INSTITUTE FOR RESEARCH IN TECHNOLOGY (IIT)

Departamento de Electrotecnia y Sistemas

A Benders' Decomposition Approach for Optimizing the Electrical System of Offshore Wind Farms

S. Lumbreras, A. Ramos

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Agenda

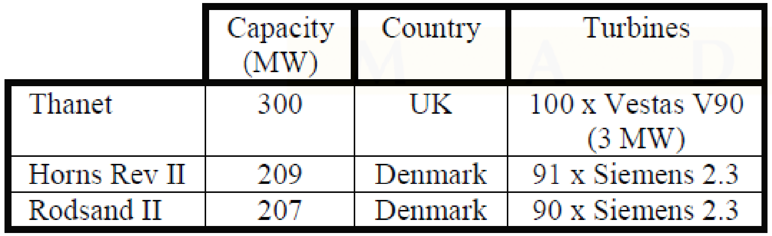
- Introduction
- State of the Art
- Model description
- Results
- Conclusions

http://www.windpowerphotos.com/

Introduction

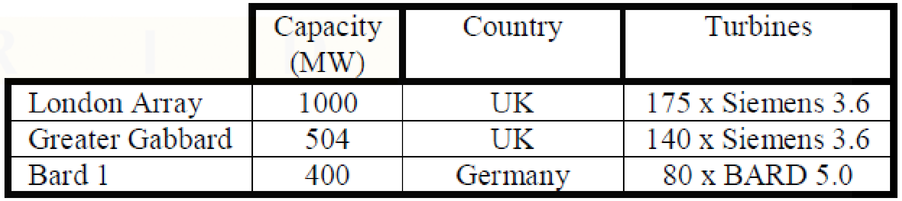
- Offshore wind power is one of the fastest-growing energy production technologies
    - Indispensable for Europe’s emission reduction targets
    - 584MW installed in 2009, approx 1000MW in 2010, 3500MW under construction
    - Average plant size was 72MW in 2009 but there are plans for much larger wind farms (10 projects over 1000MW)

TABLE 1. LARGEST OFFSHORE WIND FARMS IN OPERATION



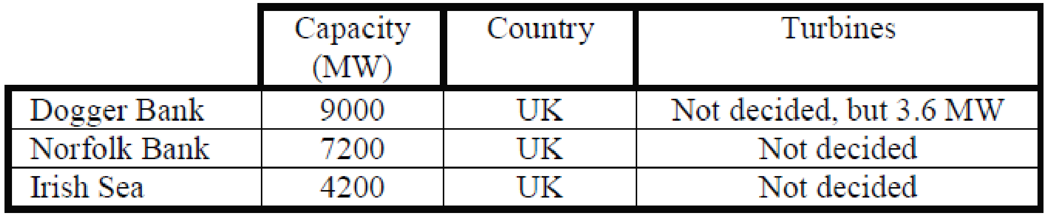
	Capacity (MW)	Country	Turbines
Thanet	300	UK	100 x Vestas V90 (3 MW)
Horns Rev II	209	Denmark	91 x Siemens 2.3
Rodsand II	207	Denmark	90 x Siemens 2.3

TABLE 2. LARGEST OFFSHORE WIND FARMS UNDER CONSTRUCTION



	Capacity (MW)	Country	Turbines
London Array	1000	UK	175 x Siemens 3.6
Greater Gabbard	504	UK	140 x Siemens 3.6
Bard 1	400	Germany	80 x BARD 5.0

TABLE 3. LARGEST OFFSHORE WIND FARMS PROPOSED



	Capacity (MW)	Country	Turbines
Dogger Bank	9000	UK	Not decided, but 3.6 MW
Norfolk Bank	7200	UK	Not decided
Irish Sea	4200	UK	Not decided

Introduction (continued)

- Turbine size is increasing
  - 2.9MW average in 2009, 3.6 in 2010
  - 5MW and even 7MW machines (RePower, Vestas)
  - Average plant size was 72MW in 2009 but there are plans for much larger wind farms
- Funds attracted
  - 1.5 bln in 2009
  - 3 bln in 2010 (expected)

http://www.windpowerphotos.com/

Introduction (continued)

- Electrical equipment is more expensive
  - Mainly because of insulation requirements
  - Imputable for 18% of the cost offshore versus 8% in onshore installations
- Reliability considerations are key
  - Failure rates are worse because of sea conditions
  - Repair rates are long
- The model OWL (Offshore Windfarm Layout optimizer) has been developed to provide optimal circuit designs having into account reliability considerations

State of the Art

- Modeling choices:
  - Stochasticity in wind

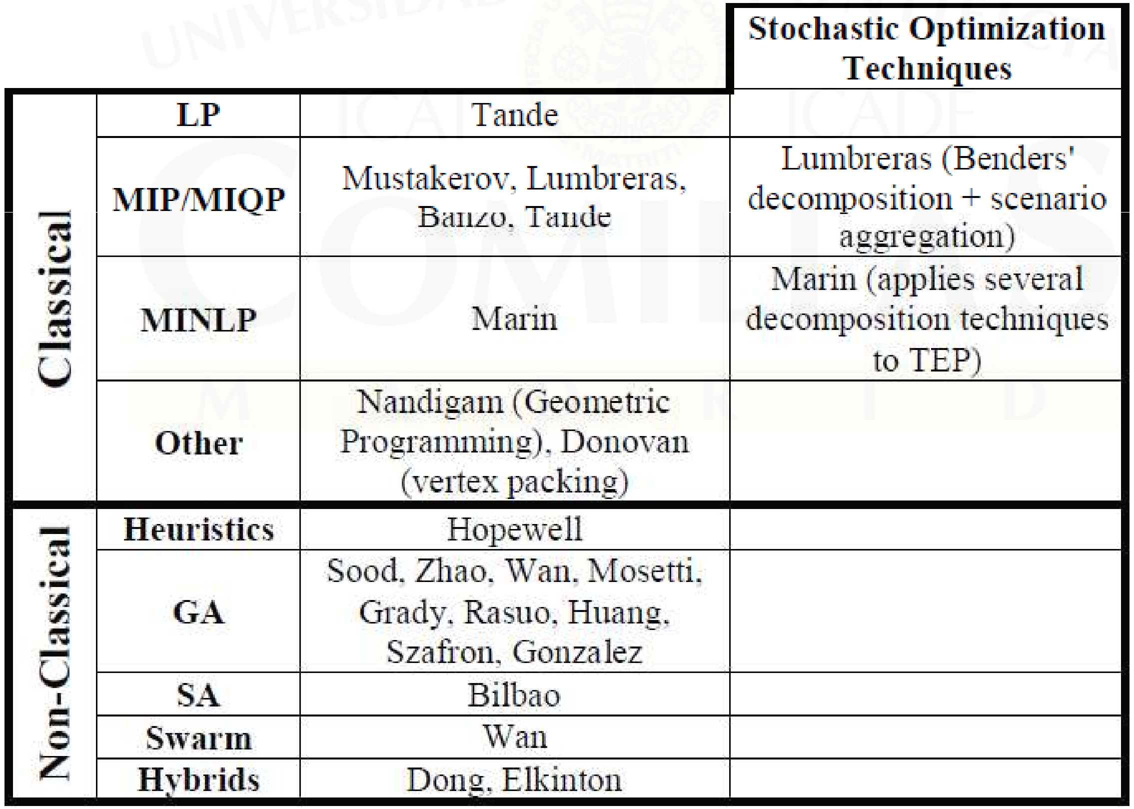
Average values	Stochastic in speed	Stochastic in speed and direction
Mustakerov, Donovan, Tande, Sood, Hopewell, Zhao, Dong, Huang, Rasuo, Wan, Szafron, Gonzalez, Elkinton	**Scenario Enumeration**: Rujula, Banzo, Lumbreras	
	Simulation: Zhao, Negra	**Simulation**: Mosetti, Grady, Bilbao, Wan

  - Reliability considerations

Reliability ignored	Deterministic	Probabilistic
Tande, Oh, Green, Lundberg, Li, Da Silva, Quinonez-Varela, Bresesti, Rujula, Hopewell	Zhao	**Scenario enumeration:** Banzo, Lumbreras
		Simulation: Negra, Sannino

State of the Art (continued)

- Solution methods
  - Many works only consider pre-established collector options



			Stochastic Optimization Techniques
Classical	LP	Tande	
	MIP/MIQP	Mustakerov, Lumbreras, Banzo, Tande	Lumbreras (Benders' decomposition + scenario aggregation)
	MINLP	Marin	Marin (applies several decomposition techniques to TEP)
	Other	Nandigam (Geometric Programming), Donovan (vertex packing)	
Non-Classical	Heuristics	Hopewell	
	GA	Sood, Zhao, Wan, Mosetti, Grady, Rasuo, Huang, Szafron, Gonzalez	
	SA	Bilbao	
	Swarm	Wan	
	Hybrids	Dong, Elkinton	

OWL- Model Description (I)

- Optimizing the design of Offshore Wind Farms:
  - Collector system (links among wind turbines)
  - Transmission system (to shore)
- Flexible definition of the plant: turbine location and characteristics, possible substations and point of connection to the onshore grid
- Decision variables (binary): cables and transformers installed, location of an offshore substation
- Operation variables (continous): power flows, curtailed production, non-served energy
- Objective function: minimize the sum of investment and non-served energy costs

OWL- Model Description (II)

- The model considers:
    - Power flow
    - Power limits
    - Nominal voltages
    - Unicity of the offshore substation
    - Correct implementation of device types and redundancies
- Stochasticity in energy generation is considered through a small set of wind speed scenarios from a Rayleigh distribution
- Reliability is taken into account using the state space method, with an N-1 criterion

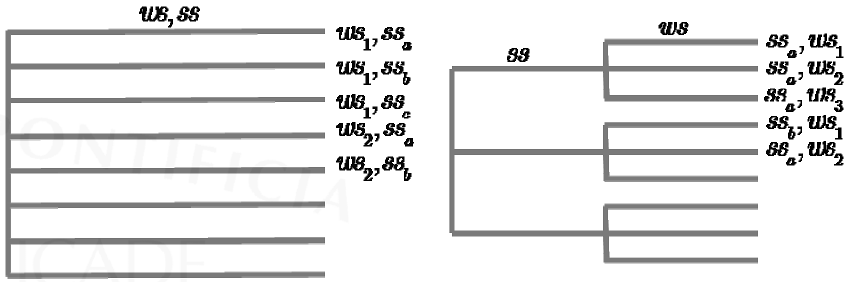
Benders' decomposition (I)

Benders' decomposition

- Can accelerate the resolution of some two-stage stochastic problems under certain conditions
    - The number of variables linking the stages is small
    - The nature of the first and second stage problems is different
- Iterates between a master problem and a subproblem
- In our case:
    - The only variables linking both stages are the ones representing installed cables and transformers
    - The investment stage is MIP and the operation is LP
- The decomposition is more efficient than the complete resolution

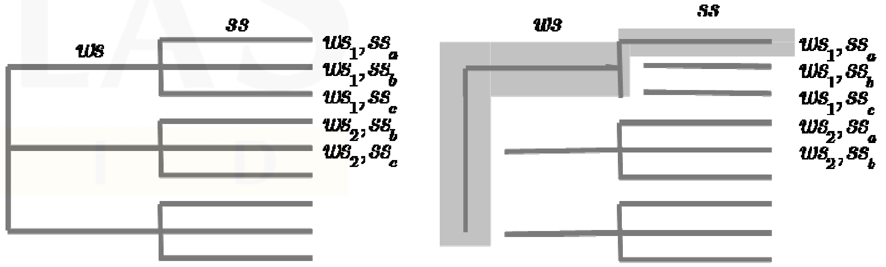
Benders' decomposition (II)

- We can decompose in different ways, that will give as a result cuts that are defined differently.
  - By wind scenario
  - By system state
  - By both wind state and system scenario
- The decomposition by wind scenario seems to be the most efficient
- Scenario aggregation was used to accelerate convergence
  - The most probable state is added to the master problem



(a) Benders' scenario decomposition by both wind and system states

(b) Benders' scenario decomposition by system states



(c) Benders' scenario decomposition by wind states

(d) Subtree partition

Case study (I)

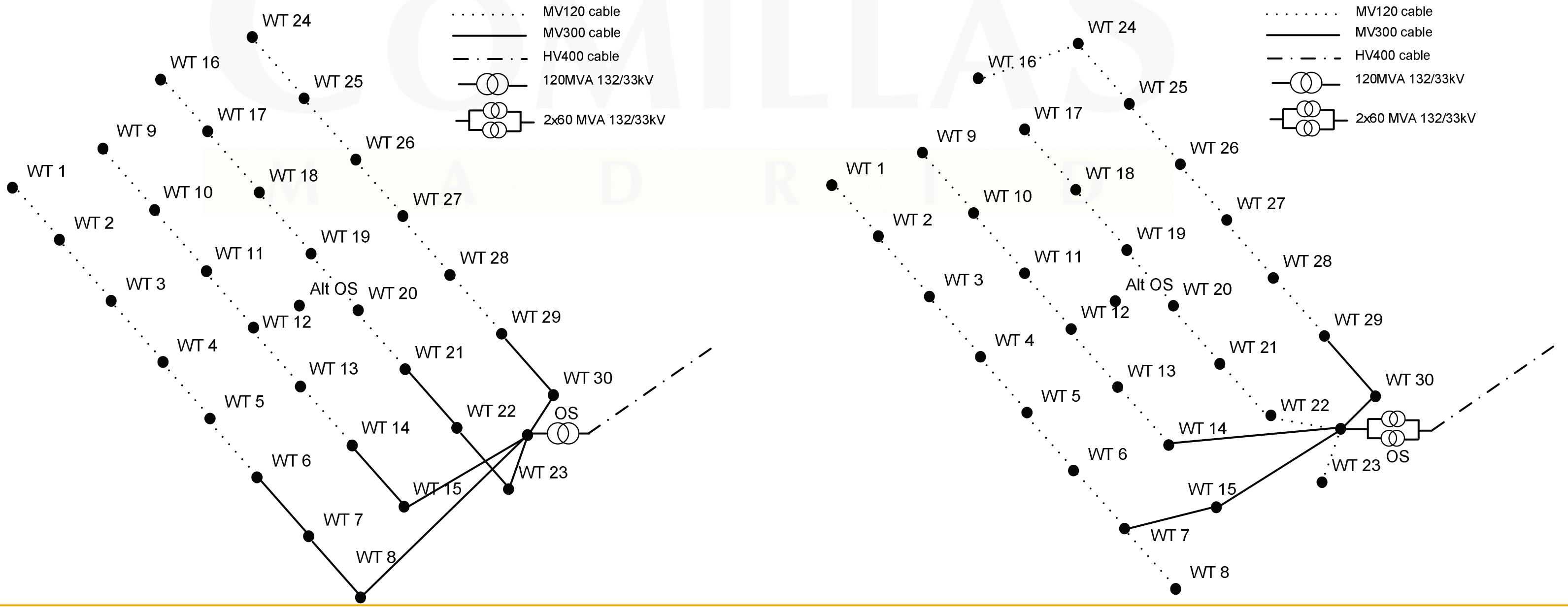
Barrow Offshore Wind Farm (BOWF)

- Project completed in 2006 by Centrica and Dong Energy in the East Irish Sea
- Solved the electrical layout to check it against the actual implemented design
    - Four rows
    - Linked with MV120 cables upgraded to MV300 close to the extremes
    - Offshore substation with a 120MVA transformer
    - Sends power to shore through a HV400 line

http://www.flickr.com/photos/silyld/1804268070/

Case study (II)

- The design proposed by OWL differs substantially from the implemented one
  - Symmetry is lost in the collector system
    - Allows to avoid some of the more expensive cables
  - Two smaller transformers replace the original one
    - Better reliability



Case study (III)

- The solution provided by OWL is better in both investment cost (0.85%) and non-served energy (6.7%) terms

	Actual layout	Stochasticity in wind scenarios	Stochasticity in wind scenarios and system states
Investment Cost (MEUR)	19.10	18.59	18.85
Cost of non served energy (MEUR)	0.66	0.66	0.61

- Solution time was affordable, with Benders' decomposition and scenario aggregation considerably improving performance
  - OWL provided the optimal design in 648.7s vs. 1697s (-61.8%) for the original problem resolution
  - Reduced to 531.3 s (-18%) when scenario aggregation is applied

* Solved on CPLEX 12.1 in GAMS 23.6.5 on a PC at 2.80 GHz running Microsoft Windows XP 32 bits. Tolerances set to 1E-3

Conclusions

- Optimizing the electrical layout of offshore wind farms is a key element in their design given cost and reliability considerations
- The solution can be quite different from a standard configuration, so a full optimization is necessary
- OWL (Offshore Windfarm Layout optimizer) can give optimal layouts for real-size plants in affordable times
- Benders' decomposition and scenario aggregation techniques considerably reduce solution time

Vestas

Annexes

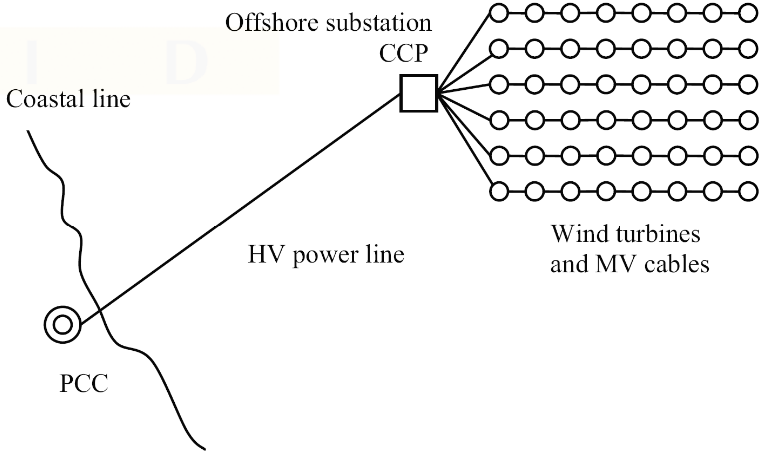
- OWL- Model description
- Benders’ decomposition
- Decomposition options

GE Wind Energy

OWL- Model Description (I)

Indices:

- p : points in the grid
    - wt_p : points where wind turbines are installed
    - cp_p : point of conection to the onshore grid (PC)
    - os_p : possible point for substation (OS)
    - $cset_{p,p'}$: possible conections between turbines
- ct : type of cable
    - $ctmvct$: medium voltage cable
    - $cthvct$: high voltage cable
- r: redundancy level
- tt: type of transformer
- ws: wind scenario
- ss: system state



OWL- Model Description (II)

Parameters:

System configuration:

- pDp,p': distance between points p and p' [m]
- pHV : high voltage [kV]
- pMV : medium voltage [kV]

Electrical components:

- pCP_{ct} : cable ct rated power [MW]
- pCR_{ct} : cable ct resistance [Ohm/m]
- pCC_{ct} : cable ct cost [€/m]
- pTP_{tt} : transformer tt rated power [MW]
- pTC_{tt} : transformer tt cost [€]

OWL- Model Description (III)

Stochastic scenarios:

$pDur^{ws}$:	duration of period ws	[h]
$pProb^{ss}$:	probability of system state ss	[pu]
$pWTPower^{ws}$:	power generated by ws	[MW]

Financial:

$pCENS$:	cost of non-served energy	[EUR/MWh]

Reliability:

- $pFaTf_{tt,r}^{ss}$ failure of transformer type tt and of redundancy r at system state ss [1-0]
- $pFaC_{p,p',r}^{ss}$ failure of cable from p to p' , of cable type ct and of redundancy r at system state ss [1-0]

OWL- Model Description (IV)

Decision variables (binary):

- vOs_p: offshore substation located at p
- $vC_{p,p',ct,r}$: cable installed between p and p' type ct and of redundancy r
- $vTf_{tt,r}$: transformer of type tt installed at substation with redundancy r

Operation variables:

- $vf_{p,p'}^{ws,ss}$ active power flow through p and p' [MW]
- $vPNS_p^{ws,ss}$ power non served in scenario ws, ss [MW], >0
- $vTotP^{ws,ss}$ total power sold in scenario ws, ss [MW],>0

OWL- Model Description (V)

Constraints:

- Balance of power flow in wind turbines:

$$\sum_{cset(p',p)} vfC^{ws,ss}_{p',p} + pWTPower^{ws}_{wt(p)} =$$

$$\sum_{cset(p,p')} vfC^{ws,ss}_{p',p} + vPNS^{ws,ss}_{wt(p)} + vTotP^{ws,ss}_{cp(p)} \quad \forall p, ws, ss$$

- Power limit through cables:

$$vfC^{ws,ss}_{p,p'} = \sum_{ct,r} vC_{p,p',ct}\left(1 - pFaC^{ss}_{p,p',r}\right) pCP_{ct}$$

$$\forall cset(p,p'), ws, ss$$

OWL- Model Description (VI)

- Power limit through transformer:

$$vTotP^{ws,ss} - pM\left(1-\sum_{tt} vTf_{tt,r0}\right) \le$$

$$\sum_{tt,r} vTf_{tt,r}\, pTP_{tt}\left(1 - pFaTf_r^{ss}\right) \; \forall ws, ss$$

- Only one substation:

$$\sum_{os(p)} vOS_p \le 1$$

- Only one type of transformer:

$$\sum_{tt} vTf_{tt,r} \le 1 \;\; \forall r$$

OWL- Model Description (VII)

- Only one type of cable is allowed for each connection:

$$\sum_{ct} vC_{p,p',ct,r} \leq 1 \ \forall p, p', r$$

- Only redundant transformer if transformer:

$$vTf_{tt,r} \leq vTf_{tt,r'} \forall tt, ord(r') < ord(r)$$

- Only redundant cables if main cables:

$$vC_{p,p',ct,r} \leq vC_{p,p',ct,r'} \ \forall p, p', ct, ord(r) > ord(r')$$

- Only HV cables if transformer installed:

$$\sum_{r} vC_{p,p',ct,r} \leq pM \sum_{r,ct} vTf_{tt,r} \ \forall p, p', cthv(ct)$$

OWL- Model Description (VIII)

- Only HV cables from substation:

$$\sum_{r} vC_{p,p',ct,r} \le pM\left(vOs_{p}\right) \ \forall p, p', cthv(ct)$$

- Only HV cables to PC:

$$\sum_{r} vC_{p,p',ct,r} \le pc_{p'} \ \forall p, p', cthv(ct)$$

- Power not served:

$$vPNS_{p}^{ws,ss} \le pWTPower^{ws} \ \forall wt(p), ws, ss$$

OWL- Model Description (IX)

- Investment cost:

$$C_{inv} = \left(\frac{pI\left(1+pI\right)^{pL} pL}{\left(1+pI\right)^{pL} - 1} \right) \left(\sum_{cset(p,p'),ct,r} vC_{p,p',ct,r}\, pD_{p,p'}\, pCC_{ct} + \sum_{tt,r} vTf_{tt,r}\, pTC_{tt} \right)$$

- Non-served energy cost:

$$C_{unav} = \sum_{p,ss,ws} pDur^{ws}\, pProb^{ss}\, vPNS^{ws,ss}_{wt(p)}$$

- Objective function: $\min C_{unav} + C_{inv} + C_{loss}$

Benders decomposition (formulation)

- The formulation for the complete problem:

$$
\begin{aligned}
&\min c_1^T x_1 + \theta_2 \\
&A_1 x_1 = b_1 \\
&\theta_2 \geq (b_2 - B_1 x_1)^T \pi_2^{lT} \\
&x_1 \geq 0 \\
&l = 1, \ldots, v
\end{aligned}
$$

- It can be divided into Master and Subproblem:

$$
\begin{aligned}
&\min c_1^T x_1 + \theta_2 \\
&A_1 x_1 = b_1 \\
&\theta_2 \geq f_2^l + \pi_2^{lT} B_1 (x_1^l - x_1) \quad l = 1, \ldots, j \\
&x_1 \geq 0
\end{aligned}
$$

$$
\begin{aligned}
&f_2^j = \min c_2 x_2 \\
&A_2 x_2 = b_2 - B_1 x_1^j : \pi_2^j \\
&x_2 \geq 0
\end{aligned}
$$

Decomposition Options

- Performance strongly depends on the decomposition scheme
  - Given that solution time increases faster than a proportion to problem size, it would be desirable to split the problem into as many pieces as possible
  - Benders' cuts would have more information
  - But the master problem will be slower
- This was the result

	By wind scenario	By system state	By both
Iterations	25	42	25
CPU time per iteration (Master problem)	0.07	0.18	0.15
CPU time per iteration (Subproblem)	0.05	0.15	0.11
CPU time per iteration (Total)	0.11	0.33	0.26
Total CPU time (s)	2.83	13.86	6.50