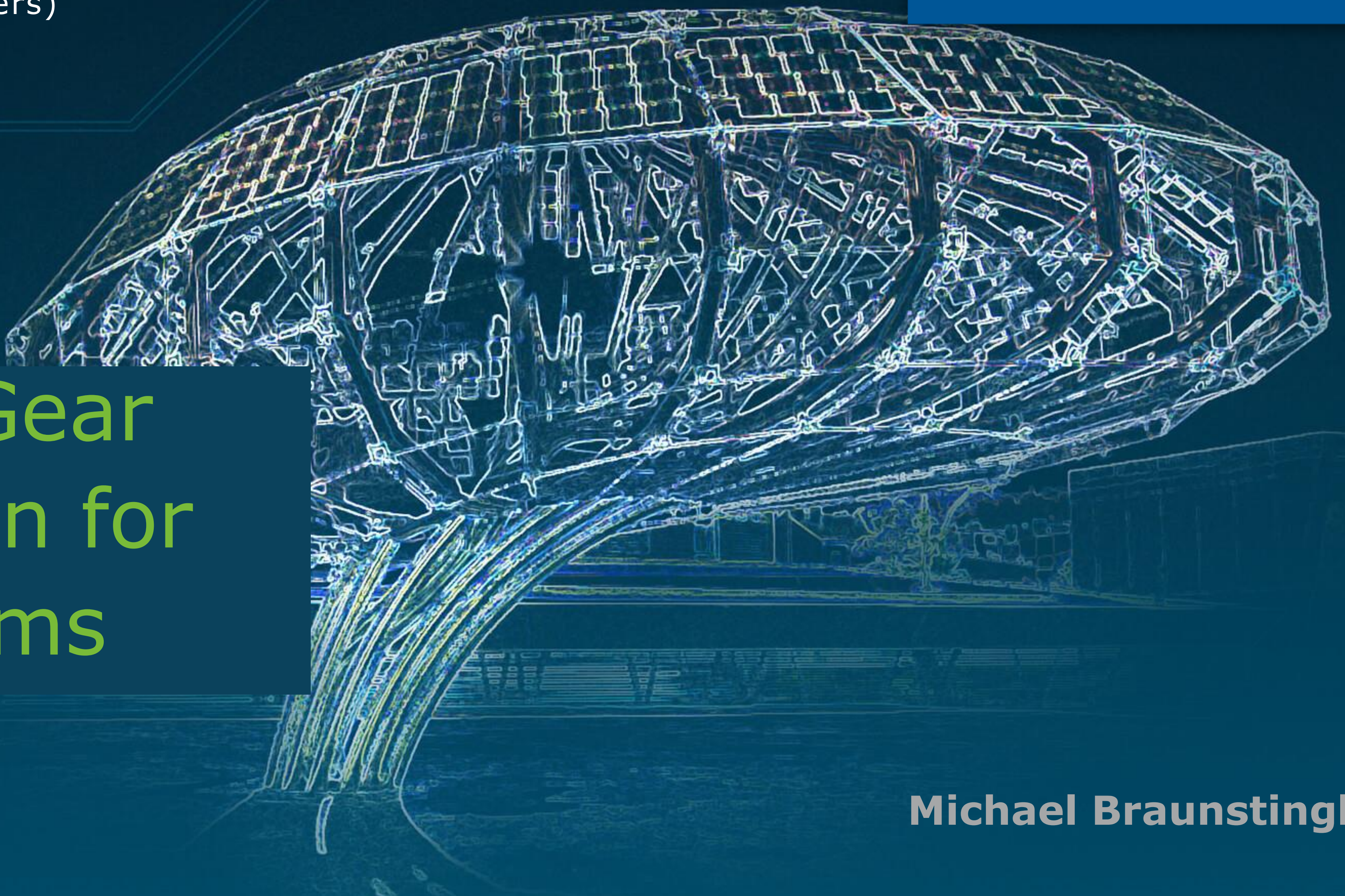
AVL List GmbH (Headquarters)



Advanced Gear Optimization for AWD Systems

Michael Braunstingl

Content

1. Introduction
- Gears in AWD Systems
- Why is the hypoid gear so difficult to optimize?
- Optimization Method: “Design of Experiment” (DOE)
- Evaluation of DOE Results

2. Simulation Models
- Base Variant Analysis Workflow
- Assembly Static Simulation Model
- Assembly Dynamic Simulation Model

3. Gear Optimization Workflow
- General Description
- Can a single tool handle the entire optimization?
- Macro Geometry Optimization
- Micro Geometry Optimization

4. Model Validation

5. Summary and Outlook

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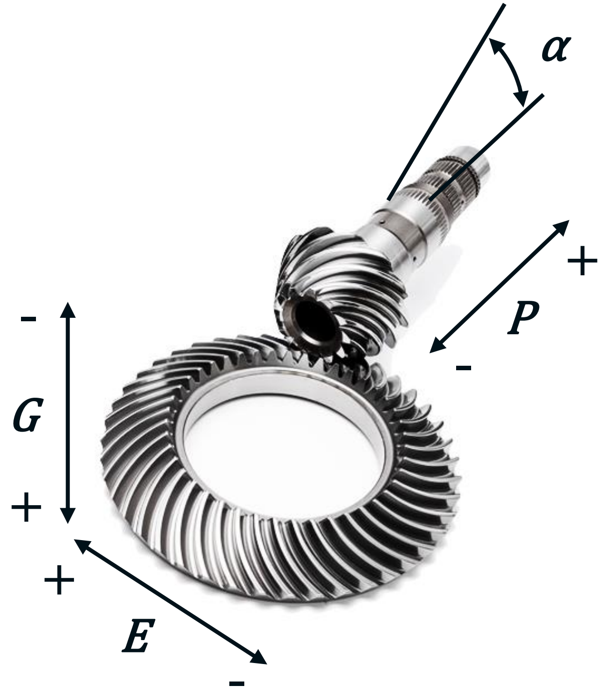
Introduction
Gears in AWD Systems

Variable speed transmission with cylindrical gears

- Parameters well understood
- Analytical tooth contact equations
- Simple production process
- Stable contact pattern with increasing load

Topic today: Differential transmission with <u>hypoid gears</u>

- Transfer very high loads
- Contact pattern varies with increasing load → "E, P, G, a"
- Tooth geometry defined by machine settings
- Complicated production processes
- Gear design based on "experience" with manual variation of parameters



Introduction

Why is the hypoid gear so difficult to optimize?

Cutting

Video: Hypoid Cutting (FH)

Define macro geometry

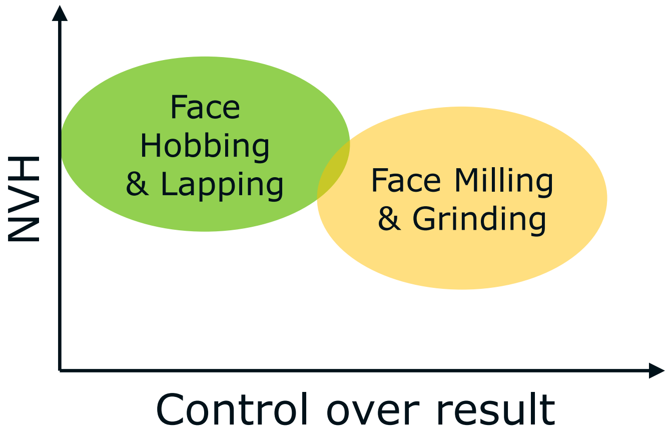
- Machine motion
- Cutter blade geometry (+ tolerances)

Heat Treatment

Improve load carrying capacity

- Introduces geometrical distortions

Lapping / Grinding



Define micro geometry

- Lapping as accelerated wear (non-deterministic)
- Better control over geometry with grinding

Introduction

Optimization Method: “Design of Experiment” (DOE)

Extremum problem ← Find the gear geometry variant that is robust against manufacturing tolerances, assembly errors, deflection

Input parameters → DOE variants → Hypersurface

Geometry definition:

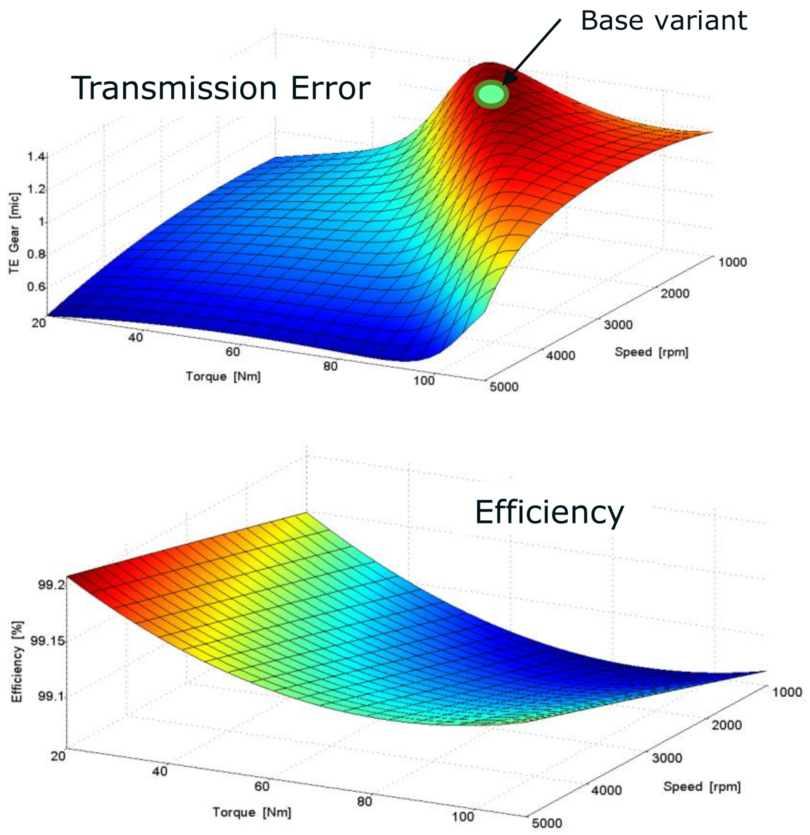
- Pressure angle
- Spiral angle
- Cutter head diameter
- Tooth height
- Tooth root radius
- ...

Disturbance:

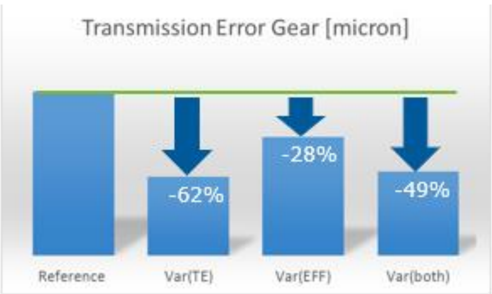
- Assembly Errors
- Manufacturing tolerances
- Temperature, Load (EPGa)

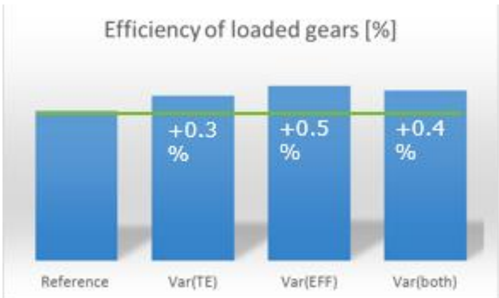
Output:

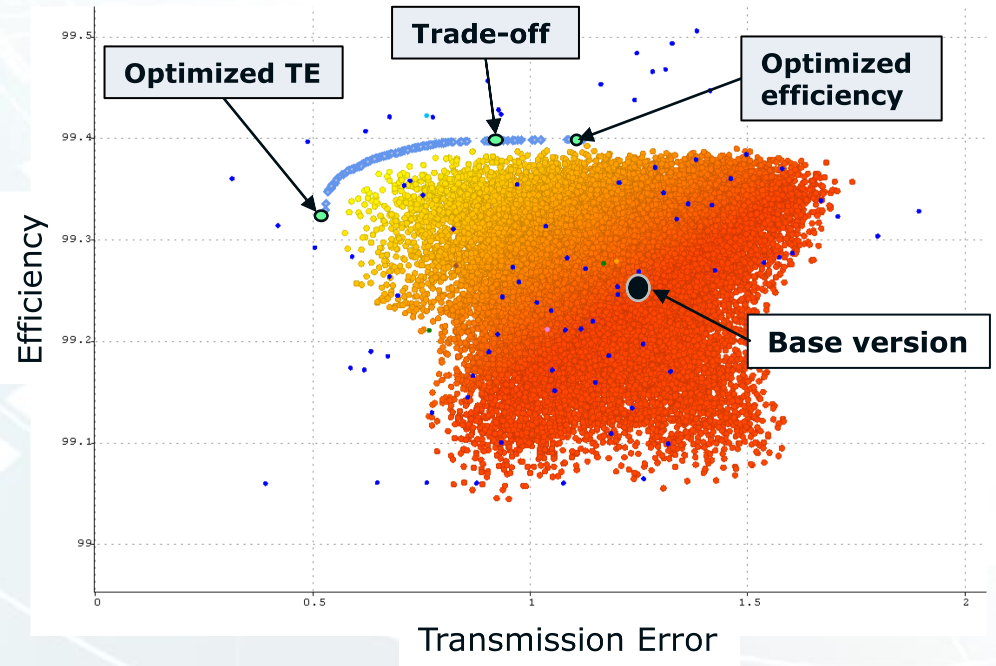
- TE, NVH
- Efficiency
- Life



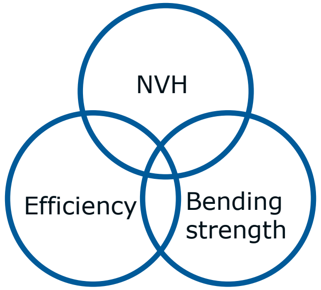
Introduction
Evaluation of DOE Results

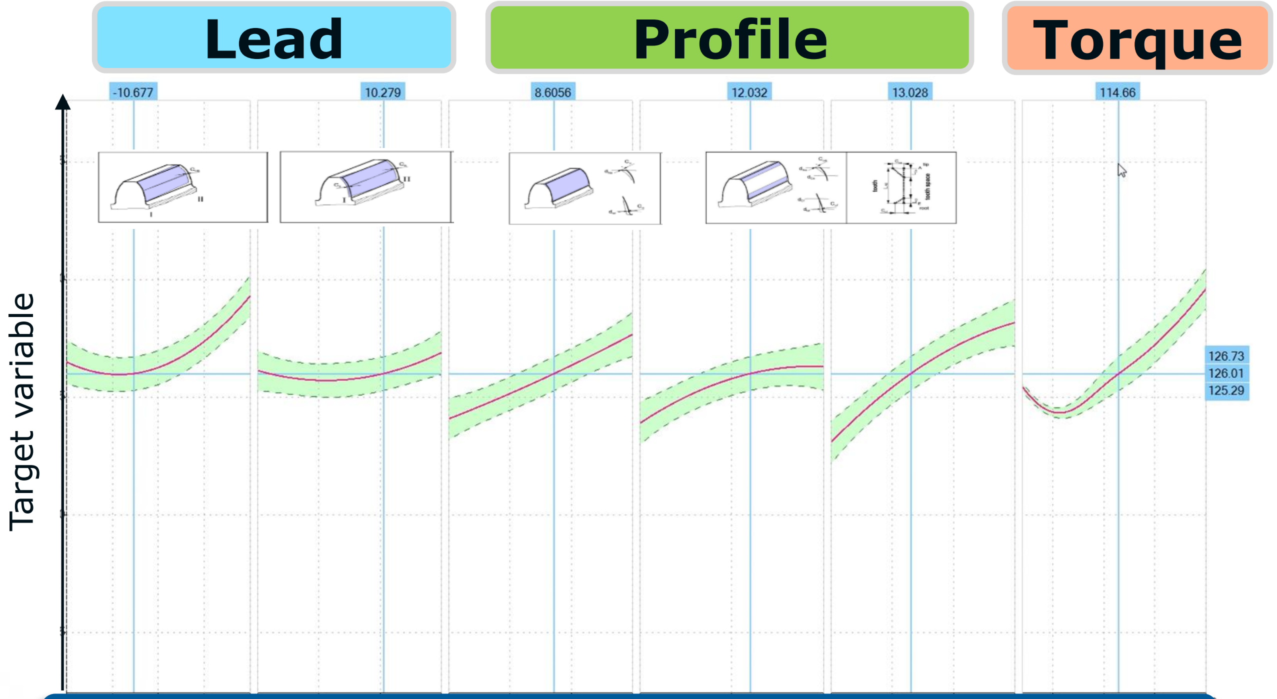






AVL CAMEO





Video: Selection of gear geometry parameters

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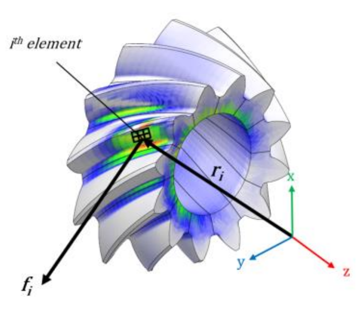
Base Variant Analysis Workflow

Load spectrum

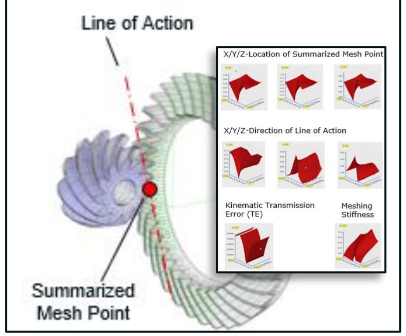
Hypoid geometry (.spa file)

Feedback loop

Loaded TCA
Ansol CALYX



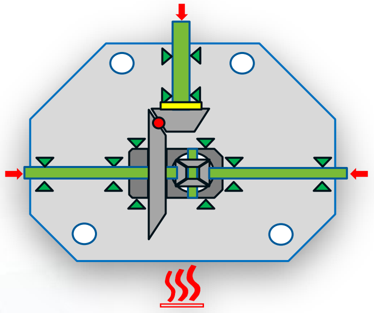
'Summarized mesh point' data



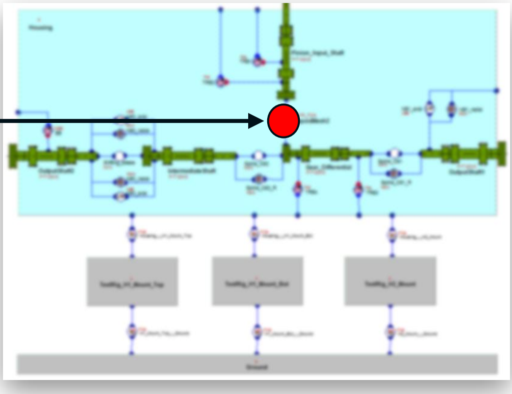
Gear deflection EPGa

@ certain loads eg:
- 30 %
+ 10 %
+ 50 %
+ 100 %

Assembly Model
Abaqus FEA

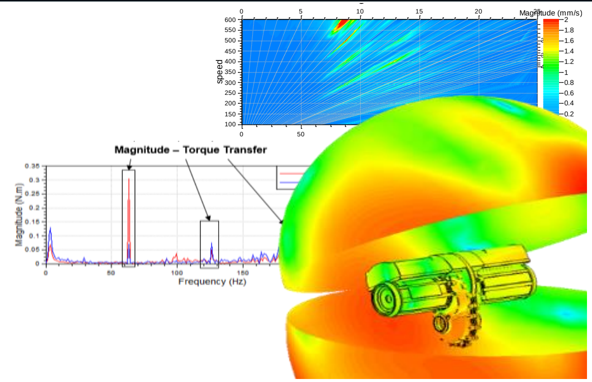


Testbed Model: Dynamic MBS
AVL EXCITE



- Block based model
- Condensed FE bodies
- Joints for bearings, gears, bushings

Noise vibration and harshness (NVH)

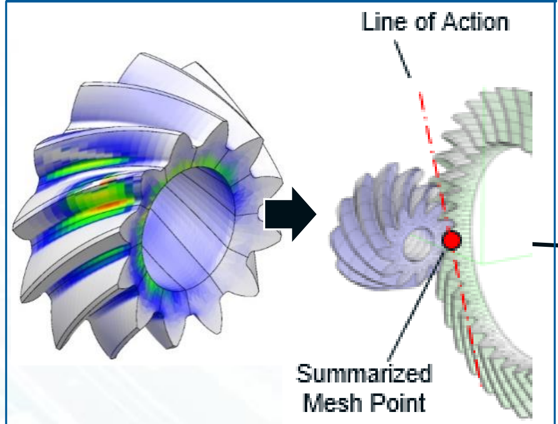


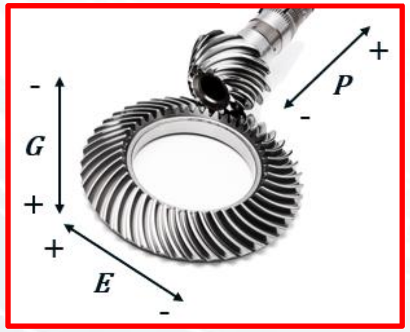
- Dynamic TE
- Campbell plots
- Structure-borne and airborne noise

Assembly Static Simulation Model

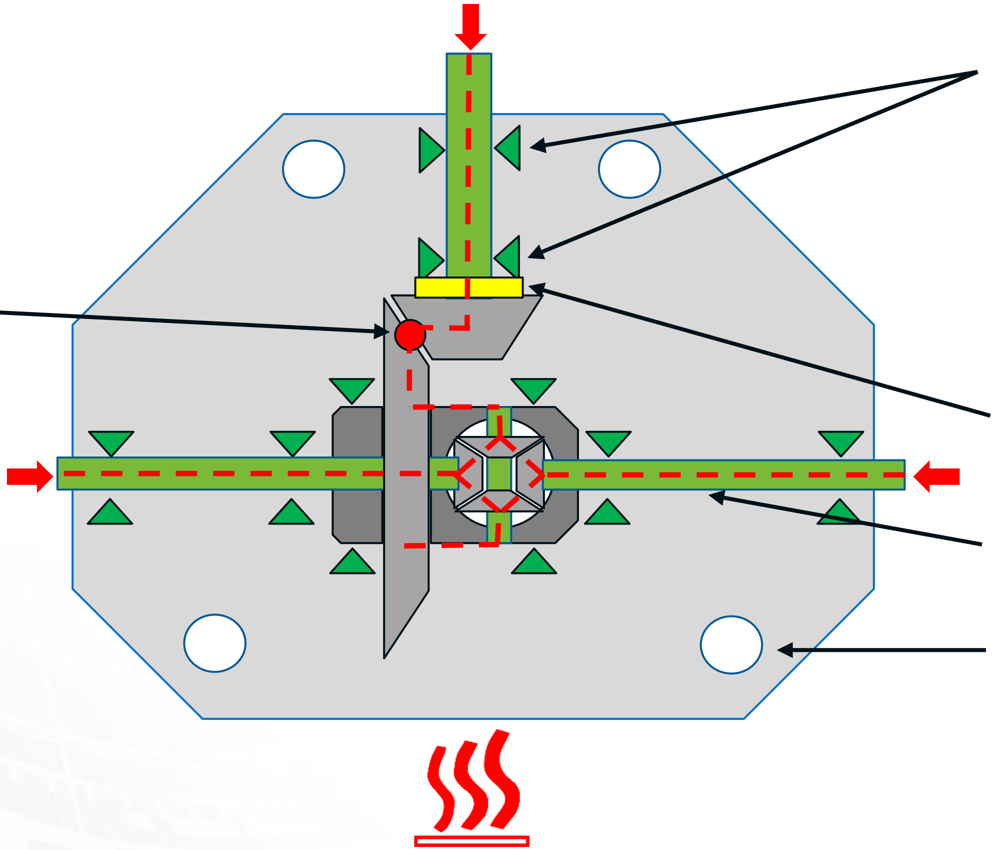
Simulia Abaqus FEA

Hypoid gear contact modelling at 'summarized mesh point' supported by numerical TCA in Finite Element solver

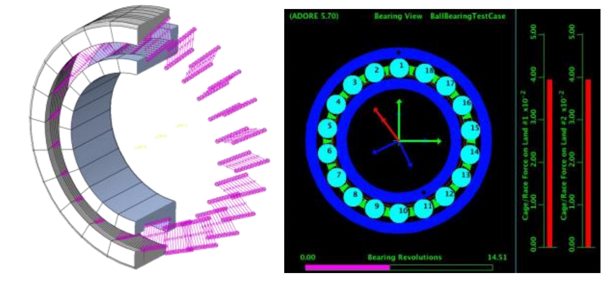




- Roller bearing
- Shaft
- Torque transfer path
- Bevel gear



Bearing stiffness modelling (preload, temperature, wear)



Plastic/elastic material properties (e.g. shims)

Shaft deflections

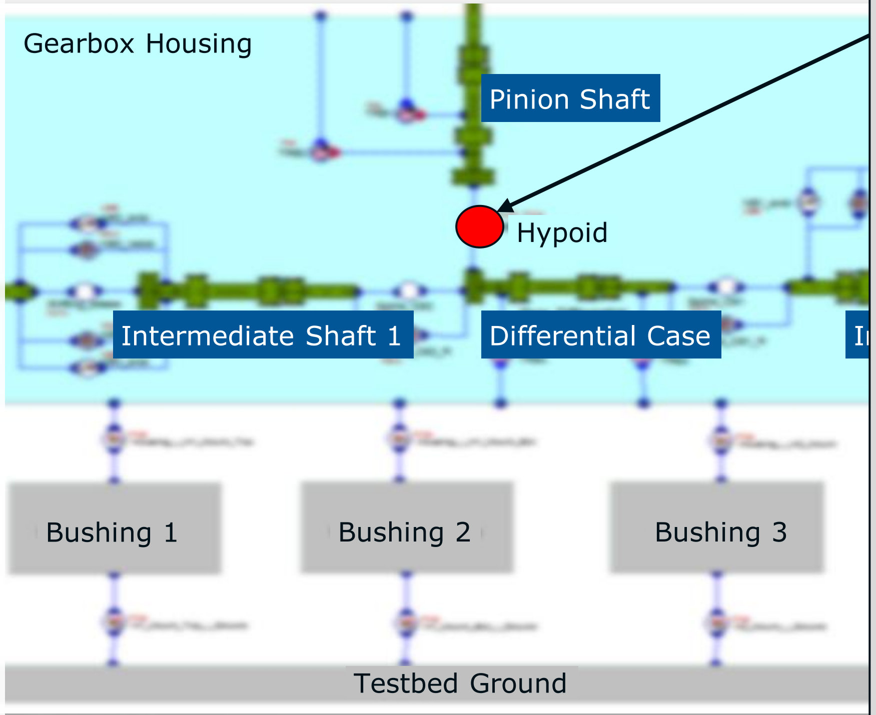
Housing with boundary conditions

- Constraints
- Bushings
- Thermal conditions

Assembly Dynamic Simulation Model
AVL EXCITE

AVL EXCITE is a block based multi body simulation tool using finite element flexible bodies

- Housing
- Shafts
- Rolling element bearings
- Flexible cylindrical gears (analytical solution)
- TCA joint (precalculated solution)

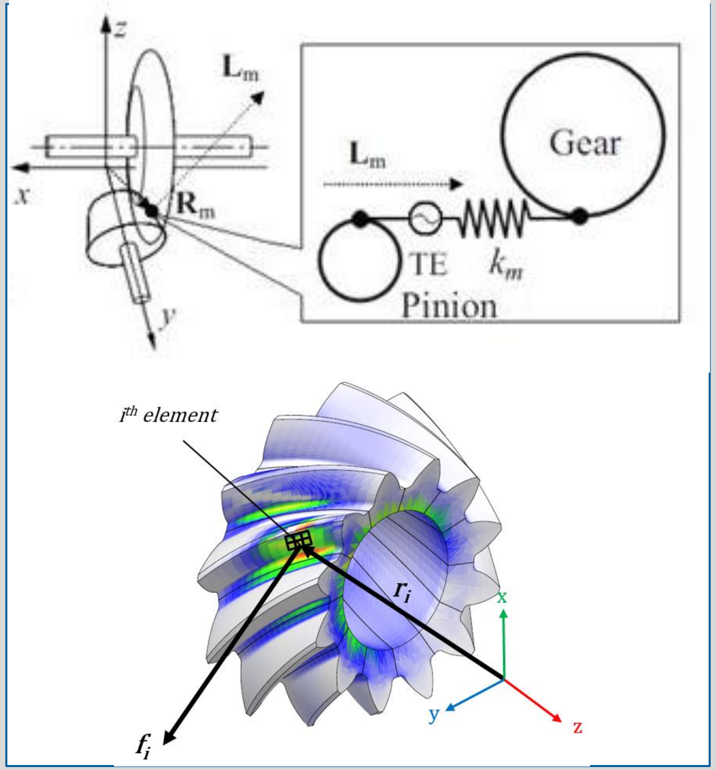


SHYP_TCA joint

Requires "summarized mesh point" data:

location, force, kinematic TE, meshing stiffness

Mesh force and torque are applied onto the condensed centroid nodes of FE parts.



Content

Introduction
Base Variant Analysis
Gear Optimization
Validation
Summary

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Gear Optimization Workflow
General Description

EAWD'19 | A4 | AVL

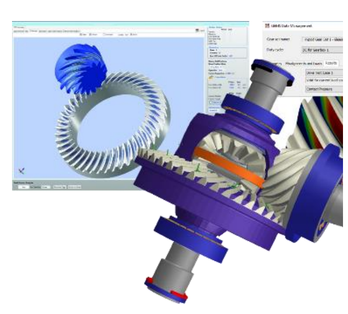
DOE plan
AVL CAMEO

Load, temperature (= EPGa)

Tooth geometry variations

~ 500-1000 variants

Unloaded TCA

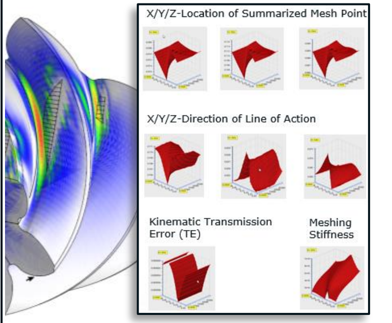


Preselection

Robustness against EPGa

50-100 variants remaining

Loaded TCA

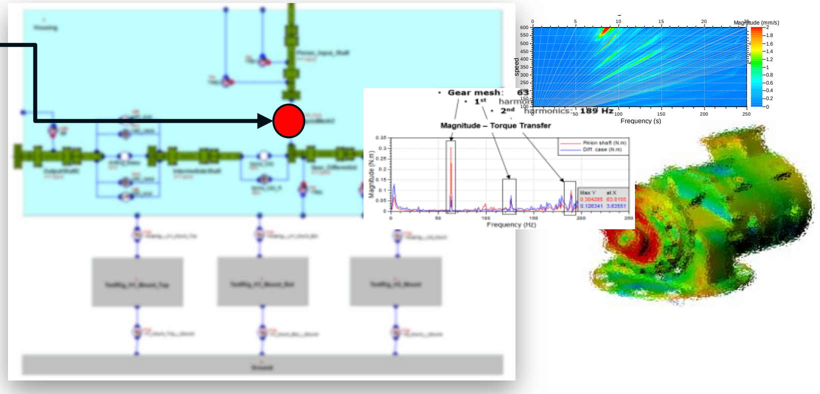


Preselection

Robustness against TE

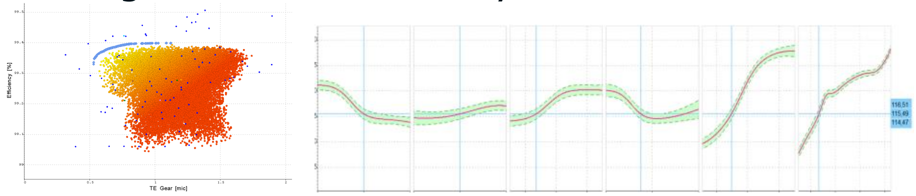
3-5 variants remaining

Testbed Model: Dynamic MBS
AVL EXCITE



Robustness Analysis

- Multi dimensional optimization / trade-off against NVH, efficiency, bending strength
- Target lowest sensitivity to EPGa deflection



Resulting geometry must be manufacturable

Gear Optimization Workflow

Can a single tool handle the entire optimization?

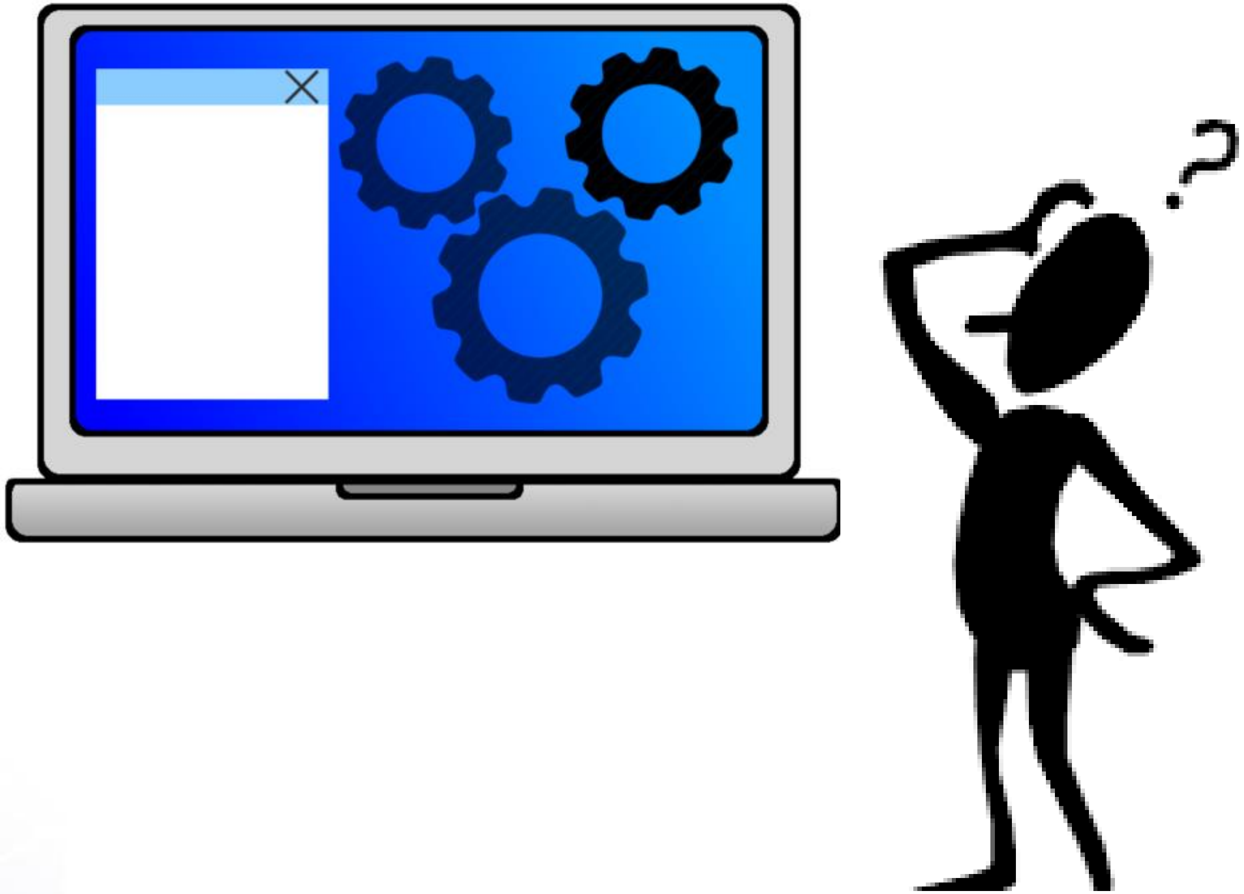
Commercially available gear design software

Advantages:

- Simple user interface
- Ease-off based optimization
- Quick response
- Manufacturability guaranteed

Disadvantages:

- No automation possible
- No external access to LTCA results
- Impossible to perform the entire DOE process



Combination of tools necessary

Gear Optimization Workflow

Macro Geometry

Introduction | Base Variant Analysis | **Gear Optimization** | Validation | Summary

Abaqus FEA → EPGa → **Unloaded TCA** → .spa EPGa → **Loaded TCA** → Look-up Tables → **Dynamics**

From base variant:

- EPGa variation space (load, temperature)

+

DOE → Machine settings

Input:

- 5-6 geometry parameters

Tolerance study:

- Variation of machine settings

Gleason GEMS

1. Design of gear macro and micro geometry

- Consideration of manufacturing tolerances by applying deviations in machine settings

2. Analysis of:

- Geometrical contact pattern (Ease-off based)
- Kinematic transmission error

3. Processing automation by hijacking KissSoft / GEMS interface

4. Manufacturability guaranteed

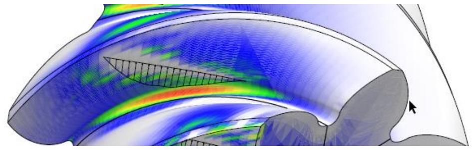
Preselection: Robustness against EPGa

Ansol CALYX

1. Tooth bending strength

2. EXPORT.DAT:

- Time based, local results



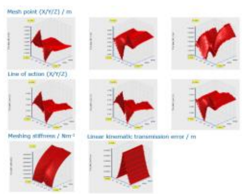
AVL Python Scripts

3. Post-processing of TCA results:

- Analytical lubrication model
- Flank damage models

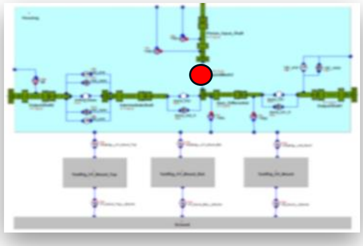
4. Loaded and kinematic transmission error

5. AVL EXCITE look-up tables

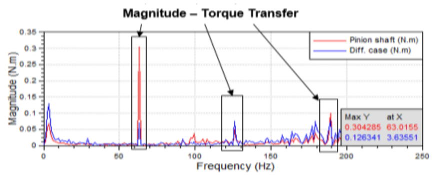


Preselection: Robustness against NVH potential

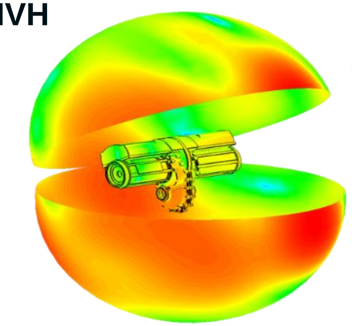
AVL EXCITE



1. Dynamic transmission error



2. NVH



Gear Optimization Workflow

Micro Geometry

Introduction | Base Variant Analysis | **Gear Optimization** | Validation | Additional models

Abaqus FEA → EPGa → **Unloaded TCA** → .spa EPGa → **LTCA** → Look-up Tables → **Dynamics**

From base variant:
- EPGa variation space (load, temperature)

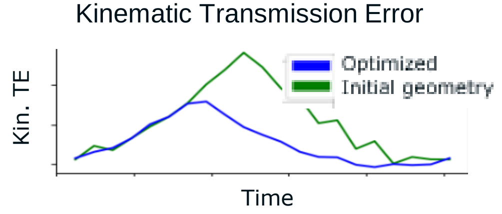
+

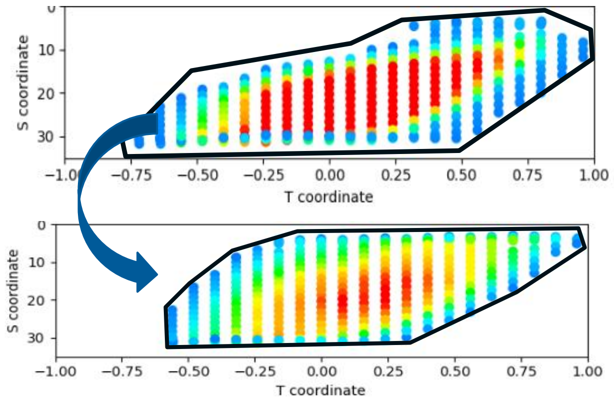
Optimized macro geometry → **LTCA results**

3 - 5 variants only

AVL Python Script / Winkler Mattress Model based TCA

1. **Contact pattern and transmission error optimization by applying local flank perturbations**



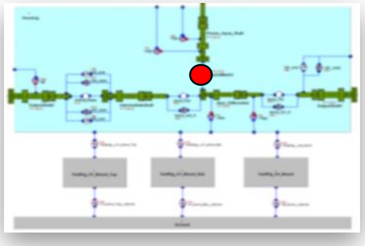


2. **Feedback of flank deviation information into GEMS**

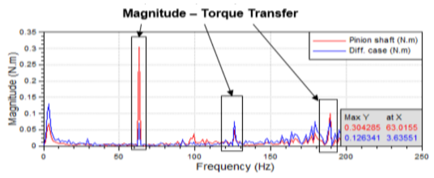
KISSsoft GEMS

3. **Manufacturability guaranteed**

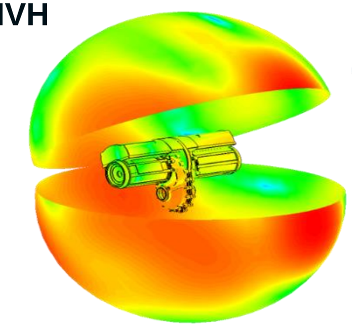
AVL EXCITE



1. **Dynamic transmission error**



2. **NVH**



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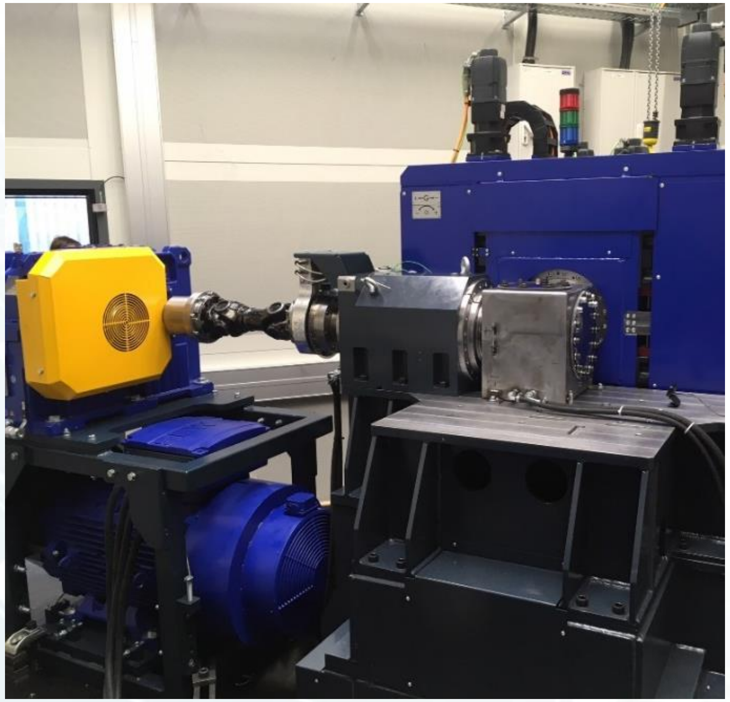
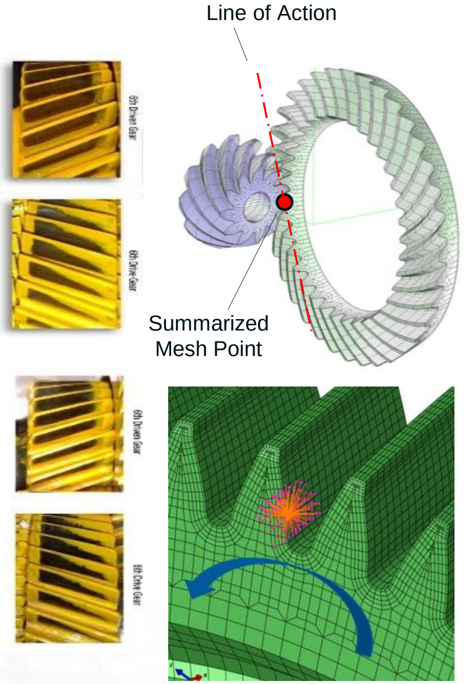
AVL Validiation Test Rig

Hypoid Gear Component Testing

Simulation → Specialized Gear Rig → Validation





Test bed dedicated for model validation by isolating gear pair failures

Benefits

Goal: Reduce development time	▪ AVL philospophy: Accurate modelling reduces time required in design and prototyping
Validation	▪ Improved control over gear contact control and additional measurements ▪ Isolation of gear pair failure modes from axle assembly
Improved product quality	▪ Quality control on component level: NVH, root bending life, surface and subsurface damage, efficiency

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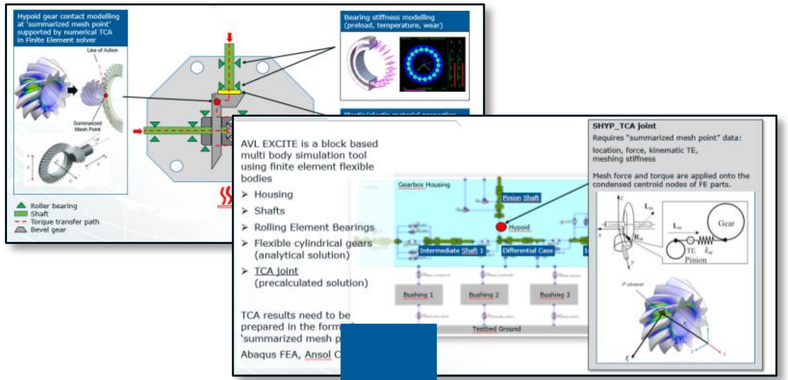
Workflow Summary

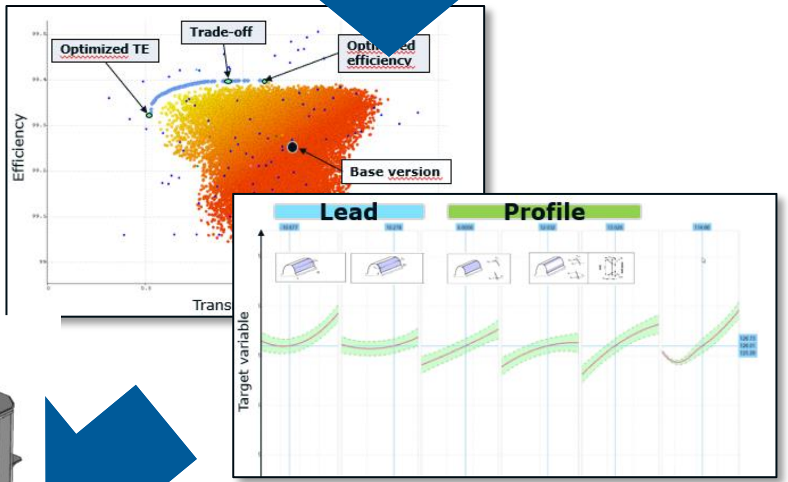
1. **Customer request for optimization**

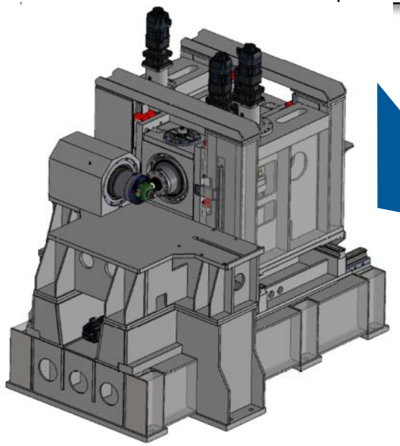
2. **Base variant analysis**
   - Input: Initial gear geometry, load spectrum
   - Output: EPGa as function of load and temperature

3. **Optimization by Design of Experiment (DOE)**
   - Input: Variation of EPGa and gear geometry parameters (+ disturbances)
   - Output: Hypersurfaces for target variables; Pareto-optimum; intersection plots

4. **Model validation**
   - Isolation of gear pair failure modes
   - Controlled environment

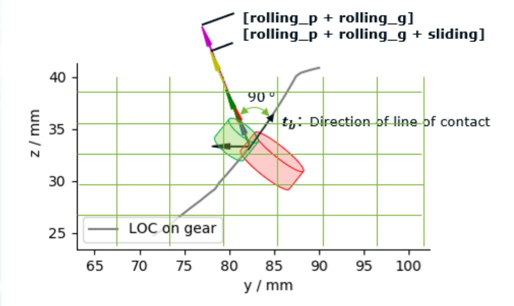




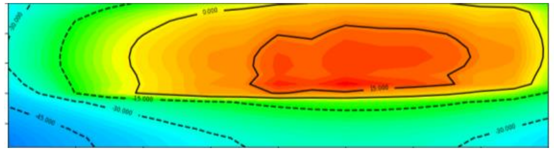


Outlook

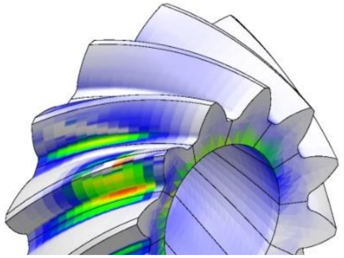
Lubricated Contact Analysis (LLTCA)
AVL Python Script
- Analytical EHL formulation
- Surface shear stress
- Thermal stress



Surface damage models
AVL Python Script
- Fretting / scuffing
- Surface wear

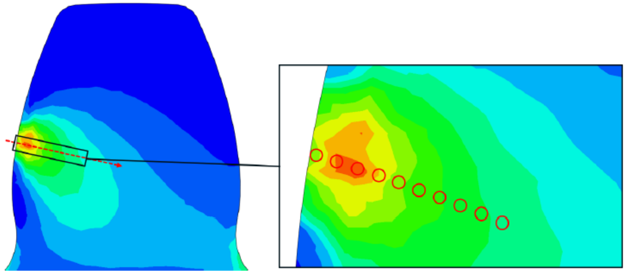


Loaded TCA

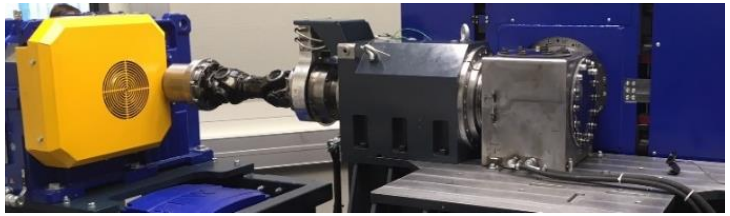


- Tooth bending strength
- Geometrical contact conditions
- Dry contact pressure

Pitting and Spalling safety
Abaqus FEA / AVL Python Script
- Mapped contact conditions from LLTCA
- Enhanced material model
- Subsurface crack initiation life



Model Validation
AVL's dedicated specialized gear rig



Manufacturing Tolerances
CALYX LTCA
- Coordinate Measurement Machine (CMM) results
- Effect on root bending life

Thank You

www.avl.com