

## Research Article

# Shrimp Feed Formulation via Evolutionary Algorithm with Power Heuristics for Handling Constraints

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Formulating feed for shrimps represents a challenge to farmers and industry partners. Most previous studies selected from only a small number of ingredients due to cost pressures, even though hundreds of potential ingredients could be used in the shrimp feed mix. Even with a limited number of ingredients, the best combination of the most appropriate ingredients is still difficult to obtain due to various constraint requirements, such as nutrition value and cost. This paper proposes a new operator which we call Power Heuristics, as part of an Evolutionary Algorithm (EA), which acts as a constraint handling technique for the shrimp feed or diet formulation. The operator is able to choose and discard certain ingredients by utilising a specialized search mechanism. The aim is to achieve the most appropriate combination of ingredients. Power Heuristics are embedded in the EA at the early stage of a semirandom initialization procedure. The resulting combination of ingredients, after fulfilling all the necessary constraints, shows that this operator is useful in discarding inappropriate ingredients when a crucial constraint is violated.

## 1. Introduction

Shrimps are crustaceans and are among the main aquatic organisms being farmed. It contributes to the fast growing aquaculture industry in the food-production sector [1]. Feed has been identified as the most expensive component of the total cost when farming shrimps [2–5]. Providing a better shrimp feed, with minimum cost, could help farmers reduce costs and increase profits.

Shrimps require several nutrients for healthy growth. Shrimp nutrients are a complex subject because the nutritional requirements change at each stage of its life cycle (i.e., larval, nursery, juvenile, and adult). Thus, shrimp feed must be specifically formulated for different stages of its life [6]. Juvenile shrimps require higher nutritional values, especially protein, than shrimps in other life stages. For this reason,

most previous studies have focused on juvenile shrimps [7–13]. This study also focusses on formulating feed for juvenile shrimps.

The quality of shrimp feed depends on two factors: nutrients and ingredients. Shrimps require specific nutritional requirements such as protein, lipid, ash, and fibre [14]. Protein is the most expensive nutrient source, comprising two different types (crude protein and amino acid). There are 22 amino acids that are commonly found in proteins [15], but shrimps require only ten essential amino acids (EAA), in a specific ratio, to achieve its optimal growth [15]. Only a small number of studies have taken into account the value of amino acids [16] due to a lack of information on the requirement of total amino acids for optimal growth of juvenile shrimp. The crude protein level, while maintaining ideal ratios of EAA, will increase growth [17]. In this paper, we take into account

the requirement of amino acid in formulating shrimp feed. However, since the real amino acid requirement for shrimps is unknown, we estimate the amino acid requirement based on expert opinion, the scientific literature, and commercial feed data.

It is important to take into account ingredients, to ensure that a shrimp's diet contains appropriate nutrients and has an attractive physical appearance to entice shrimps [18]. Fish meal is one of the most expensive ingredients and is also a primary source of protein [19]. For this reason, it is important for fish meal to be included in the shrimp diet.

This paper presents a feed formulation problem for juvenile shrimps, which is motivated by real world requirements, as experienced by the Department of Fisheries (DOF), Malaysia. The problem dataset has several new constraints in addition to those currently experienced by the DOF. Previous studies [20, 21] have obtained a ratio of ingredients based on a set of preselected ingredients. However, the combination of some ingredients is sometimes unable to return a feasible solution as each ingredient has a minimum quantity requirement. Therefore, in order to choose only the appropriate ingredients, a semirandom initialization operation [21] acts as a way of precontrolling the nutrient requirement. Our work utilises this semirandom initialization, improving upon it with a new alternative initialization operator based on the work in [22]. Our improvement differs from [22] in the computation of obtaining new ingredient values within the Evolutionary Algorithm (EA).

The organization of the rest of the paper is as follows. In Section 2, we describe the feed or diet formulation problem and present related work. In Section 3, the EA methodology for addressing the DOF feed formulation problem is described. In Section 4, we present the mathematical formulation of the problem, while in Section 5 we propose an EA with Power Heuristics as a strategy to improve the solution methodology for the feed formulation problem. In Section 6, comparisons between the variations of the EA are presented, which demonstrates the effectiveness of the proposed method. The final section concludes the paper and provides suggested future work directions.

## 2. Feed Formulation Problem

A feed formulation problem can be categorized in two forms which address humans and farmed animals. The term “*menu planning problem*” normally relates to methods used for planning menus for the human diet [23], and it can also be defined as the scheduling of meals associated with a person's needs during a given time horizon [24]. In agricultural applications, the diet formulation problem is commonly known as the feed mix problem [25] or feed formulation [26, 27]. It involves a combination of several feed ingredients in specific quantities in order to satisfy nutritional requirements at a minimum cost [25] for the diet of farmed animals. Many studies [28–31] have attempted to formulate animal diets using approaches to improve the quality of the feed. In this section we highlight past studies that have discussed the feed formulation problem involving animals. The approaches can be categorized into four classes:

algebraic, optimization, heuristics, and integrated approaches [18]. The range of methodologies which have been used to address the feed formulation problem is presented in Figure 1. The abbreviations used are as follows: PS = Pearson's Square, SAE = Simultaneous Algebraic Equation, LP = Linear Programming, GP = Goal Programming, CCP = Chance Constrained Programming, QP = Quadratic Programming, NLP = Nonlinear Programming, CH = Constructive Heuristics, and MH = Metaheuristics.

*2.1. Algebraic Approaches.* An algebraic approach is a method which involves mathematical calculations and is normally too computationally expensive. There are only two approaches that can be classified as algebraic approaches which have been applied to the feed formulation problem. These approaches are Pearson's Square (PS) [26, 32, 33] and Simultaneous Algebraic Equations (SAE) [26, 33]. The limitation of PS is it can only balance one nutrient at a time, while SAE is computationally expensive when solving many nutrients and ingredients [34]. Therefore, these methods are not suitable for handling ingredient constraints.

*2.2. Exact Approaches.* Optimization involves maximizing or minimizing a function by systematically choosing the best value in a feasible region [35]. It is also defined as the process of attempting to find the best possible solution among all those available [36]. Optimization approaches, with regard to animal feed formulation, have included Linear Programming [28, 37–62], Goal Programming [63–76], Chance Constrained Programming [32, 77–83], Quadratic Programming [84], and Nonlinear Programming [85–87]. These methodologies were frequently used in various feed formulation problems, with LP dominating the studies. LP requires that all the constraints for the problem be exactly formulated, which can be problematic for some problems.

*2.3. Heuristic and Metaheuristic Approaches.* Heuristics are based on the concept of rule of thumb [88]. When applying a heuristic technique, the expectation is to achieve the best-so-far solution in a feasible region. In the case of feed formulation, the heuristic and metaheuristic approaches are discussed together in this section due to the limited number of studies being carried out using these approaches.

A constructive heuristic starts with an empty solution and gradually builds a feasible solution, usually by incrementally adding to the growing schedule, while respecting the problem constraints [89]. M. O. Afolayan and M. Afolayan [26] used a trial and error methodology for feed formulation for poultry. The formulation was done either manually or by using a spreadsheet. Ruohonen and Kettunen [90] proposed a mixture experiment method to improve on the experimental design (ED) method. This improved method successfully shortens time when compared to traditional ED. A few years later, Forster et al. [91] used the methodology of Ruohonen and Kettunen [90] to find an optimal diet for shrimps. This mixture experiment method is a good method for real situation testing. But of course, it requires a full system for shrimp growth with tank and expertise. In 2011, [92] proposed a

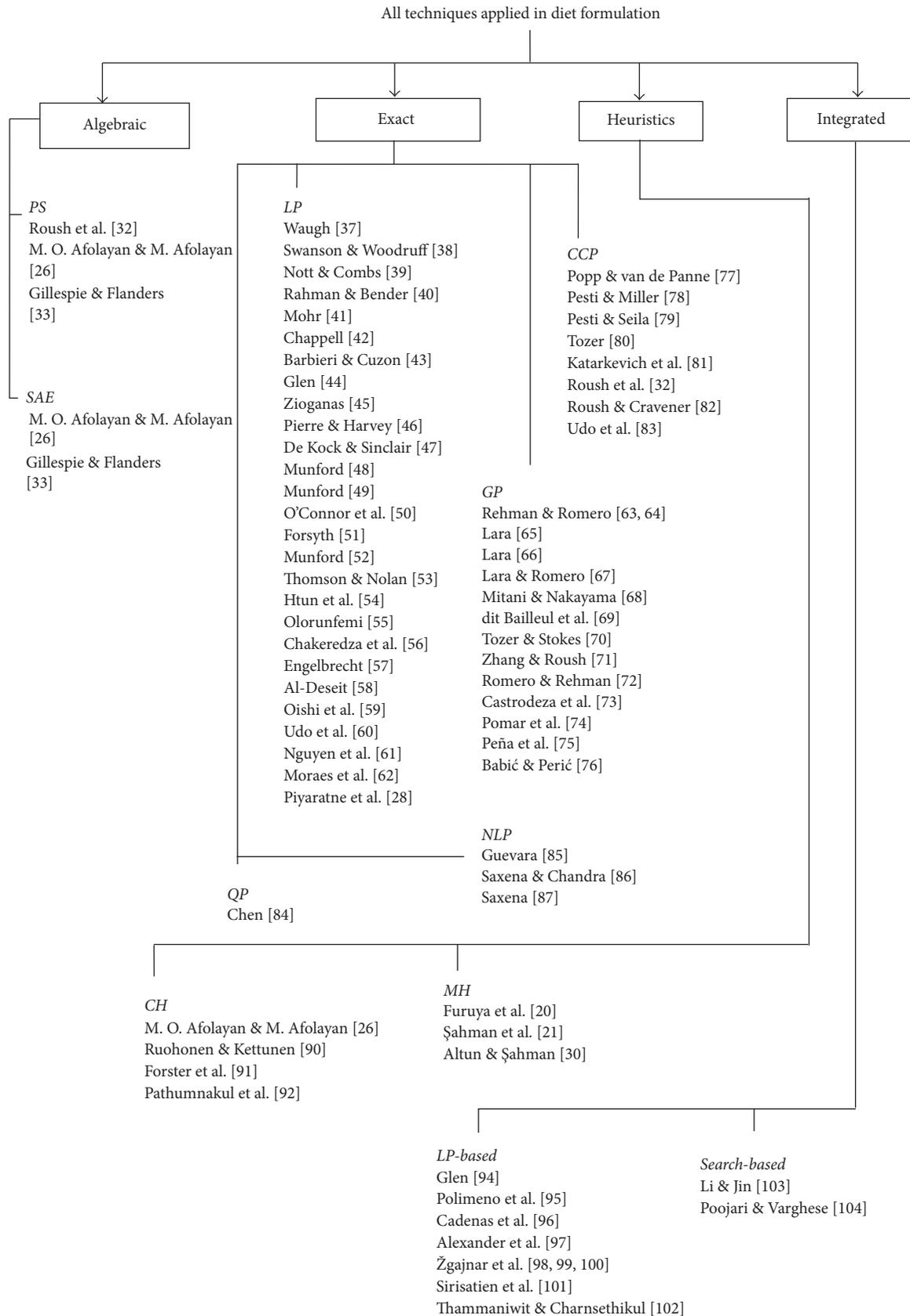


FIGURE 1: Classification of solution techniques for feed formulation problems as adapted and enhanced from Rahman (2014).

search-based heuristic algorithm to solve several small-scale problems involving four to ten ingredients for swine feed formulation. However, to gain the optimal solution using this approach requires high computational time especially when there was a lot of ingredients and nutrients that need to be considered.

A metaheuristic is a high level algorithm that provides a set of strategies or procedures, which seek an optimal solution [93]. In relation to animal feed formulation, [20, 92] conducted studies using an Evolutionary Algorithm (EA), while [30] utilised Particle Swarm Optimization. Furuya et al. [20] solved nonlinear constraints involving ratios of ingredients for livestock feed. Their study showed that an EA is a promising methodology for the diet formulation problem as a feasible solution could be obtained even for a problem that had no apparent solution. They considered minimum and maximum ratios of ingredients, with many of the ingredients being free from any requirement or constraint.

Şahman et al. [21] produced a good solution for a cattle feed problem with a few constraints, which aimed to obtain a zero value for their EA penalty function. Şahman et al. [21] also worked on the feed formulation problem for poultry, which had many nutrient constraints. Altun and Şahman [30] explored a PSO (Particle Swarm Optimization) approach to solve nonlinear constraints of nutrients. In comparison to a Genetic Algorithm, the PSO solution is superior, with respect to achieving lower penalty values. However, both [21, 30] did not consider a ratio constraint in their animal feed formulation problems.

*2.4. Integrated Approaches.* Integrated approaches are the combination of two or more methodologies. In a feed formulation problem, most of the integrated techniques are based on LP [94–102], with a few being search-based [103, 104].

*2.5. Discussion.* Considering the four approaches discussed above, an algebraic approach is not applicable since it is not able to cater for more than one nutrient. Optimization approaches are the favoured methodology in a diet formulation problem. However in determining the minimum cost feed, the linear or nonlinear constraints are increasingly complex and thus difficult to handle. In these situations, applications of standard linear or nonlinear programming techniques are both time consuming and inefficient [21]. Therefore, the EA as a metaheuristic has the potential of returning quality solutions which is the reason why it has been used by previous researchers. We hypothesize that an EA with enhanced search operators, such as in the initialization stage, will provide superior solutions even when new constraints are introduced.

### 3. Evolutionary Algorithm for the Feed Formulation Problem

An EA is a multistage algorithm, comprising initialization, selection of parents, crossover, and mutation. These operators are normally tuned in order to improve their performance.

For example, new initialization procedures have been proposed by [105], selection by [106], crossover by [107], and mutation by [22].

A new mutation operator known as Power Mutation was introduced by [22] to cater for constrained problems with real number representation. It is an enhancement of uniform mutation and makes use of both lower and upper bounds of a constraint. The advantage of using each constraint's boundaries is that we might get a number of possible solutions within that constraint's range. Deep and Thakur [22] introduced Power Mutation with the aim of using an EA without any assistance from other constraint handling techniques. The idea of Power Mutation can be further extended for other operations such as the initialization.

In an animal feed formulation, [20] has pioneered the utilisation an EA, aiming to solve the nonlinear constraints which involve a ratio of ingredients. The study showed that an EA is able to produce a near optimal solution even for a problem that has no apparent solution. [20] considered the minimum and maximum values of each ingredient. However, almost all of the minimum values were considered as free values. Reference [21] then continued the work of [20] utilising a GA to achieve the least cost diet for livestock. Their experiments produced good quality solutions for this problem. However, [21] did not consider a ratio constraint in their study. Only these two studies utilise an EA for the animal feed formulation. Hence, this paper addresses both limitations in those two studies. We investigate an EA for the minimum and maximum values for nutrients and ingredients and take into account ratio constraints between nutrients.

Previous research for animal feed formulation using metaheuristics has attempted to get the appropriate mix of ingredients. For example, eight ingredients can be used in the formulation, and then a specific percentage of all ingredients are selected to be included in the formulation. Based on expert opinion, at most ten ingredients could be included in the formulation in order to obtain a low cost diet. However, it is very difficult to find the best ten ingredients with the optimal quantities to fulfill all specified nutrients with minimum cost. This paper investigates the use of an EA, to address the feed formulation problem. Table 1 summarizes the number of ingredients included in previous studies that have used heuristic approaches. Reference [26] did not mention the number of ingredients.

As shown in Table 1, the largest number of ingredients in previous studies was Furuya et al. [20], who considered 20 ingredients. However, [20] did not consider any restriction on the minimum and maximum values. All ingredients were considered when the final formulation was calculated. In other words, if ten ingredients were preselected at the beginning, the final formulation would include all ten ingredients with a minimum value based on the restriction. However, in the real world application of feed formulation, there are many ingredients that could be included. Due to the operational costs, only a combination of some ingredients will be considered. Therefore, this study introduces a filtering heuristic that is able to choose appropriate ingredients and remove some ingredients based on predefined constraints. Fourteen ingredients were chosen as this represents real

TABLE 1: Number of ingredients used in heuristic approach.

Author	Type of animal	Technique	Number of ingredients
(1)M. O. Afolayan and M. Afolayan [26]	Poultry	TE	—
(2) Pathumnakul et al. [92]	Swine	Search	Dataset 1: 6; dataset 2: 5
(3) Furuya et al. [20]	Livestock	EA	20
(4) Şahman et al. [21]	Poultry and cattle	GA	Poultry: 11; cattle: 7
(5) Altun and Şahman [30]	Poultry, cattle, sheep, rabbit	PSO	9

data obtained from manufacturers and the Department of Fisheries, Malaysia.

#### 4. Shrimp Feed Formulation Model

In the shrimp feed formulation problem, the aim is to satisfy all the nutritional needs of farmed shrimps at a minimum cost. The minimization problem considers 14 ingredients and 18 nutrients. The main aim of this shrimp feed formulation is to minimize the overall cost of the shrimp feed. In order to obtain the minimum cost, a penalty system is used. A penalty value is given if the ingredients and nutrients selected are unable to fulfill the constraints or requirements as discussed in the following subsection.

**4.1. Objective Function and Constraints.** As part of modelling the shrimp feed formulation problem, objective function and constraints are defined as follows:

$$f(s) = \min \sum_{i=1}^{14} (X_i \times C_i), \quad (1)$$

where  $C_i$  is the cost of ingredient  $i$ ,  $X_i$  equals the weight of the  $i$ th ingredient, and  $f(s)$  is the total cost of the feed, subject to

- (i) ingredients' range based on maximum and minimum value as shown in Table 2:

$$\begin{aligned} X_i &= 0 \\ \text{or } L_{X_i} &\leq X_i \leq U_{X_i} \\ &\forall X_i, \end{aligned} \quad (2)$$

where  $L_{X_i}$  is lower bound of ingredient  $i$ ,  $U_{X_i}$  is upper bound of ingredient  $i$ , and  $X_i$  equals the weight of the  $i$ th ingredient;

- (ii) total ingredients weight is

$$\sum_{i=1}^n X_i = Y, \quad (3)$$

where  $Y$  is a total ingredients weight as predefined by the user in the user interface,

the specific amount is fixed at 100 kg;

- (iii) single nutrients' range based on maximum and minimum values as shown in Table 3:

$$L_{N_k} \leq \sum_{i=1}^n N_{k_i} X_i \leq U_{N_k}, \quad (4)$$

where  $L_{N_k}$  is lower bound of total value of nutrient  $k$ ,  $U_{N_k}$  is upper bound of total value of nutrient  $k$ , and  $N_{k_i}$  is total value of nutrient  $k$  in ingredient  $i$ ,  $k = 1, 2, \dots, 16$ ;

- (iv) combination of nutrients' range based on maximum and minimum value as shown in Table 3:

$$L_{N_{k(ij)}} \leq \sum_{i=1}^n N_{k(ij)} X_i \leq U_{N_{k(ij)}}, \quad (5)$$

where  $L_{N_{k(ij)}}$  is lower bound of combination nutrients  $i$  and  $j$  and  $U_{N_{k(ij)}}$  is upper bound of combination nutrients  $i$  and  $j$ ;

- (v) ratio of nutrients' range based on maximum and minimum value as shown in Table 3:

$$L_{\text{ratio}} \leq \frac{\sum_{i=1}^n N_{k_i}}{\sum_{i=1}^n N_{k_j}} \leq U_{\text{ratio}}, \quad (6)$$

where  $L_{\text{ratio}}$  is lower bound of ratio between nutrients  $i$  and  $j$  and  $U_{\text{ratio}}$  is upper bound of ratio between nutrients  $i$  and  $j$ .

**4.2. Ingredients and Nutrients.** In this study, 14 ingredients and 18 nutrients are considered. The ingredients have minimum and maximum percentages that can be used. These values are shown in Table 2. The nutrient constraints are categorized into three types which are single, combination, and ratio. There are 16 nutrients that are classified as a single type, that is, crude protein, lipid, fibre, ash, calcium, phosphorus, and ten essential amino acids (EAAs). These EAAs are arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine. These nutrients are shown in Table 3. For the combination types, there are two, which are combinations of methionine and cystine and also phenylalanine and tyrosine. A ratio of calcium and phosphorus is also taken into consideration. The minimum and maximum percentages and values given represent the lower and upper bounds for each of the ingredient and nutrients, respectively.

Based on our interviews with experts in the aquaculture industry and authority, shrimp can grow well if they get enough nutrients [14, 108]. In relation to nutrient levels, the best solution occurs when each of the nutrient's constraints are fulfilled. The higher the penalty value given, the more the nutrient constraints that were unable to be satisfied. The minimum value is considered the best penalty value, which relates to the minimum feed cost achieved.

TABLE 2: A list of ingredients and its specific range.

Ingredient	Minimum (%)	Maximum (%)
Rice bran, $X_1$	5	10
Soybean meal, $X_2$	15	50
Palm kernel cake, $X_3$	3	5
Local fishmeal, $X_4$	5	50
Wheat flour, $X_5$	30	40
Wheat pollard, $X_6$	5	15
Poultry meal, $X_7$	5	15
Crude palm oil, $X_8$	2	5
Imported fish meal, $X_9$	15	60
Meat and bone meal, $X_{10}$	5	15
Poultry by product, $X_{11}$	5	15
Blood meal, $X_{12}$	3	5
Krill meal, $X_{13}$	3	5
Squid meal, $X_{14}$	3	5

TABLE 3: A list of nutrients and its specific range.

Nutrients	Minimum	Maximum
<i>Single nutrient</i>		
Crude protein, %	38.00	45.00
Lipid, %	0.08	0.18
Fibre, %	—	4.00
Ash, %	—	15.00
Calcium, %	—	2.30
Phosphorus, %	0.30	0.70
Arginine, %	1.60	2.32
Histidine, %	0.60	0.84
Isoleucine, %	1.00	1.33
Leucine, %	1.70	2.16
Lysine, %	1.55	1.65
Methionine, %	0.70	0.96
Phenylalanine, %	1.40	1.60
Threonine, %	1.30	1.44
Tryptophan, %	0.20	0.32
Valine, %	1.20	1.60
<i>Nutrients combination</i>		
Methionine + cystine, %	1.00	1.44
Phenylalanine + tyrosine, %	2.70	7.10
<i>Nutrients ratio</i>		
Calcium: phosphorus, %	1:1.3	1:1.3

4.3. *The Evolutionary Algorithm Model.* The constraints function is embedded as part of the fitness function in our EA as shown in Algorithm 1.

The EA draws from other established operators, such as the Roulette Wheel Selection [109, 110], one-point crossover [110], and Power Mutation (excerpted from [22]). However, in this study we highlight the use of a Power Heuristic, which is incorporated in the initialization stage of the EA to help obtain a good quality feasible solution for formulating shrimp feed mix with many ingredients.

## 5. Power Heuristics Algorithm for EA Initialization

The original idea of Power Heuristics came from a mutation operator known as Power Mutation, introduced by [22]. Power Heuristics is capable of deleting inappropriate ingredients and, thus, searches for the most suitable combination of ingredients. When too many preferred ingredients are candidates, nutrient constraints might be violated as each ingredient has its own restrictions. Hence, Power Heuristics are embedded in the early stage of the EA, to act as a filter against a poor combination of ingredients and search for better alternatives with minimal penalty values.

Power Heuristics uses a local search concept that searches around the neighbourhood of a solution. It begins by checking the feasibility of a potential solution. If the solution is infeasible, a new ingredient will be located that is within the range of one unit (kilogram) from the current ingredient. This mechanism is able to remove a few ingredients. Finally, the penalty value for the new solution is calculated. This mechanism is useful when inappropriate ingredients need to be removed in the case of an important constraint being violated; that is, the total ingredient weight exceeds the required amount. The incorporation of this operator can at least reduce the initial penalty value, thus increasing the possibility of locating a feasible solution. The algorithms for Power Heuristics and Power Mutation are presented in Algorithms 2 and 3, respectively.

Power Heuristics is adapted from the Power Mutation operator as originally introduced by [22]. As the purpose of Power Mutation is to obtain a feasible solution, introducing a new weight for each ingredient in the mutation stage ( $X_{i_m}$ ) is designed to include a lower and upper bound as in equations (\*\*\*\*) and (\*\*\*\*\*).

Power Heuristics aims to reject some ingredients and then repair the solution to achieve a lower penalty value. The formula for getting an adjusted weight for each ingredient is designed so that the adjusted weight for the particular ingredient ( $X_{i_j}$ ) can be either zero or slightly different from the original weight as shown in equation (\*\*) (refer to Algorithm 2). Most previous studies (e.g., [111–115]), especially those that used experimental design approach, used less than ten ingredients for aquaculture feeds including shrimps. The reason was to cut down the operation costs such as ordering and storage [18].

In order to test the practicality of Power Heuristics, two initialization procedures were tested to obtain some insights and suggest the best initialization operator. The first procedure is a semirandom initialization operation which employed a formula using lower and upper bound values of the weight of each ingredient, as shown in (7). The second procedure also employed the same formula, but with the inclusion of Power Heuristics, as indicated in Algorithm 2, for filtering purposes.

For  $i = 1, 2, 3, \dots, 14$

$$\text{IPOP}_j = \text{rand} [L_{X_i}, U_{X_i}], \quad (7)$$

- (i) Initialize solution in semi random procedure  
*Incorporate Power Heuristics*
- (ii) Evaluate each individual penalty value
- (iii) Select pair to mate using either *Roulette Wheel Selection operator*
- (iv) Do Crossover using *One-Point Crossover operator*
- (v) Do *Power Mutation*
- (vi) Repair operator using *Power Heuristics*
- (vii) Apply elitism operator
- (viii) Repeat step (iii) until step (vii) until a number of generations is reached

ALGORITHM 1: The EA algorithm.

- (i) Generate uniform random number,  $r$  between  $[0, 1]$
- (ii) Get  $t$  using formula:
 
$$t = \frac{X_i - L_{X_i}}{U_{X_i} - X_i} \quad (*)$$
 where  $X_i$ : ingredient  $i$  value from initial solution,  $L_{X_i}$ : lower bound of ingredient  $i$ ,  
 $U_{X_i}$ : upper bound of ingredient  $i$
- (iii) Compare value  $t$  with  $r$  and determine which one is greater
- (iv) Find new value of  $X_{if}$  by comparing  $r$  with  $t$ 
  - If  $r > t$ ,  
Then new value of  $X_{if} = 0$
  - If  $t \geq r$ ,  
Then generate new value of  $X_{if}$  by the formula:  

$$(X_i - 1 < X_i < X_i + 1) \quad (**)$$
- (v) Repeat step (ii) to (iv) for other allele and also for other infeasible individuals
- (vi) Calculate new fitness value for the solution

ALGORITHM 2: Power Heuristics algorithm.

where  $L_{X_i}$  is ingredients' lower bound,  $U_{X_i}$  is ingredients' upper bound, and  $j$  is the number of populations.

## 6. Results and Discussions

Semirandom initialization operation, adapted from [21], was implemented to find solutions at the initial stage so as to ensure that the weight of ingredients lies within the ingredients' limitations. The experimentations between these two initialization operations were carried out and the results are shown in Table 4. The generation of the proposed EA model with a Power Heuristic operator (EA-PH) was carried out with certain established operators, which are Roulette Wheel Selection, One-Point Crossover, and Power Mutation.

The evolutionary model with semirandom initialization operation (EA-SR) was used as a benchmark. Since this work is the first attempt of filtering some ingredients from the list, the only appropriate algorithm to be compared is by using EA-SR. Each model was run 30 times using the algorithm from Algorithm 1. Experimentations of EA with two initialization operators, that is, EA-PH and EA-SR, were conducted. These initialization operators were tested, while other EA operators remain the same. As in Table 4, the EA-SR provided an infeasible solution in every run, whereas

the EA-PH model showed that no solution was infeasible. This experimentation shows that Power Heuristics allows unnecessary ingredients to be filtered out of the system. As a result, the total selected ingredients in the system might be less than fourteen. Indirectly, the requirements of ingredient's weight and nutrient's range can be fulfilled.

A sample solution for the shrimp feed formulation is shown each in Tables 5 and 6 as obtained from EA-SR and EA-PH, respectively. In comparison, the EA-SR solutions in Table 5 include all ingredients with a total weight of 124.4231 kg, while EA-PH solution in Table 6 shows that only eight ingredients were selected for the solution with a total weight of 100.0514 kg. The total price for this feed combination using EA-SR was MYR 297.34, and MYR 217.08 was the price for EA-PH. The results from this experiment conclude that Power Heuristics in the EA model is able to remove some inappropriate ingredients in searching for a feasible solution when many possible ingredients are under consideration.

In addition, the performance of the EA-PH model was statistically evaluated with  $\mu_{EA-PH} = 547.67$ ,  $\mu_{EA-SR} = 100422$ ,  $\sigma_{EA-PH} = 139.778$ , and  $\sigma_{EA-SR} = 114.816$ . As confidence level of 95% using  $z$ -test, and  $p$  value being 0.0001, performance of the EA-PH model is significantly better than that of the EA-SR model. Therefore, we can conclude that the performance

(i) Generate uniform random numbers, $s_1$ and $r$ between $[0, 1]$
(ii) Get $s$ using formula: $s = p(s_1)^{p-1}$ where $s_1$ is the random number and $p$ is the index of Power distribution
(iii) Get $t$ using formula: $t = \frac{X_{i_c} - L_{X_i}}{U_{X_i} - X_{i_c}} \quad (***)$ where $X_{i_c}$ : ingredient $i$ value from crossover stage, $L_{X_i}$ : lower bound of ingredient $i$ , $U_{X_i}$ : upper bound of ingredient $i$ If $(t < r)$ , Then generate a new value of $X_{i_m}$ by the formula $X_{i_m} = X_{i_c} - s(X_{i_c} - L_{X_i}) \quad (***)$ Else if $(t \geq r)$ Then find a new value of $X_{i_m}$ by the formula $X_{i_m} = X_{i_c} + s(U_{X_i} - X_{i_c}) \quad (***)$
(iv) Repeat step (iii) to (iv) until all alleles in chromosome $i$ are mutated.
(v) Calculate new fitness value for the solution

ALGORITHM 3: Power Mutation algorithm [22].

TABLE 4: Performance of both models based on penalty value with different initialization procedures.

Model	Minimum penalty value	Mean penalty value	Mean run time (minutes)	Number of infeasible solutions
EA-SR	100000 (infeasible)	100422 (infeasible)	165.71	30/30
EA-PH	300	547.67	201.52	0/30

TABLE 5: A sample solution obtained from the EA-SR model.

Ingredient	Minimum (kg)	Maximum (kg)	Assigned quantity (kg)
$X_1$	5	10	5.1450
$X_2$	15	50	16.4601
$X_3$	3	5	3.0234
$X_4$	5	50	10.6521
$X_5$	30	40	31.0945
$X_6$	5	15	6.1047
$X_7$	5	15	7.2478
$X_8$	2	5	2.5413
$X_9$	15	60	19.549
$X_{10}$	5	15	4.1310
$X_{11}$	5	15	6.5470
$X_{12}$	3	5	3.6587
$X_{13}$	3	5	5.2343
$X_{14}$	3	5	3.0342
<i>Total weight for a feed mix (kg)</i>			124.4231

TABLE 6: A sample solution obtained from the EA-PH model.

Ingredient	Minimum (kg)	Maximum (kg)	Assigned quantity (kg)
$X_2$	15	50	42.5860
$X_3$	3	5	4.0431
$X_6$	5	15	14.3030
$X_7$	5	15	13.1132
$X_8$	2	5	4.0231
$X_{11}$	5	15	12.1350
$X_{13}$	3	5	4.6120
$X_{14}$	3	5	5.2360
<i>Total weight for a feed mix (kg)</i>			100.0514
$X_1 = X_4 = X_5 = X_9 = X_{10} = X_{12} = 0.$			

is not a surprise since fish meal is high in demand and thus, many researchers [116, 117] have tried to substitute fish meal with alternative ingredients in their studies. The alternatives that could maintain the palatability of the shrimp feed such as krill meal [118, 119] and poultry by product meal [120] have been tested.

Many other combinations of ingredients could be obtained through this EA. When our proposed EA is run, a feasible and good solution or result is recommended by the embedded model in terms of the best combination of ingredients that fulfill the quality and cost requirements. The solution helps to reduce the number of tests that would

of EA-PH is better than EA-SR due to the significantly less penalty value obtained.

Regarding the ingredients, selecting them is based on the nutritional values obtained in the shrimp feed mix, whether fish meal is included or not. The underlying rationale for this selection is that the price of fish meal is relatively high. This

otherwise have to be carried out considering a large number of combinations of ingredients. A potential extension to this research could be to use the solution from this research as input to an ED approach to confirm how the shrimp will perform. These approaches could complement each other to obtain the best shrimp feed.

## 7. Conclusions and Future Work

A shrimp feed formulation problem was explored in this study using an EA strategy. A heuristic procedure known as Power Heuristics was incorporated at the initialization stage in an EA model to explore the neighbourhood area when the initial solution was infeasible. The function of this Power Heuristic is to filter unsuitable ingredients and remove it from the EA computation. The heuristic operator is capable of filtering some combinations of ingredients from a selected database of choices, which could lead to potentially poor solutions. It works well if many options exist in the search space, which is suitable for a large problem like an animal diet formulation with many possible ingredients being considered. In future, many new avenues can be explored, such as improving the integration of Power Heuristics with the EA or new integration with other population based techniques with various ingredients, as hundreds of possible ingredients have been tested in the literature.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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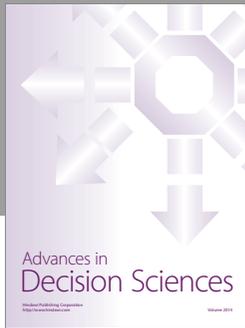
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