Applied optimization with JuMP at SINTEF

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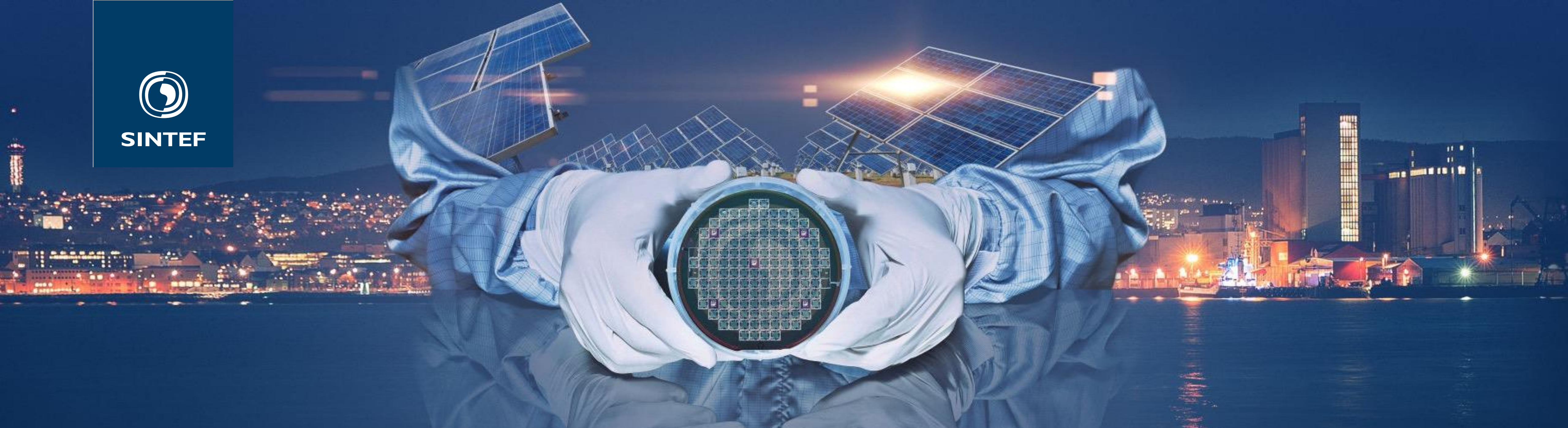
Technology for a better society

Outline

- Background, SINTEF, Julia
- How to work with large scale, complex optimization models
- Illustrative examples showing two different approaches
- Learning, experiences and how to progress



ONE OF EUROPE'S LARGEST INDEPENDENT RESEARCH ORGANISATIONS

367 million
EUR turnover

2200
employees

6400
projects

3300
customers

INTERNATIONAL
57 million EUR

NATIONALITIES
80

PUBLICATIONS (INCL. DISSEMINATION)
6200

CUSTOMER SATISFACTION
4,6 / 5

Optimization modeling @SINTEF

- Developing optimization models for industrial use and economic analysis
- Historically the primary tool has been FICO Xpress using the Mosel modelling language
- Other modeling tools: GAMS, AMPL, Pyomo
- Several models in daily operation across several industries (oil and gas, aluminium)
- Economic models for long term analysis (energy, infrastructure, regional, national and global focus)

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Why Julia and JuMP?

- Specialized algebraic modelling languages typically lack support for:
  - Easy modularization and code reuse
  - Support for multiple solvers
  - Ecosystem of surrounding packages for file IO, database access, plotting
- Commercial modeling tools are costly, and some are tied to a specific solver
- Research funding (EU and Research Council of Norway) tending towards more openly available models and software
- Julia and JuMP gradually introduced since 2020

Open packages released by SINTEF

- SparseVariables: https://github.com/sintefore/SparseVariables.jl
- UnitJuMP: https://github.com/trulsf/UnitJuMP.jl
- TimeStruct: https://github.com/sintefore/TimeStruct.jl
- EnergyModelsX: https://github.com/orgs/EnergyModelsX
- PiecewiseAffineApprox: https://github.com/sintefore/PiecewiseAffineApprox.jl

For a short introduction to the packages see presentations at JuMP-Dev 2022, 2023 and 2024 (talks by Lars Hellemo and Julian Straus).

How to handle complex optimization models

- Clear separation between input data and optimization modelling
- Multiple dispatch to control formulation and configuration
- Separate module(s) for the optimization model and associated data structures
- Automatic test routines
- Documentation

- Recommended reading
  - https://jump.dev/JuMP.jl/stable/tutorials/getting_started/design_patterns_for_larger_models/

Modeling approaches

- Single script – monolithic
- Julia supports more modular approaches, but the model is still "global" by nature

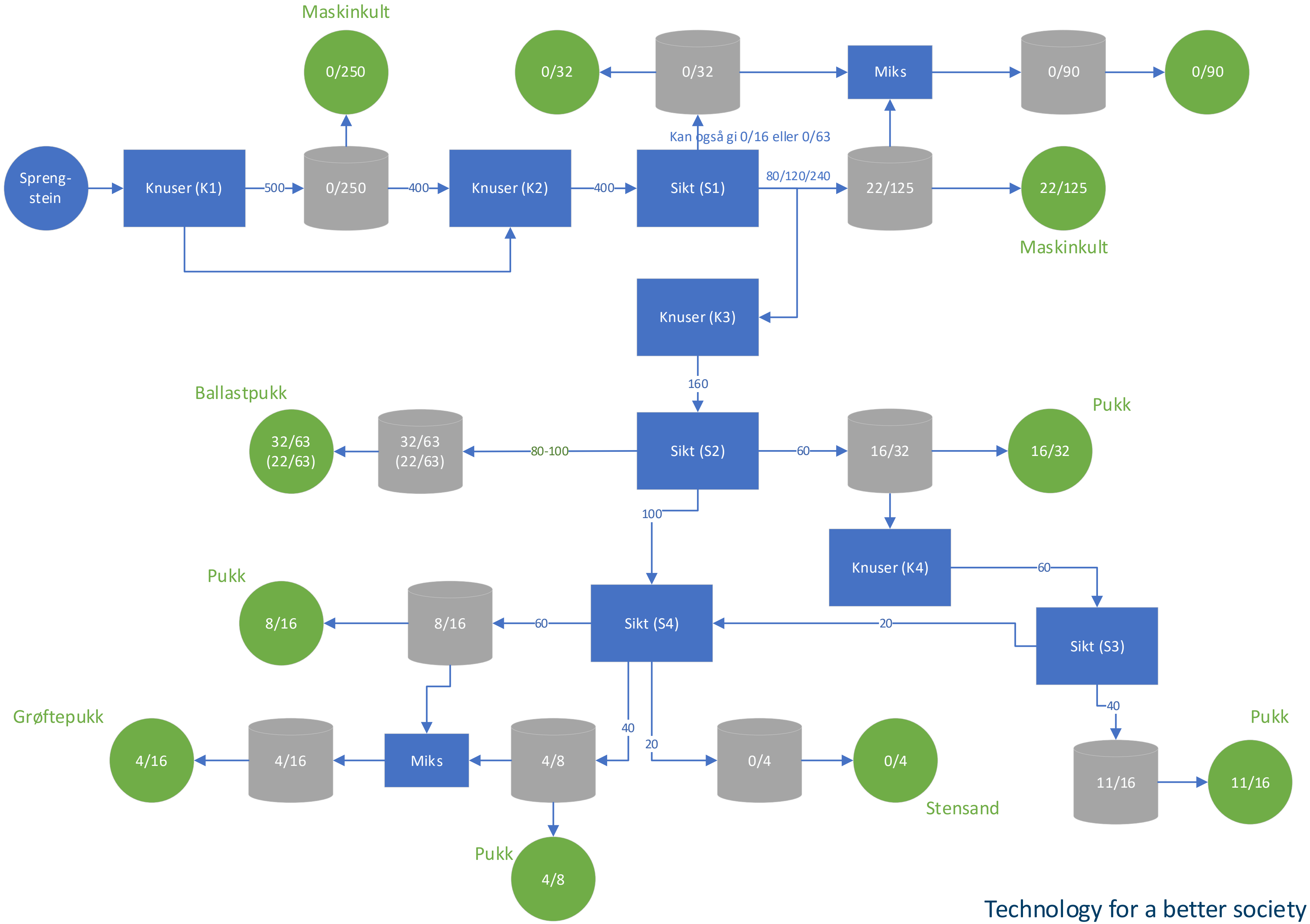
- What is the API of an optimization model?
- How can a user easily extend model functionality?
- How can we combine multiple models?

Example 1: logistics of crushed stone and excavated masses

Approach using JuMP

- **UnitJuMP** to ensure correct and flexible use of physical units
- **TimeStruct** for general time structures
- **SparseVariables** to allow dynamic generation of variables with sparse structure
- **MultiObjectiveAlgorithms** to balance economic and environmental aspects

- Separate packages for the optimization **modeling** and for setting up an **instance** based on input data



Maskinkult
0/250
0/32
0/32
Miks
0/90
0/90
Kan også gi 0/16 eller 0/63
Spreng-stein
Knuser (K1)
500
0/250
400
Knuser (K2)
400
Sikt (S1)
80/120/240
22/125
22/125
Maskinkult
Knuser (K3)
160
Ballastpukk
32/63 (22/63)
32/63 (22/63)
80-100
Sikt (S2)
60
16/32
16/32
Pukk
100
Knuser (K4)
60
Pukk
8/16
8/16
60
Sikt (S4)
20
Sikt (S3)
40
Grøftepukk
4/16
4/16
Miks
4/8
40
20
0/4
0/4
Stensand
11/16
11/16
Pukk
Pukk
4/8

Model variables

- Separate structure to collect all model variables
- Easier overview of available variables (including code completion)
- Using SparseVariables to allow dynamic variable creation
- Using UnitJuMP to include physical units

```
struct ModelVariables
    flow
    flow_mode
    n_trips
    usage_trip
    storage
    prod
    consume
    emit::Dict{Emission, IndexedVarArray}
    fuel::Dict{Fuel, IndexedVarArray}
    epd_flow::Dict{EPDIndicator, IndexedVarArray}
    usage
    usage_mode
```

UnitJuMP

```julia
@variable(m, flow[start = 𝒩, stop = 𝒩, product = 𝒫, period = 𝒯] >= 0, massunit; container = IndexedVarArray)
@variable(m, flow_mode[node = 𝒩, mode = 𝒟, product = 𝒫, period = 𝒯] >= 0, massunit; container = IndexedVarArray)

@variable(m, n_trips[trips = 𝒮, period = 𝒯] >= 0; container = IndexedVarArray)
@variable(m, usage_trip[node = 𝒩, trips = 𝒮, period = 𝒯] >= 0, timeunit; container = IndexedVarArray)
```

SparseVariables

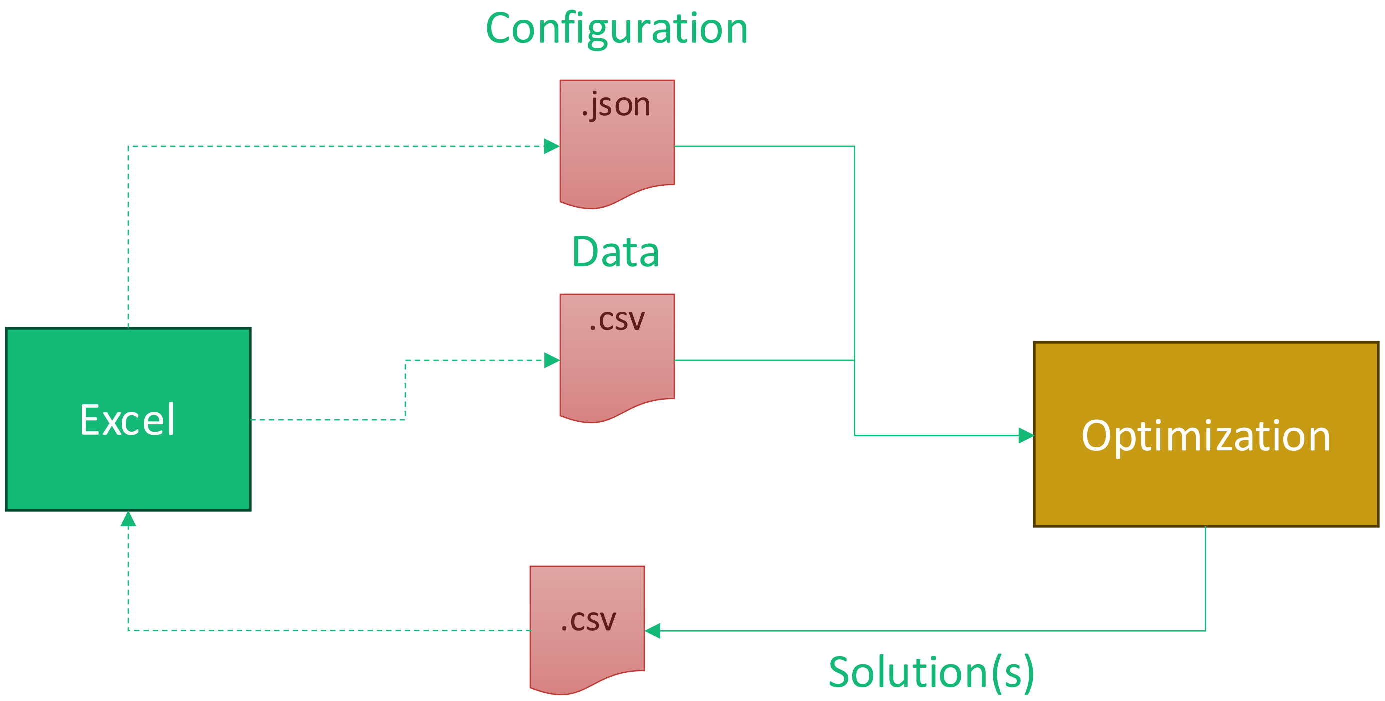
Data structures

```
function variables_node(mv, i::Market, t)
    for p in products(i)
        insertvar!(mv.sale, i, p, t)
        if !isnothing(price(i, p, t))
            insertvar!(mv.sale_income, i, p, t)
        end
        if allow_slack_min(i, p)
            insertvar!(mv.slack_demand, i, p ,t)
            insertvar!(mv.penalty_cost, i, p ,t)
        end
    end
end
```

- Each node in the network is responsible for creating its own variables, constraints and objective contributions
- Dispatching on node types

```
function massbalance(m, mv, i::Market, t, prev)
    for p in products(i)
        ctr = @constraint(m, mv.sale[i, p, t] == sum(mv.flow[:, i, p, t]))
        set_name(ctr, "mass_bal_market($i,$p,$t)")
    end
end
```

Industrial deployment



- Julia model distributed as a self-contained executable using PackageCompiler
- 382 MB zipped file

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SIRKULÆR masseforvaltning

MassePlan (v1.0) - resultat

Løsningskatalog: C:_project\CircMass\Test\Prosjekt\results

Velg...

Mulige løsninger

Løsning	Pris total [kr]	Pris transport [kr]	Pris produkt [kr]	Avgift innkjørt [kr]	EPD [kgCO2e]
1	1 630 260	357 000	1 149 510	123 750	51 743
2	1 650 775	377 515	1 149 510	123 750	52 743
3	1 713 982	440 722	1 149 510	123 750	55 712
4	1 872 027	443 767	1 304 510	123 750	57 163

Løsning: 1

	Masser inn	Masser ut	Total
Volum [tonn]	9 670	2 750	12 420
EPD A1-A3 [kgCO2e]	23 788		23 788
EPD A4 [kgCO2e]	22 237	5 718	27 955
Pris produkt [kr]	1 149 510		1 149 510
Pris transport [kr]	300 372	56 628	357 000
Avgift innkjørt [kr]		123 750	
Pris total [kr]	1 449 882	180 378	1 630 260

Masser inn

Produkt	Fra	Til	Volum [tonn]	EPD A1-A3 [kgCO2e]	EPD A4 [kgCO2e]	Pris produkt [kr]	Pris transport [kr]
22125	Lørenskog	Prosjekt	7 750	19 065	18 817	999 750	263 586
32	Bjønndalen	Prosjekt	1 920	4 723	3 421	149 760	36 786

Experiences and learnings

- The use of physical units can be a bit cumbersome, but can catch errors in modeling at an early stage
- Custom structures for holding model variables can be beneficial
- Multi objective for "free" ☺
- Deployment at customer can be a considerable challenge (but not necessarily related to Julia/JuMP)

Example 2: Locating hydrogen infrastructure in the Lofoten Islands

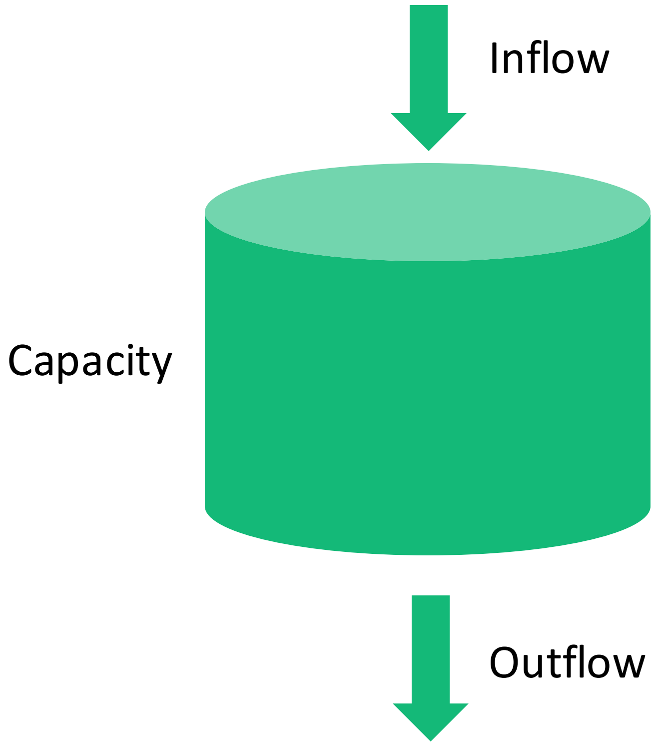
Approach using JuMP

- **TimeStruct** for flexible time structures
- **Storages** for general modeling of storage inventory (in combination with TimeStruct)
- **PiecewiseAffineApprox** to add convex piecewise linear approximations of a set of points to optimization models
- **EnergyModelsInvestement** for general modeling of investment decisions

Submodels as separate packages with well-defined APIs

- Inspired by the approach of ModelingToolkit/Modelica and Plasmo
- Create a standard library of components that can be combined through connectors
- Components can be added to an optimization model producing the required submodel

Storages



- Storage as a high-level object that can be directly added to a JuMP model
- Builds upon TimeStruct
- Exposes a small interface:

```
export init_storage, add_storage!
export set_inflow, set_outflow, set_capacity
```

- Tracking of storage levels is internal to the module

Usage example

```julia
periods = SimpleTimes(3, 1)
model = JuMP.Model(HiGHS.Optimizer)
@variable(model, cap >= 0)
@objective(model, Min, cap)

storage = Storages.init_storage(model, "Lager", Storages.Cyclic(), periods)

set_capacity(storage, periods, cap)
for t in periods
    set_outflow(storage, t, 1)
end
set_inflow(storage, first(periods), 3)

Storages.add_storage!(model, storage, StorageData(init_stock_level = FixedProfile(2)))

optimize!(model)
```

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Generated model

```
Min cap
Subject to
 _init_stock_level_Lager[sc1] == 2
 _stock_level_Lager[t1] - _init_stock_level_Lager[sc1] == 2
 -_stock_level_Lager[t1] + _stock_level_Lager[t2] == -1
 -_stock_level_Lager[t2] + _stock_level_Lager[t3] == -1
 -_stock_level_Lager[t3] + _init_stock_level_Lager[sc1] == 0
 -cap + _init_stock_level_Lager[sc1] <= 0
 -cap + _stock_level_Lager[t1] <= 0
 -cap + _stock_level_Lager[t2] <= 0
 -cap + _stock_level_Lager[t3] <= 0
 cap >= 0
 _stock_level_Lager[t1] >= 0
 _stock_level_Lager[t2] >= 0
 _stock_level_Lager[t3] >= 0
 _init_stock_level_Lager[sc1] >= 0
```

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Experiences and learnings

- Separate modules for different components and aspects allow for easy reuse
- Hiding internal model implementation reduces complexity
- Composability in Julia is excellent
- Still experimenting, more tutorials and best-practice are welcome

Summary and wishlist

- Julia and JuMP has been well received among all involved colleagues
- JuMP documentation and tutorials are very good
- JuMP has been robust and stable
- Much to gain from working with an open-source approach (code and knowledge sharing)
- Wishlist
  - Use of physical units as an integral part of JuMP
  - Model debugger (IIS detection, relaxation, activating/deactivating constraints)
  - Efficient handling of large scale and sparse models and associated solution information

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