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Precision animal feed formulation: An evolutionary multi-objective approach

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ABSTRACT

Most livestock producers aim for optimal ways of feeding their animals. Conventional algorithms approach optimum feed formulation by minimizing feed costs while satisfying constraints related to nutritional requirements of the animal. The optimization process needs to be performed every time a nutritional requirement is changed due to the nonlinear relationship between the relaxation of the different nutritional requirements and the feed cost. Consequently, decision-making becomes a time-consuming trial and error process. In addition, the nonlinear relationship changes depending on the type of materials used, their nutritional compositions and costs as well as the animal's nutritional requirements. Therefore, in this work, we formulated a multi-objective feed formulation problem comprising of two objects – a) minimizing feed cost and b) minimizing deviation from the specified requirements. The problem is solved using a population-based evolutionary multi-objective optimization algorithm (NSGA-II) that results in an optimal set of comprised solutions in a single run. The availability of the entire set of comprised solutions facilitates the understanding of the relationship between different nutritional requirements and cost, thus leading to a more efficient decision-making process. We demonstrated the applicability of the proposed method by performing experimental simulations on several cases of dairy and beef cattle feed formulation.

1. Introduction

In animal production, the main objective of feed formulation is to provide a balanced nutrition to support physiological functions such as growth, maintenance, reproduction, and lactation as well as energy source for physical and metabolic activities (Fatyanosa et al., 2018). Research on farm animals have demonstrated that growth rate and milk production depend on the availability of nutrients including amino acids, fatty acids, minerals, glucose, or other substrates (National Research Council, 2001, 2010; Montoya et al., 2017). In addition, the nutritional requirements of the animal changes depending on different life stages of the animal as well the animals' roles, for example, as seed stock, breeders, or protein providers. Improper balancing of feed nutrients may result in poor nutrition and related diseases and performance problems. In the Republic of Korea, the nutrients emphasized for beef cattle are DMI, MC, TDN, CP, Ca, and P while for dairy cattle, Met, Lys, Arg, Thr, Leu, Ile, Val, His, Phe, Trp, ME, Ca, and P makes up the nutritional requirements (Rural Development Authority, 2017). For profitability, feed formulation involves the process of finding the appropriate

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Nomenclature

Term	Description
Met	Methionine
Lys	Lysine
Arg	Arginine
Thr	Threonine
Leu	Leucine
Ile	Isoleucine
Val	Valine
His	Histidine
Phe	Phenylalanine
Trp	Tryptophan
ME	Metabolizable Energy
MP	Metabolizable Protein
Ca	Calcium
P	Phosphorous
DMI	Dry Matter Intake
MC	Moisture Content
TDN	Total Digestible Nutrients
CP	Crude Protein
Conc.	Concentrates
Rhage	Roughages
MOP	Multi-objective optimization
LP	Linear Programming
KRW	Republic of Korea currency ($1 = about 1130 KRW on February 1, 2019)
NSGA-II	Non-dominated sorting based genetic algorithm-II
MOEA	Multi-objective evolutionary algorithms
EA	Evolutionary Algorithm
Nutrient_{dev}	Deviation from specified nutrient requirement

quantities of different material combinations that meet the nutritional requirements of the animal at minimal cost.

Least-cost feed formulation has been approached as a standard optimization problem where the application of mathematical programming such as LP (Babić and Perić, 2011; Harris and Bishop, 2007; van de Panne and Popp, 1963; Jean dit Bailleul et al., 2001; Shaftel and Wilson, 1990; Waugh, 1951; Munford, 1996; Castrodeza et al., 2005; Smith, 1959), multistage multiple-choice programming algorithm (Balintfy, 1975), mixed integer programming (Armstrong and Sinha, 1974), integer programming (Balintfy, 1964), mixed integer linear programming (Sklan and Dariel, 1993) has been the norm. The main weaknesses of these approaches is the use of fixed rigid limits that allow the optimization of only one objective at a time and inability to find feasible solutions in many situations (Rehman and Romero, 1984; Tamiz et al., 1998). In other words, in conventional livestock feed formulation, the minimum nutritional requirements are expressed as rigid constraints that needs to be met. Consequently, during optimization, even a small violation regarding any of the nutritional requirements renders solutions to be infeasible and are discarded. Therefore, imposing minimum nutritional requirements may result in feed formulations that are not always cost-effective compared to solutions that are slightly infeasible but still acceptable for the breeder. A slight relaxation of one or more nutritional requirements that may not be essential for a particular growth stage (Minson, 2012; Underwood, 1999) may result in a huge reduction of the feed cost while not adversely affecting the performance of the animal. The knowledge of vital nutrient requirements for each stage and its relationship with costs may therefore, help increase the cost-effectiveness of formulated feeds. Based on this observation, an interactive feed formulation using evolutionary algorithm was proposed in (Uyeh et al., 2018) where the relaxation of each nutritional requirement is provided to the algorithm through a tolerance parameter.

Feed formulation usually involves multiple goals (objectives) in addition to minimizing the cost of the feed while satisfying the nutritional requirements. Some of the objectives considered in previous studies include maximizing land-usage (Zander and Kächele, 1999), maximizing the use of stored feeds (Lara, 1993), and reducting nitrogen and phosphorus excretion (Sudduth and Loveless, 2019). In (Zhang and Roush, 2002), the authors considered minimizing protein, methionine, and lysine variation in addition to cost minimization. The process of multi-objective optimization involves defining goals and priorities; and then iteratively finding solutions of linear or nonlinear functions. In other words, each goal is solved sequentially according to its priority, with the previous goal or goals held constant in the model. There can be several trade-offs among multiple conflicting feed formulation objectives. The process results in a set of trade-off solutions referred to as Pareto-optimal solutions. A solution that would improve any of the objectives without sacrificing at least one of the other objectives is not possible. In feed formulation literature, goal programming is considered to be a very effective approach for solving multi-objective decision making problems (Prišenk et al., 2013). However, goal programming (McCann-Rugg et al., 1983) usually requires the user to set the penalty values for objectives and the choice of the penalties seriously affects the quality of the optimized trade-off solutions resulting in ineffective decision making. Recently, evolutionary multi-objective optimization (Pamulapati et al., 2018) has been popular due its effectiveness in handling complex non-linear conflicting objectives without the need for penalties.

As mentioned previously, relaxing some of the constraints related to the nutritional requirements can reduce the cost of the feed formulation without seriously affecting the growth of the animal. In the interactive feed formulation approach described in (Uyeh et al., 2018), each nutritional requirement is assigned a tolerance parameter. The change in the tolerance parameter related to the concerned nutritional requirement results in a solution that may or may not be acceptable to the feeder. In other words, finding the relationship between tolerance parameter of each nutritional requirement and the feed cost involves a time-consuming trial and error process. In addition, the decision-making process becomes complicated due to lack of proper understanding between the different nutritional requirements and the feed cost.

In this study, the deviation of the different feed formulations from the specified requirements is considered as an objective to be minimized, in addition to the minimization of the feed cost. The two objectives – a) minimizing the feed cost and b) minimizing the deviation from the specified requirements (Nutrient_{dev}) are conflicting. Simultaneous optimization using NSGA-II; an evolutionary multi-objective optimization algorithm was done. The use of evolutionary multi-objective optimization provides as set of comprise solutions (Pareto set) in a single run without the need for penalties and priorities set in advance. The shape of the Pareto front, which represents the Pareto set, is dependent on the number and types of nutritional requirements specified for the animal and the cost of feed materials. Therefore, from the Pareto set, we can easily establish the following relationships that can be helpful to the breeder in making better decisions:

a relationship between the feed cost and the overall deviation from the specified nutritional requirements,
b relationship between the feed cost and the deviation from the individually specified nutritional requirements, and
c relationship between the different individual nutritional requirements at different feed costs.

2. Materials, problem formulation and methods

2.1. Data

The feed materials, their nutritional profiles and costs used for the dairy and beef feed ration formulations simulated were obtained from Rural Development Administration of the Republic of Korea. Values are summarized in Tables A1–A2 of the Supplementary Information. Data on the nutritional requirements of dairy and beef cattle were also obtained from the Rural Development Administration of the Republic of Korea (Table 1 and 2) and these served as specified nutritional requirements. The nutritional requirements for dairy cattle in the Republic of Korea were arranged as: Met, Lys, Arg, Thr, Leu, Ile, Val, His, Phe, Trp, ME, Ca, and P.

The nutritional requirements of beef cattle in the Republic of Korea are arranged as: DMI, MC, TDN, CP, Ca, and P. The requirements for different cases (categorized by age and weight) considered are summarized in Tables 1 and 2, respectively for dairy and beef (Rural Development Authority, 2017). In Table 2, Level 2 represents a diet with no Conc. and normal Rhage requirement.

2.2. Problem formulation

In feed formulation, enforcing rigid nutritional requirements usually leads to drastic increases in feed costs. On the other hand, relaxing some of the constraints reduces the feed cost while not affecting the physiological characteristics of the animal. The nutritional requirements that can be relaxed depends on the type and developmental stage of the animal as well as its condition. In addition, the nutritional requirements during feed formulation vary in different regions. The DMI (kg) is the amount of dry matter consumed daily while CP (%) measures the nitrogen content, including both true protein and non-protein nitrogen. The summation of the digestible fiber, protein, lipid, and carbohydrate components of a feed ration is referred to as TDN and is directly related to digestible energy. Minerals are vital components of feed with at least 17 minerals required. However, the two mostly included in

Table 1
Nutritional requirements for different stages of breeding dairy cattle in Republic of Korea.

Nutrients	Case 1 ≤ 20 Months (≤ 500 kg)	Case 2 20–40 Months (500-650 kg)	Case 3 40–46 Months (≥ 650 kg)
ME (kcal)	25.700	65.200	30.100
Ca (kg)	0.031	0.103	0.033
P (kg)	0.021	0.052	0.025
Met (kg)	0.020	0.051	0.025
Lys (kg)	0.062	0.159	0.077
MP (kg)	0.999	2.640	1.210

Table 2
Nutritional requirements for different stages of breeding beef cattle in Republic of Korea.

Nutrients	Case 1						Case 2		Case 3		Case 4	
	≤ 10 Months (≤260 kg)						10–17 Months (260–452 kg)		17–25 Months (452–640 kg)		(Maintenance)	
	Max			Min			Max	Min	Max	Min	Max	Min
DMI (kg)	6.900			6.900			9.800	9.800	8.700	8.700	5.600	5.600
CP (kg)	2.170			1.090			2.560	1.280	2.340	1.170	1.120	0.560
TDN (kg)	5.200			4.870			7.810	7.300	7.430	6.940	3.460	3.230
Ca (kg)	0.086			0.043			0.094	0.005	0.076	0.038	0.036	0.018
P (kg)	0.046			0.023			0.062	0.031	0.068	0.034	0.040	0.020
Rhage (%)	36.000			30.000			24.000	20.000	11.100	8.500	90.000	60.000
Conc.(kg)	Level 1 11.500	Level 2 0.000	Level 3 11.500	Level 1 9.200	Level 2 0.000	Level 3 5.000	16.400	9.800	14.500	11.600	9.340	7.470

computer models are Ca and P. Calcium is the most abundant mineral in the body with approximately 98% as a structural component of bones and teeth. The remaining 2% is distributed in extracellular fluids and soft tissues and is involved in such vital functions as blood clotting, membrane permeability, muscle contraction, transmission of nerve impulses, cardiac regulation, secretion of certain hormones, and activation and stabilization of various enzymes (National Research Council, 2001).

Consequently, in (Uyeh et al., 2018), modified feed formulations for dairy and beef cattle were presented to facilitate the relaxation of each nutritional requirement using a tolerance parameter. The formulations are shown below for dairy and beef cattle.

Single objective formulation for Dairy cattle

$$\text{Minimize } \sum_{i=1}^{n} w_i cost_i \geq 0 \tag{1}$$

Subject to:

$|\text{MP} - \text{M}| \leq \delta_{MP} \times \text{M}$
$|\text{Lys} - \text{N}| \leq \delta_{Lys} \times \text{N}$
$|\text{Ca} - \text{O}| \leq \delta_{Ca} \times \text{O}$
$|\text{P} - \text{Q}| \leq \delta_{P} \times \text{Q}$
$|\text{ME} - \text{R}| \leq \delta_{ME} \times \text{R}$
$|\text{Met} - \text{S}| \leq \delta_{Met} \times \text{S}$

Single objective formulation for Beef cattle

$$\text{Minimize } \sum_{i=1}^{n} w_i cost_i \geq 0 \tag{2}$$

Subject to:

$|\text{DMI} - \text{A}| \leq \delta_{DMI} \times \text{A}$
$|\text{CP} - \text{B}| \leq \delta_{CP} \times \text{B}$
$|\text{TDN} - \text{C}| \leq \delta_{TDN} \times \text{C}$
$|\text{Ca} - \text{D}| \leq \delta_{Ca} \times \text{D}$
$|\text{P} - \text{E}| \leq \delta_{P} \times \text{E}$
$|\text{Rhage} - \text{F}| \leq \delta_{Rhage} \times \text{F}$
$|\text{MC} - \text{G}| \leq \delta_{MC} \times \text{G}$
$|\text{Conc.} - \text{H}| \leq \delta \text{P}_{Conc.} \times \text{H}$

In each problem formulation, the corresponding tolerance parameter (δ) was used to provide relaxation to the requirements.

In these formulations, the breeder can change the tolerance parameter of the requirement to be relaxed and optimize the solution using evolutionary algorithms. The change of the tolerance parameter results in the change of the cost. However, the relationship between the different tolerance parameters and the cost of the feed is not evident and the process of finding the best feed formulation involves a time-consuming trial and error process.

In this work, the constraints related to the different nutritional requirements are combined to form an objective function and is simultaneously optimized with the feed cost. These two objectives conflict with each other and can be referred to as multi-objective formulations. The multi-objective formulations for dairy and beef cattle are shown in Eqs. (3) and (4) below.

As mentioned earlier, the problem was formulated based on inspiration from a previous study (Uyeh et al., 2018), where the tolerance parameter had to be changed in order to adjust to the requirements and cost needs of the formulator thus, the simulation must be done every time the tolerance parameter was changed. Consequently, in the new formulation, the constraints were formulated as an objective to eliminate repeated simulations while using Pareto fronts for nondominated solutions to be chosen as optimal if no objective could be improved without compromising at least one objective. Consequently, like in the first objective of minimizing cost using Eq. (3), (w_i), the weight of the selected material multiplied by the cost ($cost_i$) were summed, and the constants M, N, O, Q, R and S representing the nutritional requirement of dairy cattle evaluated with the materials during the search process were also summed to find the cost at every search space (Pareto front). The viewing of all the constraints along the Pareto front gives the possibility of displaying the various combinations of nutrient contents and corresponding cost.

Instance 1: Dairy cattle

Objective 1: Feed Cost

$$Minimize \sum_{i=1}^{n} w_i cost_i \tag{3}$$

Objective 2: Deviation from specified nutrient requirements

$$\text{Minimize } |\text{MP} - \text{M}| + |\text{Lys} - \text{N}| + |\text{Ca} - \text{O}| + |\text{P} - \text{Q}| + |\text{ME} - \text{R}| + |\text{Met} - \text{S}|$$

In dairy cattle, n is the number of ingredients under consideration w_i is the weight in kg and $cost_i$ is the cost (KRW/kg) of the feed materials. Correspondingly, the constants M, N, O, Q, R and S specify the requirements for MP, Lys, Ca, P, ME and Met, respectively; The requirements change with the age and weight of the cattle.

Instance 2: Beef cattle

Objective 1: Feed Cost

$$Minimize \sum_{i=1}^{n} w_i cost_i \tag{4}$$

Objective 2: Deviation from specified nutrient requirements

$$\text{Minimize } | \text{DMI} - \text{A} | + | \text{CP} - \text{B} | + | \text{TDN} - \text{C} | + | \text{Ca} - \text{D} | + | \text{P} - \text{E} | + | \text{Rhage} - \text{F} | + | \text{MC} - \text{G} | + | \text{Conc.} - \text{H} |$$

where, n is the number of ingredients under consideration, w_i is the weight in kilograms and $cost_i$ is the cost (KRW/kg).

The constants A, B, C, D, E, F, G, and H specify the requirements for DMI, CP, TDN, Ca, P, Rhage, MC and Conc., respectively. The requirements change with the age and weight of the cattle.

Unlike in single objective formulation, the multi-objective approach involves no trial and error process. In addition, the set of comprise solutions over the different feed costs and levels of nutritional requirement satisfaction were obtained. The availability of the whole set of trade-off solutions facilitates better decision-making compared to a single objective trial and error approach.

2.3. Method employed in the current study

In multi-objective optimization, due to the conflicting nature of the objectives, there exists no single optimal solution, but a set of compromise solutions referred to as Pareto front (in objective space) or Pareto set (in variable space) as shown in Fig. 1. As shown, there exists multiple Pareto fronts and the aim of multi-objective algorithms is to find an optimal Pareto front. In other words, optimal Pareto front refers to a set of solutions compared to which there exists no solution that is better in all the objectives. In addition, the solutions in the Pareto front should be well-spread or diverse to enable better decision-making.

Multi-objective problems can be solved in different ways,

a Single objective optimization specifying weights for each objective. Depending on the set of the weights the algorithm provides a single solution on the Pareto front. Therefore, to estimate the entire Pareto front, multiple runs with different combination of weights is needed. However, it is difficult to find diverse well spread solutions due to the nonlinear relationship between the weights and the Pareto front. Goal programming, that is commonly adopted in feed formulation belongs to this category.

b Evolutionary multi-objective optimization (Prišenk et al., 2013) being a population-based approach can provide the entire Pareto front in a single run.

In terms of feed optimization, the Pareto optimal solutions refers to a set of comprise solutions (Fig. 1) where: Point A is a solution with most nutritional requirement satisfaction but incurs high cost; Point B is a solution with least cost but deviation from the nutritional requirements is high; and Point C represents a compromise solution where the cost is significantly reduced with huge deviation in the nutrient requirements. The decision-making process depends on the shape of the Pareto front which in turn mainly

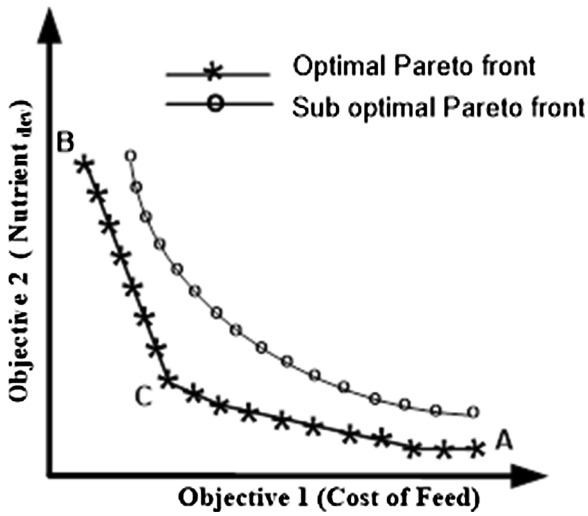

Fig. 1. Comparison between MOP and conventional single optimization.

depends on the nutritional composition and cost of the individual materials and nutritional requirements. In addition, the relationship between the different nutritional requirements over the entire cost range can be obtained. Therefore, the availability of the entire Pareto front in one run displaying the relationship between individual nutritional requirements facilitates a better decision-making.

In this study, we employed the NSGA-II, an evolutionary multi-objective optimization algorithm (Deb et al., 2002) to optimize the multi-objective problems shown in Eqs. (3) and (4). To obtain a diverse set of Pareto-optimal solutions, NSGA-II adopts the concepts of Pareto dominance and the crowding distance. More details regarding NSGA-II are provided in the Appendix.

2.4. Experimental setup and simulations

The proposed multi-objective feed formulation is simulated using – a) 3 Cases of dairy cattle and b) 4 Cases of beef cattle in the Republic of Korea as shown below and summarized in Tables 1 and 2.

2.4.1. Dairy

Case 1: Birth to 20 months and live weights of less than 500 kg

Case 2: Age 20–40 months with live weights between 500 and 650 kg

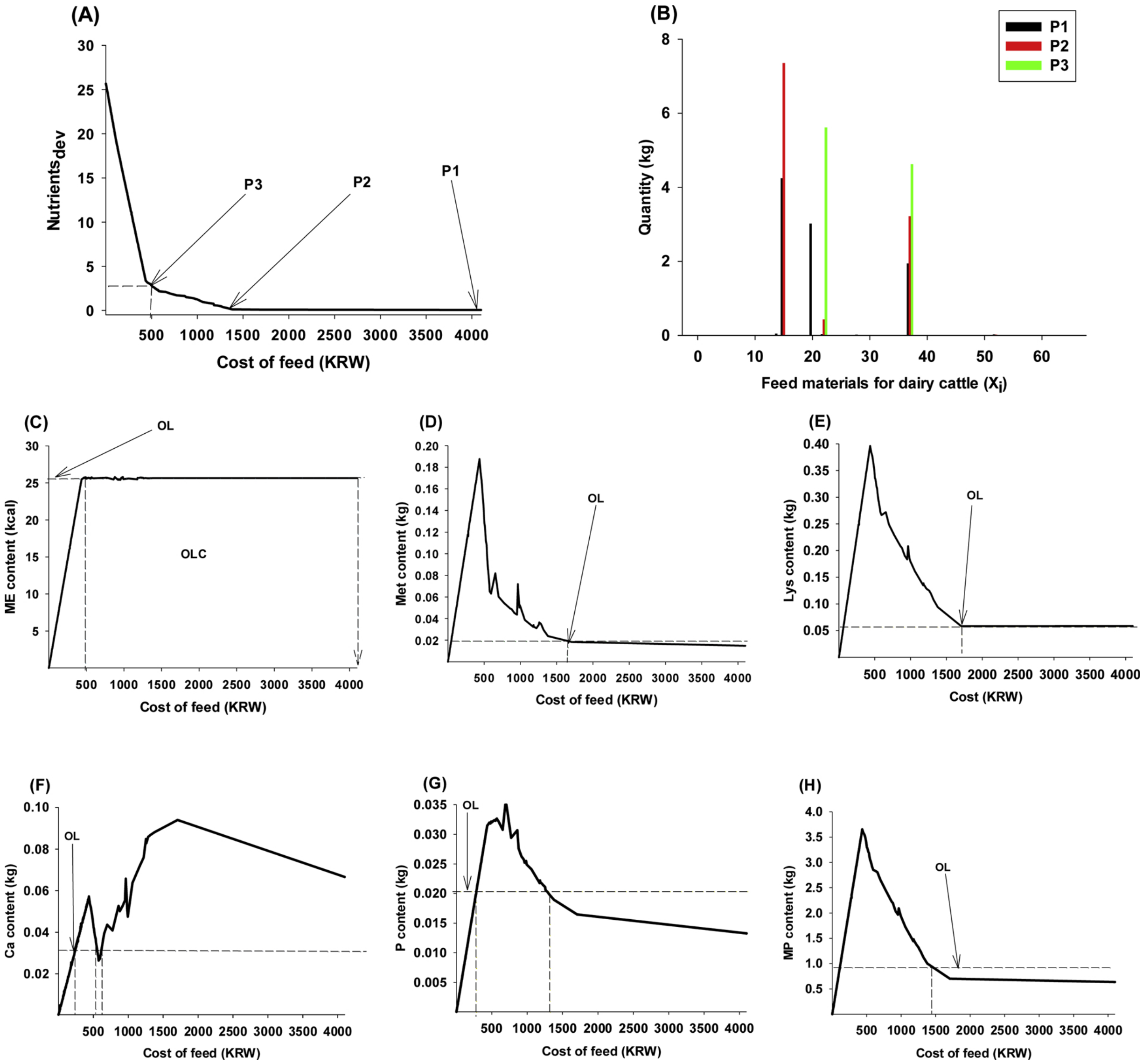

Fig. 2. Feed formulation curves for dairy cattle Case 1 (OL: Optimal Line; P1, P2, P3: Points; OLC: Optimal Line Cost; Nutrient$_{dev}$: Deviation in specified nutrients requirement).

Case 3: Age 40–46 months with live weights above 650 kg

2.4.2. Beef

Case 1: Birth to 10 months with live weights of 260 kg or less

Case 2: Age 10–17 months with live weights between 260 and 452 kg

Case 3: Age 17–25 months with live weights between 452 and 640 kg

Case 4: Maintenance stage where the farmers attempt to sustain the weight of the animal at a minimal cost. The simulations were performed in MATLAB and an average run time for each simulation of the proposed algorithm was 20 s on a 3.7 GHz Intel Core i5 processor, 8 GB RAM and 128 GB solid-state drive with a Windows 10 Operating System. The parameters of the optimization algorithm were set as:

Population size: 300

Maximum number of generations: 2000

Distribution indices for mutation (nm): 20

Distribution indices for crossover (nc): 20

Probability of crossover (Pc): 1.0

Probability of mutation (Pm): 1/10

Crossover: Simulated binary crossover

Mutation: Polynomial mutation

Constraint bond: 0–20.

3. Results and discussion

3.1. Dairy: case 1

Pareto-optimal front for the two objectives is shown in Fig. 2(A) and the quantity of different feed materials selected among solutions on the front, points P1, P2, and P3 are presented in Fig. 2(B). Fig. 2(C)–(H) present the relationship between the feed cost and individual nutritional requirements in the feed. These graphs provide insights into the contribution of the individual nutrient requirements to the total cost. In Fig. 2(A), P1 represents a solution where most of the nutritional requirements are met at a cost of approximately 4000 KRW. In Fig. 2(C)–(H), the horizontal dotted lines represent the specified requirement (OL) for the corresponding feed components while OLC represents the cost region over which the corresponding nutritional requirement is satisfied.

In Fig. 2(A), Point P2 seems to have approximately the same deviation from the requirements as that of P1 but at a significantly less cost of 1300 KRW. Also, at P2, five out of the six specified nutritional requirements by the Rural Development Administration of the Republic of Korea are met. However, Ca deviates significantly from the requirement. In the region between P1 and P2, the increase in the cost is mainly due to the attempt by the algorithm to meet the Ca requirement. However, this results in slight deviations in other nutritional requirements such as Met, P and MP. In Fig. 2(A), P3 represents a point where ME, Ca and P requirements are met while the deviations in the requirements of MP, Lys, and Met is observed. The cost variation in the region between P2 and P3 is mainly due to the attempt by the algorithm to satisfy the MP requirement. In order to satisfy the MP, Met and Lys, the Ca deviates from the requirement (Fig. 2).

From the Fig. 2, it is evident that P1 is a point where the specified nutrients were reasonably satisfied. However, moving to the left-hand side from P1 to P2, the overall deviation remains approximately the same with a major deviation in Ca. Therefore, if deviation from the specified Ca can be tolerated, then selection of P2 would result in cost reduction of 223% compared to P1. In dairy cattle, the requirement of MP depends on different factors such as age and activity of the animal. In (Wang et al., 2007), it has been reported that the milk yield and milk protein percentage did not improve in Chinese Holstein dairy cows even when their diets contained specified MP. Therefore, in this scenario, if the emphasis is on ME (Fig. 2C) then the selection of P3 would result in cost reduction of 160% compared to P2 with little impact on the quality of the feed and with likely small consequences.

From Fig. 2B and Table A1 in the Appendix, it is evident that the algorithm selected a high quantity of autumn forage at the three points (P1, P2 and P3) because of its low cost and parallel nutritional content. Also, the autumn forage contains a high ME which explains the satisfaction of this constraint at these 3 points. At P1 and P2, molasses with a reasonable content in Ca compared to the other nutrients was selected indicating the excess content of Ca at these points. The excess Ca was due to the initial selection of cheaper materials which usually had high Ca content since materials with moderate amounts of Ca and high amounts of other nutrients were usually costlier.

3.2. Dairy: case 2

For Case 2, the Pareto-optimal front is shown in Fig. 3(A) with P1, P2 and P3. The different feed materials selected at these points are presented in Fig. 3(B). Fig. 3(C)–(H) present the relationship between the feed cost and individual nutritional components present in the feed. As mentioned in Case 1, OL and OLC represent the specified requirement and the cost region which the corresponding nutritional requirement is satisfied, respectively.

From Fig. 3(A), it is evident that small deviations from the feed requirements were observed between 3600 KRW and 5000 KRW, which is a significant variation in cost. In between P1 and P2, Ca has an inverse relationship with all the other requirements. In other words, as the cost of the feed increased, the nutritional requirements such as Met, Lys, P and MP in the feeds decreased while Ca increased.

As in Case 1, Case 2 also recorded satisfaction of ME at a lower cost (P3) and showed some stability from P3 to P1. As in Case 1, depending on the user's needs, different solution regions can be selected with varied associated costs. In the selected materials, Fig. 3(B), the algorithm also opted for autumn forage in the points (P1 to P3).

This further verifies the satisfaction of ME at all the points investigated. High amounts of barley silage were selected at P3 compared to the high levels of molasses selected at P1 and P2. The low cost of barley silage and high nutritional content compared to the relatively expensive molasses with only measurable ME, Ca and P content (Fig. 3(C), (F) and (G)) explains the nutrient excesses recorded at P3 (Fig. 3(D), (E), (G) and (H) and near specified content recorded at P1 and P2. This shows that the algorithm tries to satisfy the first objective which is cost and then subsequently tries to balance the specified nutrients.

3.3. Dairy: case 3

Fig. 4 summaries the results for Case 3. At P1, the near specified requirements were observed. However, moving leftward to P2, Met (Fig. 4D), Lys (Fig. 4E) and MP (Fig. 4H) deviated from the specified values while the satisfaction of P (Fig. 4G) was met.

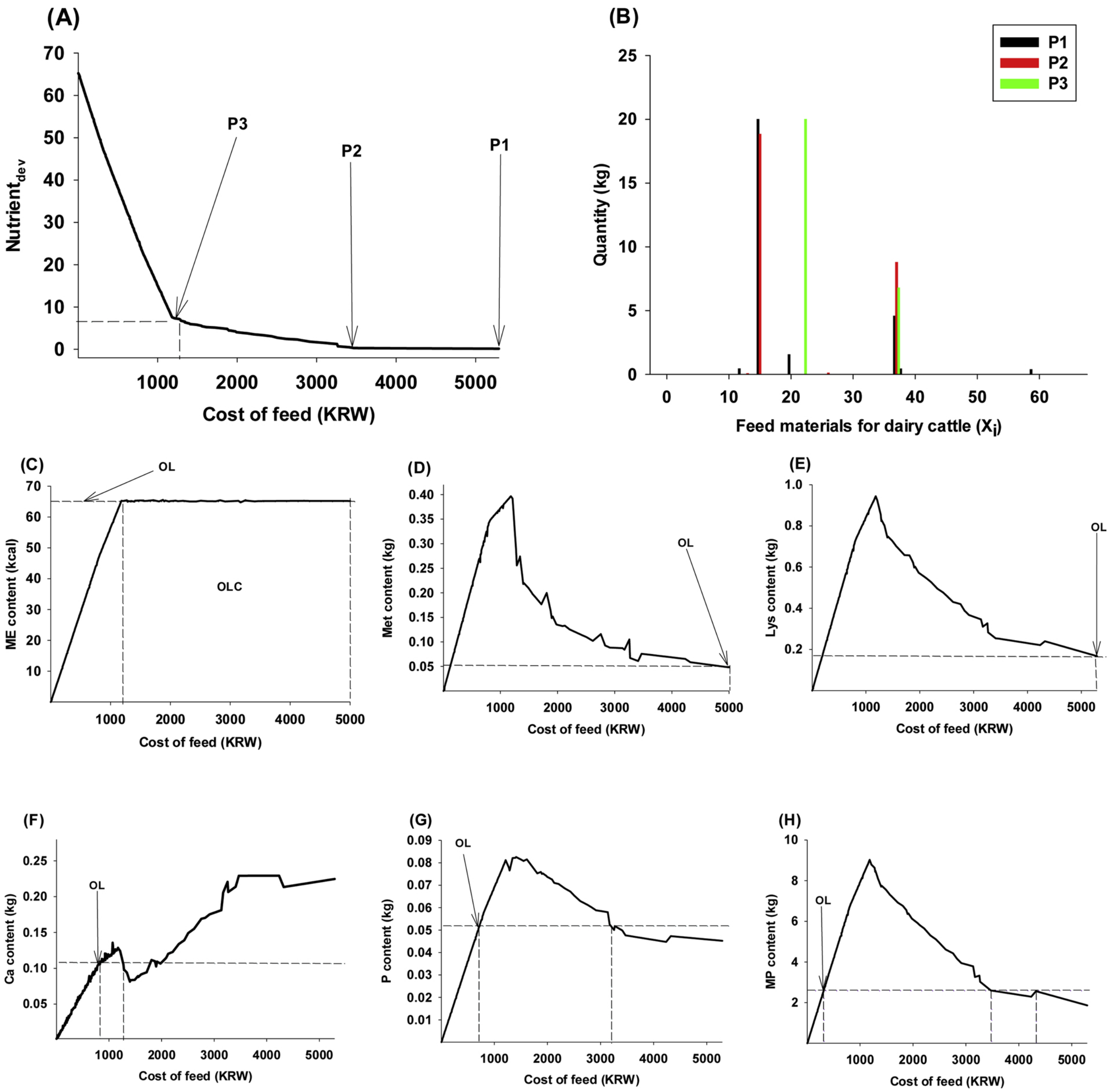

Fig. 3. Feed formulation curves for dairy cattle Case 2 (OL: Optimal Line; P1, P2, P3: Points; OLC: Optimal Line Cost; Nutrient$_{dev}$: Deviation in specified nutrients requirement).

However, as we move towards the left to P3, except Ca, all the other nutritional requirement deviate from the specified requirement. However, if the emphasis is only on ME then selecting P3 would result in 220% reduction in the cost compared to P2.

As in Cases 1 and 2, the selection of high amounts of barley silage at P3 and high amounts of molasses at P1 and P2 (Fig. 4B) was the cause of the excesses and satisfaction of the specified requirement respectively.

3.4. Beef: case 1

In beef cattle, the two main feed types, roughages (Rhage) and concentrates (Conc.), are used in varying combinations in different countries with one often dominating the other at different stages of the animal's growth

(Zhang and Roush, 2002; Saxena and Khanna, 2014). Beef cattle are usually fed predominantly Rhage after weaning until the finishing stage when more Conc. is fed (Leng, 2019; Msangi et al., 2014). The primary role of Conc. (Leng, 2019) is to provide concentrated nutrition and energy in the diet of the animal. Globally, a wide variety of cereals and grains and their by-products constitute Conc. fed to animals. As cereals and grains are often the costlier feed types, some substitution with by-products such as distillers grains helps reduce costs. Advantageously, from an economic and physiological perspective, it is possible to increase feed digestibility (a limiting factor for high forage diets) with relatively small quantities of grains and cereals without sacrificing animal growth and performance. Furthermore, other concentrated forms of nutrients that are cost effective such as supplements (Table A2) can be used to make up any nutrient shortages as needed. Therefore, the constraints around the amounts of concentrates fed can be easily relaxed. In the current study, we performed experimental simulations for 3 different levels of Conc. and a fixed Rhage as shown

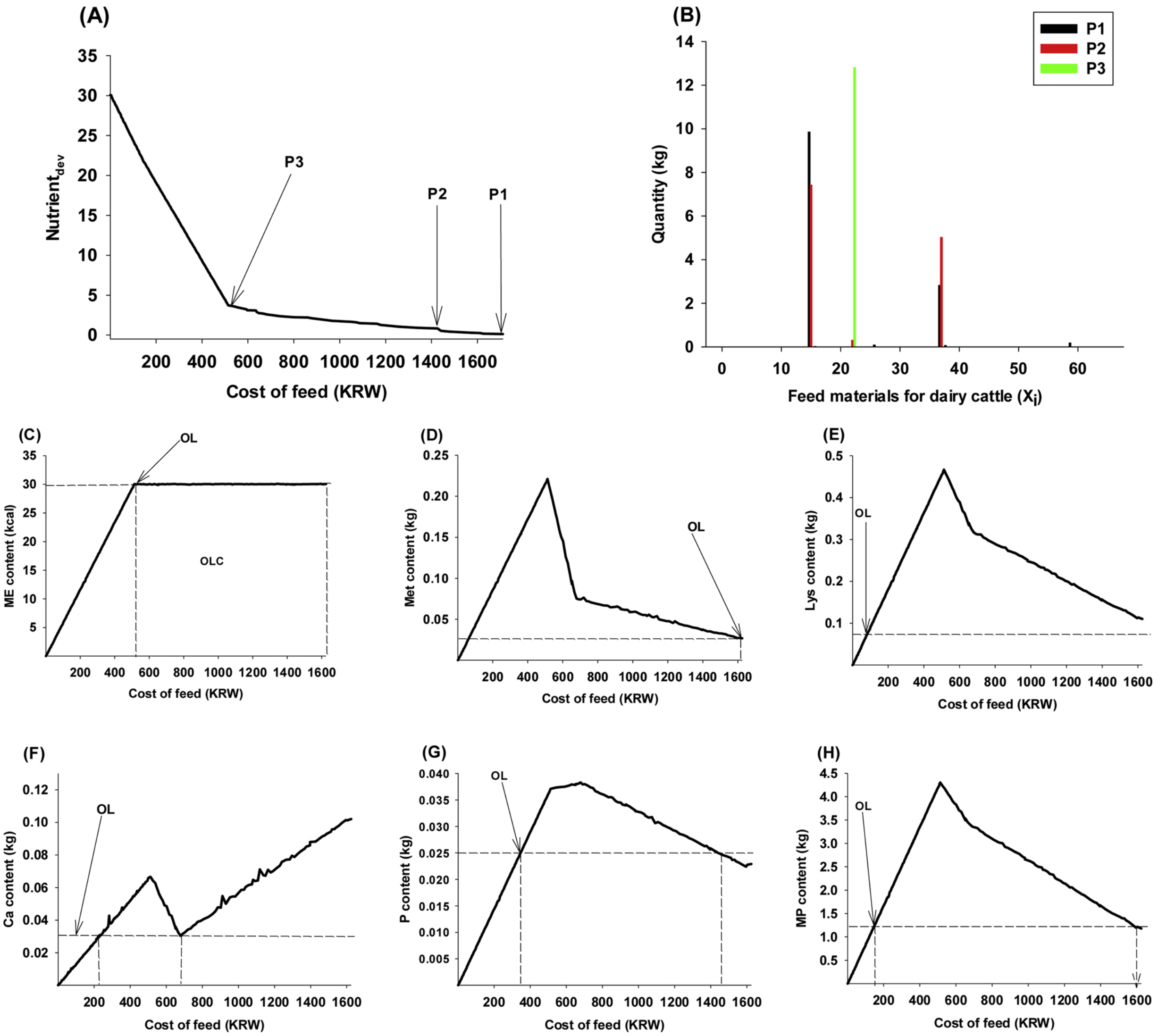

Fig. 4. Feed formulation curves for dairy cattle Case 3 (OL: Optimal Line; P1, P2, P3: Points; OLC: Optimal Line Cost; Nutrient$_{dev}$: Deviation in specified nutrients requirement).

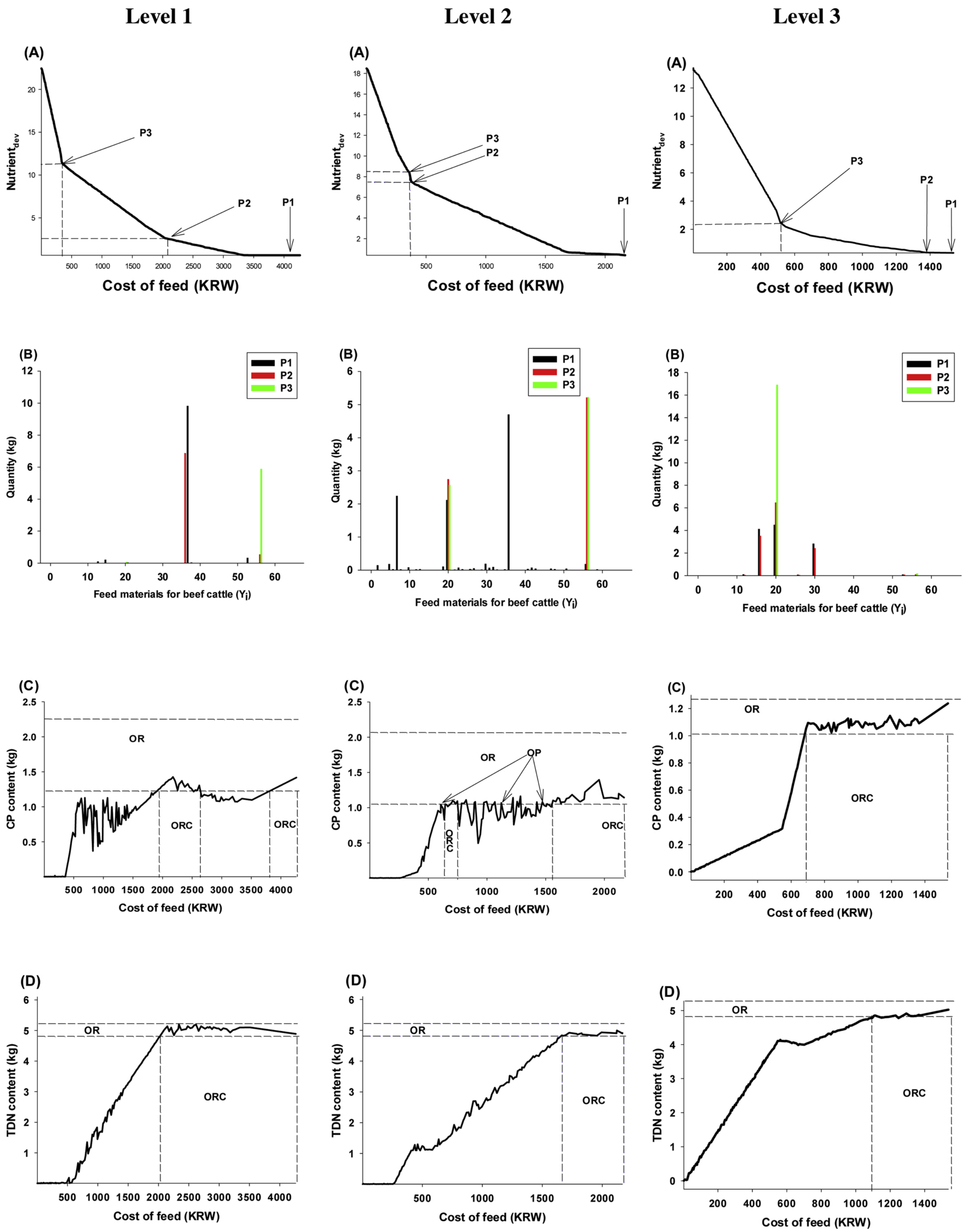

Fig. 5. Feed formulation curves for beef cattle Case 1 with each column representing the results corresponding to each of the 3 Levels considered where Levels 1, 2 and 3 are different levels of concentrates respectively. (OR: Optimal Region; P1, P2, P3: Points; ORC: Optimal Region Cost; OP: Optimal Point; Nutrient$_{dev}$: Deviation in specified nutrients requirement).

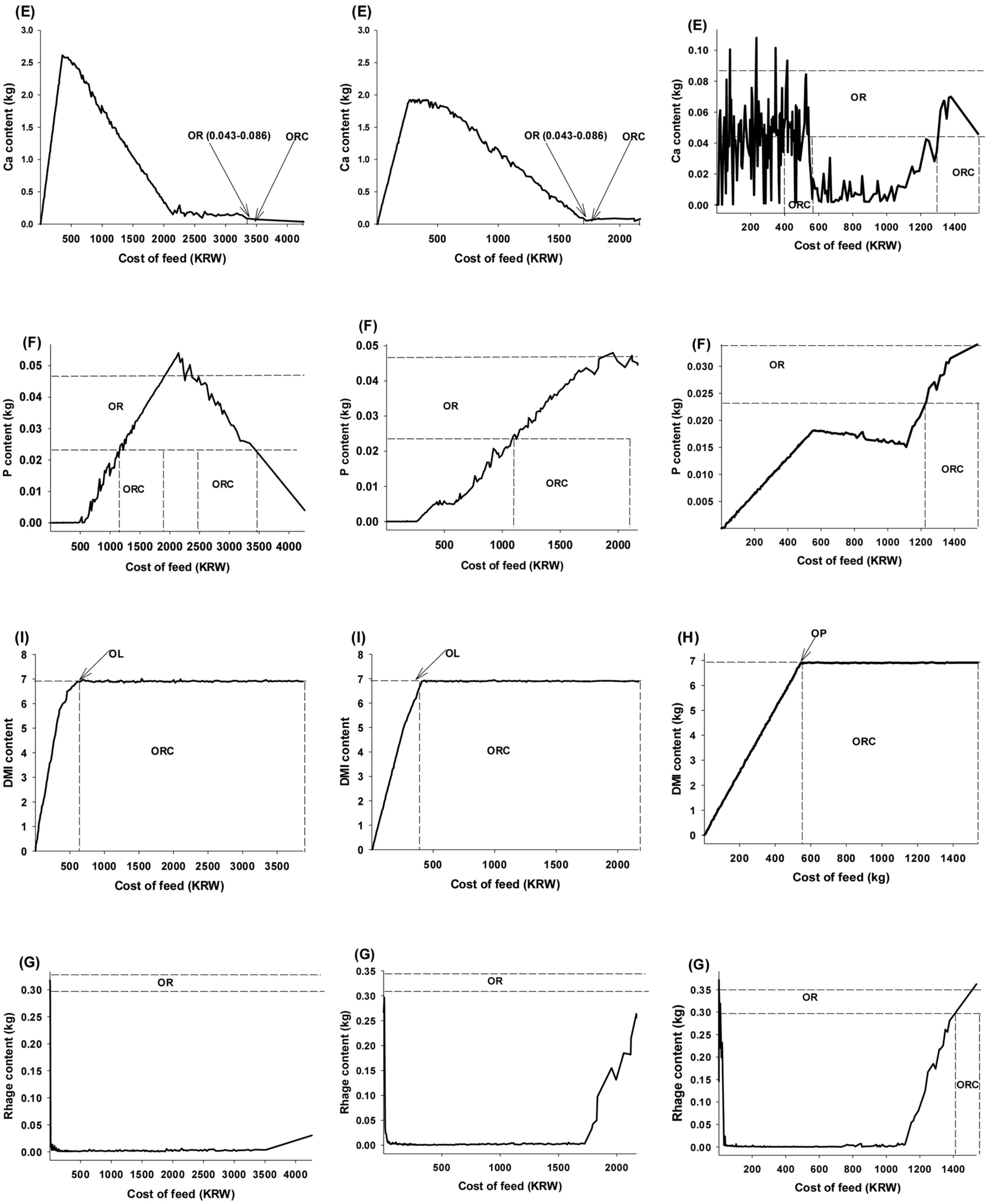

Fig. 5. (*continued*)

in Table 2. Fig. 5 shows the simulated results obtained for 3 Levels of Conc. for the first stage of beef cattle (Case 1) in Republic of Korea.

Each column in Fig. 5 represents the results corresponding to each of the 3 Levels considered. The specified optimal satisfaction regions are denoted with OR and the optimal region cost is denoted with ORC.

Level 1 represents the recommended nutrients and feed types for the beef cattle by the Rural Development Administration of the

Republic of Korea. In Level 1, all specified requirements were satisfied at P1 except for Rhage which was not possible at any feed cost. Moving leftwards to P2, specified CP, TDN, P, and DMI (Fig. 5, Level 1(C), (D), (F) and (I) were satisfied with Ca (Fig. 5, Level 1(E) and Conc. (Fig. 5, Level 1(H)) deviating from the specified values while only recommended Ca (Fig. 5, Level 1E) was met at P3 (Fig. 5, Level 1(A)). In Fig. 5B, the dominant materials selected at P1 and P2 was corn gluten feed while at P3, it was molasses. However, a higher amount of the corn gluten feed was selected at P1 than P2. This could be attributed to the molasses substituting for deficient nutrients at P2. Also, the selection of corn gluten feed with less Ca content compared to molasses at P3 led to an excess of Ca at P3 (Fig. 5, Level 1(A)). If the emphasis is on TDN, Ca, P, Conc. and DMI (Fig. 6, Level 1(D–H) and (I), the selection of P2 where these were satisfied will enable a 125% cost reduction from P1 where all the specified nutrients with exception of Rhage were met.

In Level 2, we investigated the nutrient deviation curve (Figs. 5, 2(A)) with a relaxed Conc. requirement. The results showed conflicts between Rhage and Conc. In this Case, the specified Conc. requirement by the Rural Development Administration of the Republic of Korea was reduced by 50% while the Rhage was fixed. At P1, a higher selection of brewers' grain was recorded alongside different materials (alfalfa hay, cornmeal and bakery by-products). This explains why the P1 had a better feed solution with the specified nutrient content. Multiple feed solutions with diverse nutrient contents and similar costs were recorded in Level 2 as explained in the previous section. Two solutions, (P2 and P3) were selected from this region and analyzed. For P2 and P3, 2.60 kg and 2.74 kg of brewers' grain, respectively were selected while 5.22 kg and 5.21 kg of limestone were selected for P2 and P3 in that order. However, the higher amounts of brewers' grain at P2 resulted in better costs and higher nutrients content than the P3 region. Sudan grass and corn gluten feed were selected at P1 while these were absent in the other two points. The selection of these two components

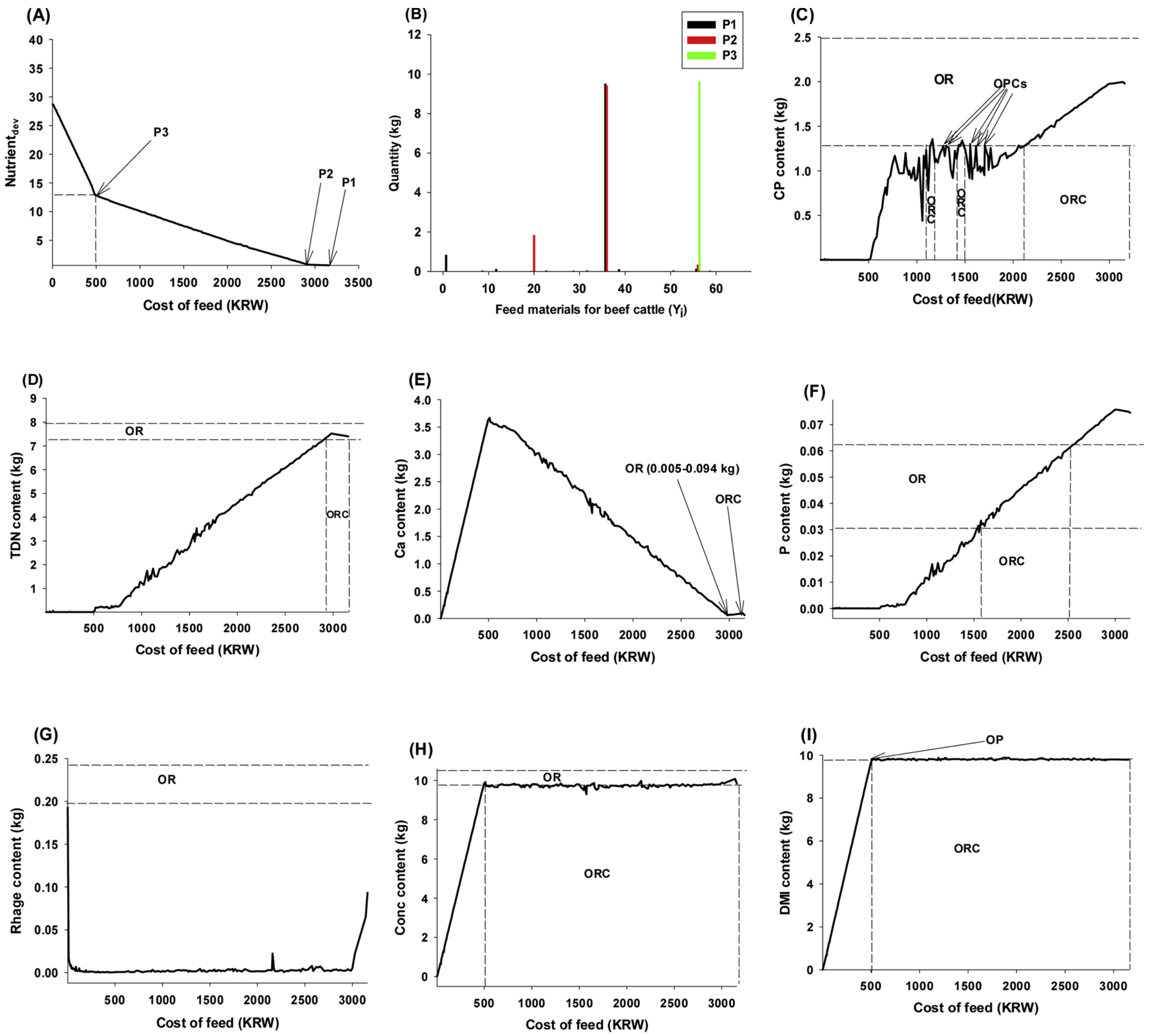

Fig. 6. Feed formulation curves for beef cattle Case 2 (OR: Optimal Region; P1, P2, P3: Points; ORC: Optimal Region Cost; OP: Optimal Point; OPC: Optimal Point Cost; Nutrient$_{dev}$: Deviation in specified nutrients requirement).

facilitated the satisfaction of the specified quantities for TDN, P and Rhage that were violated in P2 and P3.

In Level 3, a different Pareto front was obtained (Fig. 5, Level (3A)). At P1, all specified nutrient amounts were perfectly satisfied (Fig. 5, Level 3 (C-H). However, moving leftwards from P1 to P2, only the specified quantity for Rhage (Fig. 3(G)) was not met at P2. The Rhage content at P2 fell short by 0.02 kg. This shows that a 14% cost reduction can be recorded if the 0.02 kg can be tolerated. As in Level 1, only the specified amount for Ca was satisfied at P3. The results in the Level 3 further verifies the conflict between Conc. and Rhage requiring a tradeoff as recorded mostly in feed formulation (Zhang and Roush, 2002). In Level 3, various quantities of corn meal were selected at the three points (P1 to P3) because of its low cost and nutrient content compared to other by-products. Also, compared to the other low-cost by-products, it has the most TDN which is vital in cattle feed formulation. Italian ryegrass and bakery by-products were selected at P1 and P2 for balancing the ration. The lesser selection of Italian ryegrass in P2 compared to P1 led to the insufficiency in the specified Rhage requirement in P2.

From Fig. 5, it can be observed that nutritional requirements, Conc. and Rhages, conflict each other and as such, as the requirement of Conc. was relaxed (Level 1 to Level 3) finding feed formulations that satisfy the Rhages was possible. In addition, the cost of the feed at which all the requirements were met kept decreasing. That is, in Level 1, it was not possible to find a feed formulation that could satisfy all the requirements even at a cost of over 4000 KRW. However, in Level 2 and Level 3, the algorithm was able for find feed formulations that met all the requirements at the costs of approximately 2500 KRW and 1450 KRW, respectively. Comparing the 3 Levels showed that the cost of the feed formulated at Level 3 was 30% lower than Level 2 and 65% less than Level 1. Level 2 feed formulation was 50% lower than Level 1.

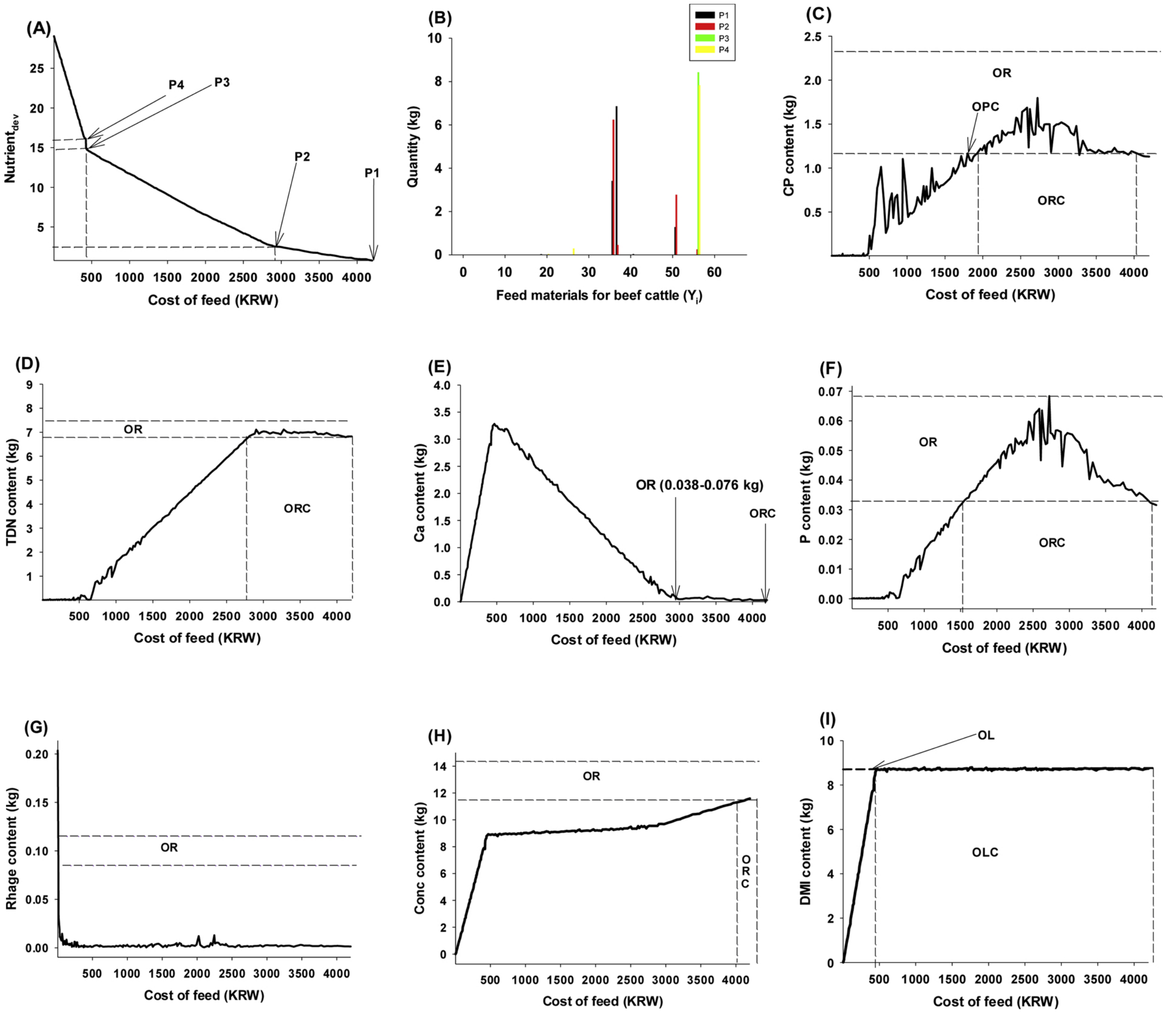

Fig. 7. Feed formulation curves for beef cattle Case 3 (OR: Optimal Region; P1, P2, P3, P4: Points; ORC: Optimal Region Cost; OP: Optimal Point; OPC: Optimal Point Cost; Nutrient$_{dev}$: Deviation in specified nutrients requirement).

3.5. Beef: case 2

P1 and P2 showed a close distance in the Pareto front with the P2 costing 13% less (Fig. 6A). However, the P2 fell short in the specified TDN (Fig. 6D) content by 0.3 kg. Even though the P1 solution for Rhage fell short of the specified by 50%, the P2 did not satisfy the specified quantity by a 100%. Also, the excess in P at P2 was better than the amount in P1. In this stage of growth (Case), 0.12 kg, 0.33 kg and 9.61 kg were selected for P1, P2 and P3 respectively. The high amount of limestone selected in P3 enabled the satisfaction of DMI (Fig. 6I) and Ca (Fig. 6E) because of the less content of water and high amount of Ca (Fig. 6E). Similar amount of corn gluten feed was selected for both P1 and P2. The selected rice straw at P1 enabled the better satisfaction of Rhage at this point compared to P2.

3.6. Beef: case 3

In Case 3 of beef cattle feed formulation, four distinct points were selected and analyzed (Fig. 7A). P1 reasonably satisfied all the specified nutrient with exception of Rhage. However, moving leftward from P1 to P2, the Conc. deviated by 18% but cost reduced by 33%. As in Case 1, Level 2, a similar trend was recorded at P3 and P4. The results in Case 3 showed that all specified nutrient satisfaction was met at P2 with exception of Conc. (Fig. 7H) and Rhage (Fig. 7G) that was not met at all the points because of the

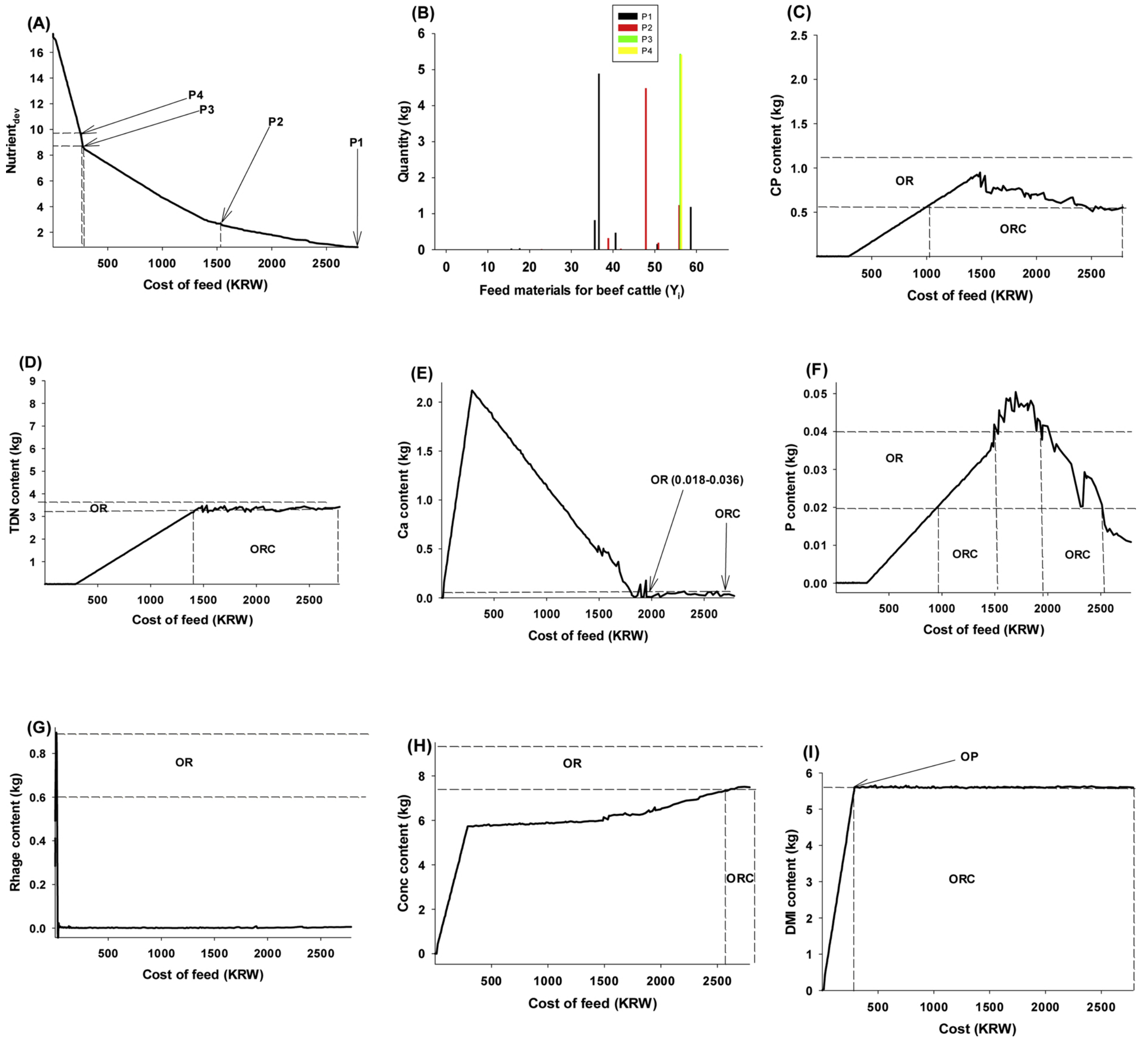

Fig. 8. Feed formulation curves for beef cattle Case 4(OR: Optimal Region; P1, P2, P3, P4: Points; ORC: Optimal Region Cost; OP: Optimal Point; Nutrient$_{dev}$: Deviation in specified nutrients requirement).

reason explained earlier in the Case 1 formulation. Various materials and quantities were selected at different points. The major materials include corn gluten feed, corn and Molasses for P2 and P1, and limestone for P2, P3 and P4.

3.7. Beef: case 4

The final case analyzed in this study for beef cattle feed formulation mimicked the Pareto front in Case 3. P1 satisfied all the recommended nutrient requirement with exception of Rhage. As in Case 2, the P2 (Fig. 8A) had satisfactory solutions except in Conc. content. (Fig. 8H) which fell short by 21%. All the points failed to meet the specified value for Rhage (Fig. 8G). As in Case 3, P3 and P4 had different solutions with slight difference in cost although both points only met the recommended DMI (Fig. 8I). Corn gluten meal, cottonseed, molasses and salt were the major materials selected at P1, soybean and wheat hull for P2 while 5.41 kg, 5.53 kg and 1.23 kg of limestone was selected for P2, P3, and P4 respectively.

4. Conclusion

In this study, the conventional feed formulation approach which is a single objective constrained problem was formulated as a multi-objective problem. The multi-objective formulation was based on observations from previous studies that – a) relaxing some of the nutritional requirements does not affect the growth or performance of the animal and b) nutritional requirement satisfaction and feed cost were sometimes conflicting. Therefore, in the proposed multi-objective feed formulation, the feed costs and the deviation of the nutrients from the specified requirements were considered as two objectives. In addition, the use of ***evolutionary*** multi-objective optimization (NSGA-II) provided the set of entire comprise solutions in a single run. The availability of the entire Pareto front helped the feed formulator to make better decisions as it provided the relationships between different nutrients and associated feed costs. The experimental simulations using different cases of dairy and beef cattle feed formulation demonstrated the applicability of the proposed framework.

Declaration of Competing Interest

The authors listed above declare that there is no conflict of interest.

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Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.anifeedsci.2019.114211.

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