Optimal Control of Greenhouse Climate using Real-World Weather Data and Evolutionary Algorithms

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Overview

- Motivation
- Integrated Greenhouse Climate Model
- Optimization using Evolutionary Algorithms
- Experiments and Results
- Summary and Future Work

Understanding the processes in the greenhouse

By development of complex models

- integrated model including
  - → greenhouse climate
  - → plant model (crop growth, yield)
  - → outside weather conditions
  - → control equipment (heating, ventilation, CO_2 injection)

- providing
  - → prediction of all inside climate conditions in a 15-60 minute time interval
  - → use for short time control tasks
    - ⇨ optimization of crop growth / yield
    - ⇨ prevention of stress

Motivation

Controlling the processes in the greenhouse

By: optimization of control

- goal: maximal yield under consideration of defined constraints

How:

- optimization of a dynamical system
- use of Evolutionary Algorithms
  - → direct and simple deployment
  - → incorporation of problem specific knowledge
  - → incorporation of constraints

Greenhouse model

Structure

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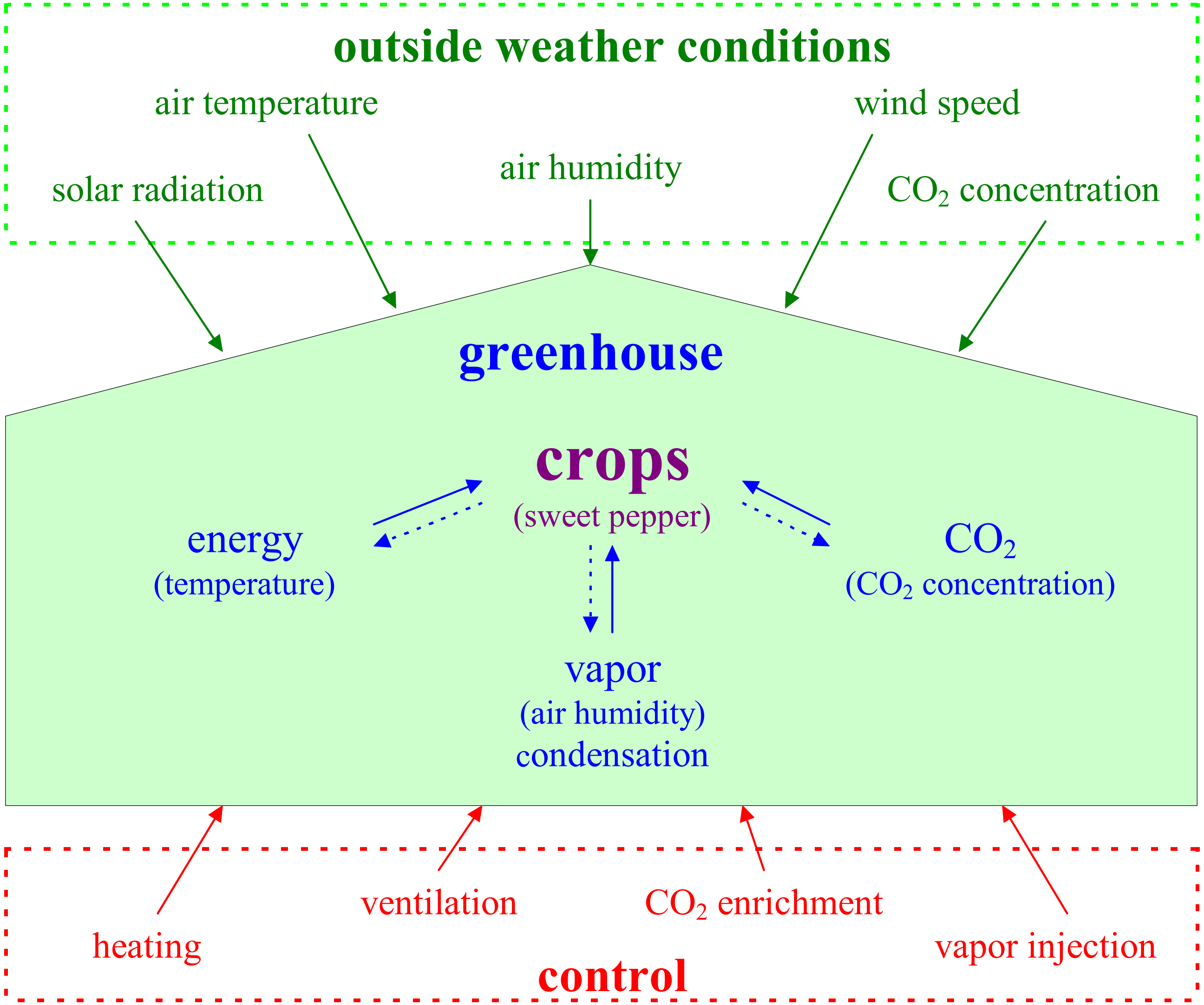
Structure of integrated greenhouse model



Simulation of the integrated model

- 4 greenhouse balance equations
  - → energy balance
  - → vapor balance
  - → CO_2 balance
  - → condensation / evaporation
- 2 plant balance equations
  - → CO_2 exchange
  - → transpiration
- yield / biomass (derived from CO_2 exchange)
- profit (yield minus control costs)

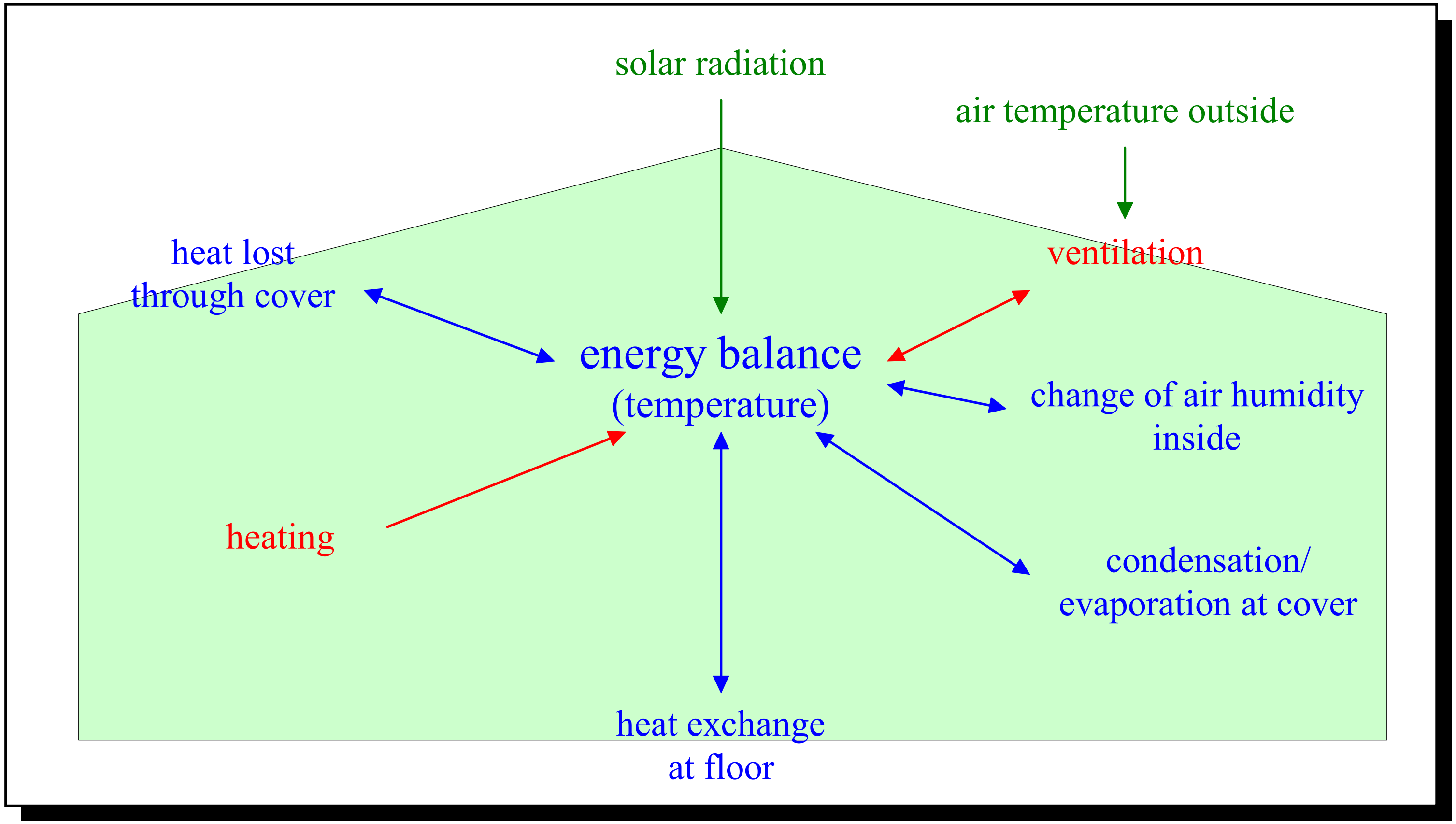
→ system of 8 first-order differential equations

- → simulated using Runge-Kutta methods of 4th(5th) order

Greenhouse model

Energy balance

Components of energy balance



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Greenhouse model

Plant model

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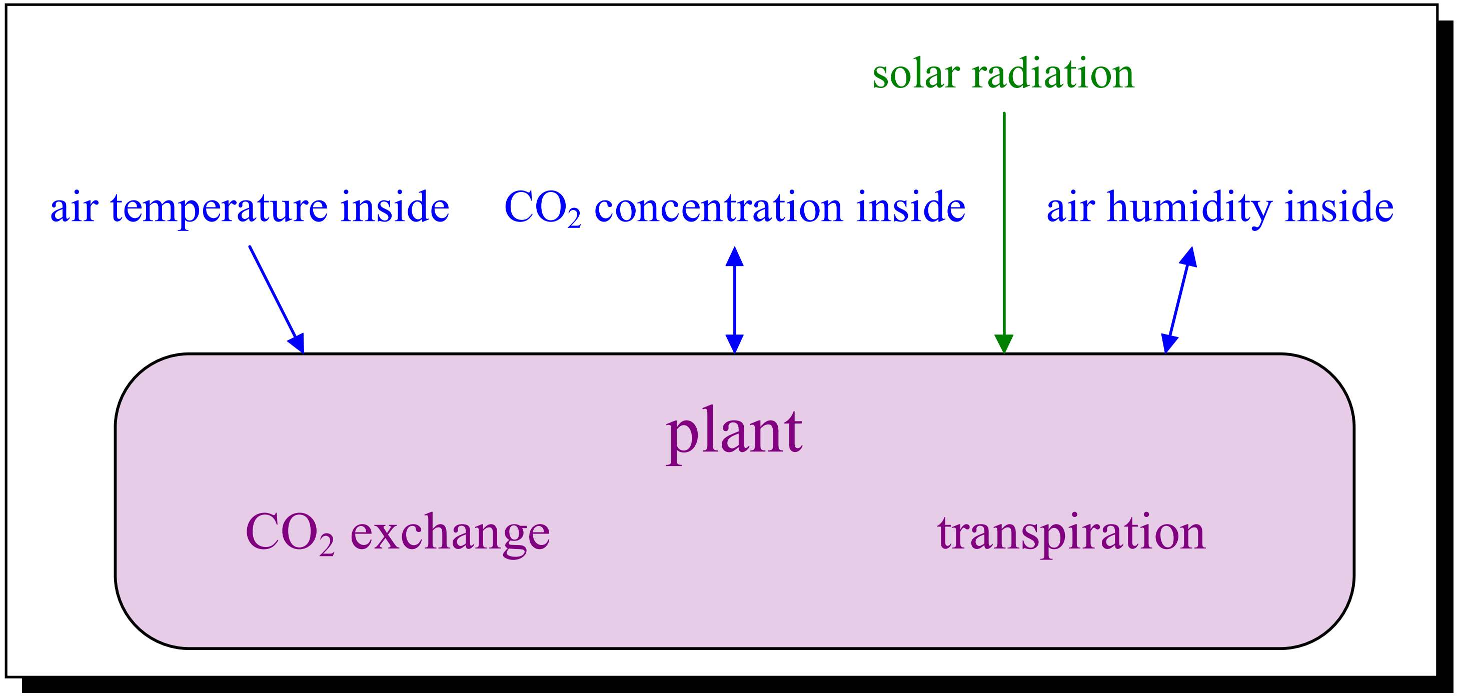
Components of plant model



- CO_2 exchange and transpiration are computed relative to standard conditions
- use of parametric equations

Motivation

- calculation of a control
  - → value of every control component over control time
  - → methods of optimization of dynamic systems
- What do we need?
  - → objective function (cost function)
  - → representation of solutions / individuals
  - → problem specific knowledge
- use of Evolutionary Algorithms
  - → straightforward application (compared to gradient methods)
  - → incorporation of problem specific knowledge
  - → incorporation of constraints

Optimization

Objective/cost function

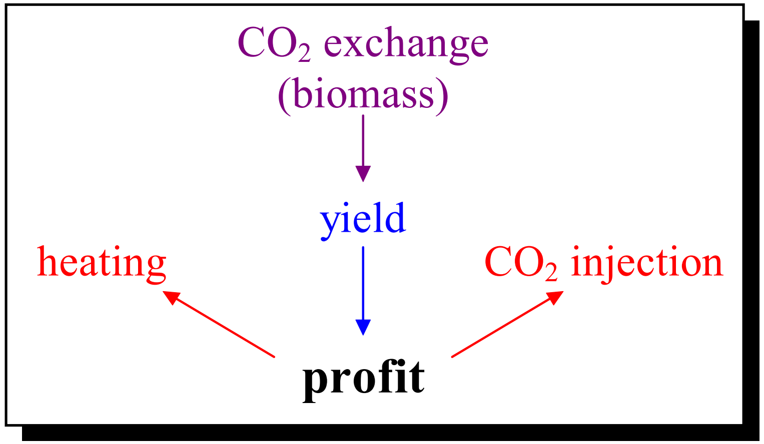
Objective function (cost function)

- maximization of profit

$$Cost = \int_{T_S}^{T_E} Profit\,dt + Penalty$$

- prevention of stress
  - → minimal/maximal temperature
  - → maximal CO_2 concentration
  - → minimal/maximal air humidity

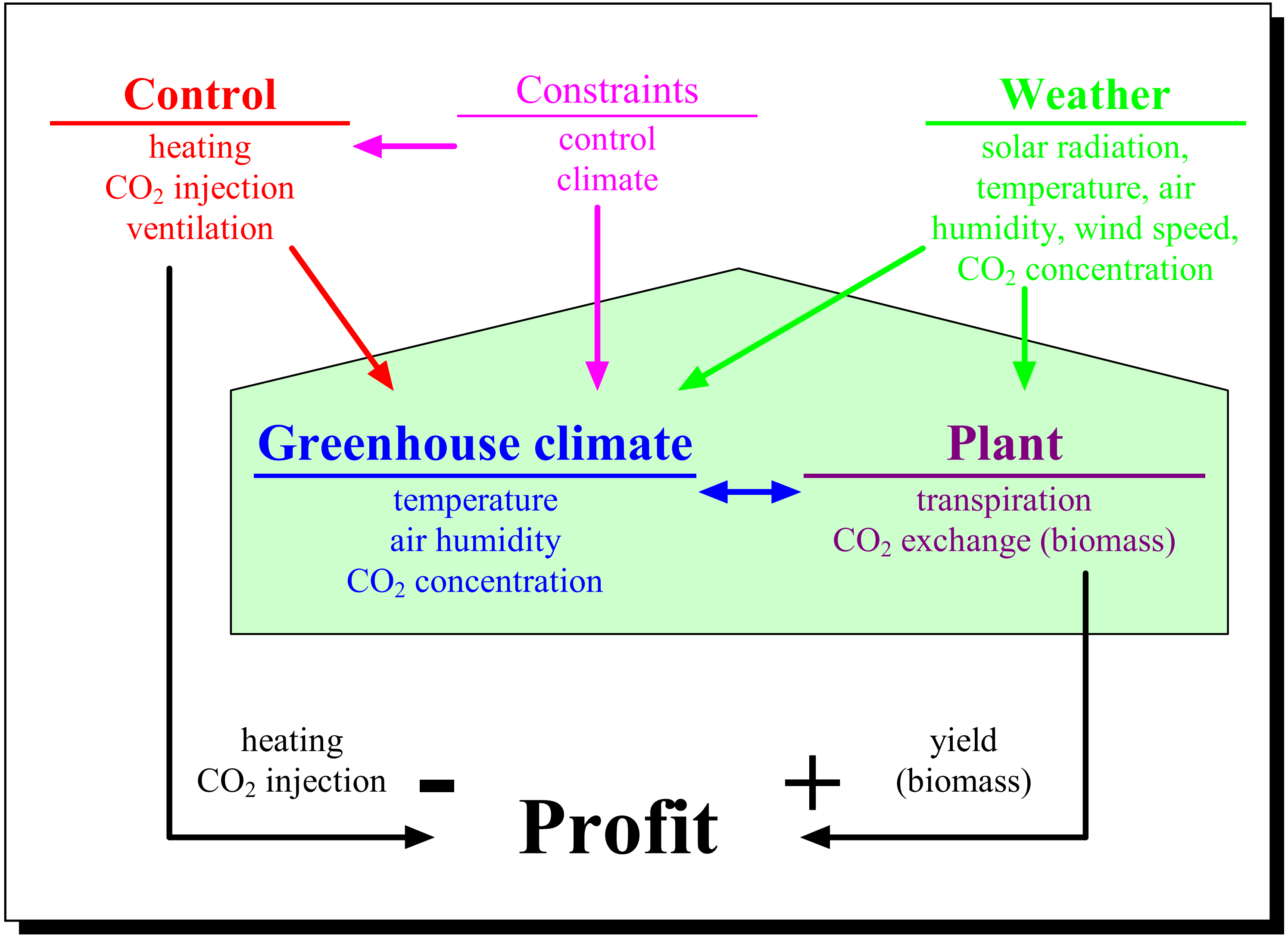
$$Penalty = \sum_{i=1}^{NumConstr} \left(W_i \cdot \int_{T_S}^{T_E} \left| \left(Val_i - Constr_i \right) > 0 \right| dt \right)$$



Optimization

Profit calculation

Interdependencies of profit calculation



Control

heating
CO_2 injection
ventilation

Constraints

control
climate

Weather

solar radiation,
temperature, air
humidity, wind speed,
CO_2 concentration

Greenhouse climate

temperature
air humidity
CO_2 concentration

Plant

transpiration
CO_2 exchange (biomass)

heating
CO_2 injection
-

Profit

+
yield
(biomass)

Optimization

Domain specific knowledge

Incorporation of domain specific knowledge

- initialization with averaged control strategies
  - → initial strategies are the result of optimization under standard (average) weather conditions
  - → good control values defined for every month and for each hour
  - → use multiple similar control strategies (previous / following months)
- changing domain of control variables
  - → restrict domain of control variables depending on time of year
    - ⇨ during winter heating is high, ventilation is low,
    - ⇨ during summer ventilation is higher than during winter, ...
  - → and time of day
    - ⇨ during night heating is higher than during day,
    - ⇨ during night ventilation is lower than during day, ...

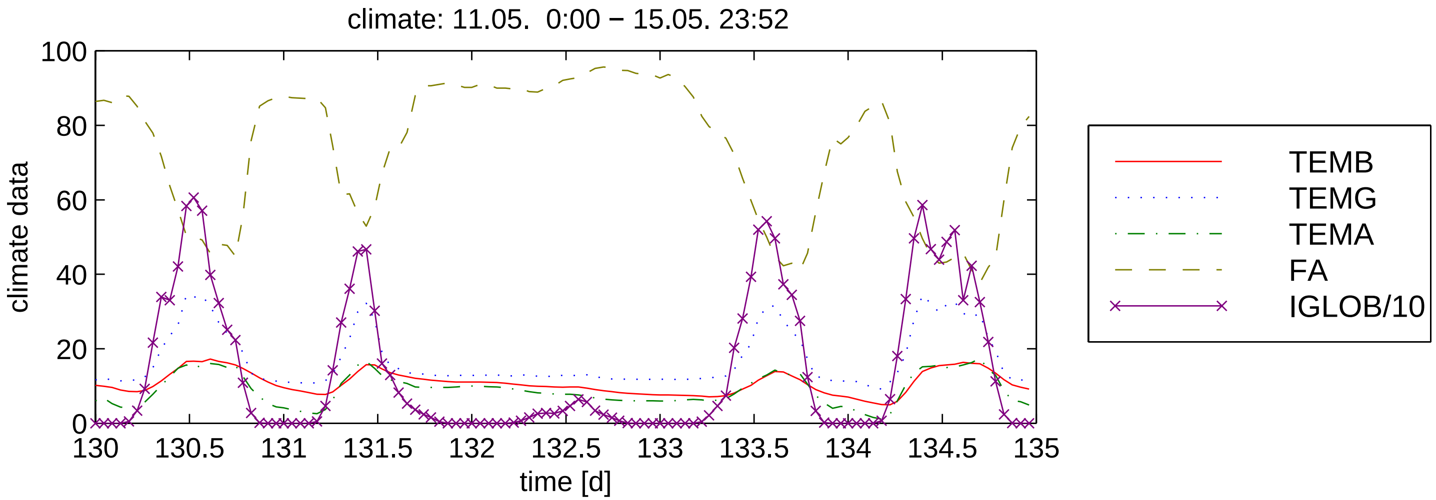
Experiments

Weather data

Results under real world weather conditions

- optimization for 5 consecutive days in May 1995
- weather data of Großbeeren (Berlin), 1995

Weather data used



TEMB: floor temperature
TEMG: cover temperature
TEMA: air temperature outside
FA: air humidity outside
IGLOB: solar radiation

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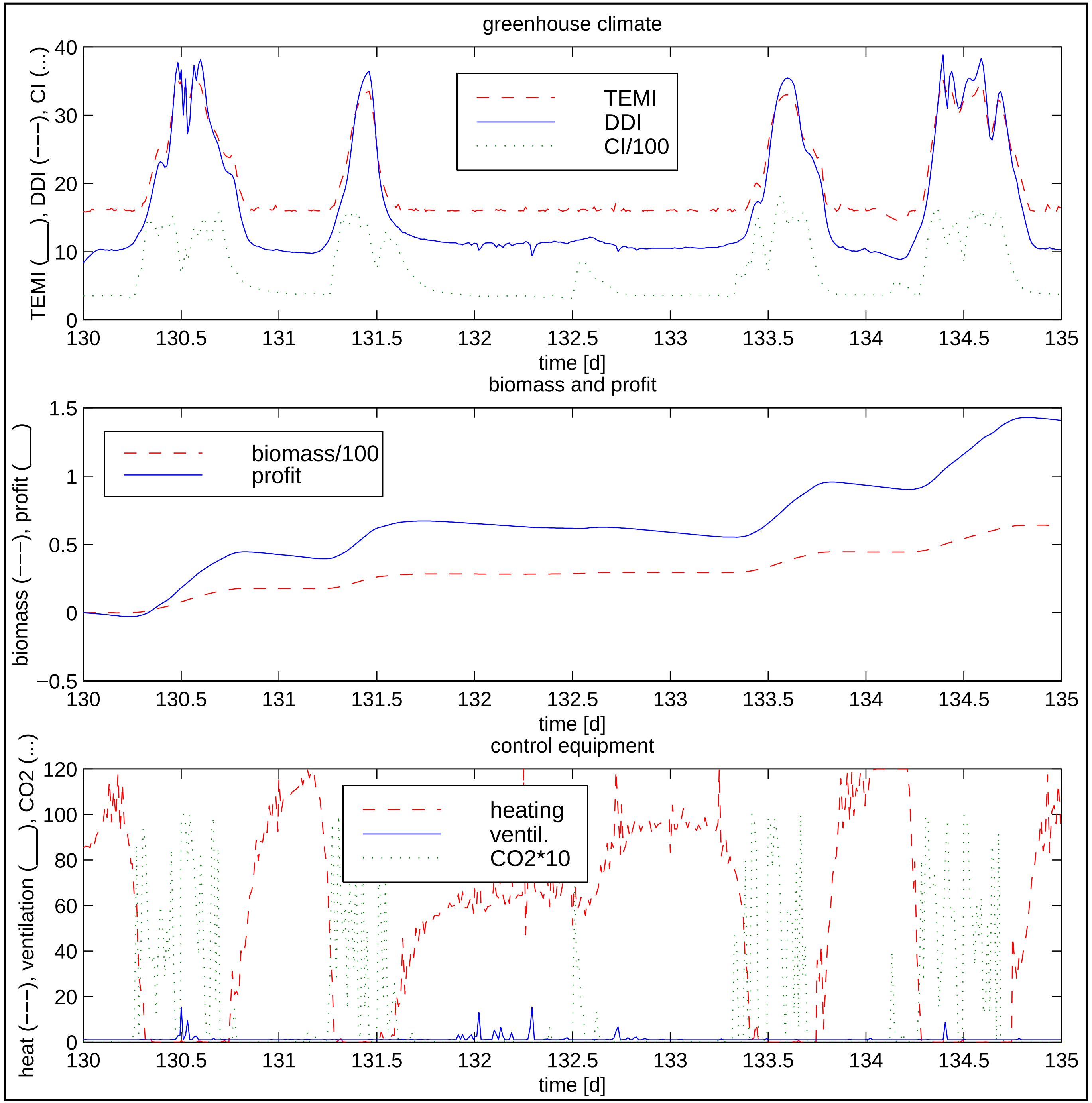
Experiments

Results



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Optimization

Evolutionary Algorithms

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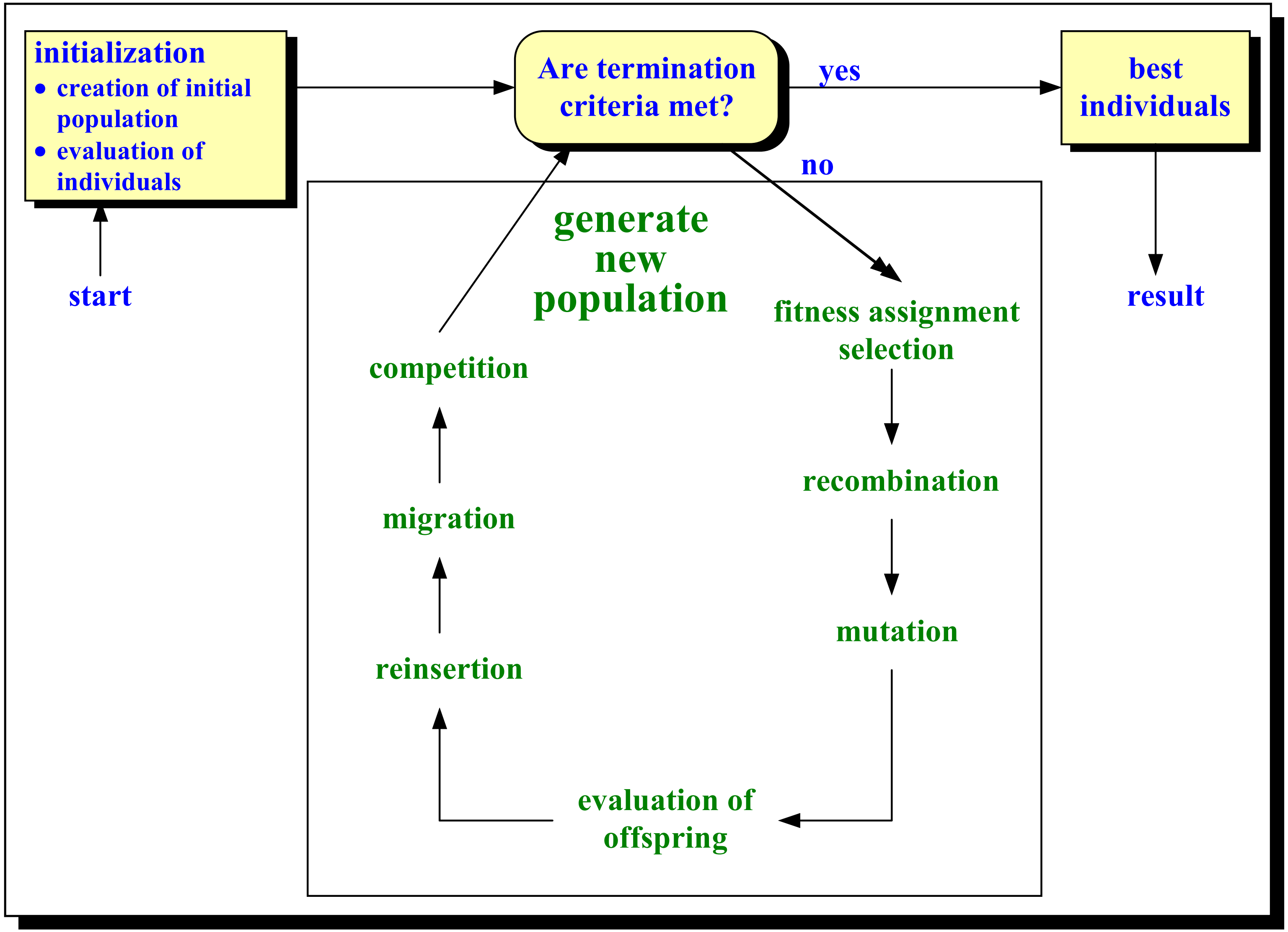
Structure of the evolutionary algorithm



initialization
- creation of initial population
- evaluation of individuals

start

Are termination criteria met?

yes

no

best individuals

result

generate new population

fitness assignment selection

recombination

mutation

evaluation of offspring

reinsertion

migration

competition

Tools and algorithms used

- **GEATbx**: Genetic and Evolutionary Algorithm Toolbox for use with MATLAB http://www.geatbx.com/
  - → Multi Strategy Competition EA
    - ⇨ 4 subpopulations with 50 individuals each
    - ⇨ linear ranking, truncation selection, generation gap 0.9 (elitest),
    - ⇨ discrete and line recombination,
    - ⇨ real valued mutation (different range and precision),
    - ⇨ unrestricted migration, competition between subpopulations
    - → globally oriented search strategy (rough and fine search combined)
  - → Evolutionary Strategy EA
    - ⇨ 1 population with 30 individuals
    - ⇨ best 5 individuals produce 6 offspring each (high selection pressure)
    - ⇨ all offspring replace parents
    - ⇨ no recombination
    - ⇨ mutation by mutation operator of an evolution strategy (Ostermeier, Hansen, TU Berlin)
    - → local search strategy (adaptation of mutation step sizes)

Summary

Advantages

- presentation of an integrated greenhouse model incl.
    - → greenhouse climate
    - → plant growth
    - → control equipment
    - → outside weather conditions
- use for short time-scale prediction tasks

- optimization using Evolutionary Algorithms
- employment of different objectives
    - → profit maximization, prevention of stress, constraints
- ready for online control
- incorporation of problem specific knowledge

Summary

Future work

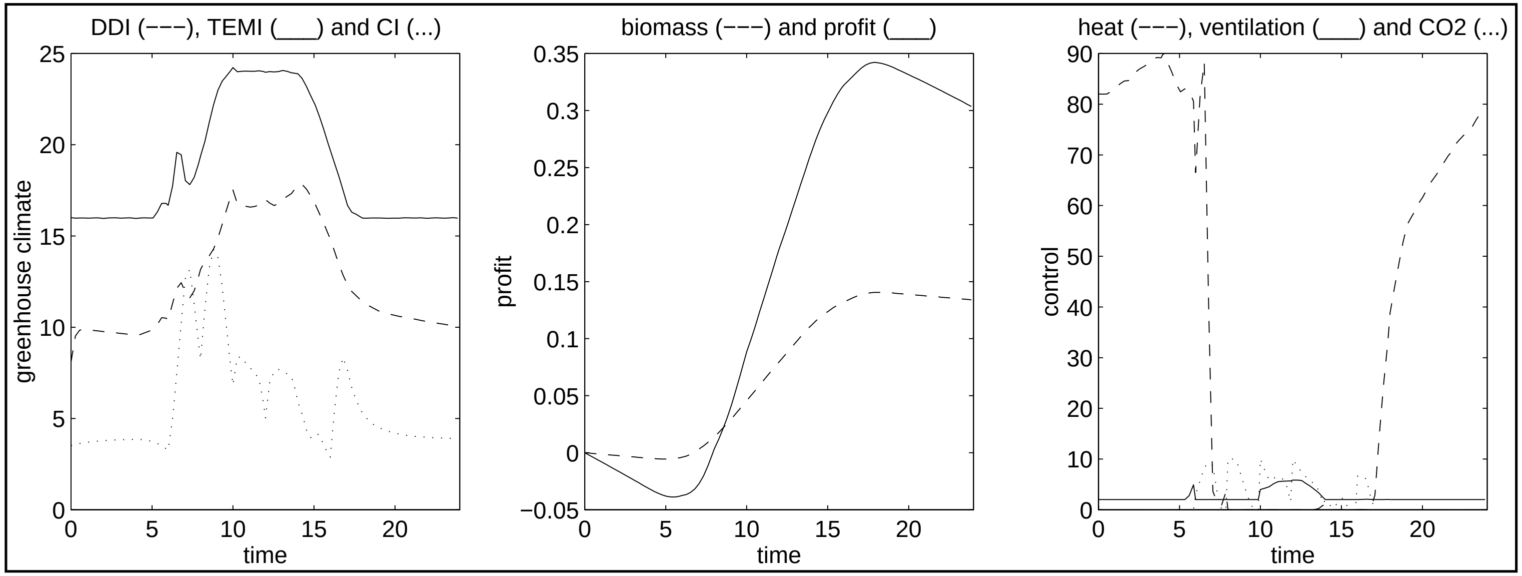
- comparison with different control strategies
  - → constant set points for greenhouse climate
- new and enhanced plant models
  - → tomato, cucumber, sweet pepper, radish
- coupling with long timescale control strategies
  - → long time-scale: high level strategy,
  - → short time-scale: low level strategy
- enhancements to the Evolutionary Algorithm
  - → refinement of multiple strategies for subpopulations
  - → multiobjective ranking of different objectives
  - → employment of problem specific genetic operators

Experiments

Typical days

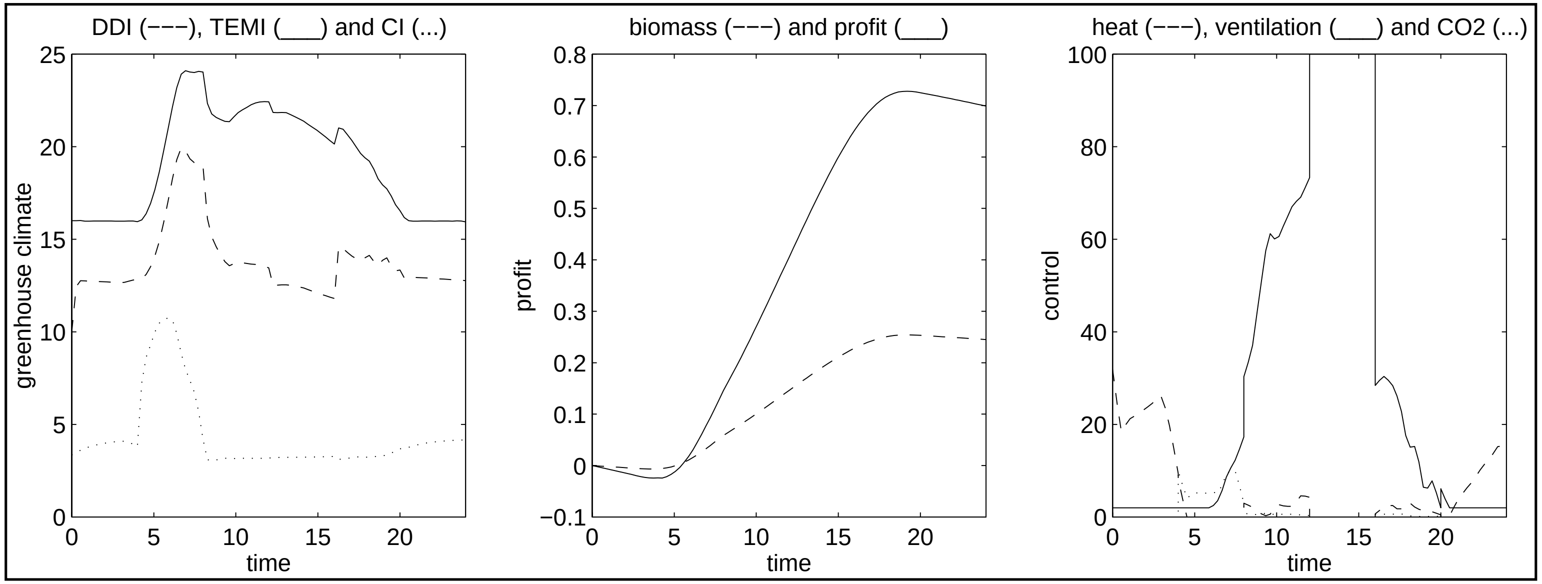
Optimal control for typical days

- optimization for April
- heating high during night (lower temperature constraint)
- ventilation around noon (upper temperature constraint 24°C)
- CO_2 injection on during day (with no or little ventilation)



Optimal control for typical days

- optimization for June
- heating on during night (lower temperature constraint)
- ventilation on during day
  (upper temperature constraint, 20°C better than 24°C)
- CO_2 injection on during morning (before ventilation opens)



Experiments

Changing prices

Optimal control under changing prices

- prices of heating (energy) and CO_2 were changed
  - → 3 times as high as standard price
  - → $^1/_3$ of standard price

- optimization for February
- high prices
  - → biomass: 1.1 g/(m²·h) profit: -0.09 Pf/(m²·h)
  - → heating as low as possible (lower temperature constraint)
  - → nearly no CO_2 injection
- low prices
  - → biomass: 1.5 g/(m²·h) profit: 0.03 Pf/(m²·h)
  - → heating higher than keeping temperature above 16°C
  - → during daytime CO_2 injection

Experiments

Comparisons

Comparison

previously published solutions

- use of models and simulation to find better set points
  - → day/night temperature
  - → night CO_2 enrichment
- no immediate reaction to changing conditions (prices)

new integrated model and evolutionary algorithms

- optimal control of greenhouse climate
- applicable for different objectives
- immediate response to changing conditions
- use for online control

Optimization

Representation

Representation of individuals

- individuals represent control of simulation period
  - → use of 3 controls (heating, ventilation, CO_2 enrichment)
  - → controls discretized at equidistant points (first order hold)
  - → control step every 15 minutes
  - → simulation period: 2-12 hours

$$NumVar = \left(\frac{SimTime}{ControlStep} + 1 \right) \cdot NumControl; \quad \begin{array}{l} ControlStep = 0.25h \\ NumControl = 3 \end{array}$$

- divide longer optimization periods into smaller pieces
  - → end states of one period are start states of next period
  - → arbitrary long time periods can be calculated
  - → size of optimization problem is adjustable to available computing power