Health-Aware Meal Recommendations using Contextual Multi-Armed Bandits

FCPS Case Study — Group 8

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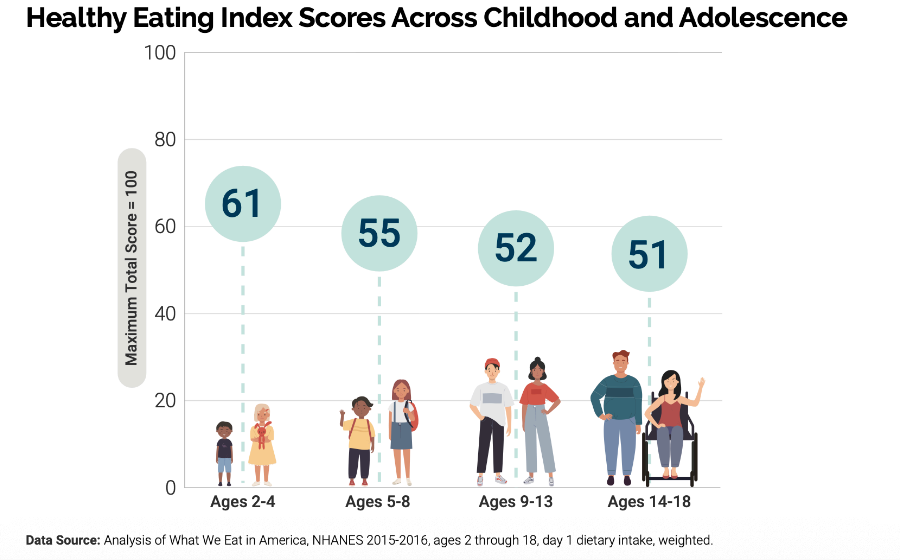
Outline

Eating Trends



Motivation

CHALLENGE

- Students missing nutritional benefits
- Static menus don't adapt to preferences

OUR VISION

- What if every school meal could be both *what kids love to eat* and *what keeps them healthy?*

SOLUTION

- Learn adaptive, data-driven meal recommendations.

Why Reinforcement Learning (RL) and CMAB?

- **Why RL?**
  - Traditional supervised models only predict outcomes from past data.
  - Meal planning, however, is an interactive problem — we choose a menu (action), observe student response (reward), and must adapt future choices.
- **Why CMAB?**
  - Each decision depends on current **context** (school, time, weekday) but not on future states.
  - CMAB provides a simple, efficient RL framework for **context-aware meal recommendations**.

CMAB Framework Overview

- **Context**: school, time_of_day, day_of_week.
- **Action**: meal (`item_id`).
- **Reward**: $r_t = \text{total\_meals\_served} \times (1 + \lambda \times \text{health\_score})$
- Focus: balancing exploration and exploitation.

Sales Dataset (FCPS)

- Includes schools, timestamps, and meal details.
- **Context variables:** school, time, day, seasonality.
- **Action space:** 160+ meal items (arms).

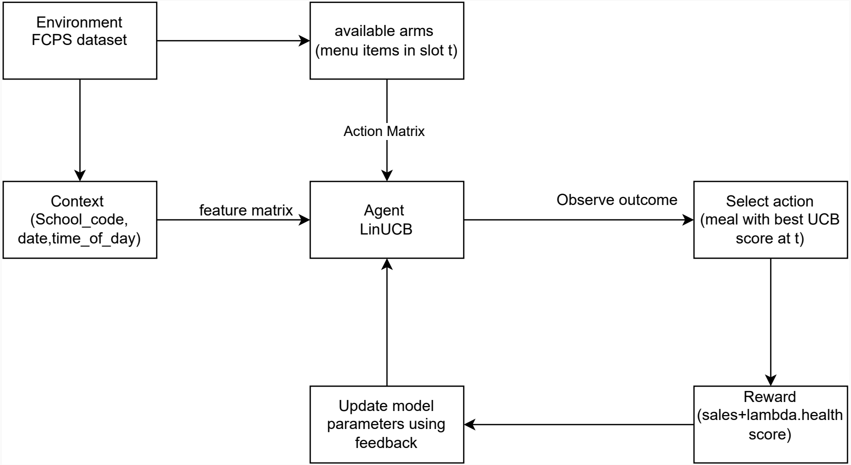
sales

time_of_day	school_code	school_name	date	item	description	total	free_meals	reduced_price_meals	full_price_meals	adults	alac_student	alac_adult	earned_student	earned_adult	earned_alac_student	earned_alac_adult	adj_alac	adj_meal
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	1146	CEREAL MEAL	19	3	0	16	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	1164	BAGEL W/CREAM CHEESE	6	0	0	6	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	1310	ALC BREAKFAST ENTREE	11	0	0	0	0	11	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	151	CEREAL/ NO MILK	13	0	0	0	0	13	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	188	$1.00 WATER 16.9oz	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	600	ALC VEGETABLE/FRUIT	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/03/2025	717	ALCJUICE 4OZ $.75	44	0	0	0	0	44	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	1146	CEREAL MEAL	17	1	0	16	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	1234	MANDARIN PARFAIT	2	0	0	2	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	1310	ALC BREAKFAST ENTREE	5	0	0	0	0	5	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	1406	TURKEY & CHEESE ON BISCUIT	1	0	0	1	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	1421	BLUEBERRY BREAD W/ STRING CHEESE	6	0	0	6	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	151	CEREAL/ NO MILK	13	0	0	0	0	13	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	188	$1.00 WATER 16.9oz	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	600	ALC VEGETABLE/FRUIT	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	700	ALC MILK	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/04/2025	717	ALCJUICE 4OZ $.75	42	0	0	0	0	42	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	1146	CEREAL MEAL	19	2	0	17	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	1310	ALC BREAKFAST ENTREE	5	0	0	0	0	5	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	1406	TURKEY & CHEESE ON BISCUIT	1	0	0	1	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	1421	BLUEBERRY BREAD W/ STRING CHEESE	4	0	0	4	0	0	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	151	CEREAL/ NO MILK	15	0	0	0	0	15	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	600	ALC VEGETABLE/FRUIT	2	0	0	0	0	2	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	700	ALC MILK	1	0	0	0	0	1	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/05/2025	717	ALCJUICE 4OZ $.75	48	0	0	0	0	48	0	0	0	0	0	0	0
breakfast	17	COLVIN_RUN_ELEMENTARY	03/06/2025	1146	CEREAL MEAL	6	1	0	5	0	0	0	0	0	0	0	0	0

Data Collection Overview

- **Nutrition Data (LINQ Connect API)**
  - Obtained through scraping of the vendor's public API endpoints.
  - Provides nutritional facts for all menu items.
  - Tracks 18 nutrients per item.
  - Coverage includes 160 unique meal items.
- **Sales Data (FCPS Records)**
  - 224,536 transaction records collected.
  - Data from 187 schools across FCPS.
  - Spans over March - May 2025.

LinUCB Flow for FCPS



System Design Overview

Modules

1. `env.py` — Build required FCPS environment such as action matrix,feature matrix etc
2. `model.py` — Implements LinUCB bandit model
3. `main.py` — Trains and evaluates the system
4. `utils.py` — helper function

Data Flow

$$\text{Dataset} \rightarrow \text{Environment} \rightarrow \text{Model} \rightarrow \text{Results}$$

LinUCB: Upper-Confidence-Bound for Contextual Bandits

- For arm a, at time t with context $x_{t,a} \in \mathbb{R}^d$:

$$p_{t,a} = \theta_a^\top x_{t,a} \; + \; \alpha\sqrt{x_{t,a}^\top A_a^{-1} x_{t,a}}$$

- Balances exploitation (expected reward $\theta_a^\top x_{t,a}$) and exploration (uncertainty term).
- Each arm maintains:
  - $A_a = \sum_{\tau=1}^{t-1} x_{\tau,a} x_{\tau,a}^\top + \lambda I_d$ (regularized covariance matrix)
  - $b_a = \sum_{\tau=1}^{t-1} x_{\tau,a} y_{\tau,a}$ (reward observations)
  - $\theta_a = A_a^{-1} b_a$ (ridge regression solution)

Training & Lifecycle

- `train()`: iteratively selects meals, observes rewards, updates model.
- `action()`: chooses arm maximizing UCB.
- `update()`: applies observed reward to statistics.
- `reset()` & `save()`: manage experiment lifecycle and persistence.

Health Score (NRF9.3 Index)

- **Good Nutrients (Encouraged):** Protein, Dietary Fiber, Vitamin D, Calcium, Iron, Potassium, Vitamin A, Vitamin C.
- **Bad Nutrients (To Limit):** Added Sugars, Saturated Fat, Sodium.
- **Formula:**

$$\text{NRF9.3} = \sum(\%\text{DV}_{\text{good}}) - \sum(\%\text{DV}_{\text{bad}})$$

- **Normalization:** Raw NRF9.3 scores are scaled to a standardized range (0–10) for comparability across meals and school groups.
- **Daily Values (DV):** Adjusted per school level (Elementary, Middle, High School) based on USDA dietary guidelines.
- Enables data-driven evaluation of meal health quality using the NRF9.3 framework.

Features

For a particular date t, we restrict our selection of menu items to only those that were actually served (mask):

$$\mathcal{A}_t \leftarrow \{\text{Cereal}, \text{Apples}, \text{Juice}\}$$

For each available item $a \in \mathcal{A}_t$, we construct feature vectors $\mathbf{x}_{t,a}$ that include nutritional, popularity and school related information:

$$\mathbf{x}_{t,a} = \begin{bmatrix} p \in \mathbb{R} \leftarrow \text{protein grams (one serving)} \\ c \in \mathbb{R} \leftarrow \text{carbohydrate grams (one serving)} \\ f_a \in \mathbb{R} \leftarrow \text{fats grams (one serving)} \\ f_i \in \mathbb{R} \leftarrow \text{fiber grams (one serving)} \\ s \in \mathbb{R} \leftarrow \text{sugar grams (one serving)} \\ h \in \mathbb{N} \leftarrow \text{historical sales count} \\ g \leftarrow \text{grade level} \\ d \leftarrow \text{day of week} \\ \vdots \end{bmatrix}$$

FeatureMatrix

feature_matrix

time_slot_id	item	item_idx	GramsPerServing	Calories	Protein	Total Carbohydrate	Dietary Fiber	Total Sugars	Added Sugars	Total Fat	Saturated Fat	Trans Fat	Cholesterol	Sodium	Vitamin D (D2 + D3)	Calcium	Iron	Potassium	Vitamin A	Vitamin C
66	CEREAL MEAL	35	56.0	230.0	3.0	46.0	2.0	12.0	12.0	5.0	1.0	0.0	0.0	320.0	2.0	100.0	15.0	0.0	500.0	6.0
66	BAGEL W/CREAM CHEESE	20	82.3495	240.0	7.0	37.0	1.0	5.0	1.0	7.0	4.0	0.0	20.0	400.0	0.0	62.0	2.0	10.0	0.0	0.0
66	ALC BREAKFAST ENTREE	7	110.97279	130.0	4.0	23.0	2.0	3.0	2.0	1.0	0.0	0.0	0.0	140.0	0.0	48.0	1.0	71.0	7.0	6.0
66	CEREAL/ NO MILK	36	56.0	235.0	3.0	46.0	2.0	12.0	12.0	5.0	1.0	0.0	0.0	335.0	2.0	100.0	15.0	0.0	500.0	6.0
66	$1.00 WATER 16.9oz	1	100.0	100.0	1.0	17.0	2.0	4.0	1.0	0.0	0.0	0.0	0.0	10.0	0.0	188.0	2.0	73.5	6.0	3.0
66	ALC VEGETABLE/FRUIT	12	127.194756	240.0	16.0	31.0	4.0	3.0	0.5	5.0	0.0	0.0	0.0	363.0	0.0	36.0	3.0	281.0	160.0	37.0
66	ALCJUICE 4OZ $.75	13	119.91839	60.0	0.0	15.0	0.0	13.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	14.5	0.0	200.0	0.0	36.0
446	CEREAL MEAL	35	56.0	230.0	3.0	46.0	2.0	12.0	12.0	5.0	1.0	0.0	0.0	320.0	2.0	100.0	15.0	0.0	500.0	6.0
446	MANDARIN PARFAIT	93	334.0135	258.0	7.0	56.0	3.0	36.0	16.0	2.0	0.0	0.0	3.0	63.0	3.0	308.0	2.0	478.0	1696.0	68.0
446	ALC BREAKFAST ENTREE	7	110.97279	130.0	4.0	23.0	2.0	3.0	2.0	1.0	0.0	0.0	0.0	140.0	0.0	48.0	1.0	71.0	7.0	6.0
446	TURKEY & CHEESE ON BISCUIT	147	204.3514	396.0	24.0	33.0	2.0	4.0	2.0	19.0	8.0	0.0	59.0	1091.0	1.0	218.0	3.0	460.0	0.0	0.0
446	BLUEBERRY BREAD W/ STRING CHEESE	29	63.0	218.0	6.0	32.0	2.0	3.0	1.0	9.0	3.0	0.0	20.0	200.0	0.0	198.0	1.0	74.0	155.0	6.0
446	CEREAL/ NO MILK	36	56.0	235.0	3.0	46.0	2.0	12.0	12.0	5.0	1.0	0.0	0.0	335.0	2.0	100.0	15.0	0.0	500.0	6.0
446	$1.00 WATER 16.9oz	1	100.0	100.0	1.0	17.0	2.0	4.0	1.0	0.0	0.0	0.0	0.0	10.0	0.0	188.0	2.0	73.5	6.0	3.0
446	ALC VEGETABLE/FRUIT	12	127.194756	240.0	16.0	31.0	4.0	3.0	0.5	5.0	0.0	0.0	0.0	363.0	0.0	36.0	3.0	281.0	160.0	37.0
446	ALC MILK	11	226.796	110.0	9.0	13.0	0.0	12.0	0.0	0.0	0.0	0.0	5.0	130.0	3.0	310.0	0.0	410.0	155.0	0.0
446	ALCJUICE 4OZ $.75	13	119.91839	60.0	0.0	15.0	0.0	13.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	14.5	0.0	200.0	0.0	36.0
826	CEREAL MEAL	35	56.0	230.0	3.0	46.0	2.0	12.0	12.0	5.0	1.0	0.0	0.0	320.0	2.0	100.0	15.0	0.0	500.0	6.0
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826	BLUEBERRY BREAD W/ STRING CHEESE	29	63.0	218.0	6.0	32.0	2.0	3.0	1.0	9.0	3.0	0.0	20.0	200.0	0.0	198.0	1.0	74.0	155.0	6.0
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826	ALC VEGETABLE/FRUIT	12	127.194756	240.0	16.0	31.0	4.0	3.0	0.5	5.0	0.0	0.0	0.0	363.0	0.0	36.0	3.0	281.0	160.0	37.0
826	ALC MILK	11	226.796	110.0	9.0	13.0	0.0	12.0	0.0	0.0	0.0	0.0	5.0	130.0	3.0	310.0	0.0	410.0	155.0	0.0
826	ALCJUICE 4OZ $.75	13	119.91839	60.0	0.0	15.0	0.0	13.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	14.5	0.0	200.0	0.0	36.0
1206	CEREAL MEAL	35	56.0	230.0	3.0	46.0	2.0	12.0	12.0	5.0	1.0	0.0	0.0	320.0	2.0	100.0	15.0	0.0	500.0	6.0
1206	MINI PANCAKES	98	85.89899	210.0	4.0	35.0	4.0	11.0	10.5	7.0	1.0	0.0	5.0	210.0	0.0	59.0	4.0	135.0	1000.0	0.0
1206	ALC BREAKFAST ENTREE	7	110.97279	130.0	4.0	23.0	2.0	3.0	2.0	1.0	0.0	0.0	0.0	140.0	0.0	48.0	1.0	71.0	7.0	6.0
1206	EGG & CHEESE ON BISCUIT	71	232.24265	522.0	23.0	55.0	3.0	6.0	2.0	23.0	9.0	0.0	18.0	1202.0	2.0	406.0	3.0	624.0	0.0	0.0
1206	CEREAL/ NO MILK	36	56.0	235.0	3.0	46.0	2.0	12.0	12.0	5.0	1.0	0.0	0.0	335.0	2.0	100.0	15.0	0.0	500.0	6.0
1206	$1.00 WATER 16.9oz	1	100.0	100.0	1.0	17.0	2.0	4.0	1.0	0.0	0.0	0.0	0.0	10.0	0.0	188.0	2.0	73.5	6.0	3.0
1206	ALCJUICE 4OZ $.75	13	119.91839	60.0	0.0	15.0	0.0	13.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	14.5	0.0	200.0	0.0	36.0
1586	CEREAL MEAL	35	56.0	230.0	3.0	46.0	2.0	12.0	12.0	5.0	1.0	0.0	0.0	320.0	2.0	100.0	15.0	0.0	500.0	6.0
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1586	BLUEBERRY MUFFIN W/ STRING CHEESE	30	59.53395	200.0	7.0	24.0	1.0	2.0	1.0	8.0	4.0	0.0	20.0	200.0	0.5	198.0	1.0	55.0	155.0	6.0
1586	MANDARIN PARFAIT	93	334.0135	258.0	7.0	56.0	3.0	36.0	16.0	2.0	0.0	0.0	3.0	63.0	3.0	308.0	2.0	478.0	1696.0	68.0
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1586	ALC VEGETABLE/FRUIT	12	127.194756	240.0	16.0	31.0	4.0	3.0	0.5	5.0	0.0	0.0	0.0	363.0	0.0	36.0	3.0	281.0	160.0	37.0

Results

```
Getting SMART recommendations using trained model...
Date: 2025-10-17, School: HERNDON_HIGH, Meal: lunch

Model loaded from src/tests/results/model_lambda_0.05.joblib
 Loaded trained model: src/tests/results/model_lambda_0.05.joblib
 Using optimal lambda balance found in training

Found 47 typically available items
TOP RECOMMENDATIONS – Using Trained Model (Optimal Balance)
================================================================================
1. SPICY CHICKEN ON BUN SECONDARY
   Sales: 224 (VERY POPULAR )
   Health: 4.3
   Model Score: 167.90 (confidence)

2. CHICKEN ON BUN SECONDARY
   Sales: 42 (Less Popular )
   Health: 4.3
   Model Score: 120.48 (confidence)

3. CHEESE STICKS W/MARINARA SECONDARY
   Sales: 107 (Popular )
   Health: 4.6
   Model Score: 116.21 (confidence)

4. PBJ POWER PACK SECONDARY
   Sales: 94 (Moderate )
   Health: 4.9
   Model Score: 96.15 (confidence)

5. CHICKEN & CHEESE QUESADILLA SECONDARY
   Sales: 68 (Moderate )
   Health: 4.7
   Model Score: 72.17 (confidence)
```

Ablation Results (Chronological)

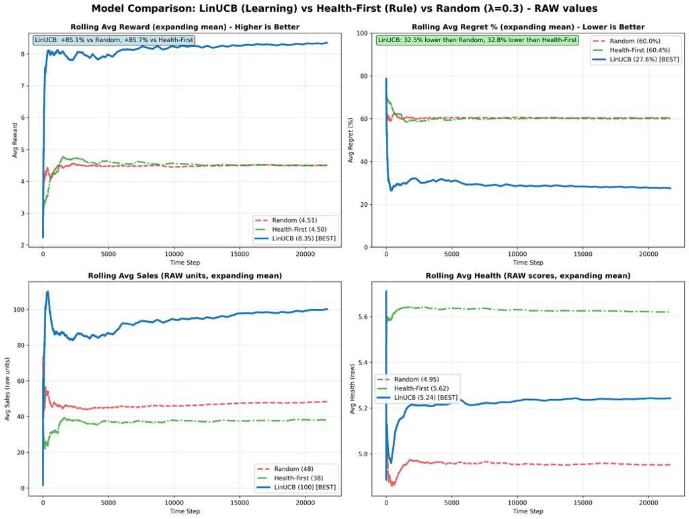
LinUCB Data Fraction Ablation (Chronological)

Fraction	Slots	Rows	Total Reward	Oracle Reward	Regret	Regret %
0.10	2,166	22,277	16,918.79	25,012.85	8,094.06	32.4%
0.20	4,332	44,699	34,074.13	49,730.29	15,656.16	31.5%
0.30	6,497	67,660	52,881.29	74,733.73	21,852.44	29.2%
0.40	8,663	90,413	71,320.84	99,779.62	28,458.78	28.5%
0.50	10,828	112,680	89,238.93	124,645.65	35,406.72	28.4%
0.60	12,994	134,919	106,523.76	149,227.04	42,703.29	28.6%
0.70	15,160	157,636	125,271.24	174,257.62	48,986.38	28.1%
0.80	17,325	180,389	143,634.66	199,184.84	55,550.18	27.9%
0.90	19,491	202,673	161,980.02	223,722.06	61,742.04	27.6%
1.00	21,656	224,536	180,809.28	248,626.74	67,817.46	27.3%

Ablation Results summary

- Percentage regret decreases consistently
- Major improvement between 10–30
- LinUCB becomes more efficient with history

Model comparision



Model Comparison Summary

Metric	LinUCB	Health-First	Random
Reward	**8.35**	4.50	4.51
Regret (%)	**27.6**	60.4	60.0
Sales	**100.18**	38.10	48.33
Health	5.24	**5.62**	4.95

Conclusion: LinUCB delivers the strongest overall trade-off between nutrition and adoption.

Conclusion

What we demonstrated

- LinUCB learns student preferences while respecting nutrition goals.
- Model performance improves consistently with data scale.

Quantitative impact

- **85.7% higher total reward** than Health-First.
- **163% increase in student engagement (sales)**.
- **54.3% reduction in regret** vs rule-based policy.
- Maintains health score within **7.2%** of optimal.

Implication

Context-aware recommendation systems enable cafeteria managers to balance nutrition and participation using data-driven decision making rather than static rules.

References

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Limitations and Future Work

Limitations

- Linear model assumption.
- Fixed reward weighting.
- Simplified nutritional scoring.

Future Directions

- Neural bandits and RL.
- Adaptive λ.

Thank You / Q&A

Questions or feedback?