{2,3},{1,4}	149,768,233
11	{3,4,2,1}	{4,2},{3,1}	149,171,538	{3,4,2,1}	{4,1},{2,3}	149,702,074
12	{3,4,2,1}	{4,3},{2,1}	149,683,009	{3,4,2,1}	{3,4},{2,1}	149,789,791
13	{3,4,2,1}	{4,1},{2,3}	149,702,074	{4,2,1,3}	{4,1},{3,2}	157,142,471
14	{3,4,2,1}	{4,2},{3,1}	149,171,538	{3,4,2,1}	{1,4},{2,3}	149,768,233
15	{3,4,2,1}	{4,1},{2,3}	149,702,074	{4,2,1,3}	{4,1},{3,2}	157,142,471
16	{3,4,2,1}	{4,1},{2,3}	149,702,074	{3,4,2,1}	{1,3},{2,4}	150,222,403
17	{3,4,2,1}	{4,2},{3,1}	149,171,538	{3,4,2,1}	{3,1},{2,4}	149,829,073
18	{3,4,2,1}	{4,1},{2,3}	149,702,074	{3,4,2,1}	{1,2},{3,4}	149,912,666
19	{3,4,2,1}	{4,2},{3,1}	149,171,538	{3,4,2,1}	{1,4},{2,3}	149,768,233
20	{3,4,2,1}	{4,2},{3,1}	149,171,538	{3,4,2,1}	{1,4},{2,3}	149,768,233
Best cost(\$)	{3,4,2,1}	{4,2},{3,1}	149,171,538	{3,4,2,1}	{4,1},{2,3}	149,702,074
Average			149,506,569			152,007,825
St.Dev			285,205			3,421,454

Table 35 concluded that a solution heat-integrated distillation sequences (HIDS), using Ant colony algorithm. The optimal of heat-integrated distillation sequences (HIDS) that is $s_k = \{3,4,2,1\}$ or ABC/DE, D/E, AB/C, A/B, $h_k = \{4,2\}, \{3,1\}$ or condenser at column 4 match steam reboiler at column 2 and condenser at column 3 match steam reboiler at column 1, with investment costs

149,171,538 USD / year, using Harmony search algorithm. The optimal of heat-integrated distillation sequences (HIDS) that is $s_k = \{3,4,2,1\}$ or ABC/DE, D/E, AB/C, A/B , $h_k = \{4,1\}, \{2,3\}$ or condenser at column 4 match steam reboiler at column 1 and condenser at column 2 match steam reboiler at column 3 , with investment costs 149,702,074 USD / year. The Ant colony algorithm is more robust Harmony search algorithm seen from the average of the Ant colony algorithm using the average is 149,506,569 USD/year was lower cost the Harmony search algorithm is the average is 152,007,825 USD/year, but both can provide the best cost the same configuration.

Table 36 The selected answers and costs of each configuration for case study 3

#	Configurations				Distillation Sequences (without heat-integrated)				Heat-integrated distillation sequences (with heat-integrated)					
	Column 1	Column 2	Column 3	Column 4	AC	Cost in (\$) 10,000	HS	Cost in (\$) 10,000	AC	Cost in (\$) 10,000	Code Match	HS	Cost in (\$) 10,000	Code Match
1	A/BCDE	B/CDE	C/DE	D/E	0	-	1	22,122	0	-	-	1	22,192	{4,1},{3,2}
2	A/BCDE	B/CDE	CD/E	C/D	0	-	2	21,532	0	-	-	0	-	-
3	A/BCDE	BC/DE	B/C	D/E	0	-	0	-	0	-	-	0	-	-
4	A/BCDE	BCD/E	B/CD	C/D	0	-	0	-	0	-	-	11	20,195	{4,1},{3,2}
5	A/BCDE	BCD/E	BC/D	B/C	0	-	0	-	0	-	-	0	-	-
6	AB/CDE	A/B	C/DE	D/E	0	-	0	-	0	-	-	15	17,238	{2,4},{1,3}
7	AB/CDE	A/B	CD/E	C/D	1	16,708	14	16,708	0	-	-	10	16,735	{3,4},{1,2}
8	ABC/DE	D/E	A/BC	B/C	3	16,262	18	16,262	8	16,266	{4,2},{1,3}	13	16,234	{3,1},{2,4}
9	ABC/DE	D/E	AB/C	A/B	7	14,980*	18	14,980*	2	14,917*	{4,2},{3,1}	5	14,970	{2,3},{4,1}
10	ABCD/E	A/BCD	B/CD	C/D	16	18,316	0	-	11	18,288	{3,4},{2,1}	10	18,291	{2,3},{4,1}
11	ABCD/E	A/BCD	BC/D	B/C	20	17,975	0	-	16	17,925	{2,1},{4,3}	5	17,951	{2,1},{3,4}
12	ABCD/E	AB/CD	A/B	C/D	25	15,729	0	-	31	15,692	{3,4},{1,2}	5	15,770	{2,3},{1,4}
13	ABCD/E	ABC/D	A/BC	B/C	15	17,012	3	17,012	16	17,004	{1,4},{3,2}	10	16,952	{3,1},{4,2}
14	ABCD/E	ABC/D	AB/C	A/B	13	15,731	44	15,731	16	15,685	{4,1},{3,2}	15	15,694	{4,3},{1,2}

* Best investment costs (USD/year)

Table 36 shows the selection by the answers of the two methods by using:

Ant colony algorithm for solving the problem of case study 3 (DS). Select the configuration number 12 which was selected the most followed by the configuration number 11 , configuration number 10 respectively. And, for solving the problem of case study 3 (HIDS). Select the configuration number 12 which was selected the most followed by the configuration number 11,13,14 ,configuration number 10 respectively.

Harmony search algorithm for solving the problem of case study 3 (DS). Select the configuration number 14 which was selected the most followed by the configuration number 8,9 ,configuration number 7 respectively. And, for solving the problem of case study 3 (HIDS). Select the configuration number 6 and configuration number 14 which was selected the most followed by the configuration number 8 , configuration number 4 respectively.

2.6 Process synthesis at steady-state process

Distillation is an energy consuming process that is used for about 95% of all fluid separation in the chemical industry and accounts for an estimated 3% of the world energy consumption, Hewitt et al. (1999). The calculation of the minimum heating and cooling requirements reveal significant energy saving. Heat-integrated distillation sequence takes an advantage of a minimum external utility usage, so plant operating costs can be saved. In the previous part, the optimal heat integrated distillation sequences have been acquired, So there are two configurations for this process that are:

- 1) Configuration number 1-process synthesis with the optimal distillation sequence.
- 2) Configuration number 2 - process synthesis with the optimal heat-integrated distillation sequence.

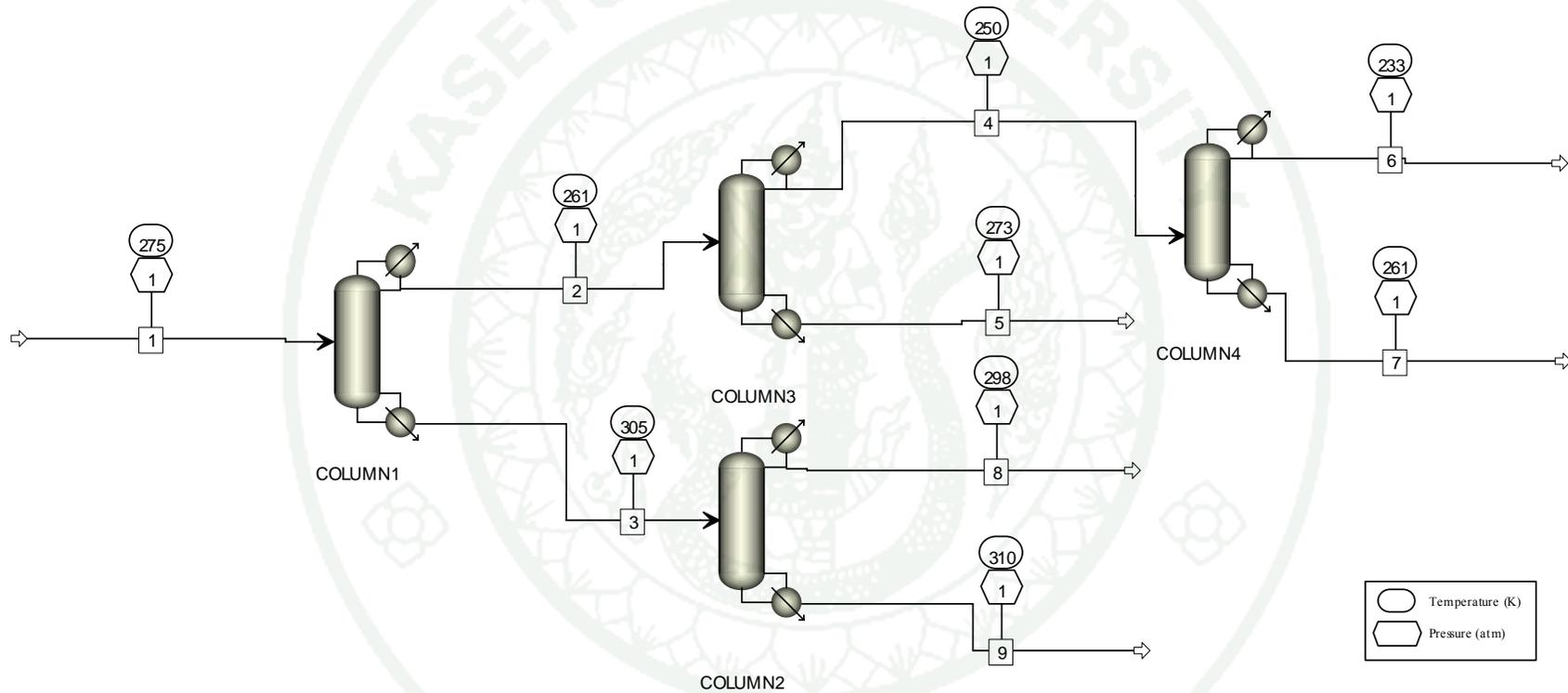


Figure 63 The optimal configuration number 1- Optimal of distillation sequences(without heat-integrated) for case study 3,
 Cost=149,809,030 USD/year

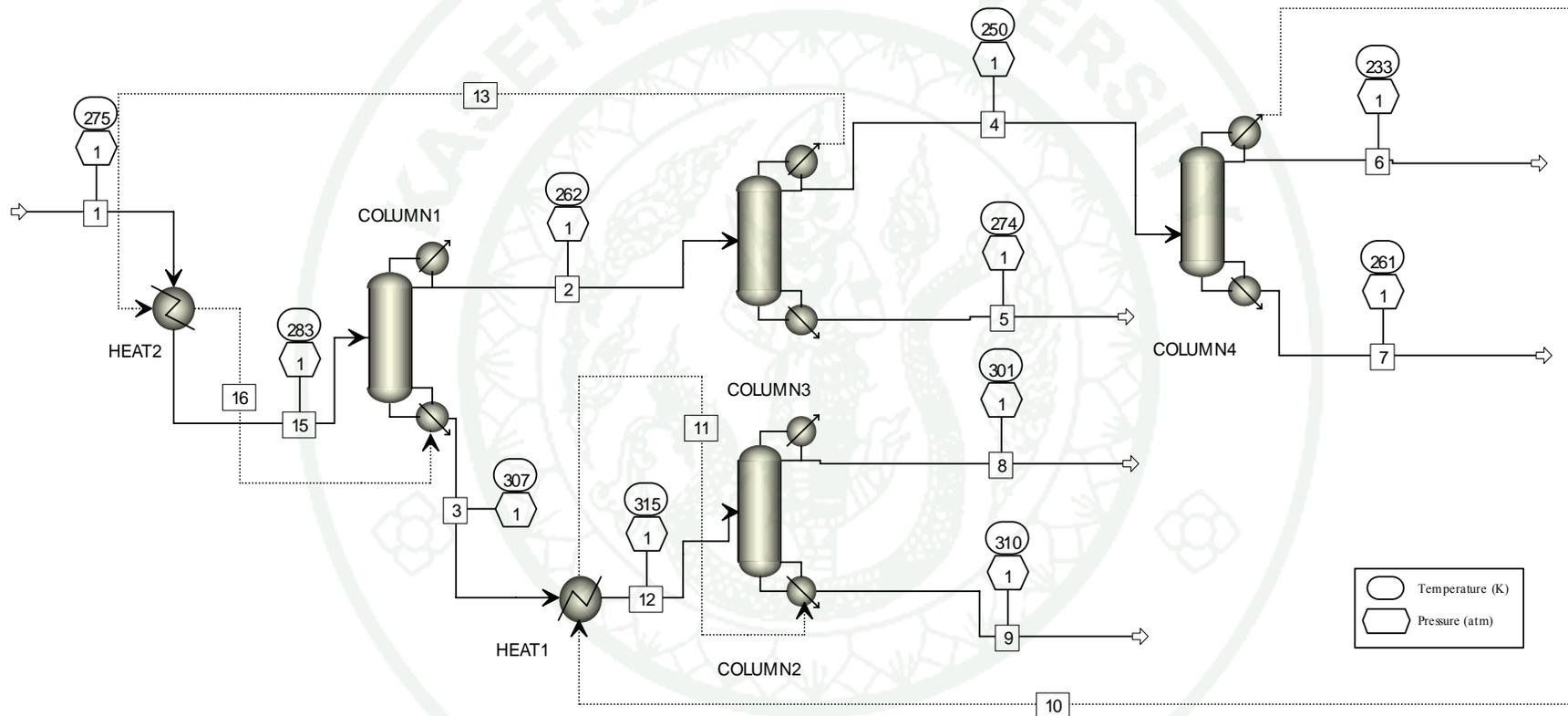


Figure 64 The optimal configuration number 2- Optimal of heat-integrated distillation sequences(with heat-integrated) for case study 3,
 Cost=149,171,538 USD/year

In configuration number 1 (Figure 63), process synthesis is the optimal sequence solution. There are four distillation columns in this sequence, which is column number 1, 2, 3 and 4. First, stream 1 is fed to column 1 to be separated Propane, iso-Butane and n-Butane as a distillate intermediate stream (stream 2) and iso-Pentane, n-Pentane is become a bottom intermediate stream (stream 3). Then, stream 3 is fed to column 2 to separate iso-Pentane as a distillate product stream (stream 8) and n-Pentane as a bottom product stream (stream 9). Stream 2 is become a feed stream of column 3 in order to separate n-Butane out as a bottom product stream (stream 5) and other component (stream 4) is sent to column 4. This column separate Propane as a distillate product stream (stream 6) and iso-Butane becomes a bottom product stream (stream 7). These four columns are Radfrac model. The operating condition of each column is shown in Table 37. The simulation result for configuration number 1 and 2 is shown in Table 38. All simulation using DSTWU result for this configuration is shown in Appendix C3.

Table 37 Operating condition of each column in the optimal distillation sequences for case study 3

Operating condition	Optimal configuration			
	Column 1	Column 2	Column 3	Column 4
Number of stages	22	60	45	16
Feed stage	11	31	23	9
Distillate to feed ratio (kmol/h)	402.96	185.71	175.63	44.92
Reflux ratio	0.888	9.68	4.17	1.86
Condenser heat duty (GJ/h)	17.04	49.40	19.33	2.45
Reboiler heat duty (GJ/h)	18.85	49.42	19.48	2.56
Condenser type	Total	Total	Total	Total
Reboiler type	Kettle	Kettle	Kettle	Kettle

Table 38 Stream result of steady-state for case study 3

Component	Mole flowrate (Kmol/h) (Steam 1)	Separated		%Purity
		Stream	Separated (Kmol/h)	
(A) Propane	45.50	6	42.21	92.77%
(B) iso-Butane	136.50	7	125.53	91.96%
(C) n-Butane	227.50	5	215.71	94.82%
(D) iso-Pentane	182.00	8	173.39	95.27%
(E) n-Pentane	318.50	9	315.91	99.19%

For configuration number 2 (Figure 64), sources and sinks of each heat integrate are showed in Table 39. The comparison of costs between process with and without heat integration is showed in Table 40. Stream result of steady-state of configuration number 1 (Figure 63) and configuration number 2 (Figure 64) for case study 3 is showed in Table 38. And the comparative study using various methods of case study 3 are showed in Table 41.

Table 39 Source and sink of each heat integration match for configuration number 2 of case study 2

Heat stream	Source-Sink
10-11	Column 4 - Column 2
13-16	Column 3 - Column 1

Table 40 The comparison of costs between process with and without heat integration of each column in the optimal configuration of case study 3

Format	Best cost (\$)	
	With heat integration	Without heat integration
Optimal configuration	149,809,030	149,171,538
Reduce the costs (%)	0.4255%	



Table 41 Comparative study using various methods of case study 3

Method	Ant colony algorithm	Harmony search algorithm	Simulated annealing	General Algebraic
Authors	This work	This work	zhong	Floudast
Optimal configuration for distillation sequences	$S_k = \{3,4,2,1\}$	$S_k = \{3,4,2,1\}$	$S_k = \{3,1,2,4\}$	$S_k = \{1,3,2,4\}$
The total annual cost (\$) (without heat-integration)	157,295,890	157,295,890	-	-
Optimal configuration for heat-integrated distillation sequences	$S_k = \{3,4,2,1\}$ $H_k = \{4,2\}, \{3,1\}$	$S_k = \{3,4,2,1\}$ $H_k = \{4,1\}, \{2,3\}$	$S_k = \{3,1,2,4\}$ $H_k = \{2,4\}$	$S_k = \{1,3,2,4\}$ $H_k = \{1,4\}$
The total annual cost (\$) (with heat-integration)	149,171,538	149,702,074	-	-

4. Case study 4

This is a six-component problem from Sophos et al (1981,1982) and the components with their mole fractions are shown in Table 42. The costs of the 42 possible sequences without and with integration are shown in Table 47.

Table 42 Components and mole fractions of the feed of case study 4

Key Component	Component	Formula	Mole fraction	Boiling Temperature
A	iso-Butane	C ₄ H ₁₀ -2	0.05	261.0 K
B	n-Butane	C ₄ H ₁₀ -1	0.05	272.6 K
C	neo-Pentane	C ₅ H ₁₂ -3	0.10	283.0 K
D	n-Pentane	C ₅ H ₁₂ -1	0.15	308.0 K
E	n-Hexane	C ₆ H ₁₄ -1	0.25	342.0 K
F	n-Heptane	C ₇ H ₁₆ -1	0.40	371.0 K

Data simulation for process

- Property method & models

Process type : Common
Base method : BK 10

- Feed state variables

Feed flow rate : 1000 kmol/h
Temperature : 298 K
Pressure : 1 atm

- Heat transfer parameters

Overall heat transfer : 1000 Watt/m²K
Log mean temperature : 10 K
Cost equations for heat exchanger network : 2143 A^{0.514}

4.1 Ant colony algorithm for distillation sequences (DS) (without heat-integrated distillation sequences)

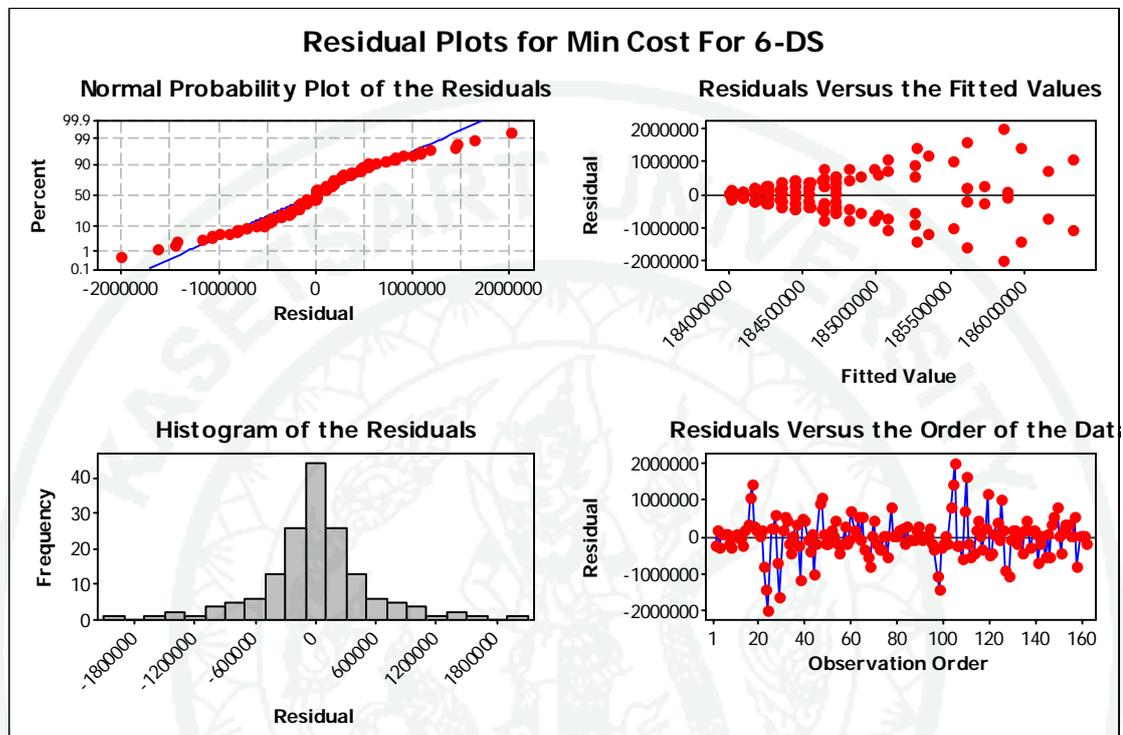


Figure 65 Hypothesis testing of Ant colony algorithm for case study 4 (6-DS)

Figure 65 show of testing the hypothesis of the Ant colony algorithm for case study 4 (6-DS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For 6-DS, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/ant	2	78971618287	78971618287	39485809144
Weight of pheromone	2	2.04045E+12	2.04045E+12	1.02022E+12
Weight of heuristic information	2	4.49616E+12	4.49616E+12	2.24808E+12
Evaporation	2	1.85502E+12	1.85502E+12	9.27510E+11
Source		F	P	
Iteration/ant		0.07	0.937	
Weight of pheromone		1.69	0.192	
Weight of heuristic information		3.72	0.029	
Evaporation		1.53	0.222	

Figure 66 Analysis of variance of the Ant colony algorithm for case study 4 (6-DS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 67 was iteration / ants (I/A) to the P-value = 0.937, weight of pheromone (WOP) to the P-value = 0.192, weight of heuristic information (WOH) for the P-value = 0.029 and evaporation rate (ER) to the P-value. = 0.222 shows that the factors is weight of heuristic information (WOH) as the impact Ant colony algorithm to find the answer for 6-HIDS which is determined by the P-value is less than 0.05. In contrast, three factors have no effect on finding answers to the iteration / ant (I / A), weight of pheromone (WOP) and evaporation rate (ER), because the P-value is greater than 0.5.

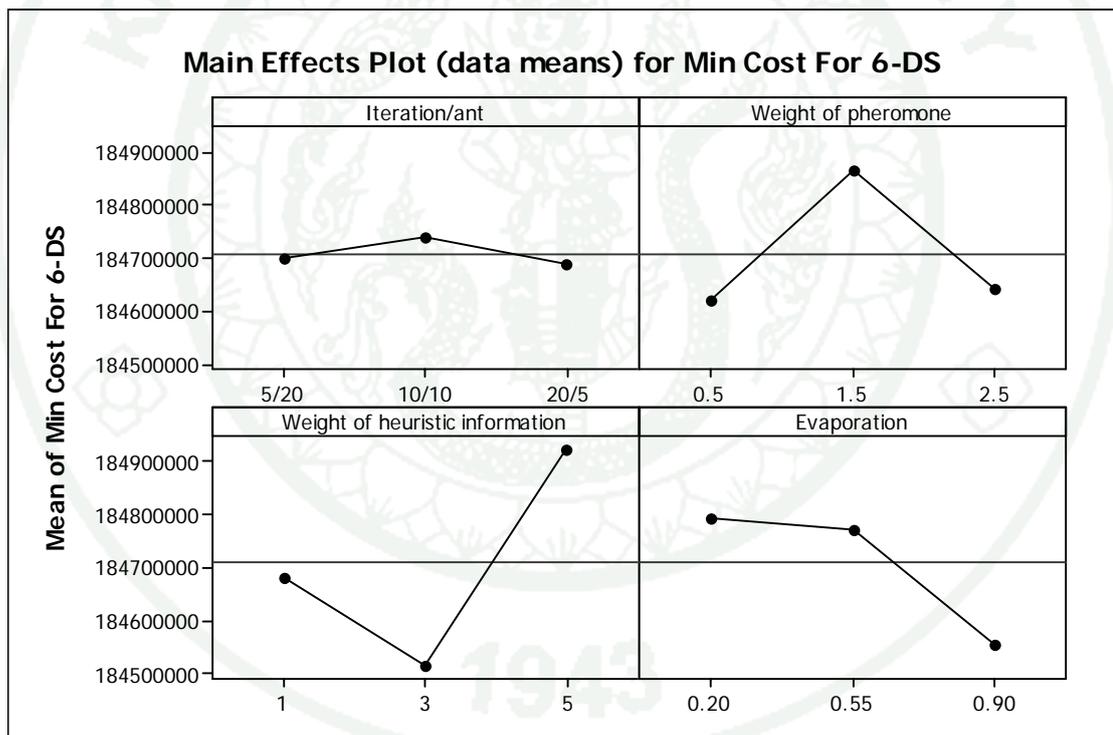


Figure 67 Impact that occurs on the main factors of Ant colony algorithm for case study 4 (6-DS)

Main effects plot caused major problems of case study 4 (6-DS) for the Ant colony algorithm was the iteration / ants (I/A) at 20 / 5, weight of pheromone (WOP) at 0.5, weight of heuristic information (WOH) at 3 and evaporation rate (ER) at 0.90.

All this resulted in answers to the most valuable minimum cost. It can be summarized in Table 43.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 68.

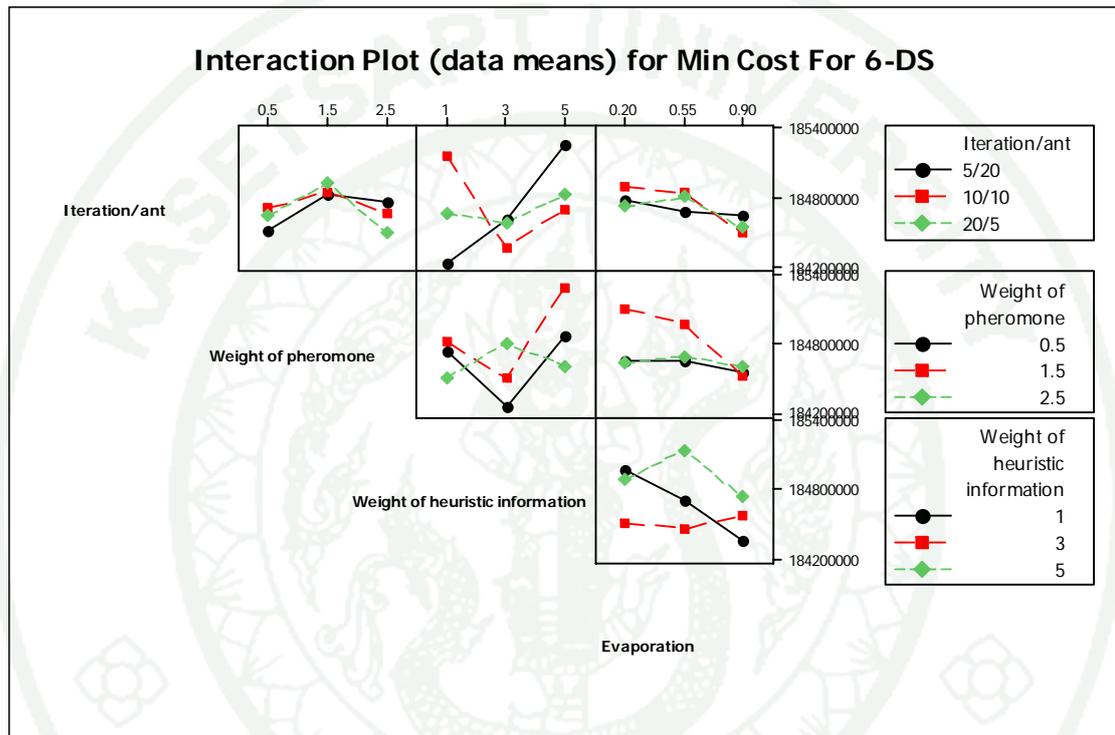


Figure 68 Interaction plot between the Ant colony algorithm for case study 4 (6-DS)

4.2 Ant colony algorithm for heat-integrated distillation sequences (HIDS) (with heat-integrated distillation sequences)

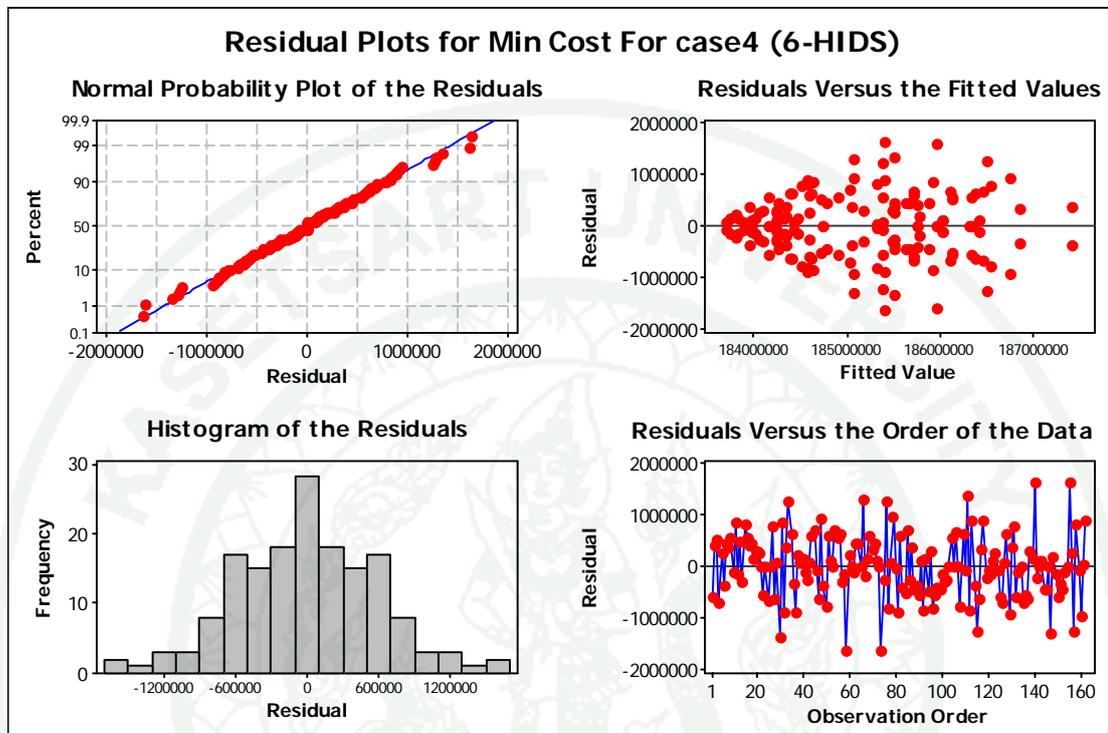


Figure 69 Hypothesis testing of Ant colony algorithm for case study 4 (6-HIDS)

Figure 69 show of testing the hypothesis of the Ant colony algorithm for case study 4 (6-HIDS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For case4 (6-HIDS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/Ants	2	3.81139E+11	3.81139E+11	1.90570E+11
Weight of pheromone	2	2.83690E+12	2.83690E+12	1.41845E+12
Weight of heuristic information	2	6.09245E+13	6.09245E+13	3.04622E+13
Evaporation rate	2	5.87150E+11	5.87150E+11	2.93575E+11
Source		F	P	
Iteration/Ants		0.26	0.771	
Weight of pheromone		1.94	0.150	
Weight of heuristic information		41.71	0.000	
Evaporation rate		0.40	0.670	

Figure 70 Analysis of variance of the Ant colony algorithm for case study 4 (6-HIDS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 71 was iteration / ants (I/A) to the P-value = 0.771, weight of pheromone (WOP) to the P-value = 0.150, weight of heuristic information (WOH) for the P-value = 0.000 and evaporation rate (ER) to the P-value. = 0.670 shows that the factors is weight of heuristic information (WOH) as the impact Ant colony algorithm to find the answer for 6-HIDS which is determined by the P-value is less than 0.05. In contrast, three factors have no effect on finding answers to the iteration / ant (I / A), weight of pheromone (WOP) and evaporation rate (ER), because the P-value is greater than 0.05.

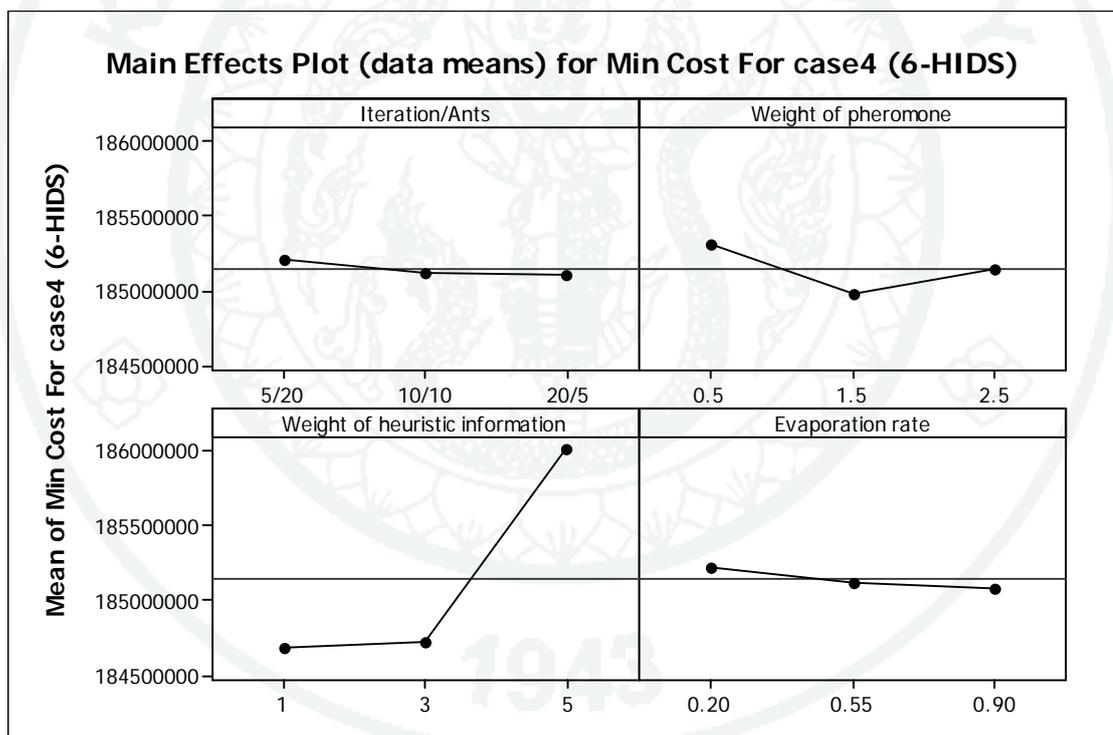


Figure 71 Impact that occurs on the main factors of Ant colony algorithm for case study 4 (6-HIDS)

Main effects plot caused major problems of case study 4 (6-HIDS) for the Ant colony algorithm was the iteration / ants (I/A) at 20 / 5, weight of pheromone (WOP) at 1.5, Weight of heuristic information (WOH) at 1 and Evaporation rate (ER) at 0.90.

All this resulted in answers to the most valuable minimum cost. It can be summarized in Table 43.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 72.

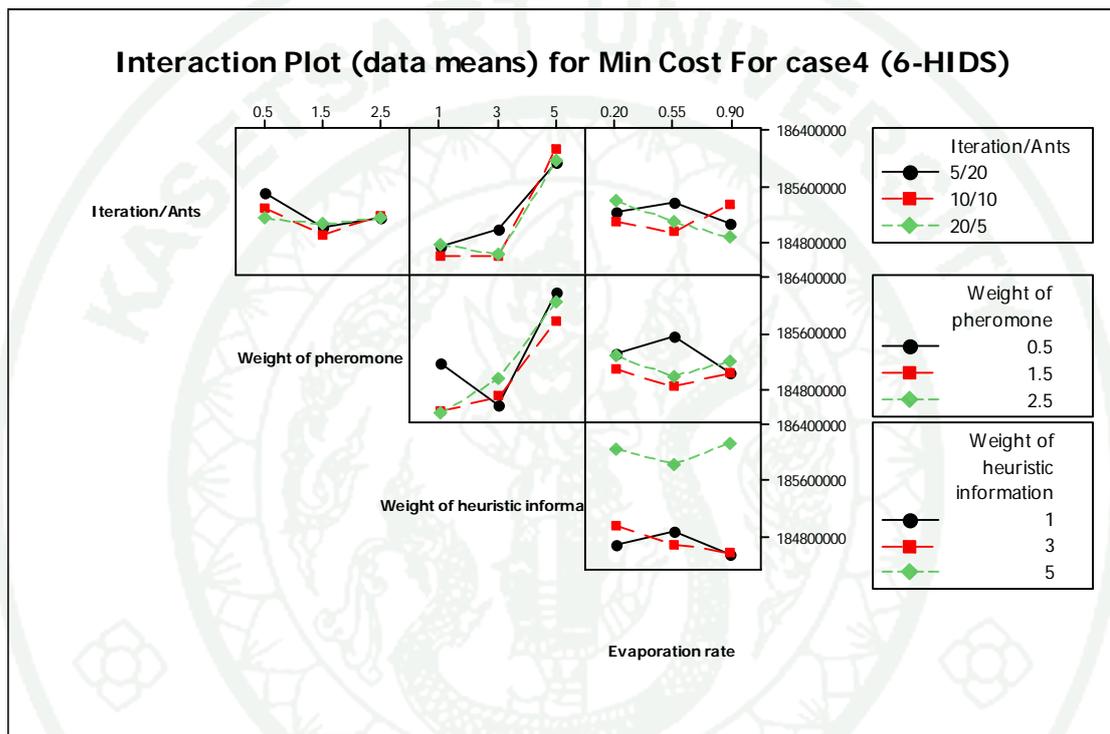


Figure 72 Interaction plot between the Ant colony algorithm for 6-HIDS

4.3 Harmony search algorithm for distillation sequences (DS) (without heat-integrated distillation sequences)

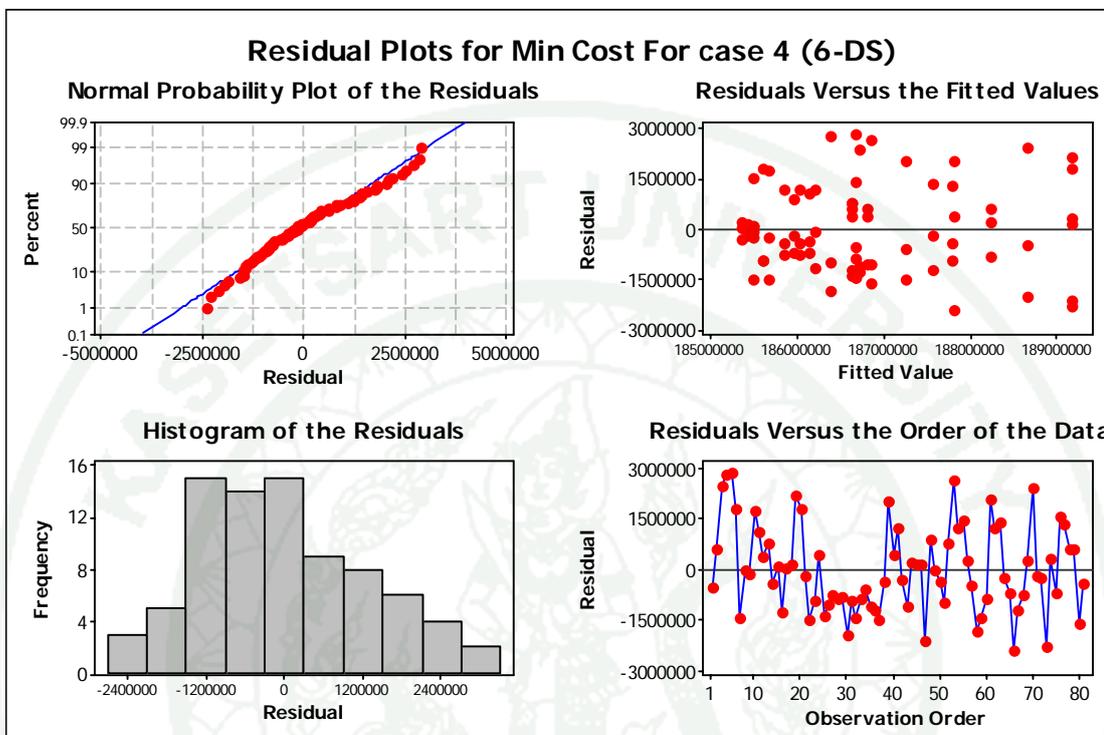


Figure 73 Hypothesis testing of Harmony search algorithm for case study 4 (6-DS)

Figure 73 show of testing the hypothesis of the harmony search for case study 4 (6-DS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For case 4 (6-DS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/Harmony size	2	1.61458E+13	1.61458E+13	8.07289E+12
Harmony Memory Considering Rate	2	2.34147E+13	2.34147E+13	1.17073E+13
Pitch Adjustment Rate	2	1.56711E+12	1.56711E+12	7.83554E+11
Source	F	P		
Iteration/Harmony size	3.29	0.045		
Harmony Memory Considering Rate	4.77	0.012		
Pitch Adjustment Rate	0.32	0.728		

Figure 74 Analysis of variance of the Harmony search algorithm for case study 4 (6-DS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 75 was iteration / harmony size (I/H) to the P-value = 0.045, harmony memory considering rate (HMCR) to the P-value = 0.012, and pitch adjustment rate (PAR) to the P-value. = 0.728 shows that the two factors is iteration / Harmony size (I/H) and harmony memory considering rate (HMCR) as the impact Harmony search algorithm to find the answer for 6-DS which is determined by the P-value is less than 0.05. In contrast, a factor have no effect on finding answers to the pitch adjustment rate (PAR) , because the P-value is greater than 0.5.

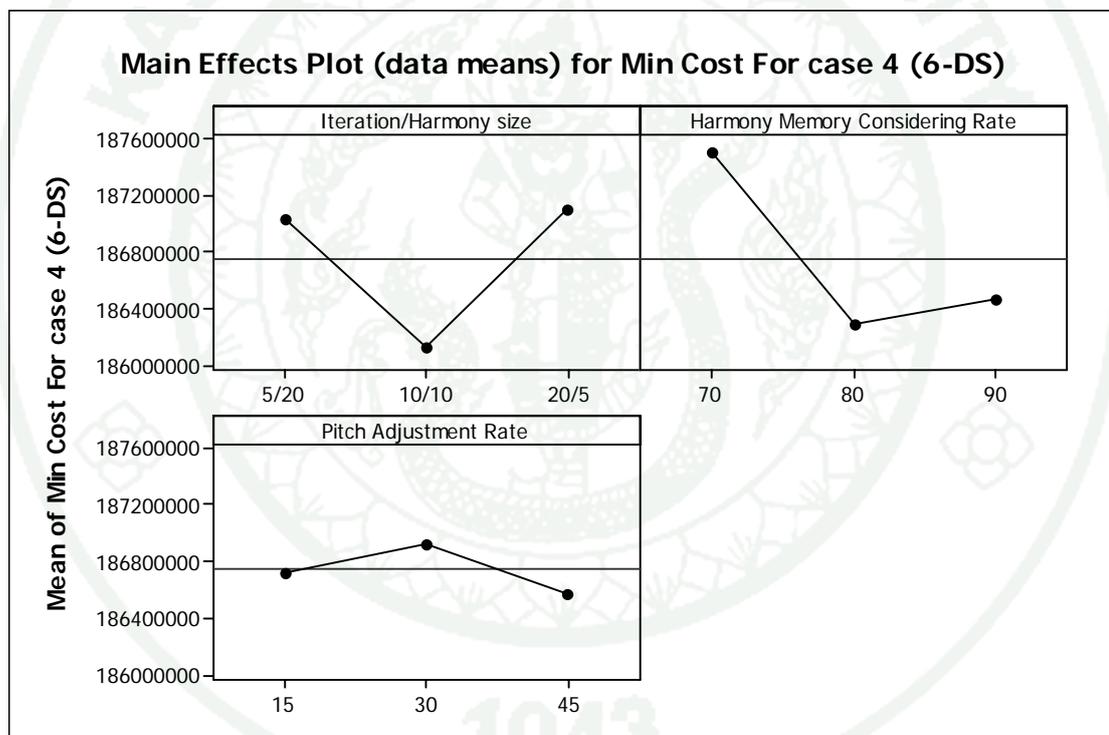


Figure 75 Impact that occurs on the main factors of Harmony search algorithm for case study 4 (6-DS)

Main effects plot caused major problems of case study 4 (6-DS).for the Harmony search algorithm was the iteration / harmony size (I/H) at 10 / 10, harmony memory considering rate (HMCR) at 80, and Pitch adjustment rate at 45. All this resulted in answers to the most valuable minimum cost. It can be summarized in Table 44.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 76.

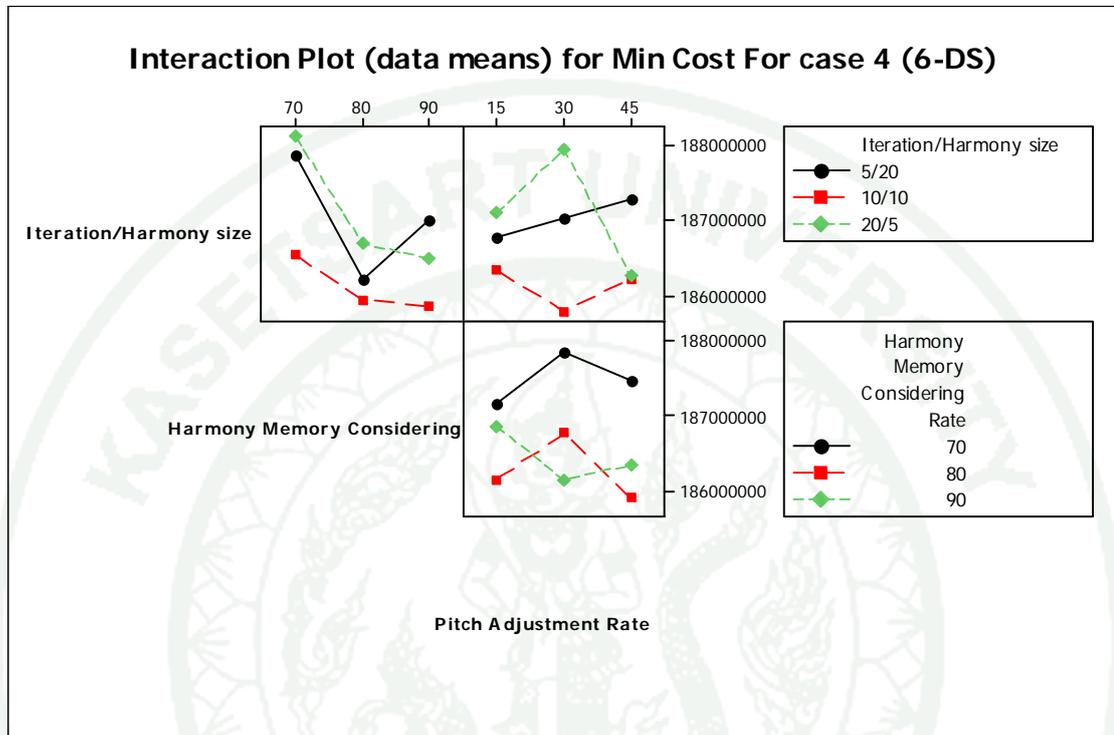


Figure 76 Interaction plot between the Harmony search algorithm for case study 4 (6-DS)

1943

4.4 Harmony search algorithm for heat-integrated distillation sequences (HIDS) (with heat-integrated distillation sequences)

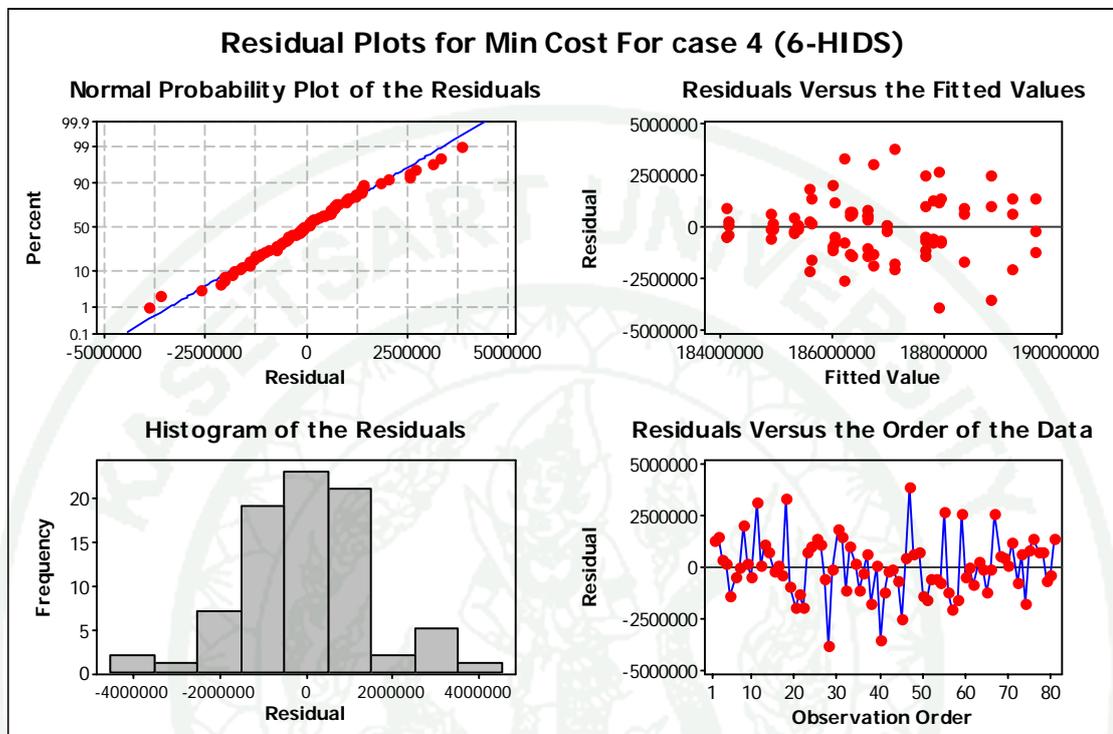


Figure 77 Hypothesis testing of Harmony search algorithm for case study 4 (6-HIDS)

Figure 77 show of testing the hypothesis of the harmony search for case study 4 (6-HIDS). The method described in the chapter on the conditions of the experiment show that not contradict the hypothesis.

Analysis of Variance for Min Cost For case 4 (6-HIDS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS
Iteration/Harmony size	2	2.99423E+13	2.99423E+13	1.49711E+13
Harmony Memory Considering Rate	2	2.90947E+12	2.90947E+12	1.45474E+12
Pitch Adjustment Rate	2	2.12500E+13	2.12500E+13	1.06250E+13
Source	F	P		
Iteration/Harmony size	4.91	0.011		
Harmony Memory Considering Rate	0.48	0.623		
Pitch Adjustment Rate	3.49	0.038		

Figure 78 Analysis of variance of the Harmony search algorithm for case study 4 (6-HIDS)

After checking the assumptions. We can analyze the variance in the form of linear equations (Anova, General linear model), which is analyzed using statistical confidence at 95% are shown in Figure 79 was iteration / Harmony size (I/H) to the P-value = 0.011, harmony memory considering rate (HMCR) to the P-value = 0.623, and pitch adjustment rate (PAR) to the P-value. = 0.038 shows that the two factors is iteration / harmony size (I/H) and pitch adjustment rate (PAR) as the impact Harmony search algorithm to find the answer for case study 4 (6-HIDS) which is determined by the P-value is less than 0.05. In contrast, a factor have no effect on finding answers to the harmony memory considering rate (HMCR) , because the P-value is greater than 0.5.

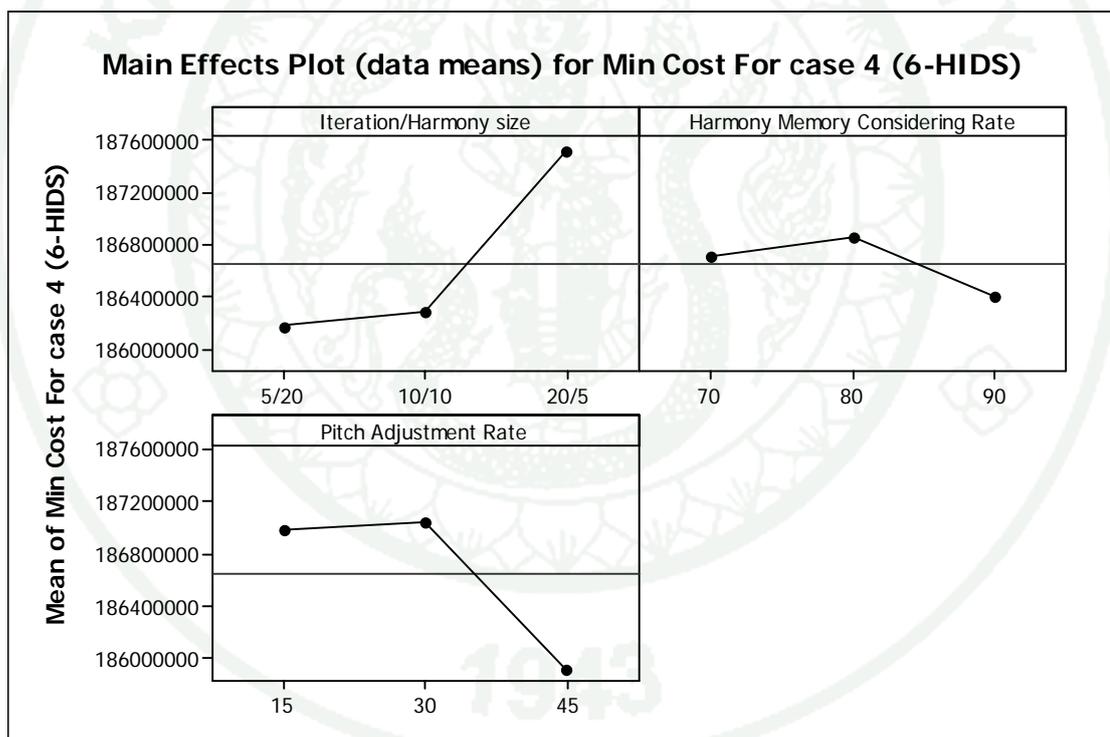


Figure 79 Impact that occurs on the main factors of Harmony search algorithm for case study 4 (6-HIDS)

Main effects plot caused major problems of case study 4 (6-HIDS) for the Harmony search algorithm was the iteration / harmony size (I/H) at 5 / 20, harmony memory considering rate (HMCR) at 90, and Pitch adjustment rate at 45. All this

resulted in answers to the most valuable minimum cost. It can be summarized in Table 44.

Main effects plot for after then can the relationship between the four determinants can be obtained from the interaction plot as shown in Figure 80.

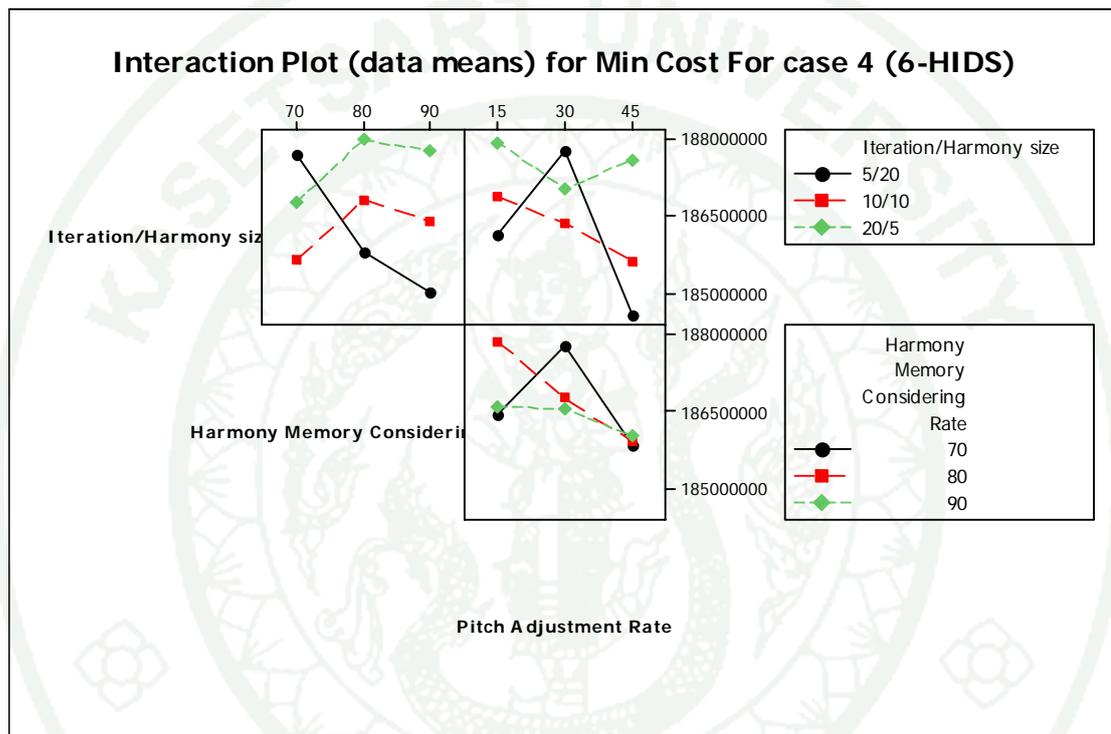


Figure 80 Interaction plot between the Harmony search algorithm for case study 4 (6-HIDS)

4.5 Comparison of results between the two methods.

After these parameters at optimal way Ant colony algorithm are shown in Table 51 and the parameters are the optimal way Harmony search algorithm are shown in Table 52 is important for them each how to enter the program Visual Studio V.8.0 to make. Run each of 20 values are shown in Table 45 and Table 46 of the two processes is to compare the distillation sequences (DS) or without heat-integrated and the heat-integrated distillation sequences (HIDS) or with heat-integrated to find a way to provide the best solution.

Table 43 Optimization of levels and factors of Ant colony algorithm for case study 4

Factors	Distillation sequences (DS)	Heat-integrated distillation sequences (HIDS)
Iteration/Ants (I/A)	5/20 (Low)	20/5 (High)
Weight of pheromone (WOP)	0.5 (Medium)	1.5 (Medium)
Weight of heuristic information (WOH)	3 (Medium)	1 (Low)
Evaporation rate (ER)	0.55 (Medium)	0.90 (High)

Table 44 Optimization of levels and factors of Harmony search algorithm for case study 4

Factors	Distillation sequences (DS)	Heat-integrated distillation sequences (HIDS)
Iteration/Harmony size (I/H)	10/10 (Medium)	5/20 (Low)
Harmony memory considering rate (HMCR)	80 (Medium)	90 (High)
Pitch adjustment rate (PAR)	45 (High)	45 (High)

Table 45 The best run of distillation sequences for case study 4 (6-DS)

K	Distillation sequences (DS)			
	Ant colony algorithm		Harmony search algorithm	
	Code Sequences (s_k)	Minimum Cost (\$)	Code Sequences (s_k)	Minimum Cost (\$)
1	{5,4,3,2,1}	187,581,833	{5,4,3,2,1}	187,581,833
2	{5,4,3,2,1}	187,581,833	{5,4,3,2,1}	187,581,833
3	{2,1,5,4,3}	187,400,433	{5,4,3,2,1}	187,581,833
4	{2,1,5,4,3}	187,400,433	{2,1,5,4,3}	187,400,433
5	{2,1,5,4,3}	187,400,433	{5,4,3,2,1}	187,581,833
6	{5,4,3,2,1}	187,581,833	{5,4,2,1,3}	191,716,104
7	{5,4,3,2,1}	187,581,833	{5,4,3,2,1}	187,581,833
8	{2,1,5,4,3}	187,400,433	{5,4,3,2,1}	187,581,833
9	{5,4,3,2,1}	187,581,833	{5,4,3,2,1}	187,581,833
10	{2,1,5,4,3}	187,400,433	{5,4,3,2,1}	187,581,833
11	{5,4,3,2,1}	187,581,833	{5,4,3,2,1}	187,581,833
12	{2,1,5,4,3}	187,400,433	{5,4,3,2,1}	187,581,833
13	{2,1,5,4,3}	187,400,433	{5,4,2,1,3}	191,716,104
14	{5,4,3,2,1}	187,581,833	{5,4,2,1,3}	191,716,104
15	{2,1,5,4,3}	187,400,433	{5,4,3,2,1}	187,581,833
16	{2,1,5,4,3}	187,400,433	{5,4,3,2,1}	187,581,833
17	{5,4,3,2,1}	187,581,833	{2,1,5,4,3}	187,400,433
18	{5,4,3,2,1}	187,581,833	{5,4,3,2,1}	187,581,833
19	{2,1,5,4,3}	187,400,433	{2,1,5,4,3}	187,400,433
20	{5,4,3,2,1}	187,581,833	{5,4,3,2,1}	187,581,833
Best cost(\$)	{2,1,5,4,3}	187,400,433	{2,1,5,4,3}	187,400,433
Average		187,491,133		188,174,764
St.Dev		93,056.236		1,527,708.52

Table 45 concluded that a solution distillation sequences (DS), using Ant colony algorithm and Harmony search algorithm gives the same run 20 times by optimal distillation sequences is {2,1,5,4,3} or AB/CDEF, A/ B, CDE/F, C/DE, D/E with investment cost is 187,400,433 USD/ year.

Table 46 The best run of distillation sequences for case study 4 (6-HIDS)

K	Heat-integration distillation sequences (HIDS)					
	Ant colony algorithm			Harmony search algorithm		
	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)	Code Sequences (s_k)	Code Match (h_k)	Minimum Cost (\$)
1	{5,4,3,2,1}	{3,4},{2,1}	187,211,644	{2,1,5,4,3}	{5,3},{4,2}	187,173,609
2	{5,4,3,2,1}	{2,4},{5,3}	187,040,390	{5,4,3,2,1}	{1,2},{4,5}	187,164,978
3	{5,4,3,2,1}	{1,2},{3,5}	187,168,450	{2,1,5,4,3}	{2,3},{1,4}	187,213,299
4	{5,4,3,2,1}	{5,1},{3,4}	187,198,516	{5,4,3,2,1}	{5,1},{4,2}	187,394,766
5	{2,1,5,3,4}	{2,5},{3,4}	186,780,025	{5,4,3,2,1}	{1,2},{5,4}	187,169,248
6	{5,4,3,2,1}	{5,1},{2,3}	187,387,073	{5,4,2,1,3}	{5,1},{4,2}	187,394,766
7	{5,4,3,2,1}	{5,1},{2,4}	187,219,226	{5,4,2,1,3}	{5,4},{2,3}	191,176,728
8	{5,4,3,2,1}	{5,1},{2,3}	187,387,073	{5,4,3,2,1}	{1,2},{5,3}	186,990,412
9	{5,4,3,2,1}	{1,2},{3,4}	186,986,559	{5,4,3,2,1}	{2,3},{1,4}	187,393,968
10	{5,4,3,2,1}	{1,2},{3,5}	187,168,450	{5,4,3,2,1}	{5,3},{4,1}	187,215,930
11	{5,4,3,2,1}	{3,4},{5,2}	187,198,516	{5,4,3,2,1}	{3,5},{2,1}	187,394,766
12	{5,4,3,2,1}	{3,4},{5,2}	187,198,516	{2,1,5,4,3}	{5,3},{4,2}	187,173,609
13	{5,4,3,2,1}	{2,1},{5,3}	187,215,497	{5,4,3,2,1}	{3,5},{2,1}	187,394,766
14	{5,4,3,2,1}	{2,4},{5,3}	187,040,390	{5,4,3,2,1}	{1,2},{5,3}	186,990,412
15	{5,4,3,2,1}	{1,2},{3,5}	187,168,450	{2,1,5,4,3}	{2,3},{1,4}	187,213,299
16	{5,4,3,2,1}	{2,1},{4,3}	187,379,141	{5,4,3,2,1}	{2,1},{5,3}	187,215,497
17	{5,4,3,2,1}	{2,3},{4,5}	187,382,803	{5,4,2,1,3}	{4,3},{2,1}	187,393,968
18	{5,4,3,2,1}	{1,2},{4,5}	187,164,978	{5,4,2,1,3}	{4,3},{2,1}	187,393,968
19	{5,4,3,2,1}	{3,2},{5,1}	187,394,732	{5,4,2,1,3}	{5,1},{4,2}	187,394,766
20	{2,1,5,3,4}	{3,1},{4,5}	186,781,963	{5,4,2,1,3}	{2,1},{3,4}	187,211,644
Best cost(\$)	{2,1,5,3,4}	{2,5},{3,4}	186,780,025	{5,4,3,2,1}	{1,2},{5,3}	186,990,412
Average			187,173,620			187,453,220
St.Dev			179,488.971			886,355.671

Table 46 concluded that a solution heat-integrated distillation sequences (HIDS), using Ant colony algorithm. The optimal of heat-integrated distillation sequences (HIDS) that is $s_k = \{2,1,5,3,4\}$ or AB/CDEF, A/B, CDE/F, C/DE, D/E, $h_k = \{2,5\}, \{3,4\}$ or condenser at column 2 match steam reboiler at column 5 and condenser at column 3 match steam reboiler at column 4 , with investment costs

186,780,025 USD / year, using Harmony search algorithm. The optimal of heat-integrated distillation sequences (HIDS) that is $s_k = \{5,4,3,2,1\}$ or ABCDE/F, ABCD/E, ABC/D, AB/C, A/B, $h_k = \{1,2\}, \{5,3\}$ or condenser at column 1 match steam reboiler at column 2 and condenser at column 5 match steam reboiler at column 3, with investment costs 186,990,412 USD / year. The Ant colony algorithm is more robust Harmony search algorithm seen from the average of the Ant colony algorithm using the average is 187,173,620 USD/year was lower cost than the Harmony search algorithm is the average is 187,453,220 USD/year, but both can provide the best cost the same configuration.

Table 47 The selected answers and costs of each configuration for case study 4

#	Configurations					Distillation Sequences			
	Column 1	Column 2	Column 3	Column 4	Column 5	Ant colony algorithm	Cost in (\$) 10,000	Harmony search algorithm	Cost in (\$) 10,000
1	A/BCDEF	B/CDEF	C/DEF	D/EF	E/F	0	-	0	-
2	A/BCDEF	B/CDEF	C/DEF	DE/F	D/E	0	-	0	-
3	A/BCDEF	B/CDEF	CD/EF	C/D	E/F	0	-	0	-
4	A/BCDEF	B/CDEF	CDE/F	C/DE	D/E	0	-	0	-
5	A/BCDEF	B/CDEF	CDE/F	CD/E	C/D	0	-	0	-
6	A/BCDEF	BC/DEF	B/C	D/EF	E/F	0	-	0	-
7	A/BCDEF	BC/DEF	B/C	DE/F	D/E	0	-	0	-
8	A/BCDEF	BCD/EF	E/F	B/CD	C/D	1	27,237	0	-
9	A/BCDEF	BCD/EF	E/F	BC/D	B/C	0	-	0	-
10	A/BCDEF	BCDE/F	B/CDE	C/DE	D/E	0	-	0	-
11	A/BCDEF	BCDE/F	B/CDE	CD/E	C/D	0	-	0	-
12	A/BCDEF	BCDE/F	BC/DE	B/C	D/E	1	25,145	0	-
13	A/BCDEF	BCDE/F	BCD/E	B/CD	C/D	0	-	0	-
14	A/BCDEF	BCDE/F	BCD/E	BC/D	B/C	0	-	0	-
15	AB/CDEF	A/B	C/DEF	D/EF	E/F	0	-	0	-
16	AB/CDEF	A/B	C/DEF	DE/F	D/E	2	26,370	0	-
17	AB/CDEF	A/B	CD/EF	C/D	E/F	3	23,979	4	23,979

Table 47 (Continued)

#	Configurations					Distillation Sequences			
	Column 1	Column 2	Column 3	Column 4	Column 5	Ant colony algorithm	Cost in (\$) 10,000	Harmony search algorithm	Cost in (\$) 10,000
18	AB/CDEF	A/B	CDE/F	C/DE	D/E	0	-	18	19,941
19	AB/CDEF	A/B	CDE/F	CD/E	C/D	2	18,740*	10	18,740*
20	ABC/DEF	A/BC	B/C	D/EF	E/F	0	-	0	-
21	ABC/DEF	A/BC	B/C	DE/F	D/E	1	21,137	0	-
22	ABC/DEF	AB/C	A/B	D/EF	E/F	2	22,712	0	-
23	ABC/DEF	AB/C	A/B	DE/F	D/E	0	-	0	-
24	ABCD/EF	E/F	A/BCD	B/CD	C/D	1	21,210	0	-
25	ABCD/EF	E/F	A/BCD	BC/D	B/C	1	20,398	10	20,398
26	ABCD/EF	E/F	AB/CD	A/B	C/D	4	19,602	0	-
27	ABCD/EF	E/F	ABC/D	A/BC	B/C	2	19,590	2	19,590
28	ABCD/EF	E/F	ABC/D	AB/C	A/B	1	19,188	6	19,188
29	ABCDE/F	A/BCDE	B/CDE	C/DE	D/E	2	25,158	10	25,158
30	ABCDE/F	A/BCDE	B/CDE	CD/E	C/D	5	23,957	0	-
31	ABCDE/F	A/BCDE	BC/DE	B/C	D/E	3	22,348	10	22,348
32	ABCDE/F	A/BCDE	BCD/E	B/CD	C/D	4	22,371	0	-
33	ABCDE/F	A/BCDE	BCD/E	BC/D	B/C	7	21,559	10	21,559
34	ABCDE/F	AB/CDE	A/B	C/DE	D/E	13	21,527	0	-
35	ABCDE/F	AB/CDE	A/B	CD/E	C/D	12	20,326	0	-

Table 47 (Continued)

#	Configurations					Distillation Sequences			
	Column 1	Column 2	Column 3	Column 4	Column 5	Ant colony algorithm	Cost in (\$) 10,000	Harmony search algorithm	Cost in (\$) 10,000
36	ABCDE/F	ABC/DE	D/E	A/BC	B/C	10	19,552	0	-
37	ABCDE/F	ABC/DE	D/E	AB/C	A/B	8	19,150	0	-
38	ABCDE/F	ABCD/E	A/BCD	B/CD	C/D	3	20,780	0	-
39	ABCDE/F	ABCD/E	A/BCD	BC/D	B/C	2	19,968	10	19,968
40	ABCDE/F	ABCD/E	AB/CD	A/B	C/D	5	19,171	0	-
41	ABCDE/F	ABCD/E	ABC/D	A/BC	B/C	3	19,159	0	-
42	ABCDE/F	ABCD/E	ABC/D	AB/C	A/B	2	18,758	20	18,758

* Best investment costs (USD/year)

Table 47 (Continued)

#	Configurations					Heat-integrated distillation sequences					
	Column 1	Column 2	Column 3	Column 4	Column 5	Ant colony algorithm	Cost in (\$) 10,000	Code Match	Harmony search algorithm	Cost in (\$) 10,000	Code Match
1	A/BCDEF	B/CDEF	C/DEF	D/EF	E/F	-	-	-	-	-	-
2	A/BCDEF	B/CDEF	C/DEF	DE/F	D/E	-	-	-	3	33,092	{2,5},{1,4}
3	A/BCDEF	B/CDEF	CD/EF	C/D	E/F	-	-	-	-	-	-
4	A/BCDEF	B/CDEF	CDE/F	C/DE	D/E	-	-	-	-	-	-
5	A/BCDEF	B/CDEF	CDE/F	CD/E	C/D	-	-	-	-	-	-
6	A/BCDEF	BC/DEF	B/C	D/EF	E/F	-	-	-	3	29,034	{4,3},{2,1}
7	A/BCDEF	BC/DEF	B/C	DE/F	D/E	-	-	-	-	-	-
8	A/BCDEF	BCD/EF	E/F	B/CD	C/D	1	27,189	{5,3},{1,4}	-	-	-
9	A/BCDEF	BCD/EF	E/F	BC/D	B/C	1	26,394	{5,1},{3,4}	-	-	-
10	A/BCDEF	BCDE/F	B/CDE	C/DE	D/E	-	-	-	9	27,879	{3,4},{5,2}
11	A/BCDEF	BCDE/F	B/CDE	CD/E	C/D	1	18,678	{4,5},{3,1}	10	26,699	{4,3},{2,1}
12	A/BCDEF	BCDE/F	BC/DE	B/C	D/E	-	-	-	-	-	-
13	A/BCDEF	BCDE/F	BCD/E	B/CD	C/D	-	-	-	-	-	-
14	A/BCDEF	BCDE/F	BCD/E	BC/D	B/C	-	-	-	-	-	-
15	AB/CDEF	A/B	C/DEF	D/EF	E/F	-	-	-	-	-	-
16	AB/CDEF	A/B	C/DEF	DE/F	D/E	-	-	-	-	-	-
17	AB/CDEF	A/B	CD/EF	C/D	E/F	-	-	-	-	-	-
18	AB/CDEF	A/B	CDE/F	C/DE	D/E	-	-	-	10	19,913	{1,2},{4,5}

Table 47 (Continued)

#	Configurations					Heat-integrated distillation sequences					
	Column 1	Column 2	Column 3	Column 4	Column 5	Ant colony algorithm	Cost in (\$) 10,000	Code Match	Harmony search algorithm	Cost in (\$) 10,000	Code Match
19	AB/CDEF	A/B	CDE/F	CD/E	C/D	1	18,678*	{3,1},{4,5}	-		
20	ABC/DEF	A/BC	B/C	D/EF	E/F	-	-	-	10	23,026	{3,2},{5,1}
21	ABC/DEF	A/BC	B/C	DE/F	D/E	1	21,083	{1,3},{5,4}	-		
22	ABC/DEF	AB/C	A/B	D/EF	E/F	-	-	-	-		
23	ABC/DEF	AB/C	A/B	DE/F	D/E	-	-	-	-		
24	ABCD/EF	E/F	A/BCD	B/CD	C/D	1	21,141	{1,4},{5,3}	-		
25	ABCD/EF	E/F	A/BCD	BC/D	B/C	2	20,364	{1,4},{5,3}	-		
26	ABCD/EF	E/F	AB/CD	A/B	C/D	2	19,559	{5,4},{2,3}	-		
27	ABCD/EF	E/F	ABC/D	A/BC	B/C	1	19,545	{1,4},{3,5}	-		
28	ABCD/EF	E/F	ABC/D	AB/C	A/B	2	19,171	{3,2},{1,5}	-		
29	ABCDE/F	A/BCDE	B/CDE	C/DE	D/E	2	25,089	{2,1},{3,4}	-		
30	ABCDE/F	A/BCDE	B/CDE	CD/E	C/D	4	23,922	{5,2},{3,4}	5	23,915	{1,2},{4,5}
31	ABCDE/F	A/BCDE	BC/DE	B/C	D/E	10	22,249	{5,2},{3,4}	-		
32	ABCDE/F	A/BCDE	BCD/E	B/CD	C/D	7	22,317	{5,4},{3,2}	5	22,317	{5,1},{3,2}
33	ABCDE/F	A/BCDE	BCD/E	BC/D	B/C	-	-	-	5	21,512	{1,2},{4,5}
34	ABCDE/F	AB/CDE	A/B	C/DE	D/E	9	21,462	{5,4},{2,3}	-		
35	ABCDE/F	AB/CDE	A/B	CD/E	C/D	14	20,266	{1,2},{3,5}	-		
36	ABCDE/F	ABC/DE	D/E	A/BC	B/C	15	19,474	{5,2},{3,4}	5	19,518	{1,4},{2,5}

Table 47 (Continued)

#	Configurations					Heat-integrated distillation sequences					
	Column 1	Column 2	Column 3	Column 4	Column 5	Ant colony algorithm	Cost in (\$) 10,000	Code Match	Harmony search algorithm	Cost in (\$) 10,000	Code Match
37	ABCDE/F	ABC/DE	D/E	AB/C	A/B	8	19,093	{2,4},{1,3}	5	19,096	{1,4},{2,5}
38	ABCDE/F	ABCD/E	A/BCD	B/CD	C/D	2	20,752	{1,5},{3,4}	-		
39	ABCDE/F	ABCD/E	A/BCD	BC/D	B/C	1	19,946	{2,4},{5,1}	-		
40	ABCDE/F	ABCD/E	AB/CD	A/B	C/D	7	19,107	{4,1},{3,2}	10	19,015	{1,2},{4,5}
41	ABCDE/F	ABCD/E	ABC/D	A/BC	B/C	4	19,115	{2,5},{3,4}	9	19,128	{4,3},{2,1}
42	ABCDE/F	ABCD/E	ABC/D	AB/C	A/B	3	18,716	{5,4},{1,2}	11	18,699*	{1,2},{5,3}

* Best investment costs (USD/year)

Table 47 shows the selection by the answers of the two methods by using:

Ant colony algorithm for solving the problem of case study 4 (DS). Select the configuration number 34 which was selected the most followed by the configuration number 35 , configuration number 36 respectively.

Harmony search algorithm for solving the problem of case study 4 (DS). Select the configuration number 42 which was selected the most followed by the configuration number 18 ,configuration number 19,25,29,31,33,39 respectively.

Ant colony algorithm for solving the problem of case study 4 (HIDS). Select the configuration number 36 which was selected the most followed by the configuration number 35 , configuration number 31 respectively.

Harmony search algorithm for solving the problem of case study 4 (HIDS). Select the configuration number 42 which was selected the most followed by the configuration number 11,18,20,40 ,configuration number 10,41 respectively.

2.6 Process synthesis at steady-state process

Distillation is an energy consuming process that is used for about 95% of all fluid separation in the chemical industry and accounts for an estimated 3% of the world energy consumption, Hewitt et al. (1999). The calculation of the minimum heating and cooling requirements reveal significant energy saving. Heat-integrated distillation sequence takes an advantage of a minimum external utility usage, so plant operating costs can be saved. In the previous part, the optimal heat integrated distillation sequences have been acquired, So there are three configurations for this process that are:

- 1) Configuration number 1 - process synthesis with the optimal distillation sequence.
- 2) Configuration number 2 - process synthesis with the optimal heat-integrated distillation sequence.
- 3) Configuration number 3 - process synthesis with the second best heat-integrated distillation sequence.

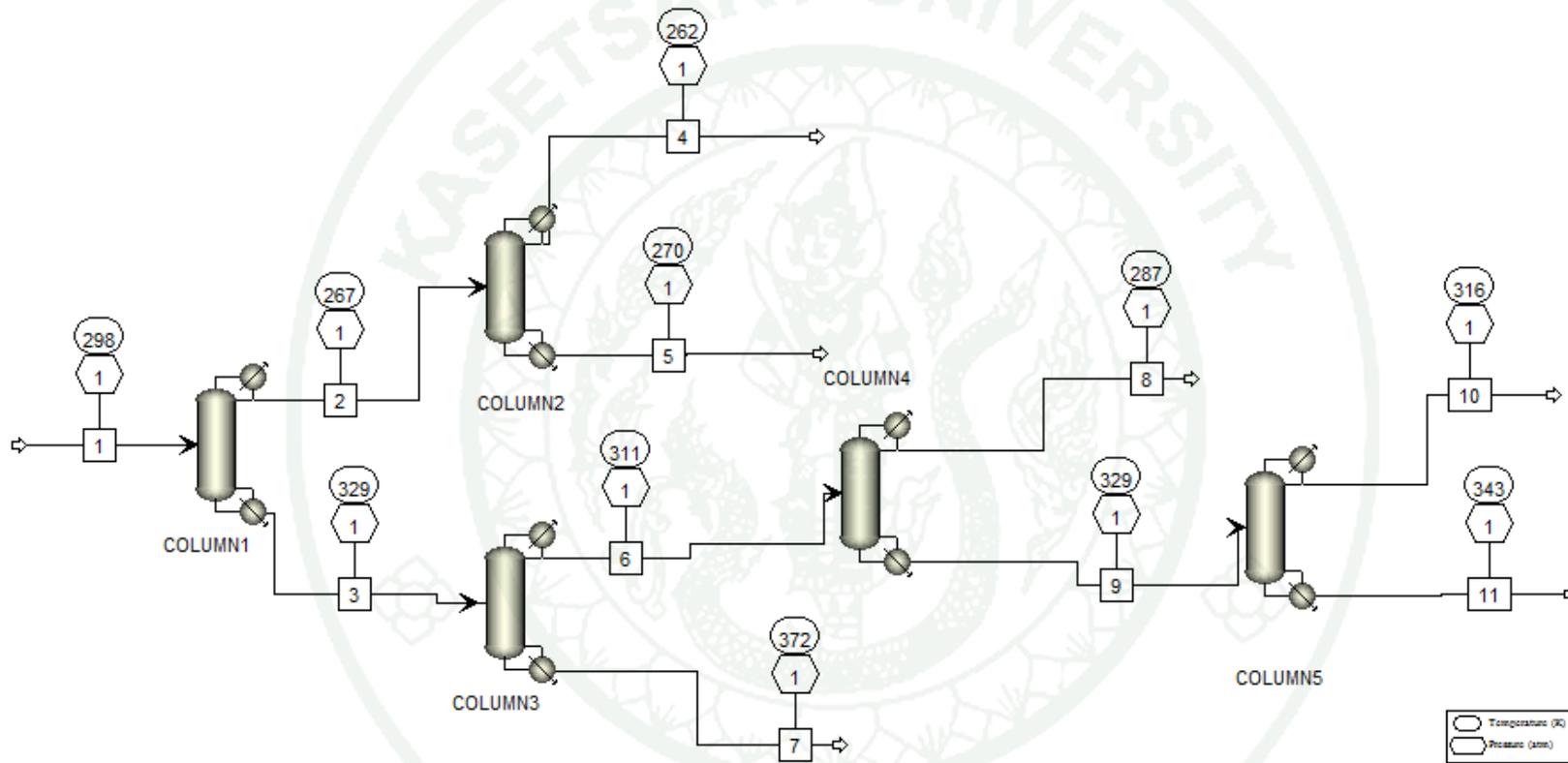


Figure 81 The optimal configuration number 1- Optimal of distillation sequences(without heat-integrated) for case study 4,
 Cost=187,400,433 USD/year

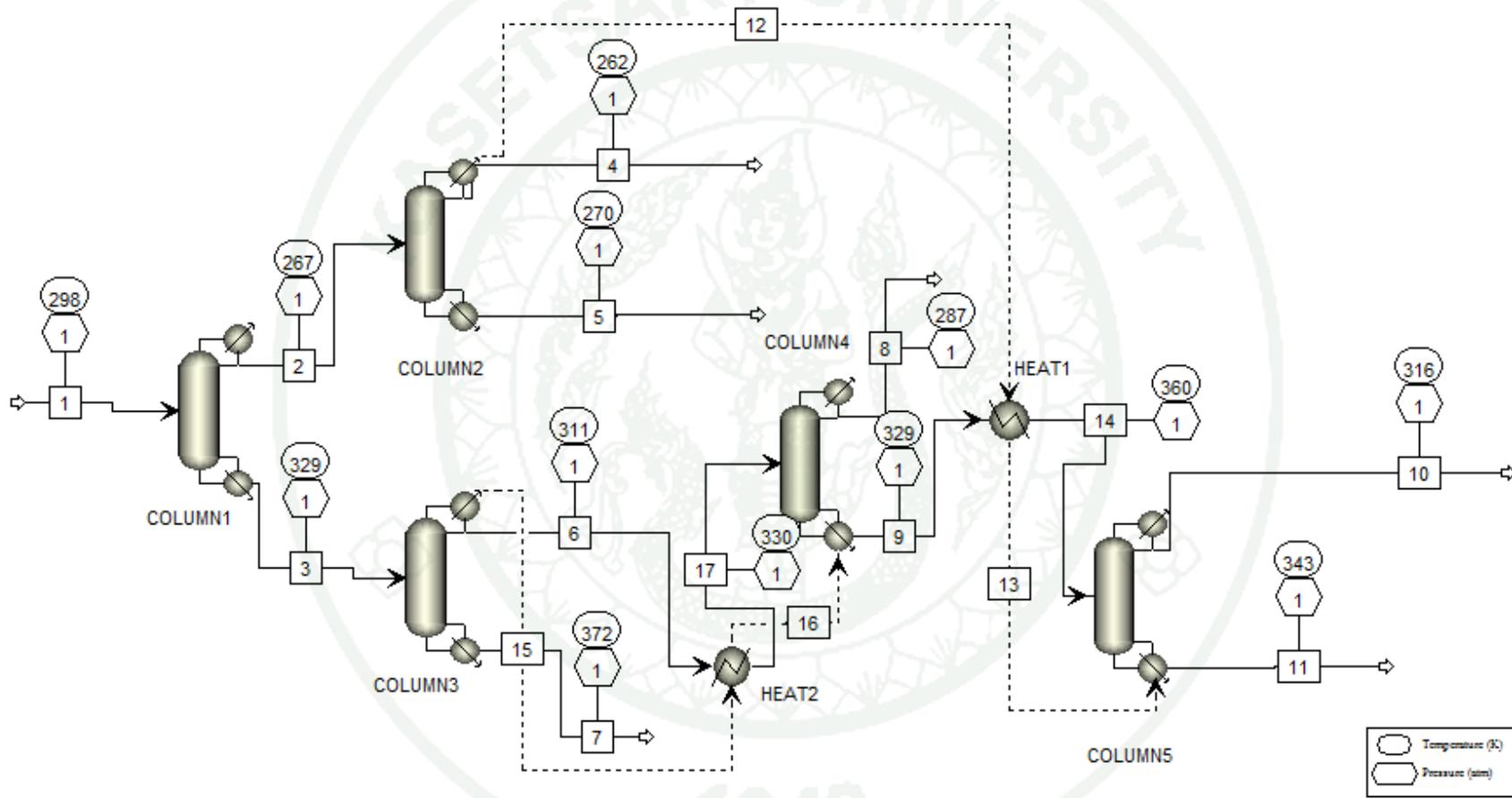


Figure 82 The optimal configuration number 2- Optimal of heat-integrated distillation sequences(with heat-integrated) for case study 4, Cost=186,780,025 USD/year.

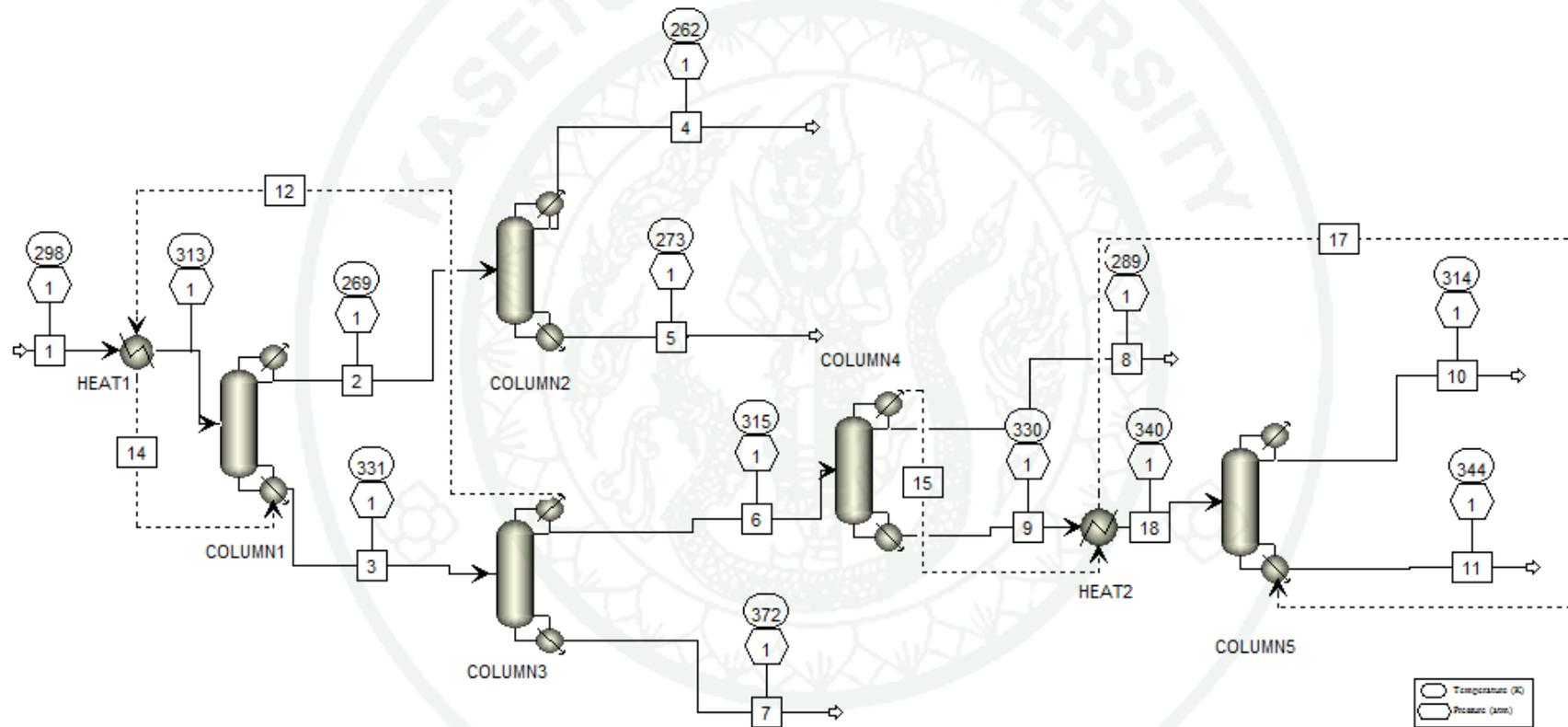


Figure 83 The second best configuration number 3- Optimal of heat-integrated distillation sequences(with heat-integrated) for case study 4, Cost=186,781,963 USD/year

In configuration number 1 (Figure 81), process synthesis is the optimal sequence solution. There are five distillation columns in this sequence, which is column number 1, 2, 3, 4 and 5. First, stream 1 is fed to column 1 to be separated iso-Butane and n-Butane as a distillate intermediate stream (stream 2) and neo-Pentane, n-Pentane, n-Hexane and n-Heptane is become a bottom intermediate stream (stream 3). Then, stream 2 is fed to column 2 to separate iso-Butane as a distillate product stream (stream 4) and n-Butane as a bottom product stream (stream 5). Stream 3 is become a feed stream of column 3 in order to separate n-Heptane out as a bottom product stream (stream 7) and other component (stream 6) is sent to column 4. This column separate neo-Pentane as a distillate product stream (stream 8) and n-Hexane, n-Heptane is become a bottom intermediate stream (stream 9). Then, stream 9 is fed to column 5 to separate n-Pentane as a distillate product stream (stream 10) and n-Hexane as a bottom product stream (stream 11). These four columns are Radfrac model. The operating condition of each column is shown in Table 48. The simulation result for configuration number 1, 2 and 3 is shown in Table 49. All simulation using DSTWU result for this configuration is shown in Appendix C4.

Table 48 Operating condition of each column in the optimal distillation sequences for case study 4

Operating condition	Optimal configuration				
	Column 1	Column 2	Column 3	Column 4	Column 5
Number of stages	48	45	22	11	18
Feed stage	25	23	11	6	9
Distillate to feed ratio (kmol/h)	99.99	49.99	500.69	98.50	150.91
Reflux ratio	4.88	3.85	1.2	14.17	2.17
Condenser heat duty (GJ/h)	13.10	5.22	33.15	34.61	12.62
Reboiler heat duty (GJ/h)	19.45	5.30	34.68	36.23	12.73
Condenser type	Total	Total	Total	Total	Total
Reboiler type	Kettle	Kettle	Kettle	Kettle	Kettle

Table 49 Stream result of steady-state for case study 4

Component	Mole flowrate (Kmol/h) (Steam 1)	Separated		
		Stream	Separated (Kmol/h)	%Purity
(A) iso-Butane	50.00	4	48.27	96.54%
(B) n-Butane	50.00	5	46.44	92.88%
(C) neo-Pentane	100.00	8	94.92	94.92%
(D) n-Pentane	150.00	10	146.11	97.41%
(E) n-Hexane	250.00	11	246.16	98.46%
(F) n-Heptane	400.00	7	397.02	99.26%

For the optimal configuration number 2 (Figure 82), sources and sinks of each heat integrate are showed in Table 50. The comparison of costs between process with

and without heat integration is showed in Table 52. Stream result of steady-state of configuration number 1 (Figure 81), configuration number 2 (Figure 82) configuration number 3 (Figure 83) for case study 4 is showed in Table 49. And the comparative study using various methods of case study 3 are showed in Table 53.

Table 50 Source and sink of each heat integration match for the optimal configuration number 2 of case study 4

Heat stream	Source-Sink
12-13	Column 2 - Column 5
15-16	Column 3 - Column 4

For the second best configuration number 3 (Figure 83), sources and sinks of each heat integrate are showed in Table 51.

Table 51 Source and sink of each heat integration match for the second best configuration number 3 of case study 4

Heat stream	Source-Sink
30-31	Column 3 - Column 1
32-18	Column 4 - Column 5

Table 52 The comparison of costs between process with and without heat integration of each column in the optimal configuration of case study 4

Format	Best cost (\$)	
	With heat integration	Without heat integration
Optimal configuration	186,780,025	187,400,433
Reduce the costs (%)	0.3310 %	

Table 53 Comparative study using various methods of case study 4

Method	Ant colony algorithm	Harmony search algorithm	ODOS
Authors	This work	This work	Hariharan
Optimal configuration for distillation sequences	$S_k = \{2,1,5,4,3\}$	$S_k = \{2,1,5,4,3\}$	$S_k = \{3,1,2,5,4\}$
The total annual cost (\$) (without heat-integration)	187,400,433	187,400,433	-
Optimal configuration for heat-integrated distillation sequences	$S_k = \{2,1,5,4,3\}$ $H_k = \{3,1\}, \{4,5\}$	$S_k = \{2,1,5,4,3\}$ $H_k = \{1,2\}, \{5,3\}$	-
The total annual cost (\$) (with heat-integration)	186,780,620	186,990,412	-

CONCLUSION AND RECOMMENDATIONS

Conclusion

The optimization of chemical separation processes can be achieved using both Ant colony algorithm and Harmony search algorithm. The algorithms solve the problems based on heuristic which determines the groups of initiated answers and improves the answer by itself. Both methods are based on mathematical modeling. In this study Mix-Integer Linear Programming (MILP) was used to solve heat integrated distillation sequence. The objective function of the optimization problem is to minimize investment costs and operating costs. This study investigated four case studies from small substrate separation of 3-components, to large substrate separation of more than 5-components were investigated in this study.

Parameter value is important for processing the answer by both methods. If the factors of the parameter are changed, the groups of answers will be changed. The suitable factors were firstly determined using statistical analysis, 95% ANOVA and P-value to find out the most impact factors. These factors are important for the optimization.

In the ant colony algorithm, there were four factors which were iteration/ants (I/A) , weight of pheromone (WOP) , weight of heuristics information (WOH) and evaporation rate (ER) . For four case studies, both distillation sequences (DS) and heat-integrated distillation sequences (HIDS), it was found that the information on the weight of heuristics was the most impactful parameter. In the case of 100-ants answers, it was found that the best answer less selected of ants compared to the second best answer. This is shown in Table 54.

Table 54 Summary of factors affecting each case study for Ant colony algorithm

factors	Case Study 1		Case Study 2		Case Study 3		Case Study 4	
	3-components		4-components		5-components		6-components	
	DS	HIDS	DS	HIDS	DS	HIDS	DS	HIDS
I/A	-	-	×	×	×	×	×	×
WOP	-	-	×	×	×	×	×	×
WOH	-	-	✓	✓	✓	✓	✓	✓
ER	-	-	×	×	×	×	×	×
✓	Effect experiments							
×	No effect experiments							

In the Harmony search algorithm there were three factors which were iteration/harmony size (I/H), harmony memory considering rate (HMCR) and pitch adjustment rate (PAR). In four case studies, both distillation sequences (DS) and heat-integrated distillation sequences (HIDS), it was found that iteration/harmony size was the most impactful parameter. In the case of 100-harmony, it was found that the best answer had less selected notes than the second best answer. This is shown in Table 55.

Table 55 Summary of factors affecting each case study for Harmony search algorithm

factors	Case Study 1		Case Study 2		Case Study 3		Case Study 4	
	3-components		4-components		5-components		6-components	
	DS	HIDS	DS	HIDS	DS	HIDS	DS	HIDS
I/H	-	-	✓	✓	✓	✓	✓	✓
HMCR	-	-	×	×	×	×	✓	×
PAR	-	-	×	×	×	×	×	✓
✓	Effect experiments							
×	No effect experiments							

Comparing algorithm Ant colony algorithm and Harmony search algorithm, it was found that both can solve small problems. However ant colony algorithm is better for solving bigger problems to get a better value and is more robust than a Harmony search algorithm. See Table 56.

Table 56 Summary of factors affecting each case study for each algorithms

Case study	Process	Best cost (\$)	
		Ant colony algorithm	Harmony search algorithm
Case study 1 (3-components)	DS	62,730,109	62,730,109
	HIDS	62,618,957	62,618,957
Case study 2 (4-components)	DS	159,274,858	159,274,858
	HIDS	158,467,709	158,467,709
Case study 3 (5-components)	DS	149,809,030	149,809,030
	HIDS	149,171,538	149,702,074
Case study 4 (6-components)	DS	187,400,433	187,400,433
	HIDS	186,780,025	186,990,412

After obtaining the best answer for each problem, two methods were used with the process synthesis. For distillation sequences (without heat-integration). All this can be summarized as shown in Table 57.

Table 57 Summary of separated %purity each case study

Case study	Distillation sequences (without heat-integrated)
	% Purity
Case study 1 (3-components)	97.02%-99.45%
Case study 2 (4-components)	95.46%-99.96%
Case study 3 (5-components)	91.96%-99.19%
Case study 4 (6-components)	92.88%-99.26%

For heat-integrated distillation sequences with heat-integrated, reduce cost by using steam in every case study was found. In case study 1 the cost can reduce the costs of the use of steam to reboiler is 0.1772%, In the case study 2 can reduce the costs at 0.5068%. In the case study 3 can reduce the costs at 0.4255% . And, In the case study 4 can reduce the costs at 0.3310%. This is summarized as shown in Table 58.

Table 58 Summary of can reduce cost each case study.

Case study	Heat-integrated distillation sequences (with heat-integrated)
	% reduce cost
Case study 1 (3-components)	0.1772%
Case study 2 (4-components)	0.5068%
Case study 3 (5-components)	0.4255%
Case study 4 (6-components)	0.3310%

Recommendations

1. Future researchers may choose to use mathematical models Mix-Integer Nonlinear Programming (MINLP) to meet the challenge of finding answers.
2. The most separation of mixed substances in the chemical industry is non-sharp separation, so there should improve both Ant colony algorithm and Harmony search algorithm for non-sharp separation in the actual situation.
3. The cost of this research is calculated only a first year only, so the cost incurred in subsequent years may be changed. This will result in distillation sequences configuration has changed. So it must be conducted in the following next years.

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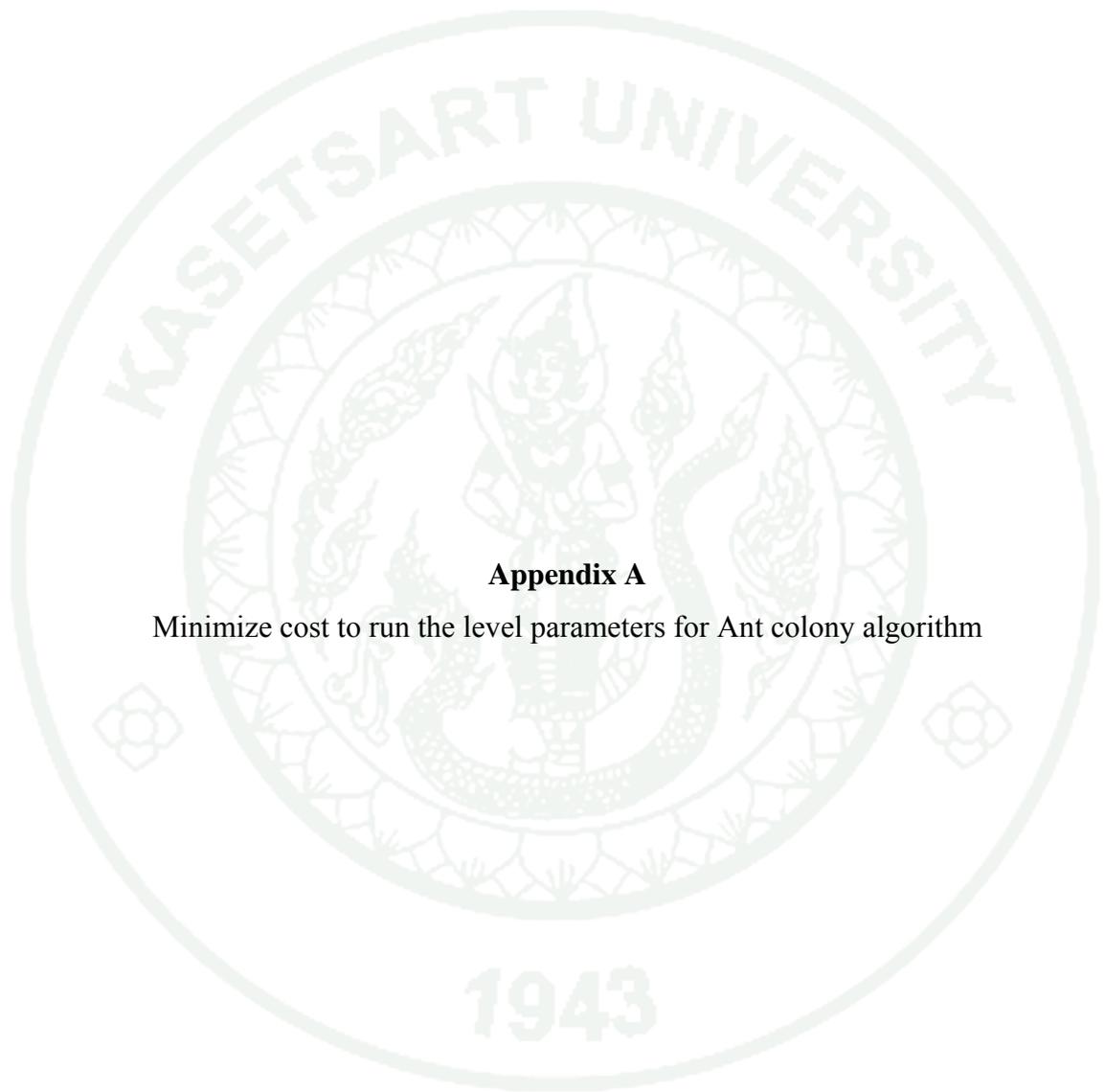
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APPENDICES



Appendix A

Minimize cost to run the level parameters for Ant colony algorithm

Appendix Table A1 Minimize cost to run the level parameters for case study 2

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
1	1	1	5/20	0.5	1	0.2	156911216	155409007
2	1	1	5/20	0.5	1	0.55	156555781	156039913
3	1	1	5/20	0.5	1	0.9	156555781	156039913
4	1	1	5/20	0.5	3	0.2	156378063	155762614
5	1	1	5/20	0.5	3	0.55	156378063	156117252
6	1	1	5/20	0.5	3	0.9	156378063	156927653
7	1	1	5/20	0.5	5	0.2	156733498	155485093
8	1	1	5/20	0.5	5	0.55	156033498	157576903
9	1	1	5/20	0.5	5	0.9	156033498	156117252
10	1	1	5/20	1.5	1	0.2	156733498	155939418
11	1	1	5/20	1.5	1	0.55	156200346	155939822
12	1	1	5/20	1.5	1	0.9	156799498	156146161
13	1	1	5/20	1.5	3	0.2	156911216	156146161
14	1	1	5/20	1.5	3	0.55	156200346	156192667
15	1	1	5/20	1.5	3	0.9	156733498	156192667
16	1	1	5/20	1.5	5	0.2	156200346	157044473
17	1	1	5/20	1.5	5	0.55	156555781	157044473
18	1	1	5/20	1.5	5	0.9	157266651	157044473
19	1	1	5/20	2.5	1	0.2	157200346	155661987
20	1	1	5/20	2.5	1	0.55	157888933	156395009
21	1	1	5/20	2.5	1	0.9	158378063	155762614
22	1	1	5/20	2.5	3	0.2	157266651	156469829
23	1	1	5/20	2.5	3	0.55	158555781	155661987
24	1	1	5/20	2.5	3	0.9	156733498	155661987
25	1	1	5/20	2.5	5	0.2	156555781	156469830
26	1	1	5/20	2.5	5	0.55	156911216	156469830
27	1	1	5/20	2.5	5	0.9	156200346	156469830
28	1	1	10/10	0.5	1	0.2	156200346	156039913
29	1	1	10/10	0.5	1	0.55	156911216	155409007
30	1	1	10/10	0.5	1	0.9	156200346	155409007
31	1	1	10/10	0.5	3	0.2	156378063	156646633
32	1	1	10/10	0.5	3	0.55	156911216	156117252
33	1	1	10/10	0.5	3	0.9	157266651	156117252
34	1	1	10/10	0.5	5	0.2	156378063	157389873
35	1	1	10/10	0.5	5	0.55	156378063	156900240
36	1	1	10/10	0.5	5	0.9	156200346	155409007
37	1	1	10/10	1.5	1	0.2	157444368	156395009
38	1	1	10/10	1.5	1	0.55	157444368	155979612
39	1	1	10/10	1.5	1	0.9	156733498	155762614

Appendix Table A1 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
40	1	1	10/10	1.5	3	0.2	156378063	157034527
41	1	1	10/10	1.5	3	0.55	157622086	155409007
42	1	1	10/10	1.5	3	0.9	156200346	155979612
43	1	1	10/10	1.5	5	0.2	156733498	156369560
44	1	1	10/10	1.5	5	0.55	156733498	156039913
45	1	1	10/10	1.5	5	0.9	156200346	155838880
46	1	1	10/10	2.5	1	0.2	156378063	156572557
47	1	1	10/10	2.5	1	0.55	157799803	156039913
48	1	1	10/10	2.5	1	0.9	156200346	156039913
49	1	1	10/10	2.5	3	0.2	156733498	156217461
50	1	1	10/10	2.5	3	0.55	156200346	156015773
51	1	1	10/10	2.5	3	0.9	157088933	155939822
52	1	1	10/10	2.5	5	0.2	156200346	156469829
53	1	1	10/10	2.5	5	0.55	156200346	155585811
54	1	1	10/10	2.5	5	0.9	156555781	156293025
55	1	1	20/5	0.5	1	0.2	156200346	156294681
56	1	1	20/5	0.5	1	0.55	156555781	156117252
57	1	1	20/5	0.5	1	0.9	156200346	156117252
58	1	1	20/5	0.5	3	0.2	156200346	156546434
59	1	1	20/5	0.5	3	0.55	156378063	156395009
60	1	1	20/5	0.5	3	0.9	156378063	155838880
61	1	1	20/5	0.5	5	0.2	156555781	155661987
62	1	1	20/5	0.5	5	0.55	156200346	156546454
63	1	1	20/5	0.5	5	0.9	156200346	156501507
64	1	1	20/5	1.5	1	0.2	156555781	155409007
65	1	1	20/5	1.5	1	0.55	156200346	156469829
66	1	1	20/5	1.5	1	0.9	156911216	157044473
67	1	1	20/5	1.5	3	0.2	156200346	155409007
68	1	1	20/5	1.5	3	0.55	156378063	155585811
69	1	1	20/5	1.5	3	0.9	156378063	156192667
70	1	1	20/5	1.5	5	0.2	156200346	155485093
71	1	1	20/5	1.5	5	0.55	156200346	155585811
72	1	1	20/5	1.5	5	0.9	156555781	157212200
73	1	1	20/5	2.5	1	0.2	156378063	156369560
74	1	1	20/5	2.5	1	0.55	156911216	155939822
75	1	1	20/5	2.5	1	0.9	156200346	155939822
76	1	1	20/5	2.5	3	0.2	156200346	155485093
77	1	1	20/5	2.5	3	0.55	156200346	155485093
78	1	1	20/5	2.5	3	0.9	156200346	155485093

Appendix Table A1 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
79	1	1	20/5	2.5	5	0.2	156378063	156900240
80	1	1	20/5	2.5	5	0.55	156378063	156900240
81	1	1	20/5	2.5	5	0.9	156378063	156900240
82	1	1	5/20	0.5	1	0.2	156733498	156146161
83	1	1	5/20	0.5	1	0.55	156200346	155939822
84	1	1	5/20	0.5	1	0.9	156200346	155939822
85	1	1	5/20	0.5	3	0.2	156200346	156649541
86	1	1	5/20	0.5	3	0.55	156200346	156015773
87	1	1	5/20	0.5	3	0.9	156200346	156117252
88	1	1	5/20	0.5	5	0.2	156200346	155661987
89	1	1	5/20	0.5	5	0.55	156555781	155939418
90	1	1	5/20	0.5	5	0.9	156200346	155409007
91	1	1	5/20	1.5	1	0.2	156911216	155979612
92	1	1	5/20	1.5	1	0.55	156733498	155585811
93	1	1	5/20	1.5	1	0.9	156733498	155838880
94	1	1	5/20	1.5	3	0.2	156555781	156334566
95	1	1	5/20	1.5	3	0.55	156378063	155979612
96	1	1	5/20	1.5	3	0.9	156378063	156572557
97	1	1	5/20	1.5	5	0.2	156200346	155979612
98	1	1	5/20	1.5	5	0.55	156200346	155661987
99	1	1	5/20	1.5	5	0.9	156200346	156117252
100	1	1	5/20	2.5	1	0.2	156200346	155661987
101	1	1	5/20	2.5	1	0.55	156200346	156039913
102	1	1	5/20	2.5	1	0.9	156378063	155585811
103	1	1	5/20	2.5	3	0.2	156378063	156501507
104	1	1	5/20	2.5	3	0.55	156200346	156369560
105	1	1	5/20	2.5	3	0.9	156555781	156157089
106	1	1	5/20	2.5	5	0.2	156200346	156512042
107	1	1	5/20	2.5	5	0.55	156555781	155838880
108	1	1	5/20	2.5	5	0.9	156555781	155661987
109	1	1	10/10	0.5	1	0.2	156200346	155661987
110	1	1	10/10	0.5	1	0.55	156200346	155485093
111	1	1	10/10	0.5	1	0.9	156911216	156192667
112	1	1	10/10	0.5	3	0.2	157622086	155485093
113	1	1	10/10	0.5	3	0.55	156555781	156039913
114	1	1	10/10	0.5	3	0.9	156555781	156323834
115	1	1	10/10	0.5	5	0.2	156200346	156369560
116	1	1	10/10	0.5	5	0.55	156555781	155485093
117	1	1	10/10	0.5	5	0.9	157266651	155762614

Appendix Table A1 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
118	1	1	10/10	1.5	1	0.2	157266651	156900240
119	1	1	10/10	1.5	1	0.55	156378063	156117252
120	1	1	10/10	1.5	1	0.9	157444368	155762614
121	1	1	10/10	1.5	3	0.2	156378063	155762614
122	1	1	10/10	1.5	3	0.55	156200346	156293025
123	1	1	10/10	1.5	3	0.9	156378063	156015773
124	1	1	10/10	1.5	5	0.2	156555781	156217461
125	1	1	10/10	1.5	5	0.55	156200346	156015773
126	1	1	10/10	1.5	5	0.9	156200346	157181830
127	1	1	10/10	2.5	1	0.2	156200346	155939418
128	1	1	10/10	2.5	1	0.55	156200346	155485093
129	1	1	10/10	2.5	1	0.9	156378063	155661987
130	1	1	10/10	2.5	3	0.2	156378063	156823436
131	1	1	10/10	2.5	3	0.55	156555781	156146161
132	1	1	10/10	2.5	3	0.9	156733498	155585811
133	1	1	10/10	2.5	5	0.2	157266651	157105201
134	1	1	10/10	2.5	5	0.55	156200346	155939822
135	1	1	10/10	2.5	5	0.9	156200346	156469829
136	1	1	20/5	0.5	1	0.2	156200346	156293025
137	1	1	20/5	0.5	1	0.55	156200346	156646633
138	1	1	20/5	0.5	1	0.9	156378063	156646633
139	1	1	20/5	0.5	3	0.2	156378063	156117252
140	1	1	20/5	0.5	3	0.55	157088933	155485093
141	1	1	20/5	0.5	3	0.9	157444368	156117252
142	1	1	20/5	0.5	5	0.2	156555781	156323834
143	1	1	20/5	0.5	5	0.55	156200346	156469829
144	1	1	20/5	0.5	5	0.9	156200346	155485093
145	1	1	20/5	1.5	1	0.2	156378063	156546454
146	1	1	20/5	1.5	1	0.55	157266651	156294681
147	1	1	20/5	1.5	1	0.9	156733498	156116222
148	1	1	20/5	1.5	3	0.2	157266651	155838880
149	1	1	20/5	1.5	3	0.55	156200346	156015773
150	1	1	20/5	1.5	3	0.9	157266651	156501507
151	1	1	20/5	1.5	5	0.2	156200346	156546454
152	1	1	20/5	1.5	5	0.55	156733498	156546454
153	1	1	20/5	1.5	5	0.9	156378063	155762614
154	1	1	20/5	2.5	1	0.2	156200346	155838880
155	1	1	20/5	2.5	1	0.55	156200346	157034527
156	1	1	20/5	2.5	1	0.9	156378063	156157089

Appendix Table A1 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
157	1	1	20/5	2.5	3	0.2	156555781	156117252
158	1	1	20/5	2.5	3	0.55	156378063	155661987
159	1	1	20/5	2.5	3	0.9	156200346	155585811
160	1	1	20/5	2.5	5	0.2	156378063	156217461
161	1	1	20/5	2.5	5	0.55	156200346	155939822
162	1	1	20/5	2.5	5	0.9	156200346	156039913



Appendix Table A2 Minimize cost to run the level parameters for case study 3

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
1	1	1	5/20	0.5	1	0.2	147699478	147762160
2	1	1	5/20	0.5	1	0.55	148178922	147900690
3	1	1	5/20	0.5	1	0.9	147060220	147346589
4	1	1	5/20	0.5	3	0.2	148019107	147102203
5	1	1	5/20	0.5	3	0.55	147220034	146879573
6	1	1	5/20	0.5	3	0.9	147379849	148372620
7	1	1	5/20	0.5	5	0.2	146900405	147977503
8	1	1	5/20	0.5	5	0.55	147060220	148431013
9	1	1	5/20	0.5	5	0.9	147859292	147977503
10	1	1	5/20	1.5	1	0.2	147060220	146804900
11	1	1	5/20	1.5	1	0.55	146900405	147900690
12	1	1	5/20	1.5	1	0.9	147060220	148888933
13	1	1	5/20	1.5	3	0.2	147539663	148158021
14	1	1	5/20	1.5	3	0.55	148338736	146991629
15	1	1	5/20	1.5	3	0.9	148178922	147443073
16	1	1	5/20	1.5	5	0.2	149457438	146788195
17	1	1	5/20	1.5	5	0.55	147220034	147585818
18	1	1	5/20	1.5	5	0.9	147379849	147039380
19	1	1	5/20	2.5	1	0.2	146900405	147581295
20	1	1	5/20	2.5	1	0.55	146900405	149221677
21	1	1	5/20	2.5	1	0.9	148898180	146782808
22	1	1	5/20	2.5	3	0.2	147060220	148797245
23	1	1	5/20	2.5	3	0.55	146900405	147900690
24	1	1	5/20	2.5	3	0.9	147220034	147021046
25	1	1	5/20	2.5	5	0.2	147699478	146879573
26	1	1	5/20	2.5	5	0.55	147060220	148111151
27	1	1	5/20	2.5	5	0.9	146900405	146935414
28	1	1	10/10	0.5	1	0.2	148019107	148313540
29	1	1	10/10	0.5	1	0.55	147699478	148750877
30	1	1	10/10	0.5	1	0.9	146900405	147266769
31	1	1	10/10	0.5	3	0.2	147699478	147023053
32	1	1	10/10	0.5	3	0.55	147859292	149417827
33	1	1	10/10	0.5	3	0.9	147699478	147033710
34	1	1	10/10	0.5	5	0.2	148178922	147998215
35	1	1	10/10	0.5	5	0.55	147699478	147021046
36	1	1	10/10	0.5	5	0.9	148019107	148372620
37	1	1	10/10	1.5	1	0.2	149617253	148060387
38	1	1	10/10	1.5	1	0.55	147859292	146942505
39	1	1	10/10	1.5	1	0.9	146900405	146863978

Appendix Table A2 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
40	1	1	10/10	1.5	3	0.2	147060220	149230672
41	1	1	10/10	1.5	3	0.55	146900405	146947720
42	1	1	10/10	1.5	3	0.9	147699478	146861261
43	1	1	10/10	1.5	5	0.2	147060220	148473519
44	1	1	10/10	1.5	5	0.55	147060220	147762159
45	1	1	10/10	1.5	5	0.9	148338736	147585812
46	1	1	10/10	2.5	1	0.2	146900405	147283530
47	1	1	10/10	2.5	1	0.55	146900405	147673625
48	1	1	10/10	2.5	1	0.9	146900405	147833604
49	1	1	10/10	2.5	3	0.2	148019107	147921703
50	1	1	10/10	2.5	3	0.55	147220034	148420299
51	1	1	10/10	2.5	3	0.9	147539663	147033710
52	1	1	10/10	2.5	5	0.2	147060220	147993582
53	1	1	10/10	2.5	5	0.55	147859292	147033710
54	1	1	10/10	2.5	5	0.9	149297624	146386753
55	1	1	20/5	0.5	1	0.2	148178922	147979758
56	1	1	20/5	0.5	1	0.55	146900405	147471424
57	1	1	20/5	0.5	1	0.9	147699478	147102203
58	1	1	20/5	0.5	3	0.2	147060220	147039380
59	1	1	20/5	0.5	3	0.55	147060220	147421597
60	1	1	20/5	0.5	3	0.9	146900405	148431013
61	1	1	20/5	0.5	5	0.2	147699478	147660188
62	1	1	20/5	0.5	5	0.55	149457438	147458646
63	1	1	20/5	0.5	5	0.9	148338736	147421597
64	1	1	20/5	1.5	1	0.2	148019107	147921703
65	1	1	20/5	1.5	1	0.55	146900405	147631355
66	1	1	20/5	1.5	1	0.9	147379849	146782808
67	1	1	20/5	1.5	3	0.2	147859292	147585818
68	1	1	20/5	1.5	3	0.55	148019107	148020465
69	1	1	20/5	1.5	3	0.9	148178922	147745343
70	1	1	20/5	1.5	5	0.2	148178922	148532309
71	1	1	20/5	1.5	5	0.55	147699478	147062547
72	1	1	20/5	1.5	5	0.9	149617253	147471424
73	1	1	20/5	2.5	1	0.2	146900405	147261900
74	1	1	20/5	2.5	1	0.55	147220034	147581295
75	1	1	20/5	2.5	1	0.9	147699478	147021046
76	1	1	20/5	2.5	3	0.2	147060220	148220085
77	1	1	20/5	2.5	3	0.55	146900405	147151561
78	1	1	20/5	2.5	3	0.9	147859292	147261900

Appendix Table A2 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
40	1	1	10/10	1.5	3	0.2	147060220	149230672
41	1	1	10/10	1.5	3	0.55	146900405	146947720
42	1	1	10/10	1.5	3	0.9	147699478	146861261
43	1	1	10/10	1.5	5	0.2	147060220	148473519
44	1	1	10/10	1.5	5	0.55	147060220	147762159
45	1	1	10/10	1.5	5	0.9	148338736	147585812
46	1	1	10/10	2.5	1	0.2	146900405	147283530
47	1	1	10/10	2.5	1	0.55	146900405	147673625
48	1	1	10/10	2.5	1	0.9	146900405	147833604
49	1	1	10/10	2.5	3	0.2	148019107	147921703
50	1	1	10/10	2.5	3	0.55	147220034	148420299
51	1	1	10/10	2.5	3	0.9	147539663	147033710
52	1	1	10/10	2.5	5	0.2	147060220	147993582
53	1	1	10/10	2.5	5	0.55	147859292	147033710
54	1	1	10/10	2.5	5	0.9	149297624	146386753
55	1	1	20/5	0.5	1	0.2	148178922	147979758
56	1	1	20/5	0.5	1	0.55	146900405	147471424
57	1	1	20/5	0.5	1	0.9	147699478	147102203
58	1	1	20/5	0.5	3	0.2	147060220	147039380
59	1	1	20/5	0.5	3	0.55	147060220	147421597
60	1	1	20/5	0.5	3	0.9	146900405	148431013
61	1	1	20/5	0.5	5	0.2	147699478	147660188
62	1	1	20/5	0.5	5	0.55	149457438	147458646
63	1	1	20/5	0.5	5	0.9	148338736	147421597
64	1	1	20/5	1.5	1	0.2	148019107	147921703
65	1	1	20/5	1.5	1	0.55	146900405	147631355
66	1	1	20/5	1.5	1	0.9	147379849	146782808
67	1	1	20/5	1.5	3	0.2	147859292	147585818
68	1	1	20/5	1.5	3	0.55	148019107	148020465
69	1	1	20/5	1.5	3	0.9	148178922	147745343
70	1	1	20/5	1.5	5	0.2	148178922	148532309
71	1	1	20/5	1.5	5	0.55	147699478	147062547
72	1	1	20/5	1.5	5	0.9	149617253	147471424
73	1	1	20/5	2.5	1	0.2	146900405	147261900
74	1	1	20/5	2.5	1	0.55	147220034	147581295
75	1	1	20/5	2.5	1	0.9	147699478	147021046
76	1	1	20/5	2.5	3	0.2	147060220	148220085
77	1	1	20/5	2.5	3	0.55	146900405	147151561
78	1	1	20/5	2.5	3	0.9	147859292	147261900

Appendix Table A2 (Continued)

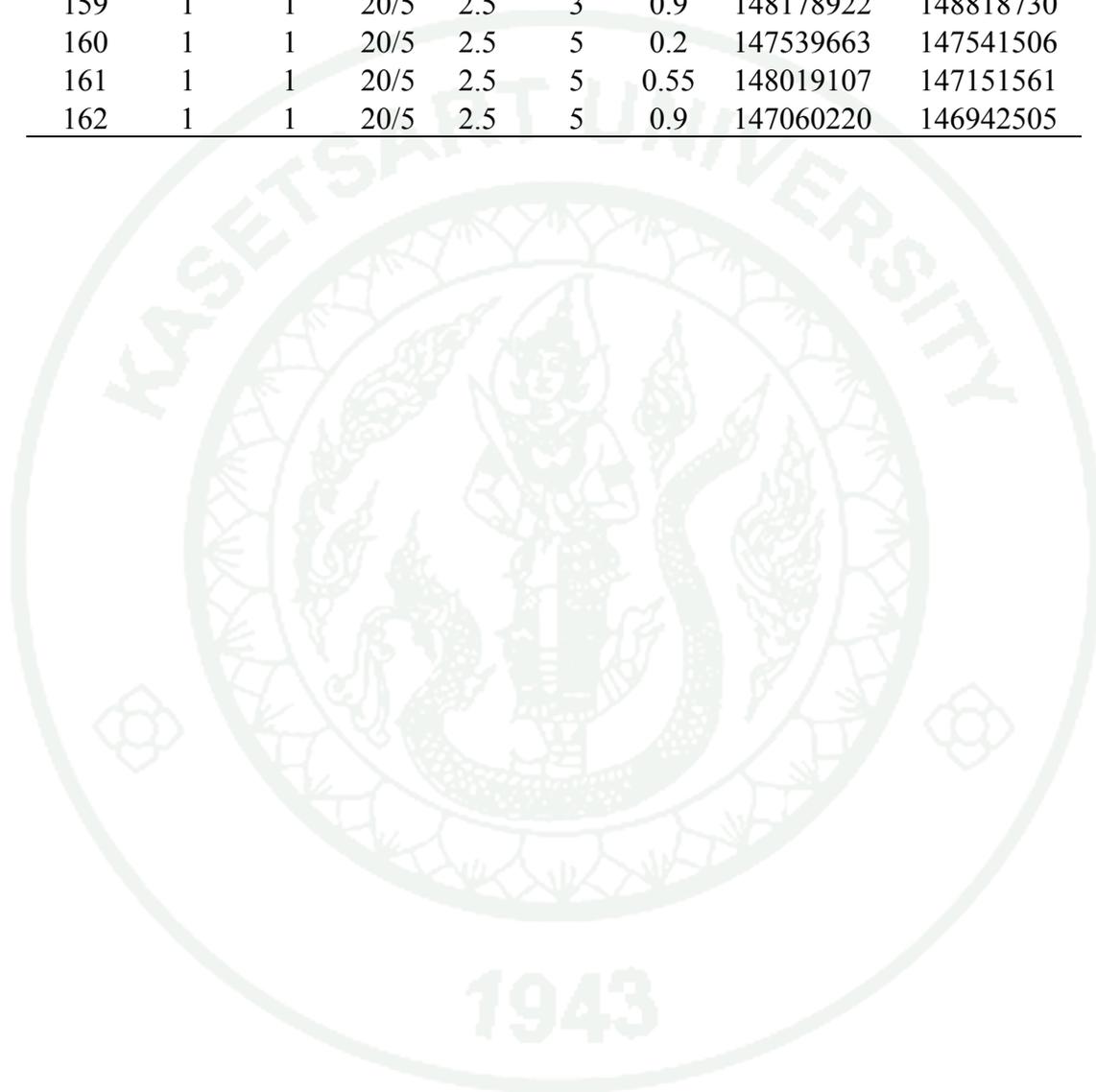
Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
79	1	1	20/5	2.5	5	0.2	147220034	147733862
80	1	1	20/5	2.5	5	0.55	146900405	146935414
81	1	1	20/5	2.5	5	0.9	147539663	147518797
82	1	1	5/20	0.5	1	0.2	148977994	147358991
83	1	1	5/20	0.5	1	0.55	146900405	147062547
84	1	1	5/20	0.5	1	0.9	146900405	147740992
85	1	1	5/20	0.5	3	0.2	147060220	147033710
86	1	1	5/20	0.5	3	0.55	147060220	146991629
87	1	1	5/20	0.5	3	0.9	147060220	146964443
88	1	1	5/20	0.5	5	0.2	147699478	148910808
89	1	1	5/20	0.5	5	0.55	146900405	147421597
90	1	1	5/20	0.5	5	0.9	146900405	147471424
91	1	1	5/20	1.5	1	0.2	147379849	148260024
92	1	1	5/20	1.5	1	0.55	147220034	147102203
93	1	1	5/20	1.5	1	0.9	147539663	147951219
94	1	1	5/20	1.5	3	0.2	147060220	147023053
95	1	1	5/20	1.5	3	0.55	146900405	146902894
96	1	1	5/20	1.5	3	0.9	147699478	147414483
97	1	1	5/20	1.5	5	0.2	148338736	146227678
98	1	1	5/20	1.5	5	0.55	147060220	146645356
99	1	1	5/20	1.5	5	0.9	147539663	147298370
100	1	1	5/20	2.5	1	0.2	148338736	149138037
101	1	1	5/20	2.5	1	0.55	148019107	148633498
102	1	1	5/20	2.5	1	0.9	147699478	147541506
103	1	1	5/20	2.5	3	0.2	147060220	147421597
104	1	1	5/20	2.5	3	0.55	148019107	146227678
105	1	1	5/20	2.5	3	0.9	147220034	147860812
106	1	1	5/20	2.5	5	0.2	149457438	146935414
107	1	1	5/20	2.5	5	0.55	146900405	148477633
108	1	1	5/20	2.5	5	0.9	146900405	148542966
109	1	1	10/10	0.5	1	0.2	147859292	148053241
110	1	1	10/10	0.5	1	0.55	148178922	148580574
111	1	1	10/10	0.5	1	0.9	147060220	147900690
112	1	1	10/10	0.5	3	0.2	146900405	147199186
113	1	1	10/10	0.5	3	0.55	147060220	149038506
114	1	1	10/10	0.5	3	0.9	147060220	148212930
115	1	1	10/10	0.5	5	0.2	147859292	147977503
116	1	1	10/10	0.5	5	0.55	146900405	146386753
117	1	1	10/10	0.5	5	0.9	148178922	147900690

Appendix Table A2 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
118	1	1	10/10	1.5	1	0.2	147859292	148379782
119	1	1	10/10	1.5	1	0.55	147539663	147701159
120	1	1	10/10	1.5	1	0.9	148178922	146935414
121	1	1	10/10	1.5	3	0.2	148019107	147900690
122	1	1	10/10	1.5	3	0.55	147859292	147102203
123	1	1	10/10	1.5	3	0.9	147379849	147618921
124	1	1	10/10	1.5	5	0.2	147699478	146935414
125	1	1	10/10	1.5	5	0.55	147539663	146628671
126	1	1	10/10	1.5	5	0.9	149297624	147673625
127	1	1	10/10	2.5	1	0.2	148178922	147660237
128	1	1	10/10	2.5	1	0.55	148977994	149330757
129	1	1	10/10	2.5	1	0.9	147859292	149098256
130	1	1	10/10	2.5	3	0.2	147220034	147518797
131	1	1	10/10	2.5	3	0.55	148019107	147660188
132	1	1	10/10	2.5	3	0.9	146900405	147199186
133	1	1	10/10	2.5	5	0.2	148019107	147426294
134	1	1	10/10	2.5	5	0.55	147699478	146788195
135	1	1	10/10	2.5	5	0.9	147699478	146227678
136	1	1	20/5	0.5	1	0.2	147379849	147021046
137	1	1	20/5	0.5	1	0.55	148019107	147443073
138	1	1	20/5	0.5	1	0.9	147859292	147500278
139	1	1	20/5	0.5	3	0.2	148178922	147102203
140	1	1	20/5	0.5	3	0.55	146900405	146879573
141	1	1	20/5	0.5	3	0.9	147859292	149433392
142	1	1	20/5	0.5	5	0.2	147539663	146782808
143	1	1	20/5	0.5	5	0.55	147859292	147095104
144	1	1	20/5	0.5	5	0.9	148019107	147261900
145	1	1	20/5	1.5	1	0.2	147060220	147860812
146	1	1	20/5	1.5	1	0.55	147379849	147062547
147	1	1	20/5	1.5	1	0.9	148178922	146704903
148	1	1	20/5	1.5	3	0.2	146900405	147340617
149	1	1	20/5	1.5	3	0.55	147699478	147979758
150	1	1	20/5	1.5	3	0.9	146900405	147733862
151	1	1	20/5	1.5	5	0.2	147859292	147921703
152	1	1	20/5	1.5	5	0.55	146900405	148099748
153	1	1	20/5	1.5	5	0.9	147220034	146902894
154	1	1	20/5	2.5	1	0.2	147379849	147222199
155	1	1	20/5	2.5	1	0.55	147539663	147762160
156	1	1	20/5	2.5	1	0.9	147379849	147977503

Appendix Table A2 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
158	1	1	20/5	2.5	3	0.55	147060220	147541506
159	1	1	20/5	2.5	3	0.9	148178922	148818730
160	1	1	20/5	2.5	5	0.2	147539663	147541506
161	1	1	20/5	2.5	5	0.55	148019107	147151561
162	1	1	20/5	2.5	5	0.9	147060220	146942505



Appendix Table A3 Minimize cost to run the level parameters for case study 4

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
1	1	1	5/20	0.5	1	0.2	183991004	184335721
2	1	1	5/20	0.5	1	0.55	184712428	187822230
3	1	1	5/20	0.5	1	0.9	183991004	185237419
4	1	1	5/20	0.5	3	0.2	187417766	184335721
5	1	1	5/20	0.5	3	0.55	184171360	185778438
6	1	1	5/20	0.5	3	0.9	184712428	183975042
7	1	1	5/20	0.5	5	0.2	185433851	186319457
8	1	1	5/20	0.5	5	0.55	183991004	185878044
9	1	1	5/20	0.5	5	0.9	183991004	186696401
10	1	1	5/20	1.5	1	0.2	184351716	183858297
11	1	1	5/20	1.5	1	0.55	183991004	185411633
12	1	1	5/20	1.5	1	0.9	183991004	183852546
13	1	1	5/20	1.5	3	0.2	184390165	184726897
14	1	1	5/20	1.5	3	0.55	184351716	184878456
15	1	1	5/20	1.5	3	0.9	185073139	186132325
16	1	1	5/20	1.5	5	0.2	187417766	186888609
17	1	1	5/20	1.5	5	0.55	184171360	186159248
18	1	1	5/20	1.5	5	0.9	184712428	185970223
19	1	1	5/20	2.5	1	0.2	184712428	184625265
20	1	1	5/20	2.5	1	0.55	184029734	184397519
21	1	1	5/20	2.5	1	0.9	184351716	184516061
22	1	1	5/20	2.5	3	0.2	184351716	186315523
23	1	1	5/20	2.5	3	0.55	185073139	183615173
24	1	1	5/20	2.5	3	0.9	184171360	184757635
25	1	1	5/20	2.5	5	0.2	183849518	185043644
26	1	1	5/20	2.5	5	0.55	184892784	185959720
27	1	1	5/20	2.5	5	0.9	185614207	187340135
28	1	1	10/10	0.5	1	0.2	185433851	183984926
29	1	1	10/10	0.5	1	0.55	183991004	184515573
30	1	1	10/10	0.5	1	0.9	184532072	184155382
31	1	1	10/10	0.5	3	0.2	185253495	185488056
32	1	1	10/10	0.5	3	0.55	185073139	183677287
33	1	1	10/10	0.5	3	0.9	183849518	184327574
34	1	1	10/10	0.5	5	0.2	183991004	187783736
35	1	1	10/10	0.5	5	0.55	184351716	187005326
36	1	1	10/10	0.5	5	0.9	184712428	186516061
37	1	1	10/10	1.5	1	0.2	185471457	184515146
38	1	1	10/10	1.5	1	0.55	184171360	184559952
39	1	1	10/10	1.5	1	0.9	185111026	183970673

Appendix Table A3 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
40	1	1	10/10	1.5	3	0.2	185073139	184469232
41	1	1	10/10	1.5	3	0.55	184712428	184155583
42	1	1	10/10	1.5	3	0.9	184171360	184335578
43	1	1	10/10	1.5	5	0.2	184532072	185483686
44	1	1	10/10	1.5	5	0.55	184532072	186313688
45	1	1	10/10	1.5	5	0.9	184171360	186799251
46	1	1	10/10	2.5	1	0.2	186155275	183613717
47	1	1	10/10	2.5	1	0.55	186155275	183778935
48	1	1	10/10	2.5	1	0.9	184351716	186001736
49	1	1	10/10	2.5	3	0.2	184171360	184692120
50	1	1	10/10	2.5	3	0.55	184171360	183742160
51	1	1	10/10	2.5	3	0.9	184892784	185973248
52	1	1	10/10	2.5	5	0.2	183991004	186151597
53	1	1	10/10	2.5	5	0.55	185253495	185763104
54	1	1	10/10	2.5	5	0.9	183991004	187156009
55	1	1	20/5	0.5	1	0.2	183991004	186674036
56	1	1	20/5	0.5	1	0.55	184351716	185043644
57	1	1	20/5	0.5	1	0.9	184712428	183929388
58	1	1	20/5	0.5	3	0.2	185794563	183598957
59	1	1	20/5	0.5	3	0.55	184171360	183783742
60	1	1	20/5	0.5	3	0.9	185794563	184038539
61	1	1	20/5	0.5	5	0.2	184351716	186327574
62	1	1	20/5	0.5	5	0.55	184712428	186313721
63	1	1	20/5	0.5	5	0.9	185794563	186135528
64	1	1	20/5	1.5	1	0.2	185794563	185218759
65	1	1	20/5	1.5	1	0.55	185253495	184151630
66	1	1	20/5	1.5	1	0.9	184351716	186375068
67	1	1	20/5	1.5	3	0.2	184171360	185591725
68	1	1	20/5	1.5	3	0.55	185794563	183971031
69	1	1	20/5	1.5	3	0.9	183991004	185189023
70	1	1	20/5	1.5	5	0.2	184892784	185807464
71	1	1	20/5	1.5	5	0.55	185433851	186067234
72	1	1	20/5	1.5	5	0.9	184171360	186147012
73	1	1	20/5	2.5	1	0.2	183991004	183971423
74	1	1	20/5	2.5	1	0.55	184532072	184352558
75	1	1	20/5	2.5	1	0.9	184351716	183779558
76	1	1	20/5	2.5	3	0.2	184351716	186645432
77	1	1	20/5	2.5	3	0.55	185794563	183750771
78	1	1	20/5	2.5	3	0.9	184171360	184337572

Appendix Table A3 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
79	1	1	20/5	2.5	5	0.2	183991004	187698176
80	1	1	20/5	2.5	5	0.55	184532072	185293652
81	1	1	20/5	2.5	5	0.9	184491360	185043644
82	1	1	5/20	0.5	1	0.2	184491360	185498847
83	1	1	5/20	0.5	1	0.55	184351716	187034384
84	1	1	5/20	0.5	1	0.9	184532072	184190799
85	1	1	5/20	0.5	3	0.2	184532072	185729659
86	1	1	5/20	0.5	3	0.55	184532072	185231743
87	1	1	5/20	0.5	3	0.9	183991004	184706414
88	1	1	5/20	0.5	5	0.2	185794533	185443993
89	1	1	5/20	0.5	5	0.55	184532072	185150422
90	1	1	5/20	0.5	5	0.9	183991004	185571005
91	1	1	5/20	1.5	1	0.2	184171360	184101682
92	1	1	5/20	1.5	1	0.55	184029734	183746034
93	1	1	5/20	1.5	1	0.9	184029734	184183941
94	1	1	5/20	1.5	3	0.2	184892784	183791249
95	1	1	5/20	1.5	3	0.55	183991004	185474677
96	1	1	5/20	1.5	3	0.9	184351716	184504408
97	1	1	5/20	1.5	5	0.2	185253495	185778935
98	1	1	5/20	1.5	5	0.55	184532072	185370223
99	1	1	5/20	1.5	5	0.9	184171360	185056438
100	1	1	5/20	2.5	1	0.2	184351716	184316445
101	1	1	5/20	2.5	1	0.55	184029734	183804538
102	1	1	5/20	2.5	1	0.9	184029734	183963909
103	1	1	5/20	2.5	3	0.2	185433851	186313721
104	1	1	5/20	2.5	3	0.55	186696342	184706414
105	1	1	5/20	2.5	3	0.9	187858605	184740175
106	1	1	5/20	2.5	5	0.2	184390165	186381693
107	1	1	5/20	2.5	5	0.55	184390165	185971456
108	1	1	5/20	2.5	5	0.9	184390165	185775107
109	1	1	10/10	0.5	1	0.2	186876698	185235553
110	1	1	10/10	0.5	1	0.55	187237410	184363180
111	1	1	10/10	0.5	1	0.9	184171360	186867730
112	1	1	10/10	0.5	3	0.2	184171360	183791249
113	1	1	10/10	0.5	3	0.55	188042913	185461067
114	1	1	10/10	0.5	3	0.9	185253495	183598957
115	1	1	10/10	0.5	5	0.2	184892784	185252619
116	1	1	10/10	0.5	5	0.55	184351716	185750771
117	1	1	10/10	0.5	5	0.9	183991004	187214592

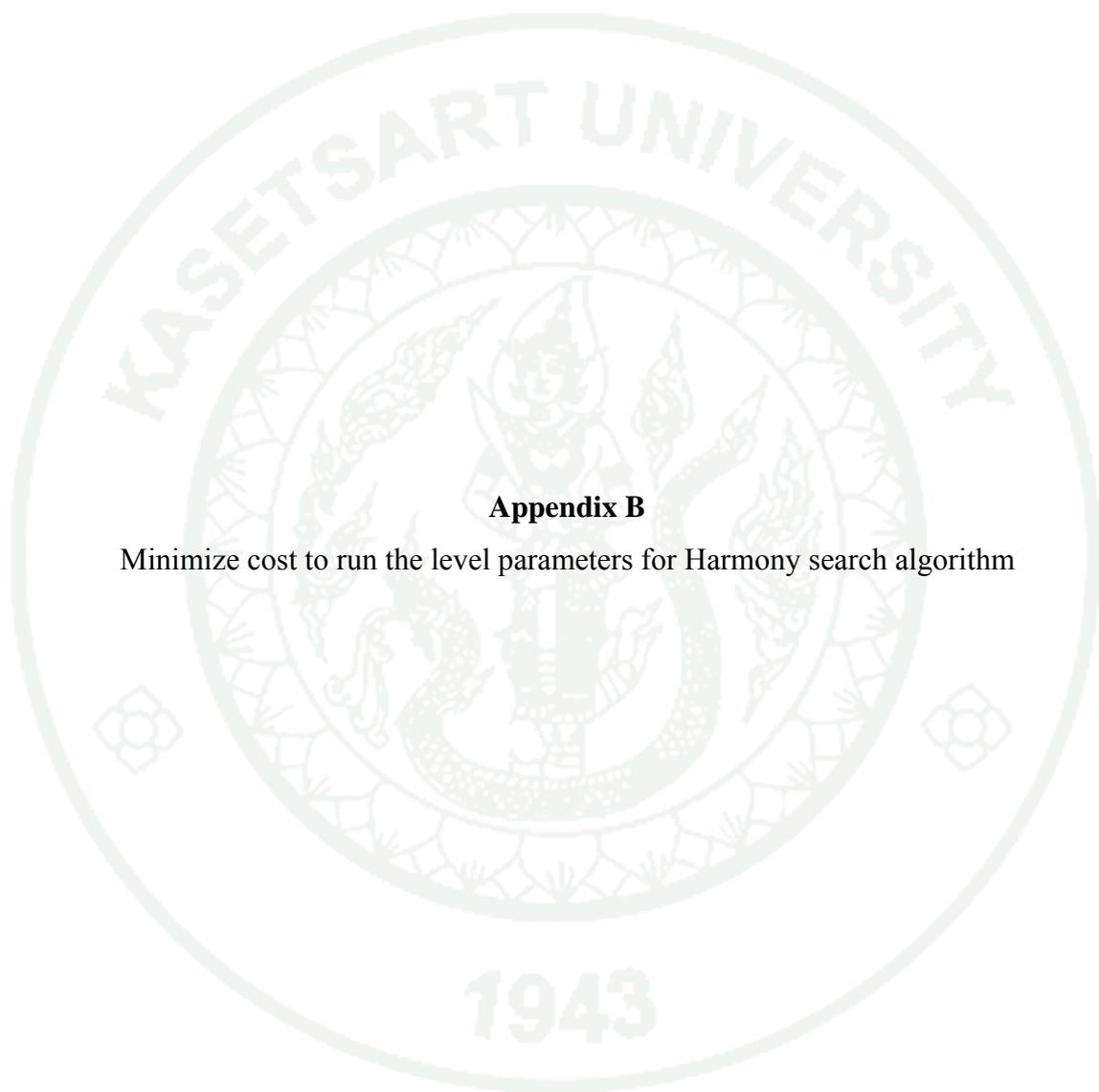
Appendix Table A3 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
118	1	1	10/10	1.5	1	0.2	185974919	186319553
119	1	1	10/10	1.5	1	0.55	186515986	184150847
120	1	1	10/10	1.5	1	0.9	184171360	183807464
121	1	1	10/10	1.5	3	0.2	188227222	184190799
122	1	1	10/10	1.5	3	0.55	184351716	184352558
123	1	1	10/10	1.5	3	0.9	184930811	184871900
124	1	1	10/10	1.5	5	0.2	184351716	185303540
125	1	1	10/10	1.5	5	0.55	186515986	185147404
126	1	1	10/10	1.5	5	0.9	184532072	185429181
127	1	1	10/10	2.5	1	0.2	184351716	183790076
128	1	1	10/10	2.5	1	0.55	183991004	185024122
129	1	1	10/10	2.5	1	0.9	184171360	184136287
130	1	1	10/10	2.5	3	0.2	187237410	185432120
131	1	1	10/10	2.5	3	0.55	184532072	185300237
132	1	1	10/10	2.5	3	0.9	187417766	184820727
133	1	1	10/10	2.5	5	0.2	183991004	185913049
134	1	1	10/10	2.5	5	0.55	184351716	185773165
135	1	1	10/10	2.5	5	0.9	184351716	185775969
136	1	1	20/5	0.5	1	0.2	184892784	185592991
137	1	1	20/5	0.5	1	0.55	184712428	183778935
138	1	1	20/5	0.5	1	0.9	184171360	184552252
139	1	1	20/5	0.5	3	0.2	184532072	183915253
140	1	1	20/5	0.5	3	0.55	186155275	187055504
141	1	1	20/5	0.5	3	0.9	184351716	183571005
142	1	1	20/5	0.5	5	0.2	183991004	186345101
143	1	1	20/5	0.5	5	0.55	184712428	186528260
144	1	1	20/5	0.5	5	0.9	184712428	185232248
145	1	1	20/5	1.5	1	0.2	185974919	184345101
146	1	1	20/5	1.5	1	0.55	184171360	184169487
147	1	1	20/5	1.5	1	0.9	185073139	183778935
148	1	1	20/5	1.5	3	0.2	185253495	185973248
149	1	1	20/5	1.5	3	0.55	185614207	183677287
150	1	1	20/5	1.5	3	0.9	183991004	184011056
151	1	1	20/5	1.5	5	0.2	183991004	185179169
152	1	1	20/5	1.5	5	0.55	185794563	185190799
153	1	1	20/5	1.5	5	0.9	184892784	185934324
154	1	1	20/5	2.5	1	0.2	184712428	183984726
155	1	1	20/5	2.5	1	0.55	184532072	187583995
156	1	1	20/5	2.5	1	0.9	184351716	184331020

Appendix Table A3 (Continued)

Run Order	Pt Type	Blocks	I/A	WOP	WOH	ER	Minimize Cost(\$)	
							DS	HIDS
157	1	1	20/5	2.5	3	0.2	185433851	184147404
158	1	1	20/5	2.5	3	0.55	185433851	185405241
159	1	1	20/5	2.5	3	0.9	184171360	184157392
160	1	1	20/5	2.5	5	0.2	183991004	185815041
161	1	1	20/5	2.5	5	0.55	184532072	185345101
162	1	1	20/5	2.5	5	0.9	184171360	186795594





Appendix B

Minimize cost to run the level parameters for Harmony search algorithm

Appendix Table B1 Minimize cost to run the level parameters for case study 2

Run Order	Pt Type	Blocks	I/H	HMCR	PAR	Minimize Cost(\$)	
						DS	HIDS
1	1	1	5/20	70	15	156378063	155979612
2	1	1	5/20	70	30	156911216	156217461
3	1	1	5/20	70	45	158332956	157004401
4	1	1	5/20	80	15	157088933	155979612
5	1	1	5/20	80	30	156555781	156866996
6	1	1	5/20	80	45	156378063	155939418
7	1	1	5/20	90	15	156200346	155979612
8	1	1	5/20	90	30	156200346	155838880
9	1	1	5/20	90	45	156733498	155939822
10	1	1	10/10	70	15	157088933	156546454
11	1	1	10/10	70	30	156200346	156927653
12	1	1	10/10	70	45	156378063	156900240
13	1	1	10/10	80	15	156378063	156294681
14	1	1	10/10	80	30	156200346	156501507
15	1	1	10/10	80	45	156200346	155979612
16	1	1	10/10	90	15	157266651	157221949
17	1	1	10/10	90	30	156378063	156927653
18	1	1	10/10	90	45	157088933	156900240
19	1	1	20/5	70	15	157088933	156823436
20	1	1	20/5	70	30	157266651	156293025
21	1	1	20/5	70	45	157088933	156546454
22	1	1	20/5	80	15	157088933	157105201
23	1	1	20/5	80	30	157266651	156546454
24	1	1	20/5	80	45	157088933	156293025
25	1	1	20/5	90	15	157088933	156369560
26	1	1	20/5	90	30	157266651	156546454
27	1	1	20/5	90	45	157088933	156293025
28	1	1	5/20	70	15	156733498	155762614
29	1	1	5/20	70	30	156378063	155585811
30	1	1	5/20	70	45	156200346	155838880
31	1	1	5/20	80	15	156555781	155585811
32	1	1	5/20	80	30	156555781	156146161
33	1	1	5/20	80	45	156378063	156334566
34	1	1	5/20	90	15	156911216	155661987
35	1	1	5/20	90	30	156555781	155585811
36	1	1	5/20	90	45	156733498	156750105
37	1	1	10/10	70	15	157266651	156823436
38	1	1	10/10	70	30	157266651	156900240
39	1	1	10/10	70	45	156200346	155485093

Appendix Table B1 (Continued)

Run Order	Pt Type	Blocks	I/H	HMCR	PAR	Minimize Cost(\$)	
						DS	HIDS
40	1	1	10/10	80	15	157088933	155979612
41	1	1	10/10	80	30	157088933	155661987
42	1	1	10/10	80	45	157088933	155661987
43	1	1	10/10	90	15	157266651	157181830
44	1	1	10/10	90	30	156200346	156646633
45	1	1	10/10	90	45	156200346	156546454
46	1	1	20/5	70	15	157266651	156469829
47	1	1	20/5	70	30	157088933	157884258
48	1	1	20/5	70	45	156200346	156723347
49	1	1	20/5	80	15	157088933	156469829
50	1	1	20/5	80	30	157266651	156469829
51	1	1	20/5	80	45	157088933	157282748
52	1	1	20/5	90	15	157266651	156723347
53	1	1	20/5	90	30	157088933	156546454
54	1	1	20/5	90	45	157266651	156823436
55	1	1	5/20	70	15	156200346	156117252
56	1	1	5/20	70	30	156200346	155838880
57	1	1	5/20	70	45	156378063	156293025
58	1	1	5/20	80	15	156733498	155485093
59	1	1	5/20	80	30	156733498	156469829
60	1	1	5/20	80	45	156378063	156293025
61	1	1	5/20	90	15	156555781	157044473
62	1	1	5/20	90	30	156911216	155939822
63	1	1	5/20	90	45	158155238	157004401
64	1	1	10/10	70	15	157088933	156546454
65	1	1	10/10	70	30	156200346	157105201
66	1	1	10/10	70	45	157266651	156546454
67	1	1	10/10	80	15	156200346	156157089
68	1	1	10/10	80	30	156200346	157105201
69	1	1	10/10	80	45	157266651	156117252
70	1	1	10/10	90	15	156200346	156293025
71	1	1	10/10	90	30	157266651	155661987
72	1	1	10/10	90	45	157266651	156369560
73	1	1	20/5	70	15	157088933	156293025
74	1	1	20/5	70	30	157088933	156866996
75	1	1	20/5	70	45	157088933	156293025
76	1	1	20/5	80	15	157266651	156293025
77	1	1	20/5	80	30	157266651	156293025
78	1	1	20/5	80	45	157088933	156293025

Appendix Table B1 (Continued)

Run Order	Pt Type	Blocks	I/H	HMCR	PAR	Minimize Cost(\$)	
						DS	HIDS
79	1	1	20/5	90	15	157088933	156646633
80	1	1	20/5	90	30	156911216	156826971
81	1	1	20/5	90	45	157266651	156546454



Appendix Table B2 Minimize cost to run the level parameters for case study 3

Run Order	Pt Type	Blocks	I/H	HMCR	PAR	Minimize Cost(\$)	
						DS	HIDS
1	1	1	5/20	70	15	147699478	147407660
2	1	1	5/20	70	30	148977994	147321592
3	1	1	5/20	70	45	147539663	147321592
4	1	1	5/20	80	15	147220034	147248156
5	1	1	5/20	80	30	156254032	146890197
6	1	1	5/20	80	45	147220034	146890197
7	1	1	5/20	90	15	148019107	154061252
8	1	1	5/20	90	30	147699478	147321592
9	1	1	5/20	90	45	146900405	157667555
10	1	1	10/10	70	15	148178922	149278406
11	1	1	10/10	70	30	155581866	147688392
12	1	1	10/10	70	45	148338736	147886171
13	1	1	10/10	80	15	147699478	149560792
14	1	1	10/10	80	30	155749908	148138435
15	1	1	10/10	80	45	149617253	149164196
16	1	1	10/10	90	15	149137809	146989465
17	1	1	10/10	90	30	149617253	149004515
18	1	1	10/10	90	45	147060220	148738878
19	1	1	20/5	70	15	155413824	149438214
20	1	1	20/5	70	30	155413824	148587515
21	1	1	20/5	70	45	149777067	149441203
22	1	1	20/5	80	15	166516736	155278119
23	1	1	20/5	80	30	166337938	149720735
24	1	1	20/5	80	45	149137809	157026099
25	1	1	20/5	90	15	166874330	148587515
26	1	1	20/5	90	30	164907561	147528753
27	1	1	20/5	90	45	148178922	149019962
28	1	1	5/20	70	15	148658365	150190347
29	1	1	5/20	70	30	146900405	154703228
30	1	1	5/20	70	45	148178922	146730559
31	1	1	5/20	80	15	149457438	146730559
32	1	1	5/20	80	30	149457438	146730559
33	1	1	5/20	80	45	149777067	146730559
34	1	1	5/20	90	15	147060220	146730559
35	1	1	5/20	90	30	148178922	148046423
36	1	1	5/20	90	45	148178922	149198998
37	1	1	10/10	70	15	155245783	155799574
38	1	1	10/10	70	30	149617253	148266948
39	1	1	10/10	70	45	155077741	146730559

Appendix Table B2 (Continued)

Run Order	Pt Type	Blocks	I/H	HMCR	PAR	Minimize Cost(\$)	
						DS	HIDS
40	1	1	10/10	80	15	148178922	148046423
41	1	1	10/10	80	30	155749908	154436720
42	1	1	10/10	80	45	148178922	155348135
43	1	1	10/10	90	15	147859292	153759139
44	1	1	10/10	90	30	146900405	147680327
45	1	1	10/10	90	45	146900405	154454683
46	1	1	20/5	70	15	149617253	149441203
47	1	1	20/5	70	30	149297624	147726667
48	1	1	20/5	70	45	149777067	147641478
49	1	1	20/5	80	15	155413824	155463351
50	1	1	20/5	80	30	147699478	149281568
51	1	1	20/5	80	45	157262282	149164196
52	1	1	20/5	90	15	148019107	155647394
53	1	1	20/5	90	30	147859292	149358895
54	1	1	20/5	90	45	149137809	164862764
55	1	1	5/20	70	15	157262282	149039102
56	1	1	5/20	70	30	148019107	153865970
57	1	1	5/20	70	45	148977994	149162202
58	1	1	5/20	80	15	147060220	147019946
59	1	1	5/20	80	30	147060220	147209475
60	1	1	5/20	80	45	146900405	147818867
61	1	1	5/20	90	15	148019107	155905629
62	1	1	5/20	90	30	147699478	147680327
63	1	1	5/20	90	45	147699478	148145675
64	1	1	10/10	70	15	148178922	147680327
65	1	1	10/10	70	30	147699478	165705775
66	1	1	10/10	70	45	147859292	149838585
67	1	1	10/10	80	15	148019107	148046423
68	1	1	10/10	80	30	147539663	149598022
69	1	1	10/10	80	45	154573616	147466578
70	1	1	10/10	90	15	154405575	154061252
71	1	1	10/10	90	30	148658365	147019946
72	1	1	10/10	90	45	149617253	147625815
73	1	1	20/5	70	15	149297624	149164196
74	1	1	20/5	70	30	149777067	149284780
75	1	1	20/5	70	45	147859292	166940556
76	1	1	20/5	80	15	147699478	149643242
77	1	1	20/5	80	30	155581866	148159751
78	1	1	20/5	80	45	148178922	149321705

Appendix Table B2 (Continued)

Run Order	Pt Type	Blocks	I/H	HMCR	PAR	Minimize Cost(\$)	
						DS	HIDS
79	1	1	20/5	90	15	148178922	147659083
80	1	1	20/5	90	30	149617253	155984401
81	1	1	20/5	90	45	155413824	167135992



Appendix Table B3 Minimize cost to run the level parameters for case study 4

Run Order	Pt Type	Blocks	I/H	HMCR	PAR	Minimize Cost(\$)	
						DS	HIDS
1	1	1	5/20	70	15	186139300	189106166
2	1	1	5/20	70	30	188831303	191013982
3	1	1	5/20	70	45	191147742	185871425
4	1	1	5/20	80	15	189200001	185795959
5	1	1	5/20	80	30	189568699	186254389
6	1	1	5/20	80	45	187400434	183569492
7	1	1	5/20	90	15	185778438	184871540
8	1	1	5/20	90	30	186139300	188040381
9	1	1	5/20	90	45	187401494	184233229
10	1	1	10/10	70	15	187401494	184349863
11	1	1	10/10	70	30	187221155	189839812
12	1	1	10/10	70	45	188193435	185411633
13	1	1	10/10	80	15	187401494	189856601
14	1	1	10/10	80	30	185417759	187033303
15	1	1	10/10	80	45	185417759	185055986
16	1	1	10/10	90	15	185417759	187035503
17	1	1	10/10	90	30	185417759	185585408
18	1	1	10/10	90	45	185598099	189521158
19	1	1	20/5	70	15	191347165	185625907
20	1	1	20/5	70	30	190978225	185051752
21	1	1	20/5	70	45	185778438	185233337
22	1	1	20/5	80	15	183975042	187198983
23	1	1	20/5	80	30	186860476	187040390
24	1	1	20/5	80	45	187220272	189311709
25	1	1	20/5	90	15	185237419	189304700
26	1	1	20/5	90	30	185778438	188703974
27	1	1	20/5	90	45	185238489	187185868
28	1	1	5/20	70	15	185778438	183996301
29	1	1	5/20	70	30	187401494	189459408
30	1	1	5/20	70	45	186679786	187409937
31	1	1	5/20	80	15	185417759	187030123
32	1	1	5/20	80	30	185238489	186499231
33	1	1	5/20	80	45	184696401	185056438
34	1	1	5/20	90	15	186680136	185080181
35	1	1	5/20	90	30	185057080	184892594
36	1	1	5/20	90	45	186319457	183782165
37	1	1	10/10	70	15	184155382	185491042
38	1	1	10/10	70	30	185778438	184878112
39	1	1	10/10	70	45	189855233	185411633

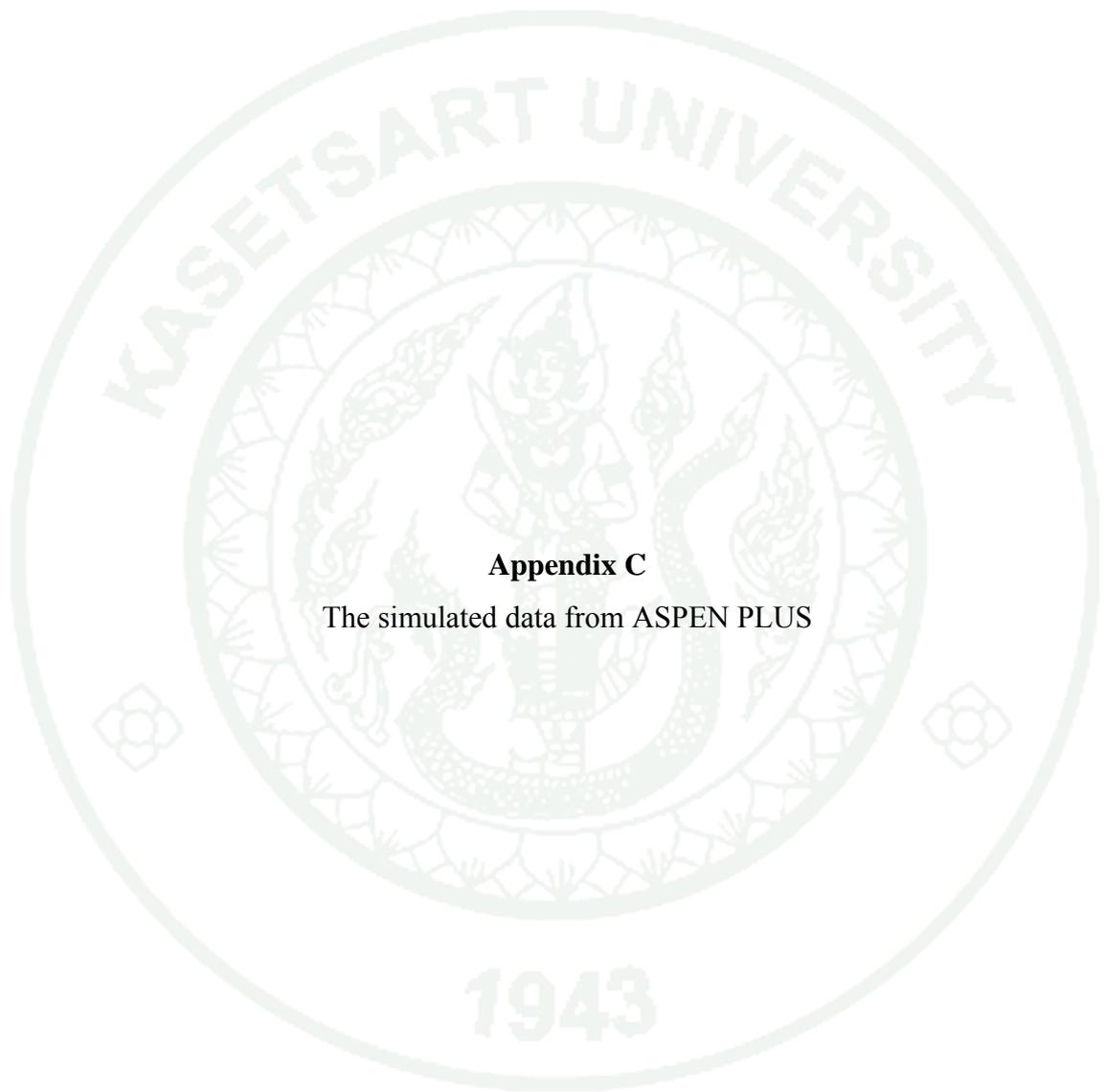
Appendix Table B3 (Continued)

Run Order	Pt Type	Blocks	I/H	HMCR	PAR	Minimize Cost(\$)	
						DS	HIDS
40	1	1	10/10	80	15	187040110	185225074
41	1	1	10/10	80	30	187040815	185038781
42	1	1	10/10	80	45	185057080	185114204
43	1	1	10/10	90	15	185598099	186810643
44	1	1	10/10	90	30	185598099	185307805
45	1	1	10/10	90	45	185598099	183603749
46	1	1	20/5	70	15	189317995	187035503
47	1	1	20/5	70	30	187040815	190943059
48	1	1	20/5	70	45	186860476	187206906
49	1	1	20/5	80	15	185417759	189885442
50	1	1	20/5	80	30	187400434	184941131
51	1	1	20/5	80	45	185778438	186676436
52	1	1	20/5	90	15	187401494	187290558
53	1	1	20/5	90	30	189502465	187005723
54	1	1	20/5	90	45	187220272	187034384
55	1	1	5/20	70	15	188093907	190581145
56	1	1	5/20	70	30	188462605	188361725
57	1	1	5/20	70	45	188193435	183460415
58	1	1	5/20	80	15	184516061	184041716
59	1	1	5/20	80	30	185238489	190217867
60	1	1	5/20	80	45	184696401	183603749
61	1	1	5/20	90	15	189317995	184860977
62	1	1	5/20	90	30	187401494	185091870
63	1	1	5/20	90	45	188949055	184359372
64	1	1	10/10	70	15	185417759	184772913
65	1	1	10/10	70	30	185417759	185408594
66	1	1	10/10	70	45	185417759	185241879
67	1	1	10/10	80	15	185417759	191381530
68	1	1	10/10	80	30	185057080	186853017
69	1	1	10/10	80	45	185598813	185765574
70	1	1	10/10	90	15	189133525	187023498
71	1	1	10/10	90	30	185238489	187242608
72	1	1	10/10	90	45	185237419	185446676
73	1	1	20/5	70	15	186860476	187223941
74	1	1	20/5	70	30	189502465	185280844
75	1	1	20/5	70	45	185238489	187429804
76	1	1	20/5	80	15	187040815	190594754
77	1	1	20/5	80	30	189133525	187055504
78	1	1	20/5	80	45	187401494	189046642

Appendix Table B3 (Continued)

Run Order	Pt Type	Blocks	I/H	HMCR	PAR	Minimize Cost(\$)	
						DS	HIDS
79	1	1	20/5	90	15	187220272	187214559
80	1	1	20/5	90	30	185237419	187202398
81	1	1	20/5	90	45	185598099	189115259



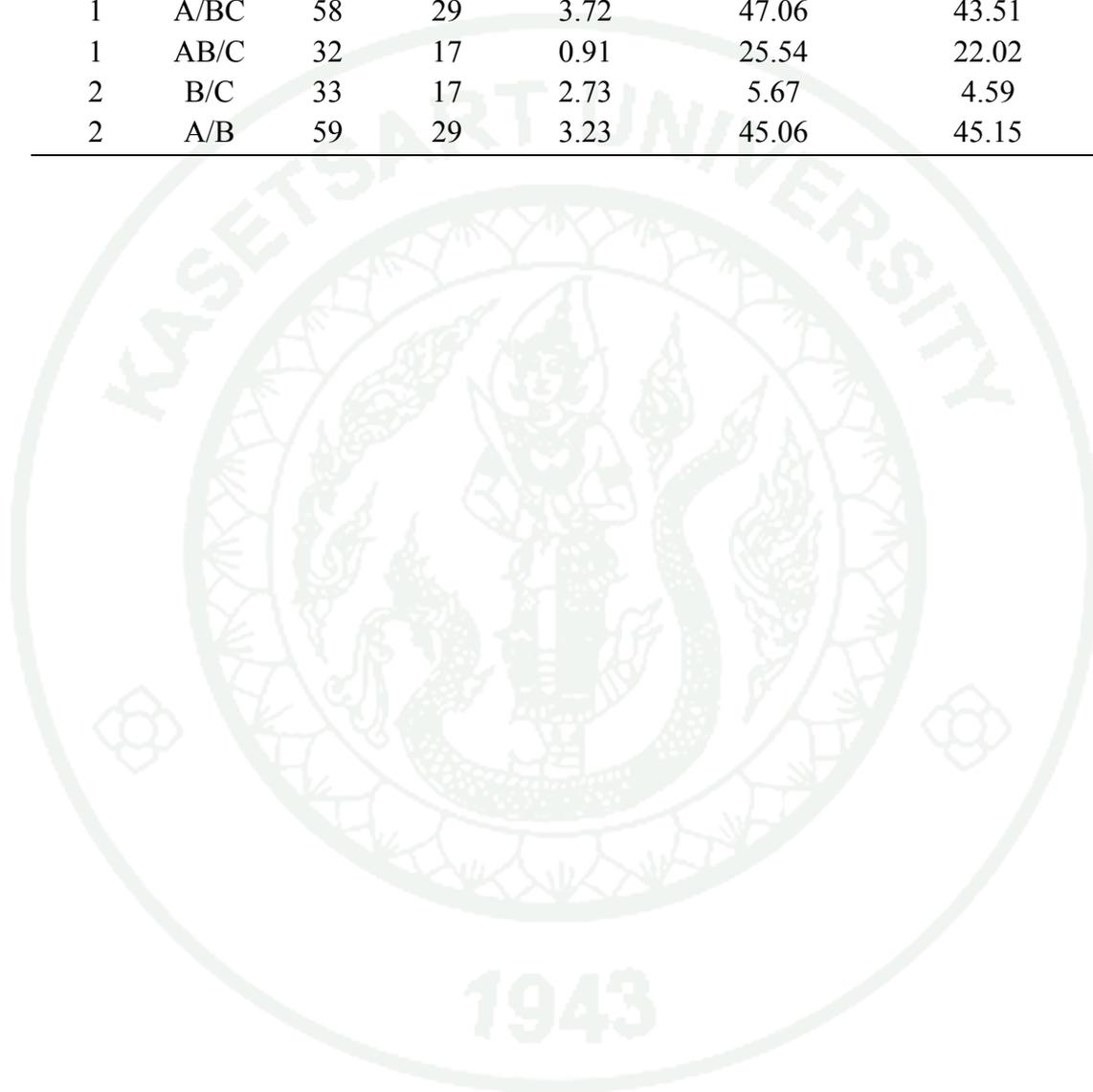


Appendix C

The simulated data from ASPEN PLUS

Appendix Table C1 The simulated data from ASPEN PLUS for case study 1

Column	Cut	Number of Stage	Feed Stage	Minimum Reflux ratio	Reboiler duty (GJ/hr)	Condenser duty (GJ/hr)
1	A/BC	58	29	3.72	47.06	43.51
1	AB/C	32	17	0.91	25.54	22.02
2	B/C	33	17	2.73	5.67	4.59
2	A/B	59	29	3.23	45.06	45.15



Appendix Table C2 The simulated data from ASPEN PLUS for case study 2

Column	Cut	Number of Stage	Feed Stage	Minimum Reflux ratio	Reboiler duty (GJ/hr)	Condenser duty (GJ/hr)
1	A/BCD	49	27	12.58	19.34	39.48
1	AB/CD	21	11	0.88	16.68	18.29
1	ABC/D	72	38	3.24	43.93	64.76
2	B/CD	20	12	3.43	13.16	24.79
2	BC/D	8	6	3.82	17.71	29.42
2	A/B	42	22	5.12	20.74	20.67
2	AB/C	20	10	1.64	24.68	23.79
2	A/BC	49	25	10.06	19.27	32.13
3	C/D	60	31	8.19	48.52	48.54
3	B/C	20	10	2.37	7.68	17.36
3	A/B	42	22	5.12	20.74	20.67

Appendix Table C3 The simulated data from ASPEN PLUS for case study 3

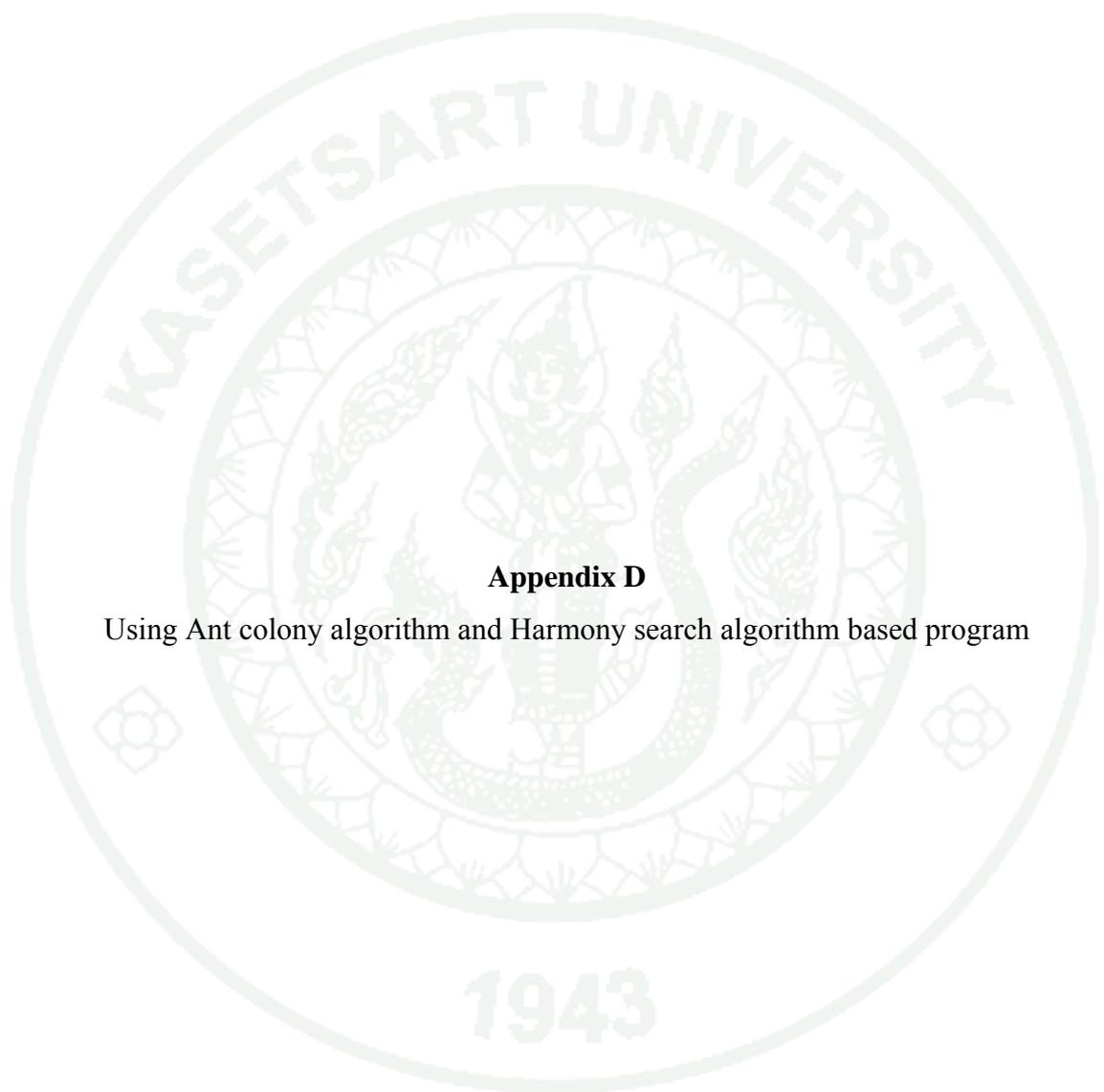
Column	Cut	Number of Stage	Feed Stage	Minimum Reflux ratio	Reboiler duty (GJ/hr)	Condenser duty (GJ/hr)
1	A/BCDE	18	10	4.53	6.63	4.68
1	AB/CDE	51	26	5.55	25.86	23.72
1	ABC/DE	22	11	0.74	18.85	17.04
1	ABCD/E	72	36	3.33	50.41	73.20
2	B/CDE	51	26	7.64	26.41	23.93
2	BC/DE	22	11	1.39	21.18	18.34
2	BCD/E	72	36	3.06	51.07	48.85
2	A/B	18	10	1.14	2.74	2.45
2	D/E	60	31	8.07	49.42	49.40
2	A/BCD	18	10	4.81	5.14	4.90
2	AB/CD	51	26	3.80	22.85	21.63
2	ABC/D	21	11	0.98	17.02	16.97
3	C/DE	22	11	2	17.94	14.73
3	CD/E	72	36	4.17	50.49	47.78
3	B/C	46	24	7.04	37.12	36.62
3	B/CD	50	26	7.26	23.38	22.87
3	A/BC	18	10	4.63	4.36	4.75
3	AB/C	45	23	3.48	19.33	19.48
3	BC/D	21	11	1.12	16.73	16.23
3	A/B	16	9	1.55	2.56	2.45
4	D/E	60	31	8.07	49.42	49.40
4	C/D	21	11	1.27	13.18	13.30
4	B/C	46	24	7.04	37.12	36.62
4	A/B	16	9	1.55	2.56	2.45

Appendix Table C4 The simulated data from ASPEN PLUS for case study 4

Column	Cut	Number of Stage	Feed Stage	Minimum Reflux ratio	Reboiler duty (GJ/hr)	Condenser duty (GJ/hr)
1	A/BCDEF	45	23	6.24	13.29	7.82
1	AB/CDEF	48	25	4.07	19.45	13.10
1	ABC/DEF	21	11	1.20	17.95	10.14
1	ABCD/EF	18	9	0.72	23.67	15.04
1	ABCDE/F	22	11	0.58	38.32	31.31
2	B/CDEF	48	25	7.87	16.95	10.28
2	BC/DEF	21	11	1.49	16.9	8.74
2	BCD/EF	18	9	0.83	23.02	13.94
2	BCDE/F	22	11	0.78	35.06	27.26
2	A/B	45	23	3.21	5.30	5.22
2	A/BC	45	28	9.37	6.3	11.15
2	AB/C	49	25	5.04	8.57	13.48
2	E/F	22	11	1.78	30.47	20.74
2	A/BCDE	45	23	6.98	9.64	8.61
2	AB/CDE	48	25	4.47	13.55	12.22
2	ABC/DE	21	11	1.21	11.85	10.17
2	ABCD/E	18	9	0.54	17.22	15.02
3	C/DEF	21	11	1.93	15.26	6.87
3	CD/EF	18	9	0.98	22.07	12.67
3	CDE/F	22	11	1.00	34.68	33.15
3	B/C	49	24	9.52	8.49	12.14
3	E/F	22	11	1.78	30.47	20.74
3	B/CDE	48	25	8.66	12.79	11.17
3	BC/DE	21	11	1.56	10.97	8.96
3	BCD/E	18	9	0.78	15.37	13.47
3	A/B	45	23	3.21	5.30	5.22
3	A/B	45	23	3.21	5.30	5.22
3	A/BCD	45	23	12.8	6.3	14.86
3	AB/CD	48	24	6.85	8.99	17.53
3	ABC/D	24	12	8.48	13.85	13.61
3	D/E	18	9	1.49	12.73	10.01
4	D/EF	18	9	1.51	20.07	10.13
4	DE/F	22	11	1.12	33.92	24.5
4	C/D	18	9	1.81	12.73	12.62
4	C/DE	21	11	2.15	9.6	7.35

Appendix Table C4 (continued)

Column	Cut	Number of Stage	Feed Stage	Minimum Reflux ratio	Reboiler duty (GJ/hr)	Condenser duty (GJ/hr)
4	CD/E	11	6	11.81	36.23	34.61
4	B/CD	48	26	13.09	9.35	16.28
4	BC/D	20	12	2.48	5.09	12.11
4	B/C	49	24	9.52	8.49	12.14
4	A/B	45	23	3.21	5.30	5.22
4	A/BC	45	28	9.37	6.3	11.15
4	AB/C	48	24	4.19	13.85	13.61
5	E/F	22	11	1.78	30.47	20.74
5	D/E	18	9	1.49	12.73	10.01
5	C/D	18	9	1.81	12.73	12.62
5	B/C	49	24	9.52	8.49	12.14
5	A/B	45	23	3.21	5.30	5.22



Appendix D

Using Ant colony algorithm and Harmony search algorithm based program

1. Start the program by selecting the desired Algorithm.



Appendix Figure D1 Main display for optimization

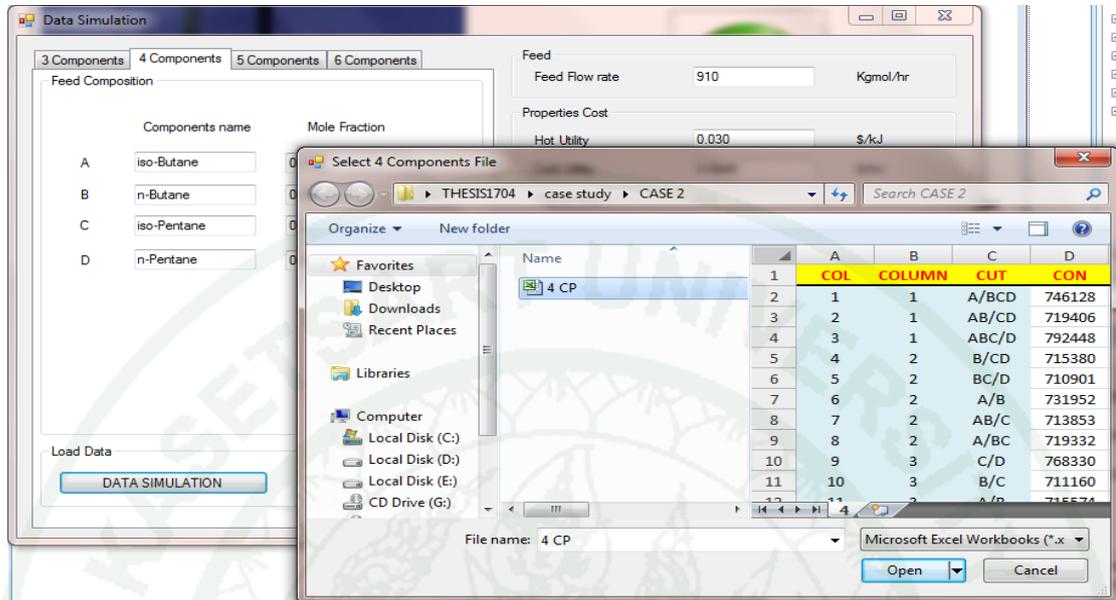
2. Enter the information you need to find optimization.

Components name	Mole Fraction
A iso-Butane	0.157
B n-Butane	0.263
C iso-Pentane	0.212
D n-Pentane	0.368

Parameter	Value	Unit
Feed Flow rate	910	Kgmol/hr
Hot Utility	0.030	\$/kJ
Cold Utility	0.0045	\$/kJ
Payout time	0.4	
Correction factor	0.52	
Log-Mean temperature difference	10	K
Over-All tranfer coefficient	800	Watt/sqm-k

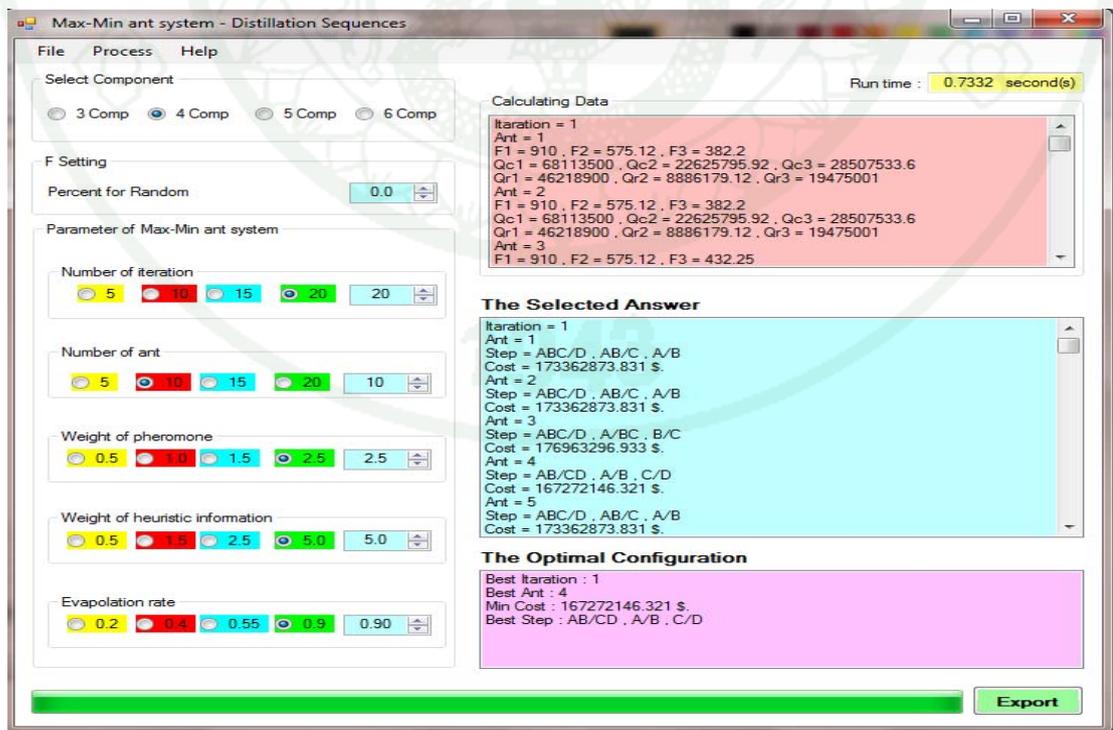
Appendix Figure D2 Main data simulated for optimization

3. Information contained in Microsoft Excel to be download for use in optimization.



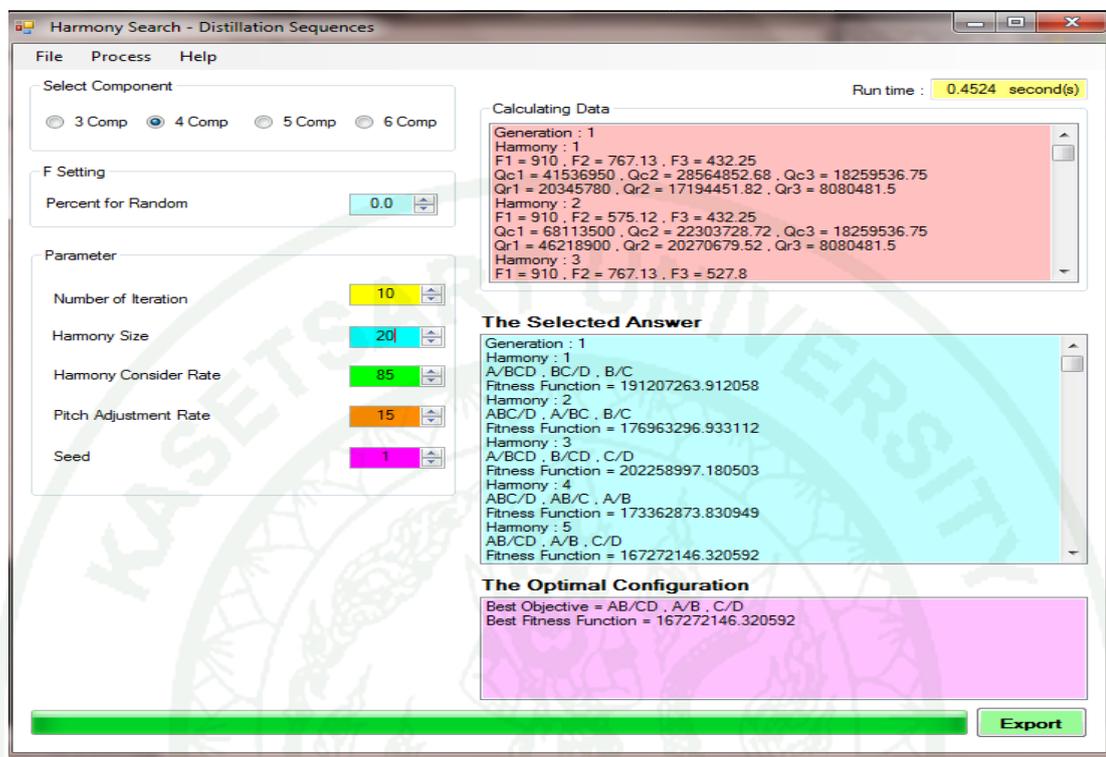
Appendix Figure D3 Download data sheet from Microsoft Excel

4. Factor each of the selected parameters Ant colony algorithm.



Appendix Figure D4 Display screen to run the Ant colony algorithm

5. Factor each of the selected parameters Harmony search algorithm.



Appendix Figure D5 Display screen to run the Harmony search algorithm

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