INCREASING ENERGY EFFICIENCY BY MODEL BASED DESIGN

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FLANDERS MAKE
MANUFACTURING INNOVATION NETWORK

FLANDERS MAKE

- **Strategic Research Center** for the manufacturing industry
- Integrating the power of **industry, industrial research centers** (FMTC, Flanders' DRIVE) & **university research labs** in one common research agenda
- Open innovation environment enabling **structural collaboration** in research between industry - Flanders Make - academia
- **Accelerate** technological innovation in the Flemish manufacturing industry
- Cross-border and **international** collaboration

MISSION FLANDERS MAKE

- “To strengthen the **long-term international competitiveness of the Flemish manufacturing industry**
- by carrying out
  excellent, industry-driven, pre-competitive research

  in the domains of mechatronics, product development methods and advanced manufacturing technologies”

FLANDERS MAKE RESEARCH PROGRAMS

- **Clean energy efficient motion systems**
- Smart monitoring systems
- High-performance Autonomous Mechatronic Systems
- **Intelligent product design methods**
- Design and Manufacturing of Smart and Lightweight Structures
- Additive Manufacturing
- Manufacturing for high precision products
- Agile & Human-centered production and robotic systems

- Model based design for energy efficiency!

Overview

- **Introduction**
- Example 1: energy storage in a hydrostatic drivetrain
- Example 2: energy efficiency increase of a badminton robot
- Summary and conclusions

INTRODUCTION

NEED FOR INCREASED ENERGY EFFICIENCY

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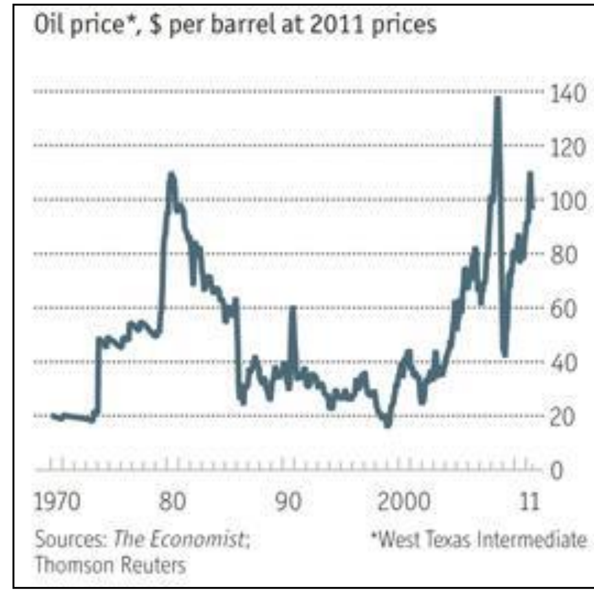
Background: scarcity of energy

- Societal awareness
  - Consider energetic impact of the things you are doing
  - Be ‘green’
  - Increasingly stringent legislation

- Economic angle
  - Increasing prices for energy
  - Contribution of cost of consumed energy during use phase of machine in Total Cost of Ownership increases

- As a results
  - Need to reduce energetic footprint machines
  - Energy efficiency (during use phase) becomes a differentiating performance characteristic



Reduce energy consumption during the use phase (I)

- General approach

1. Avoid useless energy consumption
   - E.g. Reduce stand-by losses

2. Minimize inevitable losses in functional components
   - E.g. Use energy efficient components, e.g. energy-efficient motors

3. If the process generates energy, recuperate it or reuse it
   - Braking energy
   - Waste heat

Reduce energy consumption during the use phase (II)

- Applied to drivelines of production machines and vehicle
  - Component level
    - Use energy efficient components
    - However: might cause performance changes, e.g. electrical motor for dynamic applications
  - System level
    - Allows taking into account interaction between components in machine
    - Most opportunities, but less straightforward

⇒ *Take energy consumption into account during the design of new machines*

Motivation, vision, objective and approach

- Vision
  - Future mechatronic systems will be developed following a model-based design approach
- Motivation
  - Model-based design is essential to
    - Reduce development effort/cost
    - Decrease the time-to-market
    - Explore the space of possible designs more rigorously
    - Deal with increasing number of system requirements

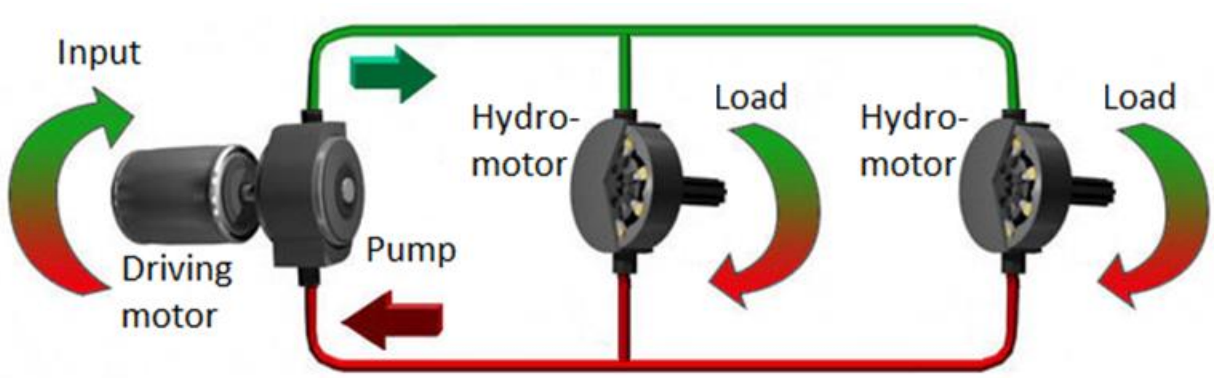
Model based design taking into account energy efficiency

- Model based design
  - Opportunity to quickly evaluate the impact of design changes
    - Describe behavior components mathematically
    - Combine components
    - Simulate and analyze machine behavior
  - Difficulty with energy
    - Multi-disciplinary (mechanical, electrical, hydraulic, etc.)
    - Changes form during a machining process
    - 1D Simulation softwares exist that allow modeling of energetic behaviour

CASE STUDY 1:
ENERGY STORAGE IN A HYDROSTATIC DRIVETRAIN

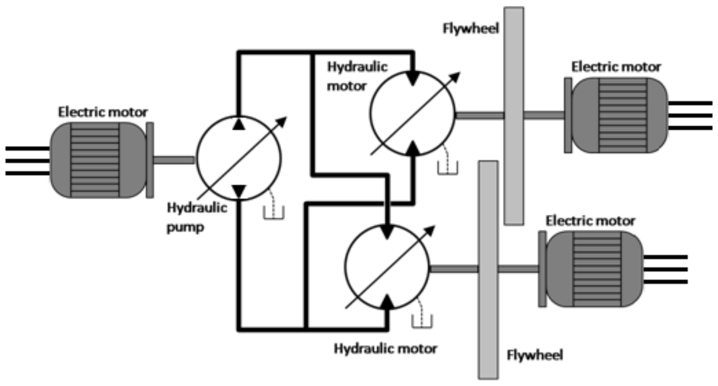
Hydrostatic drivetrain

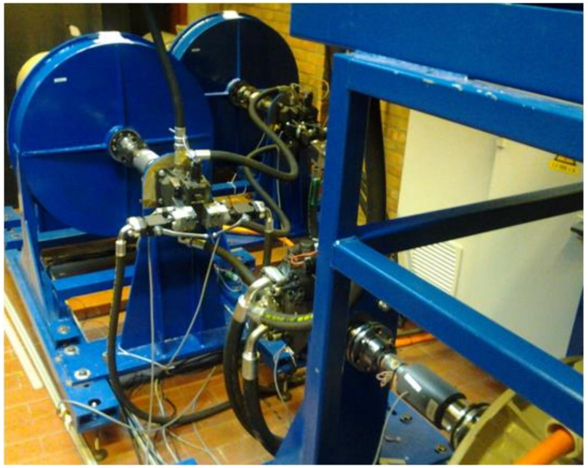
- Heavy load vehicles
  - Hydrostatic drivetrain
    - Combustion engine to pump to hydraulic motors to 1 or more loads
    - Variable stroke volumes
      → continuously variable transmission ratio



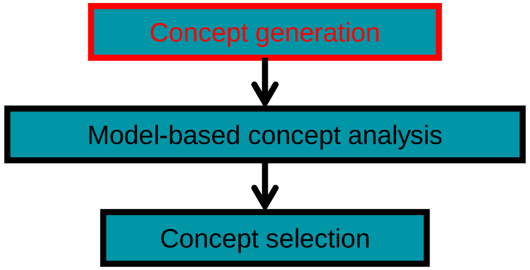
Hydrostatic drivetrain

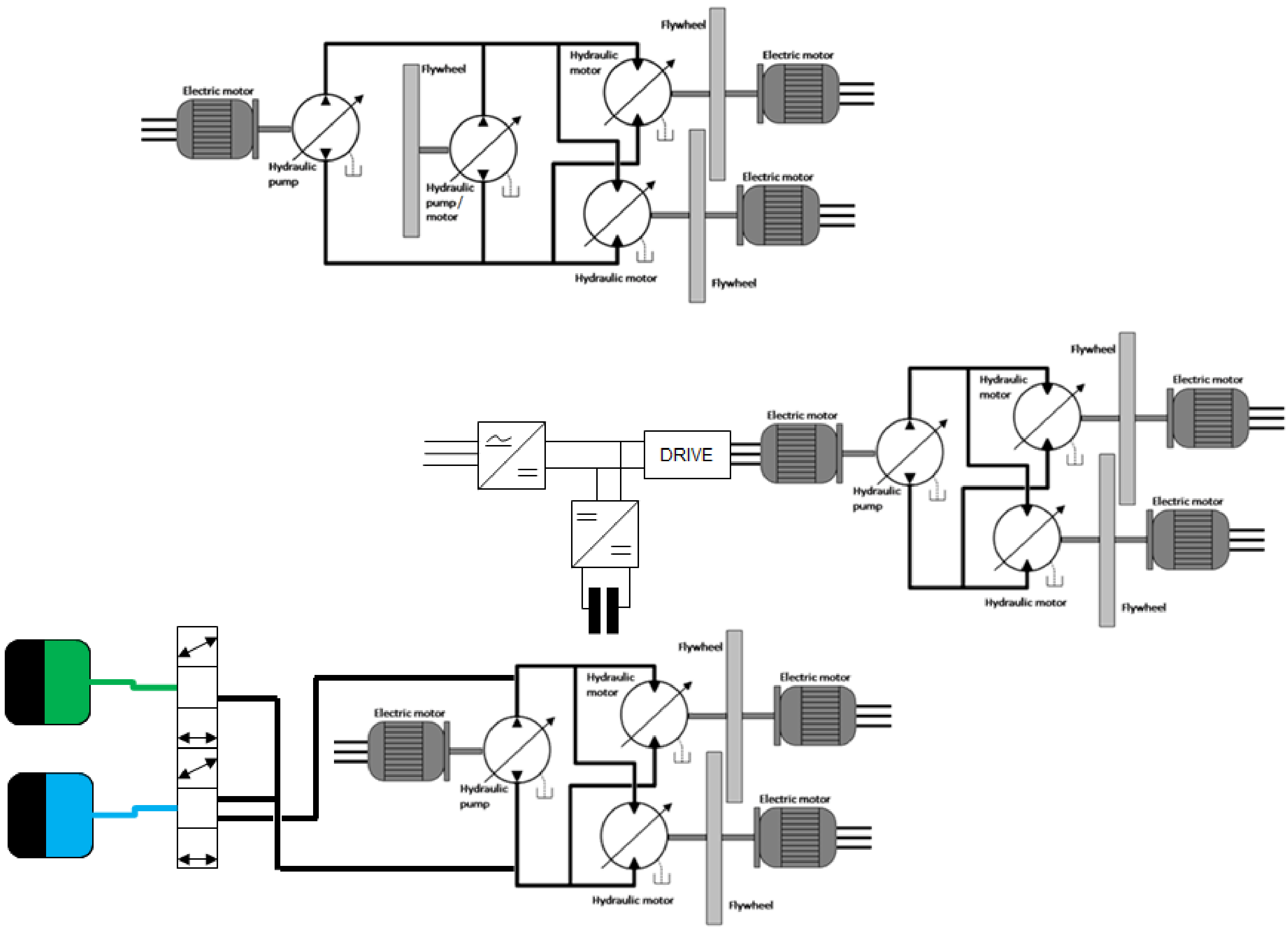
- Experimental setup at FMTC
  - Simulate a loaded hydrostatic drivetrain
    - Speed controlled electric motor instead of diesel engine
    - Torque controlled electric motors and flywheels to emulate load
  - Energy storage?



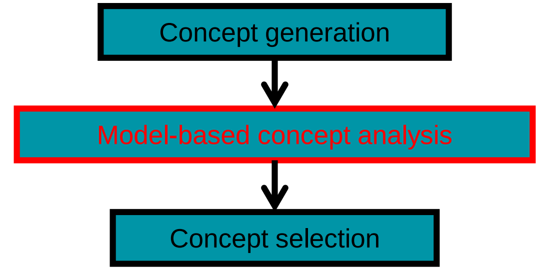


Concept generation

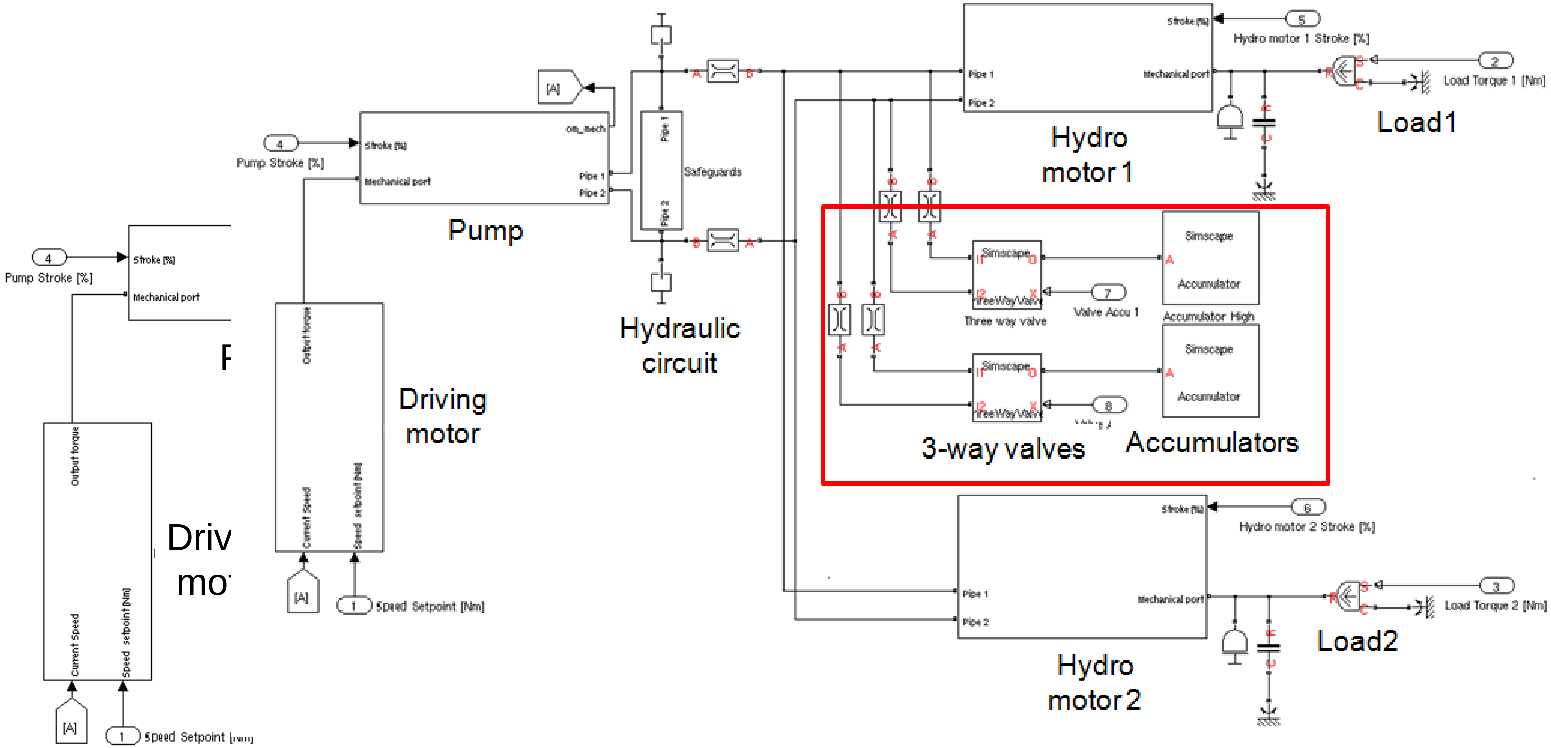


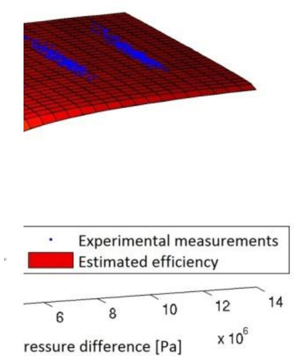


Energetic model



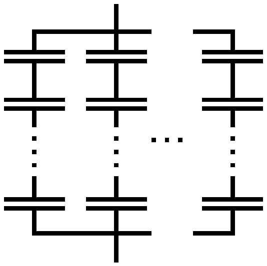
- Start from model of original set-up
- Identify loss parameters based on experiments
- Expand model with models of energy storage elements

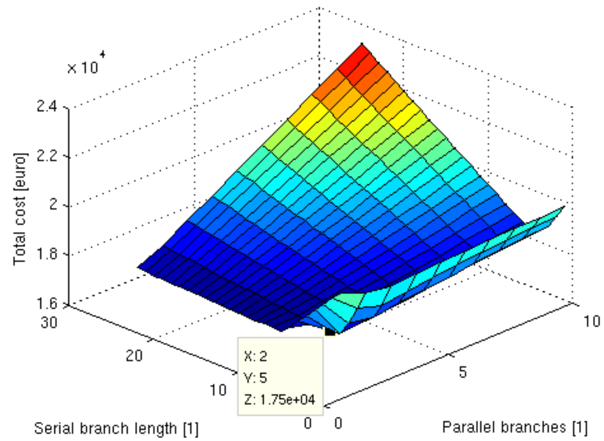




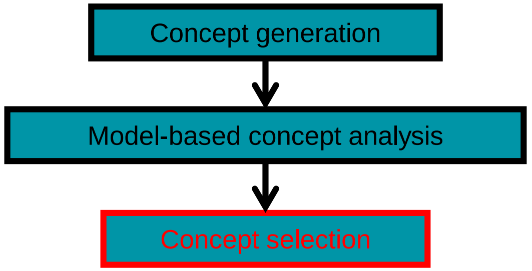
Component optimization

- Cost function
  - Total cost of ownership
- Optimal control
- Electrical hybrid
  - Capacitor bank dimensioning
    - Number of capacitors per serial branch
    - Number of parallel branches
- Hydraulic hybrid
  - Accumulator volume

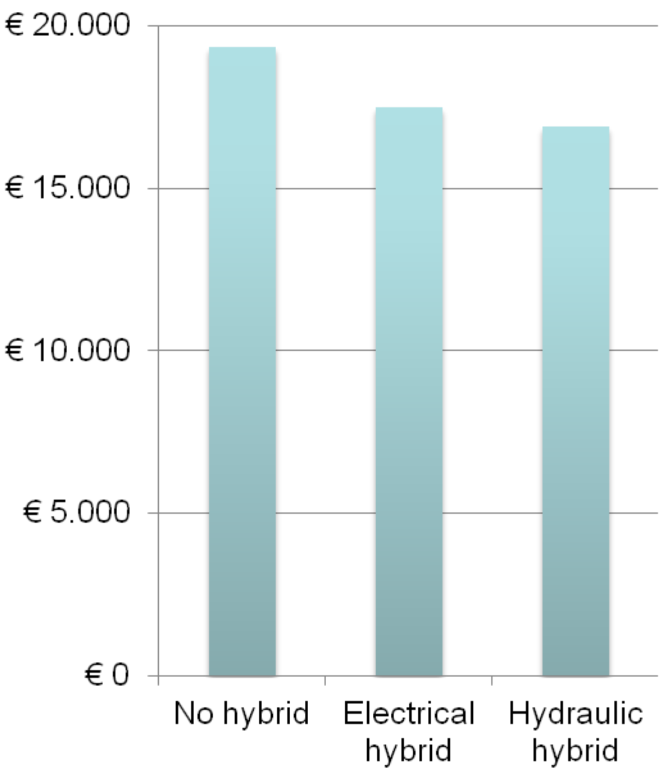




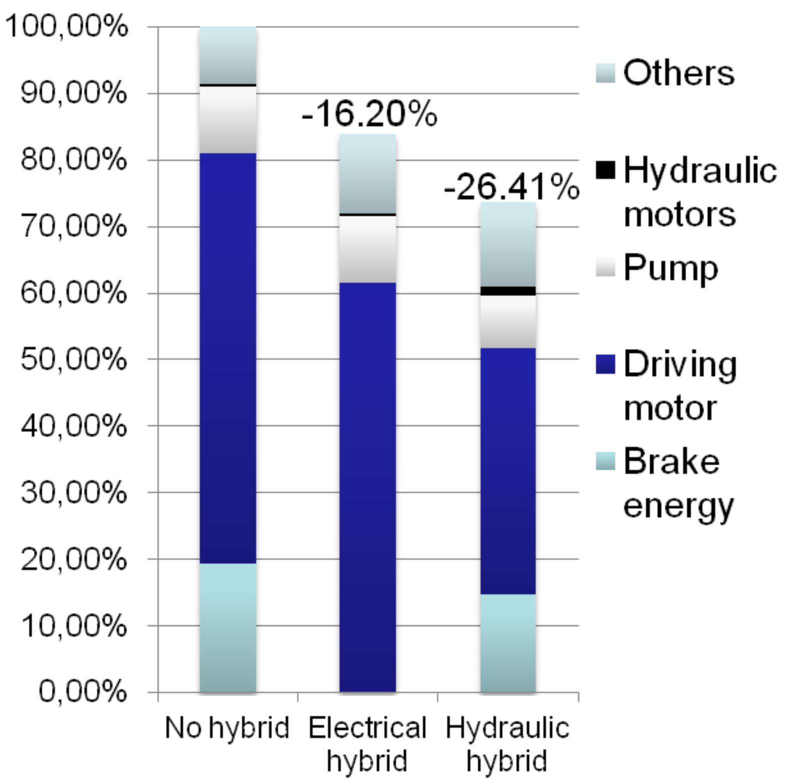
Concept selection



Total cost

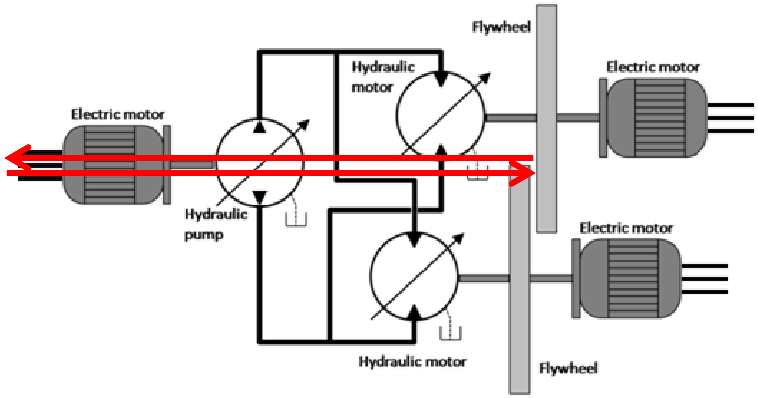


Energy losses

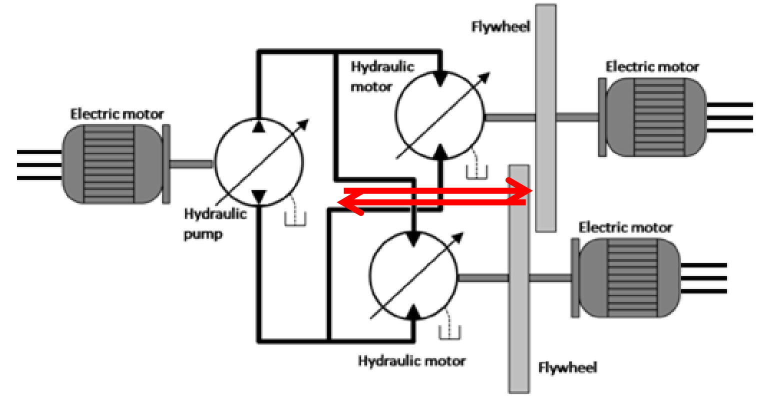


Physical interpretation

- Electrical hybrid



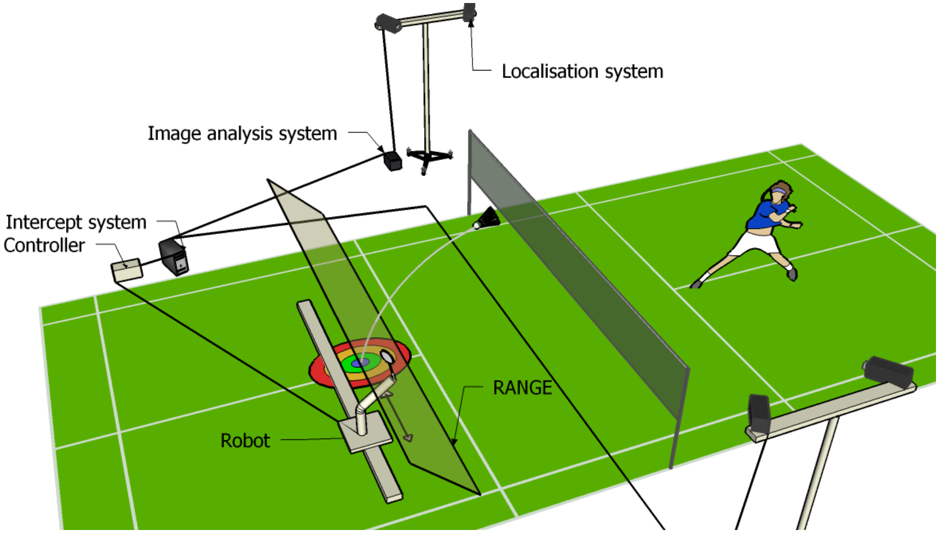
- Hydraulic hybrid

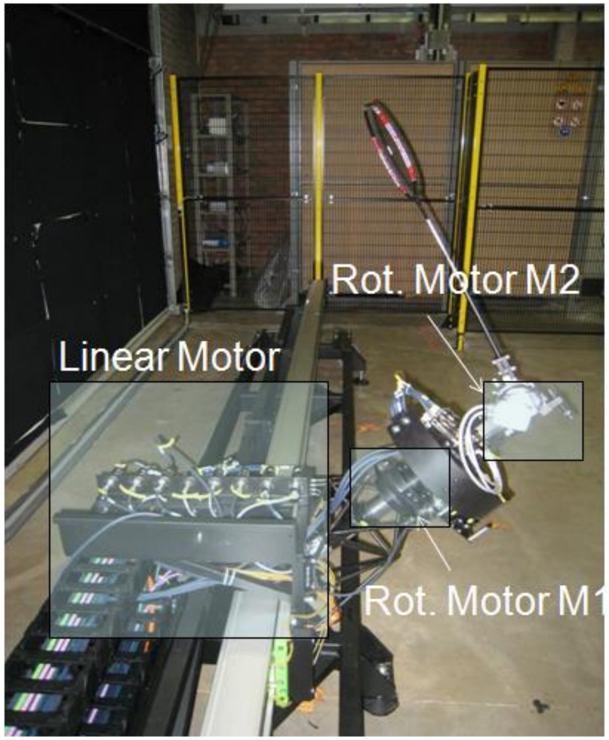


CASE STUDY 2:
ENERGY EFFICIENCY INCREASE OF A BADMINTON ROBOT

Badminton robot

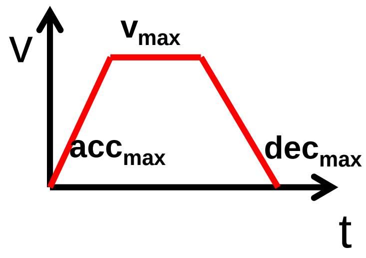
- Demonstration platform





First attempt to reduce energy consumption

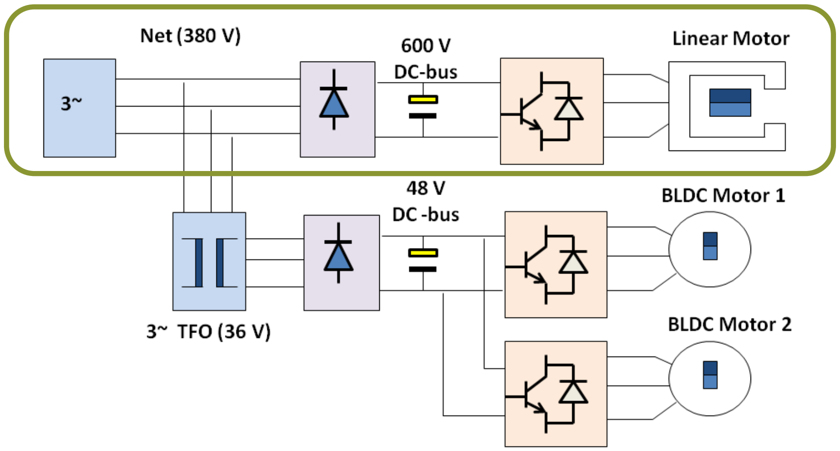
- Engineering reasoning of main losses
  - Robot is mainly accelerating and decelerating masses
  - Deceleration energy is ‘burned’ in braking resistor

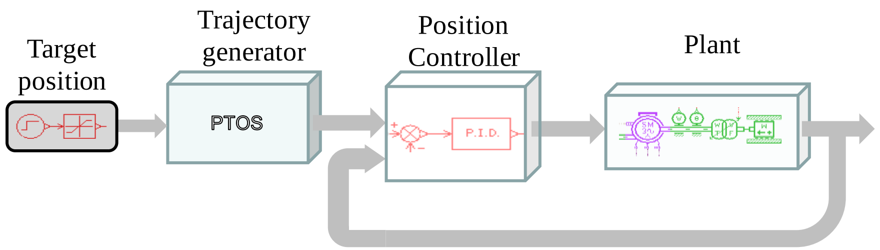


- Reduce energy consumption?
  - Recuperate braking energy and reuse this energy
  - Capacitors added to system
  - Very little reduction in energy consumption (under 5%)!

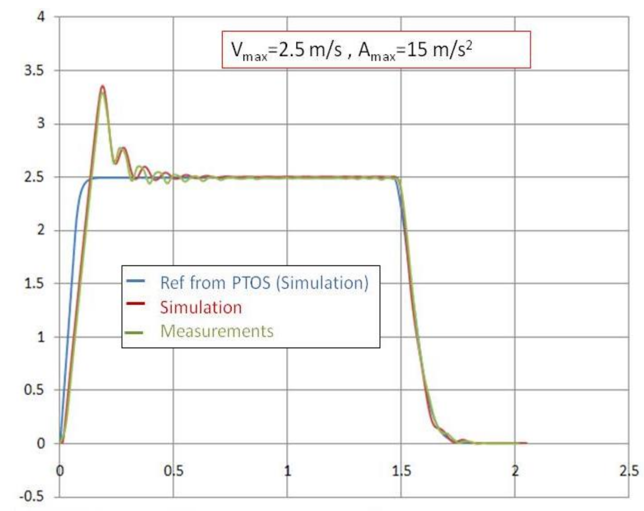
- Why is this so?
  - More systematic analysis needed!

Goal of the analysis

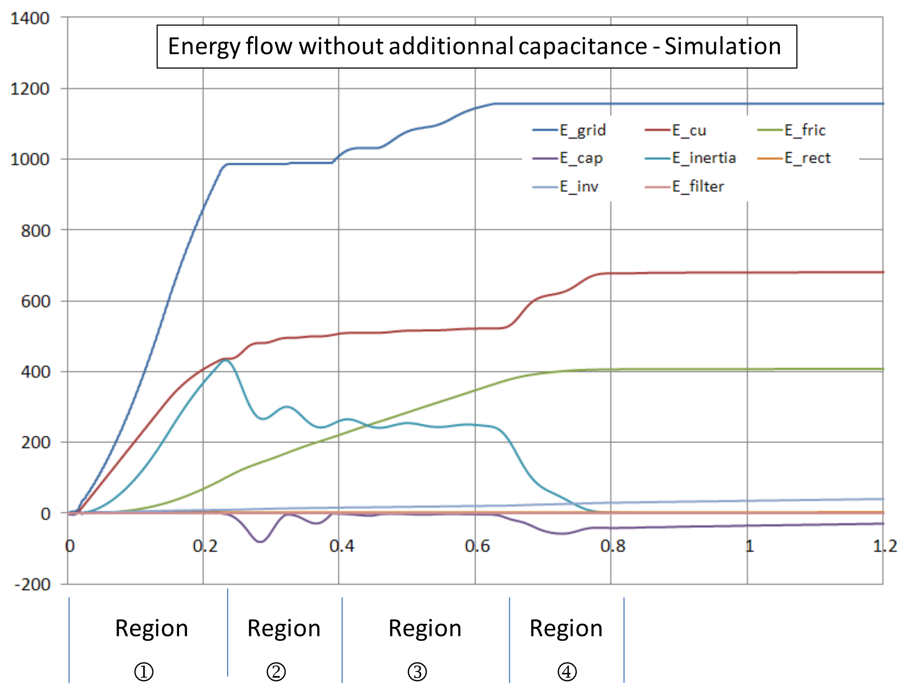




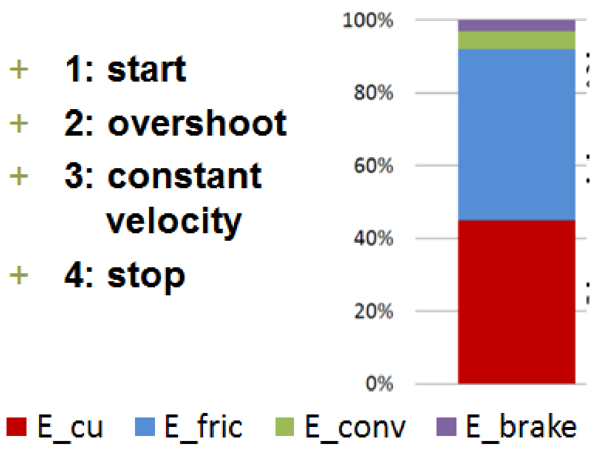
- Energy consuming elements in model
  - E.g. Brake resistance, coil resistance, friction,...
  - Parameter tuning
    - From catalogues (e.g. motor parameters)
    - Experimentally (e.g. friction parameters)



Energy analysis

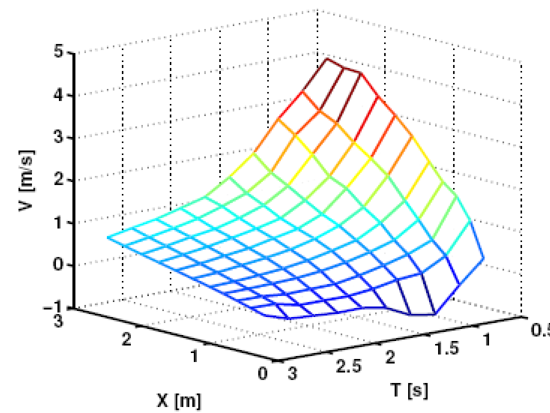


- 1: start
- 2: overshoot
- 3: constant velocity
- 4: stop

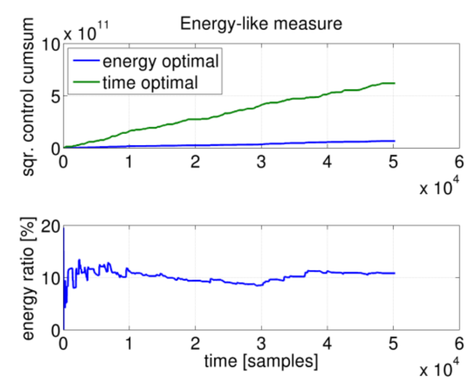


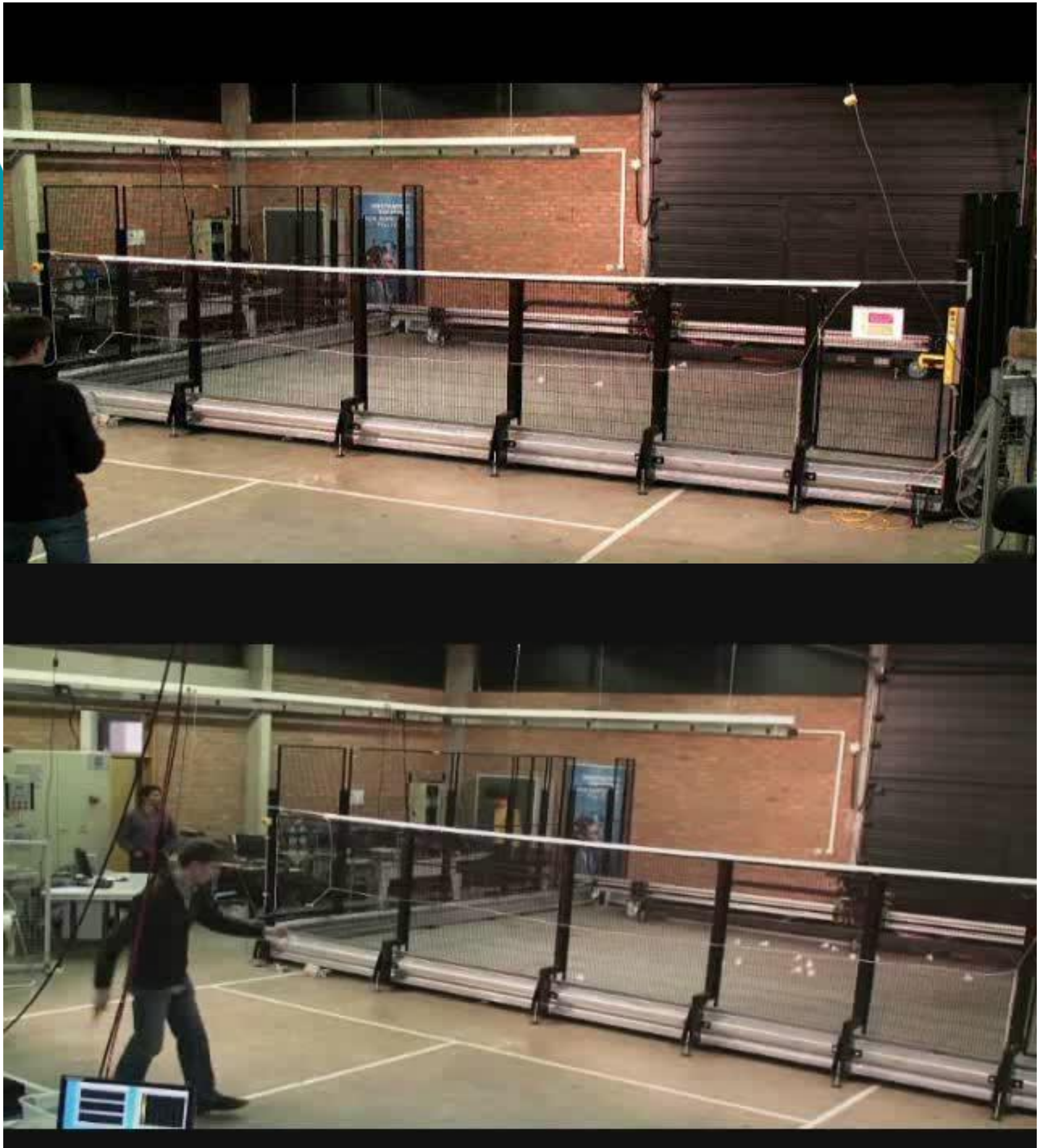
- **Energy flow analysis results**
  - Main loss can be attributed to copper losses and friction losses
- **Solution?**
  - Reduce friction losses
    - Other guides? => reduce friction
    - $\sim I^2$; I~F; F~acceleration => reduce acceleration!

Improvement: Energy efficient controller



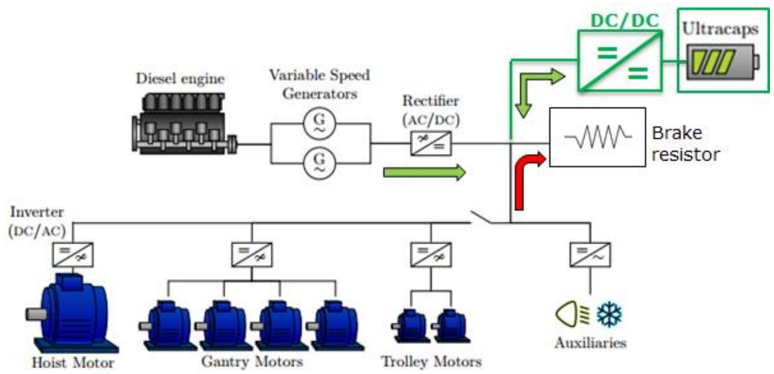
- Go from Time Optimal to Just-In-Time controller
  - Current implementation
    - Time optimal
  - Just-in-time controller
    - Same structure
    - Bounds on trajectory parameters: V_{max} and A_{max}
    - Parameters found using Multi-Objective optimization using the model of the robot
  - Significant reduction in energy consumption!
    … without loss of effectiveness!
    - more than 50 % of energy reduction

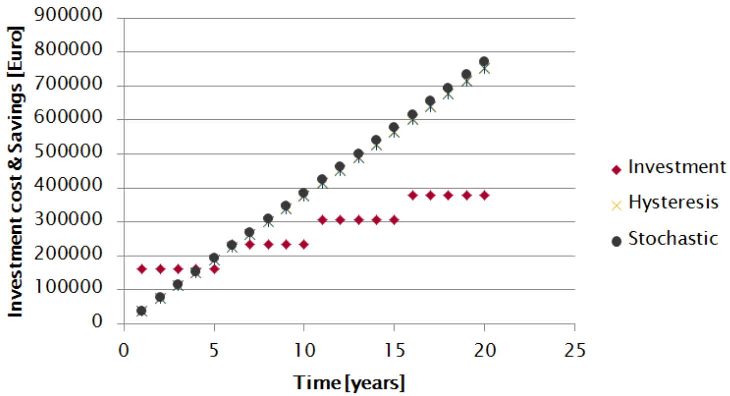




Industrial application

- Similar design analysis and controller development has been applied to the design of the drivetrain of a crane





CONCLUSIONS

Conclusion

- Motivation: Energy reduction for environmental and economic reasons

- Approach
  - Take energy consumption into account on system level
  - Following mechatronic model based approach allows to optimize (energy efficiency of) the design