Multi-Objective Design of the Rotor System

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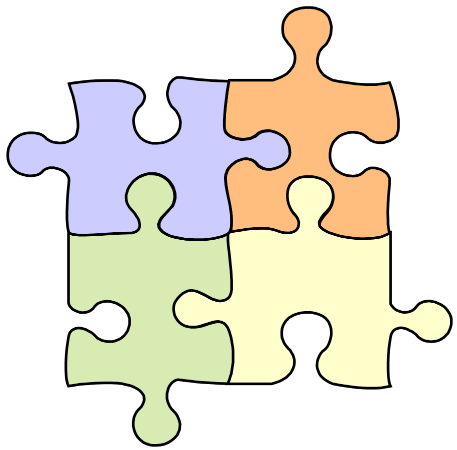
- Recap: the rotor design problem
- Recap: SWP rotor optimization process
- Application of MDO: Analysis of a design space by comparison of different technology (Pareto) fronts for changing system constraints
- Example: NREL 5MW rotor design problem
- Technical challenges of industrial MDO application
- Conclusions

How to minimize total COE? Accurate cost modelling

- Many disciplines, complex, coupled system, many aspects are unpredictable

  - engineering
  - admin
  - BOM
  - manufacturing



  - transport & construction
  - service
  - balance of station
  - financing

- Cost model that combines various sub-disciplines may not be desirable –
  many 'costs' cannot be estimated up-front (i.e. organizational cost, market 'fit' etc.)
  or there is insufficient data to construct a meaningful model useful for optimization

- **Simplify** – solve the problem using a multi-objective approach –
  give decision-makers the data necessary to make trade-off choices directly including 'non-quantifiable' costs

Multi-objective rotor design problem w/ non-linear constraints:

- Performance
  - AEP
  - Capacity factor (some markets)
  - Robustness / soiling insensitivity
- Acoustics
  - Site and region specific
- Loads & Controls
  - Normal operation, emergency stop, fault conditions,
  - Blade loads: fatigue and extreme
  - Component loads: fatigue and extreme
- Blade Structure
  - Blade mass / cost
  - Fatigue strain / extreme loads, tip deflection constraint
  - Panel buckling, edge buckling
  - Manufacturing constraints
- Drive Train
  - Generator torque limit
  - Power & frequency converter limits

Simplify to ~3 objective problem, with the rest being constraints- for example, find Pareto front in terms of:

1. **AEP**
2. **Loads Metric**
3. **Blade Mass**

Many ways to setup the problem (nesting etc)

More objectives possible, but for every additional objective, computational cost **x10**

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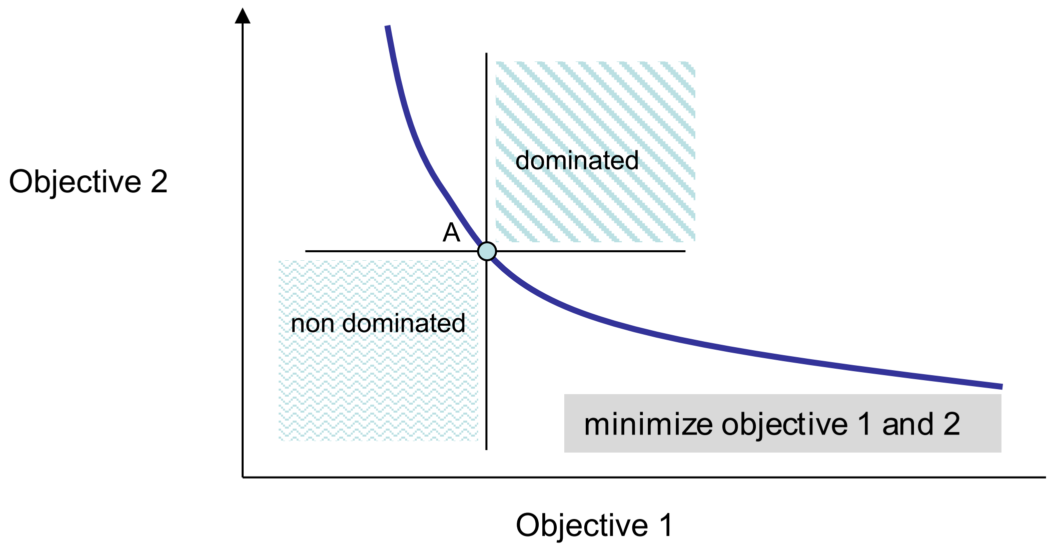
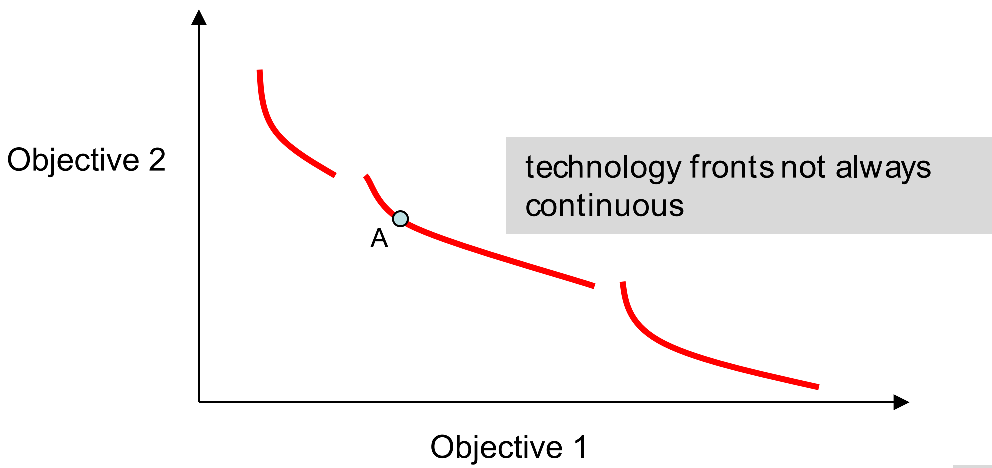
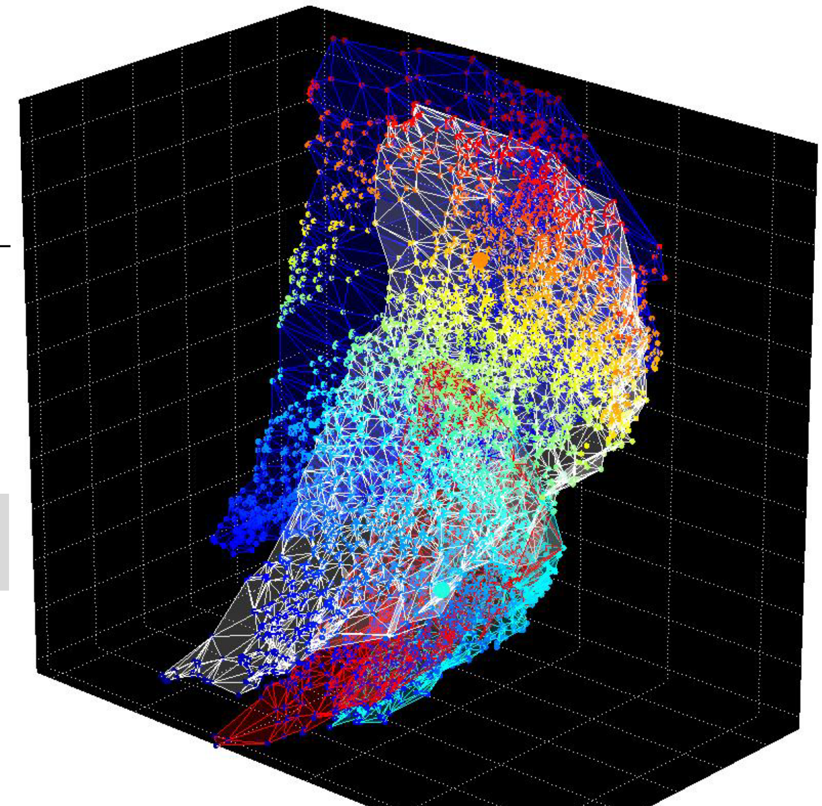
A Pareto front gives the set of best possible trade-offs between objectives







example: 3 objective front

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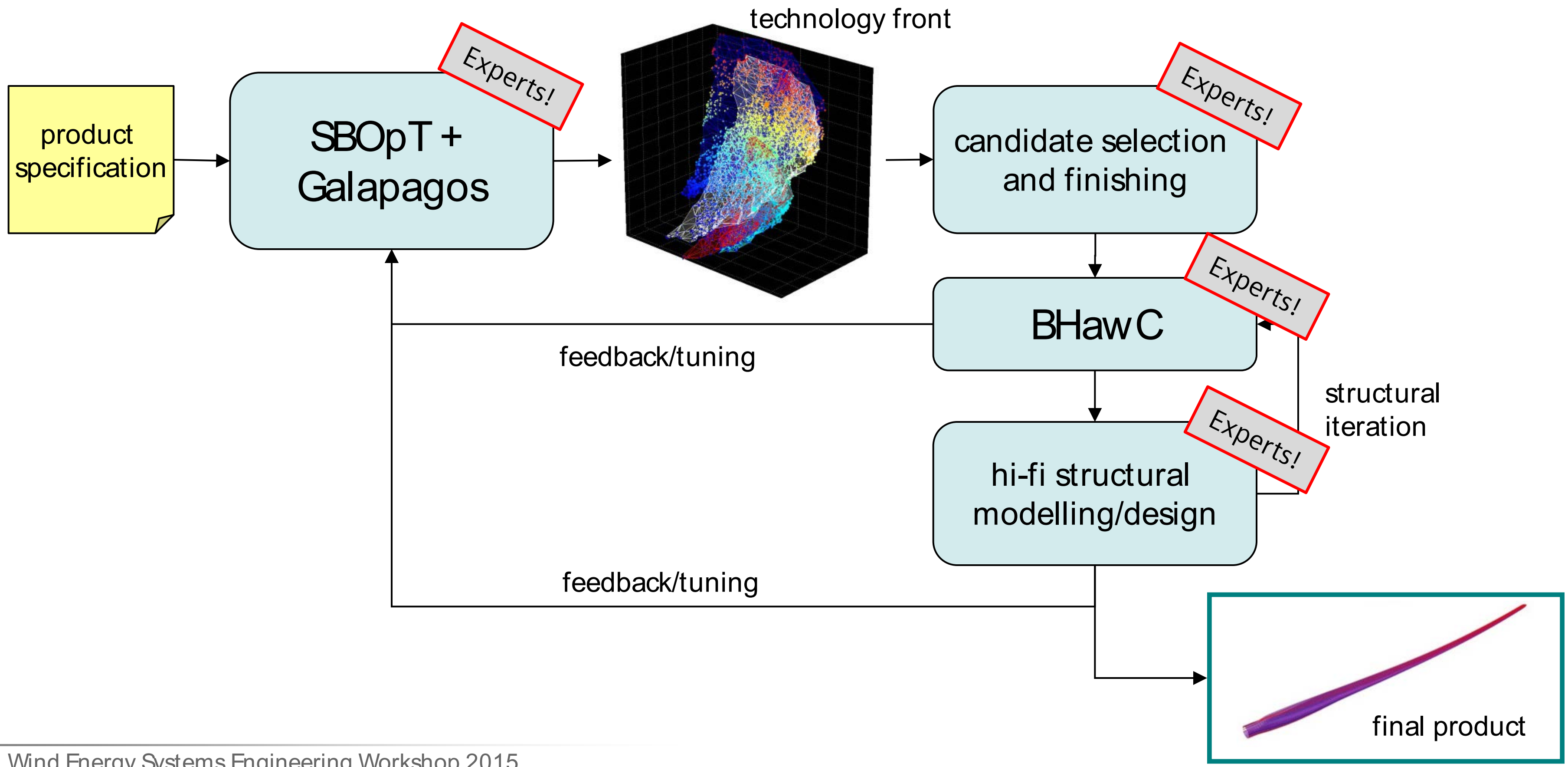
Siemens Blade Optimization Tool (SBOpT) + Galapagos GA Optimizer

- Evaluates 500,000+ blades in an evening within Galapagos and HPC cluster, produces N-dimensional Pareto front between various design objectives

BHawC

- FE code for aero-elastic simulation of entire turbine system



Design Space Evaluation by Comparison of Pareto Fronts

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- Parameter studies about a fixed planform can only go so far…
- Instead, it's desirable to assess the multi-objective impact of various system constraints / parameters in a way that takes advantage of full design freedom that is available
- Compare Pareto fronts generated for slightly different problems (i.e. constraints, technology assumptions etc.)

- Noise
- Soiling sensitivity
- Allowable tip deflection
- Blade structural technology / material choice
- Component load constraints

- Airfoil selection
- Rated power / rated torque
- Wind resource
- Design for manufacture
- Transportation
- Cost

and many others…

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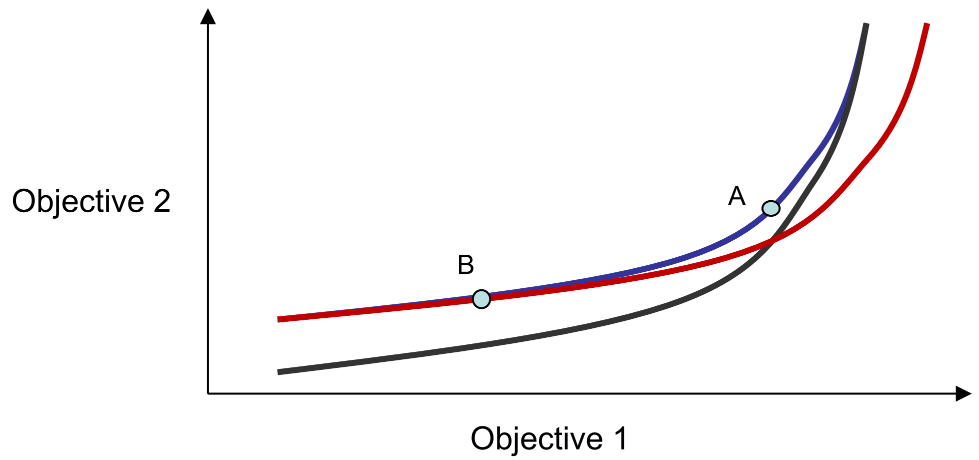

Advantages of front comparison over conventional parameter/sensitivity studies:

- DOFs are fully exploited (optimized) to take advantage or compensate for system parameter/constraint changes such that solution set is pareto optimal and represents the **fully-coupled impact** of desired change
- Sensitive to design space location – *design sensitivity in context*
- Optimizer can discover non-intuitive solutions that may be unique to problem description - Useful for challenging conventional wisdom (i.e. *are high modulus materials really necessary?)*

Example Rotor Design: NREL 5MW

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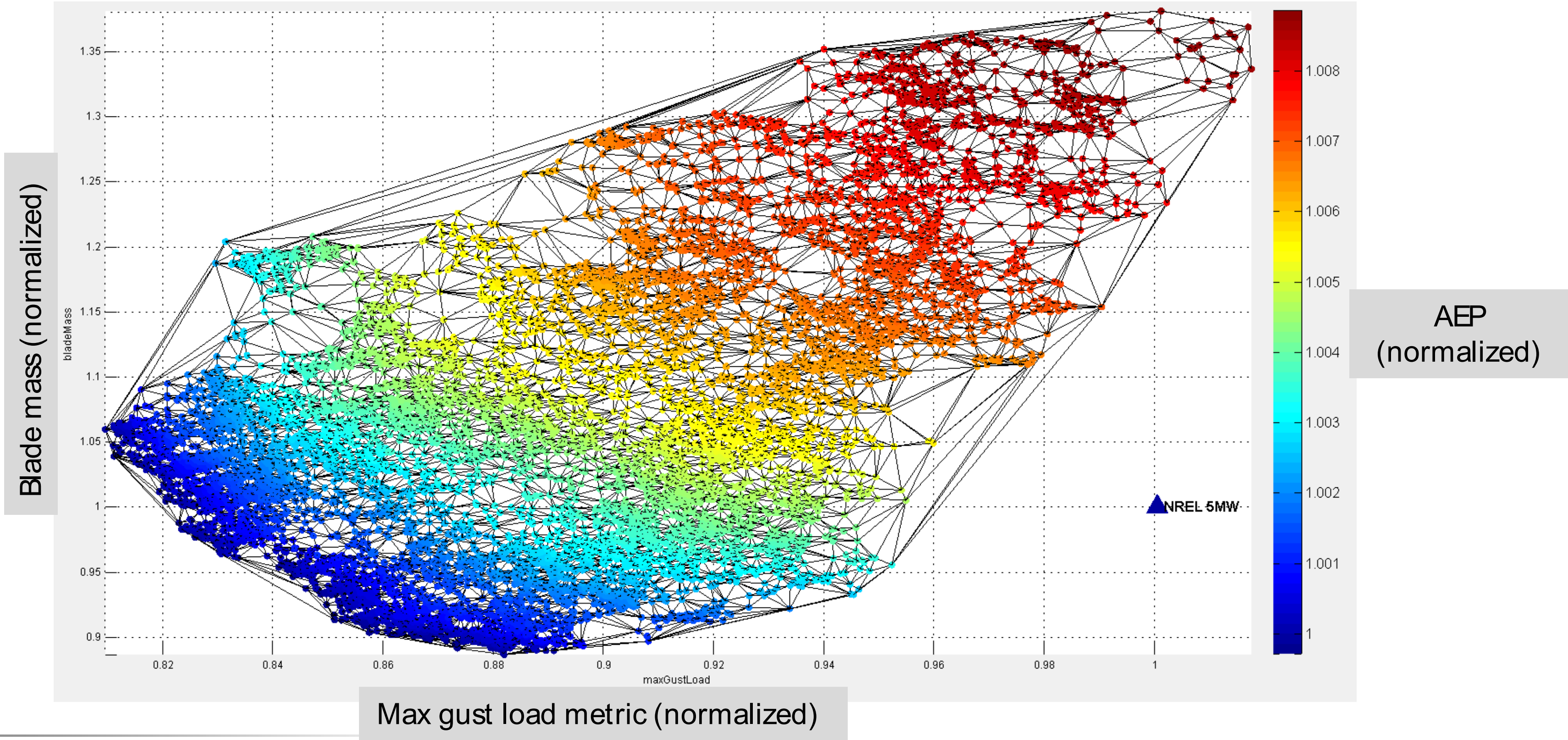
- NREL 5MW rotor as described in *NREL/TP-500-38060*
  http://www.nrel.gov/docs/fy09osti/38060.pdf J. Jonkman et. al.
- Spanwise distributions of relative thickness, twist and chord treated as free DOFs
- All other turbine parameters left as-is.
- 1A wind resource
- NREL 5MW evaluated using SWP *Integral Blade™* structural technology



Example Rotor Design: NREL 5MW

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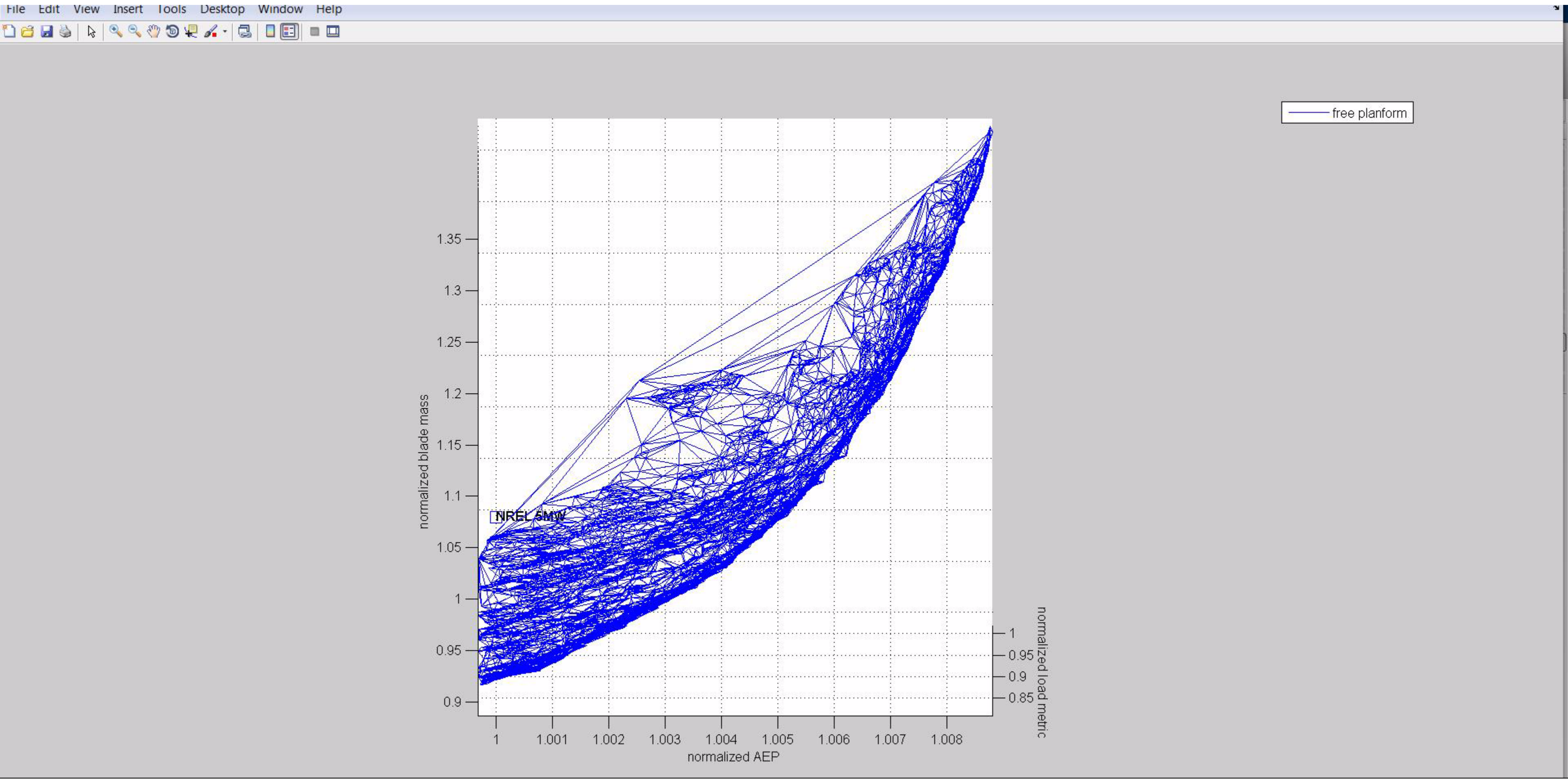
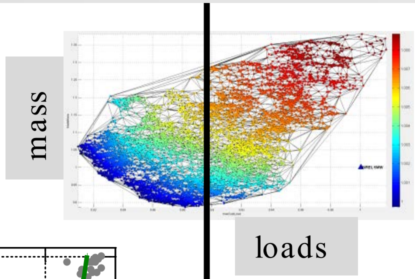
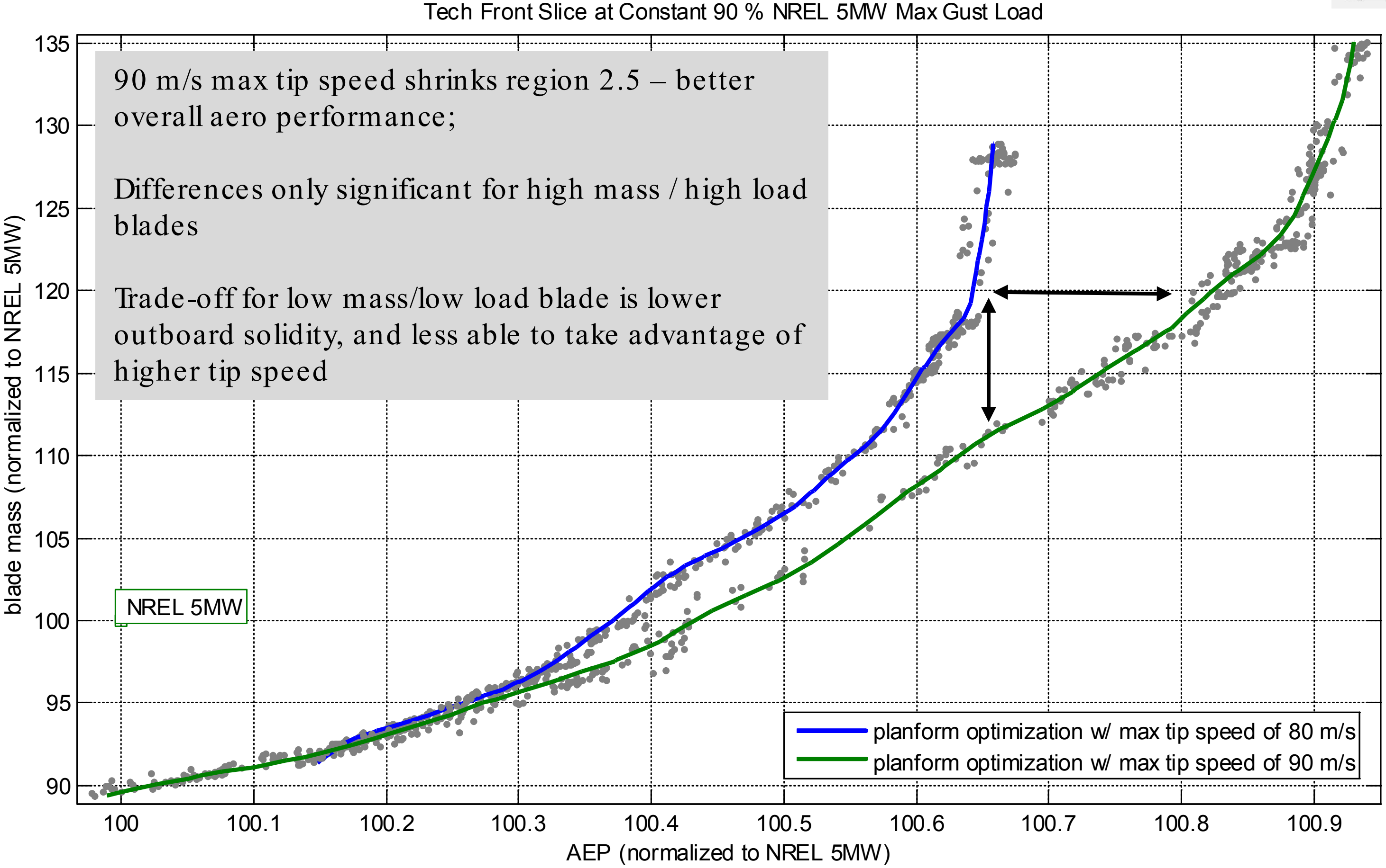


Comparison NREL 5MW Technology Fronts

- 80m/s vs. 90 m/s maximum tip speed planform design Pareto (technology) fronts

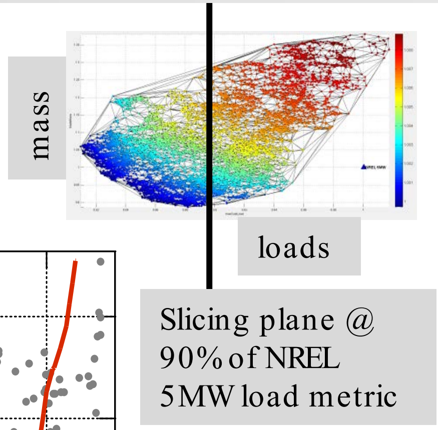


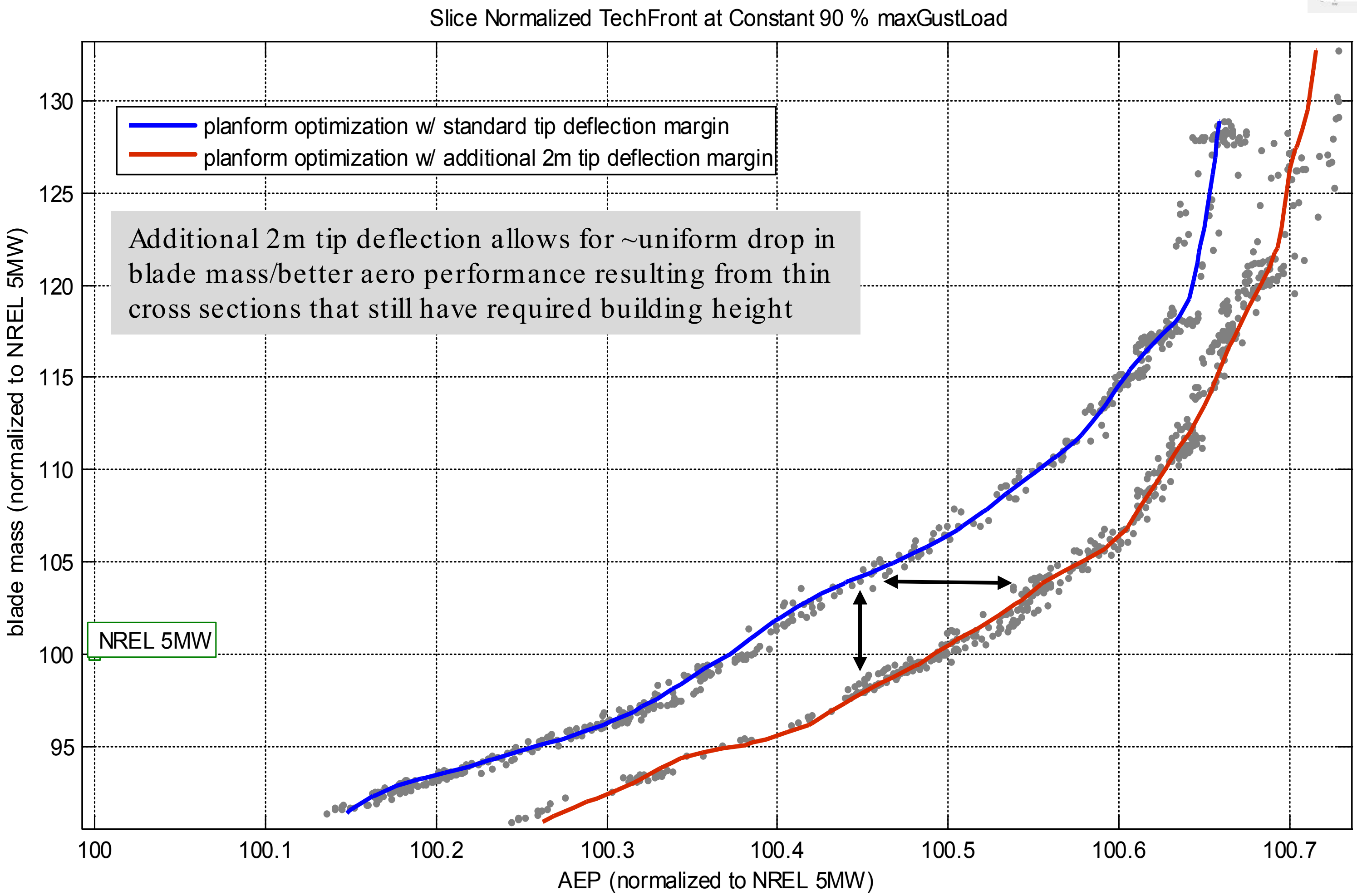
Slicing plane @ 90% of NREL 5MW load metric



Comparison NREL 5MW Technology Fronts

- Standard vs. 2m additional tip deflection margin planform design technology fronts.





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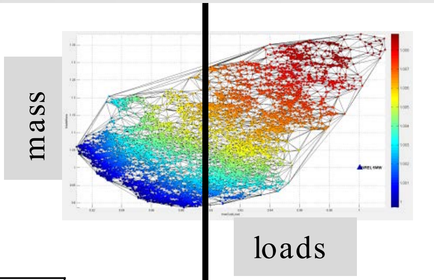
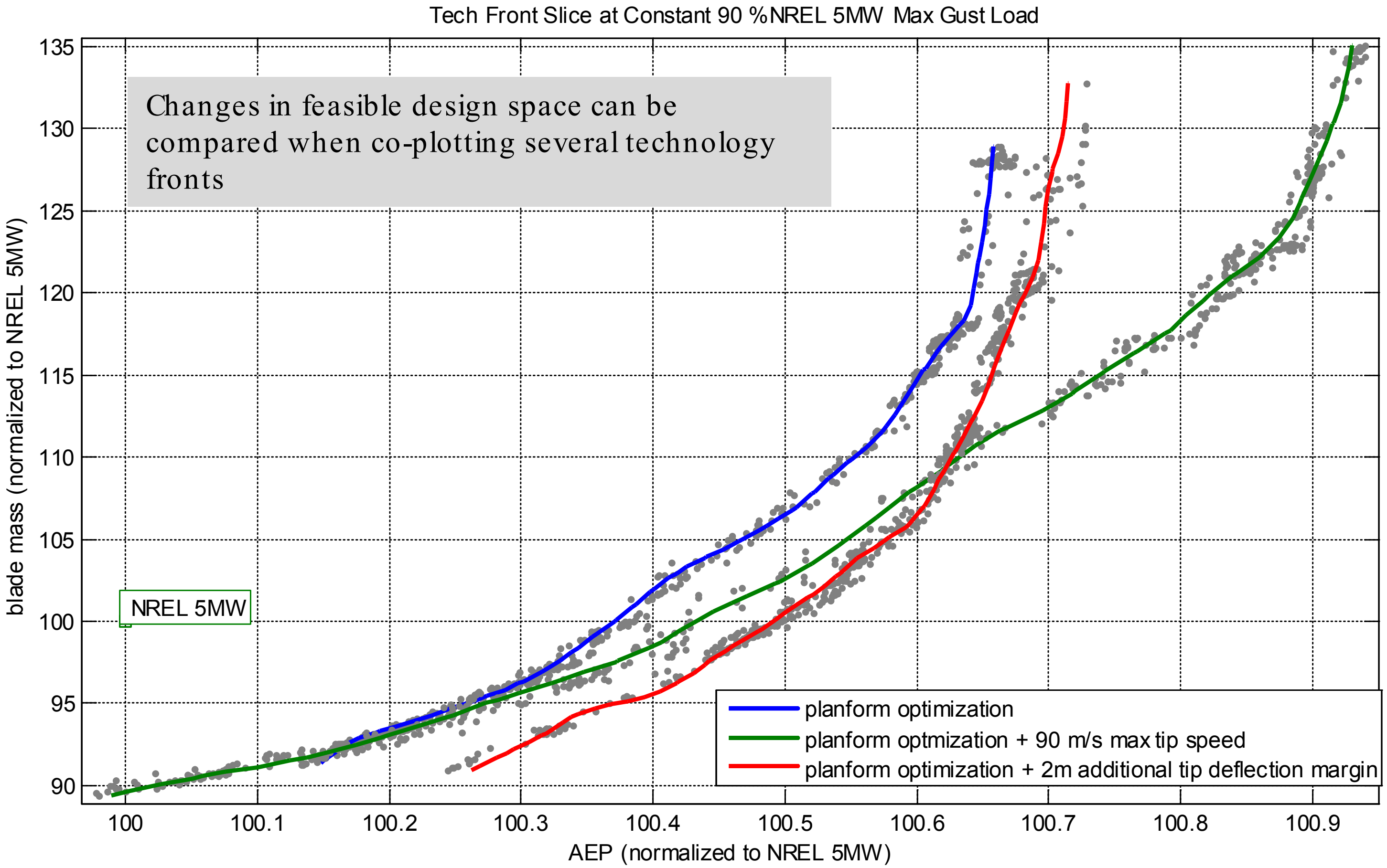
- Both 90 m/s and +2m tipDef planform fronts show vs. standard planform design front





Comparison NREL 5MW Technology Fronts

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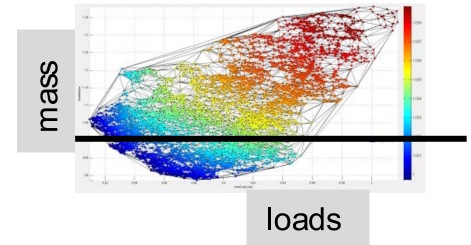
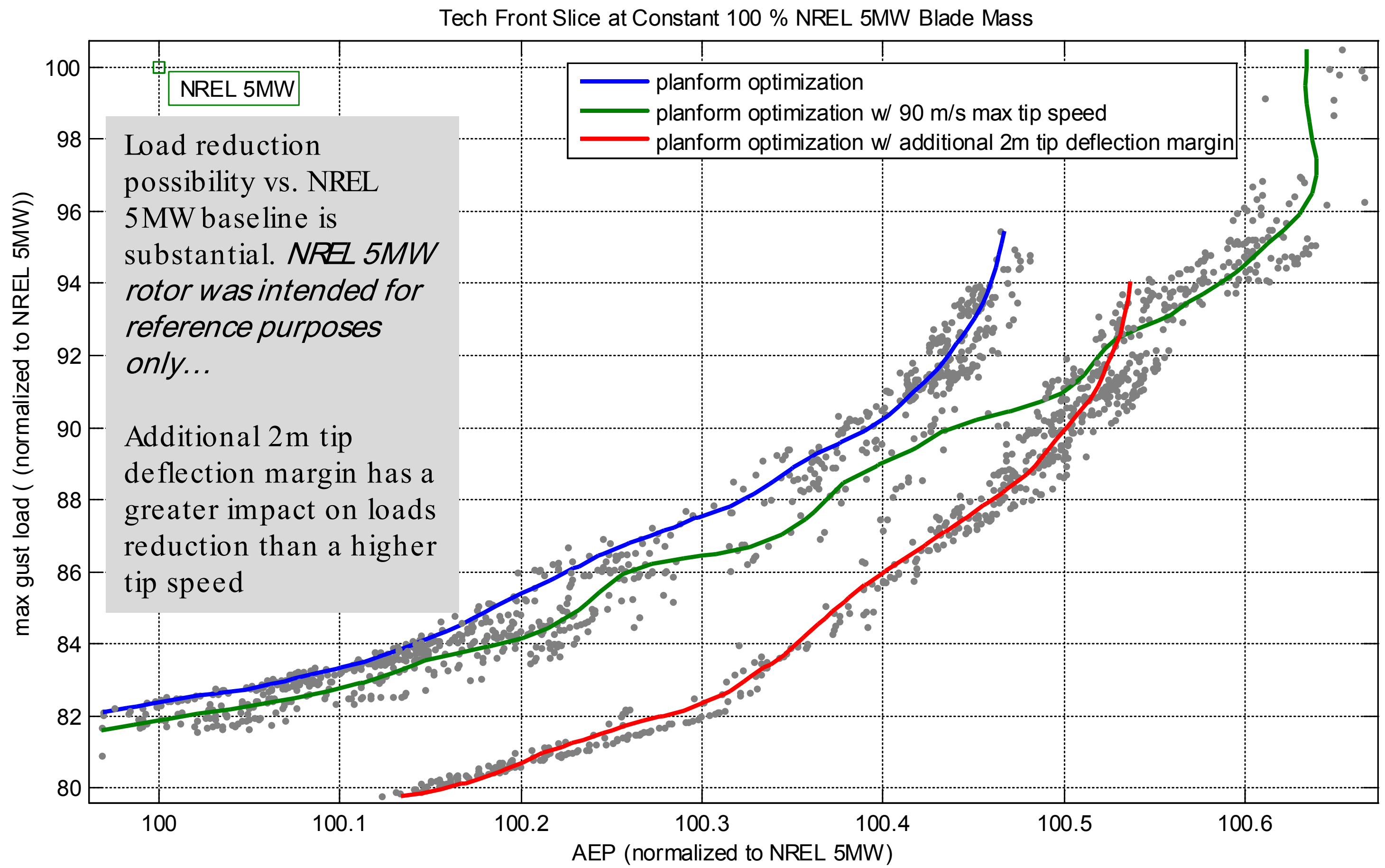
- Both 90 m/s and +2m tipDef planform fronts shown vs. standard planform design front when **sliced at a constant blade mass**



Slicing plane @ 100% of NREL 5MW blade mass metric



Example Rotor Design: NREL 5MW

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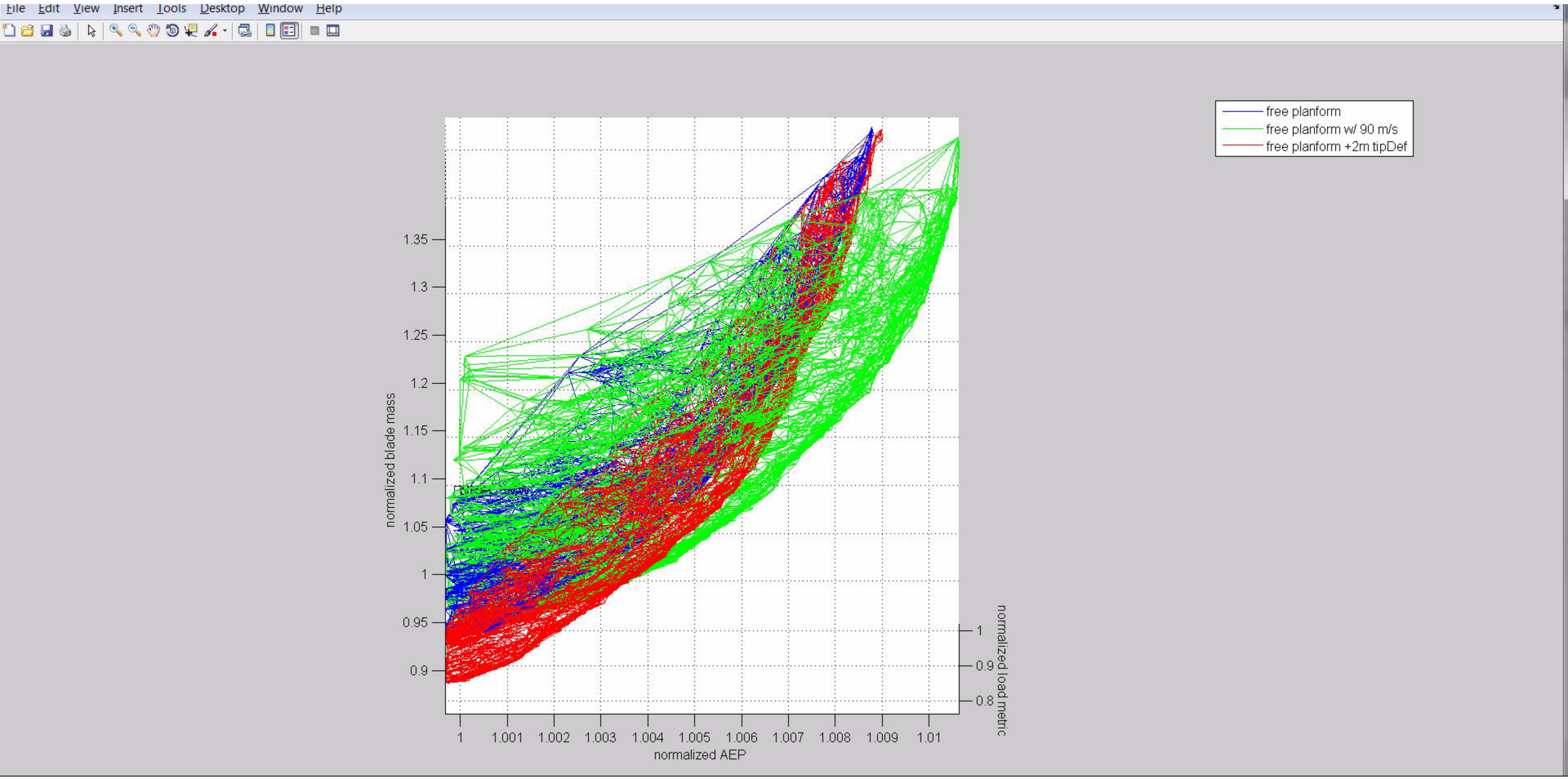

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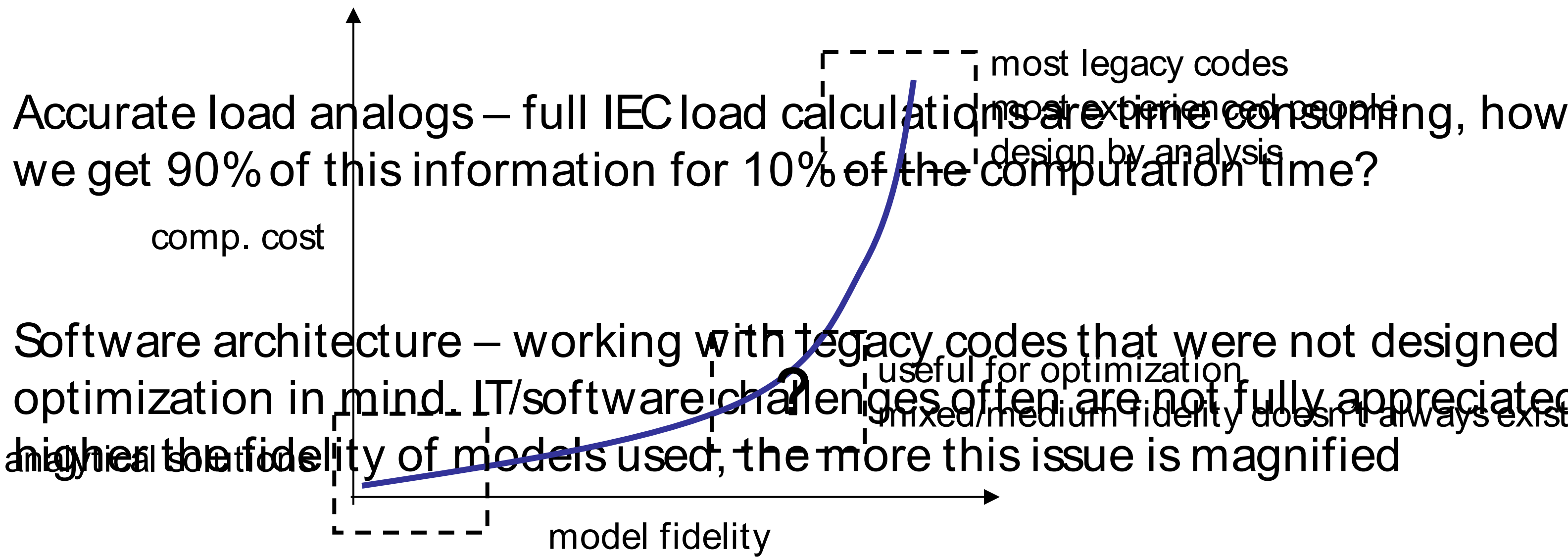
- Speed vs. fidelity trade-off OR cycle time vs. confidence level

- Maximizing engineering iterations <1 day cycle time

- Accurate load analogs – full IEC load calculations are time consuming, how can we get 90% of this information for 10% of the computation time?

- Software architecture – working with legacy codes that were not designed with optimization in mind. IT/software challenges often are not fully appreciated. The higher the fidelity of models used, the more this issue is magnified



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- The technique of Pareto front comparison has been demonstrated for an example NREL 5MW design space
- Pareto front comparison is useful for evaluating fully coupled impact of technology changes / system parameters on rotor design
- Expert knowledge can be used to inform/tune low and medium fidelity models that make wide ranging design space exploration and exploitation possible in a practical timeframe
- Avoid the rushing immediately to complex models/systems until lower fidelity representations have been exhausted *especially* when doing optimization
- MDO techniques are not push button – communication and expectations must be managed carefully
- Potential of SE for COE reduction is significant!

MDO Success Stories

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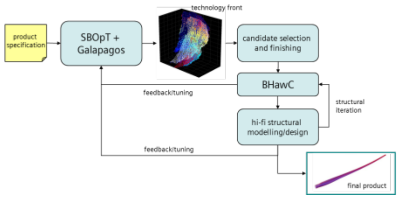
- SWT-6.0-154
- SWT-4.0-130
- SWT-3.0-108
- SWT-2.3-108



Thanks for your attention - Questions?

contact: kristian.dixon@siemens.com

Example Rotor Design: NREL 5MW

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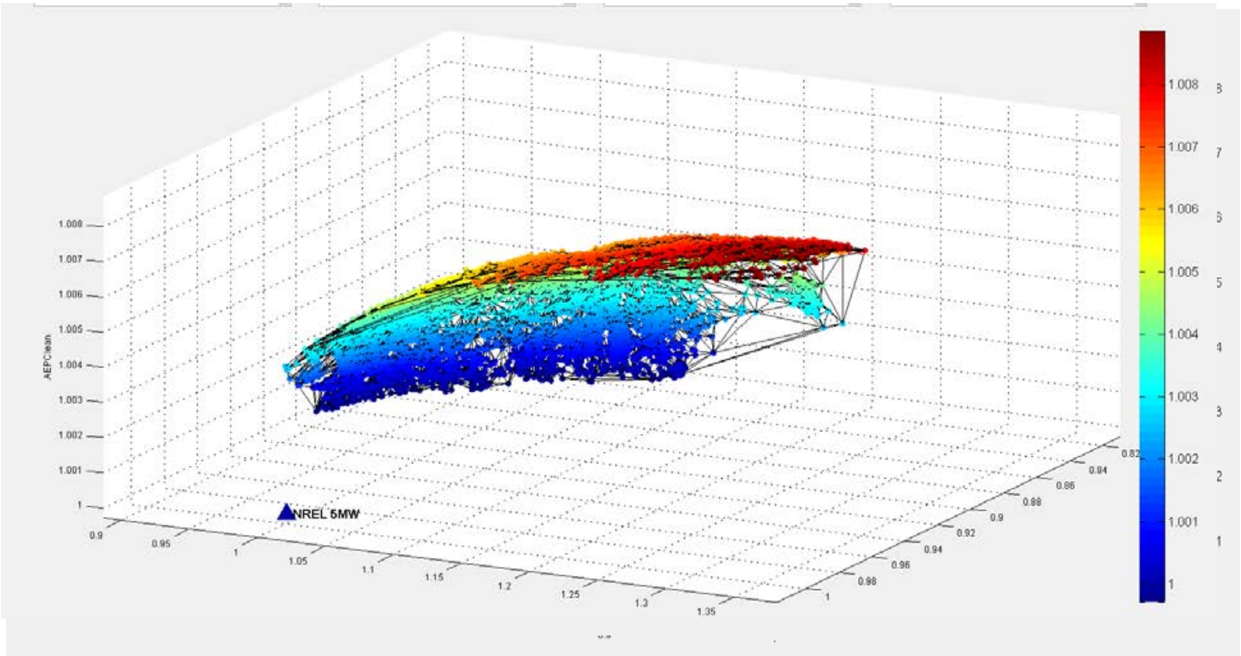

back-up poor-man's video in case ppt fails…