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A systematic molecular design framework with the consideration of competing solvent recovery processes

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Abstract

This paper presents a Computer Aided Molecular Design (CAMD) framework that considers both the solute extraction and solvent recovery steps simultaneously during the solvent design. The choice of a solvent has significant role not only on the effectiveness of the process, but also on the safety, health and environmental impact. In addition, the energy required for solvent regeneration is dependent on both the chosen solvent and its recovery techniques. Therefore, we have incorporated physicochemical property targets, safety, health and environmental (SHE) aspects and utilities cost needed to recover the solvent during the design stage. Fuzzy Analytic Hierarchy Process (FAHP) weighting approach is applied to assign consistent weights to the multiple objective functions. Through this approach, the designed solvents with favourable

25 functionalities can be recovered through an economically efficient and environment friendly
26 process. The developed methodology is used to design a solvent to be used in palm oil industry
27 for residual oil extraction from palm pressed fibre.

28 Keywords: multi-objective optimisation, Computer Aided Molecular Design (CAMD), Solvent
29 design, Fuzzy Analytic Hierarchy Process (FAHP), Solvent recovery process,

30

31 **1. Introduction**

32 Solvent often acts as a medium for chemical reactions and purification processes. In most of
33 the conventional practices, solvents are regenerated and recovered for reuse in the process.
34 Therefore, cost of solvent recovery and increasing environmental legislations against emissions
35 have been some of the major concerns in chemical industries. In the industry, there are several
36 types of separation process that can be used for recovering solvents (e.g., distillation,
37 crystallisation, filtration, centrifugation, etc). Among these existing solvent recovery
38 technologies, more than 95% of the chemical industries use distillation to recover solvents¹.
39 Solvent recovery through distillation process usually consumes excessive energy to recover
40 solvent from a mixture, which will have a significant effect on the greenhouse gases emission.
41 Hitherto the choice between solvent recovery alternatives is usually made based on the basis
42 of economic analysis. Note that the earlier work of Ooi et al.² reported that high energy
43 consumption during solvent recovery results in adverse impact on the environment. Therefore,
44 there is a need to consider environmental hazard of a solvent recovery process when choosing
45 solvent recovery alternatives.

46 Based on the literature review, there are approaches that are developed to include
47 environmental hazard as a factor when making choices between various solvent recovery

48 alternatives. For example, Seyler et al.³ performed environmental evaluation on solvent
49 recycling using distillation, solvent incineration and solvent disposal for Swiss chemical
50 industry. In their work, two case studies were performed to illustrate the integration of
51 environmentally friendly waste-solvent treatment into the planning of a chemical production.
52 Recently, in order to develop a more environment friendly solvent recovery processes, Luis et
53 al.¹ designed a hybrid process that comprised pervaporation and distillation to separate
54 methanol from tetrahydrofuran (THF). Besides energy requirement, environmental effect of
55 the hybrid process and pressure swing distillation to that of incineration has been compared by
56 carry out life cycle assessment (LCA). From the results, the hybrid process required less energy
57 compared to pressure swing distillation. Since the utilities needed for the hybrid process and
58 pressure swing distillation were used as input data to conduct environmental evaluation for
59 LCA, it showed that hybrid process exerted the lowest impact on environment. Since different
60 solvent recovery technologies have different energy requirements, it is important to regenerate
61 solvents using technology that requires minimum energy. In addition, it is also noted that each
62 solvent is associated with its own physicochemical properties that allow them to be recovered
63 using different amount of energy. For this reason, it is often difficult to identify an optimal
64 solvent with favourable properties that can be recovered using least amount of energy from
65 literature search. Besides, it is time-consuming to perform solvent screening from different
66 databases. Hence, a more effective methodology is required to determine solvents that can
67 simultaneously attain their functionalities and being recovered through a less energy intensive
68 process.

69 Computer Aided Molecular Design (CAMD) technique has capability to systematically predict,
70 estimate and design solvents that need to be verified through experiments. It has always been
71 one of the most reliable techniques for solvent design and selection. This is because CAMD

72 techniques allow cost-effective and quick estimation of large sets of molecular properties.
73 CAMD is described as reverse property prediction, which aims at designing molecules with
74 specific chemical structures based on molecular building blocks and a set of target properties⁴.
75 Throughout the years, CAMD techniques are widely applied for solvent design in separation
76 process. Separation process plays a major role in processing industries as it usually dictates the
77 core energy requirement of the whole process. For example, a hybrid methodology that
78 combine mathematical modelling and heuristic approaches together with thermodynamic
79 insights has been developed for solving optimisation models related to solvent design and
80 selection and synthesis of separation process⁵. In the previous work⁵, two case studies are
81 utilised to demonstrate the proposed hybrid method. The first case study includes the
82 identification of an ideal flowsheet for separating acetone from an acetone-chloroform
83 azeotropic mixture whereas the second example is to identify environmentally friendly solvents
84 for removing acetic acid from wastewater. Kim and Diwekar⁶ propose a multi-objective
85 programming framework to solve simultaneous integration of in-process solvent (IPS)
86 recycling and environmentally benign solvent (EBS) selection for acetic acid removal from
87 water process. Their result reports an improvement in economic and environmental
88 characteristics as there is a reduction in solvent loss but increase in recovery yield of acetic
89 acid without the change of process flowsheet structure. Furthermore, an integrated process and
90 product design problem is solved to separate volatile organic compounds from metal
91 degreasing process⁷. In their design problem, optimal property targets of solvents are
92 determined in a reduced – order space provided by clustering methods. Besides, a CAMD
93 framework is developed to design solvents for crystallisation in pharmaceutical industry⁸. In
94 their crystallisation solvent design problem, safety, toxicity and solubility properties are
95 selected as property constraints. Decomposition approach is employed to solve their design

96 problem. Later, a more advanced methodology that integrates targeted bench-scale experiments
97 and database search approach into CAMD is developed to design solvents for crystallisation of
98 carboxylic acid⁹. A CAMD framework that integrates both group contribution method and
99 stochastic optimisation has also been developed to generate environmental friendly solvent for
100 its application in extractive distillation and liquid-liquid extraction process¹⁰.

101 Recently, environmentally benign amine-based solvents with favourable properties are
102 designed using a novel CAMD technique that incorporates fuzzy and bilevel optimisation¹¹.
103 Besides, a systematic CAMD methodology built on efficient ant colony optimisation (EACO)
104 algorithm has been proposed to generate solvents that can remove acetic acid from process
105 waste streams¹². As shown in the previous work¹², the results reveal that new solvents that exert
106 improved thermodynamic properties are suitable for acetic acid extraction. Furthermore, a
107 systematic two stage approach has been proposed for generating and selecting a few potential
108 solvents to chemically absorb carbon dioxide¹³. The chosen criteria for evaluating the
109 performance of solvent include sustainability, reactivity and thermodynamic properties. In
110 another relevant contribution, CAMD tools have been extended into the design of the mixture
111 of amines by considering a large number of decision criteria¹³. CAMD techniques are also
112 applied for the development of novel chelating resin polymers in removing metal ions from
113 water¹⁴. The results indicate that the designed resin polymers with enhanced adsorption
114 capacity are effective in removing copper ions from drinking water. Besides, a COSMO-
115 CAMD optimisation based framework is proposed to generate new solvents by estimating
116 solvent properties with COSMO-RS¹⁵. This COSMO-CAMD optimisation-based framework
117 have successfully designed new promising solvents for extracting hydroxymethylfurfural and
118 phenol from water. In addition, outer-approximation algorithm has been recently modified to
119 solve Computer Aided Molecular and Process Design (CAMPD) problems to separate CO₂ and

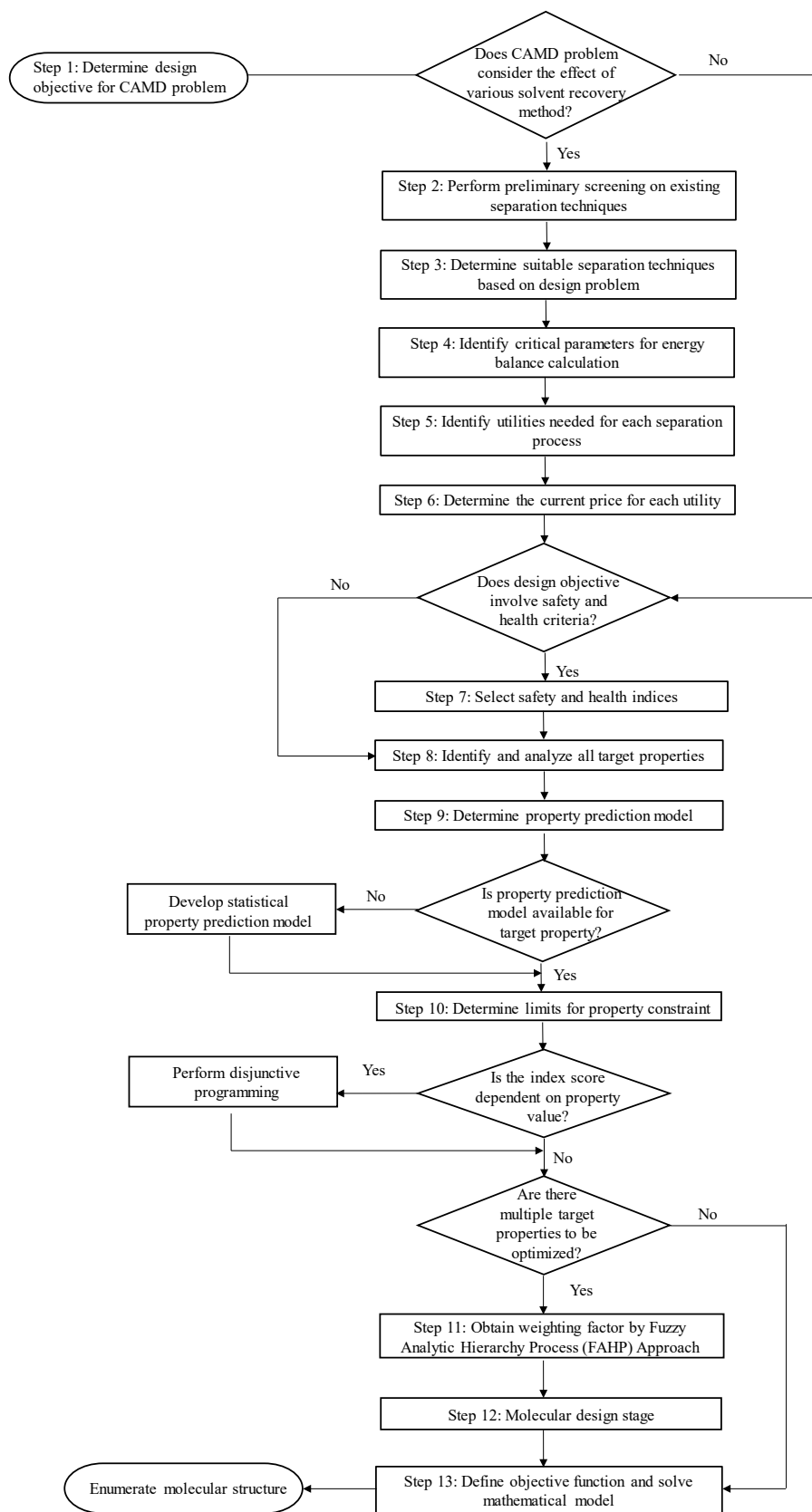
120 methane at high pressure¹⁶. This proposed methodology simultaneously optimises solvent
121 properties and process variables. Additionally, this approach can address the numerical
122 challenges that usually encounter owing to the highly non-linear interactions between process
123 and solvent. Apart from that, solvent and/or solvent mixtures are also designed for
124 crystallisation and liquid-liquid extraction process using a systematic approach that employs
125 Generalized Disjunctive Programming (GDP) technique¹⁷. A framework that integrates
126 structural characteristic into CAMD has been proposed to choose solvents for extracting
127 dihydric phenols from coal gasification wastewater¹⁸. The extraction efficiencies of chosen
128 solvents are further tested by experiment. Based on the experimental results, methyl propyl
129 ketone (MPK) can remove a higher percentage of phenols compared to that of using diisopropyl
130 ether (DIPE) or methyl isobutyl ketone (MIBK). Besides, the cost estimation on wastewater
131 treatment process shows that phenols separation process using MPK solvent is more
132 economically feasible. In another recent contribution, a systematic methodology that integrates
133 CAMD and ionic liquid based separation process design is developed to identify the optimal
134 ionic liquid and corresponding process design configuration¹⁹. Moreover, the cost for
135 recovering ionic liquid is also considered in their proposed framework. The proposed
136 framework is demonstrated through the separation of azeotropic mixtures such as acetone-
137 methanol and ethanol-water.

138 Note that the abovementioned works show the applicability of CAMD techniques in designing
139 solvents for various separation processes. However, the solvent design for solute extraction
140 together with its recovery step should also incorporate the safety, health and environmental
141 aspects of the solvent. The appropriate selection approach of solvents should also consider its
142 recovery process to enhance the economic feasibility and sustainability of a chemical process.
143 This is because energy consumption during solvent recovery process will vary according to the

144 solvent properties. Moreover, optimal solvent for an application will also change with the
145 selected separation technique. For example, if a solvent with high boiling point were to extract
146 a heat sensitive material, distillation may destruct the material as temperature has to be raised
147 to vaporise the solvent. However, if a non-thermal separation technique were chosen, the
148 solvent with high boiling point will become an optimal solvent as heat sensitive material will
149 not undergo degradation. To bridge the gap, it is of vital importance to develop a CAMD
150 framework that consider both the solvent application and its recovery step to enhance solvent
151 functionalities together with improvement in economic performance.

152 **2. Methodology**

153 This work aims to develop a systematic CAMD framework which considers complete cycle of
154 solvent from its application to its recovery process. Solvent recovery using different separation
155 techniques are integrated into CAMD framework to evaluate its effect on solvent selections.
156 The energy requirement and total utilities cost for solvent separation is integrated into CAMD
157 formulation. This method allows the design of solvents with optimal functionalities through
158 the cheapest, safest and environmentally favourable process. The developed methodology is
159 stated in the subsequent steps, shown in Figure 1.



160

161 Figure 1: CAMD methodology with the consideration of competing solvent recovery process

162 **2.1 Identification of design objective**

163 First, design objective has to be identified for CAMD problem. The aim of this paper is to
164 design solvents with optimal functionalities that can be regenerated by the cheapest, safest and
165 environmentally favourable process. Since the entire cycle of solvent from its application to
166 recovery are integrated into molecular design, criteria belong to both molecular and process
167 perspectives are considered. Under molecular properties, physicochemical and SHE properties
168 are included to design a safe and environmentally favourable solvent for a certain application.
169 Safety and health performance of the designed solvents are assessed by suitable indices, which
170 will be further discussed in Section 2.3. In terms of process perspective, yield and economic
171 potential are the chosen criteria to ensure that the generated solvent achieve expected
172 performance such as process yield during its application. Besides, this methodology compares
173 the effect on solvent design if the designed solvent were to be recovered through different
174 separation techniques. The suitability of a separation technique can be dictated by estimating
175 the total utilities cost required for recovering the designed solvents. The steps in integrating
176 different solvent recovery processes into CAMD framework is illustrated in Section 2.2. The
177 desired criteria and/or properties are then chosen as design objectives.

178 **2.2 Assessment of separation techniques for solvent recovery**

179 As aforementioned, solvent selection affects the sustainability of a chemical process. In the
180 earlier work presented in Ooi et al.², the generated solutions had shown that reducing the energy
181 required for solvent separation can minimise environmental burden of a process. The energy
182 requirement for solvent separation relies on the physicochemical properties of the solvent. In
183 another word, it means that different solvents need distinct amount of energy for their
184 separation process. Greater energy requirement often leads to more adverse impact on the
185 environment. This is because for a solvent that requires more energy during its recovery process,

186 larger amount of steam is supplied to vaporise the solvent, which inevitably emits higher
187 amount of greenhouse gases. The methodology developed in the previous work² only focused
188 on reducing the energy required to regenerate solvent through a specific separation technique.
189 However, there are numerous separation techniques available in literature that can be used to
190 recover solvent from a mixture. Operating condition of a separation technique often affects
191 performance and energy consumption of a chemical process. For example, heat sensitive
192 material can only be recovered through low temperature operating condition. If heat sensitive
193 material were to be separated through high temperature process, process yield will be reduced
194 due to degradation. Hence, it is important to incorporate the effect of various separation
195 techniques on solvent design into CAMD framework.

196 To begin with, preliminary screening on existing methods for solvent recovery is performed to
197 select suitable separation techniques based on the design problem. After that, important
198 parameters are identified for estimating energy balance for each chosen separation technique.
199 For example, information such as latent heat of vaporization and/or specific heat capacity of a
200 chemical substance is usually needed to calculate energy balance of evaporation process under
201 standard condition. Energy balance around the evaporator (either normal or vacuum condition)
202 can be calculated using Equation (1):

$$203 \quad \Delta H^{\text{feed, evap}} + q_H^{\text{evap}} = \Delta H^{\text{top, evap}} + \Delta H^{\text{bottom, evap}} \quad (1)$$

204 where $\Delta H^{\text{feed, evap}}$ is the enthalpy change for evaporator feed; $\Delta H^{\text{top, evap}}$ is the enthalpy change
205 for top product (solvent vapour); $\Delta H^{\text{bottom, evap}}$ is the enthalpy change for bottom product
206 (residual oil) and q_H^{evap} represents the heat transferred from steam to the evaporator.

207 Besides, if a process were to be performed under vacuum condition, energy needed to create
208 vacuum has to be calculated. Steam ejector has been widely chosen to create vacuum for

209 evaporator since it is cheaper and easier for maintenance. Steam ejector creates vacuum using
 210 expansion of motive steam. A single stage steam ejector normally generates up to 75 mmHg
 211 of vacuum. The following equations are used to estimate motive steam consumption in a single
 212 stage steam ejector. Equation (2) to Equation (4) can be used for the estimation of temperature
 213 entrainment ratio, TC_a and molecular weight entrainment ratio of solvent vapour, MW_c
 214 respectively²⁰.

$$215 \quad TC_a = -4 \times 10^{-10} T_{sg}^3 + 3 \times 10^{-7} T_{sg}^2 - 0.0005 T_{sg} + 1.0131 \quad (2)$$

216 *For* $0 < M_w < 60$;

$$MW_c = 1 \times 10^{-5} M_w^3 - 0.0013 M_w^2 + 0.0642 M_w + 0.0161 \quad (3)$$

217 *For* $60 < M_w < 150$;

$$MW_c = -2 \times 10^{-5} M_w^3 + 0.0077 M_w^2 + 0.9464 \quad (4)$$

218 where T_{sg} is the temperature of suction gas in °C, M_w is the molecular weight of designed
 219 solvent. Later, suction gas stream is converted into dry air equivalent (DAE) using Equation
 220 (5).

$$221 \quad DAE \text{ of suction gas} = \frac{M_{vs}}{TC_a \times MW_c} \quad (5)$$

222 R_a can be defined as the consumption of motive steam for compressing a unit DAE mass of
 223 suction gas in a steam ejector, which can be estimated through Equation (6)²¹.

$$224 \quad R_a = \left[P_d / P_a \left(0.434 - 1.338 / P_a + 0.475 \times 10^{-3} P_a \right) - 0.187 \right] (1.2 - (P_v - 10.2) / 20) \quad (6)$$

225 where P_a and P_d represent suction and discharge pressures measured in torr respectively, P_v
 226 is the motive steam pressure in barg. Equation (7) can then be used to estimate the amount of
 227 motive steam, $M^{\text{steam,motive}}$ needed for a steam ejector.

$$M^{\text{steam,motive}} = DAE \times R_a \quad (7)$$

The following step is to identify the utilities required for each separation process. Typical utilities include steam, electricity, natural gas, cooling water, refrigeration etc. The price for each utility is then identified based on current market rate in Malaysia and presented in USD. Appendix A shows the cost of each utility based on the latest tariff given by Malaysia. The production costs of steam, cooling water and refrigeration are estimated using the steps given by Turton et al.²². The total utilities cost for a normal evaporation process, $Cost_{\text{evap},n}$, can be calculated using Equation (8). For evaporation process operated under vacuum condition, steam ejector utility cost is considered in the calculation. The estimation of total operating cost for vacuum evaporation, $Cost_{\text{evap},v}$, is shown in Equation (9). By performing all these steps, the total energy consumption along with utilities cost can be integrated into CAMD formulation.

$$Cost_{\text{evap},n} = \text{heating utility cost} + \text{cooling utility cost} \quad (8)$$

$$Cost_{\text{evap},v} = \text{heating utility cost} + \text{cooling utility cost} + \text{steam ejector utility cost} \quad (9)$$

2.3 Selection of safety and health indices

At this stage, explosiveness index (I_{EX}) and flammability index (I_{FL}) are estimated to evaluate safety performance of the molecule. Boiling point (T_b) and flash point (F_p) are used for evaluating I_{FL} whereas I_{EX} is assessed based on the lower explosion limit (LEL) and upper explosion limit (UEL). Penalty scores for I_{FL} and I_{EX} are extracted from National Fire Protection Association (NFPA) rating²³ and Inherent Safety Index (ISI)²⁴.

On the other hand, exposure limit index (I_{EL}) and acute health hazards (I_{AH}) can be used to evaluate health characteristic of a molecule. Oral rat LD₅₀ toxicity and permissible exposure

249 limit (PEL) are used to assess I_{AH} and I_{EL} . The indices score for I_{AH} is obtained from NFPA
250 health hazard rating²³ whereas the indices score for I_{EL} is obtained from Inherent Occupational
251 Health Index (IOHI)²⁵. The penalty scores for the abovementioned safety and health indices
252 are dictated in Appendix B. The safety and health aspects of all generated molecules can later
253 be compared by calculating their total weighted penalty score ($I_{SHI,w}$), which is expressed in
254 Equation (10). The lower the $I_{SHI,w}$ value, the better the safety and health performance of a
255 molecule.

$$256 \quad I_{SHI,w} = w_{FL}I_{FL} + w_{EX}I_{EX} + w_{EL}I_{EL} + w_{AH}I_{AH} \quad (10)$$

257 where w_{FL} denotes weighting factor for sub-index I_{FL} ; w_{EX} indicates weighting factor for
258 sub-index I_{EX} ; w_{EL} represents weighting factor for sub-index I_{EL} ; w_{AH} indicates weighting
259 factor for sub-index I_{AH} .

260 **2.4 Disjunctive programming**

261 Disjunctive programming is a modelling technique for monitoring the abrupt change over a
262 given variable using discontinuous function²⁶. The health and safety sub-indices written in
263 Section 2.3, their penalty scores are dependent on the property values. Safety and health sub-
264 indices are described by several intervals to represent different magnitudes of hazard level.
265 Thus, it shows that disjunctive programming is capable in translating the molecular properties
266 into penalty scores.

267 Equation (11) is one example of the estimation of a sub-index score. From Equation (13), it
268 can be seen that a score of I_A is allocated to the sub index if the corresponding property, p
269 value were lesser than a predefined property value, p_{switch} , whereas the sub index takes a score
270 of I_B if the p value were equal to or higher than p_{switch} .

271
$$I_p = \begin{cases} I_A & p < p_{switch} \\ I_B & p \geq p_{switch} \end{cases} \quad (11)$$

272 Binary integer variable (I) is then introduced to formulate this sub index model that involves
 273 discontinuous function into the following mixed-integer formulation.

274
$$I_p = I_A * I + I_B * (I - 1) \quad (12)$$

275 under the following condition:

276
$$I = \begin{cases} 0 & p < p_{switch} \\ 1 & p \geq p_{switch} \end{cases} \quad (13)$$

277 To model the condition that assigned the value of I to be 1 or 0, the following constraint,
 278 shown in Equation (14), has to be included.

279
$$(p_L - p_{switch}) \times I < p - p_{switch} \leq (p_U - p_{switch}) \times (1 - I) \quad I \in \{0,1\} \quad (14)$$

280 where p_L and p_U are the lower and upper bounds to possible values of p .

281 When p is smaller than p_{switch} , the value of $p - p_{switch}$ becomes negative, which force I to be 1
 282 to satisfy both equalities in the constraint (16). Similarly, I has to take the value 0 to fulfil both
 283 equalities in constraint (16) when p is equal to or greater than p_{switch} .

284 **2.5 Computation of weighting factor of each objective function**

285 Since this is a multi-objective CAMD problem, FAHP approach is introduced to estimate the
 286 weighting factor for each chosen objective function. FAHP approach is a variant of the
 287 traditional Analytic Hierarchy Process (AHP) that breaks down the decision-making problem
 288 into a hierarchical manner. FAHP approach can deal with the fuzziness and ambiguity of
 289 subjective views which happened during pairwise comparison. FAHP uses triangular fuzzy

290 numbers rather than exact numerical values to pairwise compare the decision elements. The
 291 use of triangular fuzzy number can quantify the confidence level of decision maker. Hence, the
 292 inability of traditional AHP method to cope with the uncertainties that arise from ambiguity
 293 involved during pairwise comparison can be resolved by employing FAHP approach. The
 294 procedure in performing FAHP approach are summarised as follows:

295 The first step of FAHP approach involves structuring the decision-making problem as a
 296 hierarchy. The hierarchy framework places the primary goal of design problem at the top,
 297 followed by criteria and/or sub-criteria, leaving alternatives at the bottom²⁷. Using a hierarchy
 298 model, the connection between elements of one stage and those of the stage below can be
 299 demonstrated. Next, pairwise comparisons are conducted based on expert judgement to deduce
 300 the relative importance between criteria at a specific level. For instance, a comparison can be
 301 made between two criteria by answering the following question: “How much more important
 302 is criterion i in fulfilling the objective of decision problem when compared to that of criterion
 303 j ?” Solution ratio, which is represented by w_i / w_j , can be used to denote the ratio of their
 304 relative importance. A verbally expressed judgement involved in a typical AHP problem is
 305 translated into a numerical ratio w_i / w_j through the use of fundamental AHP 9-point²⁷.
 306 Nevertheless, rather than using the exact numerical value, the vagueness and uncertainty of
 307 comparative judgement can be expressed by applying a fuzzy scale to represent the value
 308 judgement \hat{a}_{ij} as Triangular Fuzzy Number (TFN) to approximate w_i / w_j . Equation (15)
 309 shows a typical FAHP pairwise comparison matrix.

$$310 \quad A = \begin{pmatrix} \langle 1,1,1 \rangle & \hat{a}_{12} & \cdots & \hat{a}_{1n} \\ \hat{a}_{21} & \langle 1,1,1 \rangle & \cdots & \hat{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{a}_{n1} & \hat{a}_{n2} & \cdots & \langle 1,1,1 \rangle \end{pmatrix} \quad \text{where } \hat{a}_{ji} = 1 / \hat{a}_{ij} = (1 / \hat{L}_{ij}, 1 / \hat{M}_{ij}, 1 / \hat{U}_{ij}) \quad (15)$$

311 where A is fuzzy pairwise comparison matrix, \hat{a}_{ij} is fuzzy judgement, depicted by TFN (lower
312 bound \hat{L}_{ij} , modal value \hat{M}_{ij} and upper bound \hat{U}_{ij}). For example, TFN $\langle 1/1 + \delta_c, 1, 1 + \delta_c \rangle$
313 depicts \hat{a}_{ij} that is known to be more or less equally important. When \hat{a}_{ij} is more important over
314 the other, it can be represented by the fuzzy scale listed in Table 1. Note that δ_c denotes the
315 confidence level of a decision maker wherein a greater value indicates a lower degree of
316 confidence. When performing comparative judgements, the high, moderate and low level of
317 confidence are shown by δ_c value of one, two and three respectively²⁸.

318 Table 1: Summary of fuzzy scale²⁹

Fuzzy number, \hat{a}_{ij}	Verbal scale for comparison of properties
$\langle 1/1 + \delta_c, 1, 1 + \delta_c \rangle$	More or less equal importance
$\langle \max(1, 3 - \delta_c), 3, \min(9, 3 + \delta_c) \rangle$	Moderate importance
$\langle \max(1, 5 - \delta_c), 5, \min(9, 5 + \delta_c) \rangle$	Strong importance
$\langle \max(1, 7 - \delta_c), 7, \min(9, 7 + \delta_c) \rangle$	Very strong importance
$\langle \max(1, 9 - \delta_c), 9, \min(9, 9 + \delta_c) \rangle$	Extreme importance

319

320 Nonlinear programming (NLP) formulation proposed by Promentilla et al.²⁸ is employed to
321 compute the optimal priority vector (w) that approximate the solution ratio in pairwise
322 comparison matrix. The NLP formulation is expressed by Equation (16a) to Equation (16f).

$$323 \quad \max \lambda \quad (16a)$$

324 subject to:

$$325 \quad \lambda(M_{ij} - L_{ij})(w_j) - w_i + w_j L_{ij} \leq 0; \quad (16b)$$

$$326 \quad \lambda(M_{ji} - L_{ji})(w_i) - w_j + w_i L_{ji} \leq 0; \quad (16c)$$

$$327 \quad \lambda(U_{ij} - M_{ij})(w_j) - w_i + w_j U_{ij} \leq 0; \quad (16d)$$

328 $\lambda(U_{ji} - M_{ji})(w_i) - w_j + w_i U_{ji} \leq 0;$ (16e)

329 $\sum_{m=1}^n w_m = 1; w_m > 0$ (16f)

330 where L_{ij} and U_{ij} are the lower and upper bounds of properties, M_{ij} is the modal value, and
331 lambda (λ) is the consistency index that indicates the degree of satisfaction of computed weight
332 ratios that would fulfil the initial fuzzy judgments. λ should have the value between 0 to 1. λ
333 value of 0 implies that the comparative judgements are fulfilled at the boundaries whereas a
334 value of 1 shows perfect consistency²⁸. The most consistent set of w within the fuzzy scales
335 chosen by the designer can be obtained by maximising λ . However, there will be no solution
336 for the case where λ value falls outside the range due to totally inconsistent pairwise
337 comparison. In such case, it is compulsory to perform the comparative judgement again. The
338 next step estimate the weighting factor of each sub-criterion, w_m by multiplying w of sub-
339 criterion with w of its primary criterion.

340 **2.6 Molecular design phase**

341 Appropriate first order molecular groups are then chosen based on the design targets. To
342 generate structurally feasible acyclic and monocyclic compounds, structural constraints are
343 applied to remove infeasible solution. First, total number of groups must be more than 0 for the
344 existence of a molecule. This rule can be expressed mathematically by Equation (17).

345 $\sum_{k=1}^{G_T} N_k > 0$ (17)

346 where N_k is the number of occurrences of group k and G_T is the total number of molecular
347 groups chosen as the building blocks. The second constraint applied is to ascertain that there is
348 no free bond in the designed molecules as depicted in Equation (18).

349
$$\sum_{k=1}^{G_T} N_k (2 - v_k) = 2g \quad (18)$$

350 where v_k is the valence of group k and g will take the values 1, 0, -1 or -2 respectively for
351 acyclic, monocyclic, bicyclic and tricyclic compounds. In this work, both acyclic compounds
352 and monocyclic compounds are considered during molecular design stage. Thus, Equation (18)
353 can be represented by Equations (19) and (20):

354
$$\sum_{k=1}^{G_T} N_k (2 - v_k) = 2 \quad (19)$$

355
$$\sum_{k=1}^{G_T} N_k (2 - v_k) = 0 \quad (20)$$

356 In addition to ensure the structural feasibility of molecule, it is essential to ensure that the
357 selected molecules can be used as effective solvents. The considerations include the ability to
358 synthesize and stability of the predicted structures. In this work, the feasibility rules developed
359 in two previous works^{30, 31} have been adapted. Molecular groups have been classified into class
360 and categories by Gani et. al³¹. The class of a molecular group represents number of valences
361 in the group. For example, group of class 1 has one free attachment. On the other hand, category
362 of a class of group denotes the degree of restriction of a group joining with another molecular
363 group. Generally, if a molecular group falls under higher category, the group will have more
364 restriction on connecting with other molecular groups. Hence, the selected molecular groups
365 must be first grouped into respective class and category, followed by fulfilling the rules on the
366 restriction of a molecular group joining with another group developed by Gani et. al³¹.

367 For cyclic molecules, the additional constraints from the work of van Dyk & Nieuwoudt³⁰
368 which classified the types of free bonds as shown in Table 2.

369 Table 2: Free bond types³⁰

Type of free bond	Description
I	Bonding atom is hetero atom bonded to a hydrogen atom
II	Bonding atom is hetero atom bonded to a carbon atom
III	Bonding atom is carbon atom bonded to a hetero atom which is bonded to a hydrogen atom
IV	Bonding atom is carbon atom bonded to a hetero atom which is bonded to a carbon atom
V	Bonding atom is carbon atom bonded to another carbon atom

370

371 The sum of type 4 and 5 bonds must be greater than the sum of type 1 and 2 for the molecule
 372 to be considered as a solvent³⁰ as shown in Equation (21):

$$373 \quad n_4 + n_5 \geq n_1 + n_2 \quad (21)$$

374 where n_i is the number of groups of type i in the molecule.

375 Next, most of targeted properties stated in Sections 2.1, 2.2 and 2.3 can be predicted using
 376 Group Contribution Method (GCM) by Marrero and Gani³². Empirical correlations and
 377 relationships is used when target properties cannot be estimated using GCM equations. The
 378 upper and lower bounds of property constraints are then defined based on process requirement
 379 or customers' need. The range of a targeted property can be expressed by Equation (22).

$$380 \quad v_p^L \leq V_p \leq v_p^U \quad \forall p \in P \quad (22)$$

381 where V_p is the value of the target property p , v_p^L and v_p^U represents the bounds of the property.

382 2.7 Optimisation model

383 In this work, CAMD problem is formulated as a multi-objective optimisation problem because
384 of the conflicting design targets. The earlier works performed by Ooi et al.^{2, 33, 34} demonstrated
385 that weighted sum method is suitable for solving multi-objective optimisation model. The use
386 of weighted sum method enables multiple objectives to be transformed into a combined scalar
387 objective function. The overall objective function can be obtained by first allocating the pre-
388 defined weighting factor (using FAHP approach) to each objective function, followed by
389 adding up all the contributors. The formulation steps are summarised as below:

390 All the chosen targeted properties are first translated into linear membership functions,
391 represented by their respective target property operators, Ω_p . Owing to the reason that all the
392 target properties and/or sub-indices belong to distinct categories, they are usually defined by
393 different measurement units and scales. Hence, it is necessary to perform normalisation to bring
394 all the properties to the same magnitude. Equation (23) and Equation (24) are applied to
395 normalise Ω_p that has to be maximised and minimised respectively.

$$396 \lambda_{pm} = \frac{\Omega_p - \Omega_p^{\min}}{\Omega_p^{\max} - \Omega_p^{\min}} \quad (23)$$

$$397 \lambda_{pm} = \frac{\Omega_p^{\max} - \Omega_p}{\Omega_p^{\max} - \Omega_p^{\min}} \quad (24)$$

398 where Ω_p^{\min} and Ω_p^{\max} are the lowest and highest values of target property operators estimated by
399 independantly optimising the target properties. It can be noticed that the normalised target
400 property operator, λ_{pm} , can have a value between 0 and 1. In the next step, this multi-objective
401 optimisation model is solved by employing weighted sum method. Equation (25) shows the
402 overall objective function.

403 $F^{\text{weighted sum}} = w_1\lambda_{p1} + w_2\lambda_{p2} + \dots + w_m\lambda_{pm}$ (25)

404 where $F^{\text{weighted sum}}$ is the overall objective function and w_m is the weighting factor for each
405 normalised target property operator λ_{pm} . The optimal solution is obtained by maximising
406 $F^{\text{weighted sum}}$. Integer cuts are then applied to attain a set of optimal and near-optimal molecules
407 with proper rankings.

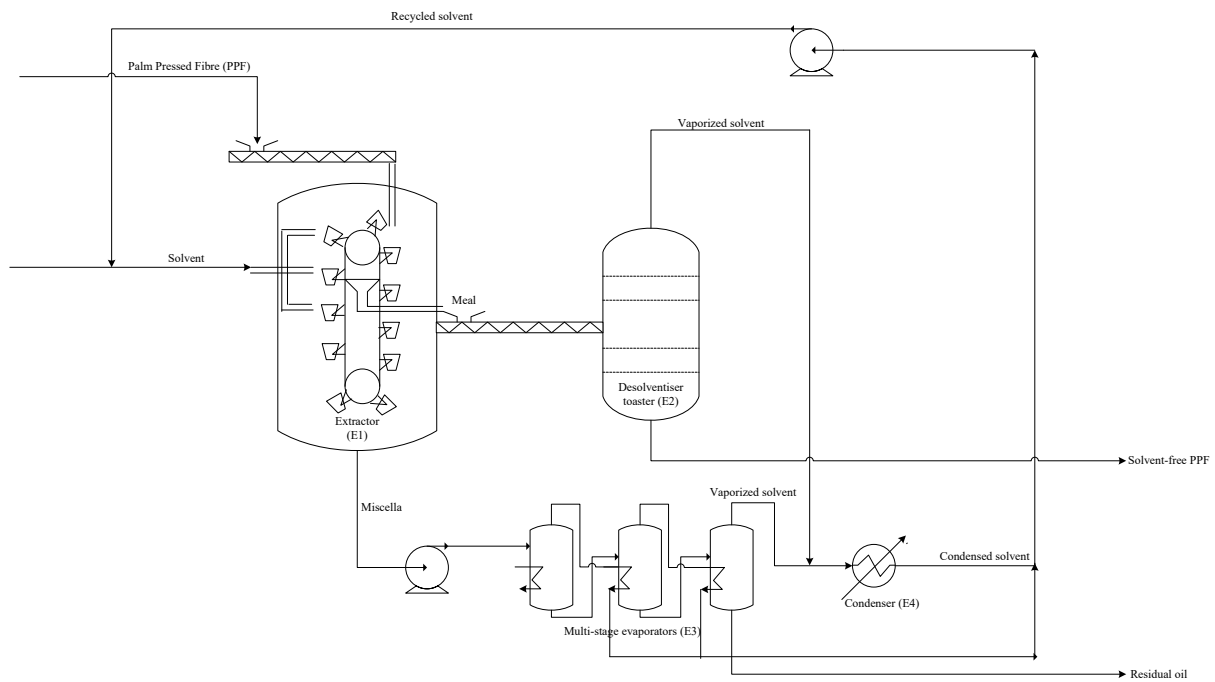
408 3. Case study

409 3.1 Problem statement

410 Palm Pressed Fibre (PPF) is a by-product obtained after the process of extracting crude palm
411 oil (CPO) from fresh fruit bunches (FFB). It has been figured out that the remaining 5-7% of
412 residual oil in the PPF is enriched with 2400 – 3500 ppm of vitamin E, 4000 – 6000 ppm of
413 carotenes and 4500 – 8500 ppm of sterols³⁵. This case study aims to identify a suitable solvent
414 to substitute hexane for extracting residual oil that is enriched with carotene from the PPF.
415 Among all the existing solvents, hexane has been the popular choice in industries for its low
416 cost and high oil solubility³⁶. In conventional practice, normal evaporation is used to recover
417 hexane from residual oil after the solvent extraction process.

418 A typical process flow diagram for residual oil removal from PPF is shown in Figure 2. To
419 ensure efficient oil removal, counter current extractor (E1) is usually employed by industries.
420 Extraction takes place when there is a diffusion of oil into the solvent. The meal (solvent-
421 saturated PPF) is then transferred to desolventiser toaster (E2) for solvent recovery. Multistage
422 evaporation units are employed to recover residual oil from the miscella (oil-rich solvent).
423 Solvent vapours from both evaporators and desolventising toaster and evaporator are then
424 passed through condenser (E4) and recycled into the extraction unit. Nonetheless, there are a
425 few drawbacks for using hexane to remove residual oil from PPF. For instance, hexane vapour

426 often forms photochemical smog upon released into the surrounding air. Moreover, hexane is
 427 highly flammable, which poses serious safety hazards in the plant since solvents are handled
 428 above its flash point. It is not appropriate to use hexane for edible oil extraction process owing
 429 to its toxicity that will result in fatality if swallowed or inhaled. Besides, carotene starts to
 430 degrade when the operating temperature is higher than 70°C. Since hexane has a boiling point
 431 of 69°C, the higher temperature in the evaporation process will inevitably lead to carotene
 432 degradation. Thus, besides design solvents with improved physicochemical and SHE properties,
 433 this work aims in exploring the potential of various separation processes for solvent recovery
 434 through multi-objective CAMD method.



435
 436 Figure 2: Typical process for residual oil recovery from PPF via solvent extraction
 437

438 3.2 Identification of design objective

439 Since this case study aims to design alternate solvents for replacing hexane in residual oil
 440 extraction from PPF, the designed solvents must exert desirable properties from both molecular

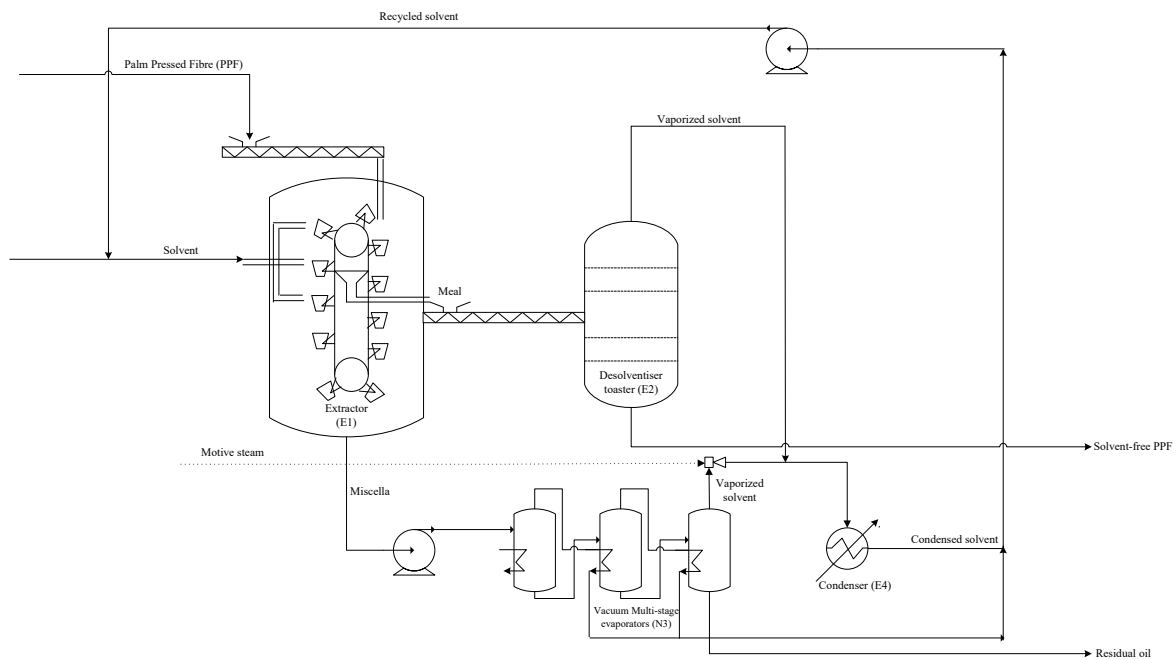
441 and process perspective. For instance, solvent must attain expected functionalities for it to be
442 utilised in an application. In addition, solvent should be less hazardous and shows greater
443 reduction in emissions. From process perspective, besides able to minimise the degradation
444 rate of carotene in residual oil, the designed solvents should be recovered with minimal utilities
445 cost through the selected separation technique. As the major energy consumption of a process
446 usually comes from solvent recovery, process economic can be dictated by the utilities cost
447 needed to recover the solvent. The translation of all favourable qualitative attributes of the
448 designed solvents into their respective measurable properties is reported in Appendix C. From
449 Appendix C, it clearly shows that all the chosen objectives are necessary to design solvents
450 with favourable functionalities and SHE properties. The chosen objectives are all independent
451 of each other, which makes FAHP approach a suitable tool to evaluate their weighting factors.

452 **3.3 Assessment of separation techniques for solvent recovery**

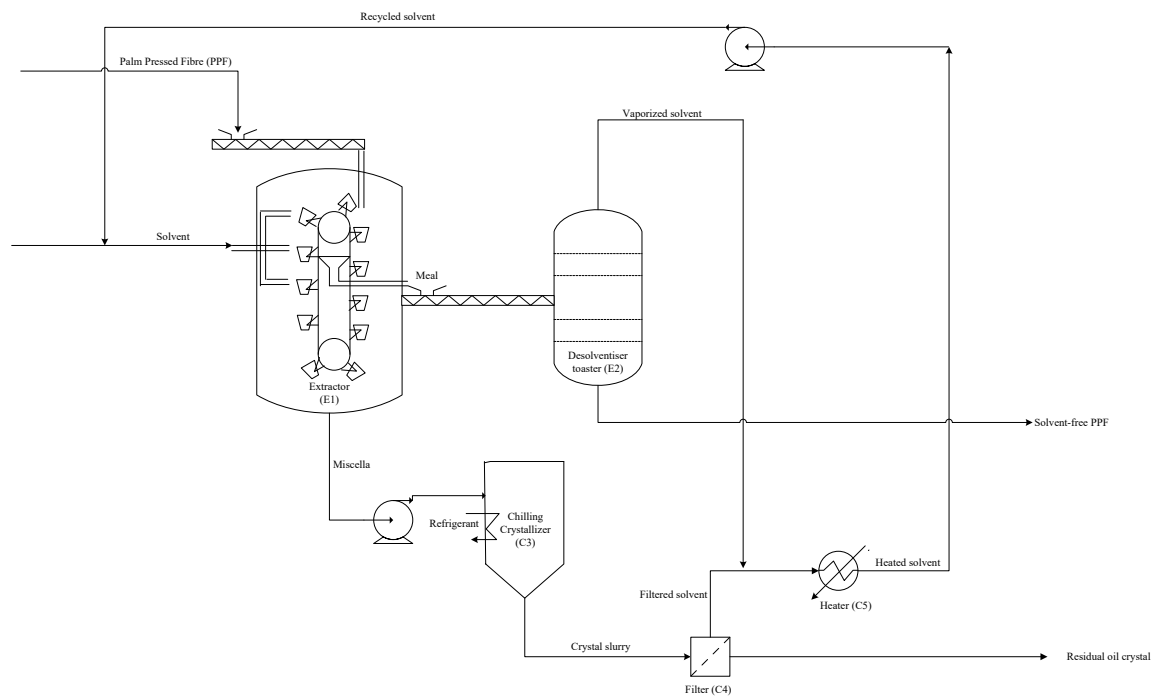
453 The following step includes perform literature review on all the existing separation processes
454 used for recovering solvent from miscella. As mentioned before, carotene degradation usually
455 occurs when solvent is recovered from miscella through normal multistage evaporation. This
456 is because the operating temperature of the evaporator must be equal to or higher than the
457 boiling point of the designed solvent to vaporise solvent from the oil. Thus, to minimise
458 carotene degradation, there is a need to identify other separation techniques that can recover
459 solvent from oil at a lower temperature. Vacuum evaporation, cooling crystallisation and
460 membrane technology can be used for recovering solvent from miscella at a lower temperature.
461 The relationship between boiling point of a liquid solvent and its vapor pressure can be
462 estimated using Clausius-Clapeyron Equation, expressed by Equation (26).

$$463 \quad \ln\left(\frac{P_2}{P_1}\right) = \frac{H_v}{R} \left(\frac{1}{T_{b1}} - \frac{1}{T_{b2}} \right) \quad (26)$$

464 where T_{b1} and P_1 represent the initial operating temperature and pressure of the evaporator
 465 respectively. T_{b2} is the estimated solvent boiling point at operating pressure, P_2 , H_v is the heat
 466 of vaporisation of designed solvent and R is the universal gas constant. Note that Clausius-
 467 Clapeyron Equation assumes that H_v does not change with temperature. On the other hand,
 468 cooling crystallisation involves cooling of miscella at a controlled temperature to allow
 469 crystallisation of solid portion followed by the filtration of two phases. Figure 3 and Figure 4
 470 show the typical process of residual oil recovery from PPF using solvent extraction followed
 471 by vacuum evaporation and cooling crystallisation process respectively.



472
 473 Figure 3: Residual oil recovery from PPF via solvent extraction followed by vacuum
 474 evaporation process



475

476 Figure 4: Residual oil recovery from PPF via solvent extraction followed by cooling
 477 crystallisation process

478

479 The application of membrane technology in this process is not appropriate due to its
 480 poor stability in relation to organic solvents and low membrane flux which affects the process
 481 economic³⁷. Furthermore, membrane is prone to fouling which results in a deterioration in
 482 process performance. This means that membrane process can initially achieve a very good
 483 performance, characterised by high flux but decreases drastically when materials accumulate
 484 on the surface. The fouling phenomenon also causes an increase in operating cost since
 485 chemical cleaning must be done to remove the foulant. Besides, when fouling occurs, there will
 486 be an increase in mass transfer resistance which leads to an increase in energy consumption.
 487 Larger amount of energy is needed to increase the pressure of membrane for maintaining
 488 constant flux³⁸. In addition, distillation is not used in this process because there might be some
 489 residual solid in the miscella fed to recovery system, which will clog a packed column.
 490 Therefore, in this work, we focus on the effect of vacuum evaporation and cooling
 crystallisation on solvent design to that by normal evaporation.

491 3.3.1 Energy balance calculation for each solvent recovery process

492 Next, parameters required for energy balance calculations are determined based on the data
493 obtained from oil extraction process using hexane. The C_p of residual oil has the value of
494 1.902 kJ/kg K whereas the heat of fusion of oil, ΔH_{fus} has the value of -91.3 kJ/kg; PPF
495 comprises of 10 % water and 5 % residual oil; miscella has 25 weight % of oil in it. The targeted
496 purity of recovered oil is 98 weight % if miscella were recovered through normal evaporation
497 and vacuum evaporation. Nonetheless, if miscella were recovered through cooling
498 crystallisation, the final product is assumed to contain 100 weight % of oil.

499 The basis chosen for this work is to produce 250 kg of oil with the use of 750 kg of solvent.
500 The extractor is assumed to operate at 35°C isothermally. Operating temperature of normal
501 multistage evaporator, T^{evp} is based on the boiling point of the solvent to ensure complete
502 recovery of the solvent. For vacuum multistage evaporator, its operating temperature is fixed
503 at 65°C to avoid degradation of carotene. The total amount of vacuum needed to ensure the
504 designed solvent has boiling point of 65°C at the suppressed operating pressure is then
505 estimated using Clausius-Clapeyron equation.

506 By treating the feed temperature as reference temperature, Equation (1) is reduced to Equation
507 (27), which can also be shown in the form as Equation (28).

$$508 \quad q_H^{evap} = \Delta H^{top, evap} + \Delta H^{bottom, evap} \quad (27)$$

$$509 \quad M^{steam} \lambda^{steam} = M_s C_{ps} (T^{evp} - T^{feed}) + M_{vs} H_v + M_o C_{po} (T^{evp} - T^{feed}) \quad (28)$$

510 where M^{steam} is the mass of steam needed (kg); λ^{steam} is the latent heat of steam (kJ/kg); M_s is
511 the total mass of designed solvent fed (kg); M_{vs} is the mass of vaporised solvent (kg), C_{ps} is

512 the average heat capacity of designed solvent (kJ/kg °C); T^{evp} is temperature of the evaporator
 513 (°C); T^{feed} is temperature of the feed (°C); H_v is the heat of vaporisation of the designed
 514 solvent (kJ/kg) ; M_o is the mass of residual oil (kg); C_{po} is the specific heat capacity of
 515 residual oil. The vaporised solvent is then condensed to 35°C for it to be recycled back to the
 516 extractor. The energy balance around the condenser is estimated using Equation (29):

$$517 \quad q_c^{\text{evap}} = M_{vs} C_{ps} (T^{\text{out,condenser}} - T^{\text{evp}}) - M_s H_v \quad (29)$$

518 where q_c^{evap} represents the duty of condenser located after evaporator (kJ), $T^{\text{out,condenser}}$ is the
 519 condenser outlet temperature which was fixed at 35°C.

520 In this work, steam ejector has been chosen to create vacuum for evaporator. Discharge
 521 pressure of steam ejector is assumed to be 1.5 bar to account for the pressure drop in equipment.
 522 Besides, motive steam at 8 barg is supplied to steam ejector. Note that suction gas temperature
 523 is equal to operating temperature of vacuum evaporator (65°C). Equation (2) to Equation (7)
 524 are then applied to calculate the amount of motive steam needed for creating vacuum using
 525 steam ejector.

526 Palm oil comprises 93 % - 95% triacylglycerols (TAG). Crystallisation of palm oil can be
 527 classified into two distinct categories of TAG which crystallise at different temperature³⁹.
 528 Crystallisation of higher melting TAG usually starts at temperature around 28.5 °C whereas
 529 lower melting TAG crystallise around 12.4 °C³⁹. Hence, in this work, the operating temperature
 530 of cooling crystalliser is set at 10°C to ensure complete crystallisation of residual oil. Energy
 531 balance around the cooling crystalliser can be estimated using Equation (30).

$$532 \quad q_c^{\text{cryst}} = M_s C_{ps} (T^{\text{cryst}} - T^{\text{feed}}) + M_o H_{fo} + M_o C_{po} (T^{\text{cryst}} - T^{\text{feed}}) \quad (30)$$

533 where q_c^{crys} is cooling duty needed for crystallisation (kJ), T^{crys} is operating temperature of
 534 crystalliser (°C). For heater, energy balance can be estimated using Equation (31).

$$535 \quad q_H^{\text{crys}} = M_s C_{ps} (T^{\text{out,heater}} - T^{\text{crys}}) \quad (31)$$

536 where q_H^{crys} is the heating duty needed for heater located after crystalliser (kJ), $T^{\text{out,heater}}$ is heater
 537 outlet temperature at 35°C.

538 **3.3.2 Utilities cost calculation for each solvent recovery process**

539 The cost of each utility used in this case study is extracted from Table 1 under section 2.2.
 540 Equation (8) which is previously presented to calculate the utilities cost needed for normal
 541 evaporation, $Cost_{\text{evap},n}$ can be written in the form of Equation (32). On the other hand,
 542 Equation (9) can be rewritten in the form of Equation (33) to calculate the total operating cost
 543 for vacuum evaporation, $Cost_{\text{evap},v}$.

$$544 \quad Cost_{\text{evap},n} = M^{\text{steam}} \times \text{Price of steam /kg} + q_c^{\text{evap}} \times \text{Cost of cooling water/kJ} \quad (32)$$

$$545 \quad Cost_{\text{evap},v} = M^{\text{steam}} \times \text{Cost of steam /kg} + q_c^{\text{evap}} \times \text{Cost of cooling water/kJ} \quad (33)$$

$$+ M^{\text{steam,motive}} \times \text{Cost of steam /kg}$$

546 For cooling crystallisation, the utilities cost is calculated by the same equation expressed by
 547 Equation (8). However, refrigerant cost is accounted for the cooling utilities cost since cooling
 548 water is not able to bring down the temperature to 10°C. Hence, Equation (32) is rewritten in
 549 the form of Equation (34) for calculating total operating cost needed for cooling crystallisation,
 550 $Cost_{\text{crys}}$.

$$551 \quad Cost_{\text{crys}} = M^{\text{steam}} \times \text{Cost of steam /kg} + q_c^{\text{crys}} \times \text{Cost of refrigerant/kJ} \quad (34)$$

552 3.4 Quantification of the yield of extracted carotene

553 The assumption made in this work is that the yield of extracted carotene refers to the amount
554 of carotene left in residual oil if the degradation of carotene occurs during the solvent recovery
555 process. If there were no degradation of carotene, the yield of extracted carotene is assumed to
556 be 100% with reference to the initial concentration of carotene found in residual oil. Thus, the
557 yield of extracted carotene can be deduced from its degradation kinetics. The degradation
558 kinetics of carotene is represented by first order kinetic model ⁴⁰, which is given by Equation
559 (35).

$$560 \quad \ln\left(\frac{C}{C_0}\right) = -kt \quad (35)$$

561 where C is the concentration of carotene (mg/kg) at time t , C_0 is the initial concentration of
562 carotene (mg/kg), k is the temperature dependent rate constant (min^{-1}), t is the heating time
563 (min). In this work, C_0 is assumed to be 5000 ppm as 4000 – 6000 ppm of carotene can be
564 found in residual oil³⁵. Since degradation rate constant, k depends on temperature, Arrhenius
565 equation can represent the relationship. Arrhenius equation is expressed by Equation (36):

$$566 \quad k = k_0 \exp(-E_a / RT) \quad (36)$$

567 where k is the rate constant at temperature T (K), k_0 is the pre-exponential factor, E_a is the
568 activation energy (J/mol) and R is the gas constant (8.314 J/mol K). Based on Arrhenius
569 equation, a straight line can be obtained by plotting $\ln k$ against versus $1/T$ and gradient
570 represents $-E_a / R$.

571 In this work, k_0 and E_a are estimated from the experiment carried out by Dutta et al.⁴⁰. In their
572 work, the degradation kinetics of carotene of pumpkin puree are determined at a temperature

573 range of 70 – 100°C for 2 hours. Their results showed that at temperature lies between 70°C
574 and 100°C, the degradation of carotene follows first order reaction kinetics. Based on their
575 experimental data, Equation (36) can be re-written as:

$$576 \quad k = 47.98 \exp(-3231.7/T) \quad (37)$$

577 It is evident that degradation kinetics of carotene is dependent on unit operation with the highest
578 operating temperature. For this case study, separation unit such as multistage evaporator under
579 standard condition usually operates at a temperature higher than boiling point of solvent to
580 vaporise the solvent from miscella. Hence, boiling point of a designed solvent will indirectly
581 affect the yield of extracted carotene. Besides, degradation of carotene follows first order
582 kinetics at temperature range from 70 - 100°C and there is no degradation of carotene at
583 temperature below 70°C. For these reasons, disjunctive programming is used to simultaneously
584 calculate the yield of carotene when a solvent is designed. The yield of carotene can be
585 calculated using Equation (38).

$$586 \quad \text{Yield of carotene} = \frac{\text{Final concentration of carotene, } C_f}{\text{Initial concentration of carotene, } C_0} \times 100\% \quad (38)$$

587 The value of C_f can either be the same as C_0 or can be found from degradation kinetics
588 expressed in Equation (35), depending on the operating temperature of separation unit. If the
589 operating temperature of separation unit is less than 70°C, the concentration of carotene after
590 time t , C will be the same as C_0 . On the other hand, if the operating temperature of separation
591 unit falls between 70°C to 100°C, C can be calculated using Equation (39).

$$592 \quad C = C_0 \exp(-kt) \quad (39)$$

593 Binary integer variable is then used to model these functions. By introducing integer variable,
594 I_{conc} , C_f can be then calculated based on T.

$$595 \quad C_f = C_0 \times I_{conc} + C \times (1 - I_{conc}) \quad (40)$$

596 Subject to the condition:

$$597 \quad I_{conc} = \begin{cases} 0 & T \geq 343.15K \\ 1 & T < 343.15K \end{cases} \quad (41)$$

598 In order to model condition (41) which allocates the value of I_{conc} to be either 0 and 1 based on
599 value of T, the following constraint is considered:

$$600 \quad (0 - 343.15) \times (I_{conc}) \leq T - 343.15 < (1000 - 343.15) \times (1 - I_{conc}) \quad I_{conc} \in \{0,1\} \quad (42)$$

601 **3.5 Identification of property prediction model**

602 After determining the target properties of the possible solvent, the property prediction models
603 and correlations to estimate properties from chemical structure are identified. The models and
604 correlations used to estimate T_b , T_m , σ , μ , δ , F_p , PEL , M_w , LC_{50} , LD_{50} , PCO , $\log K_{oc}$,
605 BCF , UEL , LEL , H_v and C_p are reported in Appendix D.

606 Next, upper and lower limits of property constraint are determined for solvent design. Lower
607 limit is imposed to F_p because solvent with higher F_p is less likely to cause fire and explosion.

608 In addition, to ensure that the properties of designed solvent is better than those of hexane,
609 upper and lower limits are imposed to $\log K_{oc}$, BCF and $R_{carotene}$. Note that the constraints set
610 for T_b are different if the solvent were to be recovered through different separation techniques.

611 Table 3 reports the summary of property constraints ranges of the solvent.

612 Table 3: Upper and lower limits of solvent properties

Property		Lower Limit	Upper limit
T_b (°C)	Normal evaporation process	40	100
	Vacuum evaporation process	65	-
	Cooling crystallisation	40	-
F_p (K)		242	-
$\log BCF$		-	3.3
R_{carotene} (unit)		-	3.4
$\log K_{oc}$		-	4.5

613

614 3.6 Development of hierarchical decision structure

615 Figure 5 shows the four-level hierarchical decision structure constructed for the case study.

616 The case study aims to design solvents with desirable physical and SHE properties for its

617 application in residual oil removal from PPF. Besides, solvents should simultaneously improve

618 the yield of carotene as well as being recovered through a cheaper separation technique. From

619 Figure 5, two main properties such as molecular and process aspects have been selected to

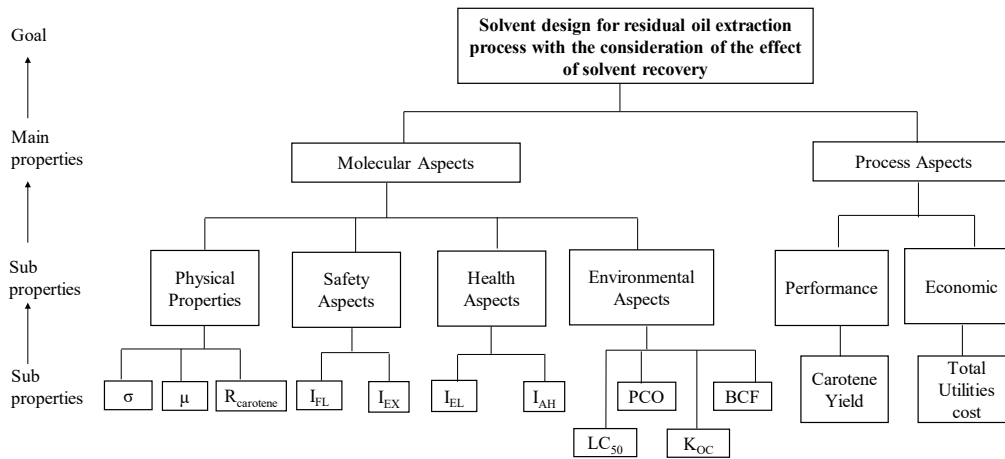
620 fulfill the design objective. There are four sub-properties including physicochemical, safety,

621 health and environmental properties classified under molecular aspects. On the other hand,

622 economic and performance are the sub-properties considered under process aspect. The

623 mentioned properties are then further sorted into quantitative sub-properties shown in

624 Appendix C.



625

626

Figure 5: Hierarchical decision model for this case study

627 3.7 Computation of weights for each objective function

628 At this stage, FAHP approach are applied to elicit the pairwise comparative judgements. The
 629 relative importance between the properties is evaluated based on the literature or supporting
 630 theory. The detailed steps on how to perform FAHP approach are discussed in Section 2.6. In
 631 this work, both molecular and process aspects are assumed to be more or less equally important
 632 with a moderate level of confidence. This is to ensure that the designed solvents exert desirable
 633 physicochemical properties and fulfil SHE regulations. Moreover, it is important to ensure that
 634 maximum amount of carotene and good economic potential can be attained when the designed
 635 solvents are applied in the process. The fuzzy pairwise comparison matrix of main properties
 636 with respect to the goal are reported in Table 4. Based on confidence level, relative importance
 637 of molecular aspect over process aspect is reflected together with lower and upper bound of
 638 the comparison. This judgement is perfectly consistent in this pairwise comparison matrix as
 639 the λ value is equal to one.

640 Table 4: Fuzzy pairwise comparison matrix of main properties for solvent design in residual
 641 oil extraction process

	Molecular Aspects	Process Aspects	Priority Vector
Molecular Aspects	1	(1/3, 1, 3)	0.5
Process Aspects		1	0.5

 $\lambda = 1$

642

643 Table 5 shows the pairwise comparison matrix of process sub-properties using fuzzy scale.
644 Process performance and economic are assumed to be more or less equally importance with
645 moderate degree of confidence. It is of vital importance to ensure that the process can reach
646 the targeted performance with minimum energy cost required for solvent regeneration. Other
647 than achieving maximum carotene yield, process with low utilities cost is an additional merit
648 to business investors.

649 Table 5: Fuzzy pairwise comparison matrix of process sub-properties for solvent design in
650 residual oil extraction process

	Performance	Economic	Priority Vector
Performance	1	(1/3, 1, 3)	0.5
Economic		1	0.5

 $\lambda = 1$

651

652 On the other hand, pairwise comparisons for all the molecular sub-properties were previously
653 performed in the earlier work presented in Ooi et al². Appendix E depicts fuzzy pairwise
654 comparison matrix of sub-properties in satisfying the molecular aspects when designing the
655 molecules. The step is then followed by the calculation of final weighting factor of each sub
656 property in the overall system. It is calculated by the multiplication between weighting factors
657 of sub-properties and their respective main properties, as reported in Appendix F.

658 Note that if the solvents were to be recovered through vacuum evaporation or crystallisation,
659 process economic carried the weighting factor of 0.5 since process performance is omitted as
660 an objective. This is because the operating temperature of vacuum evaporator and crystalliser
661 are less than the degradation temperature of carotene. Hence, there will be no carotene loss if
662 solvents were to be recovered through vacuum evaporator or crystalliser.

663 In short, by having a systematic CAMD algorithm built on FAHP approach, it helps in dealing
664 with the ambiguity occurred when assess the weightage of each property, especially on the
665 inevitable trade-off between the cost and environmental impact. This is because instead of
666 directly assign weightages to cost and environmental impact, the CAMD problem is first
667 modelled as a four-level hierarchical model. As discussed in Section 3.6, molecular and process
668 aspects were the two key criteria chosen to achieve the design goal. Environmental impact is
669 the sub-property under molecular aspect whereas utilities cost is the sub-property under process
670 aspect. In this work, environmental impact is not considered as one of the sub-property under
671 process aspect as the previous work stated in Ooi et al² shows that the environmental burden
672 of a process is minimised by lowering energy requirement during solvent recovery process.
673 Therefore, to avoid over-specify the optimisation model, environmental impact is not chosen
674 as the sub-property under process aspect. However, under molecular aspects, environmental
675 impact is still considered to ensure that the solvent generated will have lower potential in
676 causing environmental impact if it were unintentional leak to the environment. After
677 constructing the hierarchical model, comparative judgement is first carried out to derive the
678 relative importance between molecular aspect and process aspect to achieve the design goal.
679 Environmental aspect is then pairwise compared with other sub-properties under molecular
680 aspect whereas process economic is then pairwise compared with the process performance,
681 which is also a sub-property under process aspect. The weightage of cost and environmental
682 aspect can then be obtained by multiplying their weighting factors with their respective main
683 properties. Appendix F shows that all the environmental properties under molecular aspect
684 have significantly lower weighting factors compared to that of utilities cost. Since utilities cost
685 carries a significantly higher weighting factor, it denotes that direct environmental hazard, such
686 as greenhouse gases emissions has been given much more priority in designing a solvent. The

687 obtained weighting factors are consistent with the fact that direct environmental hazard should
 688 be given higher priority than the indirect environmental impact, which will only happen if there
 689 is accident or the solvent is leaked to the environment.

690 3.8 Molecular design stage

691 The functional groups present in the conventional solvents applied in oil extraction process are
 692 selected for this case study. The chosen molecular groups comprise C, CH, CH₂, CH₃, CH₃CO,
 693 CH₃O, CH₂O, OH, COOH, CH₂=CH, CH-O, CHO, CH₃COO and NH₂. Feasible acyclic and
 694 monocyclic compounds can be synthesised by the implementation of structural constraints
 695 stated in Section 2.6.

696 3.9 Optimisation model

697 At the last stage, the chosen design objectives are transformed into their respective property
 698 operators (Ω_p) to decrease non-linearity equations in optimisation model. Subsequently, Ω_p is
 699 normalised using either Equation (23) or Equation (24) depending on whether the property is
 700 to be maximised or minimised respectively. Equation (43) shows the overall objective function
 701 for the case where the designed solvent is assumed to be recovered through normal evaporation.
 702 On the other hand, when the designed solvent is assumed to be recovered through vacuum
 703 evaporation or cooling crystallisation, the overall objective function expressed by Equation (44)
 704 is used.

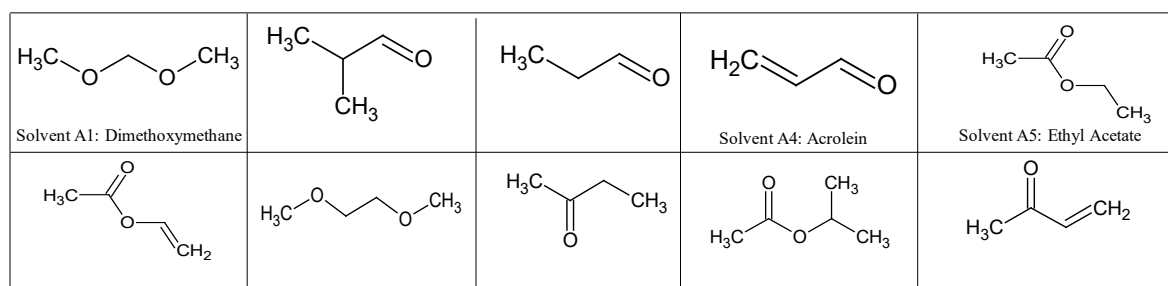
$$705 \quad F^{\text{weighted sum}} = w_1\lambda_{\sigma} + w_2\lambda_{\mu} + w_3\lambda_{R_{\text{carotene}}} + w_4\lambda_{LC_{50}} + w_5\lambda_{PCO} + w_6\lambda_{\log K_{oc}} + w_7\lambda_{BCF} \\ + w_8\lambda_{I_{FL}} + w_9\lambda_{I_{EX}} + w_{10}\lambda_{I_{EL}} + w_{11}\lambda_{I_{AH}} + w_{12}\lambda_{\text{yield}} + w_{13}\lambda_{\text{cost}} \quad (43)$$

$$706 \quad F^{\text{weighted sum}} = w_1\lambda_{\sigma} + w_2\lambda_{\mu} + w_3\lambda_{R_{\text{carotene}}} + w_4\lambda_{LC_{50}} + w_5\lambda_{PCO} + w_6\lambda_{\log K_{oc}} \\ + w_7\lambda_{BCF} + w_8\lambda_{I_{FL}} + w_9\lambda_{I_{EX}} + w_{10}\lambda_{I_{EL}} + w_{11}\lambda_{I_{AH}} + w_{12}\lambda_{\text{cost}} \quad (44)$$

707 where w_1, w_2, \dots, w_{13} are the weighting factors estimated using FAHP approach. Design
 708 objective of this optimisation model is to maximise $F^{\text{weighted sum}}$ along with structural and
 709 property constraints. To produce alternate molecular structures, integer cuts procedure is
 710 employed.

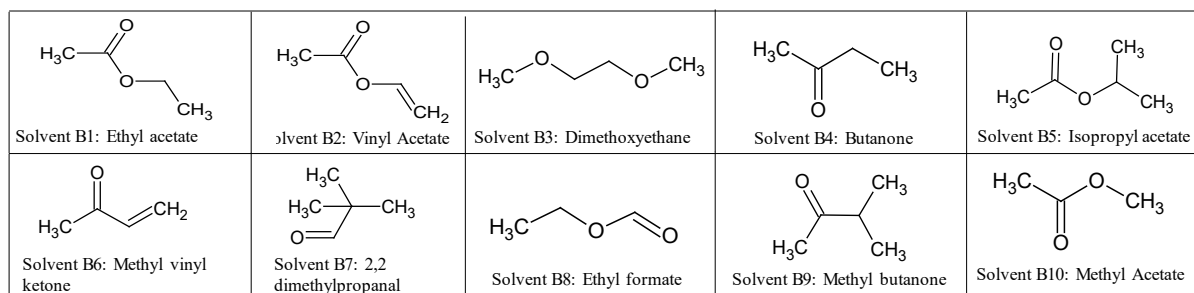
711 3.10 Results and discussions

712 Both monocyclic and acyclic solvents are targeted for all the three cases, where the solvents
 713 are recovered through normal evaporation, vacuum evaporation and cooling crystallisation.
 714 Figure 6 shows molecular structures of the designed solvents when the designed solvents are
 715 to be recovered through normal evaporation. It can be noticed that the top ten generated
 716 solvents in all three cases are acyclic molecules. For designed solvents which are recovered
 717 through vacuum evaporation, their molecular structures are reported in Figure 7. Lastly, the
 718 molecular structures for solvents that are recovered through cooling crystallisation are depicted
 719 in Figure 8. The properties of top ten designed solvents for all the three cases are reported in
 720 Appendix H. The ranking of each molecule is indicated by $F^{\text{weighted sum}}$. Molecule that has the
 721 highest value of $F^{\text{weighted sum}}$ has the highest potential for a specific application. Since this
 722 ranking is not absolute, there is a need to conduct experiment to verify the potential molecules
 723 in a later stage.



724
 725 Figure 6: Designed solvents with their respective molecular structures if solvents were to be
 726 recovered through normal evaporation

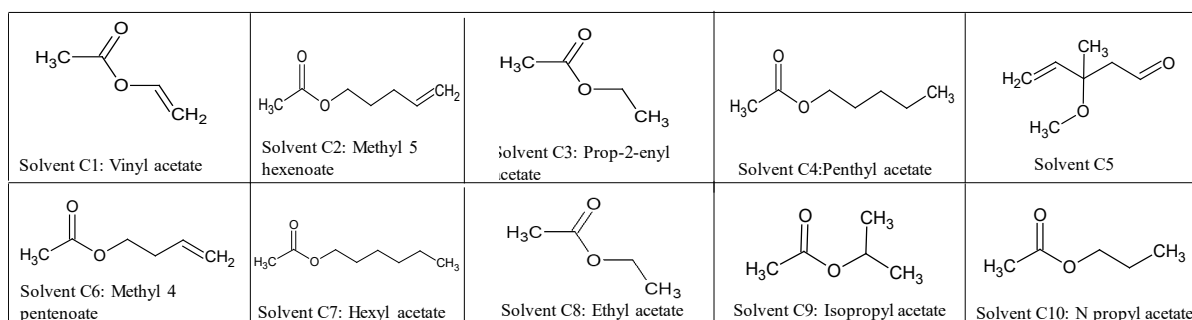
727



728

729 Figure 7: Designed solvents with their respective molecular structures if solvents were to be
730 recovered through vacuum evaporation

731



732

733 Figure 8: Designed solvents with their respective molecular structures if solvents were to be
734 recovered through cooling crystallisation

735

736 From the results, it shows that there will be no carotene degradation if the applied solvents
737 were recovered by cooling crystallisation or vacuum evaporation process. For solvents
738 recovered through normal evaporation process, it is discovered that solvent A5 to solvent A10
739 are not able to achieve 100% carotene yield due to their high boiling point. However, solvent
740 A5 to solvent A10 turn out to be the top 6 solvents when designed solvents are assumed to be
741 regenerated through vacuum evaporation. This is because their higher boiling points result in
742 carotene degradation when they are recovered through normal evaporation process. Through
743 vacuum evaporation, their boiling points can be suppressed by lower their vapor pressures. In
744 addition to good abilities in extracting carotene (which are indicated by low R_{carotene} values),
745 their better SHE features such as having higher F_p value and lower tendency in causing aquatic

746 toxicity, led to their higher rankings when recovered through vacuum evaporation. Nonetheless,
747 operating cost for vacuum evaporation is at least three times higher compared to normal
748 evaporation process despite no carotene loss. On the other hand, when solvent design is
749 performed by assuming that the solvent will be subjected to cooling crystallisation for recovery,
750 all the designed solvents are able to achieve 100% carotene yield with minimum utilities cost.
751 The reason behind is that energy needed for crystallise small amount of residual oil is
752 remarkably lower compared to the energy required to vaporise large amount of solvents.
753 Besides, the generated acyclic and monocyclic solvents have significantly higher F_p compared
754 to cases where solvents are recovered through normal and vacuum evaporation.

755 Appendix G depicts the properties of hexane. Properties of all generated solvents are compared
756 with that of hexane. When total utilities costs are compared for all cases, it is figured out that
757 cooling crystallisation process is nearly 6 to 7 times cheaper compared to that of hexane which
758 is recovered using normal evaporation process. Since all the generated solvents have smaller
759 R_{carotene} , carotene is more soluble in the generated solvents compared to hexane. Besides having
760 lower toxicity, all the designed solvents are less likely to accumulate in soil and aquatic
761 organism.

762 All generated solvents are then compared with existing solvents in literature. Based on
763 the results obtained by Strati and Oreopoulou⁴¹, a higher carotene extraction yield of 42.61
764 mg/kg can be achieved by using Ethyl acetate (solvent B1) compared to hexane which can only
765 extract 34.45 mg/kg carotene. Moreover, in a recent study, Ethyl acetate is more capable in
766 extracting oil from echium seed at low temperature compared to hexane⁴². Despite being the
767 best solvent for the case where it is recovered through vacuum evaporation, Ethyl acetate was
768 also one of the top 10 solvents for the other two cases. 1,2-Dimethoxyethane (Solvent B3) is
769 found to be able to extract the highest yield of algal oil (80.2%) from wet algal biomass

770 compared to other tested solvents such as hexane, chloroform and ethyl acetate ⁴³. In another
771 contribution, 1,2-dimethoxyethane is applied to extract carotene ⁴⁴. The solubility of carotene
772 in 1,2-dimethoxyethane is better than that of 2-propanone but lower than that of hexane.
773 Additionally, methyl acetate (Solvent B10) also has the ability in recovering oil from oilseeds
774 ⁴⁵. Hence, the result shows that all designed solvents possess similar or better extraction yield
775 than that of hexane.

776 **4. Conclusion**

777 In this work, the effect of various separation techniques on solvent selection is integrated into
778 multi-objective CAMD framework. The key contribution of this improved method is that
779 entire solvent application steps are considered during solvent design. This CAMD framework
780 considers the whole cycle of solvent from its application to its recovery process. Despite having
781 expected functionalities, the designed solvents can be recovered through a more economically
782 viable separation technique. Normal evaporation, vacuum evaporation and cooling
783 crystallisation are the separation techniques selected to evaluate its effect on solvent design in
784 this work. Other than targeted properties, utilities cost consumption together with process
785 performance are incorporated into CAMD framework. The proposed methodology is
786 demonstrated by solving a case study on generating solvent to remove residual oil from PPF.
787 The results depict that most of the designed solvents have better functionalities and SHE
788 properties than that of hexane. Besides, it shows that solvent recovery through cooling
789 crystallisation is the cheapest pathway since the utilities cost is significantly lower than that of
790 normal and vacuum evaporation. Hence, it can be concluded that by considering both solvent
791 application and its recovery process simultaneously, it can maximise process performance and
792 enhance the overall cost saving. Future work can be conducted by considering social aspect

793 such as process reliability, equipment process safety, employment opportunities etc into
794 CAMD framework.

795 **Acknowledgment**

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797 Grant (LRGS/2013/UKM-UNMC/PT/05).

798 **Supporting Information**

799 The tables of the cost of various utilities, the penalty scores for the two safety sub-indexes (I_{FL}
800 and I_{EX}) and the revised penalty scores of the five health sub-indexes (I_{η} , I_{MS} , I_V , I_{EL} and I_{AH}),
801 translation of attributes into properties, group contribution models, feasibility rules, fuzzy
802 pairwise comparison matrix, weighting factors, properties of hexane and case study results with
803 details.

804 **Abbreviation**

AHP	Analytic Hierarchy Process (AHP)
CAMD	Computer Aided Molecular Design
CAMPD	Computer Aided Molecular and Process Design
CO ₂	Carbon Dioxide
CPO	Crude palm oil
DIPE	Diisopropyl Ether
EACO	Efficient Ant Colony Optimisation
FAHP	Fuzzy Analytic Hierarchy Process
FFB	Fresh Fruit Bunches
GCM	Group Contribution Method

805	GDP	Generalised Disjunctive Programming
	IOHI	Inherent Occupational Health Index
	ISI	Inherent Safety Index
	LCA	Life Cycle Assessment
	NFPA	National Fire Protection Association
	NLP	Nonlinear Programming
	PPF	Palm Pressed Fibres
	SHE	Safety, health and environmental
	TAGs	Triglycerides
	TFNs	Triangular Fuzzy Numbers
	THF	Tetrahydrofuran
806	Sets	
807	P	Set of target property $\{p \mid p = 1, 2, \dots, E\}$
808	Parameters	
	A	Positive reciprocal pairwise comparison matrix
	a_{ij}	Relative importance of property i to property j
	\hat{a}_{ij}	Fuzzy number
	C_0	Initial concentration of carotene
	C_i	Contribution of first order group of type- i
	C_{po}	Heat capacity of residual oil

DAE	Dry air equivalent
D_j	Contribution of second order group of type- j
E_a	Activation energy
E_k	Contribution of third order group of type- k
g	Coefficient to represent the type (acyclic, monocyclic, bicyclic or tricyclic) of compounds
G_T	Total number of groups selected
ΔH_{fus}	Heat of fusion of oil
I	Binary integer variable
\hat{L}_{ij}	Lower bound of triangular fuzzy number
\hat{M}_{ij}	Modal value of triangular fuzzy number
M_o	Mass of residual oil
M_s	Mass of designed solvent fed
M_{vs}	Mass of vaporised solvent
MWc	Molecular weight entrainment ratio of solvent vapour
O_k	Frequency of third order group of type- k
P_1	Initial operating pressure of the evaporator
P_2	Designed operating pressure of the evaporator
p_L	Lower bound of feasible p value
P_a	Suction pressure of steam ejector
P_d	Discharge pressure of steam ejector

P_{switch}	Property boundary value
P_U	Upper bound of feasible p value
R	Universal gas constant
R_a	Consumption of motive steam for compressing a unit mass DAE mass of suction gas in a steam ejector
t	Heating time
T	Operating temperature of separation unit
T_{bl}	Initial operating temperature of the evaporator
TC_a	Temperature entrainment ratios
T_{crys}	Operating temperature of crystalliser
T_{evp}	Operating temperature of the multistage evaporator
T^{feed}	Temperature of the feed
$T^{out,condenser}$	Condenser outlet temperature
$T^{out,heater}$	Heater outlet temperature
T_{sg}	Suction gas temperature
\hat{U}_{ij}	upper bound of triangular fuzzy number
V_i	Valence of group i
V_p	Value of target property p
v_p^L	Lower bound of target property p
v_p^U	Upper bound of target property p
w	Principal eigenvector (optimal priority vector)
w_{AH}	Weighting factor for sub-index I_{AH} .

w_{EL}	Weighting factor for sub-index I_{EL}
w_{EX}	Weighting factor for sub-index I_{EX}
w_{FL}	Weighting factor for sub-index I_{FL}
w_i	Principal eigenvector of property i
w_j	Principal eigenvector of property j
w_i / w_j	Solution ratio
w_m	Weighting factor for each normalised target property operator
y	Binary coefficient for second order molecular group
z	Binary coefficient for third order molecular group

809

810 **Variables**

BCF	Bioconcentration factor
C	Concentration of carotene after time t
C_f	Final concentration of carotene
C_p	Specific heat capacity
C_{ps}	Average heat capacity of designed solvent
$Cost_{crys}$	Total utilities cost for cooling crystallisation process
$Cost_{evap,n}$	Total utilities cost for a normal evaporation process
$Cost_{evap,v}$	Total utilities cost for a vacuum evaporation process
F_p	Flash point
$F^{\text{weighted sum}}$	Overall objective function

H_v	Latent heat of vaporisation
$\Delta H^{\text{feed, evap}}$	Enthalpy change for feed for the evaporator
$\Delta H^{\text{top, evap}}$	Enthalpy change for top product
$\Delta H^{\text{bottom, evap}}$	Enthalpy change for bottom product
I_A	Sub-index value for $p < p_{\text{switch}}$
I_B	Sub-index value for $p > p_{\text{switch}}$
I_{AH}	Acute health hazard index
I_{EL}	Exposure limit based index
I_{EX}	Explosiveness based index
I_{FL}	Flammability based index
$I_{SHI, w}$	Total weighted penalty score for safety and health aspect of molecules
k	Temperature dependent rate constant
LC_{50}	Oral rat acute toxicity
LD_{50}	Fathead minnow toxicity
LEL	Lower explosion limit
LFL	Lower flammability limit
$\log K_{oc}$	Soil sorption coefficient
M_j	Frequency of second order group of type- j
M^{steam}	Mass of steam needed
$M^{\text{steam, motive}}$	Total amount of motive steam needed for steam ejector
M_w	Molecular weight

N_i	Frequency of first order group of type- i
O_k	Frequency of third order group of type- k
PCO	Photochemical oxidation potential
PEL	Permissible exposure limit (mol/m ³)
q_c^{crys}	Cooling duty needed for crystallisation
q_c^{evap}	Duty of condenser located after evaporator
q_H^{crys}	Heating duty needed for heater located after crystalliser
q_H^{evap}	Heat transferred from steam to the evaporator
$R_{carotene}$	Difference of Hildebrand solubility parameter between solvent and carotene
S	Explosiveness (UEL – LEL) (vol%)
T_b	Boiling Point
T_{b2}	Estimated boiling point of the solvent at operating pressure, P_2
UEL	Upper explosion limit
UFL	Upper flammability limit

811

812 **Greek Symbols**

λ_{max}	Principal eigenvalue
λ_{pm}	Normalised target λ property operator
λ_{steam}	Latent heat of steam
Ω_p	Target property operator

Ω_p^{\min}	Minimum value of target property operator
Ω_p^{\max}	Maximum value of target property operator
δ	Hildebrand solubility parameter
δ_c	Degree of confidence
μ	Viscosity
σ	Surface tension

813

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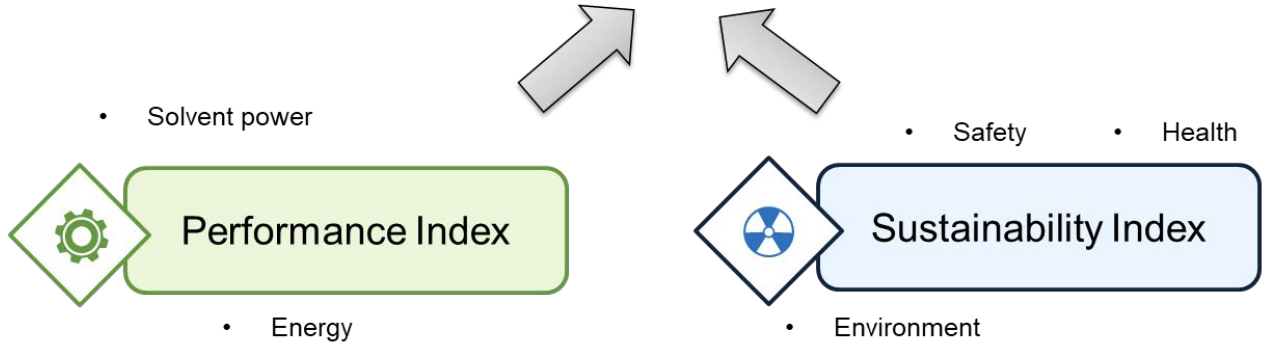
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936

937 **Graphical Table of Content**



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