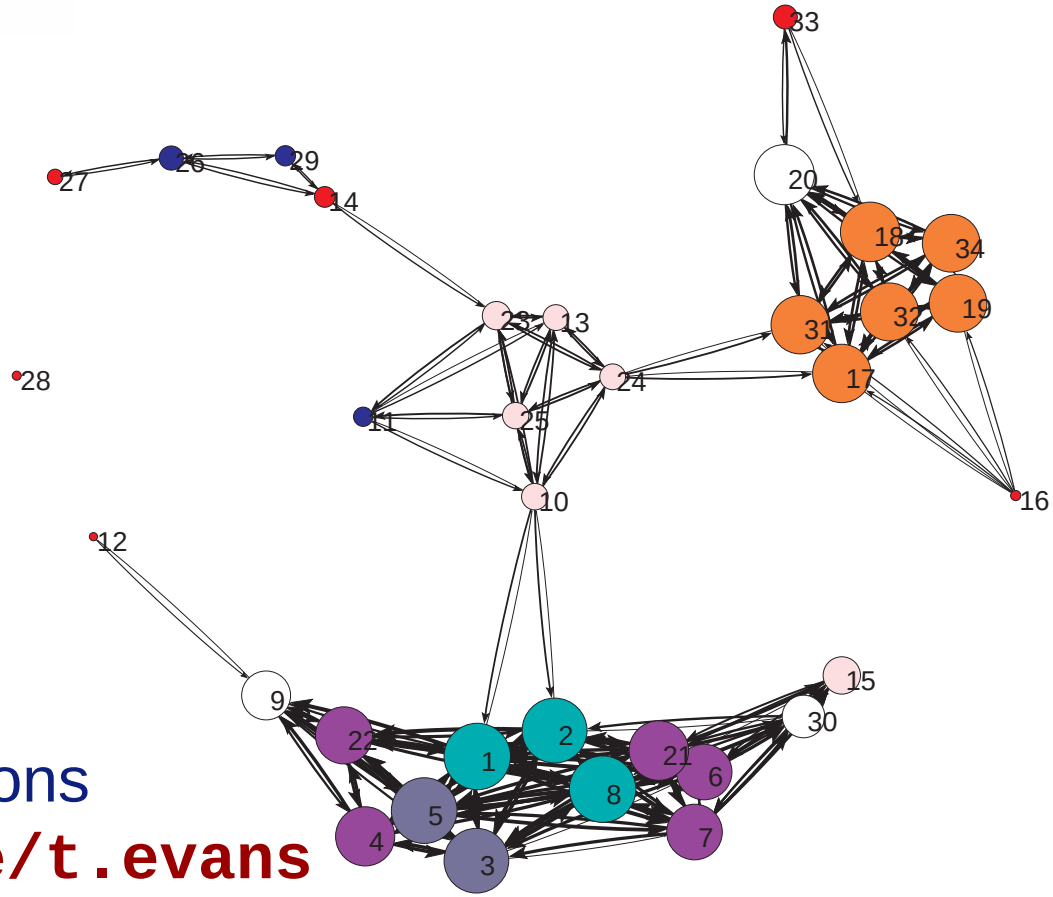
Tim Evans
Theoretical Physics

Imperial College London

Networks for the Minoan Aegean



Tim Evans (Imperial),
Carl Knappett (Exeter),
Ray Rivers (Imperial)

See web site for publications
www.ic.ac.uk/people/t.evans

- e.g. see **ISCOM** project *D.Lane et al. (ed.s) 2007*
"Physical and Relational Networks in the Aegean Bronze Age"

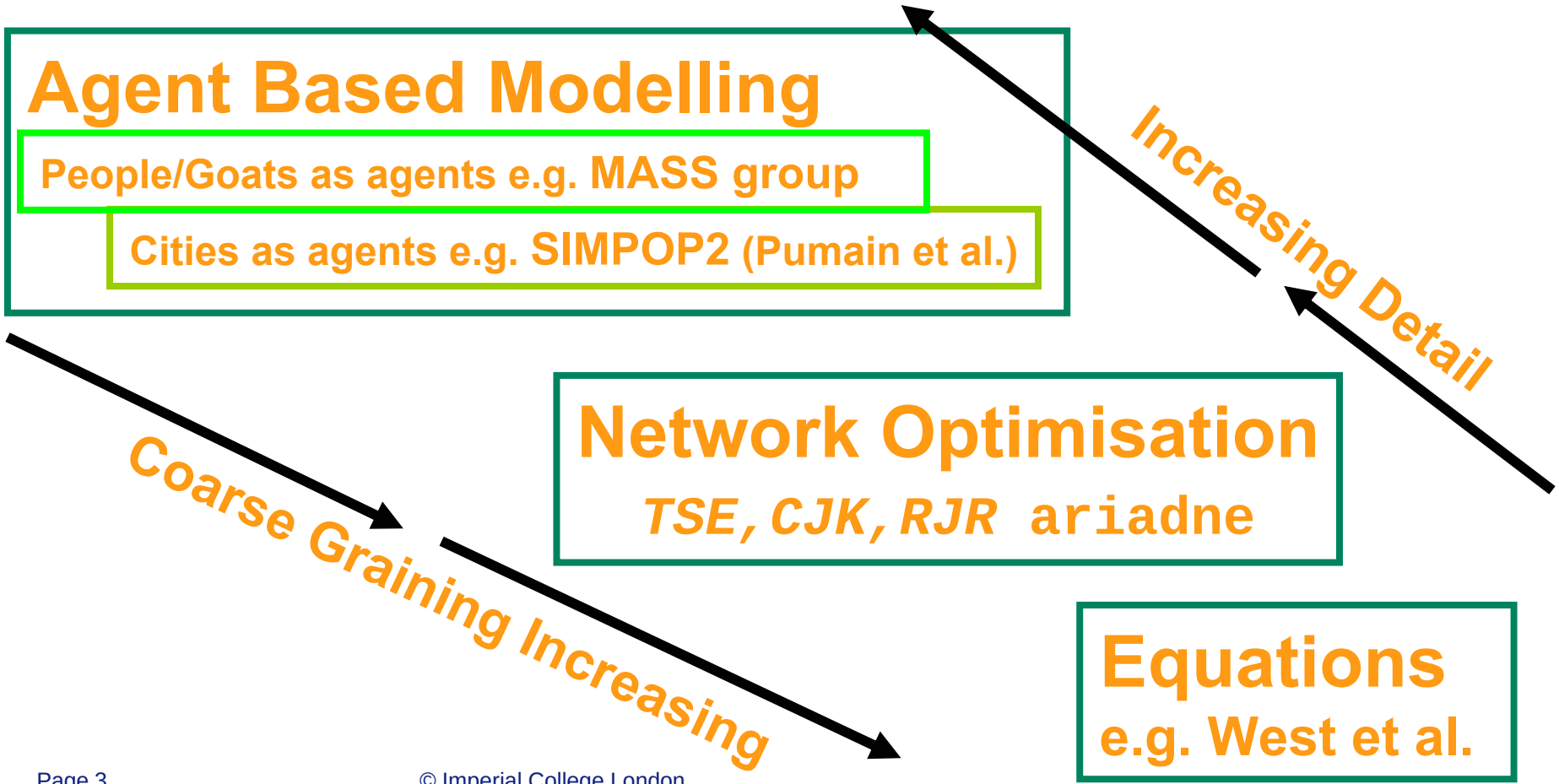
`Minoa'

A reconstruction on show in Chania, Crete

Approaches to Modelling

Several approaches when studying settlement patterns, many take *settlements* as the core unit.

- e.g. see ISCOM project D.Lane et al. (ed.s) 2007



Site-Site Interactions

- In archaeology relatively little attention has been given to the potential of interactions between sites being involved in the generation of those sites

⇒ Network models may prove to be useful

- Most models focused on local interactions, often just nearest neighbour interactions
  - Malta (*Renfrew & Level, 1979*);
    Geometric Greece (*Rihll & Wilson, 1991*);
    Proximal Point Analysis (*Terrell 1977; Irwin 1983; Hage and Harary, 1991, 1996; Broodbank 2000*)

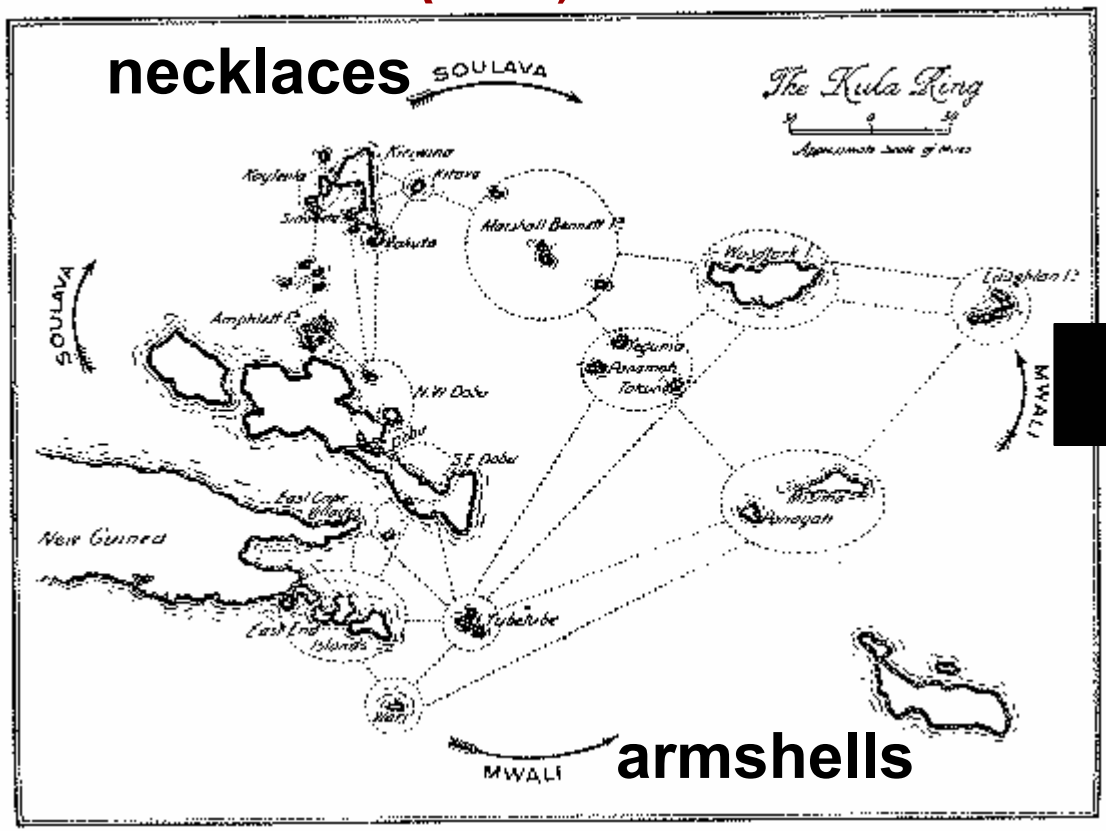
Island Archipelagos as an Ideal Laboratory

- Vertices = Major Population or Resource Sites
- Edges = Exchange between sites
  - physical trade of goods *or* transmission of culture
  - direct contact *or* island hopping links

- Sea isolates communities → **Natural Vertices**
- Interactions controlled by physical limitations of ancient sea travel → **Simple Links**
- Coastal Sites often isolated like islands due to geography and difficulty of ancient land travel

Earlier work: includes The Kula Ring

Malinowski (1922)



Hage and Harary (1991)

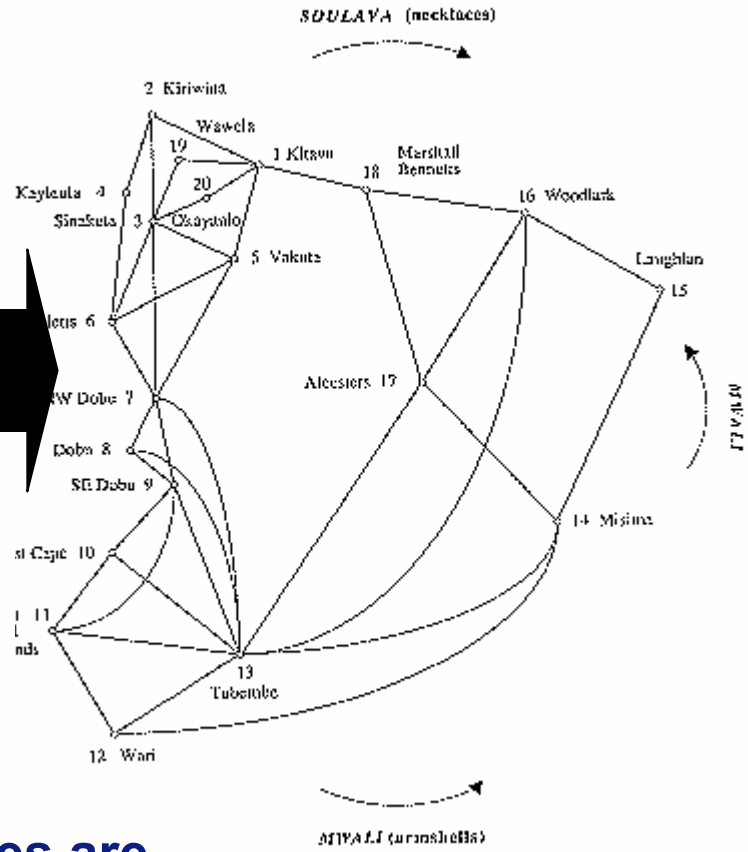


Fig. 5.1. The graph G of the *kula* ring

Hage and Harary formed a graph where edges are exchange relations and used random walkers to analyse the *global* properties of the system

***Also* Terrell 1977; Irwin 1983; Broodbank 2000**

Focus: Middle Bronze Age (MBA) Aegean

- Clear temporal delineation
  clear gaps (`dark ages') or shifts in record
  - c.2000BC distinct Minoan culture starts, and sail replaces oar
  - c.1500BC end of Minoan cultural dominance

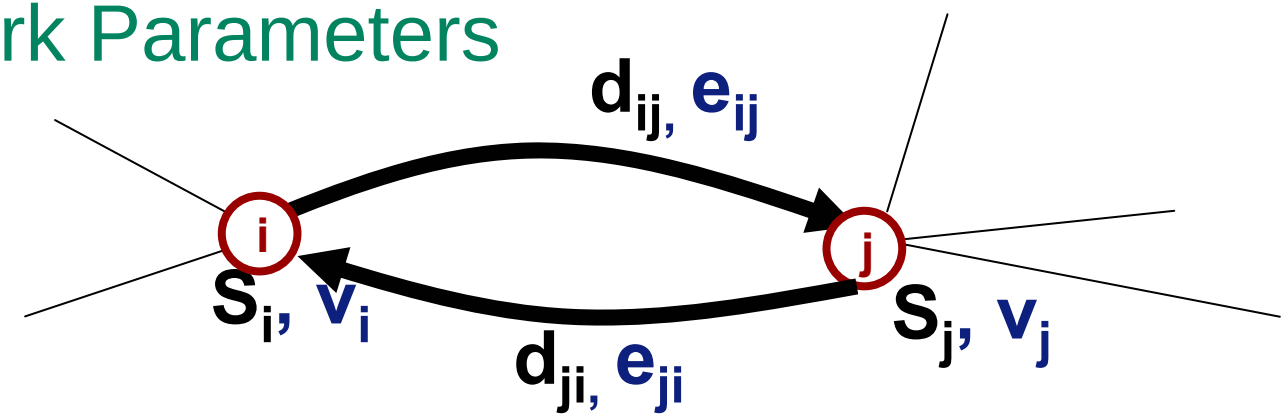
- Physically largely self contained
  - questions regarding relationship to Egyptian culture

Some Questions

- **The Knossos Question**
  What is the connection between macro-scale development of regional networks and the emergence of a primary centre?
  The palace at Knossos does not have the best local environment

- **Minoanisation**
  What can explain the spread of and the variability in Minoan influence across the southern Aegean c.1700 BC?

Network Parameters



- We want to find our optimal network given:-

Inputs:

- **Site sizes** S_i
- **Site separation** d_{ij}

Outputs:

- **Site occupation** v_i
- **Interaction levels** e_{ij}
- **Total population** $\Sigma_j (S_i v_i)$
- **Trade activity** $\Sigma_j (S_i v_i e_{ij})$

Optimal Networks

- Adjust site and edge variables to optimise the ‘cost ‘ H of the network:

$$H = -\lambda E - \kappa L + j P + \mu T$$

where

- **E – all exchange/trade**
  Increase parameter λ and interaction produces more benefits
- **L – all local production**
  Increase parameter κ and internal processes more profitable
- **P – total population**
  Increase parameter *j* and cost per person is increased
- **T – total strength of links**
  Increase parameter μ and interaction links more expensive to maintain

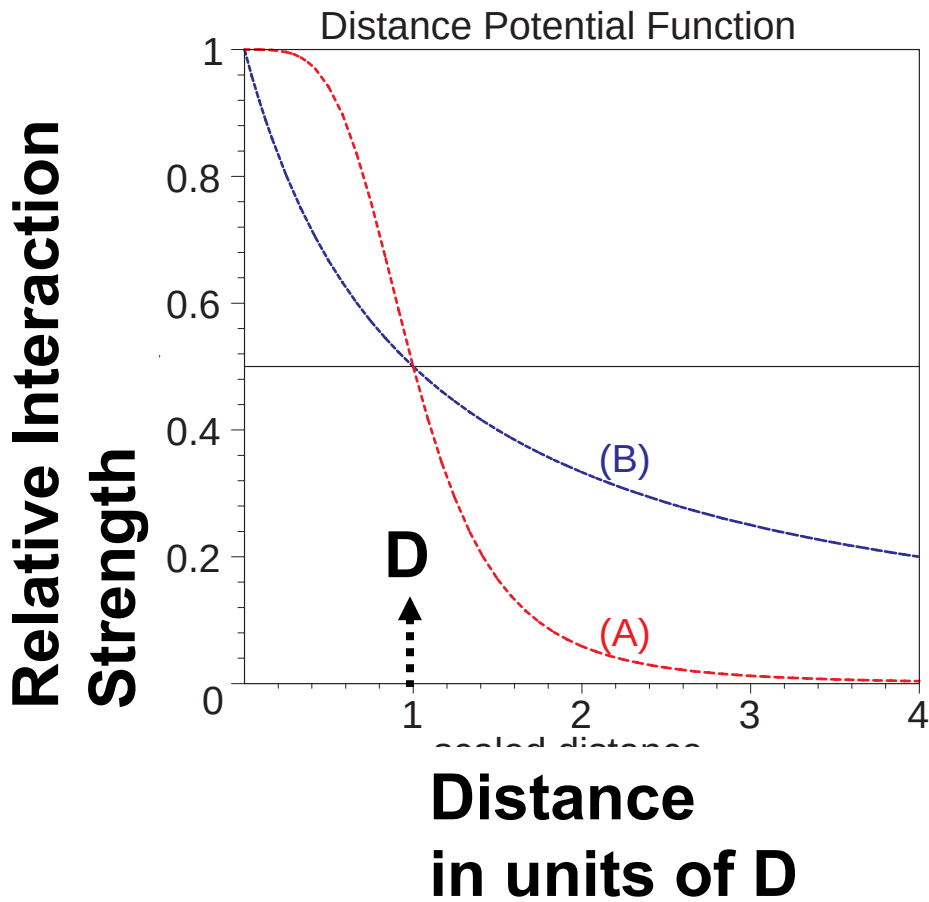
Distance Scale D

We use: D=100km for sail D=10km for rowing

(after 2000BC) (pre 2000BC)

Interaction term for each pair of sites depends on distance d_{ij} between sites such that for distances longer than a scale D the benefit is zero

i.e. no effective direct interaction



Analysis

- Working with 34 sites
- Can not assign parameter values in model from physical data so make comparisons between different data sets

  e.g. vary one parameter, hold rest fixed.

  This represents slow evolution where system remains in effective equilibrium.
- For any given set of (reasonable) values:

  a) can analyse intrinsic parameters

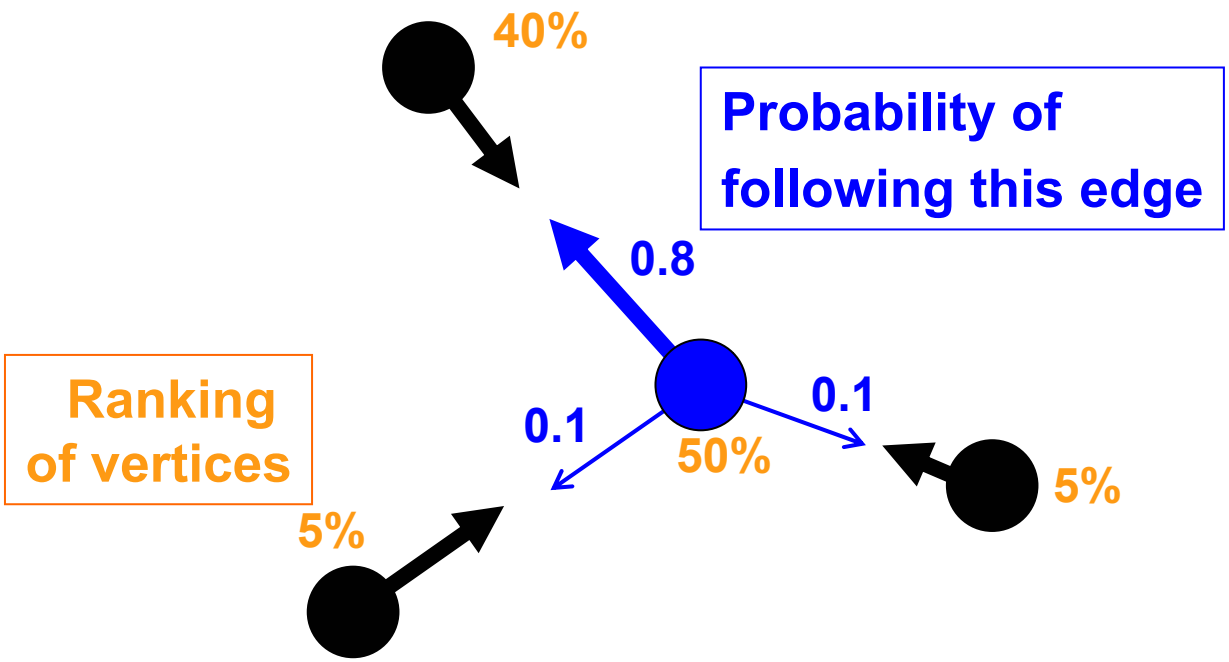
  b) can perform further `games' to analyse properties e.g. simulate trade in physical objects, cultural transmission models.

The 34 Sites Used

Analysis Methods: Ranking

- The percentage of time spent at each node by a random walker on the network.
  The walker chooses to follow a link with probability proportional to its strength. (Other choices possible).

  ⇒ **Measure of GLOBAL network properties**



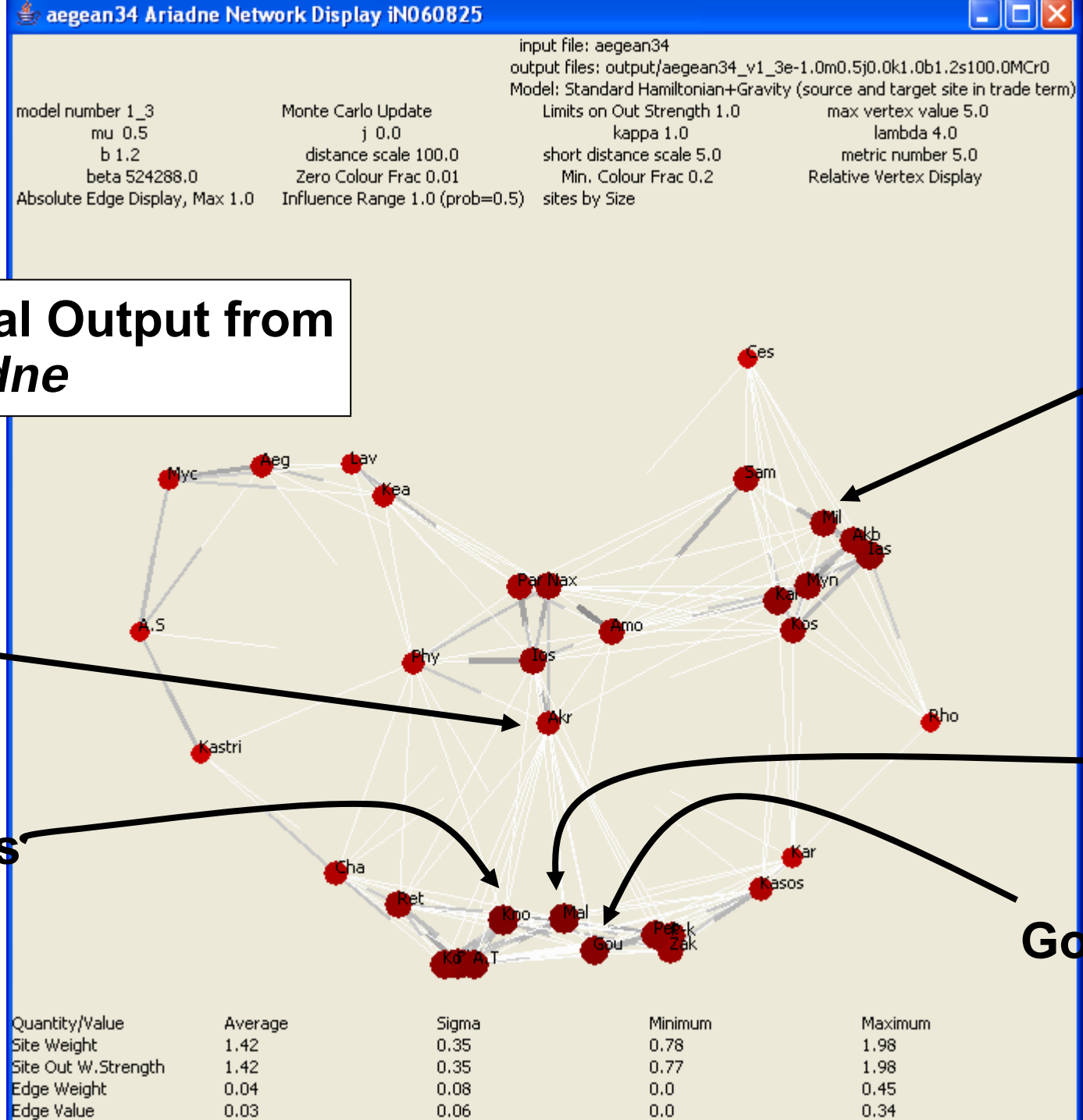
As used by Hage & Harary 1991, and Google UK

Analysis of Single Network

- The new few slides show the analysis of one result of our model
- Look for sites which are off any general trends

j=0, m=0.5, k=1.0, l=4.0

Typical Output from *ariadne*



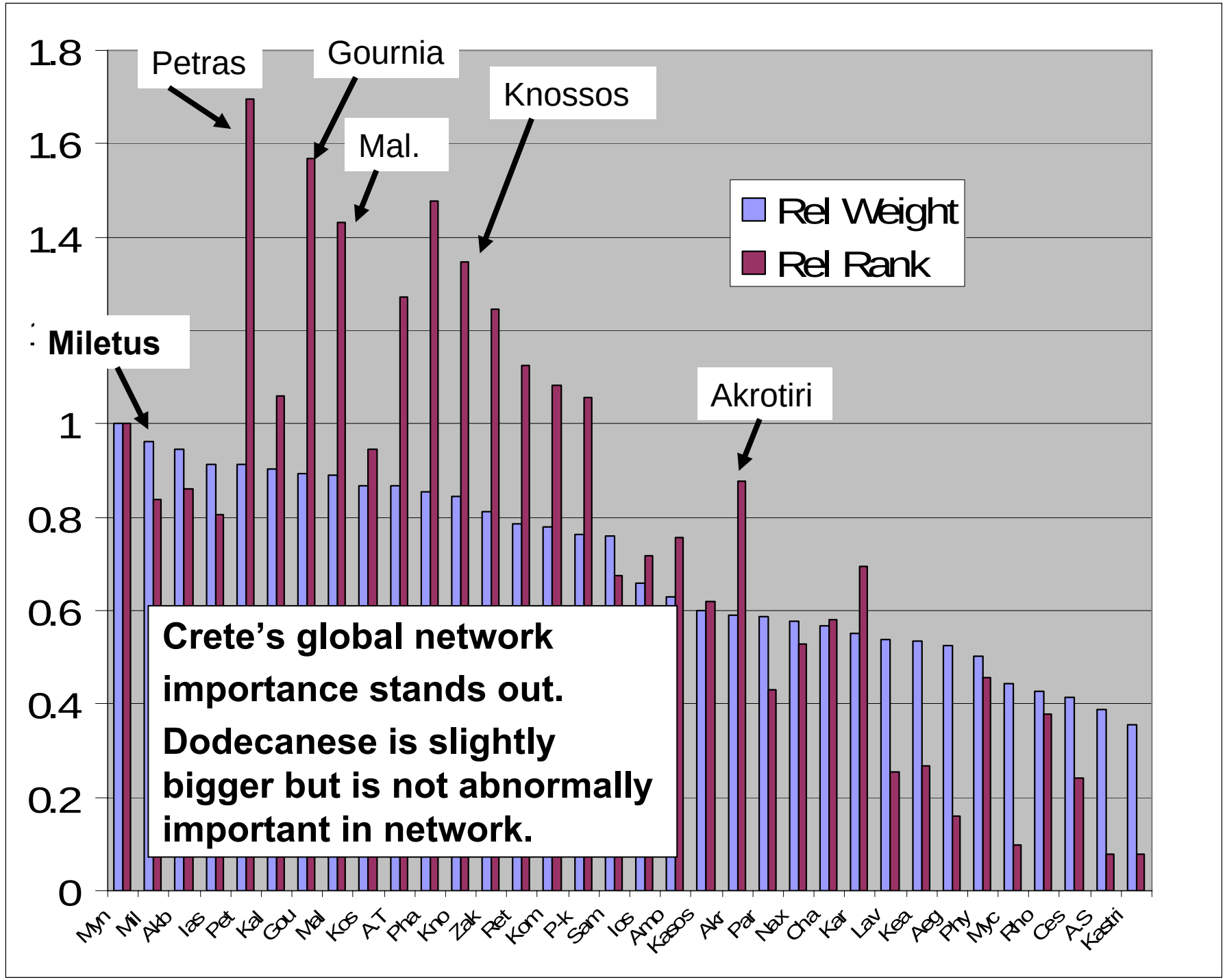
Miletus

Akrotiri

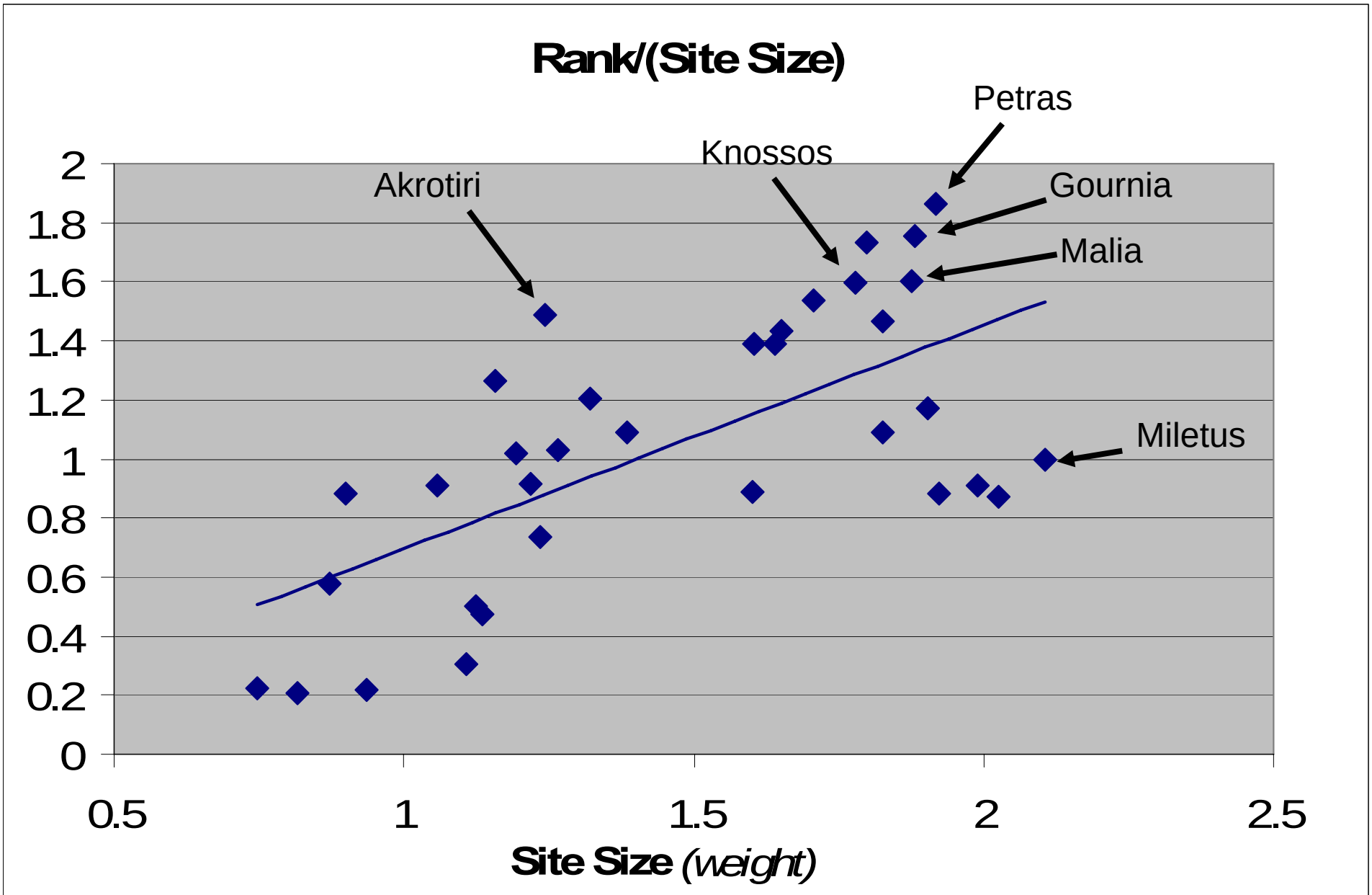
Malia

Knossos

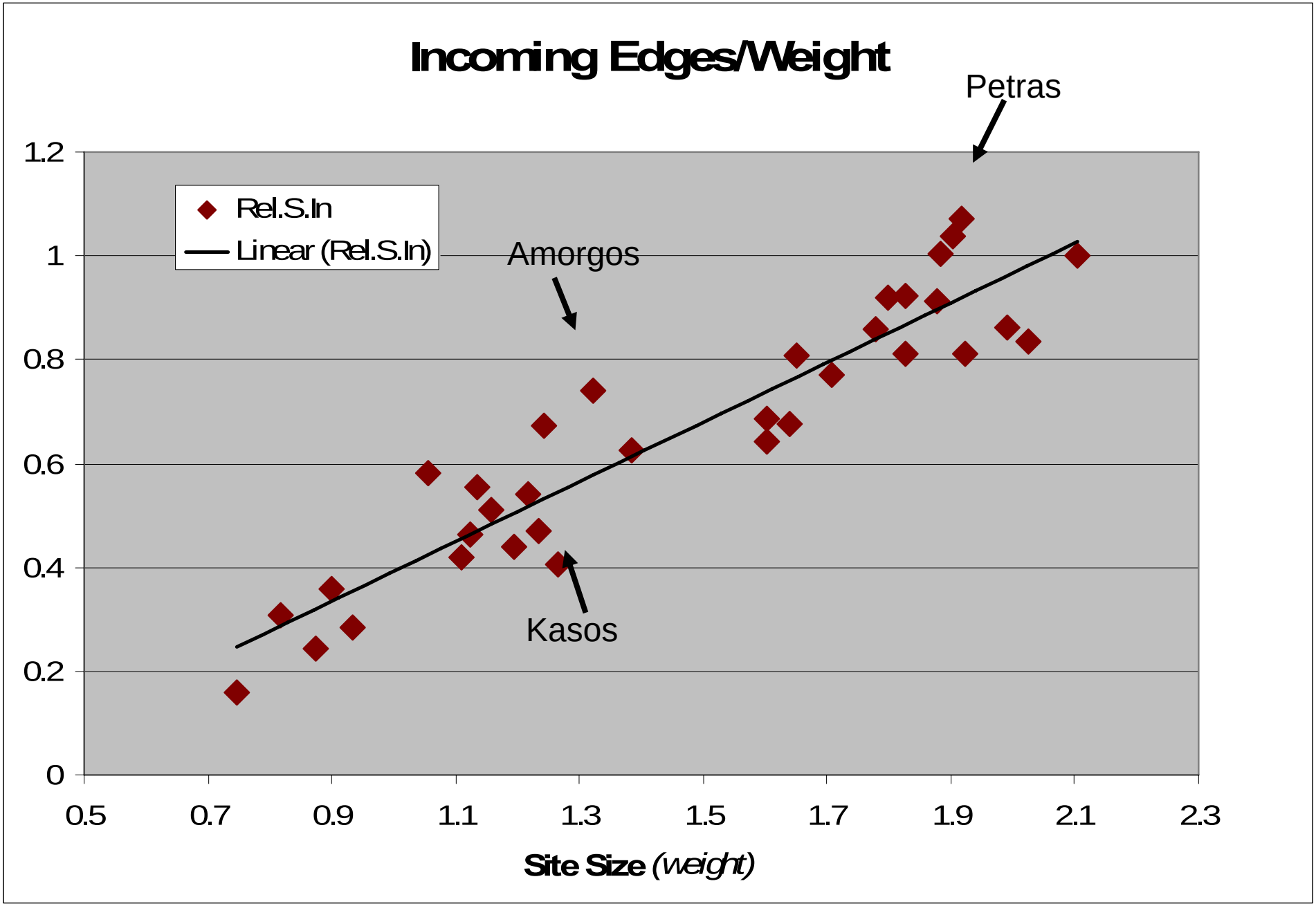
Gournia


1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Petras
Gournia
Knossos
Mal.
Miletus
Akrotiri
Rel Weight
Rel Rank
Crete's global network importance stands out.
Dodecanese is slightly bigger but is not abnormally important in network.
Myn
Mil
Akb
Ias
Pet
Kal
Gou
Mal
Kos
A.T
Pha
Kno
Zak
Ret
Kom
P-k
Sam
Ios
Amo
Kasos
Akr
Par
Nax
Cha
Kar
Lav
Kea
Aeg
Phy
Myc
Rho
Ces
A.S
Kastri

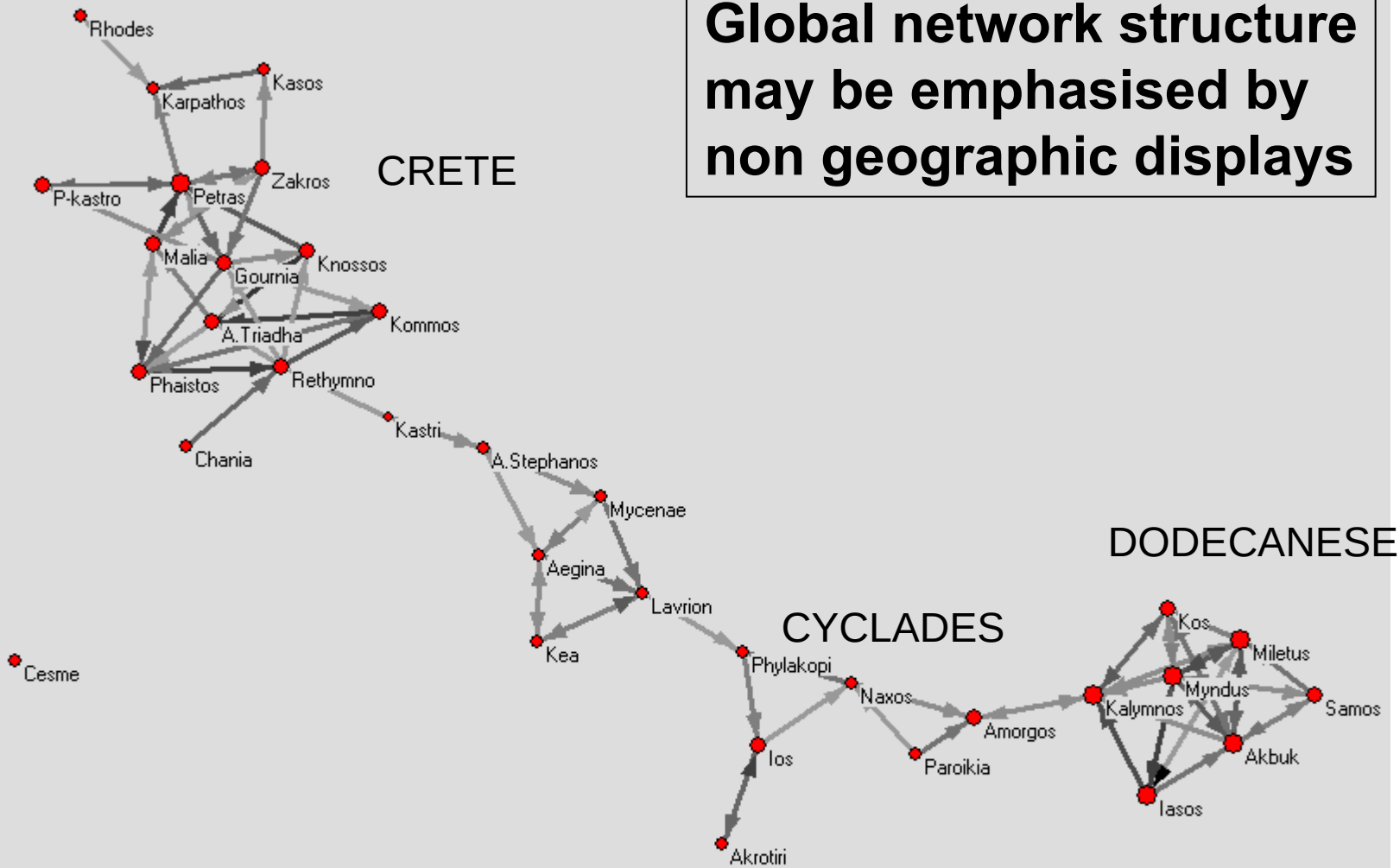
Rank vs. Size shows Crete's is more important to the global network that its size suggests, not so for Dodecanese



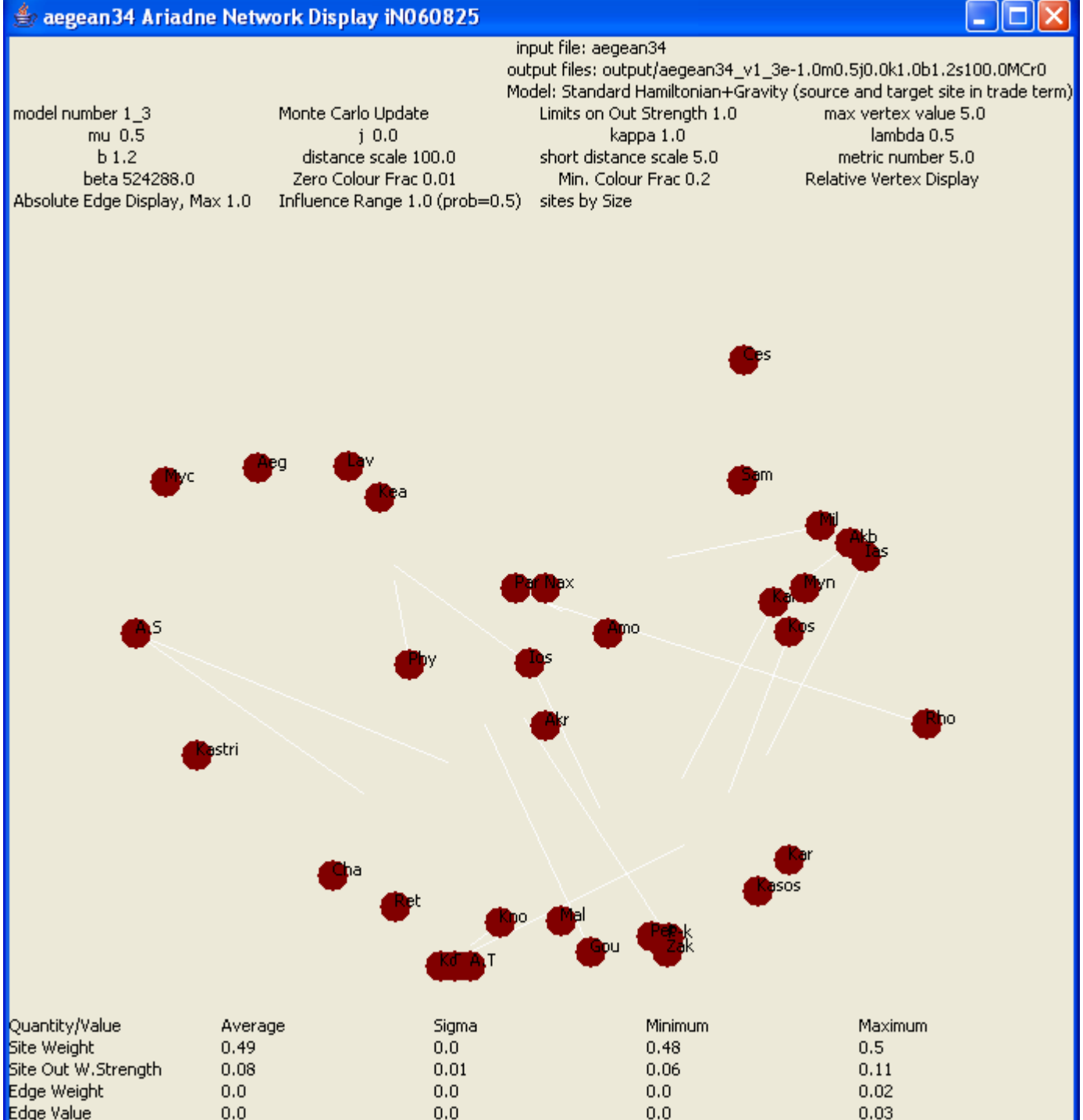
Local properties often scale closely with site size (weight)



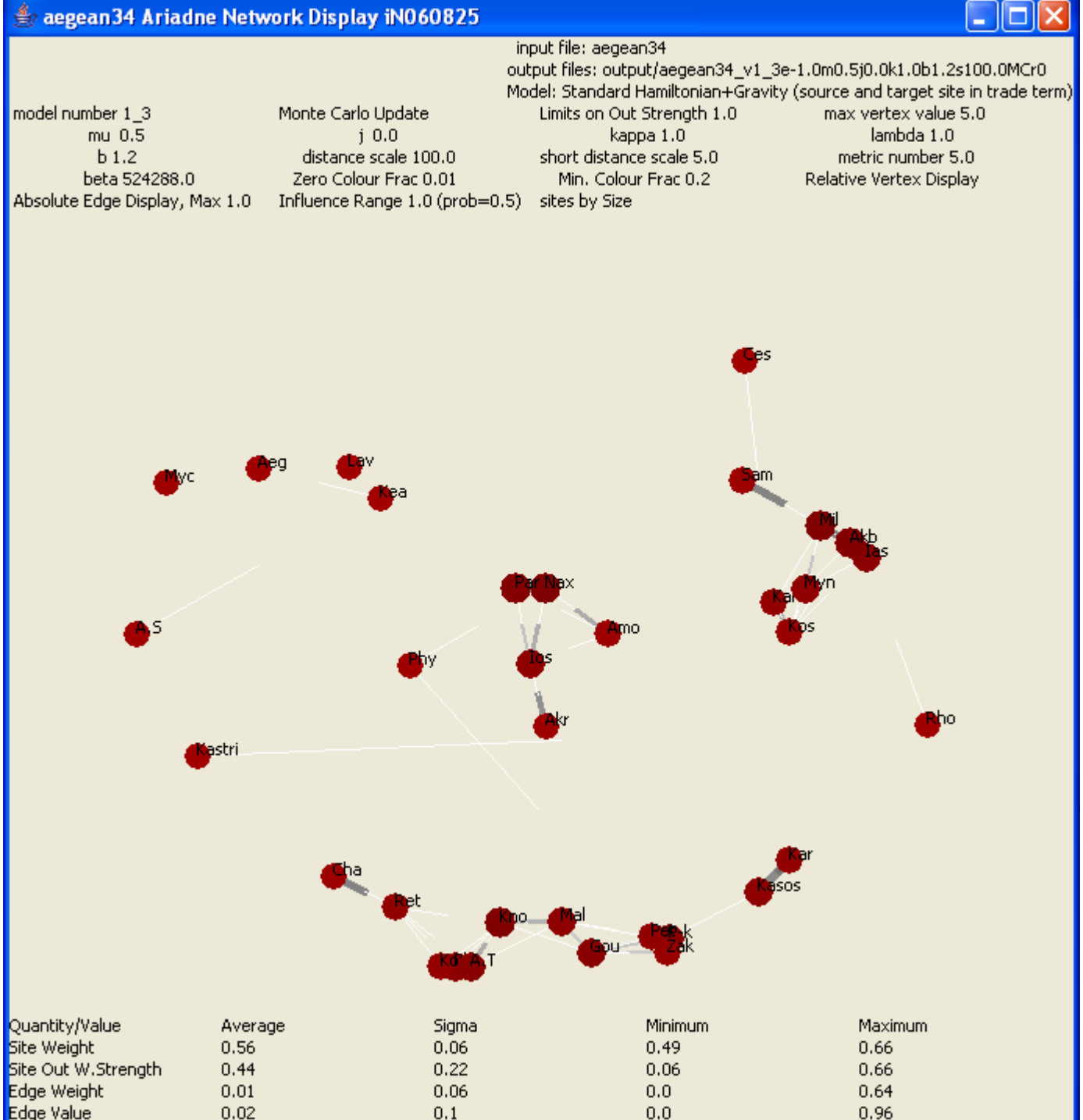
Global network structure may be emphasised by non geographic displays



Increasing Interaction Benefits (λ)



Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	0.49	0.0	0.48	0.5
Site Out W.Strength	0.08	0.01	0.06	0.11
Edge Weight	0.0	0.0	0.0	0.02
Edge Value	0.0	0.0	0.0	0.03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model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 0.5
j 0.0
kappa 1.0
lambda 1.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
Sam
Mil
Akb
Tas
Myn
Kar
Kos
Par
Nax
Amo
Ios
Phy
Akr
Rho
Kastri
Myc
Aeg
Lav
Kea
A S
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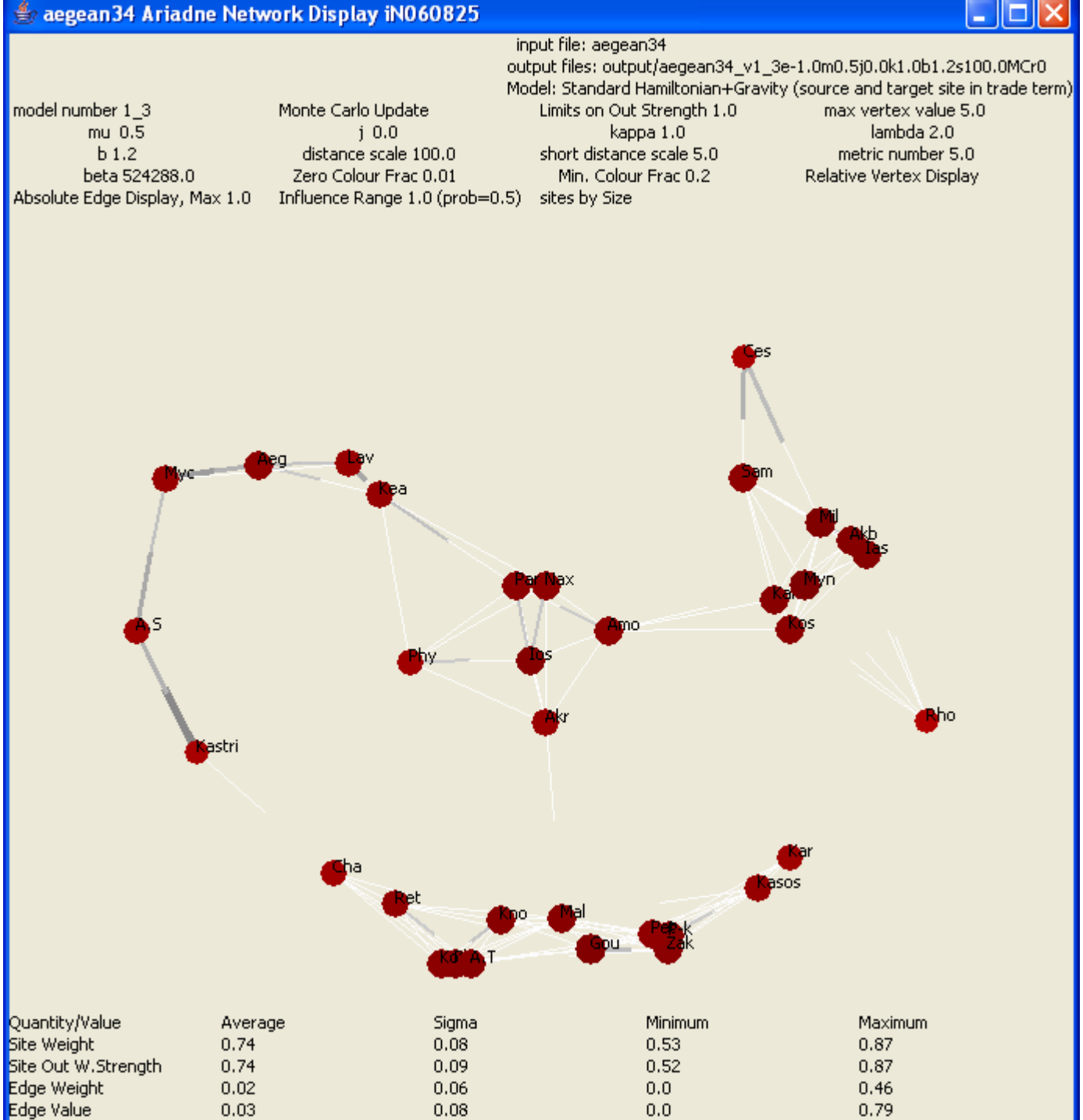
Ret
Kno
Mal
Pet
Zak
Gou
Kd
A T
Kar
Kasos
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
0.56
0.06
0.49
0.66
Site Out W.Strength
0.44
0.22
0.06
0.66
Edge Weight
0.01
0.06
0.0
0.64
Edge Value
0.02
0.1
0.0
0.96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model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 0.5
j 0.0
kappa 1.0
lambda 2.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
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Kar
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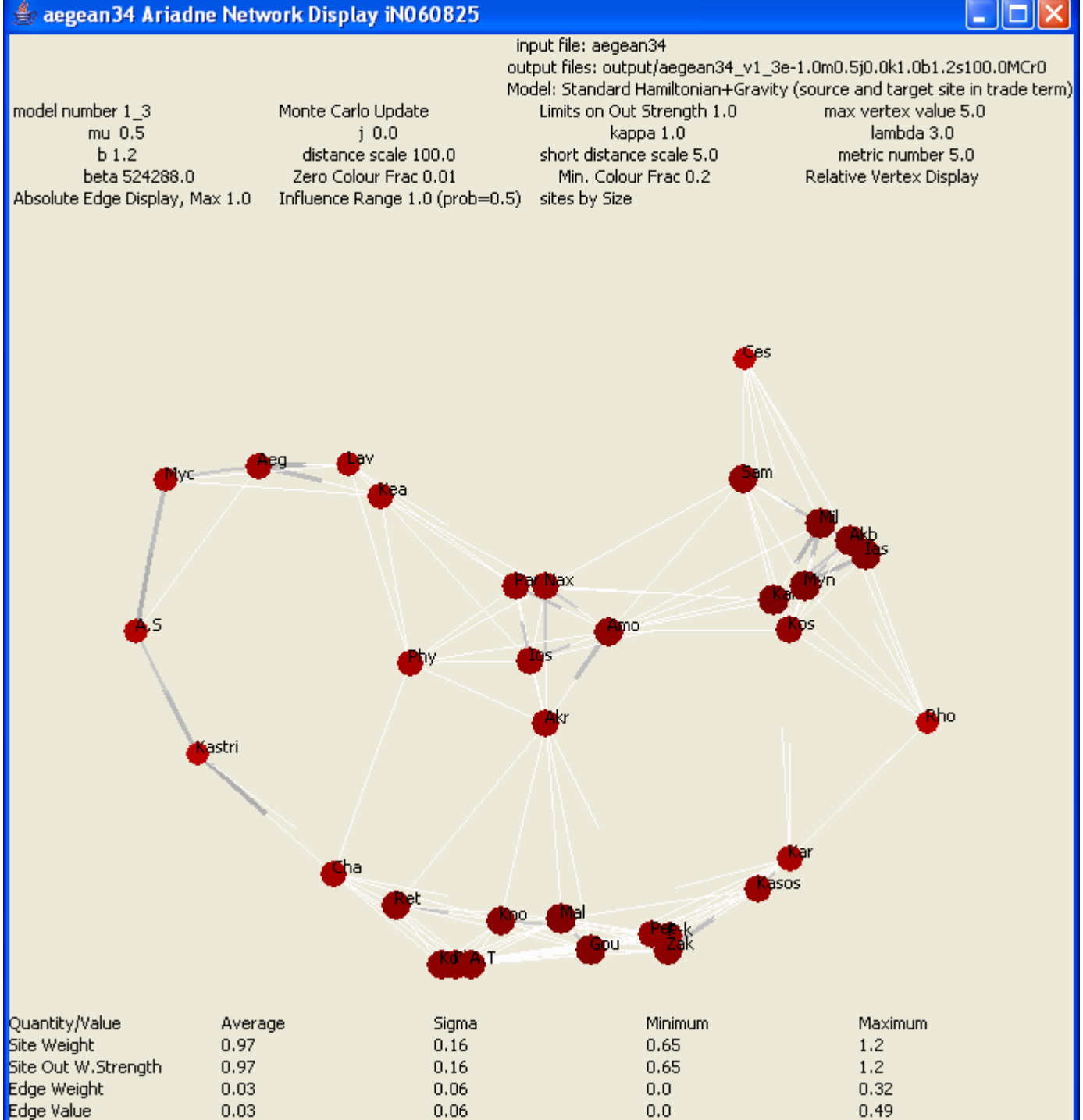
Pet
Zak
Gou
Kd
A.T
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
0.74
0.08
0.53
0.87
Site Out W.Strength
0.74
0.09
0.52
0.87
Edge Weight
0.02
0.06
0.0
0.46
Edge Value
0.03
0.08
0.0
0.79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model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 0.5
j 0.0
kappa 1.0
lambda 3.0
b 1.2
distance scale 100.0
short distance scale 5.0
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Phy
Ios
Akr
Rho
Kastri
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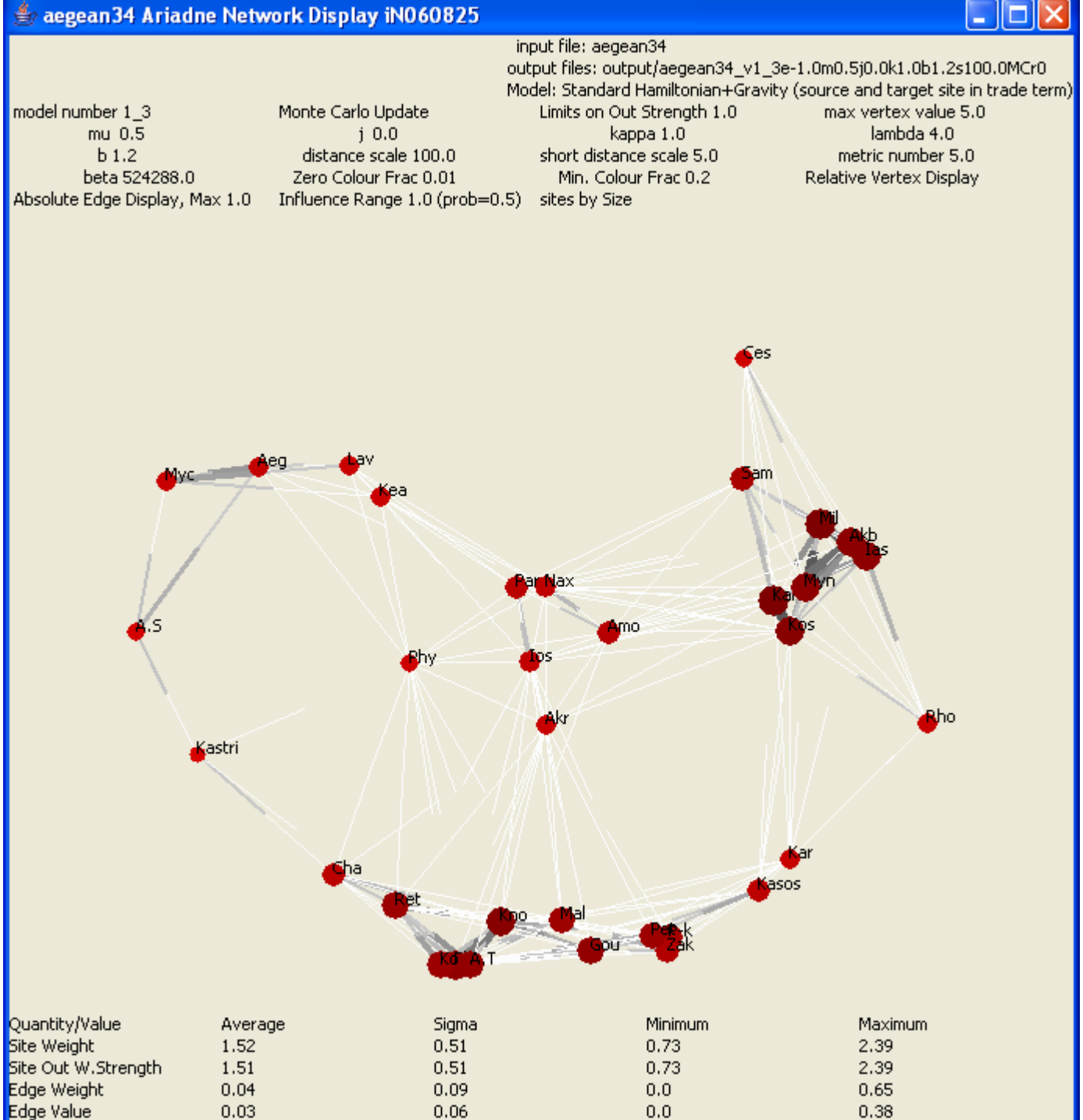
Kno
Mal
Pet
Zak
Gou
Kd
A.T
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
0.97
0.16
0.65
1.2
Site Out W.Strength
0.97
0.16
0.65
1.2
Edge Weight
0.03
0.06
0.0
0.32
Edge Value
0.03
0.06
0.0
0.49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Limits on Out Strength 1.0
max vertex value 5.0
mu 0.5
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
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Cha
Ret
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Kar
Kasos
Quantity/Value
Average
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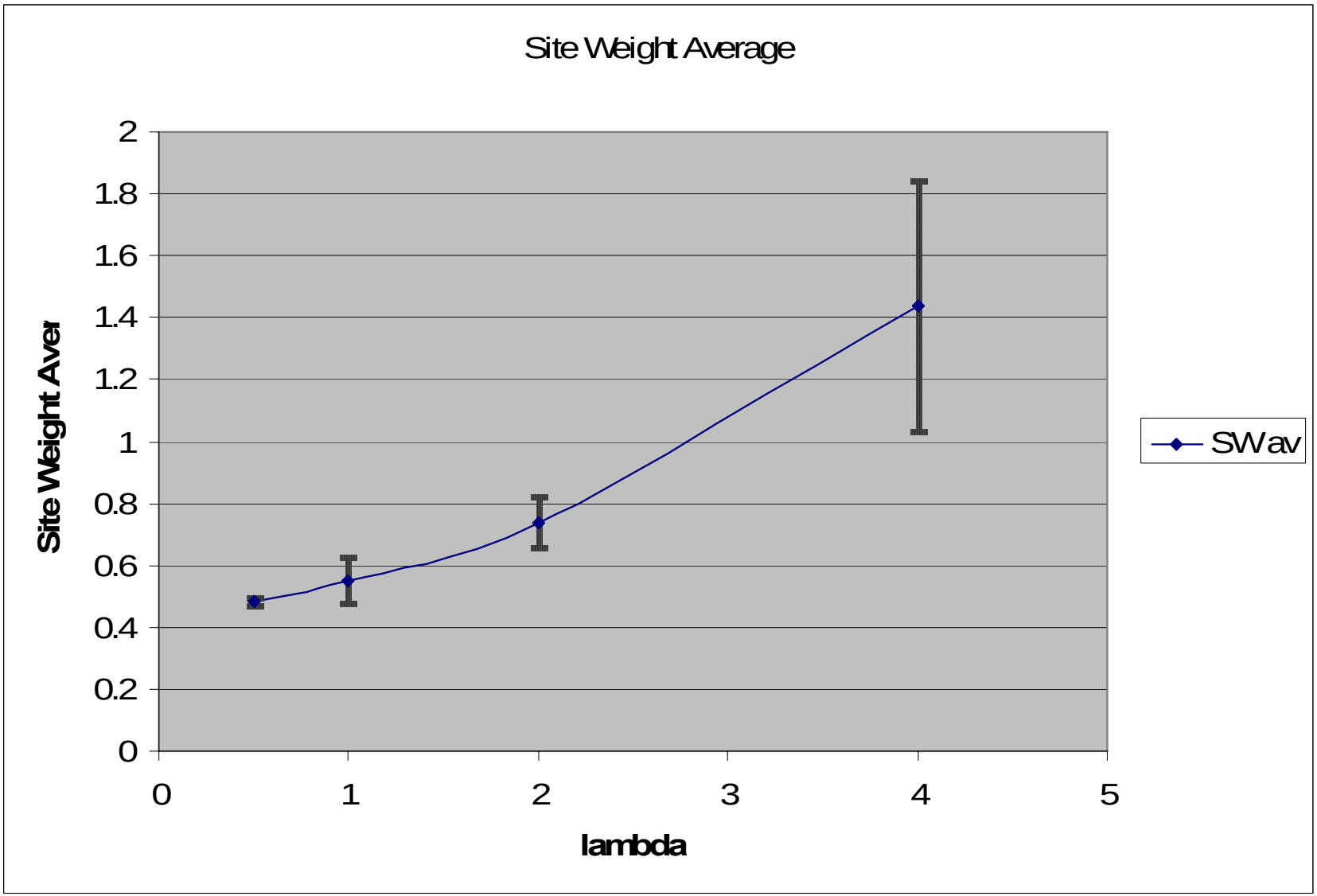
Minimum
Maximum
Site Weight
1.52
0.51
0.73
2.39
Site Out W.Strength
1.51
0.51
0.73
2.39
Edge Weight
0.04
0.09
0.0
0.65
Edge Value
0.03
0.06
0.0
0.38

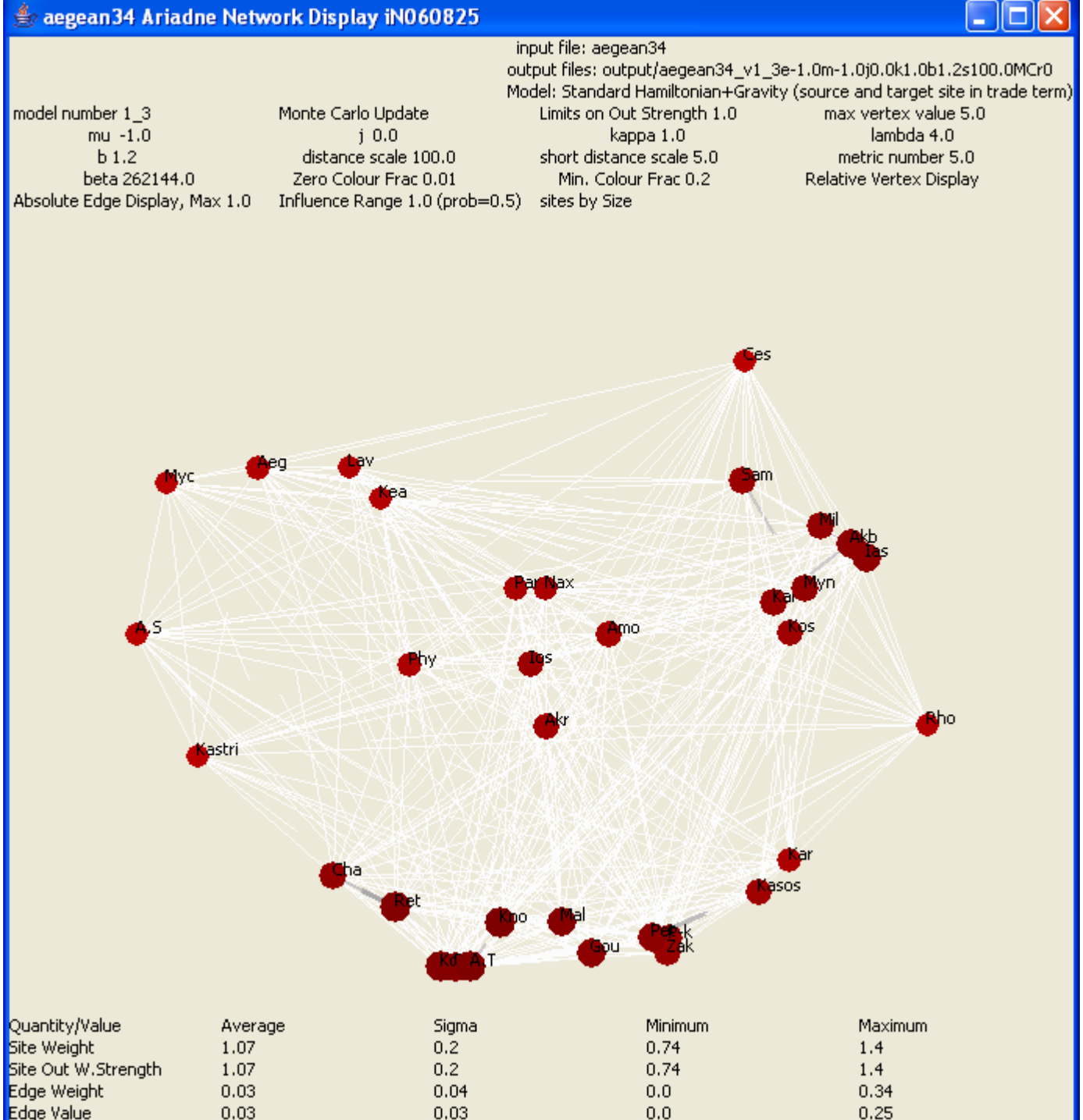


Increasing Edge Cost (μ)

Next 7 slides

- for large interaction benefits *(λ=4.0, j=0, κ=1.0)*

- Increasing μ causes edges to concentrate on decreasing profitable routes.
- The largest site size goes up while the smallest stays the same.
- Total cost in edges the same (as vertex out strength) but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model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu -1.0
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 262144.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
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Ios
Rho
Akr
Kastri
Kar
Cha
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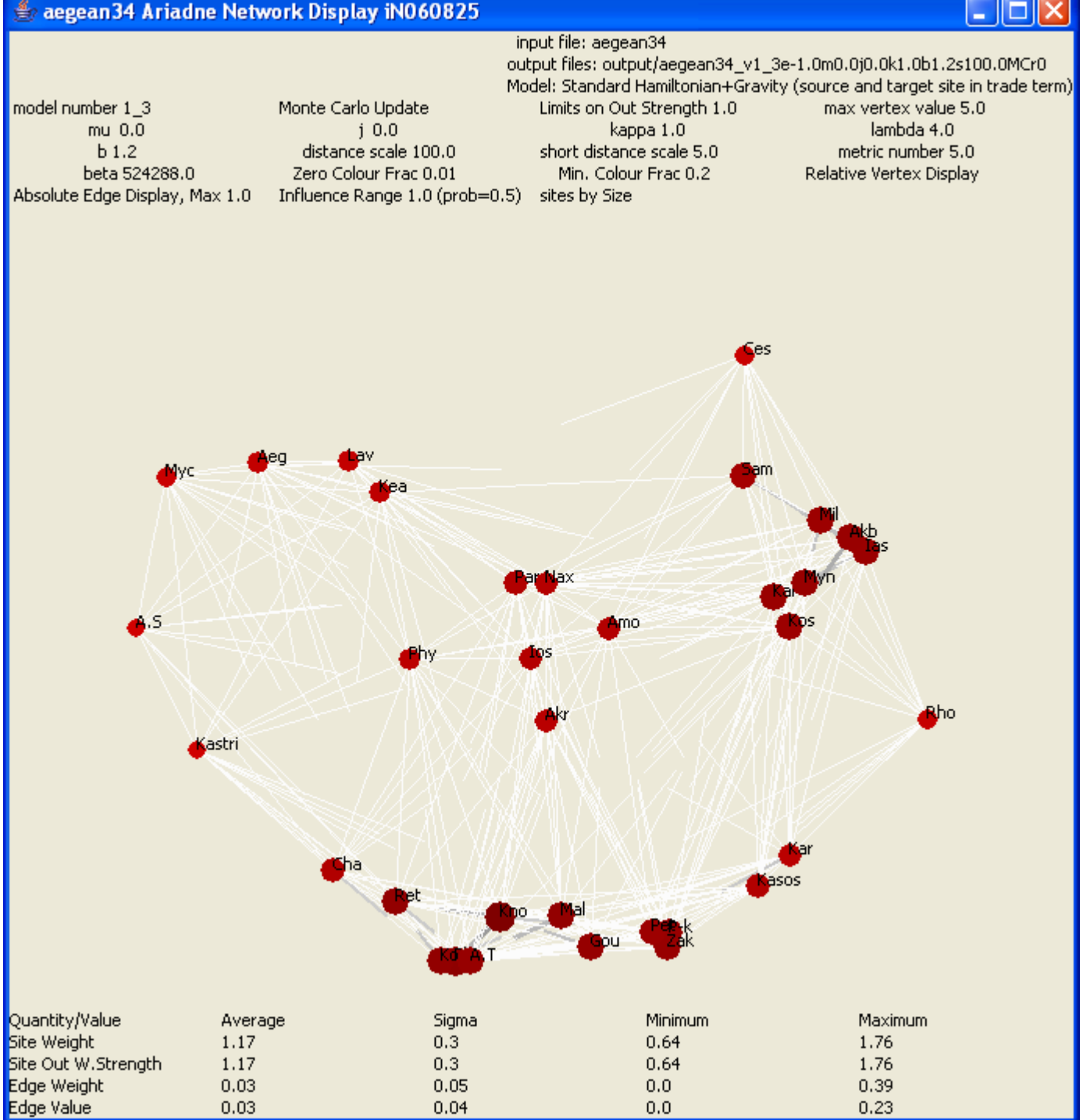
Kd
A.T
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
1.07
0.2
0.74
1.4
Site Out W.Strength
1.07
0.2
0.74
1.4
Edge Weight
0.03
0.04
0.0
0.34
Edge Value
0.03
0.03
0.0
0.25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Model: Standard Hamiltonian+Gravity (source and target site in trade term)
model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 0.0
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
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Kos
Phy
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Akr
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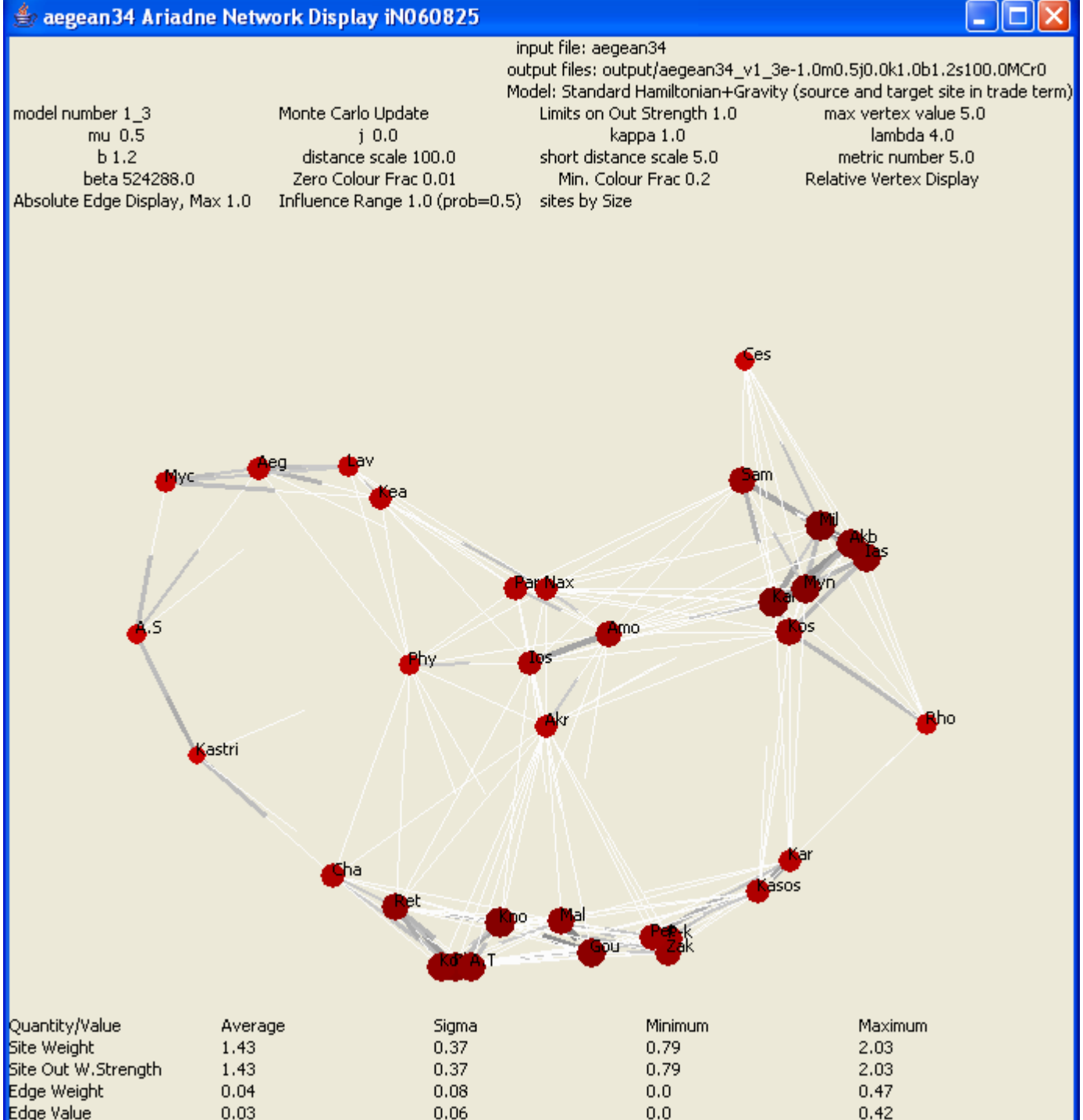
A.T
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
1.17
0.3
0.64
1.76
Site Out W.Strength
1.17
0.3
0.64
1.76
Edge Weight
0.03
0.05
0.0
0.39
Edge Value
0.03
0.04
0.0
0.23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Model: Standard Hamiltonian+Gravity (source and target site in trade term)
model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 0.5
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
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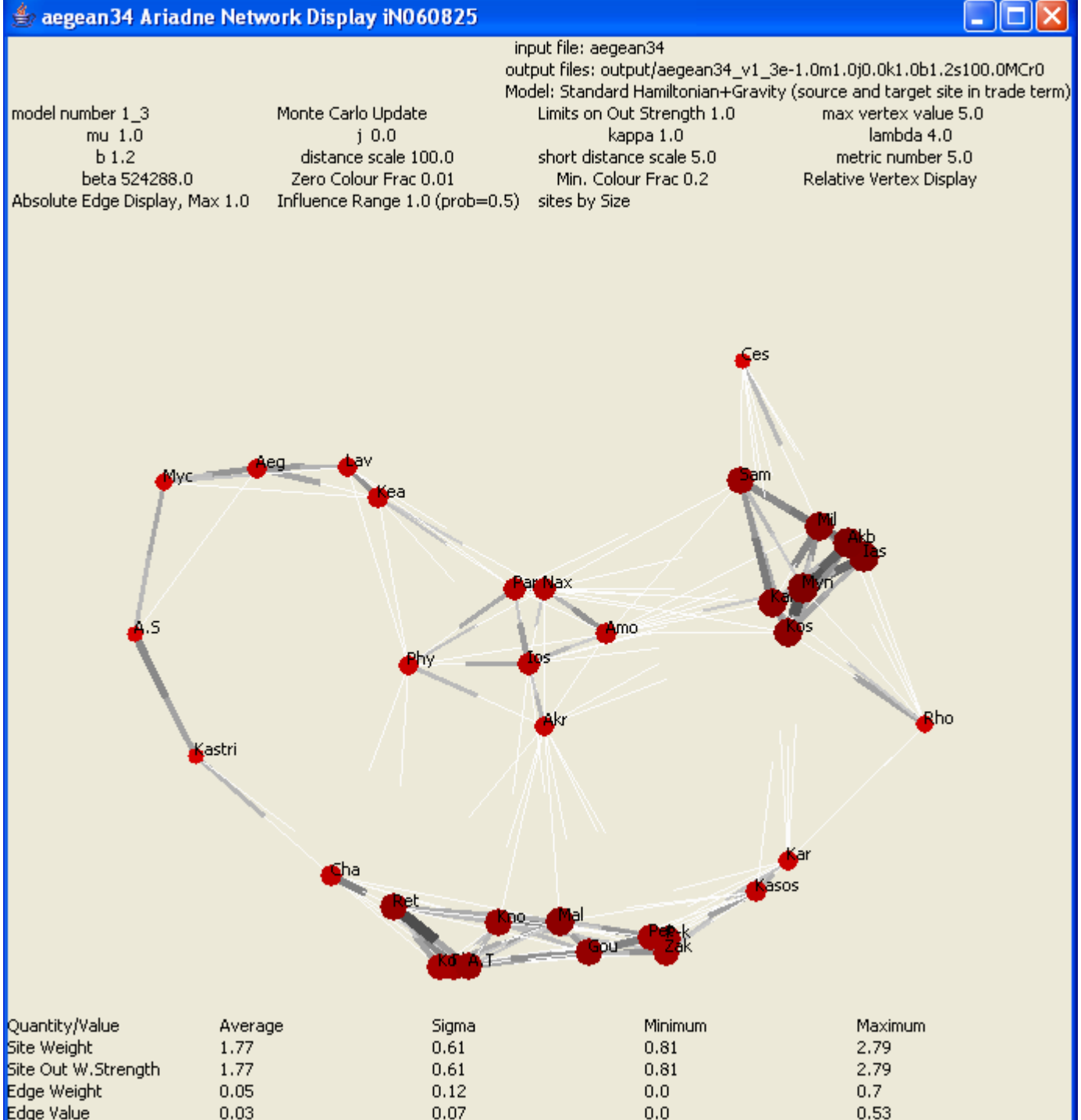
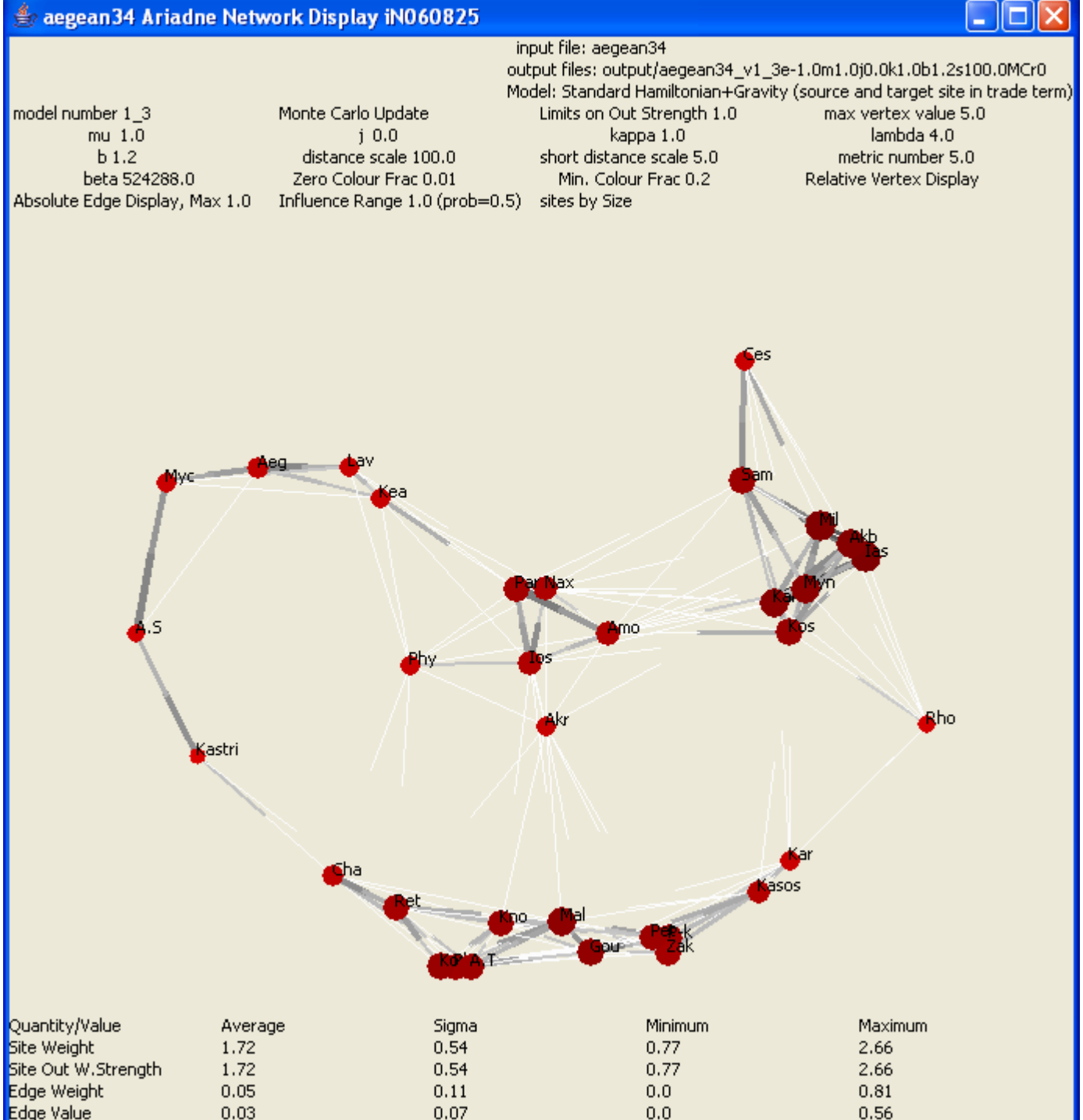
Cha
Ret
Kno
Mal
Pet
Zak
Gou
Kd
A.T
Kar
Kasos
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
1.43
0.37
0.79
2.03
Site Out W.Strength
1.43
0.37
0.79
2.03
Edge Weight
0.04
0.08
0.0
0.47
Edge Value
0.03
0.06
0.0
0.42



Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.77	0.61	0.81	2.79
Site Out W.Strength	1.77	0.61	0.81	2.79
Edge Weight	0.05	0.12	0.0	0.7
Edge Value	0.03	0.07	0.0	0.53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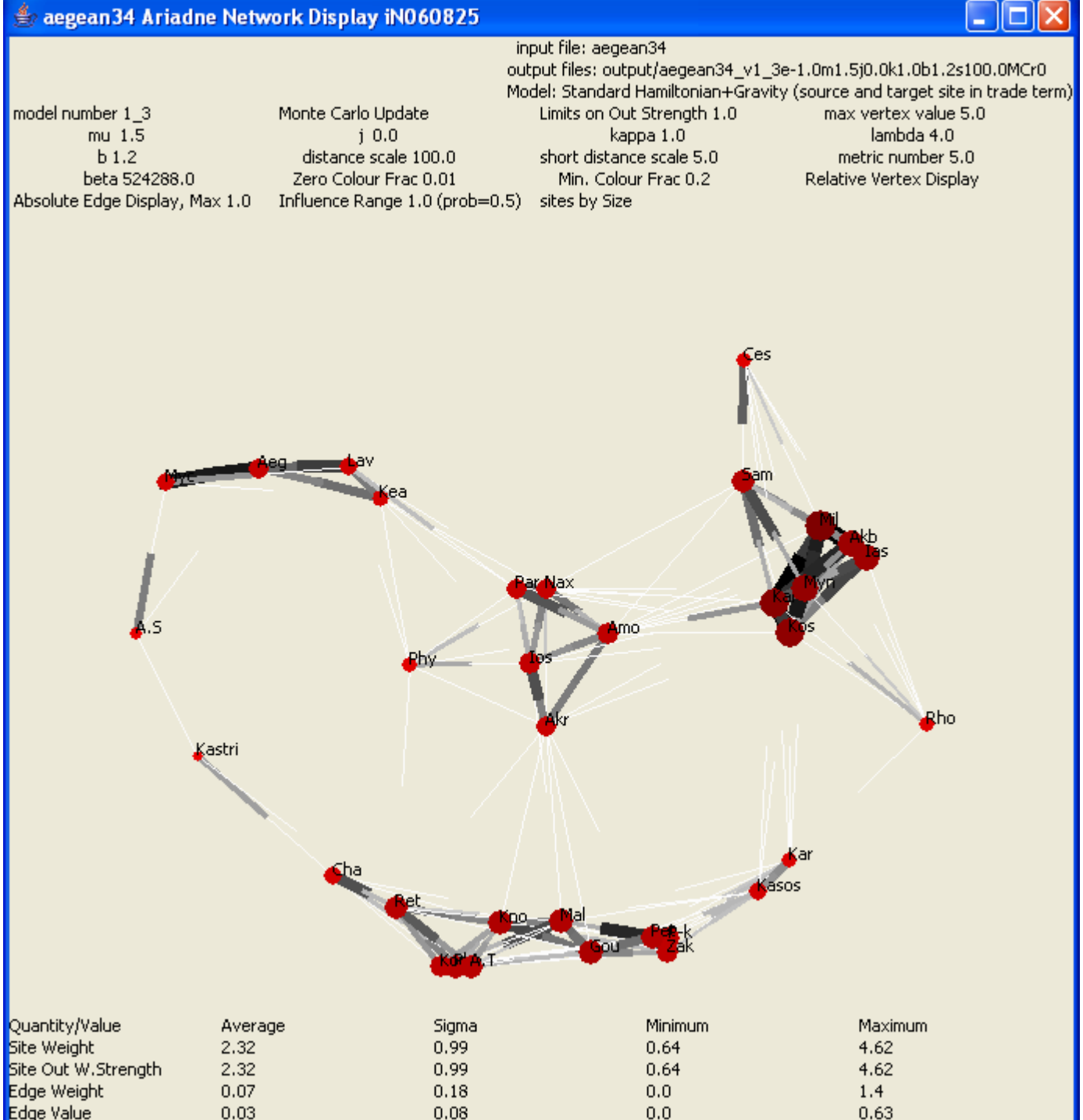
Model: Standard Hamiltonian+Gravity (source and target site in trade term)
model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 1.0
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
Sam
Mil
Akb
Ias
Myc
Aeg
Lav
Kea
Par
Nax
Myn
Kar
Kos
Amo
A.S
Phy
Ios
Akr
Rho
Kastri
Kar
Cha
Kasos
Ret
Kno
Mal
Pet
Zak
Gou
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
1.72
0.54
0.77
2.66
Site Out W.Strength
1.72
0.54
0.77
2.66
Edge Weight
0.05
0.11
0.0
0.81
Edge Value
0.03
0.07
0.0
0.56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model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 1.5
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
Aeg
Lav
Kea
Sam
Mil
Akb
Ias
Par
Nax
Myn
Kal
Kos
Amo
A.S
Phy
Ios
Akr
Rho
Kastri
Kar
Kasos
Cha
Ret
Kno
Mal
Pet
k
Zak
Gou
Kdr
A.T
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
2.32
0.99
0.64
4.62
Site Out W.Strength
2.32
0.99
0.64
4.62
Edge Weight
0.07
0.18
0.0
1.4
Edge Value
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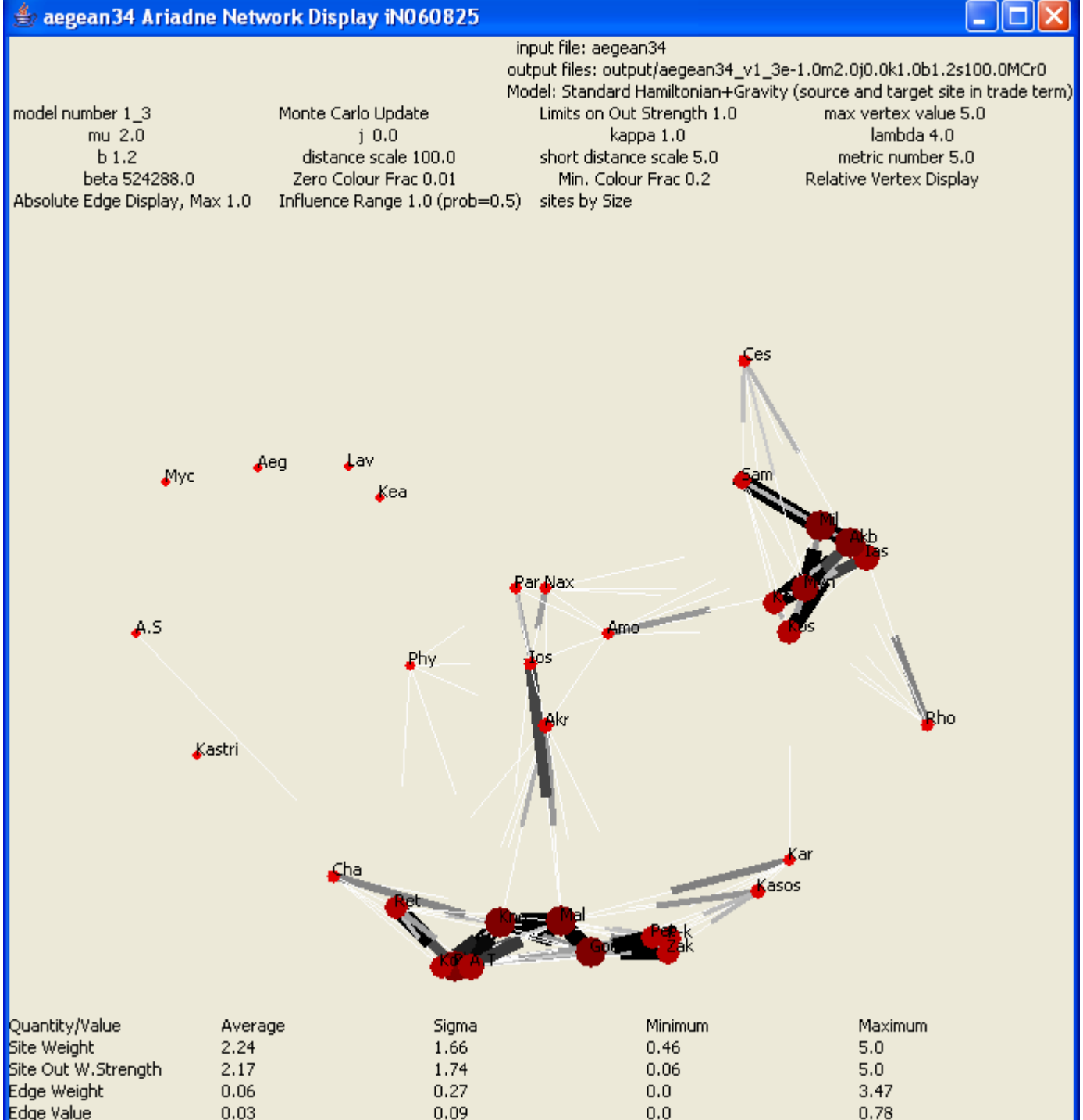
0.08
0.0
0.63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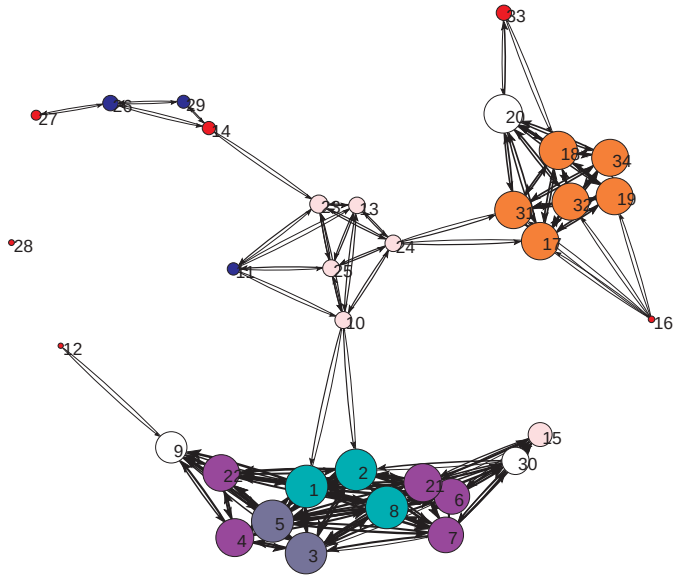
Model: Standard Hamiltonian+Gravity (source and target site in trade term)
model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 2.0
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
Sam
Mil
Akb
Ias
Par
Nax
Amo
Kos
A.S
Phy
Ios
Akr
Rho
Kastri
Kar
Kasos
Cha
Mal
Zak
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
2.24
1.66
0.46
5.0
Site Out W.Strength
2.17
1.74
0.06
5.0
Edge Weight
0.06
0.27
0.0
3.47
Edge Value
0.03
0.09
0.0
0.78

End of increasing μ sequence

Minoanisation Analysis Methods



- **Diffusion**
  Use random walkers doing variable short range walks to assess how ideas can percolate through system.
- **Cultural Transmission**
  Use the networks produced here as substrate for well known models of cultural transmission (Bentley & Shennan 2003) and language transmission (Stauffer et al. 2006)
  - based on copying (drift) and innovation (mutation) processes

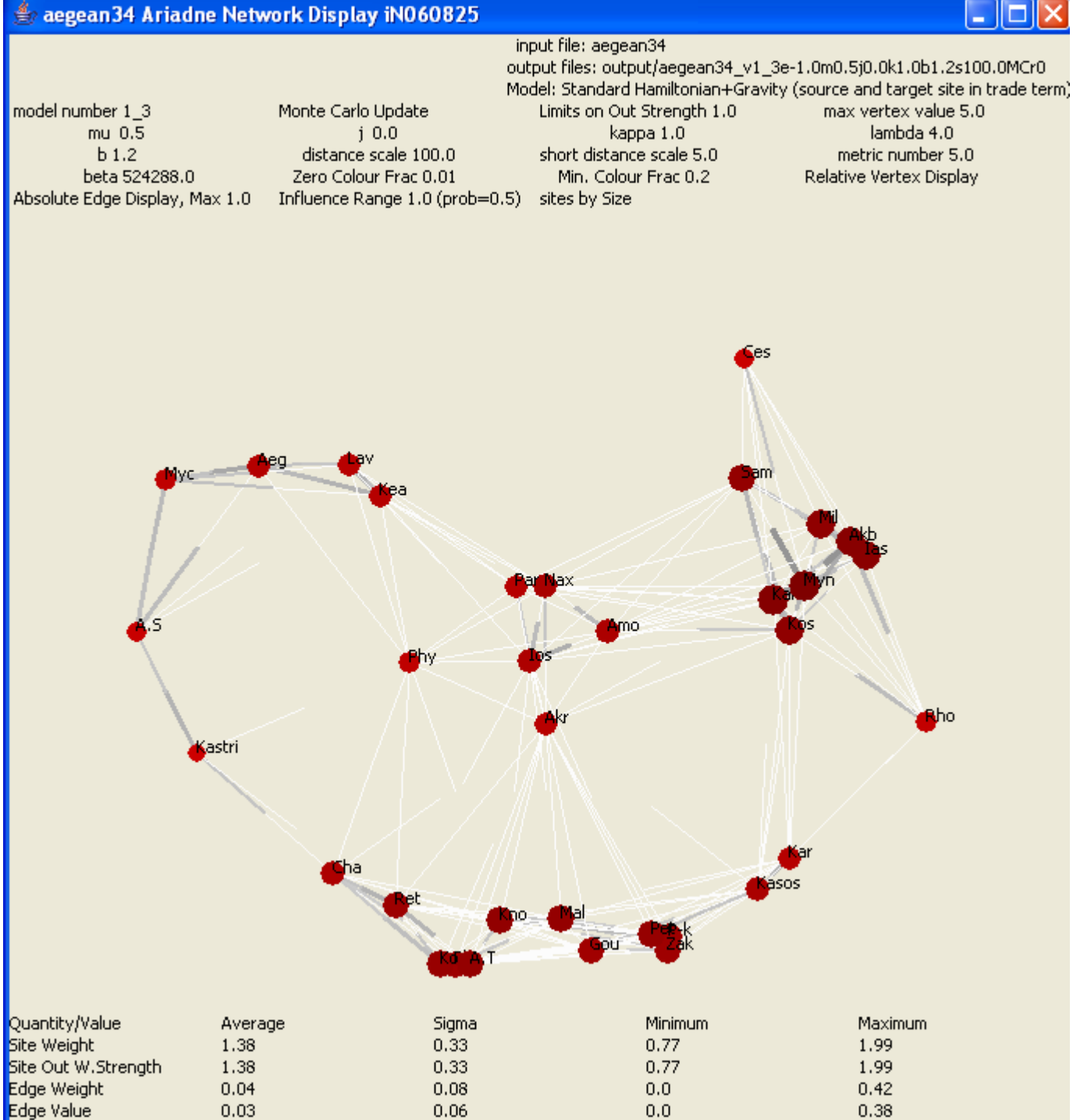
Summary

- Starting to extract basic results systematically
- Some behaviour looks interesting to an archaeologist
  – Crete and Dodecanese usually form strongest clusters
- Some types of behaviour do not appear to be possible
  - Greek mainland rarely gives significant sized sites
- Some factors seem to be playing a key role
  – small differences in physical distance from Crete may be significant
- **Many options remain to be explored**
  – more analysis tools, more what if scenarios, EBA vs MBA, general time evolution, other data sets

Additional Material

Statistical Variation Constant Values

- The variables are held constant so simple statistical variations are evident
- These are resonable, strengths of individual components vary by reasonable amounts, the details remain similar.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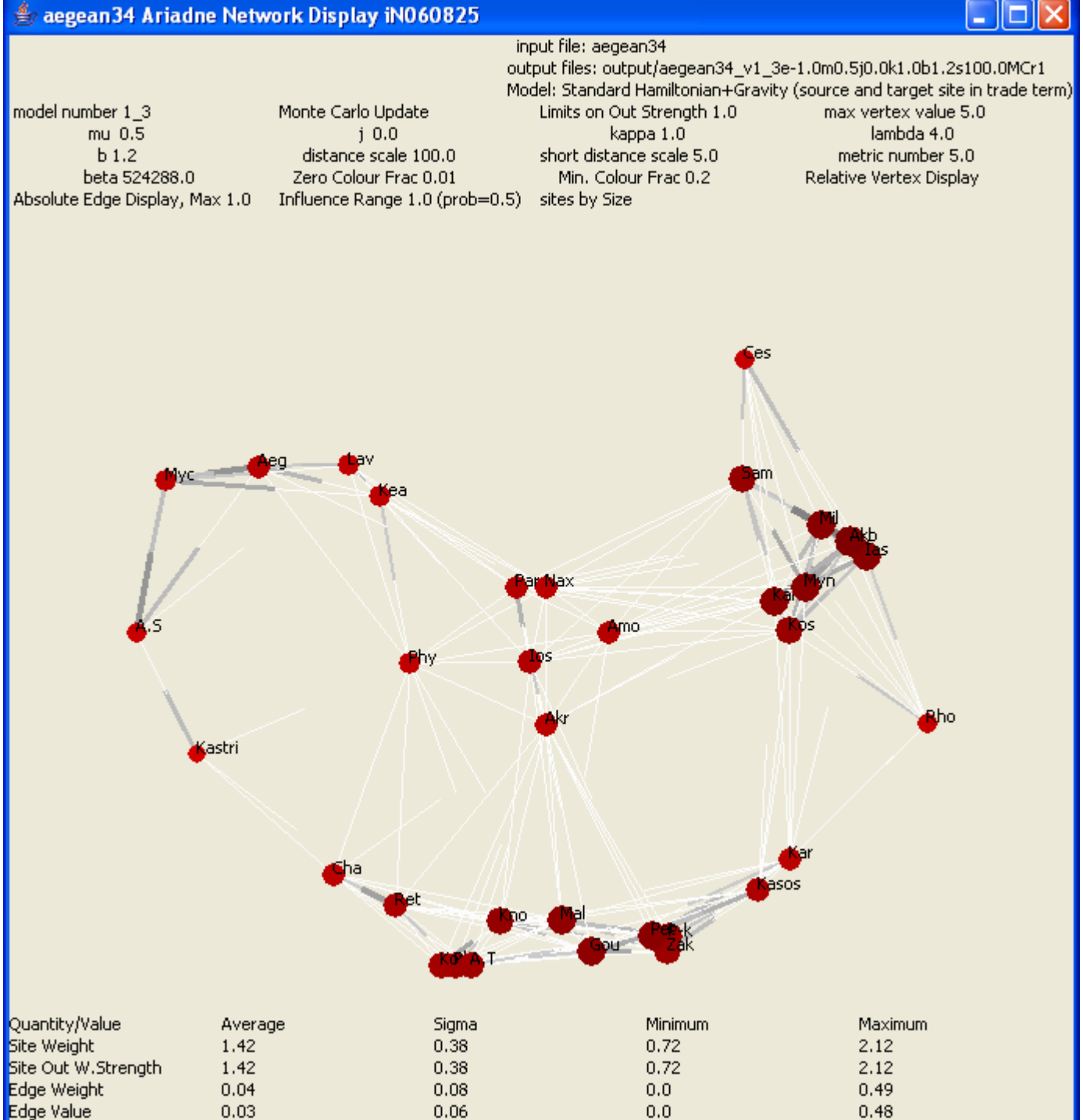
model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 0.5
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
Aeg
Lav
Myc
Sam
Kea
Mil
Akb
Ias
Par
Nax
Myn
Kar
A.S
Amo
Kos
Phy
Ios
Akr
Rho
Kastri
Kar
Cha
Kasos
Ret
Kno
Mal
Pet
k
Gou
Zak
Ko
A
T
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
1.38
0.33
0.77
1.99
Site Out W.Strength
1.38
0.33
0.77
1.99
Edge Weight
0.04
0.08
0.0
0.42
Edge Value
0.03
0.06
0.0
0.38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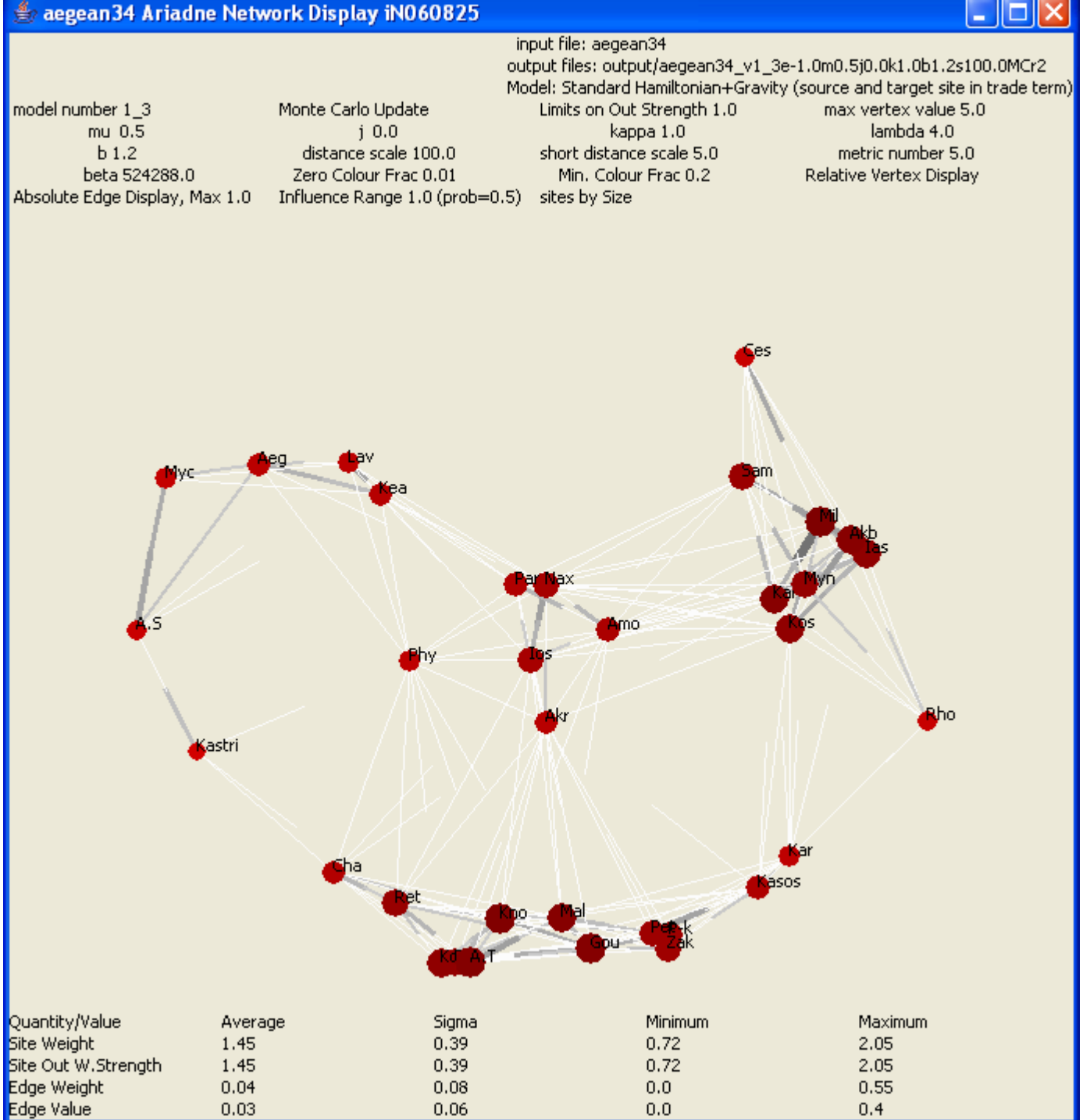
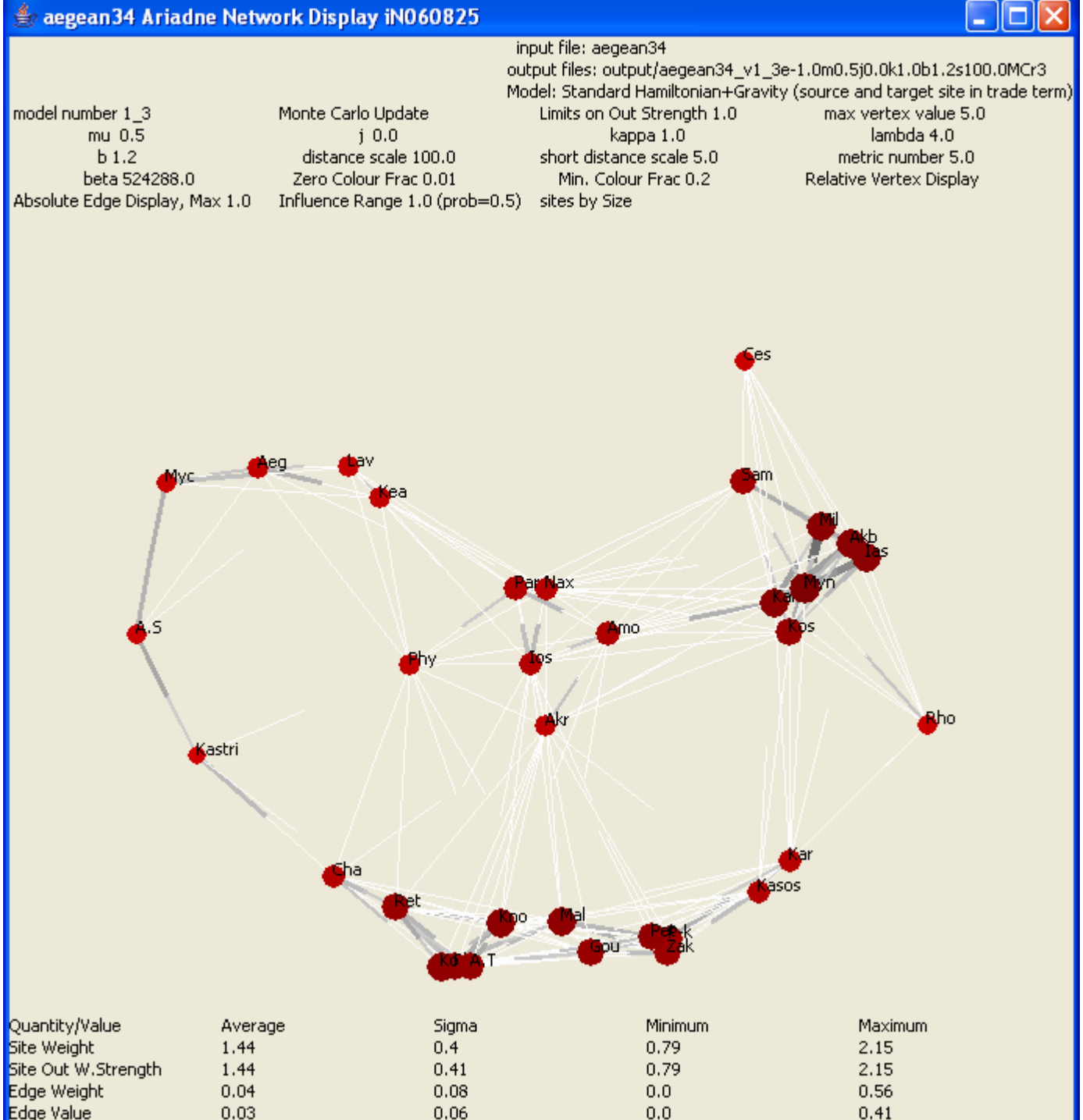
model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 0.5
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
Aeg
Lav
Myc
Kea
Sam
Mil
Akb
Ias
Par
Nax
Myn
Kar
A.S
Amo
Kos
Phy
Ios
Rho
Akr
Kastri
Kar
Cha
Kasos
Ret
Kno
Mal
Pet
Zak
Gou
KdP
A.T
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
1.42
0.38
0.72
2.12
Site Out W.Strength
1.42
0.38
0.72
2.12
Edge Weight
0.04
0.08
0.0
0.49
Edge Value
0.03
0.06
0.0
0.48



Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.45	0.39	0.72	2.05
Site Out W.Strength	1.45	0.39	0.72	2.05
Edge Weight	0.04	0.08	0.0	0.55
Edge Value	0.03	0.06	0.0	0.4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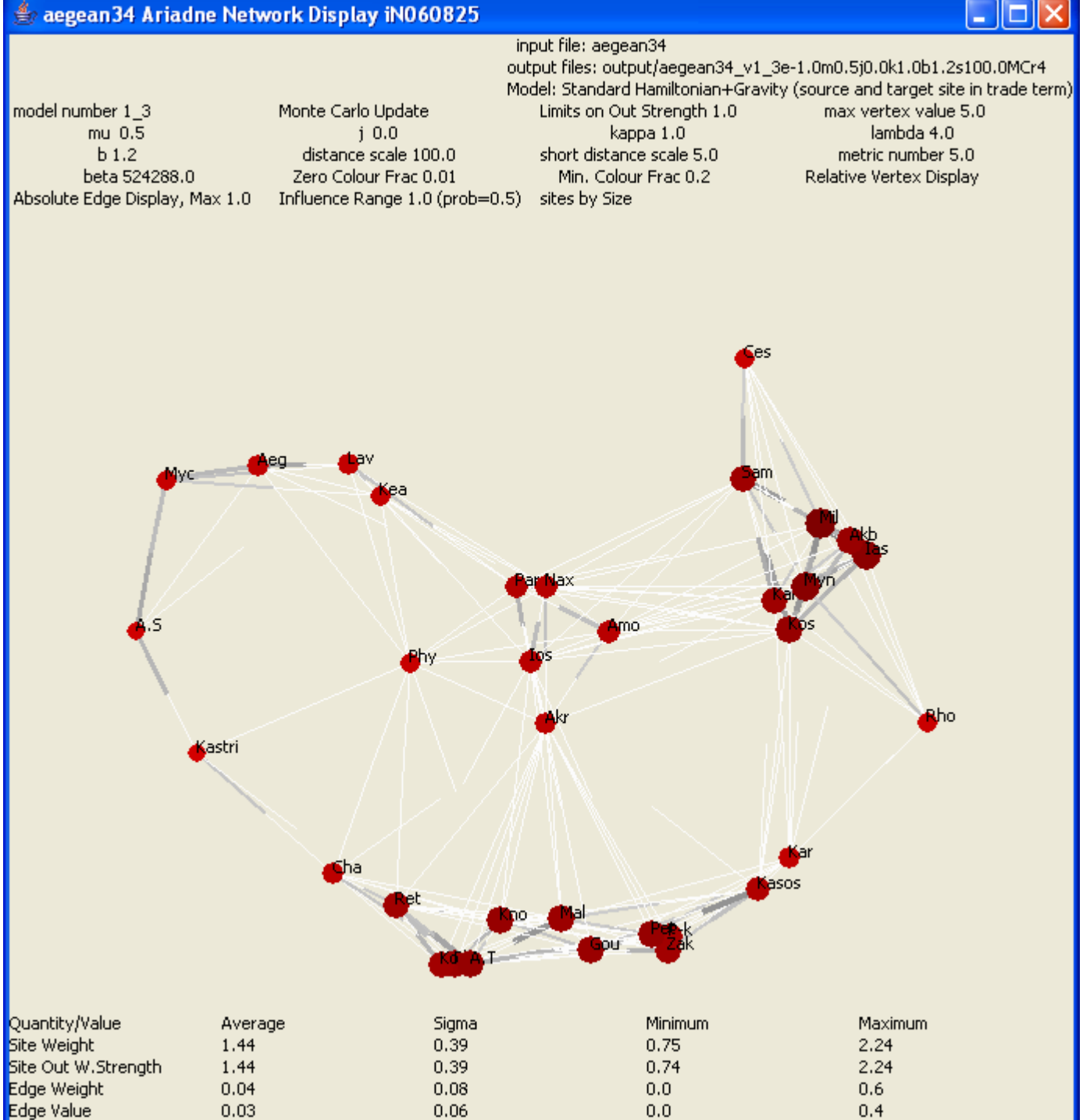
output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr3
Model: Standard Hamiltonian+Gravity (source and target site in trade term)
model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 0.5
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
Aeg
Lav
Myc
Sam
Kea
Mil
Akb
Tas
Par
Nax
Myn
Ker
A.S
Amo
Kos
Phy
Ios
Akr
Rho
Kastri
Kar
Cha
Kasos
Ret
Kno
Mal
Pet
Zak
Gou
Kd
A.T
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
1.44
0.4
0.79
2.15
Site Out W.Strength
1.44
0.41
0.79
2.15
Edge Weight
0.04
0.08
0.0
0.56
Edge Value
0.03
0.06
0.0
0.41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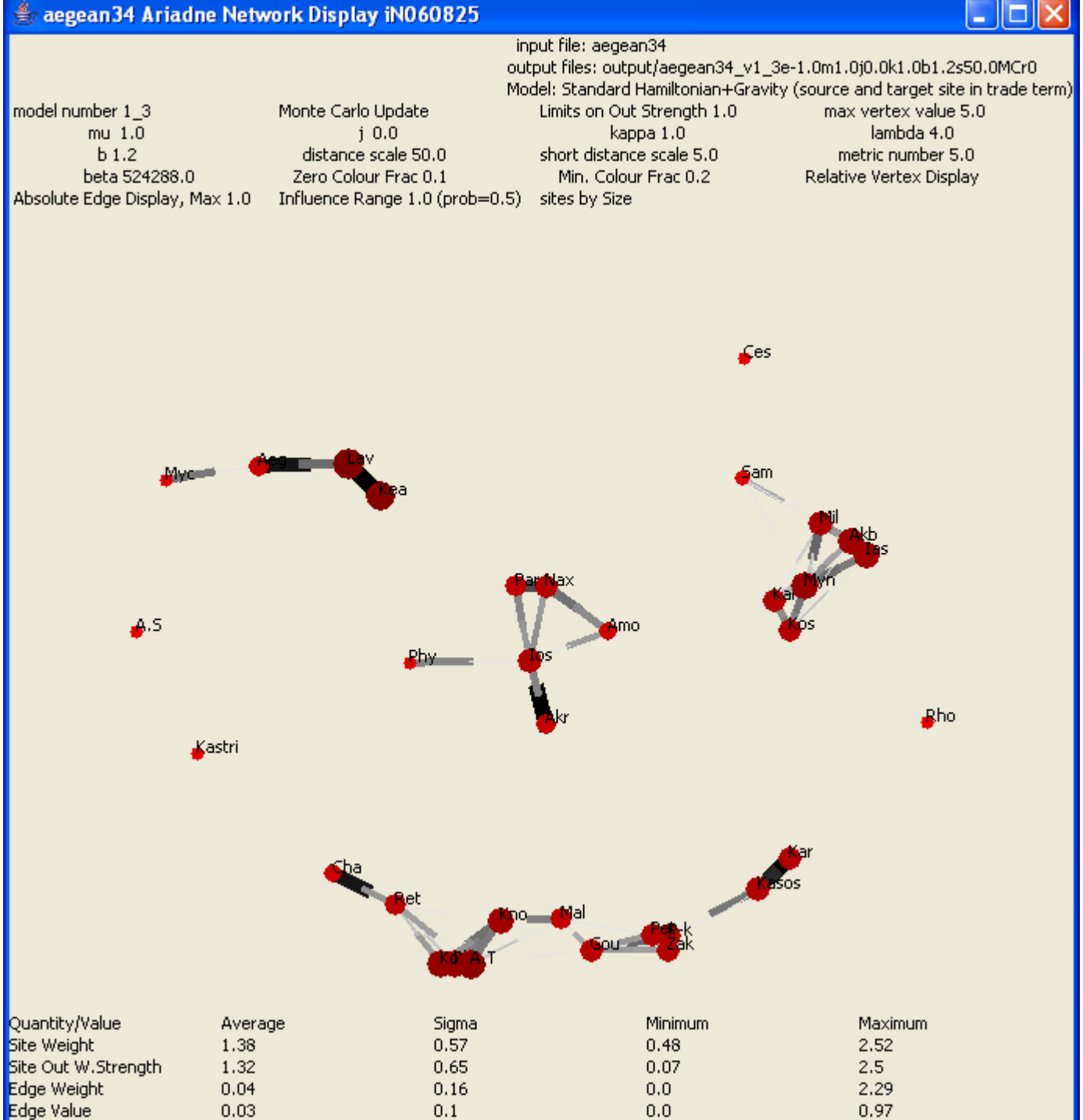
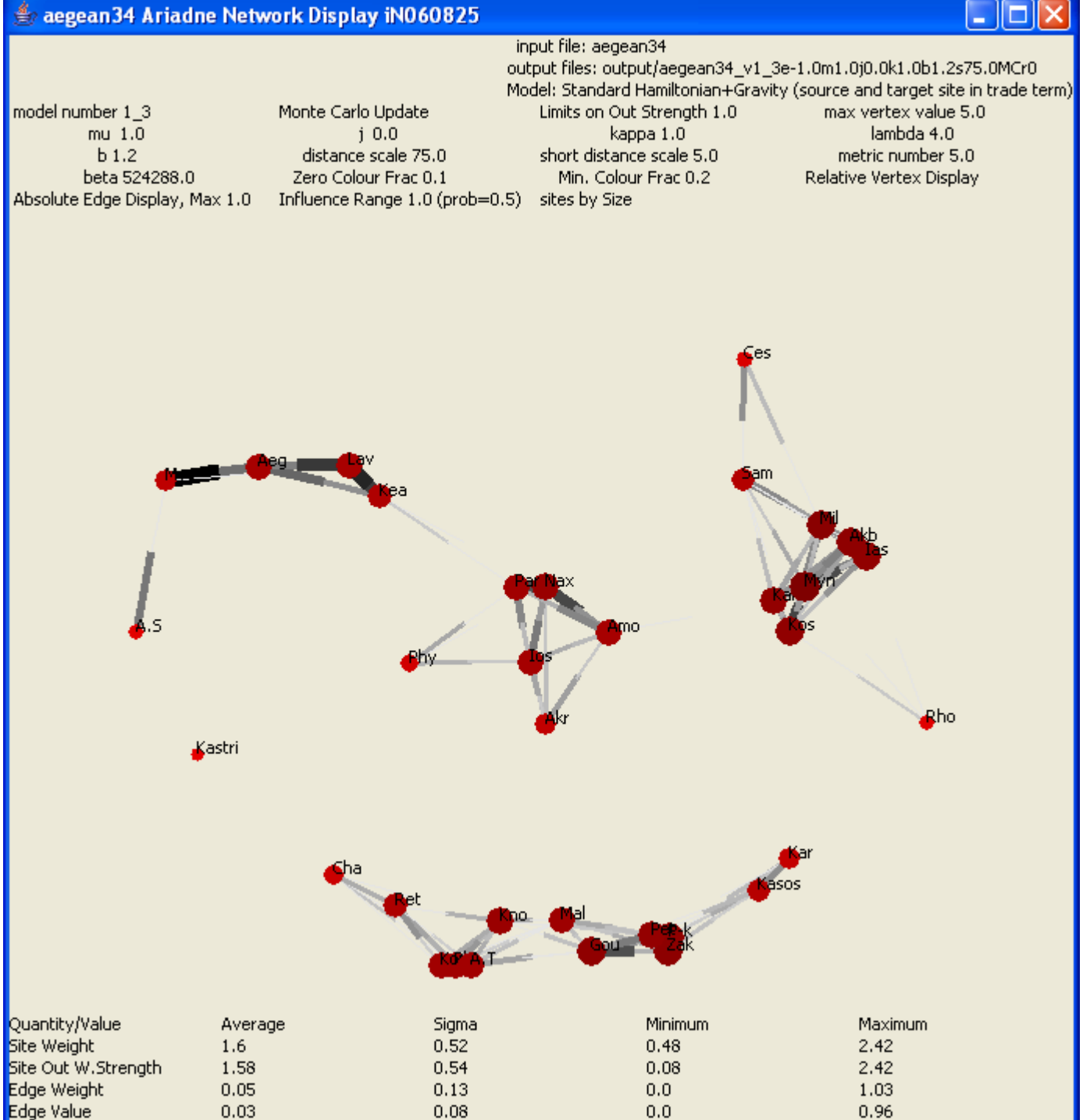
input file: aegean34
output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr4
Model: Standard Hamiltonian+Gravity (source and target site in trade term)
model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 0.5
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 100.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.01
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
Aeg
Lav
Myc
Sam
Kea
Mil
Akb
Ias
Par
Nax
Myn
Kar
A.S
Amo
Kos
Phy
Ios
Rho
Akr
Kastri
Kar
Cha
Kasos
Ret
Kno
Mal
Pet
k
Gou
Zak
Kd
A.T
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
1.44
0.39
0.75
2.24
Site Out W.Strength
1.44
0.39
0.74
2.24
Edge Weight
0.04
0.08
0.0
0.6
Edge Value
0.03
0.06
0.0
0.4

Range of Distance Scales (*d*)

- Next 4 slides



Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.38	0.57	0.48	2.52
Site Out W.Strength	1.32	0.65	0.07	2.5
Edge Weight	0.04	0.16	0.0	2.29
Edge Value	0.03	0.1	0.0	0.97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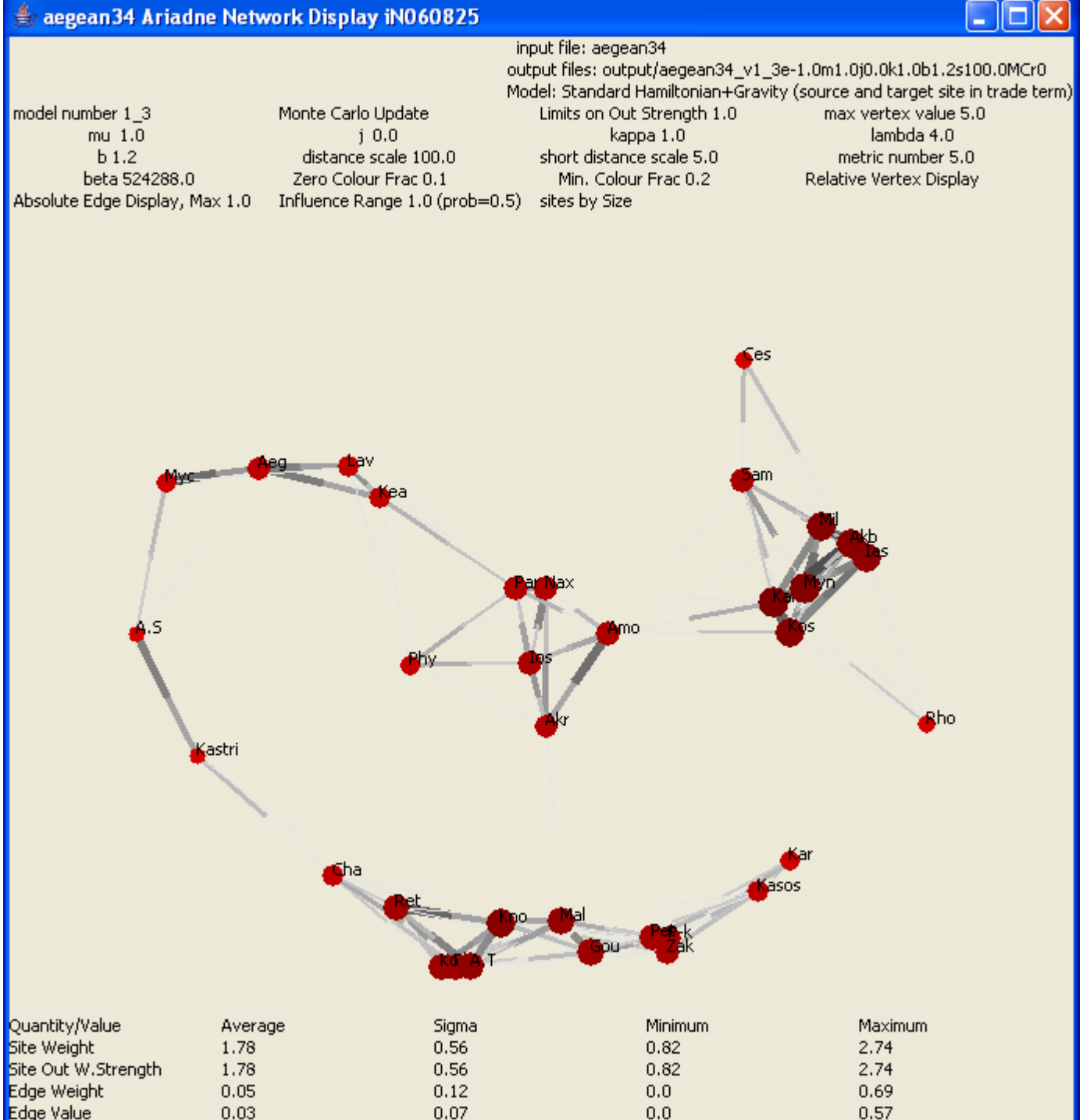
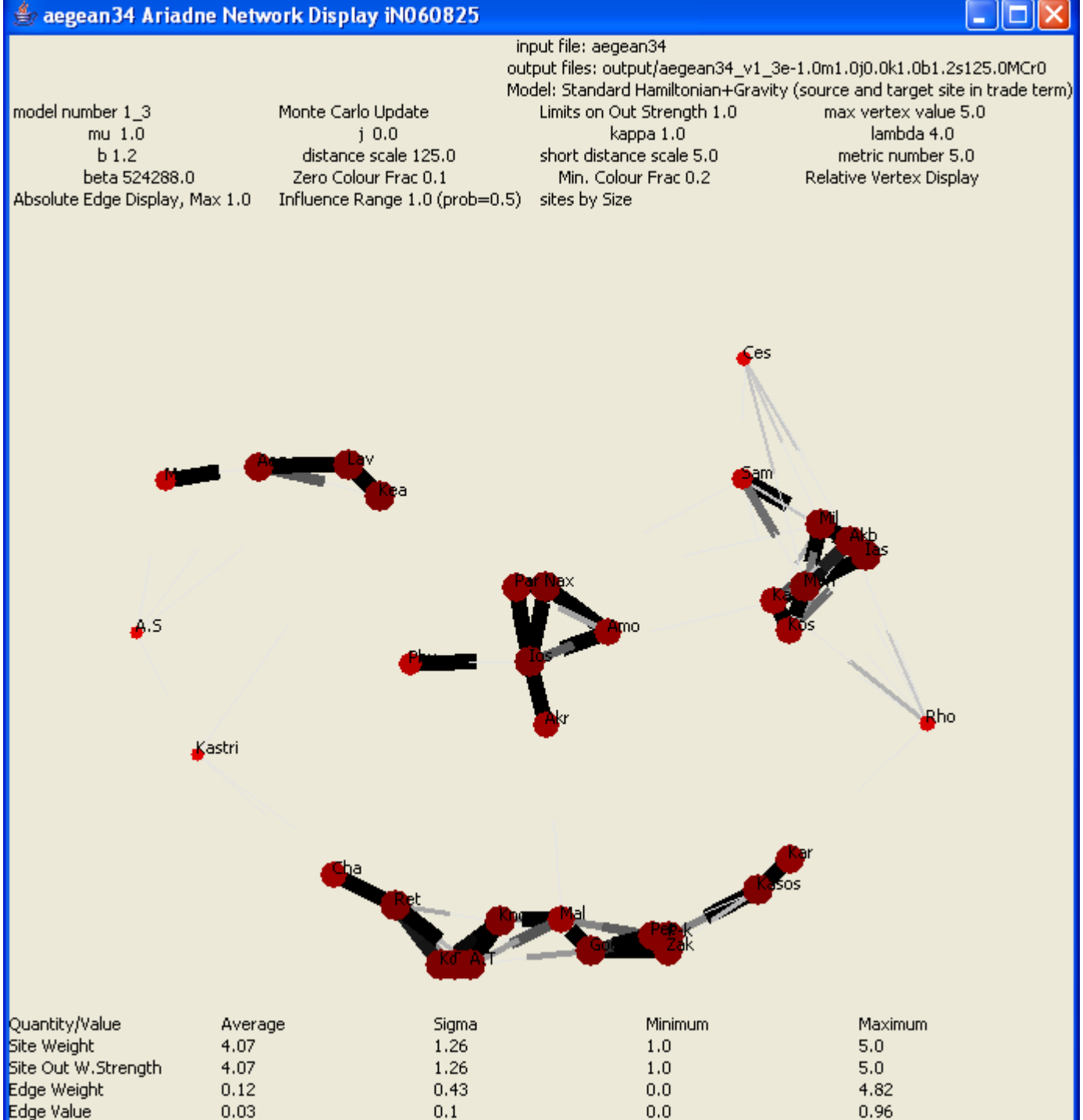
Model: Standard Hamiltonian+Gravity (source and target site in trade term)
model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 1.0
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 75.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.1
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
Aeg
Lav
Kea
Sam
Mil
Akb
Ias
Par
Nax
Myr
A.S
Amo
Phy
Ios
Kos
Akr
Rho
Kastri
Cha
Kar
Kasos
Ret
Kno
Mal
Pet
Gou
Zak
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
1.6
0.52
0.48
2.42
Site Out W.Strength
1.58
0.54
0.08
2.42
Edge Weight
0.05
0.13
0.0
1.03
Edge Value
0.03
0.08
0.0
0.96



Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.78	0.56	0.82	2.74
Site Out W.Strength	1.78	0.56	0.82	2.74
Edge Weight	0.05	0.12	0.0	0.69
Edge Value	0.03	0.07	0.0	0.57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Model: Standard Hamiltonian+Gravity (source and target site in trade term)
model number 1_3
Monte Carlo Update
Limits on Out Strength 1.0
max vertex value 5.0
mu 1.0
j 0.0
kappa 1.0
lambda 4.0
b 1.2
distance scale 125.0
short distance scale 5.0
metric number 5.0
beta 524288.0
Zero Colour Frac 0.1
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
Sam
Mil
Akb
Ias
Kos
Rho
Par
Nax
Amo
Akr
A.S
Kastri
Lav
Kea
Cha
Ret
Mal
Kar
Kasos
Zak
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
4.07
1.26
1.0
5.0
Site Out W.Strength
4.07
1.26
1.0
5.0
Edge Weight
0.12
0.43
0.0
4.82
Edge Value
0.03
0.1
0.0
0.96

Network Description

- d_{ij} Fixed distance between sites identified from the archaeological record
  may be physical but may include penalties for prevailing winds, currents, land travel, ...
- S_i Fixed site size = maximum local resources
- v_i Variable site occupation fraction
  so if $v_i > 1$ then site needs external resources
  $\Longrightarrow$ Site **Weight** ($S_i\ v_i$) = Site `*population*'
- e_{ij} Fractional Edge values $\boldsymbol{0 \leq \Sigma_j e_{ij} \leq 1}$
  $\Longrightarrow$ Edge **Weights** ($S_i\ v_i\ e_{ij}$)
  = '*Trade*' (interaction) going from site i to site j

Robustness

- Are we finding a model that gives us the results we want?
  - Select on the basis of some pre-determined notion of reasonable results.
  - Do comparisons, do not use absolute results
- Do results depend on fine details of model?
  - Topological Congruence, Universality Classes
- Do results depend on how we encode the input data?
  - Scaling behaviour - when is an archaeological site a vertex?

Optimisation of what?

`Energy', resources

Isolated sites have optimal size $v_i = 0.5$

Trade (interactions) bring benefits

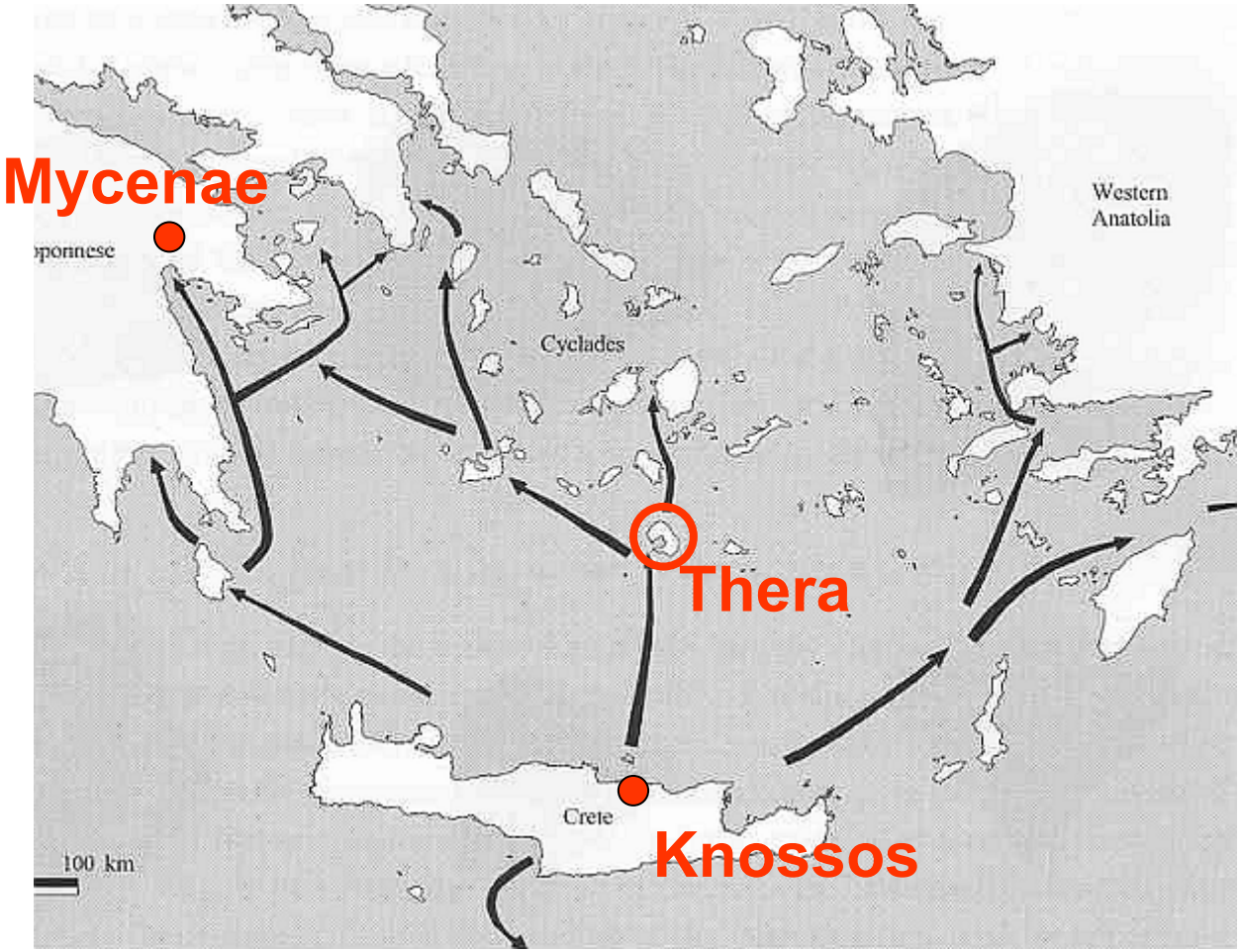
Increasing 'population' has a cost

Each trade link has a cost

$$H = -\kappa \sum_i S_i v_i (1 - v_i) - \lambda \sum_{i,j} (S_i v_i . e_{ij}) . V(d_{ij} / D) . (S_j v_j) + j \sum_i S_i v_i + \mu \sum_{i,j} S_i v_i e_{ij}$$

$$0 \le \sum_j e_{ij} \le 1 \qquad 0 \le v_i$$

Middle Bronze Age Aegean (2000-1500 BC)



Palaces on Crete

'Minoanisation' begins

Theran eruption 1600 BC

'Collapse' – 1500 BC

DIFFERENT TO EBA of Broodbank (2000)

- **Scale of networks**
- **Uneven site size**
- **Length of links**
- **Directionality**

Brief Chronology of the Aegean

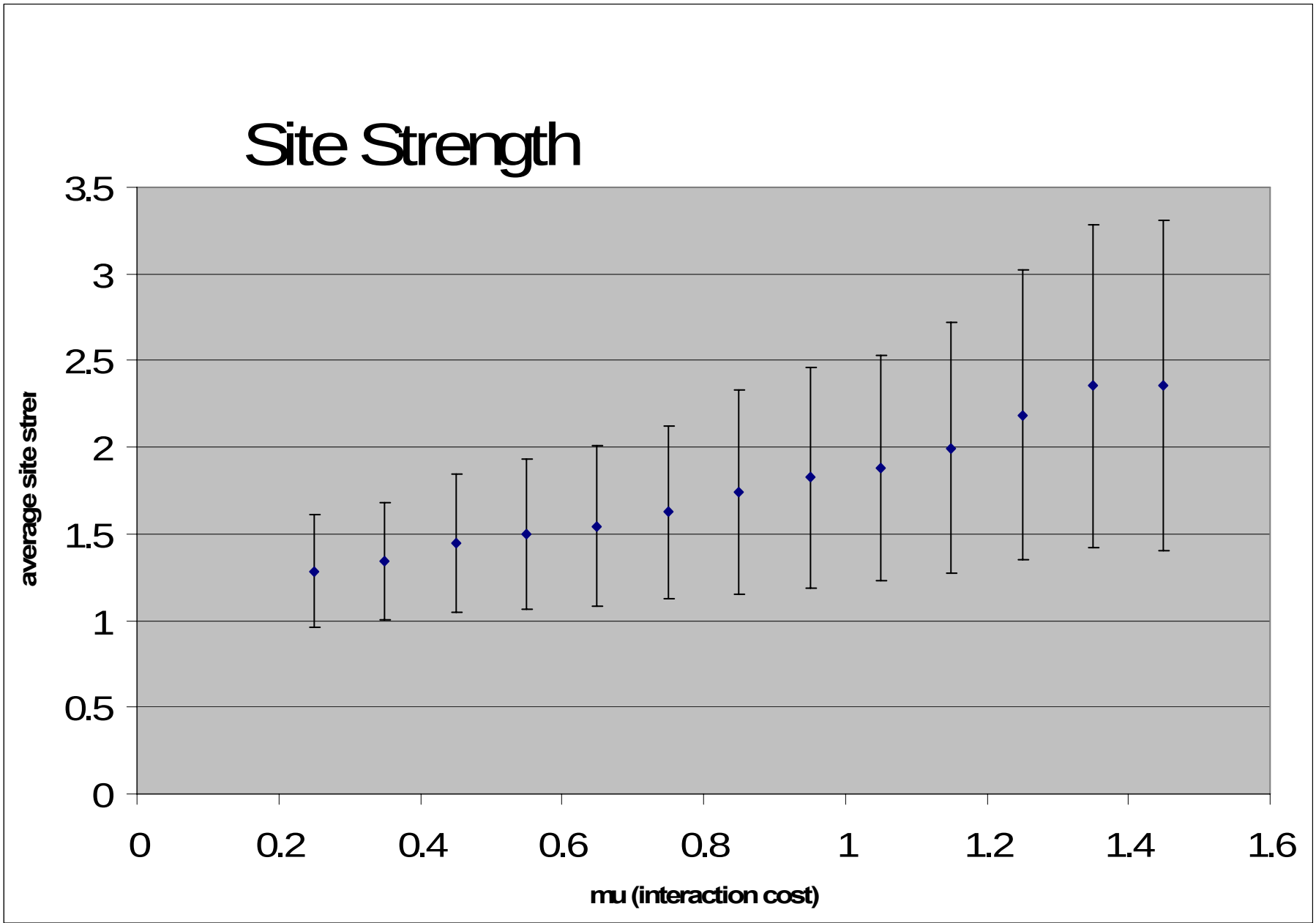
Neolithic	7000 BC	•Initial colonisation – introduction of farming
	4000 BC	•Secondary colonisation of small islands
EBA	2500BC	•Nucleation and hierarchy in 3rd millennium BC
	2200 BC	•Partial collapse?
MBA	1900BC	•Emergence of Minoan civilisation in 2nd mill BC on Crete, sail technology appears
	1500BC	•Collapse
LBA	1450 BC	•Mycenaean mainlanders emerging power
	1200 BC	•Bronze Age collapse
	1100 BC	•'Dark Ages'

Minoa

- A reconstruction using original tools and techniques, as far as they are known, in order to make the best guess at the methods, design and capabilities of Minoan ships

Efficiency?

- Need not be space filling in any sense.
- Need not be lowest number of links needed to connect all sites (Minimal Spanning Tree).
- ‘Deliberate Waste’ -
  may well favour redundancy to reduce path lengths, to increase possible interactions, to increase resilience to change.


Site Strength
average site stren
3.5
3
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
mu (interaction cost)