Heuristics-based design and optimization of offshore wind farms collection systems

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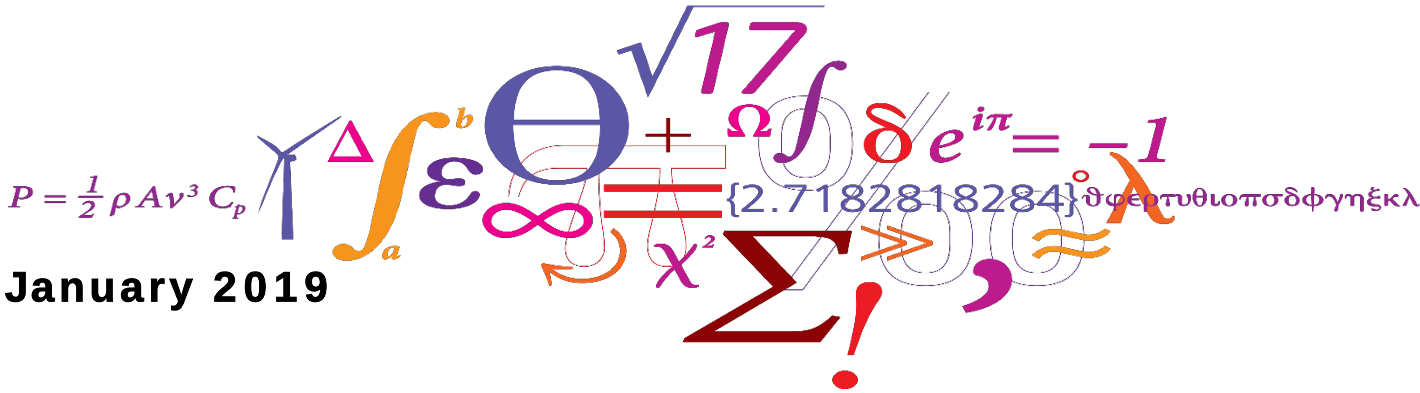

DTU Wind Energy
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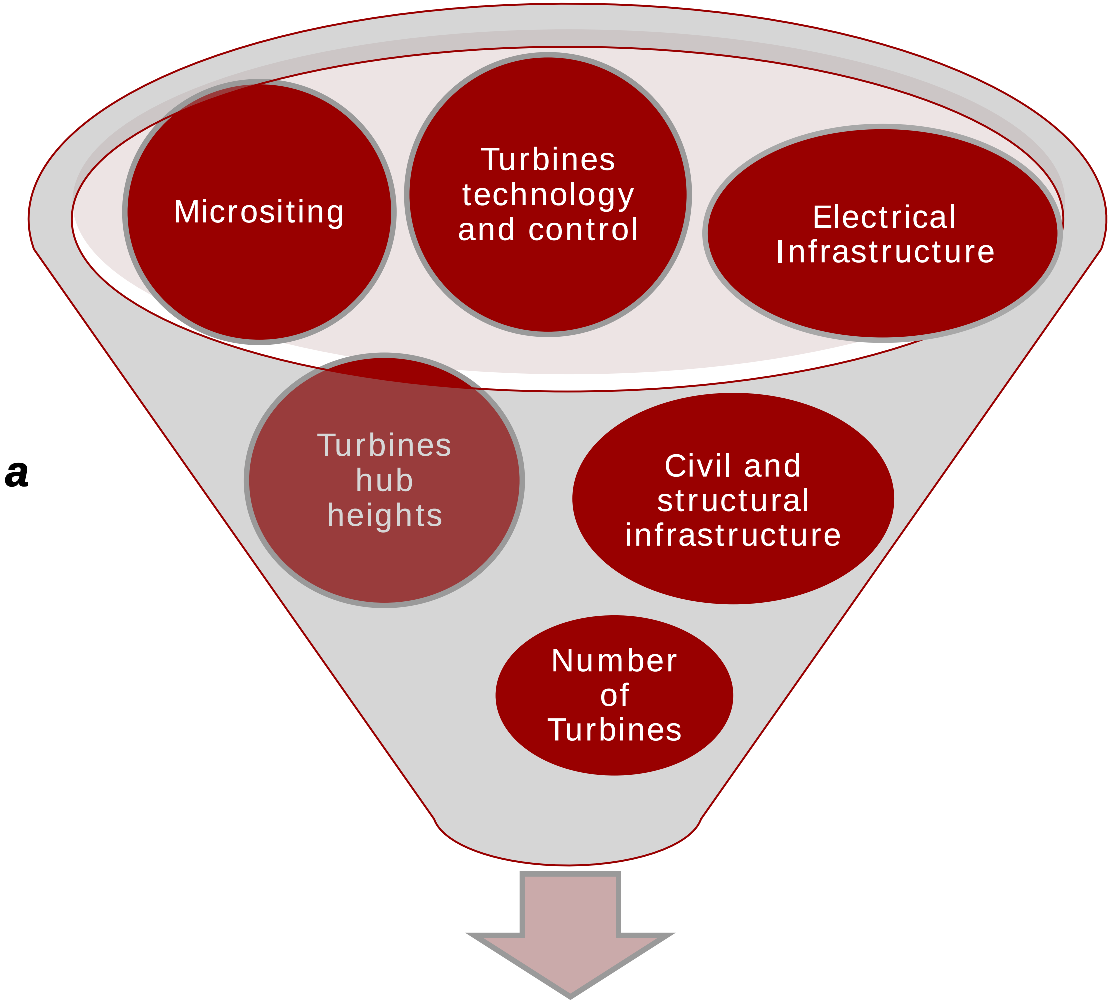
1 INTRODUCTION

Numerical optimization plays a major role by considering all variables involved:

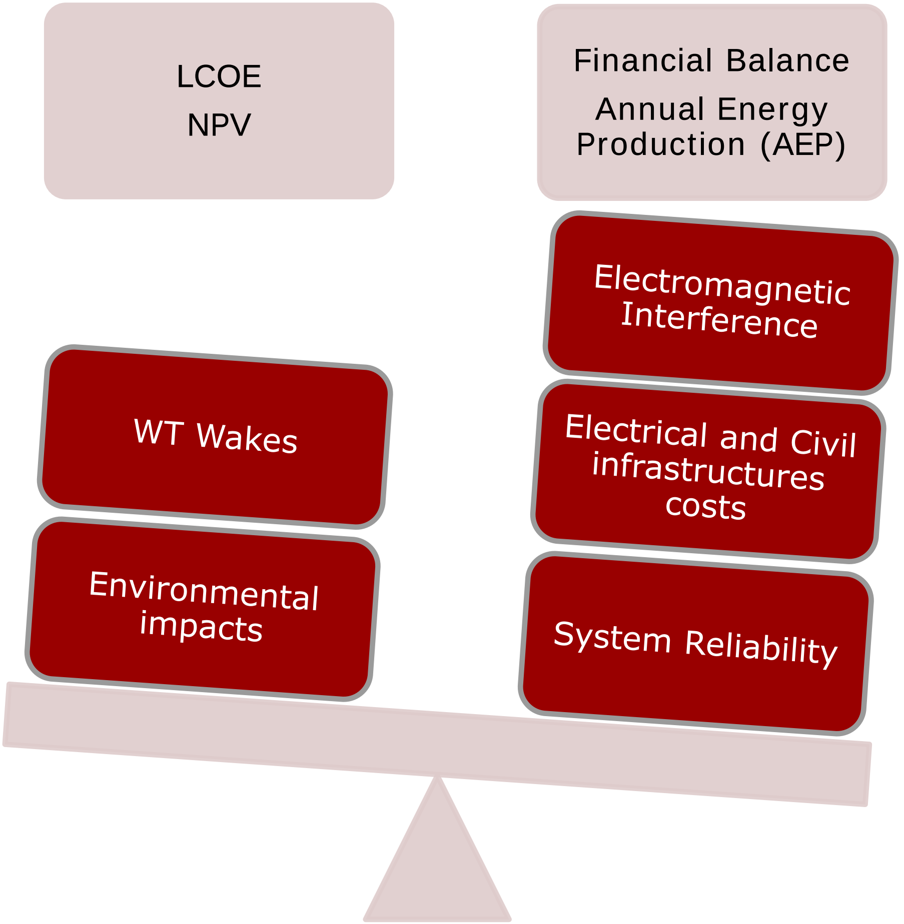
Enormous amount



Offshore Wind Farm Design and Optimization Problem (OWiFDO)

1 INTRODUCTION

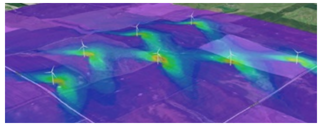
Balance between adverse factors to extremize performance metrics



Offshore Wind Farm Design and Optimization Problem (OWiFDO)

1 INTRODUCTION

Macrositing
- Selection of the project areas



Micrositing
- Allocation of Wind Turbines

Electrical layout
- Topological Design.
- Technology choices.
- Components rating selection.
- Number and location of OSSs.

Control and Operation
- Control and operation strategy

Multi-step optimization approach

1 INTRODUCTION

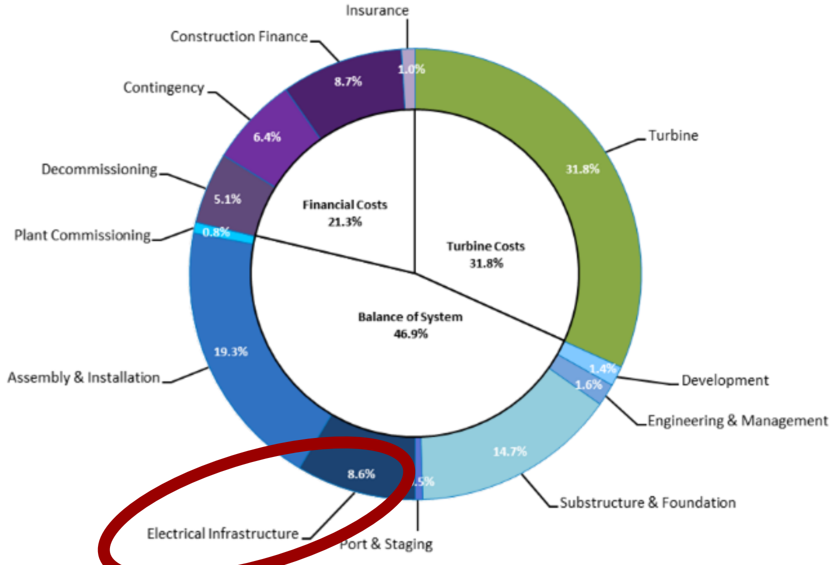


Figure 14. Capital expenditures for the 2015 fixed-bottom offshore wind reference project
Source: NREL

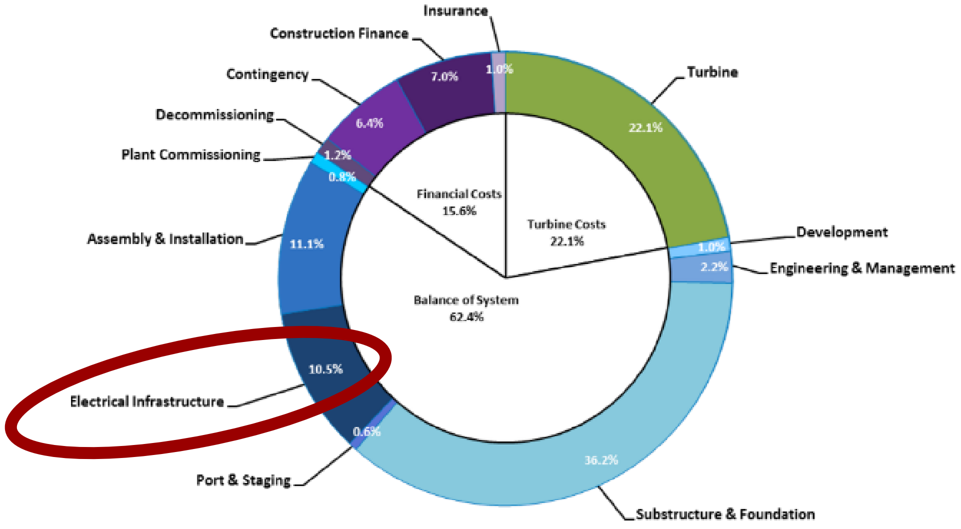


Figure 15. Capital expenditures for the 2015 floating offshore wind reference project
Source: NREL

- Overall electrical infrastructure costs can range from 8.6% to 10.5% of the total costs.
- The collection systems of OWFs represent an important share of the electrical infrastructure capex.
- The collection systems of OWFs have a critical impact on the operation: losses and overall reliability.

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2 PROBLEM DEFINITION

NP-Hard Problem

$$\left(t \times \left[N_{t-1} + 0.5\sum_{i=1}^{t-2}\frac{(t-1)!}{i!\,(t-1-i)!}N_i N_{t-1-i}\right]\right) \times \frac{(t\sigma)!}{(t!^{\sigma}) \times \sigma!}$$

Jenkins, A. M., M. Scutariu, and K. S. Smith. "Offshore wind farm inter-array cable layout." *PowerTech (POWERTECH), 2013 IEEE Grenoble*. IEEE, 2013.

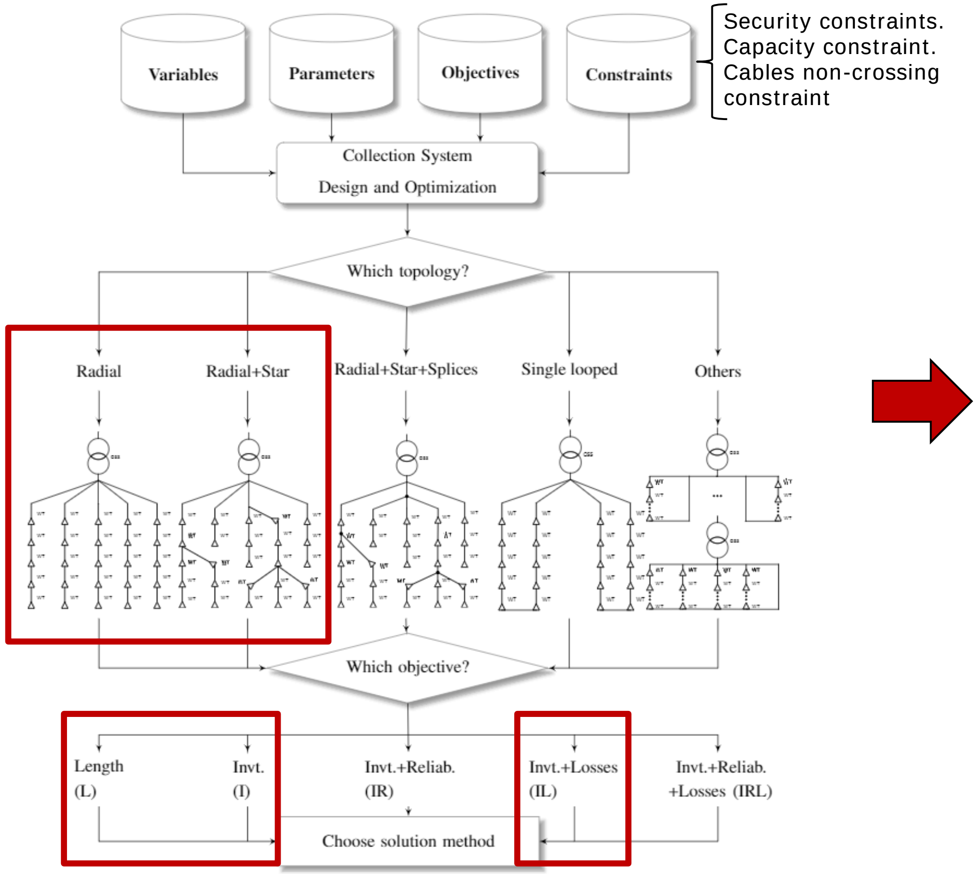
Where ***t*** *is the number of turbines per string (TPS) and* ***σ*** *is the number of strings.*

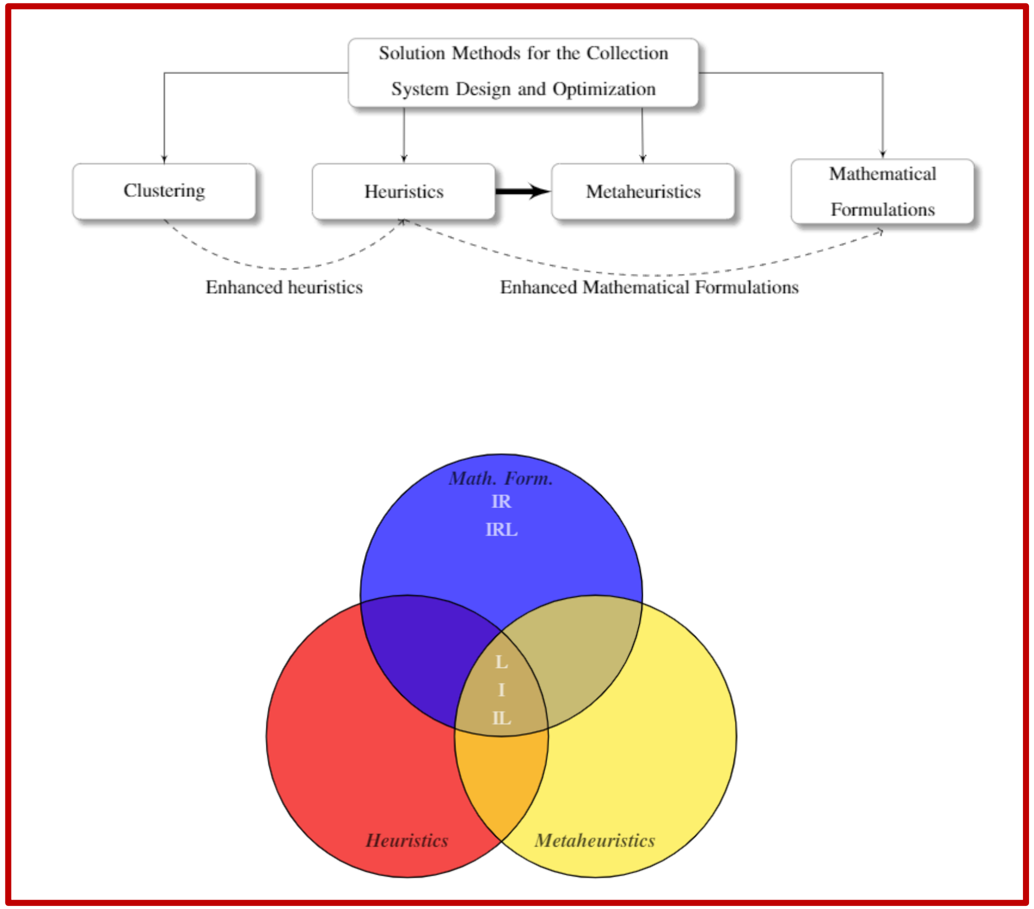
Consider an instance with ***75 WTs*** *and* ***5 TPS****, this result in* $\mathbf{1.19} \times 10^{107}$ ***potentials****, taking around* $\mathbf{9.45} \times 10^{89}$ ***years*** *using a high-speed 4.0 GHz computer to check all possible solutions!*

The age of the Earth is 4.54 ± 0.05 billion years ($\mathbf{4.54} \times 10^{9}$ *years)*

2 PROBLEM DEFINITION

Applicability in OWFs





2 PROBLEM DEFINITION

Applicability in OWFs

- Sol. Methods
  - Heuristics
    - - A priori bound for worst-case behavior.
      - Polynomial running time.
    - - A priori primal bound is typically very weak.
      - Purpose-built algorithms.
  - Metaheuristics
    - - Framework that fits different problems.
      - Provides with good primal bounds on most problems.
    - - Hardly any theory about quality and running time.
      - No worst-case analysis
  - Mathematical Formulations
    - - Framework that fits different problems.
      - A dual bound is available during computations.
    - - Running time unknown.
      - **Requires external solver**
      - **Computation time scales up exponentially**

Efficient implementations would require combinations with heuristics and/or decomposition strategies. Needs external solver.

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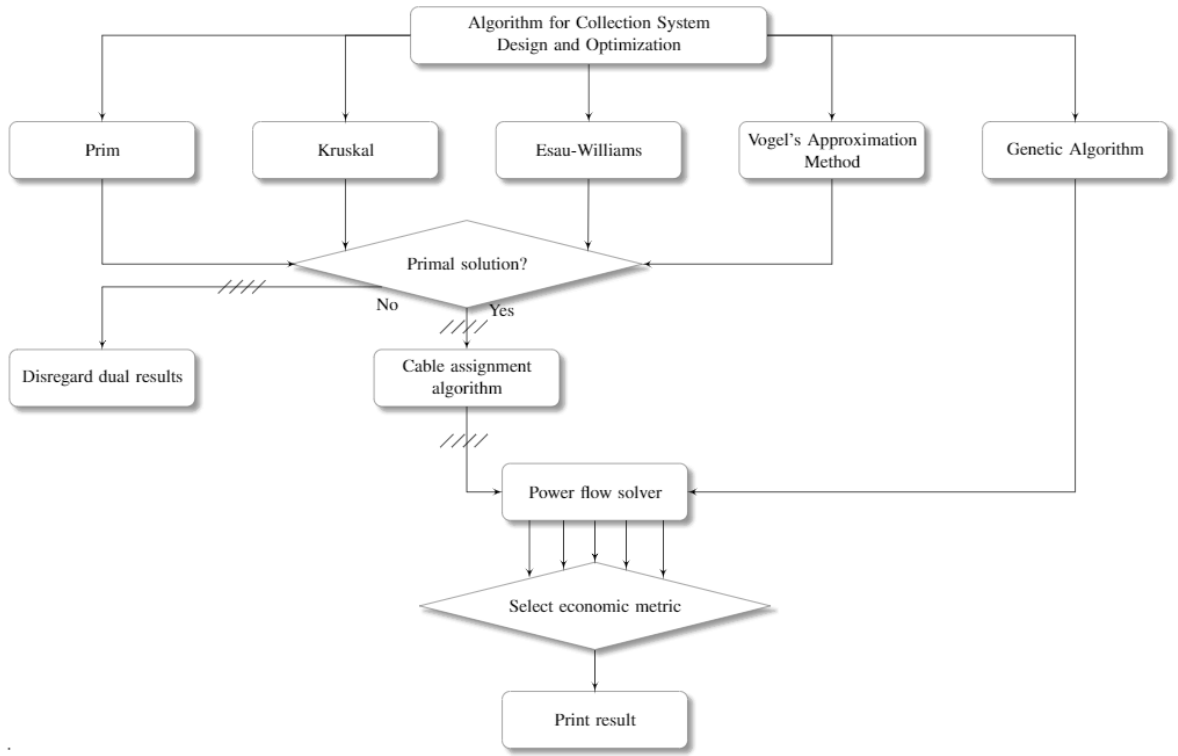
3 METHODOLOGY

Full methodology flow chart



3 METHODOLOGY

The heuristics

- Define for each branch e_{ij} the trade-offs values: $t_{ij} = w_{ij} - p_i$ and $t_{ji} = w_{ij} - p_j$. Get the triple set $\boldsymbol{T}(i, j, t_{ij})$.
- Where $p = a \cdot (b \cdot w_{i1} + (1 - b) \cdot w_{lm}) \, \forall \, v \in \boldsymbol{P}$. See table below for each heuristic.

Table 1. Nodal weight parameter definition.

Heuristic	Initialization	Update when $\{i, j\}$ is chosen
Prim	$p_1 = 0 \wedge p = -\infty \, \forall \, v \in \boldsymbol{V} \setminus \{1\}$	$p_j = 0$
Kruskal	$p = 0 \, \forall \, v \in \boldsymbol{V}$	No update
Esau-Williams	$p = w_{i1} \, \forall \, v \in \boldsymbol{V}$	$w_i = w_j \, \forall \, v \in \boldsymbol{C_{node}}(\boldsymbol{i})$
Vogel's Approximation Method	$p = b_i - a_i \, \forall \, v \in \boldsymbol{V}$	$w_i = b_i - a_i$. On the merged new component.

The heuristics

Input: $G(V, E, W)$,$Coordinates(V)$,U,Heuristic
Output: $G_T(V_T, E_T, W_T)$

Initialize empty V_T, E_T, W_T.
Initialize P *in function of the input: 'Heuristic'.*
Initialize $T(i, j, t_{ij})$, *in function of* P.
Initialize C, S, C_{node}, R_{node}.
$go = true$.
while *(go == true)* **do**
  $tob = \min_{t_{ij}} T(i, j, t_{ij}) \wedge \{u, v\} = \arg\min_{t_{ij}} T(i, j, t_{ij})$.
  if *(tob ==* ∞*)* **then**
    go == false.
  end if
  if *(loop-creation constraint with* $C_{node}(u)$ *and* $C_{node}(v)$ *== true)* **then**
    $t_{uv} = \infty$.
    $t_{vu} = \infty$.
  else
    if *(capacity constraint with* C, S, *and* C_{node}, R_{node}*== true)* **then**
      $t_{uv} = \infty$.
      $t_{vu} = \infty$.
    else
      if *(crossing cables constraint with* E_T *and* $Coordinates(V)$ *== true)* **then**
        $t_{uv} = \infty$.
        $t_{vu} = \infty$.
      else
        $E_T = \{E_T, \{u, v\}\}$
        $W_T = \{W_T, w_{uv}\}$.
        Update V_T.
        Update P *in function of the input: 'Heuristic'.*
        Update $T(i, j, t_{ij})$, *in function of updated* P.
        Update C, S, C_{node}, R_{node}.
        $t_{uv} = \infty$.
        $t_{vu} = \infty$.
      end if
    end if
  end if
  if *(columns(C) == 1)* **then**
    go == false.
  end if
end while

Algorithm 1: The unified heuristic algorithm

The worst-case scenario big O notation is given by the expression: $\mathcal{O}(|V|^2 \log|V| + C|V|^2 + |V|^4)$.

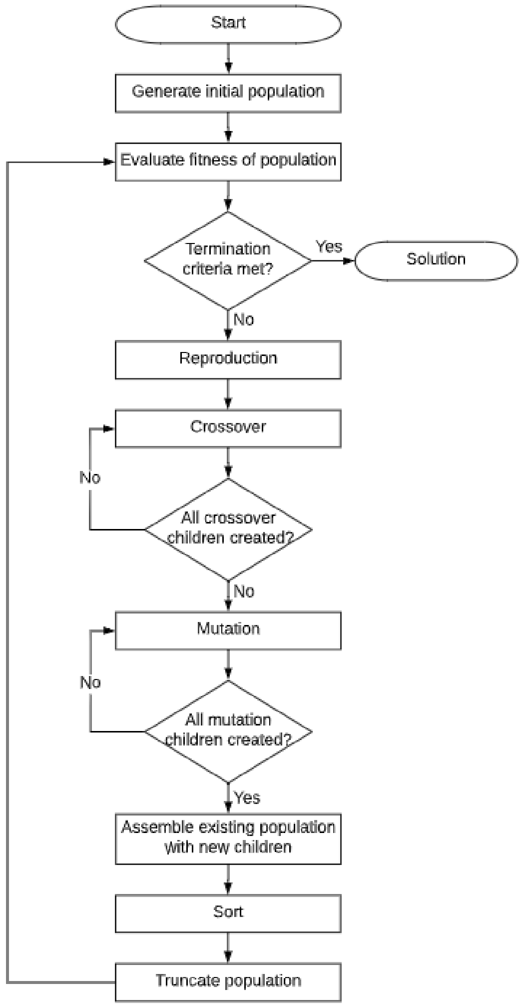
3 METHODOLOGY

The Metaheuristic

Genetic Algorithm

Uses an implementation of genetic algorithms

- cMST -> NP-hard
- Formulation of graph problems adapts well
- Offer great flexibility for adding constraints
- Implementations present in literature



Hermosilla Minguijón D, Pérez-Rúa J A, Das K and Cutululis N A 2019 Metaheuristic-based Design and Optimization of Offshore Wind Farms Collection Systems IEEE PowerTech at Milan (submitted) pp 1–6

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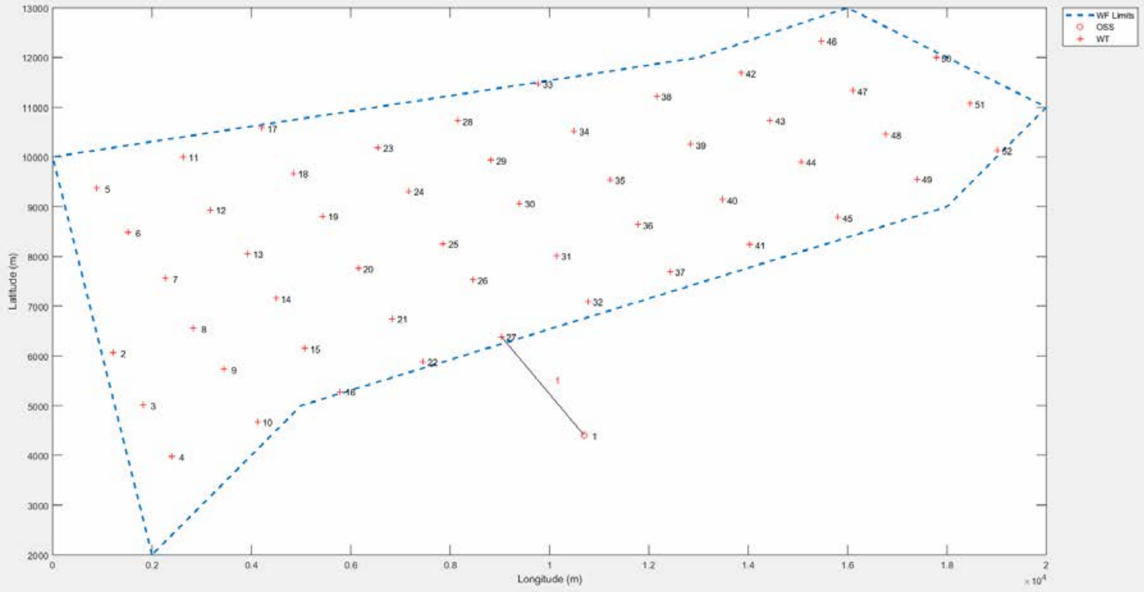
4 COMPUTATIONAL EXPERIMENTS

Single cable

Prim



The OWF:

WTs number: 51
WT nominal power: 4 MW
Collection system nominal voltage: 33 kV
Set of cables available: {500 mm^2}
Capacity constraint: 9

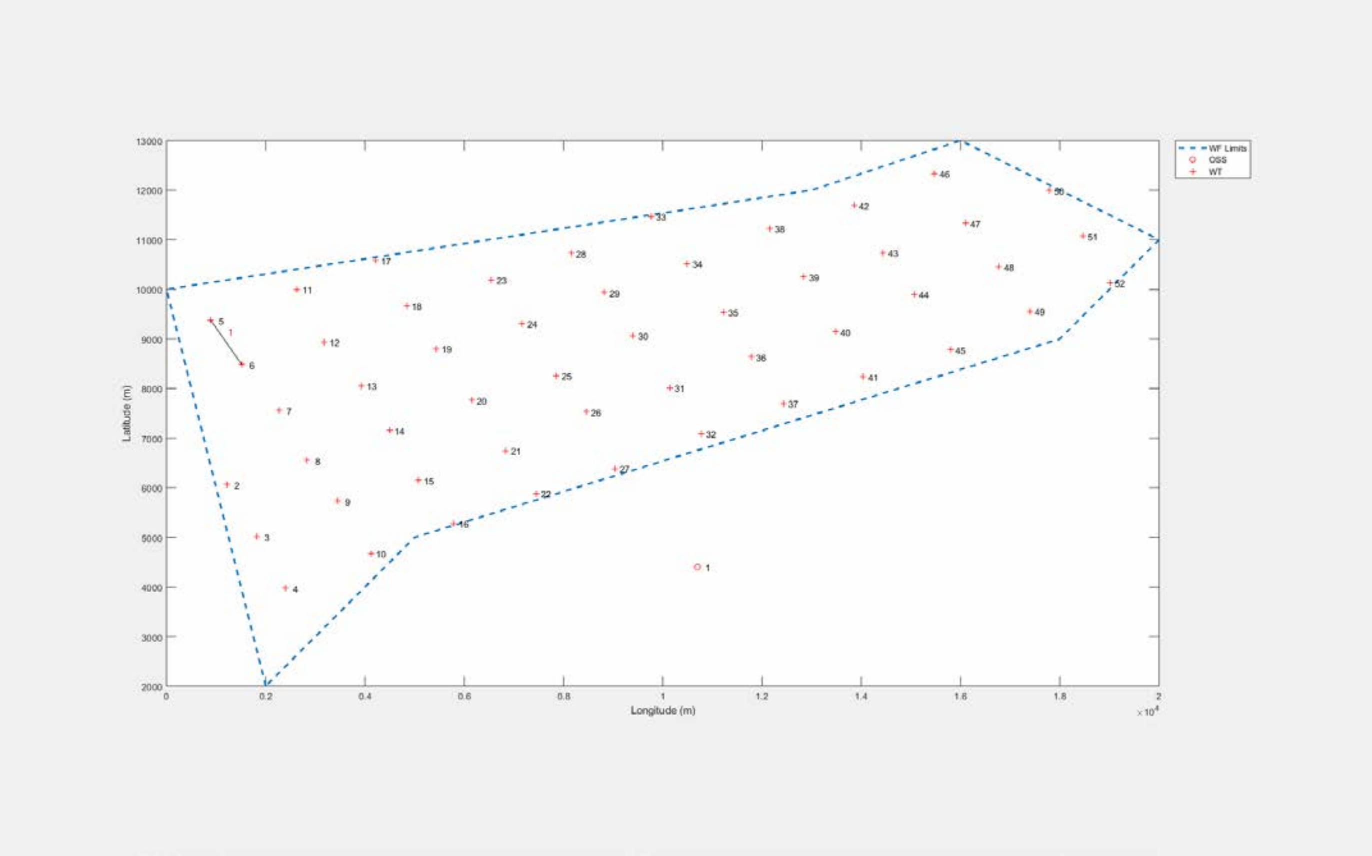
4 COMPUTATIONAL EXPERIMENTS

Single cable

The OWF:

WTs number: 51
WT nominal power: 4 MW
Collection system nominal voltage: 33 kV
Set of cables available: {500 mm^2}
Capacity constraint: 9

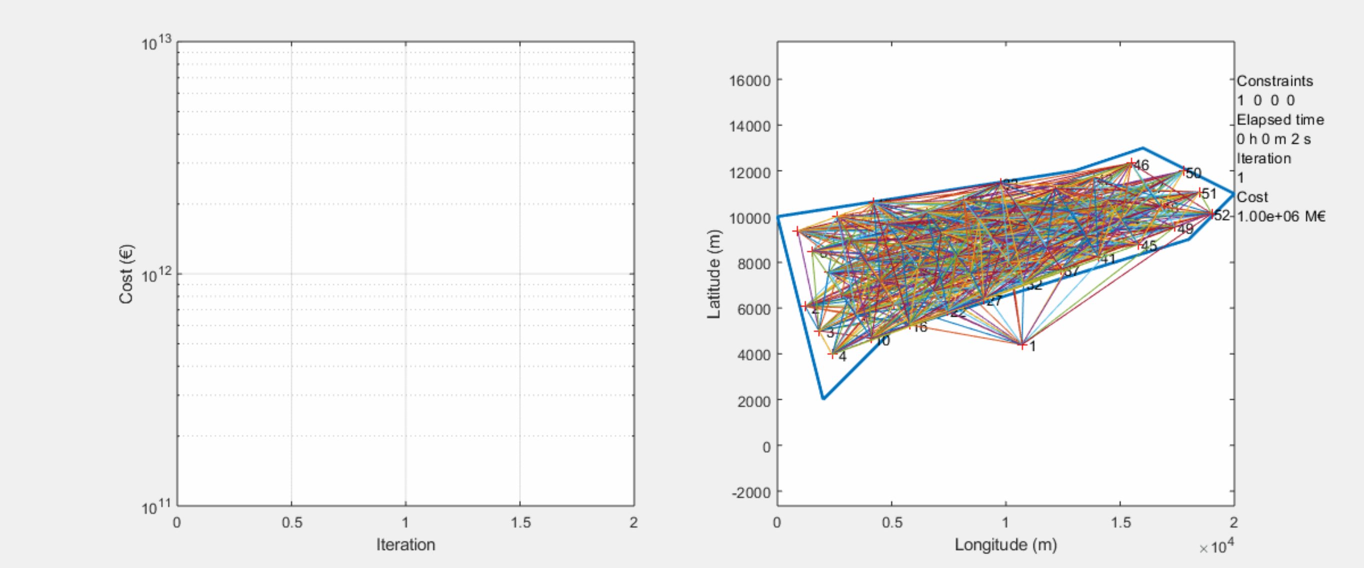
Esau-Williams



4 COMPUTATIONAL EXPERIMENTS

Single cable

GA



<u>The OWF:</u>

WTs number: 51
WT nominal power: 4 MW
Collection system nominal voltage: 33 kV
Set of cables available: {500 mm²}
Capacity constraint: 9

4 COMPUTATIONAL EXPERIMENTS

Single cable

Table 2. Single cable results.

	Prim	Kruskal	Esau-Williams	Vogel's Appr. Method	Genetic Algorithm
Feasible	Yes	Yes	Yes	Yes	Yes
AEP [GWh]			855.36		
Losses [GWh]	4.82	$\boxed{3.75}$	4.17	3.75	4.41
Initial Investment CS [M€]	41.22	39	38.13	39	39.30
Diff. with best [%]	8.12	2.30	0	2.30	3.08
$LCOE_{cs}$ [€/MWh]	2.96	2.80	2.74	2.80	2.82
Diff. with best [%]	8	2.19	0	2.19	2.92
NPV_{cs}^{BC} [M€]	356.64	359.36	360	359.36	358.75
NPV_{cs}^{1} [M€]	621.89	624.94	625.49	624.94	624.13
Δdiff. with best w.r.t BC [%]	6	−19	–	−19	6
NPV_{cs}^{2} [M€]	887.13	890.52	890.94	890.52	889.50
Δdiff. with best w.r.t BC [%]	12	−38	–	−38	12

4 COMPUTATIONAL EXPERIMENTS

Multiple cables

<u>The OWF:</u>

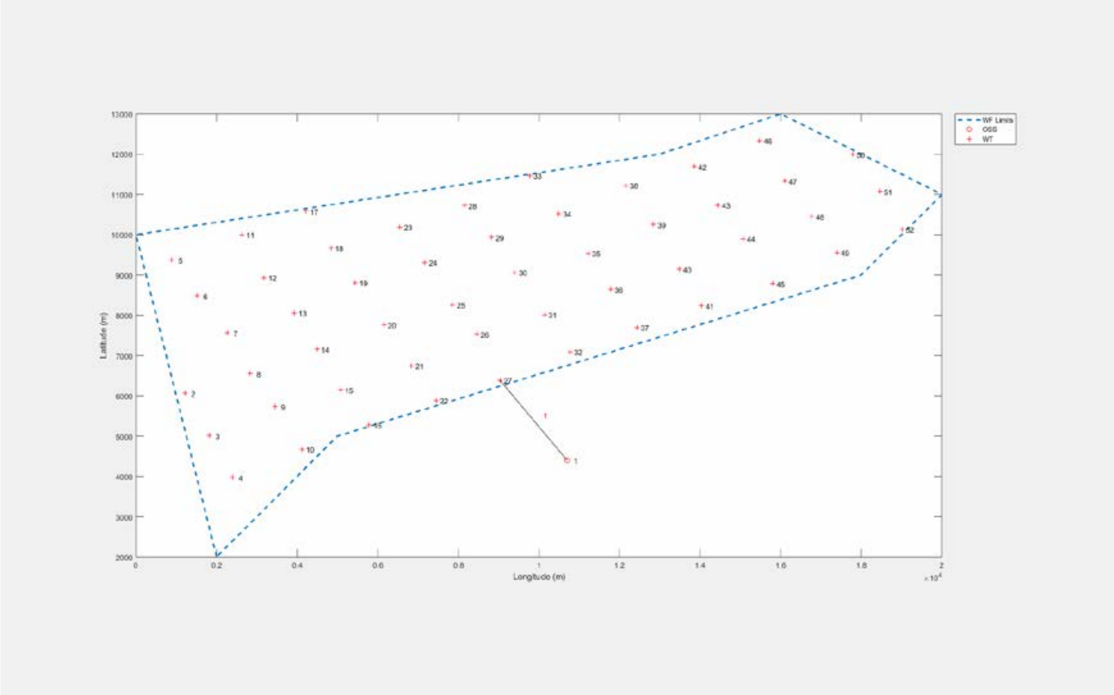
WTs number: 51
WT nominal power: 4 MW
Collection system nominal voltage: 33 kV
Set of cables available: {138, 300 mm^2}
Capacity constraint: 7

(Single case was 9)

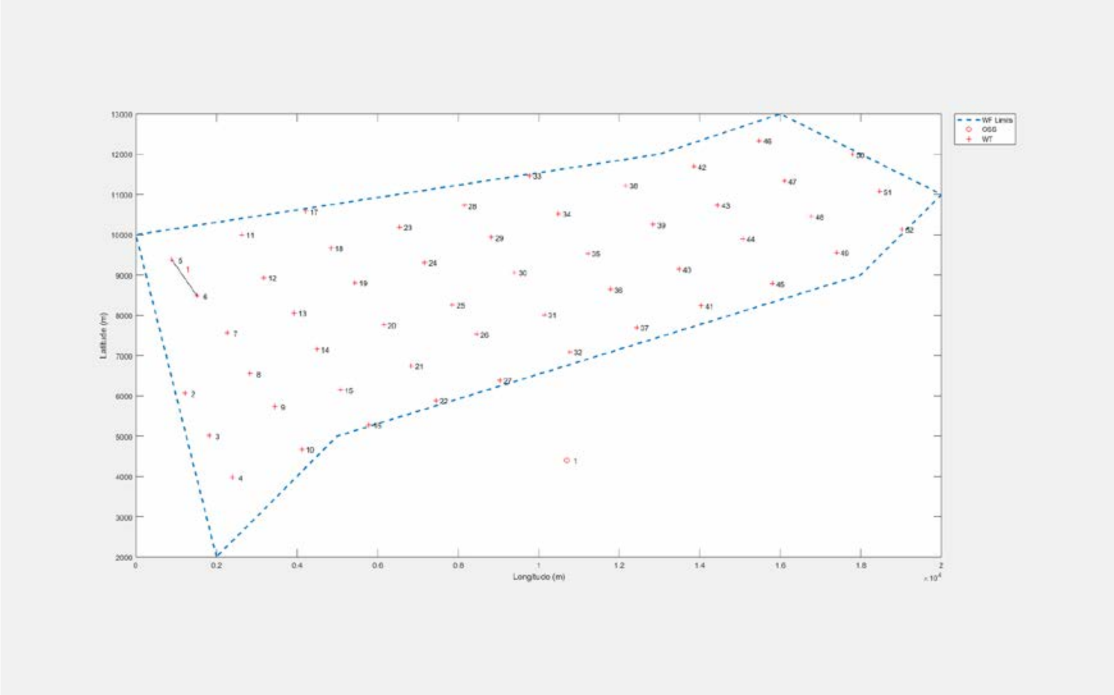
4 COMPUTATIONAL EXPERIMENTS

Multiple cables

Prim



Esau-Williams



4 COMPUTATIONAL EXPERIMENTS

Multiple cables

Table 3. Multiple cables results.

	Prim	Kruskal	Esau-Williams	Vogel's Appr. Method	Genetic Algorithm
Feasible	No	Yes	Yes	Yes	Yes
AEP [GWh]			855.36		
Losses [GWh]	–	$\boxed{7}$	7.3	$\boxed{7}$	7.99
Initial Investment CS [M€]	–	28.42	27.93	28.42	27.90
Diff. with best [%]	–	1.80	0.05	1.80	0
$LCOE_{cs}$ [€/MWh]	–	2.05	2.01	2.05	2.01
Diff. with best [%]	–	1.99	0	1.99	0
NPV_{cs}^{BC} [M€]	–	368.42	368.77	368.42	368.47
NPV_{cs}^{1} [M€]	–	632.98	633.24	632.98	632.73
Δdiff. with best w.r.t BC [%]	–	-25	–	-25	70
NPV_{cs}^{2} [M€]	–	897.54	897.71	897.54	896.99
Δdiff. with best w.r.t BC [%]	–	-51	–	-51	139

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05 **SUMMARY**

5 SUMMARY

- Heuristic represents a good tool for designing collection systems in OWFs. They have mathematical expressions for worst case running time, and can come up with very good solutions very fast.
- Exhaustive computational experiments indicate that, Esau-Williams is the most likely heuristic to provide feasible solutions. This is due to its trade-off function. For single cable, provides the best solution, and in the case of multiple cables, provide the solution with the best investment-losses balance.
- Exhaustive computational experiments indicate that, Kruskal and VAM, are the most likely heuristics to come up with the lowest losses. This is due to their trade-off function.
- Exhaustive computational experiments indicate that, Prim, is the most likely heuristic to provide infeasible solutions. This is due to its trade-off function.
- Evolutionary algorithms, such as the Genetic Algorithm, are a very valuable tool for solving the unfeasibility problem from heuristics. They can be designed to optimize the initial investment, in contrast to the heuristics.
- The Genetic Algorithm tends to form smaller WTs clusters into feeders than Esau-Williams, therefore, being able to provide cheaper initial investment solutions, albeit with greater power losses.
- Future work consists on implementing a MILP-heuristic-based solver to tackle this problem; combining mathematical formulations and high-level heuristics (as the ones designed in this work).

THANKS!

Questions?