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Robust Design of Controlled Environment Agriculture Systems for Venture Investment Decision-Making

Dimitri Alston, Alireza Miraliakbar, Nia Samuels
Matthew Stuber, P&W Associate Professor in Advanced Systems Engineering

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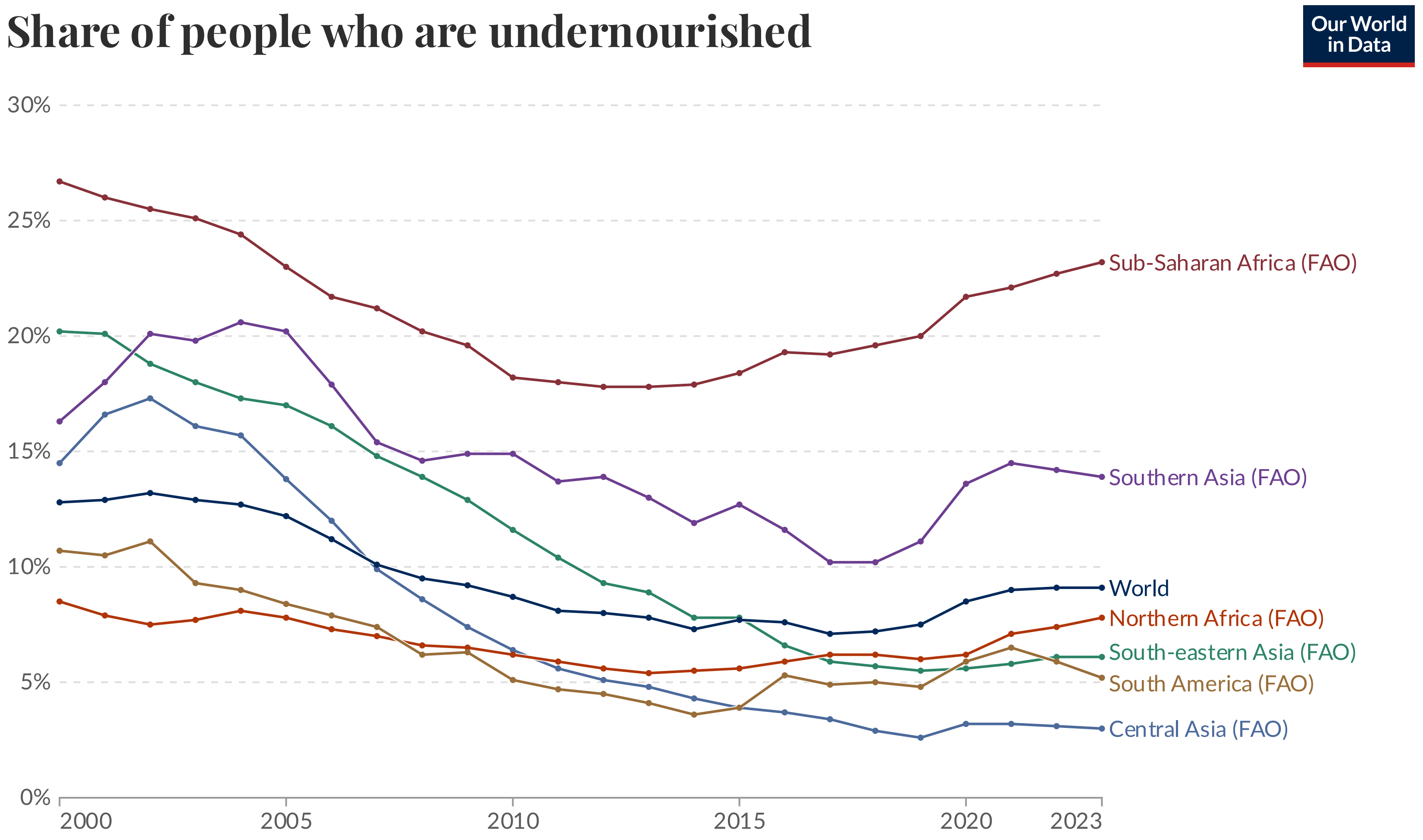
2025 AIChE ANNUAL MEETING

Process Systems and Operations Research Laboratory

Introduction



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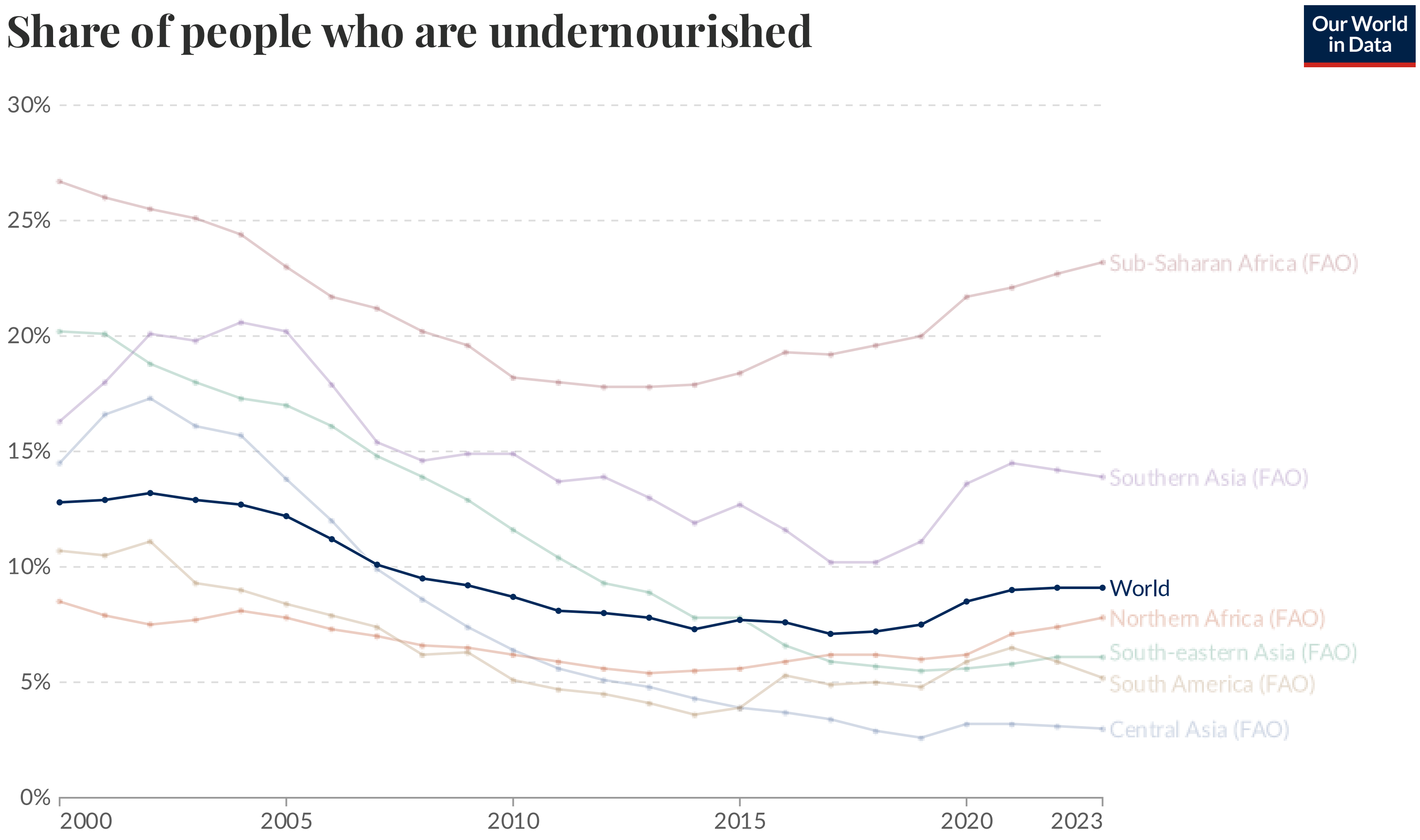

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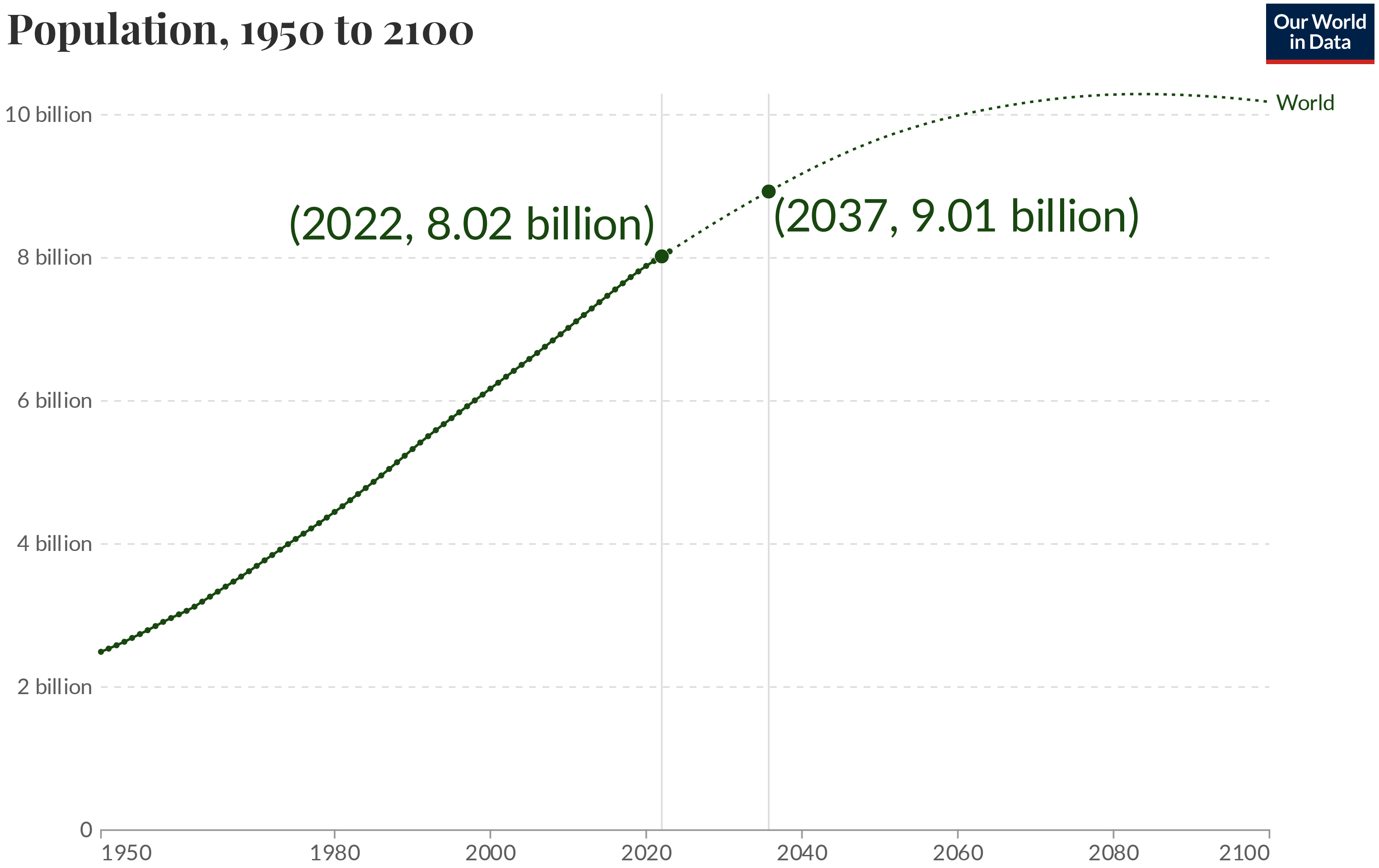

[2] Ritchie, H. et. al. “Population Growth” Published online at OurWorldinData.org. (2023) Retrieved from: 'https://ourworldindata.org/population-growth'

Introduction

Problem:

- Food insecurity is a rising issue [3]
- Current agricultural practices are not enough

Solution:

- Controlled environment agriculture (CEA)

[4]

[3] Cetegen, S.A. and Stuber, M.D. Optimal design of controlled environment agricultural systems under market uncertainty. Computers & Chemical Engineering, 149:107285, 2021. ISSN 0098-1354.
[4] https://amplifiedaginc.com/why-controlled-environment-agriculture-cea-is-mission-critical/

Agricultural Practices

Traditional Methods

[5]

- Hindered by unpredictable environmental changes [6]
- Contribute to climate change [6]
- Use a significant amount of land [6]
- Transportation spoilage [6]

CEA Systems

[4]

- Climate controlled
- Flexible location

- Have substantial operating costs [3,7]
- Venture risk [3]

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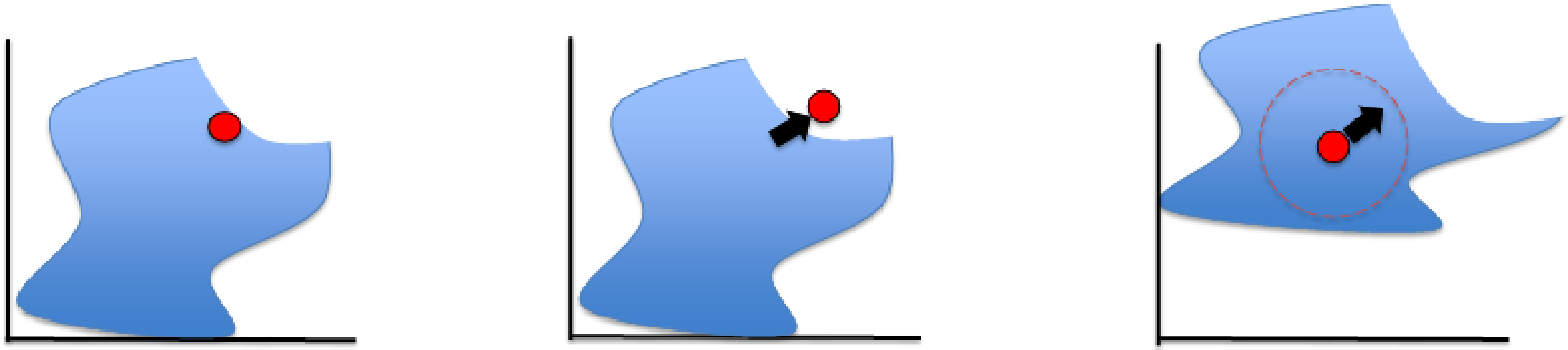
[5] https://www.dahu.bio/en/knowledge/agriculture/traditional-agriculture
[6] Food and Agriculture Organization of the United Nations (FAO). The State of Agricultural Commodity Markets - Agricultural Trade, Climate Change, and Food Security. 2018.
[7] Calvo-Baltanás, V. et al. The future potential of controlled environment agriculture. PNAS Nexus, page 078, 03 2025. ISSN 2752-106542.

Robust Optimization

- Decision-making under uncertainty
  - Account for the worst-case



Optimal design | Uncertainty realized | Robust-optimal design

Uncertainty in Agriculture

- What is uncertain?
  - Weather
  - Market prices

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$$\boxed{\text{Revenue} = \text{Yield} \times \text{Market price}}$$

Modeling CEA Systems

Cetegen & Stuber

- First documented robust optimization approach for CEA systems
- Multiple perspectives
  - Trader’s (commodities trader)
    - Modern portfolio theory
  - Grower’s (farmer)

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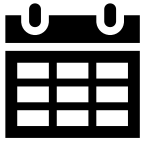

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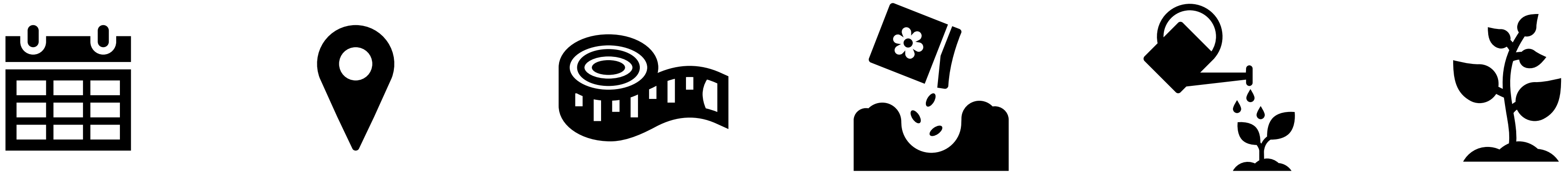

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Grower's Model

- Simultaneously find worst-case uncertainty and design and optimize it

$$f^* = \max_{\mathbf{d}\in D, \mathbf{X}\in\Xi} f_{\mathrm{NPV}}(\mathbf{d}, \mathbf{X})$$

$$\text{s.t.}\ \ \mathbf{1}^{\mathrm{T}}\mathbf{x}_j = 1,\ j = 1,\ldots,n_p$$

$$d_{z+2} = \left(\sum_{\xi=1}^{\mu} d_{\xi+2}\right)\left(\sum_{i\in\kappa_z} x_{i,j}\right),\ j = 1,\ldots,n_p,\ z = 1,\ldots,\mu$$

$$\mathbf{Qp}_{\min} \le \left(\sum_{\xi=1}^{\mu} d_{\xi+2}\right)\left(\mathbf{Y}\sum_{j=1}^{4}\mathbf{x}_{j+4(q-1)}\right) \le \mathbf{Qp}_{\max},\ q = 1,\ldots,n_y$$

$$0 \ge \max_{j\in\{1,\ldots,n_p\}} \left\{ \max_{\mathbf{M}_j\in M_j} \mathbf{x}_j^{\mathrm{T}}\mathbf{M}_j\mathbf{x}_j - t_r : \mathbf{M}_j \succeq 0,\ M_j \in \mathbb{R}^{n_c\times n_c},\ j = 1,\ldots,n_p \right\}$$

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Inner Program

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Crop allocation and capacity

$$\mathbf{Qp}_{\min} \le \left(\sum_{\xi=1}^{\mu} d_{\xi+2}\right)\left(\mathbf{Y}\sum_{j=1}^{4}\mathbf{x}_{j+4(q-1)}\right) \le \mathbf{Qp}_{\max}, \; q = 1,\ldots,n_y$$

Production limits

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Production limits

Multi-period risk exposure

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Example

- 4 crops

- 25% risk tolerance
- 30-year project horizon

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Example

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- 30-year project horizon

Optimal Capacity	26,672 sq ft.
Optimal NPV	$21.68 million
Capital Expenses	$11.5 million
Average Quarterly Operating Expenses	$5.0 million
Average Quarterly Revenue	$9.94 million

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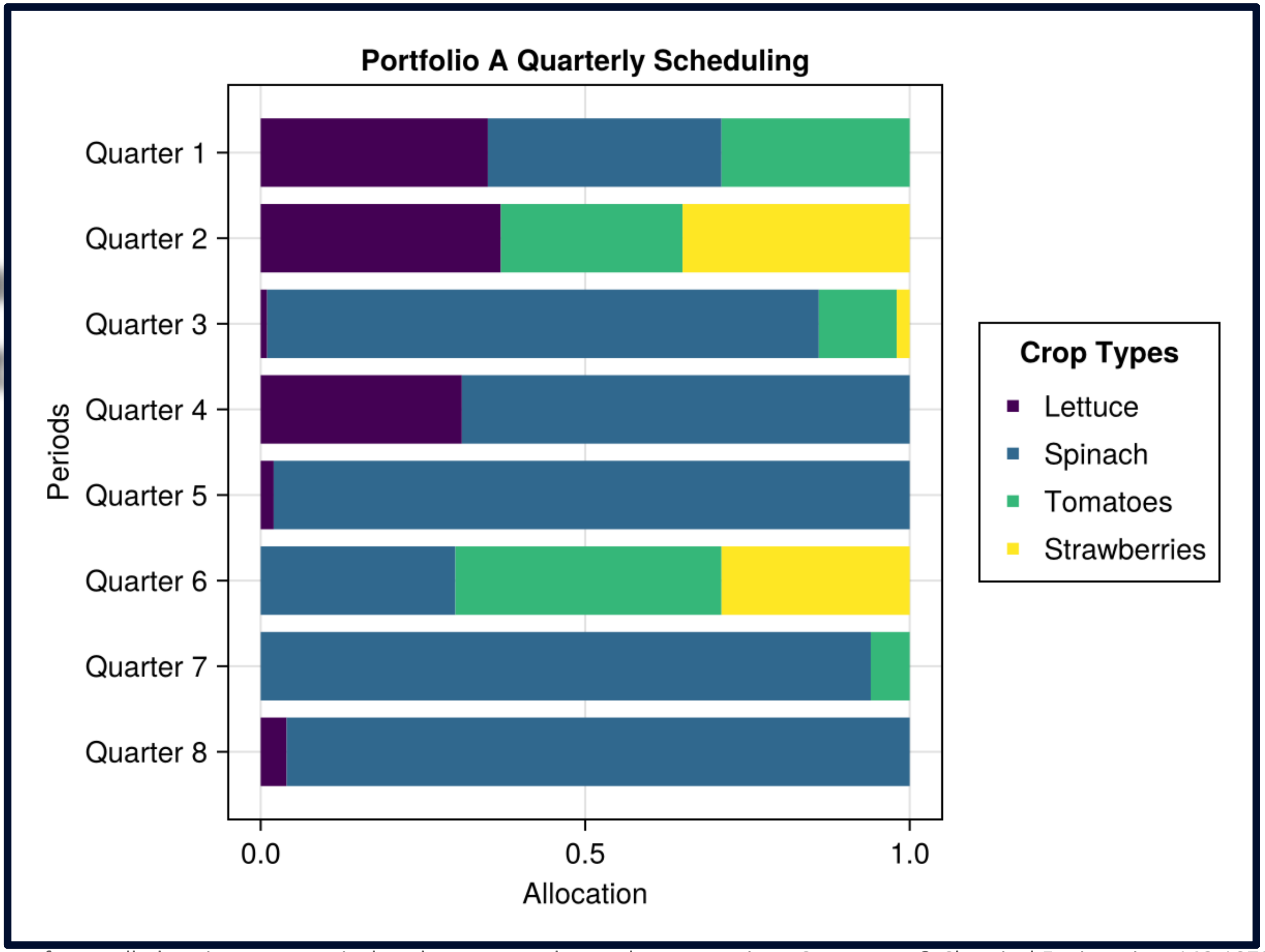

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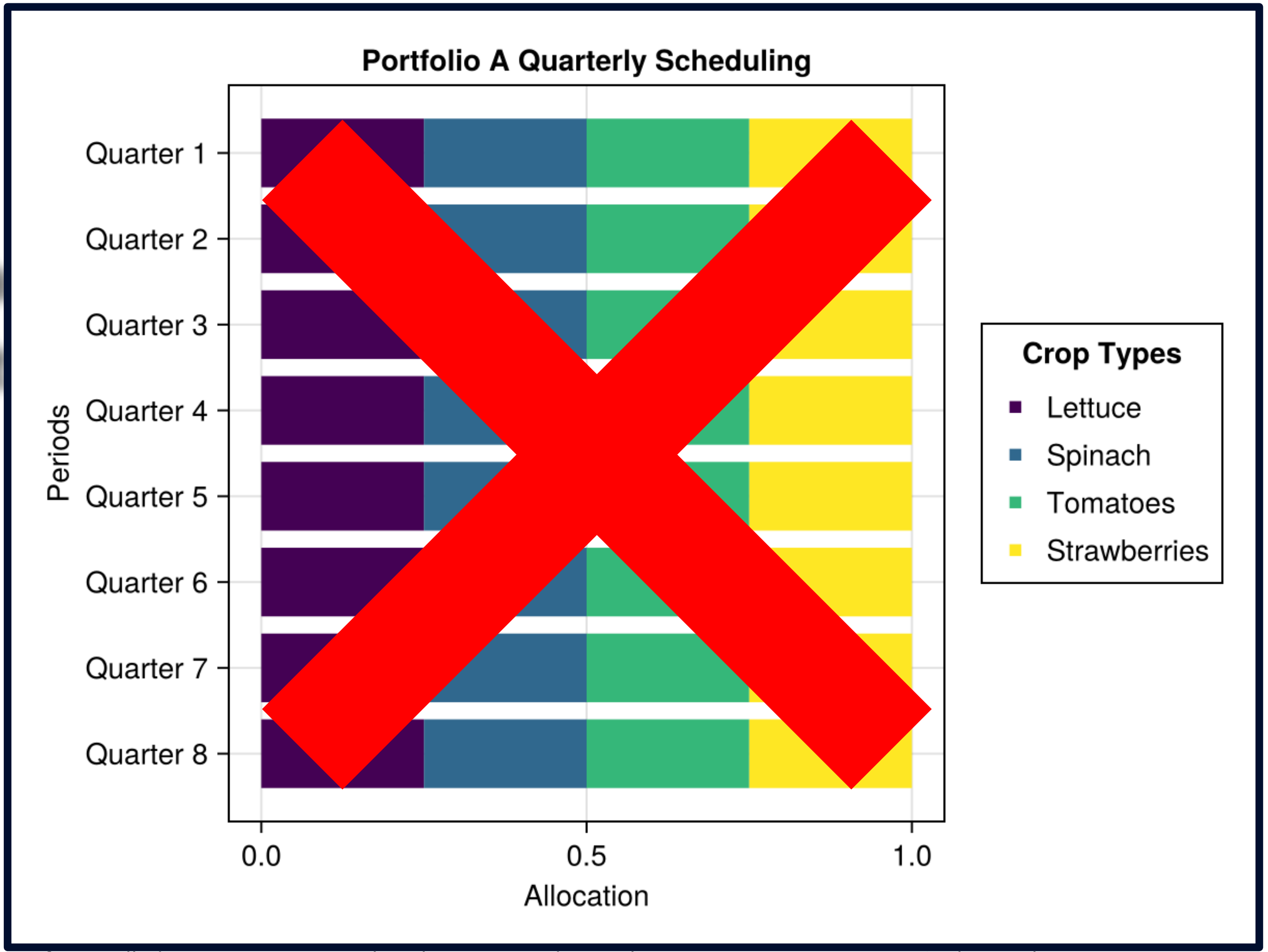

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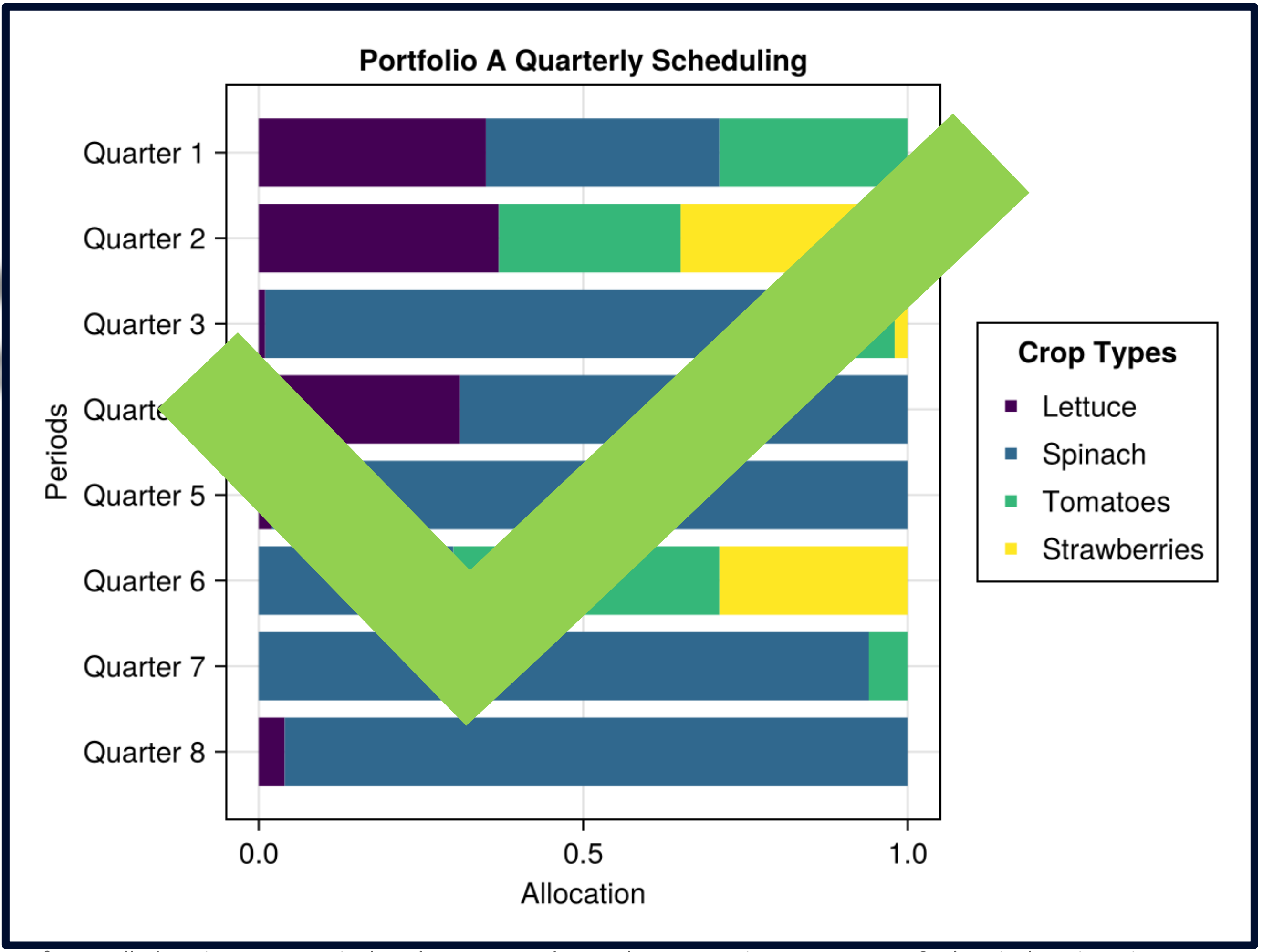

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Improvements

- Develop a more accurate model
  - Adjust grow periods

Crop	Growth Period
Lettuce	3 months
Spinach	3 months
Tomatoes	3 months
Strawberries	3 months

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Crop	Growth Period
Lettuce	1 month
Spinach	1.5 months
Tomatoes	2 months
Strawberries	2 months

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Lettuce	3 months
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Crop	Growth Period
Lettuce	1 month
Spinach	1.5 months
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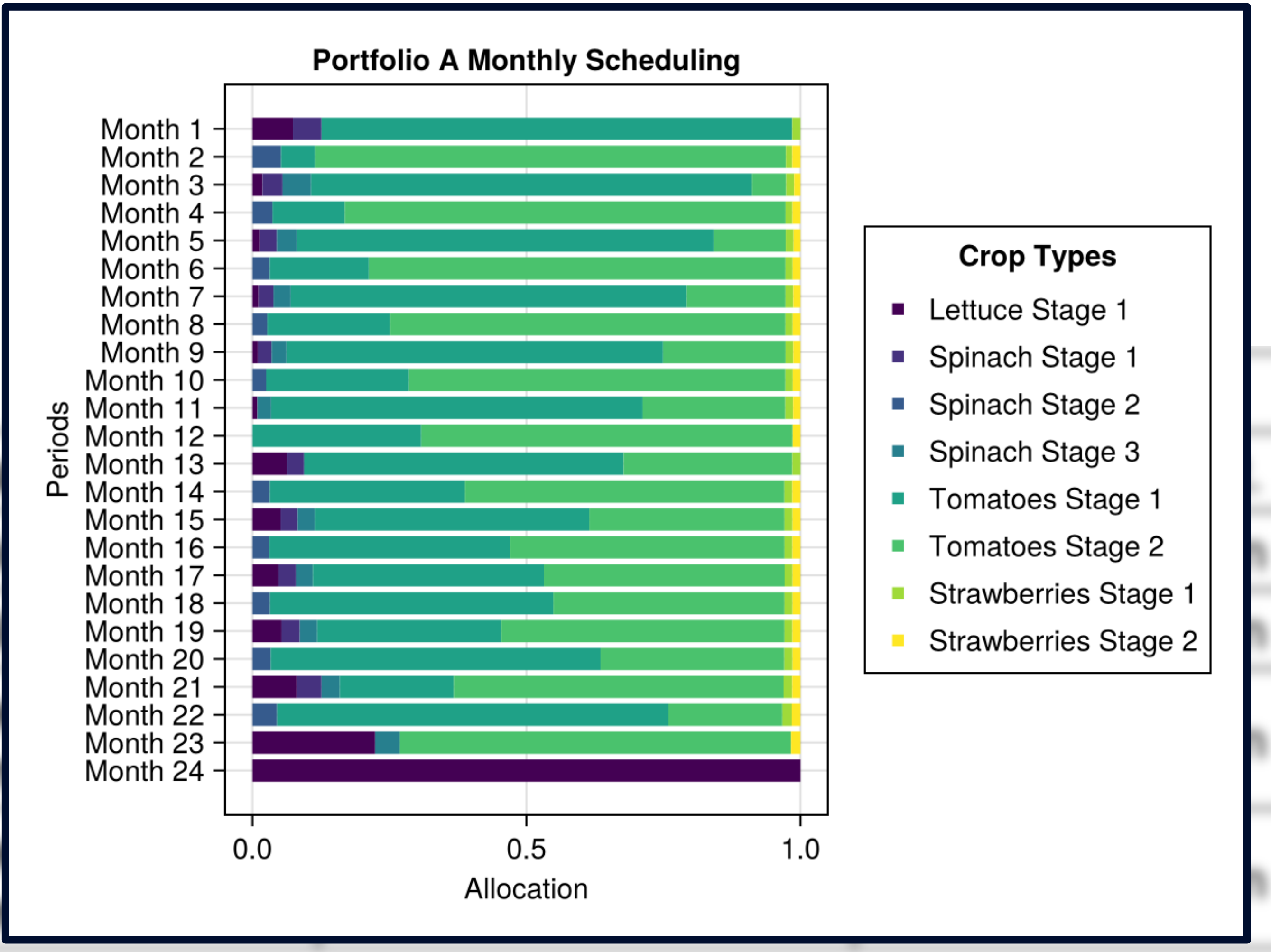
$$35 \text{ variables} \rightarrow 195 \text{ variables}$$

Example Revisited

- 4 crops

	Quarterly	Monthly
Optimal Capacity	26,672 sq ft.	70,716 sq ft.
Optimal NPV	\$21.68 million	\$14.5 million
Capital Expenses	\$11.5 million	\$27.7 million
Average Quarterly Operating Expenses	\$5.0 million	\$13.0 million
Average Quarterly Revenue	\$9.94 million	\$20.9 million

Example Revisited



CEA.jl

- Open-source software tool
- Tunable parameters
  - Number of crops
  - Grow periods
  - Project horizon
  - Tolerable risk
- Efficient
  - Uses current state-of-the-art solvers such as IPOPT, Gurobi, and EAGO

Conclusion

- CEA systems are a good supplement
  - High operating costs
  - Venture risk
- CEA.jl identifies robust-optimal solutions
  - Coming soon
- One step closer to dealing with food insecurity issues

Acknowledgements

Members of the Process Systems and Operations Research Laboratory at the University of Connecticut (https://www.psor.uconn.edu)

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Questions?

Process Systems and Operations Research Laboratory

The PSOR Laboratory at UConn develops numerical analysis methods and software for process systems engineering applications.

22 followers | University of Connecticut, Storrs, CT, ... | https://psor.uconn.edu | stuber@uconn.edu

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