Tall Tower Optimization

Siemens Corporation, Corporate Technology
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Siemens Corporation, Corporate Technology

Overview

- Objectives and Siemens' Role
- Optimization Work Flow
- FEA Using Siemens NX Open
- Optimization Results
- Summary and Conclusions

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Roles and Objectives

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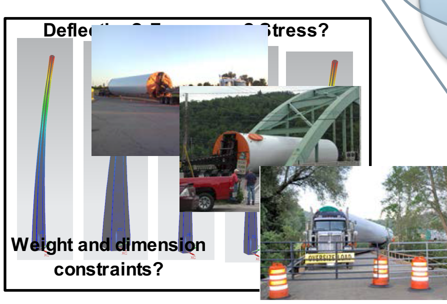
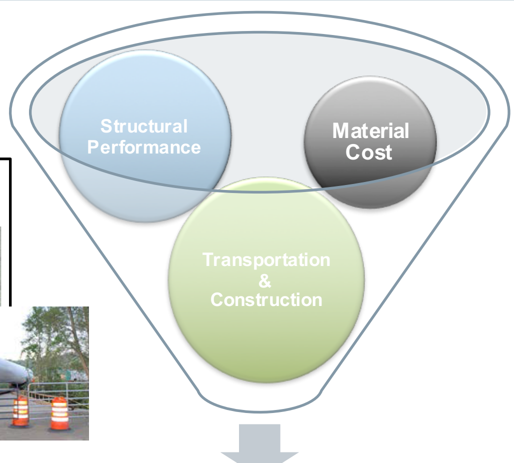
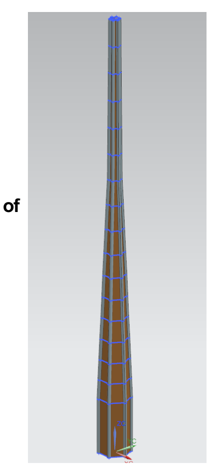
Why Tower Optimization?





Material Cost of Panels? Columns?



Goal: Explore better design solution with engineering confidence

How can we ensure we have the best design?

Siemens's Role

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Siemens Wind Power

- Initial load estimates
- Tower design constraints (nacelle interface, blade clearance)
- Tower frequency, deflection range

Siemens Corporate Technology (CT RDA AUC PSM)

- Design exploration and optimization
- Automate FEA for design variations

Tall Tower Optimization Formulation

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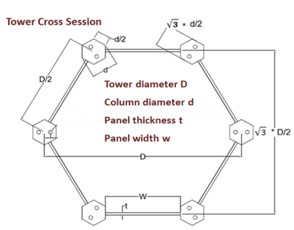

Optimization Problem

Objective Function:

$$Tower\ Cost = \mathrm{f}(\boldsymbol{H}, \boldsymbol{D}, \boldsymbol{d}, n, \boldsymbol{t}, \mathbf{Mat})$$

Constraints

Structural Constraints
- Deflection Limit
- Frequency
- Section Moment Capability
- Section Stress

Geometric Dimension Limit

Transportation Constraints
- Weight, length, width

Construction Constraints
- Section weight

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Optimization Workflow

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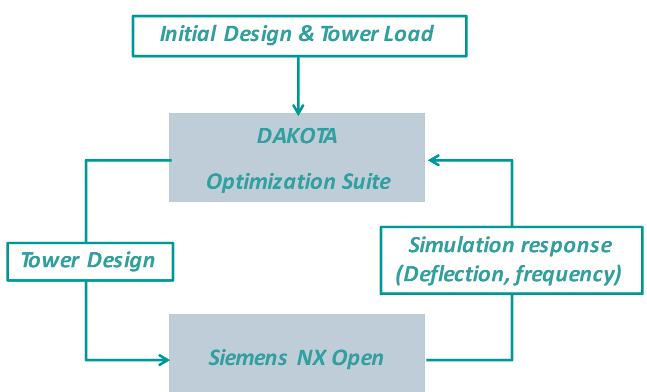
Overall Workflow



Workflow Details

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Integrate NX Nastran capability with DAKOTA optimization interface

➢ **Explore better design solution with engineering confidence**

DAKOTA

Genetic Algorithm

- ➢ Gradient-free method
- ➢ Population-based search
- ➢ Parallelized
- ➢ Simulate the evolution power in natural selection (Selection, Crossover, Mutation)

NX Open

NX Nastran

- ➢ Siemens PLM software's NX CAE and Nastran tools
- ➢ Parameterized CAD Design
- ➢ SOL 101 and 103 for structural analysis
- ➢ NX Open software to customize tower design and automatic FEA analysis

Workflow Details

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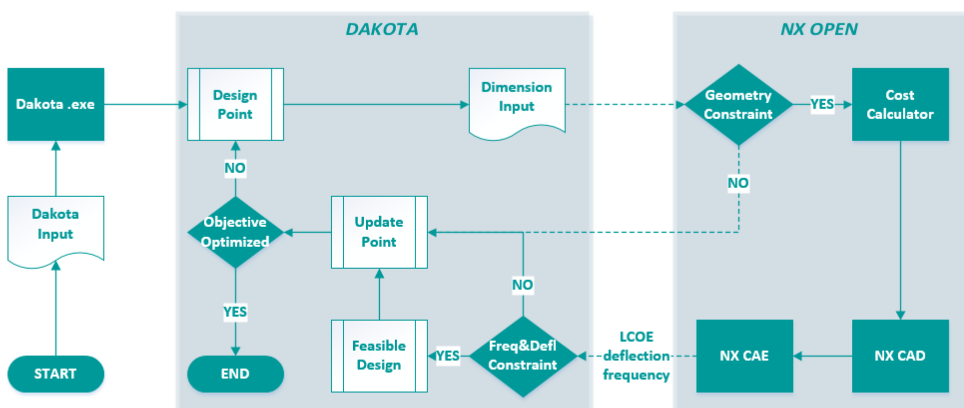

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FEA Using Siemens NX Open

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NX Open → CAD and CAE

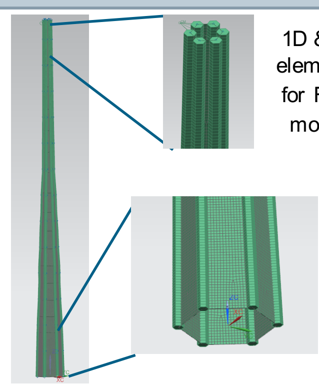
- Automatic creation of parameterized CAD model → Dimensions encoded in NX expressions to allow easy update
- Number of sections can be varied as well

Design variables
- •Tower diameter
- •Column diameter
- •No. of strands
- •Panel thickness
- •Section height
- •No. of sections

Panel and column volume

Valid Design?

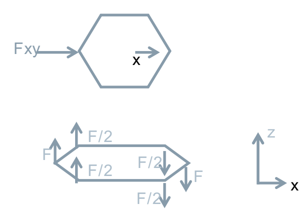
Creation of FEA Model



1D &2D elements for FEA model

FEA Analysis

Boundary conditions
SOL 101 Linear Statics → Deflection
- Fxy
- Mxy



SOL 103 Real Eigenvalues → Frequency
- Gravity

Deflection and Frequency

Optimization Setup (FEA Results Using NX CAE)

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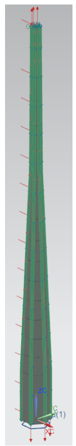
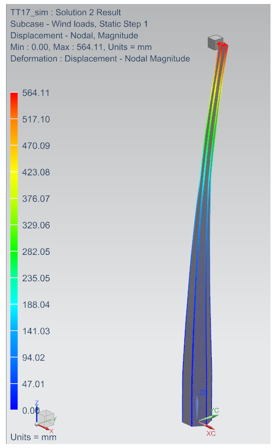
Initial Design





Tower D = 8.87 – 31.03 ft
Column d = 3.59 – 3.83 ft
No. of strands = 46

Total Panel Vol. (ft^3) = 5671
Total Column Vol. (ft^3) = 23394

Max. deflection = 564.11 mm
Frequency = 0.318 Hz

Tower Cost($) = 2.44e+006
LCOE($/MWh) = 35.86

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Optimization Results

Optimization Results – More cost efficiency solution

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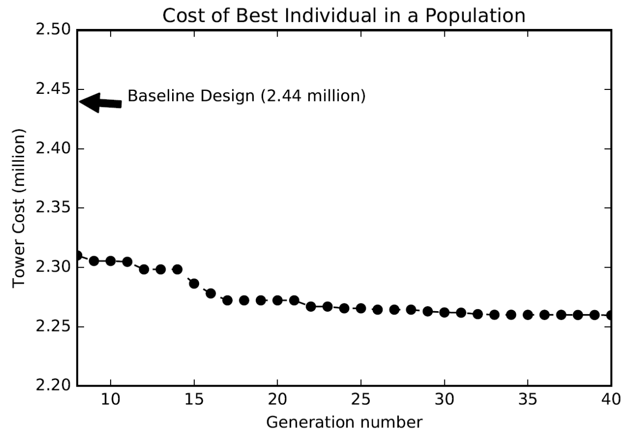
Genetic algorithm parameter settings

Population number	200
Generation number	40
Crossover rate	0.85
Mutation rate	0.15

Optimization case study run:

- 20 hours on 8 processors parallel simulation
- Optimal design showed 7.3% lower cost than baseline tower design, optimal total cost is reduced to 2.259 million.



Optimization results – Frequency and Deflection analysis

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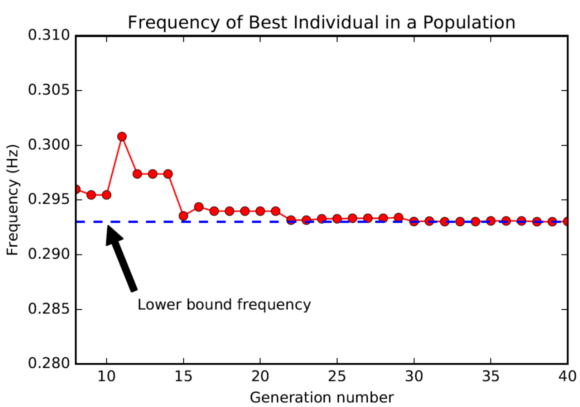
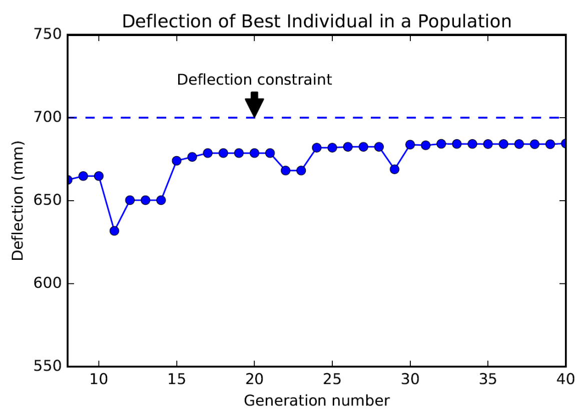
- Record the frequency and deflection constraint function evaluations as optimization evolves





Lower bound frequency constraint is governing the optimal design solution

Initial Design VS Optimized Design

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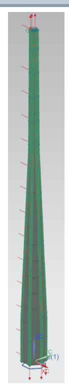
17 Sections; Tower height = 450.6ft ; Panel thickness = 0.33 – 0.42 ft

Initial Design



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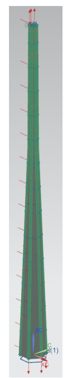
Max. deflection = 564.11 mm
Frequency = 0.318 Hz
Tower Cost($) = 2.44e+006
LCOE($/MWh) = 35.86

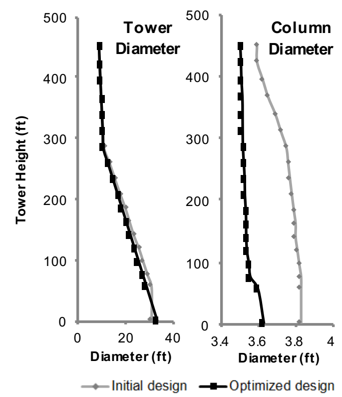
Optimized Design



Tower D = 8.90 – 33.11 ft
Column d = 3.50 – 3.63 ft
No. of strands = 45

Total Panel Vol. (ft^3) = 5501
Total Column Vol. (ft^3) = 20680

Max. deflection = 684.73 mm
Frequency = 0.293 Hz
Tower Cost($) = 2.26e+006
LCOE($/MWh) = 35.17



Optimization results – Plotting multiple design objectives

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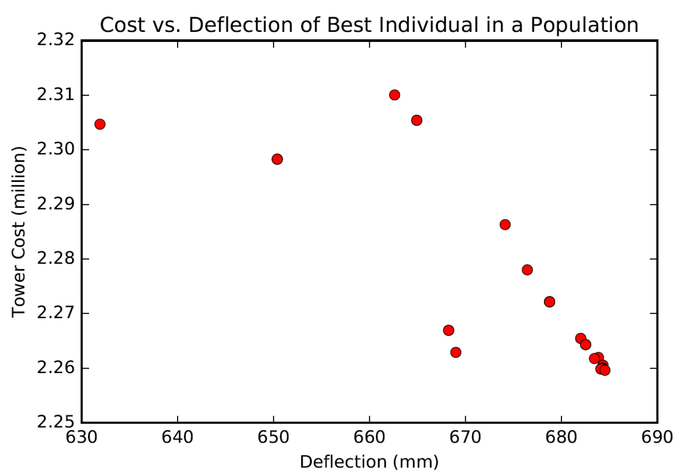
- Plot shows that Cost and Deflection are conflicting objectives (Optimal-cost design shows largest deflection)
- Multi-objective optimization (MOO) can reveal trade-offs between multiple design objectives for decision maker
  - Maximize flexural stiffness; Minimize vibration, etc.
  - Genetic algorithm can easily be used for MOO



Summary and Conclusions

- Summary
  - Implemented automated NX Open software to generate CAD and simulation models for frequency and deflection
  - Optimization framework implementation completed
    - Integration of CAD models, simulation models, cost calculators, constraint checkers, and optimization tool
  - Performed optimization studies, tested and refined optimization framework
    - Included tower diameter, column diameter and no. of strands as design variables

- Conclusions
  - Setting up initial design and determine the appropriate load conditions takes more time than optimization itself
  - Optimization improved initial design without violating constraints
  - LCOE modeling is a complex problem, difficult to access realistic cost model
  - Genetic Algorithm is complex and time consuming → Possible use of High Performance Computing

Contact

Questions/Comments/Suggestions?

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Tower Design and Tower Loads

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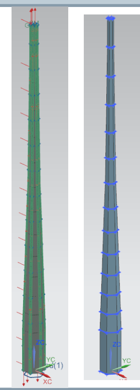
Hexcrete Tower 2 (HT2) Initial Design



14 Sections

Tower height = 450.6ft

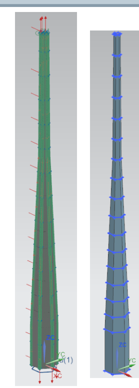
D= 7.5 – 25 ft

d= 3.09 – 3.33 ft

t= 0.5 ft

No. of strands = 38

Hexcrete Tower 3 (HT3) Initial Design



17 Sections

Tower height = 450.6ft

D = 8.87 – 31.03 ft

d= 3.59 – 3.83 ft

t= 0.33 – 0.42 ft

No. of strands = 46

Tall Tower Optimization Formulation

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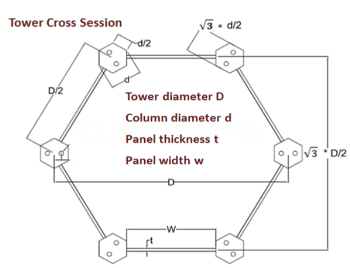
Optimization Problem

Objective Function – the Levelized Cost of Energy:

$$LCOE = \mathrm{f}(\boldsymbol{H}, \boldsymbol{D}, \boldsymbol{d}, n, \boldsymbol{t}, \mathbf{Mat})$$

Optimization Goal → Minimize (LCOE)



Constraints

1. Structural constraints

   $\text{deflection} \leq 5\,[\text{mm/m}] = 700\,[\text{mm}]$

   $0.293\,[\text{Hz}] \leq \text{frequency} \leq 0.6[\text{Hz}]$

   Section Moment Capacity: $M_i \geq M_i^{\text{load}}, i = 0, 1, \ldots 17$

   Section Stress: $\left(\frac{F}{A_i}\right) + \left(\frac{M_i}{S_i}\right) \leq 5.85\,[\text{ksi}], i = 0, 1, \ldots 17$

2. Dimension bound

   $22\,[\text{ft}] \leq D_0 \leq 36[\text{ft}]$, $D_i(i = 1 \sim 11)$ in taper1, $D_i(i = 11 \sim 17)$ in taper2

   $3.5[\text{ft}] \leq \boldsymbol{d} \leq 6\,[\text{ft}], d_{i+1} \leq d_i$ $60 \leq n \leq 130$

3. Transportation constraints

   Max Length $\leq$ Truck Length Limit $= 54[\text{ft}]$

   Max Width $\leq$ Truck Height Limit $= 14[\text{ft}]$

   Max Weight $\leq$ Truck Load Limit $= 80{,}000\,[\text{lb}]$

4. Construction constraints

   Crane below 260[ft]: Section Weight $\leq 240\,[\text{kips}]$

   Crane above 260[ft]: Section Weight $\leq 225\,[\text{kips}]$

   Blade Tip: Outermost Diameter at $274\,[\text{ft}] \leq 14.75[\text{ft}]$

Tall Tower Optimization Formulation

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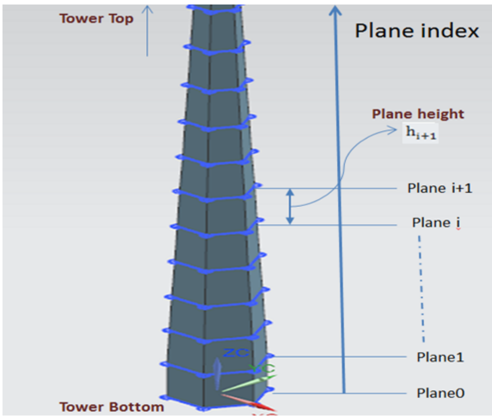
Design Parameters



HT3 TOWER DETAILS

- 18 sections : 19 planes (index = 0, … 18)
- Tower plane Diameter $\boldsymbol{D} = [D_0, D_1, \dots D_{18}] \in \boldsymbol{R}^{19}$
- Column Diameter $\boldsymbol{d} = [d_0, d_1, \dots d_{18}] \in \boldsymbol{R}^{19}$
- Plane height $\boldsymbol{H} = [h_0, h_1, h_1, \dots h_{18}] \in \boldsymbol{R}^{19}$
- Column Strand $n \in [60, 130]$
- Panel Thickness $\boldsymbol{t}$ -- *tbd*
- Column/Panel Material $\boldsymbol{Mat}$ -- *tbd*
- Transportation Parameter $\boldsymbol{T}$ -- *tbd*
- Material cost parameter – $\boldsymbol{M}$ -- *tbd*
- Construction parameter -- $\boldsymbol{C}$ -- *tbd*

Tall Tower Optimization Formulation

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Optimization Constrants (cont.)

Transportation constraint:

- $Maximal\ part\ weight\ \ <=\ 40{,}000\ lb$
- $Maximal\ part\ length\ \ <=\ 48\ ft.$
- $Maximal\ part\ width\ <= 14\ ft$

Source: *Federal Size Regulations for Commercial Motor Vehicles* (U.S. Department of Transportation Federal Highway Administration)

Construction constraint:

- *Tower plane diameter at top* $D_{18} = 8.86\ ft$

LCOE

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Levelized Cost of Energy($/MWh)

$$\mathrm{LCOE} = \frac{\mathrm{ICC} \times \mathrm{FCR} + \mathrm{AOE}}{\mathrm{AEP_{net}}}$$

ICC	Installed Capital Cost ($/kW)	Tower Cost included
FCR[1]	Fixed Charge Rate (%)	9.5%
AOE[1]	Annual Operating Expenses ($/kW/yr)	35 $/kW/yr
AEP_{net}[2]	Net Annual Energy Production (MWh/MW/yr)	7697 MWh/MW/yr

1. Source: NREL Cost of Wind Energy Review
2. Source: Iowa State University

Tall Tower Optimization Formulation

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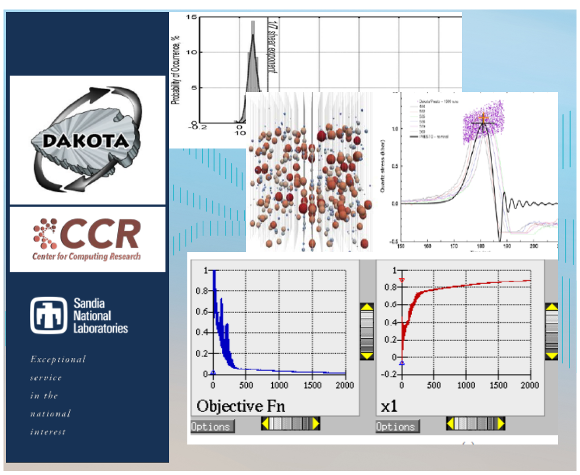
Introduction to DAKOTA



Dakota is a computing framework which is/allows
- Multilevel Parallel
- Object-Oriented
- Design Optimization
- Parameter Estimation
- Uncertainty Quantification
- Sensitivity analysis

The key Dakota capabilities
- Generic interface to simulations
- Time-tested and advanced algorithms
- Strategies to combine methods for advanced studies
- Mixed deterministic / probabilistic analysis
- Supports scalable parallel computations on cluster

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Tall Tower Optimization Formulation

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Example -- Parameter Study

TTsim_multi_3v_eval.in

```
# Dakota Input File: TTsim_multi_3v_eval.in
# Usage:
# dakota -i TTsim_multi_3v_eval.in -o TTsim_multi_3v_eval.out

environment
  # graphics
  tabular_data
    tabular_data_file = 'TTsim_multi_3v_eval.dat'

method
  multidim_parameter_study
    partitions 7 7 7

model
  single

variables
  continuous_design = 3
    lower_bounds      1.0       1.0     1.0
    upper_bounds      2.0       2.0     2.0
    descriptors       'x1'      "x2"    "x3"

interface
  analysis_driver = 'TTSimBuilderNX9'
    fork
    #file_tag
    #file_save
    parameters_file = 'params.in'
    results_file    = 'results.out'

responses
  num_response_functions = 1
  no_gradients
  no_hessians
```

```
TT_Command dakota -i TTsim_multi_3v_eval.in -o TTsim_multi_3v_eval.out
```

Six specification blocks

- Environments
- Method
- Model
- Variables
- Interface
- Response

In this task:

method = "multidim_parameter_study"

– meaning to evaluate to multi variables.

Interface:

analysis_driver = 'TTSimBuilderNX9'

– specify the simulation .exe generated from NX Open

Tall Tower Optimization Formulation

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Example -- Genetic Algorithm

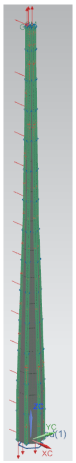
```
# Dakota Input File: TTsim_3v_soga.in
# Usage:
#   dakota -i TTsim_3v_soga.in -o TTsim_3v_soga.out > TTsim_3v_soga.stdout

environment
  # graphics
  tabular_data
    tabular_data_file = 'TTsim_3v_soga.dat'

method
  max_iterations = 20
  max_function_evaluations = 400
  soga
    seed = 11011011
    population_size = 20
    fitness_type merit_function
    mutation_type replace_uniform
    mutation_rate 1.0
    crossover_type multi_point_binary = 4
    crossover_rate 0.0
    replacement_type favor_feasible

model
  single

variables
  continuous_design = 3
    lower_bounds      1.0       1.0     1.0
    upper_bounds      2.0       2.0     2.0
    descriptors       'x1'      "x2"    "x3"

interface
  analysis_driver = 'TTSimBuilderNX9_Cpp'
    fork
    #file_tag
    #file_save
    parameters_file = 'params.in'
    results_file    = 'results.out'

responses
  objective_functions = 1
  no_gradients
  no_hessians
```

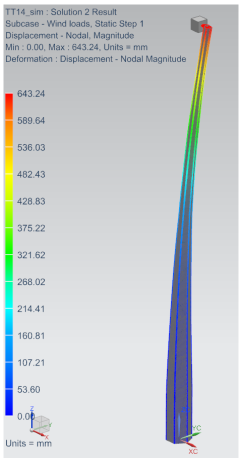
Running Genetic Algorithm

- 'soga' – single object genetic algorithm
- Seed – the specified starting random value for population
- population_size – the number of children for each iteration
- mutation_rate – control how the evolution to reach out to different area (exploration)
- crossover_rate – control how well the algorithm can reserve good candidates (exploitation).

HT2 Baseline Model – FEA Results Using NX CAE

<u>Initial Design</u>





14 Sections
Tower height = 450.6ft
D= 7.5 – 25 ft
d= 3.09 – 3.33 ft
t= 0.5 ft
No. of strands = 38

Total Panel Vol. (ft^3) = 6535
Total Column Vol. (ft^3) = 16750

Max. deflection = 643.24 mm
Frequency = 0.266 Hz

Tower Cost($) = 2.04e+006