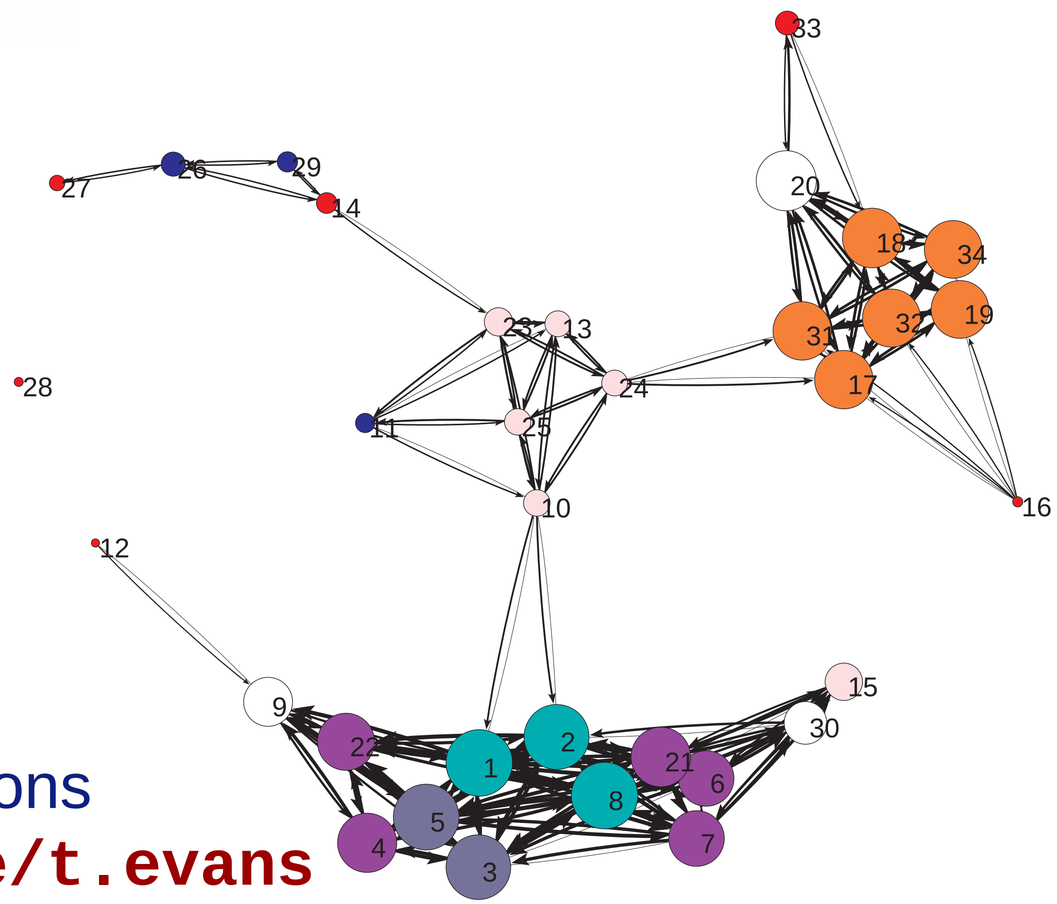
Imperial College London

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

See commentary on the modern context of this reconstruction

Approaches to Modelling

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

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

Agent Based Modelling

People/Goats as agents e.g. MASS group

Cities as agents e.g. SIMPOP2 (Pumain et al.)

Increasing Detail

Network Optimisation

***TSE,CJK,RJR* ariadne**

Coarse Graining Increasing

Equations

e.g. West et al.

Site-Site Interactions

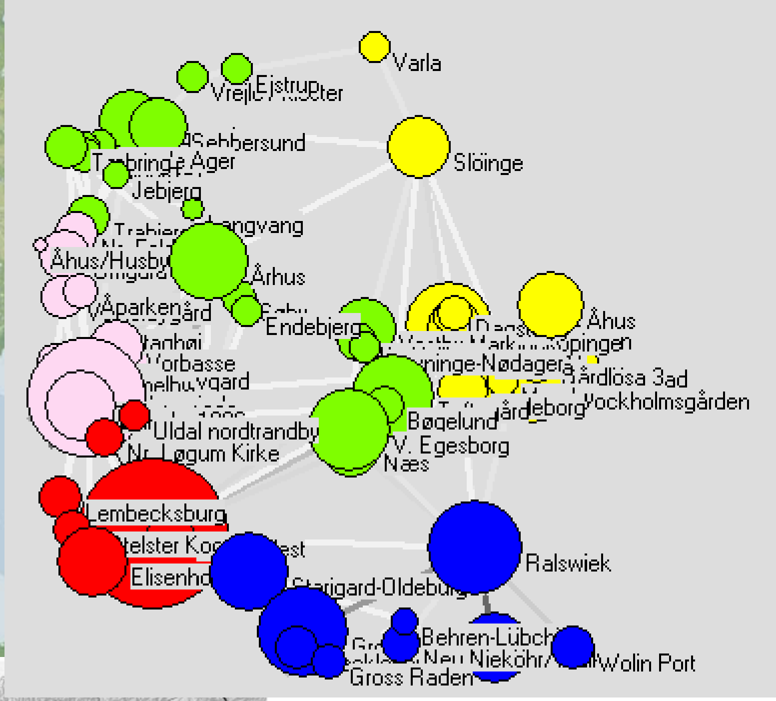
- In archaeology relatively little attention has been given to the potential of interactions between sites being involved in the generation of those sites

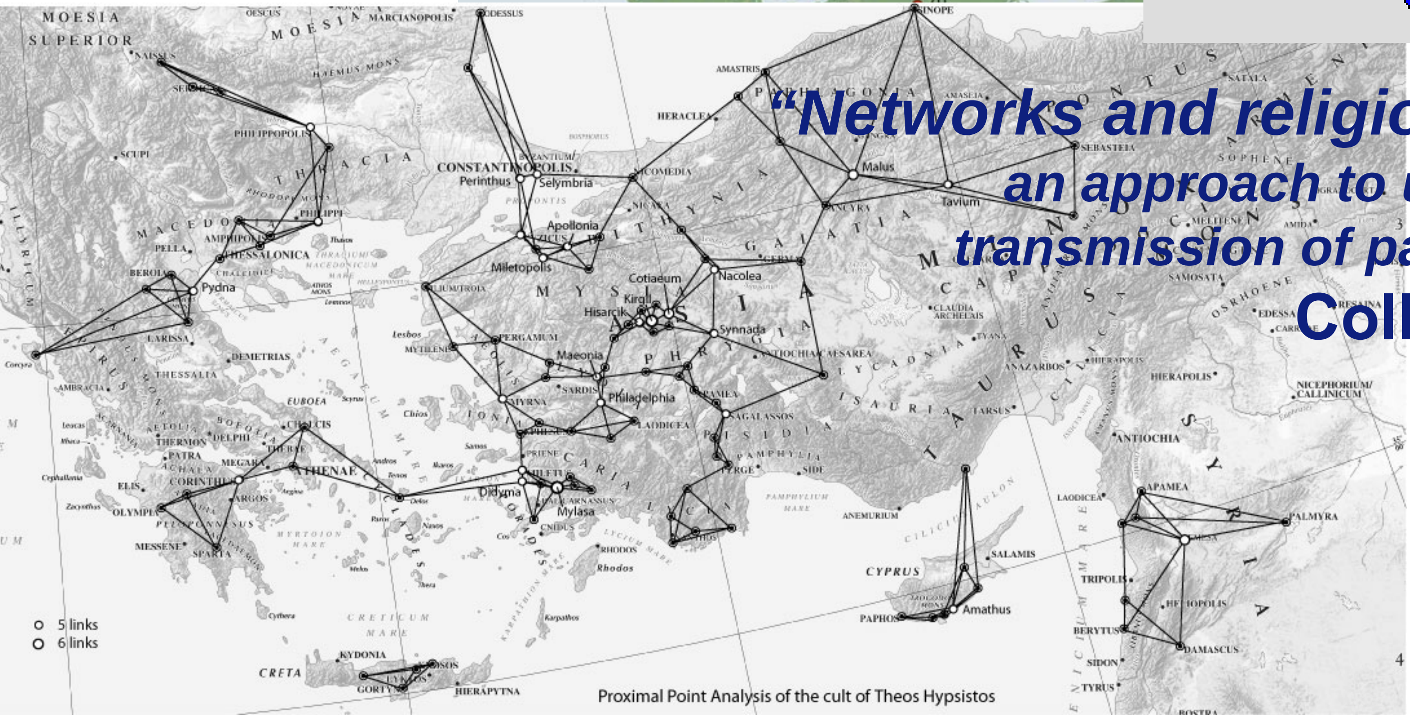
⇒ Network models may prove to be useful

- Most models fixed site sizes, 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; Sindbæk (in prep.); Collar (in prep.)*)

***"The Small World of the Vikings"*, Sindbæk, Aarhus Univ.**

Anskar's Vita + data from finds, 9th c. AD





"Networks and religious innovation:
an approach to understanding the transmission of pagan monotheism"
Collar, Exeter Univ.

Hypsistos cult inscriptions, 1-4c.AD

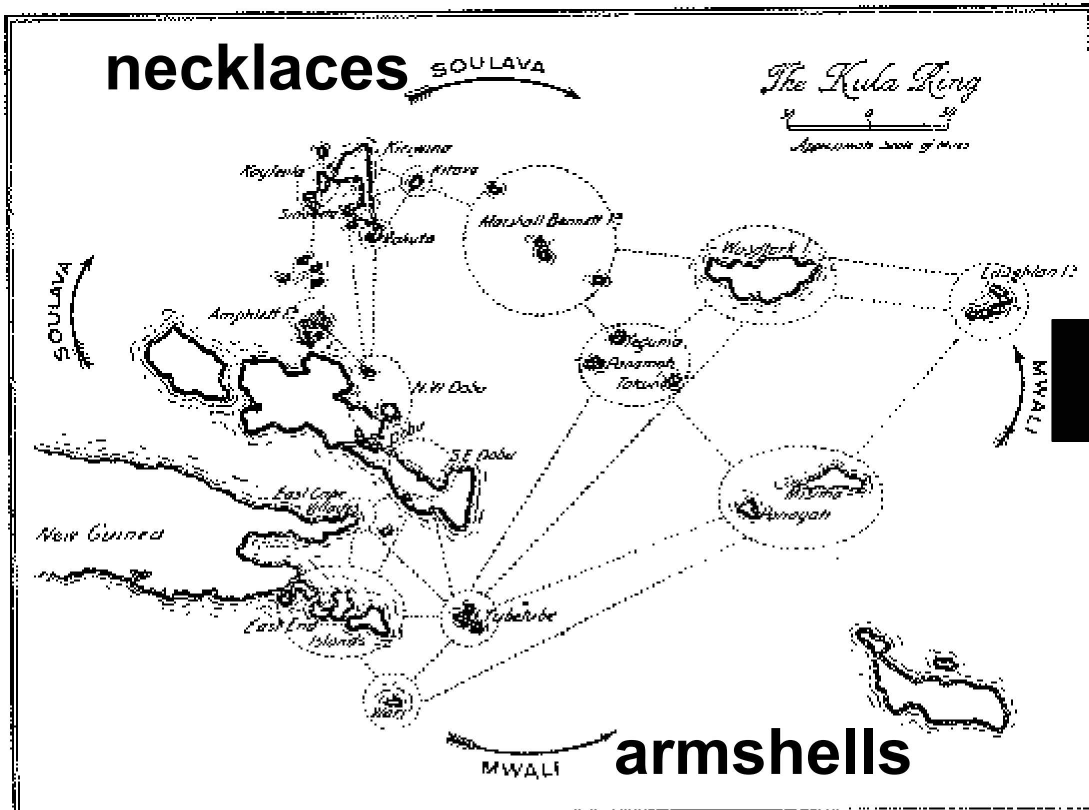
Island Archipelagos as an Ideal Network

- 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 Island Network:- The Kula Ring

Malinowski (1922)



Hage and Harary (1991)

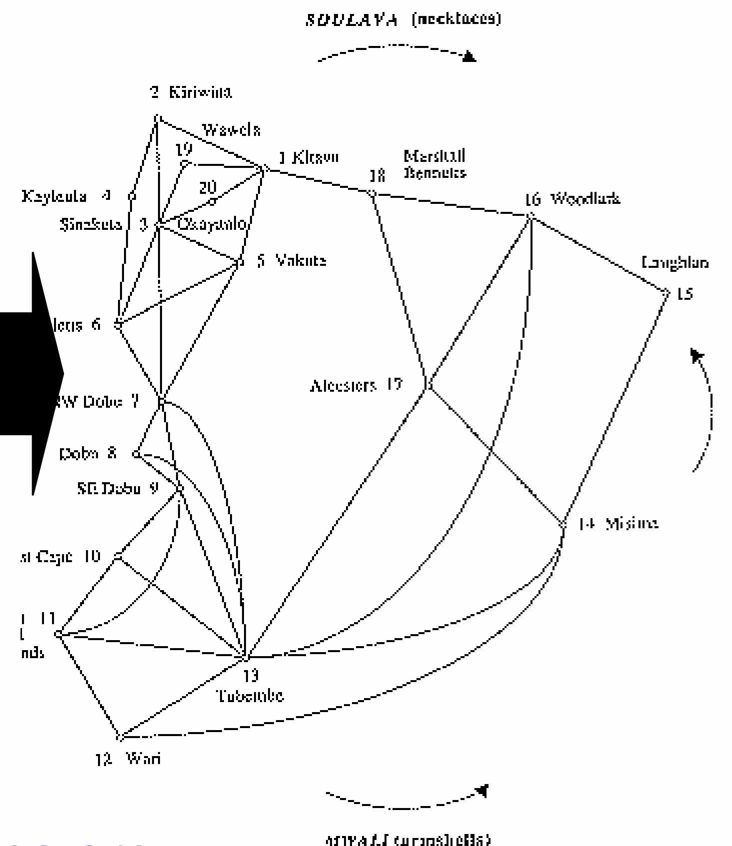


Fig. 5.1. The graph *G* of the *kula* ring

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

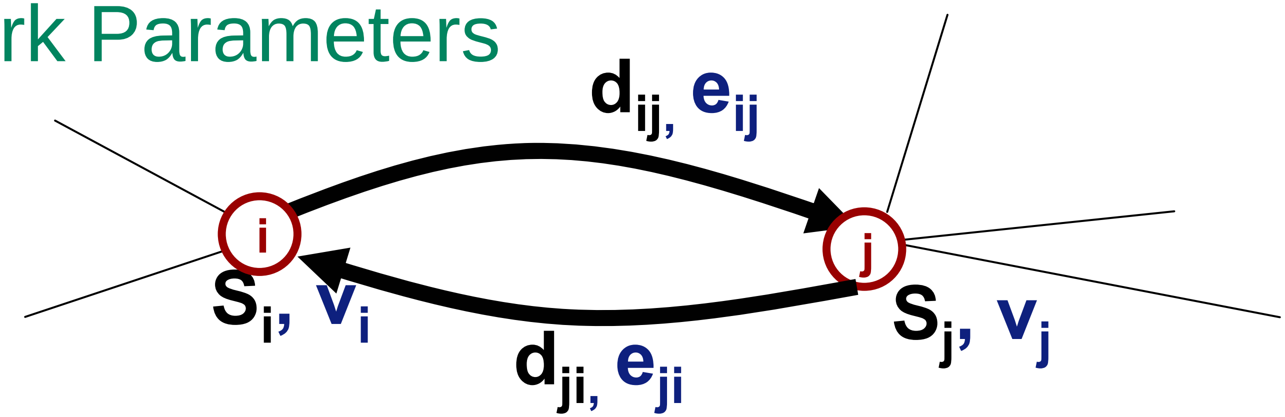
- Physically largely self contained
  - questions regarding relationship to Egyptian culture

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

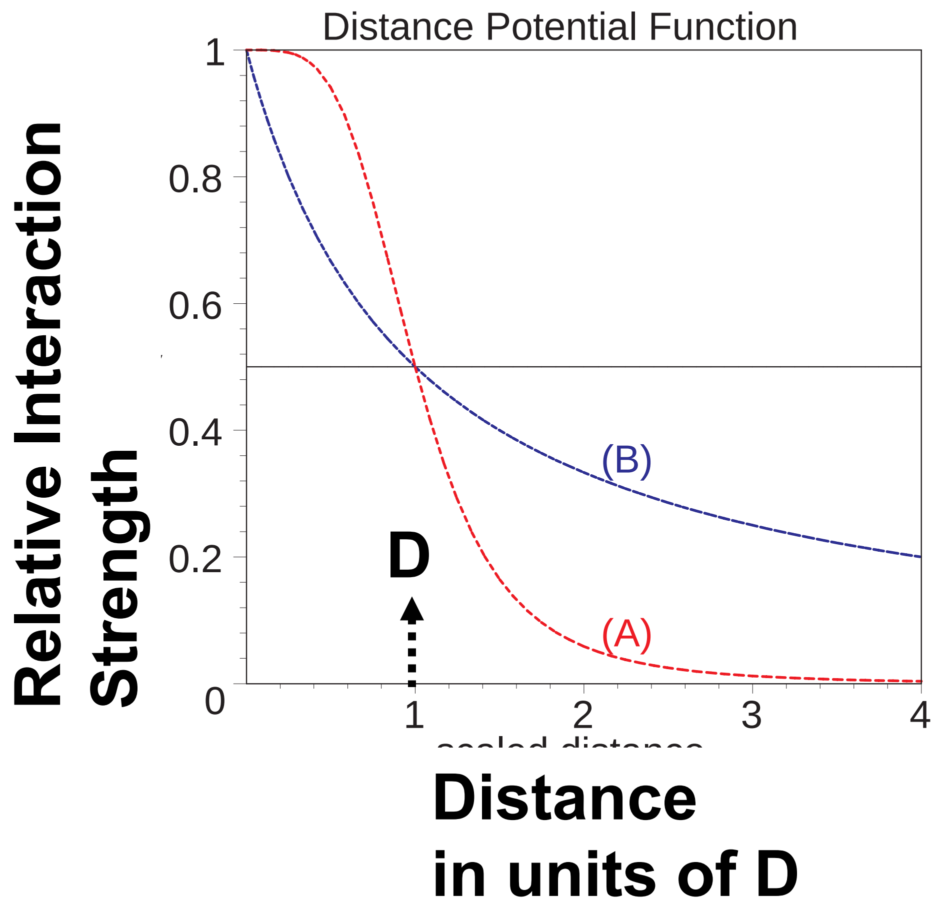
Distance Scale D

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



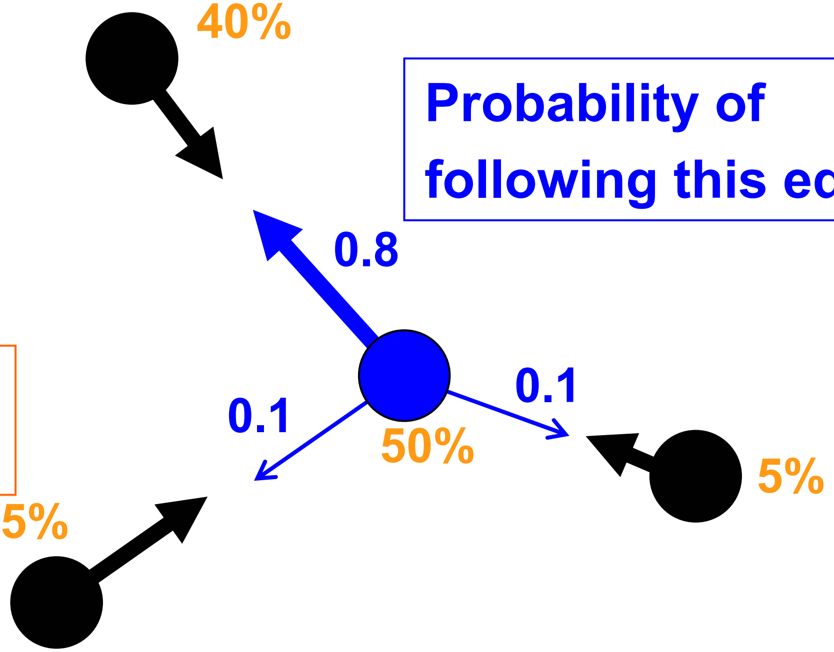
Analysis

- 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.

Analysis Methods: Ranking

- The percentage of time spent at each node by an *imaginary* random walker on the network. The walker moves from site to site, choosing to follow a link with probability proportional to its strength. (Other choices possible).

  ⇒ **Measure of GLOBAL network properties**



Ranking of vertices

As used by Hage & Harary 1991, and Google

The 34 Sites Used

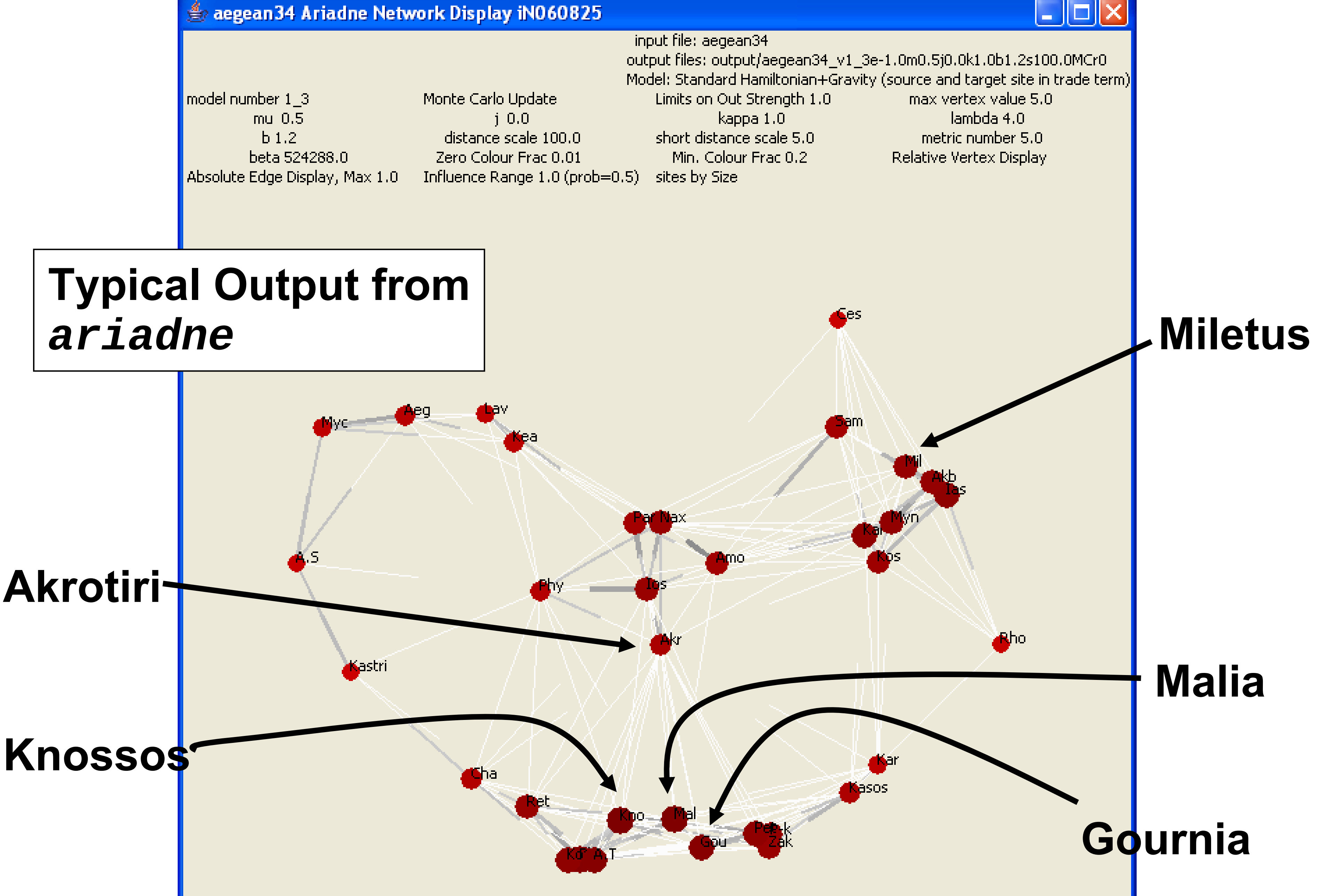
Analysis of Single Network

- The new few slides show the analysis of one result of our model

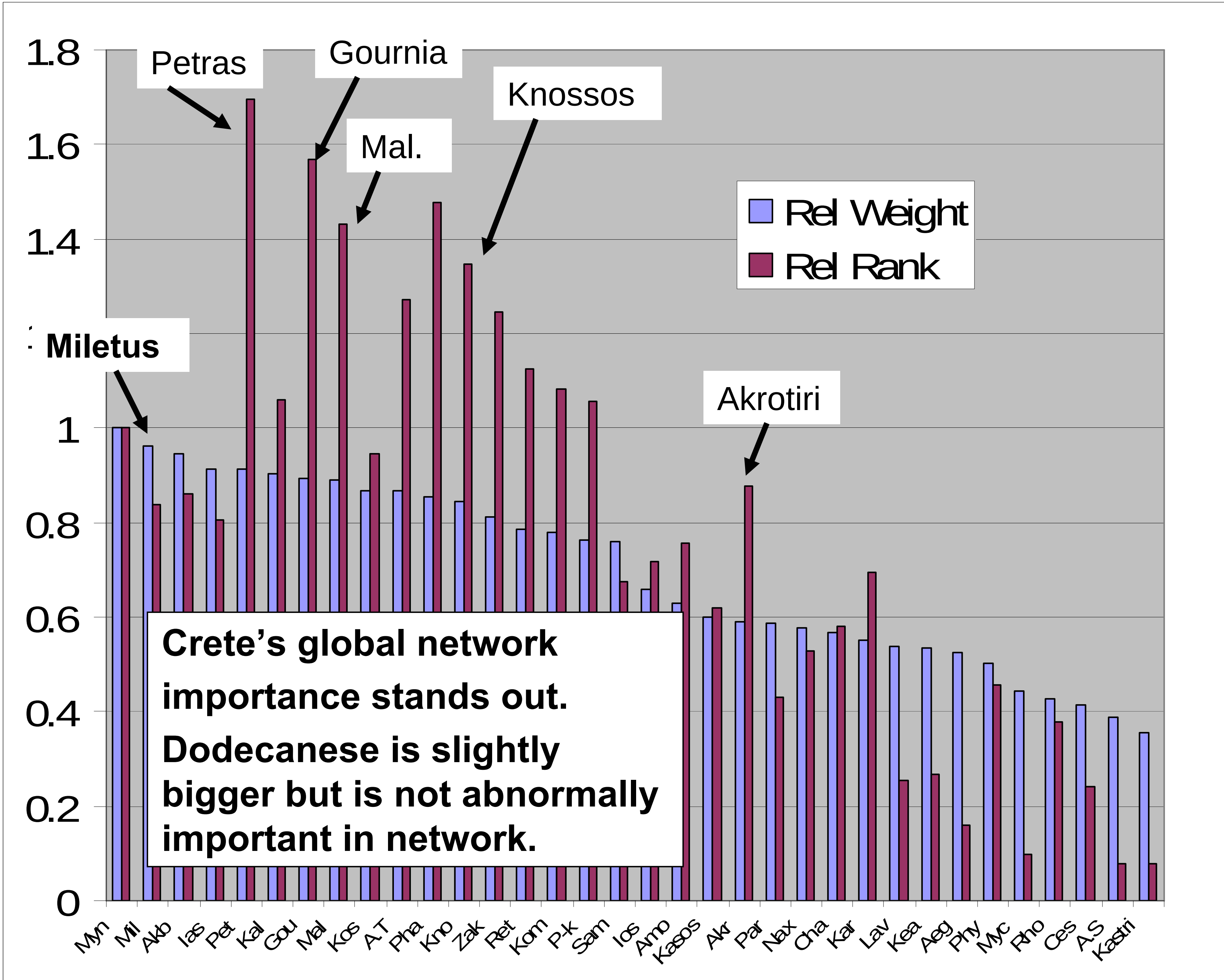
- Look for sites which are off any general trends

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

Typical Output from *ariadne*

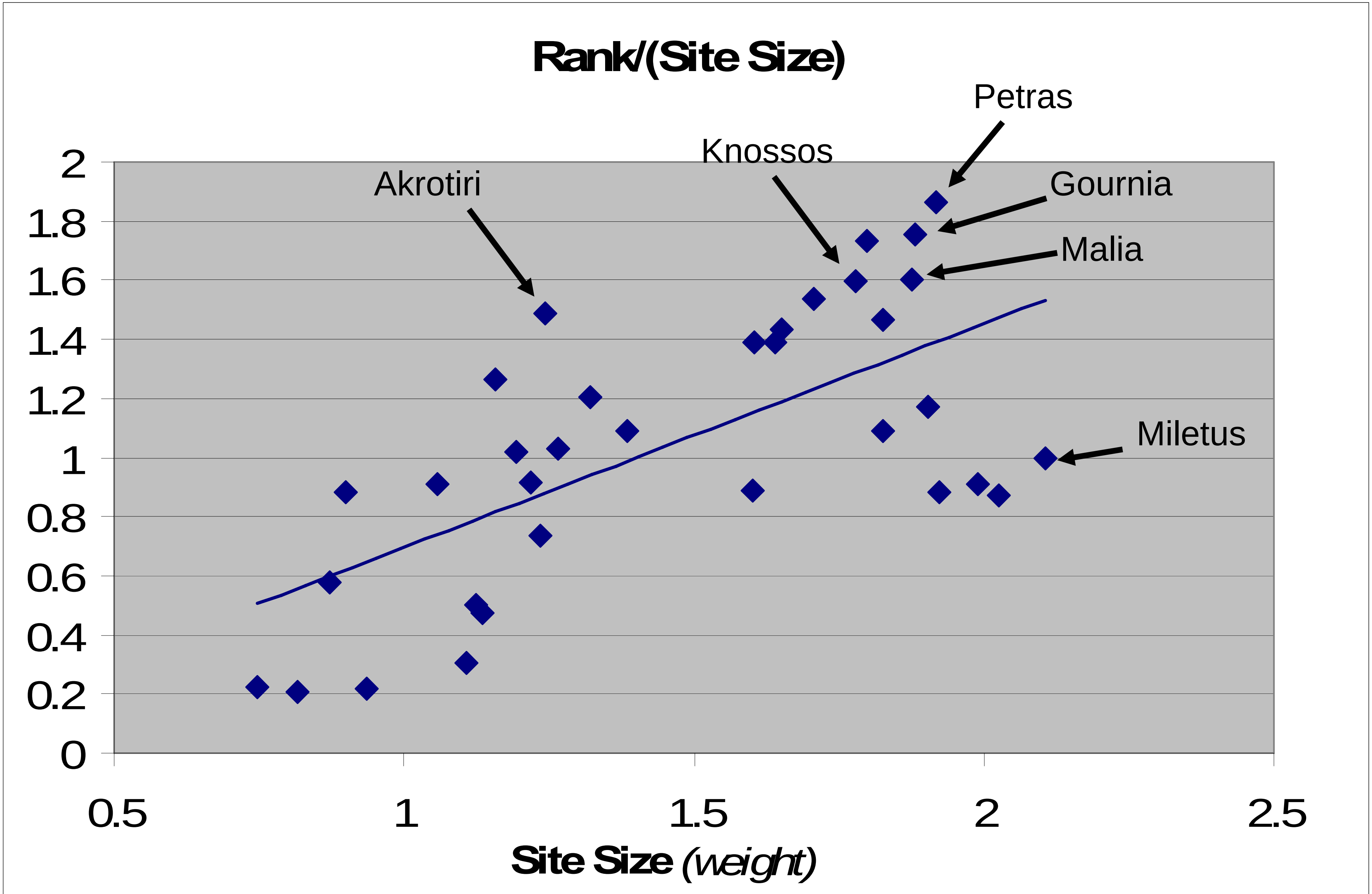


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.42	0.35	0.78	1.98
Site Out W.Strength	1.42	0.35	0.77	1.98
Edge Weight	0.04	0.08	0.0	0.45
Edge Value	0.03	0.06	0.0	0.34

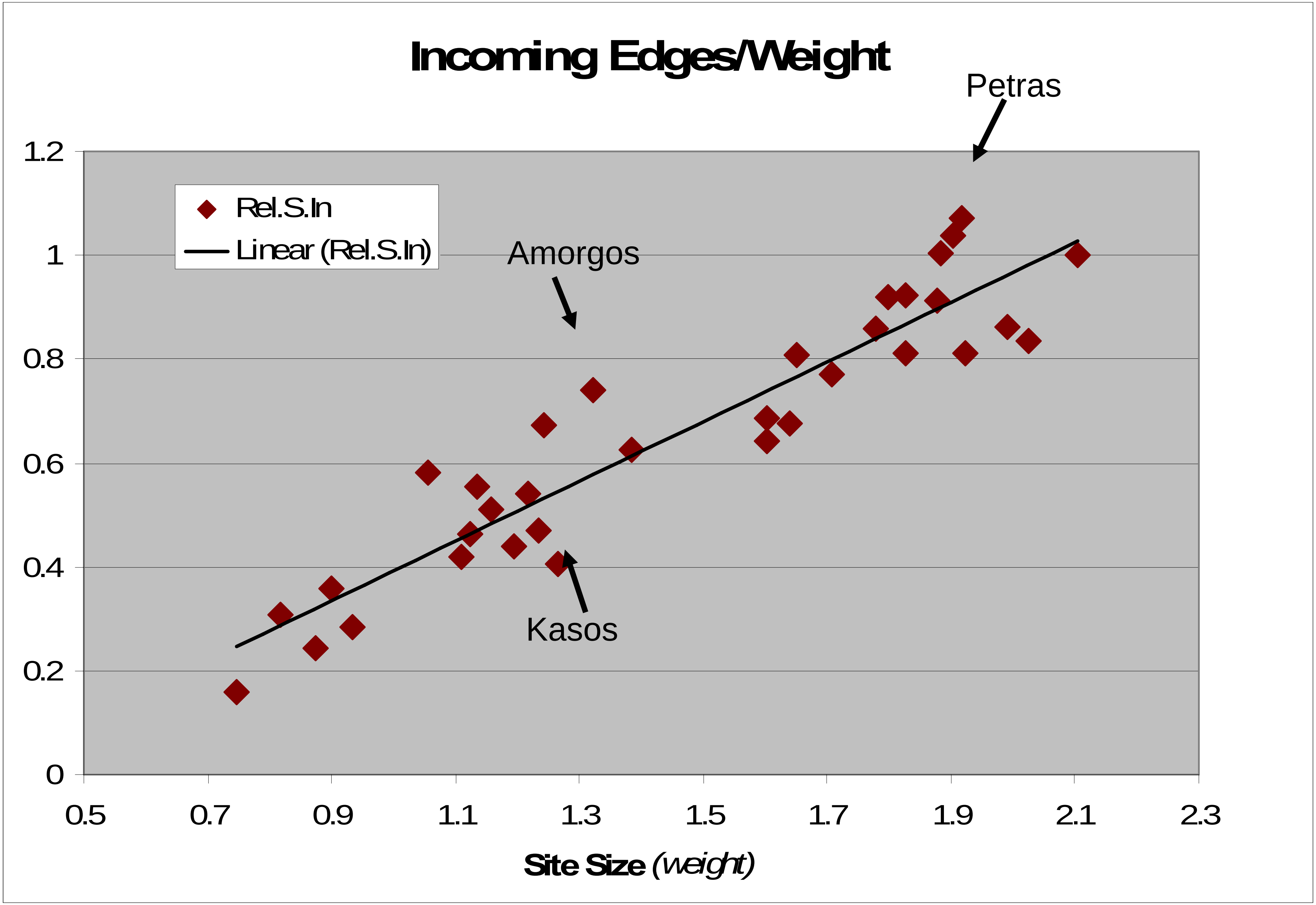


1.8
1.6
1.4
1
0.8
0.6
0.4
0.2
0
Petras
Gournia
Knossos
Mal.
Miletus
Akrotiri
Rel Weight
Rel Rank
Crete's global network importance stands out.
Dodecanese is slightly bigger but is not abnormally important in network.
Myn
Mil
Akb
Ias
Pet
Kal
Gou
Mal
Kos
A.T
Pha
Kno
Zak
Ret
Kom
P-k
Sam
Ios
Amo
Kasos
Akr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

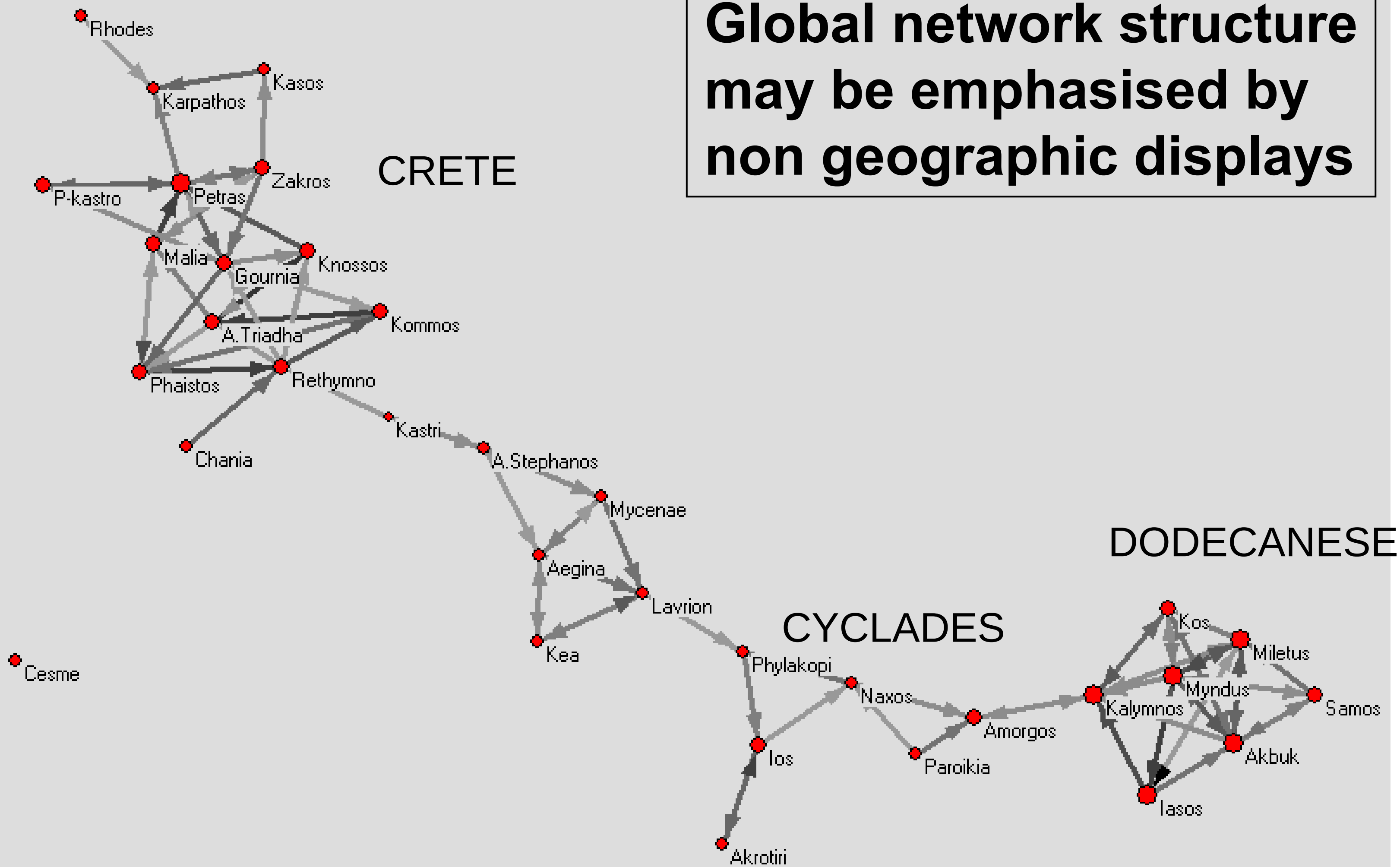
Rank vs. Size shows Crete's is more important to the global network that its size suggests, not so for Dodecanese



Local properties often scale closely with site size (weight)



Global network structure may be emphasised by non geographic displays



Increasing Edge Cost (μ)

Next 7 slides

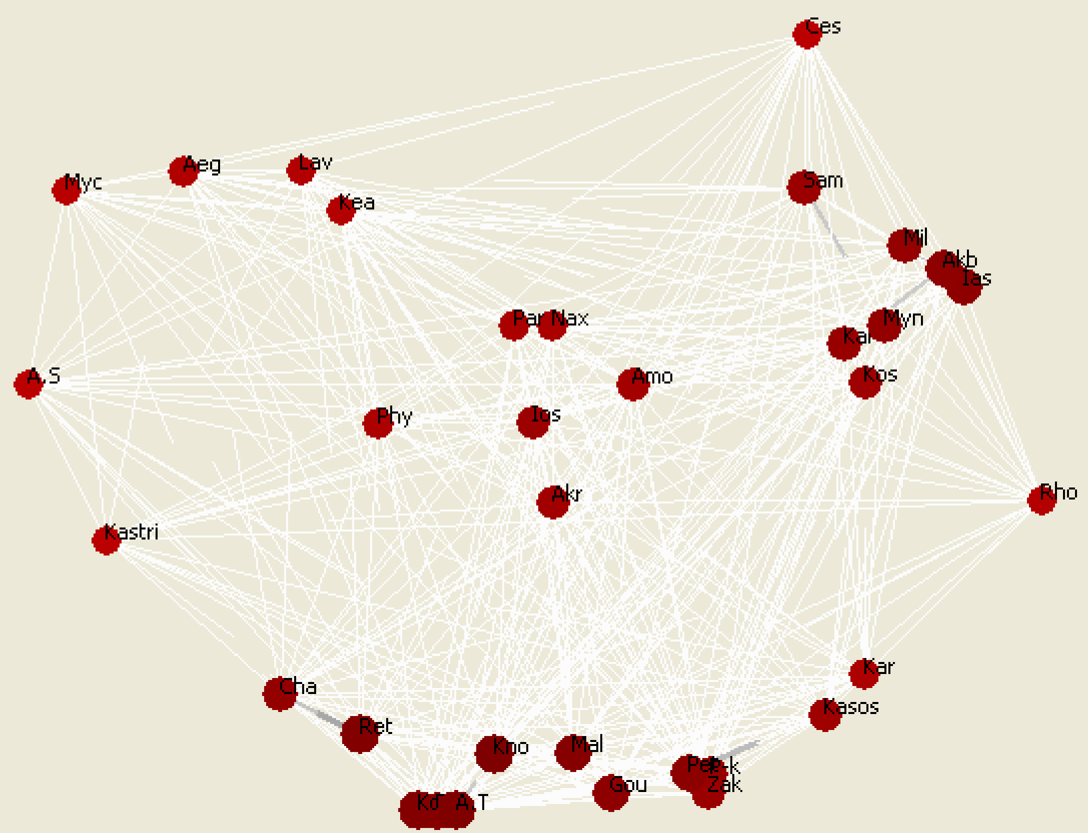
- for large interaction benefits *(λ=4.0, j=0, κ=1.0)*

- 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

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m-1.0j0.0k1.0b1.2s100.0MCr0
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 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	

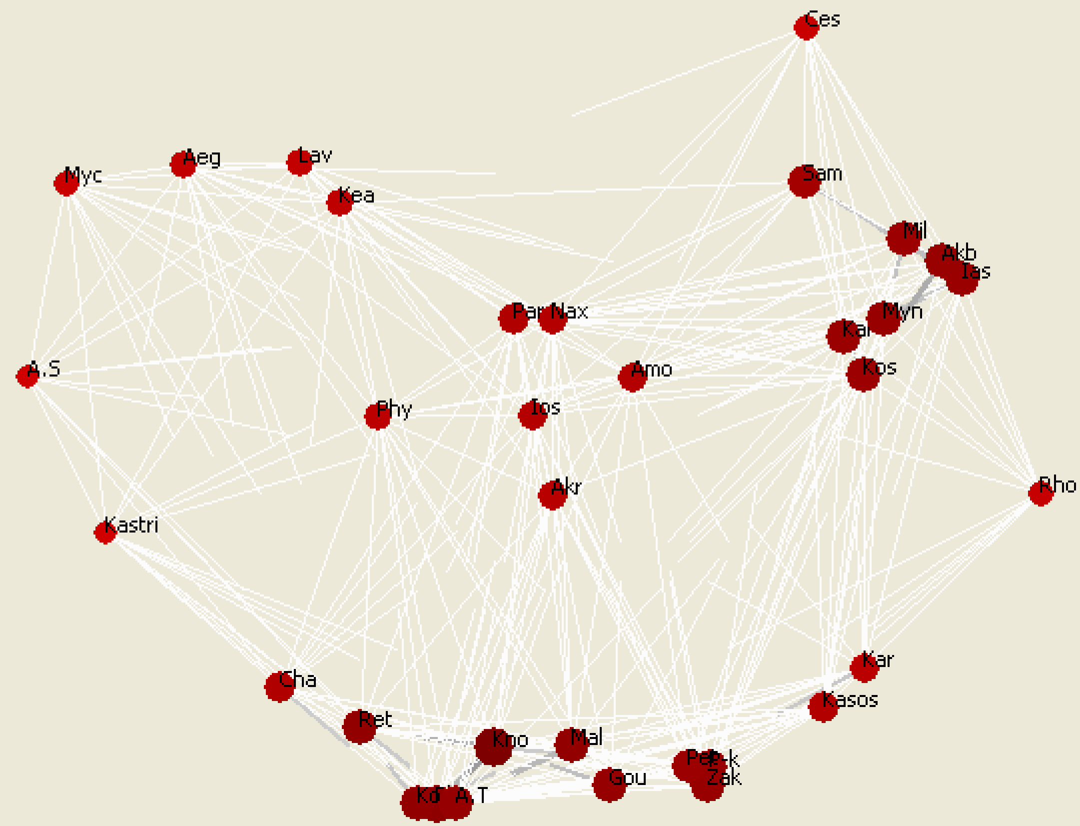


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.07	0.2	0.74	1.4
Site Out W.Strength	1.07	0.2	0.74	1.4
Edge Weight	0.03	0.04	0.0	0.34
Edge Value	0.03	0.03	0.0	0.25

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m0.0j0.0k1.0b1.2s100.0MCr0
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	



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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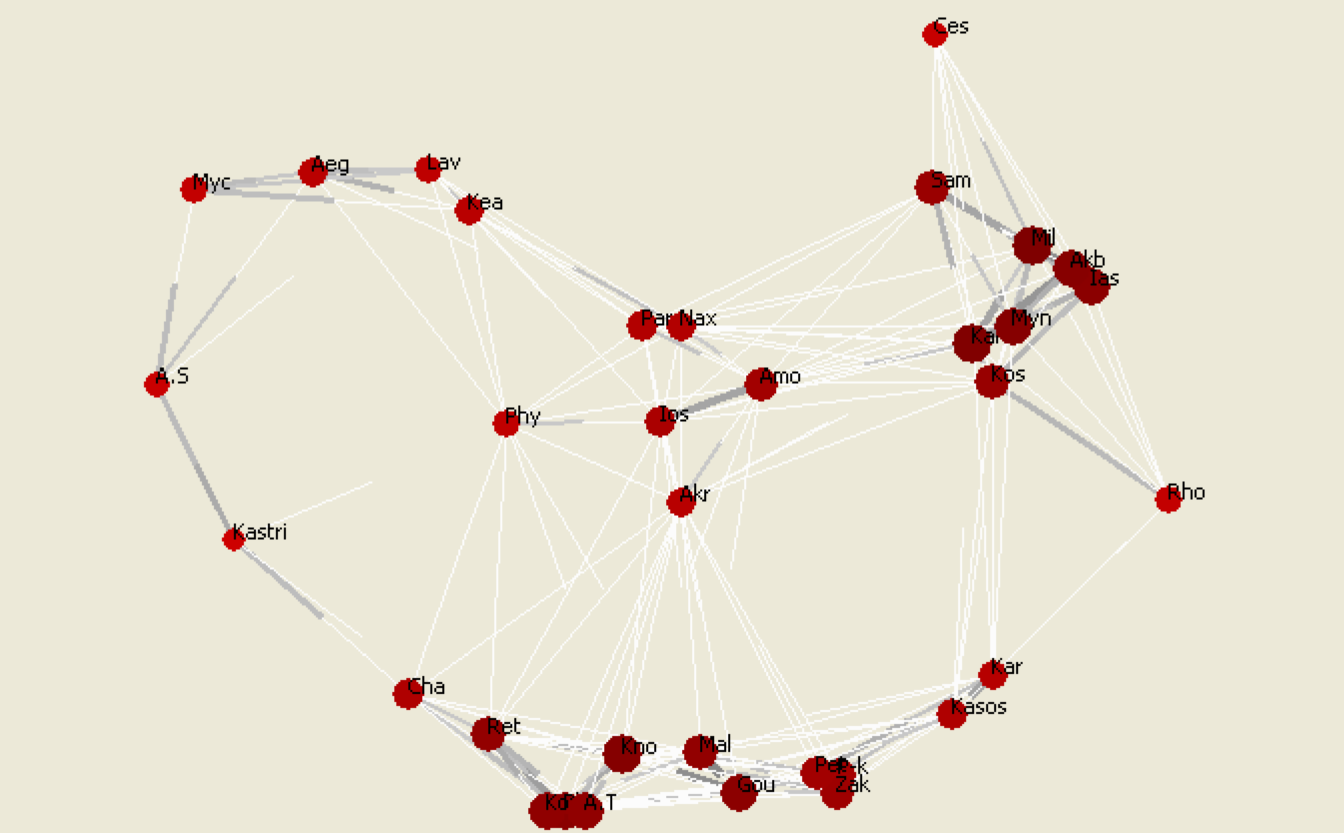
input file: aegean34
output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0
Model: Standard Hamiltonian+Gravity (source and target site in trade term)

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	

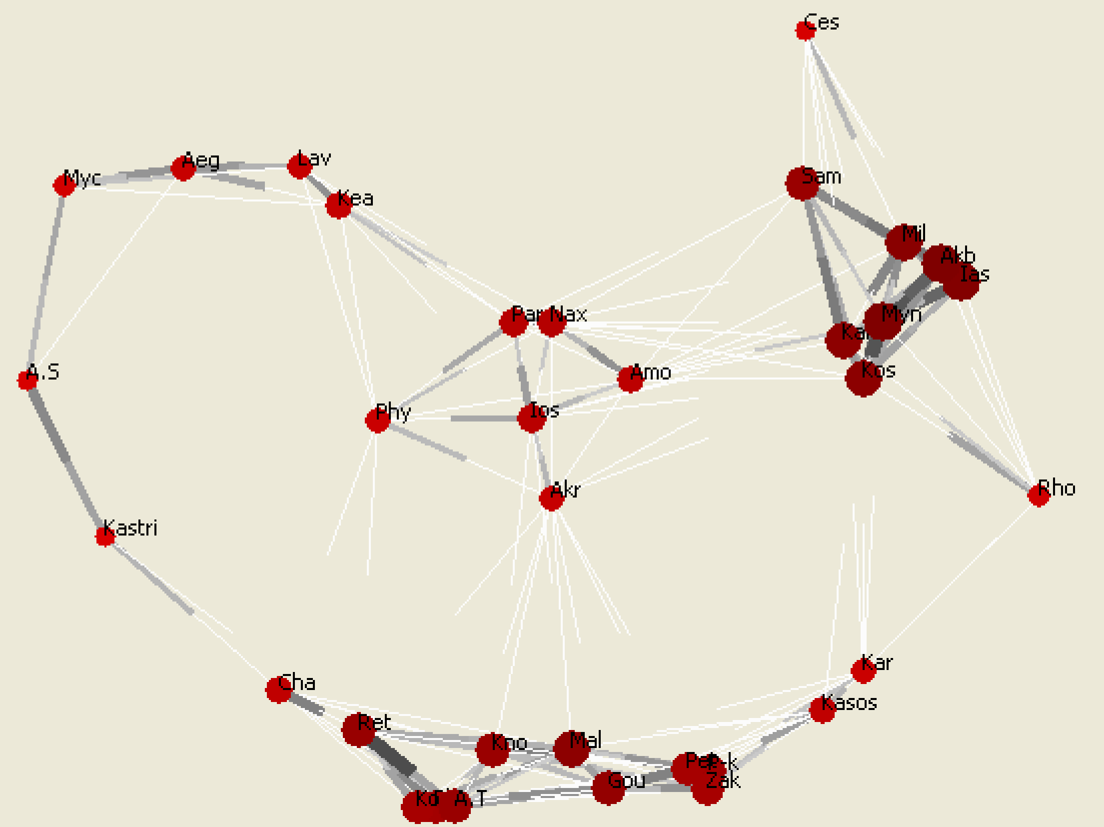


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.43	0.37	0.79	2.03
Site Out W.Strength	1.43	0.37	0.79	2.03
Edge Weight	0.04	0.08	0.0	0.47
Edge Value	0.03	0.06	0.0	0.42

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s100.0MCr0
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	

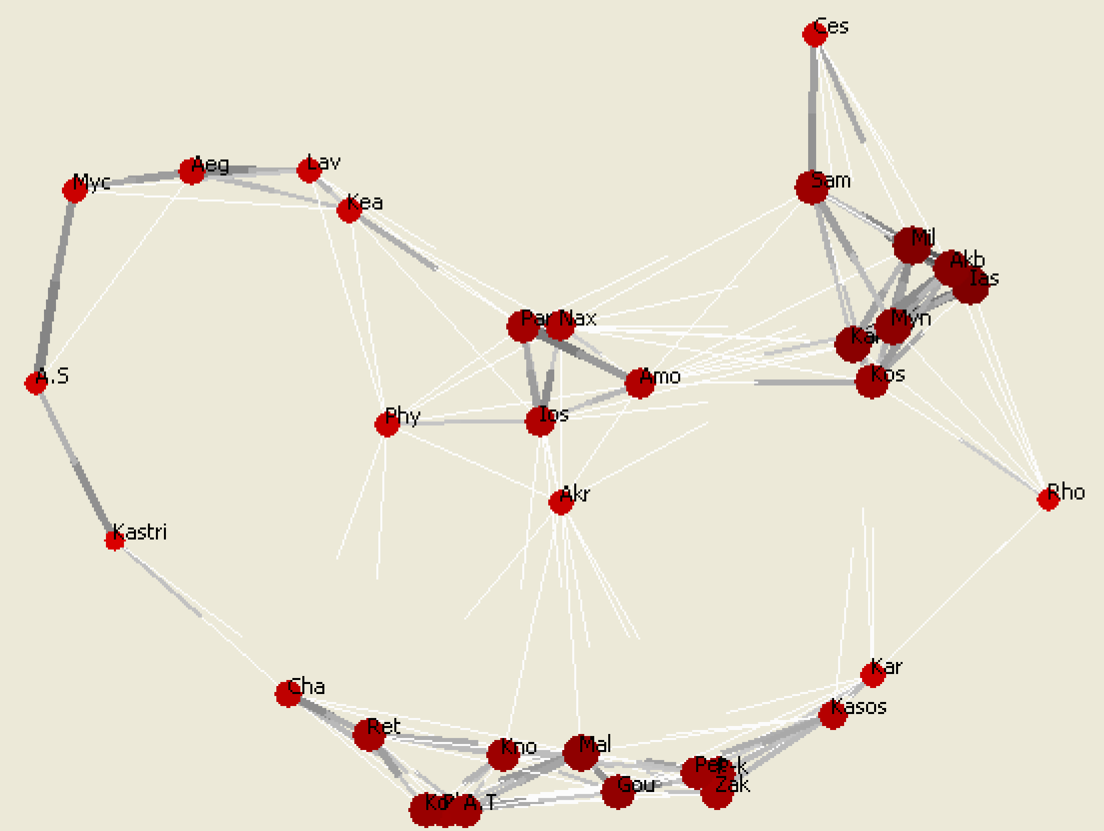


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.77	0.61	0.81	2.79
Site Out W.Strength	1.77	0.61	0.81	2.79
Edge Weight	0.05	0.12	0.0	0.7
Edge Value	0.03	0.07	0.0	0.53

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s100.0MCr0
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	

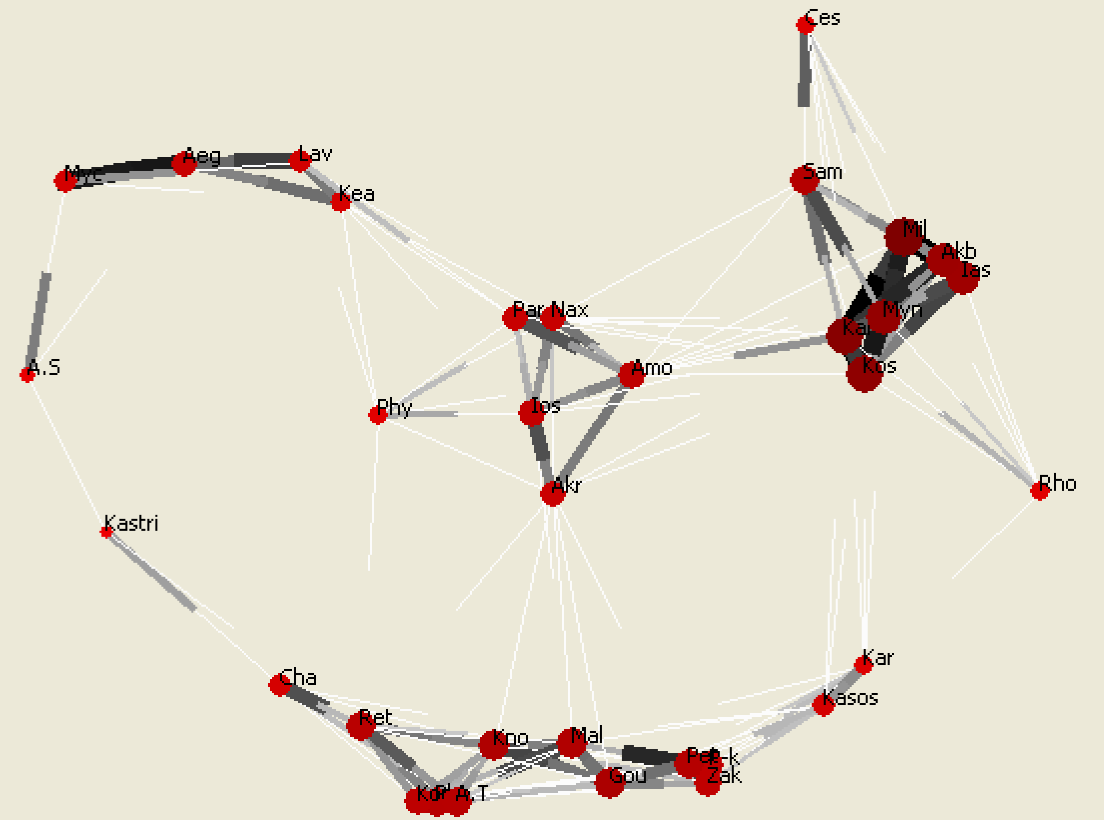


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.72	0.54	0.77	2.66
Site Out W.Strength	1.72	0.54	0.77	2.66
Edge Weight	0.05	0.11	0.0	0.81
Edge Value	0.03	0.07	0.0	0.56

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m1.5j0.0k1.0b1.2s100.0MCr0
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 1.5	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	



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	0.03	0.08	0.0	0.63

aegean34 Ariadne Network Display iN060825

input file: aegean34
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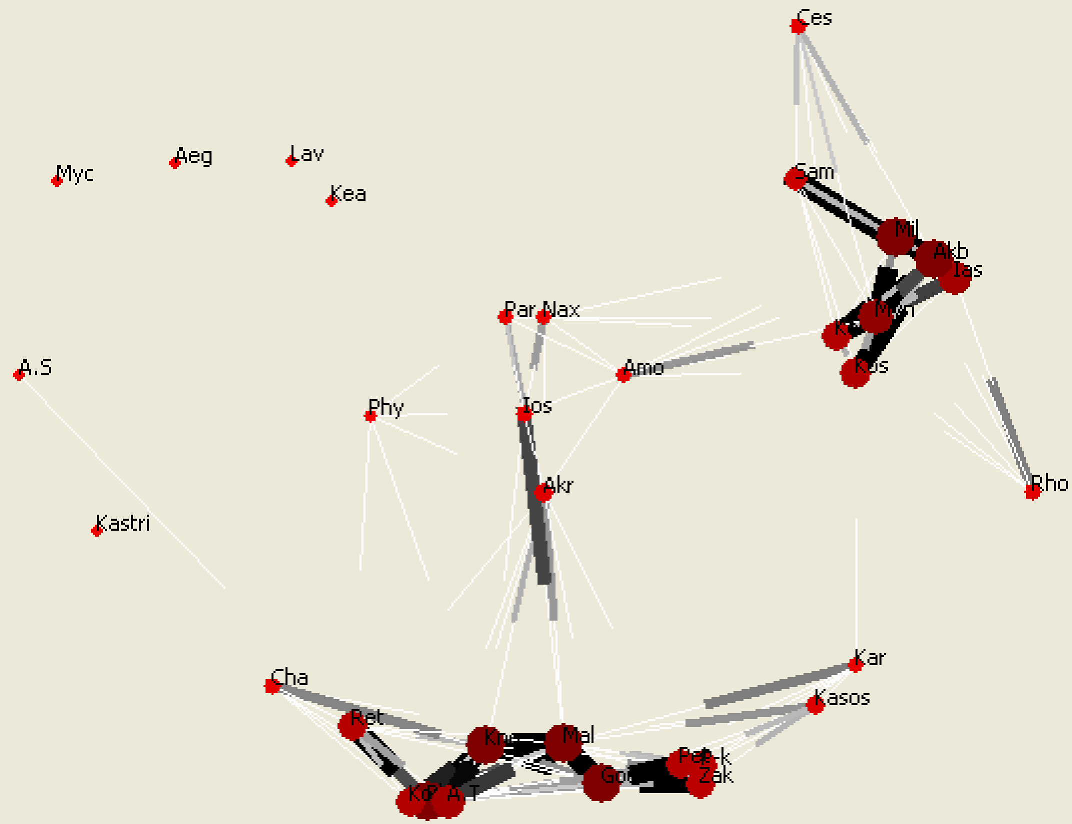
Model: Standard Hamiltonian+Gravity (source and target site in trade term)

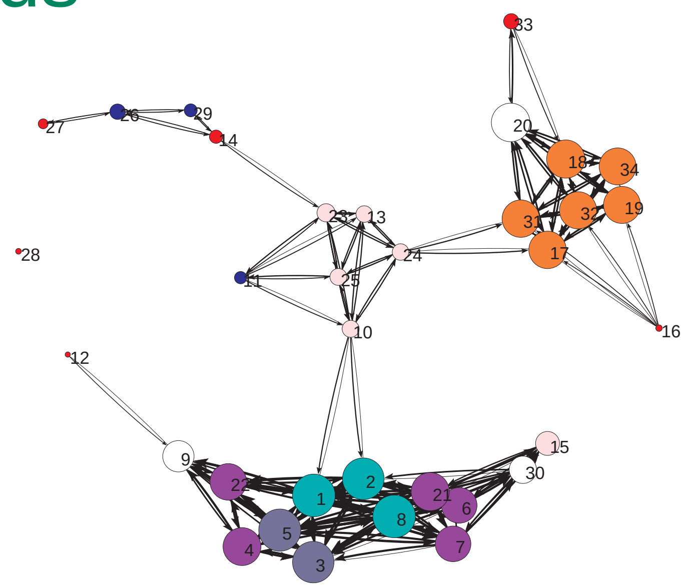
model number 1_3	Monte Carlo Update	Limits on Out Strength 1.0	max vertex value 5.0
mu 2.0	j 0.0	kappa 1.0	lambda 4.0
b 1.2	distance scale 100.0	short distance scale 5.0	metric number 5.0
beta 524288.0	Zero Colour Frac 0.01	Min. Colour Frac 0.2	Relative Vertex Display
Absolute Edge Display, Max 1.0	Influence Range 1.0 (prob=0.5)	sites by Size	



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**
  – improve distance data, more analysis tools, more what if scenarios, EBA vs MBA, general time evolution, other data sets

Additional Material

More stuff …

PPA - Proximal Point Analysis

Most models focused on local interactions, often just nearest neighbour interactions

- Malta (*Renfrew & Level, 1979*)
- Geometric Greece (*Rihll & Wilson, 1991*)
- Proximal Point Analysis
  Connect each vertex to 3 (or whatever) nearest neighbours
  - (Terrell 1977; Irwin 1983; Hage and Harary, 1991, 1996)
  - EBA Aegean (Broodbank 2000)
  - Vikings (Sindbæk, in prep.)
  - Hypsistos Cult (Collar, in prep.)

Increasing Interaction Benefits (λ)

Next 5 slides …

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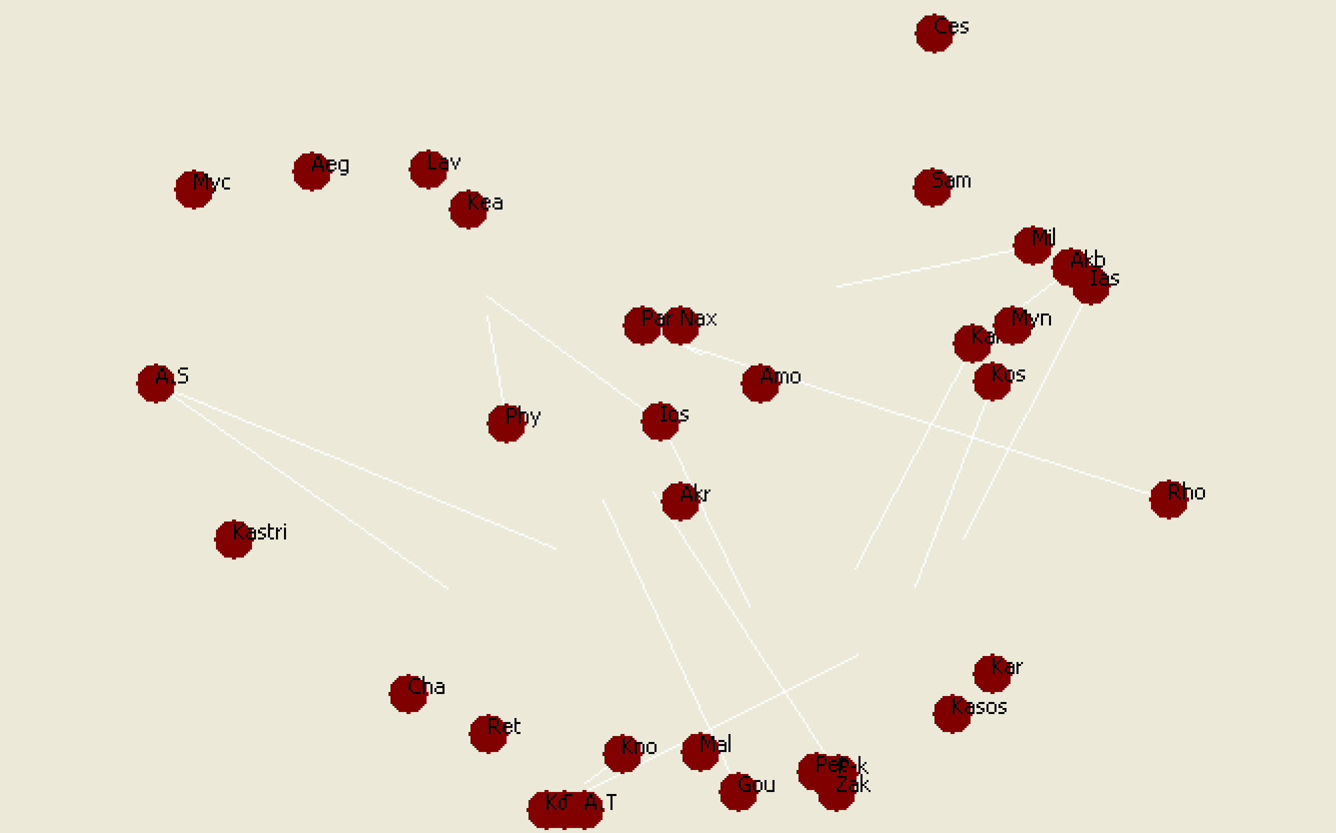
Model: Standard Hamiltonian+Gravity (source and target site in trade term)

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 0.5
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	



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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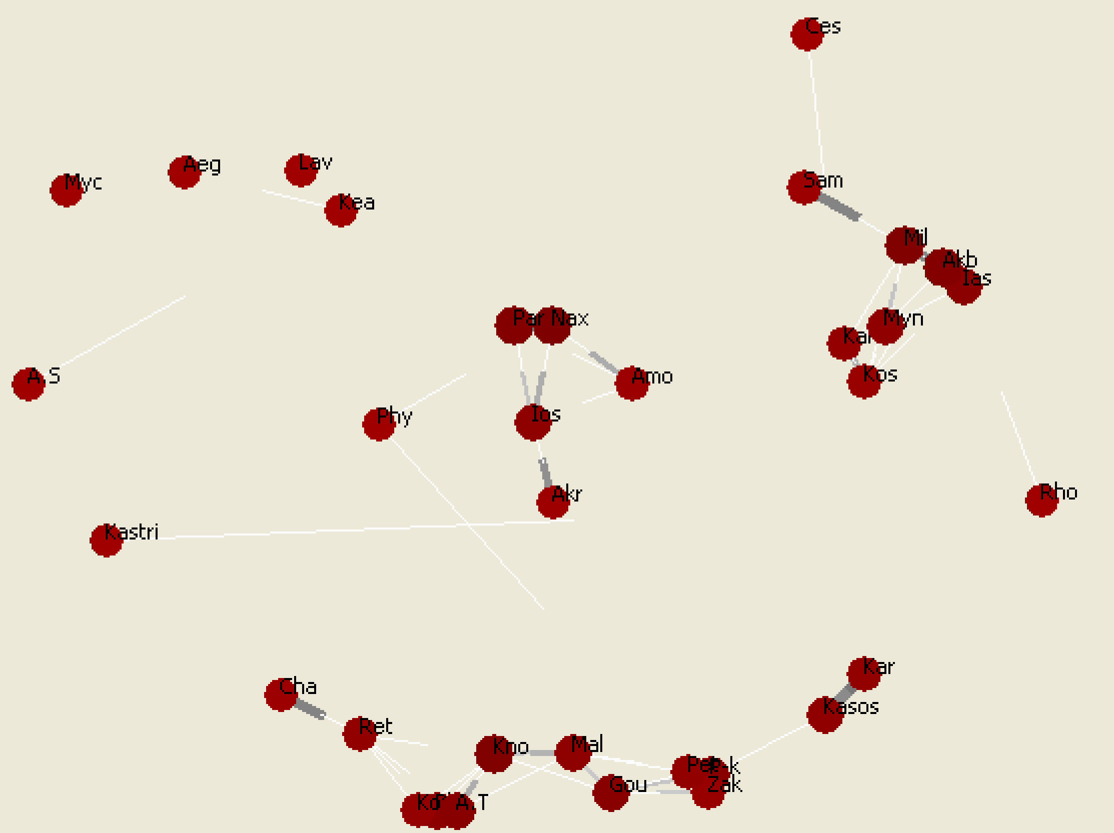
b 1.2	distance scale 100.0	short distance scale 5.0	metric number 5.0
beta 524288.0	Zero Colour Frac 0.01	Min. Colour Frac 0.2	Relative Vertex Display
Absolute Edge Display, Max 1.0	Influence Range 1.0 (prob=0.5)	sites by Size	



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

aegean34 Ariadne Network Display iN060825

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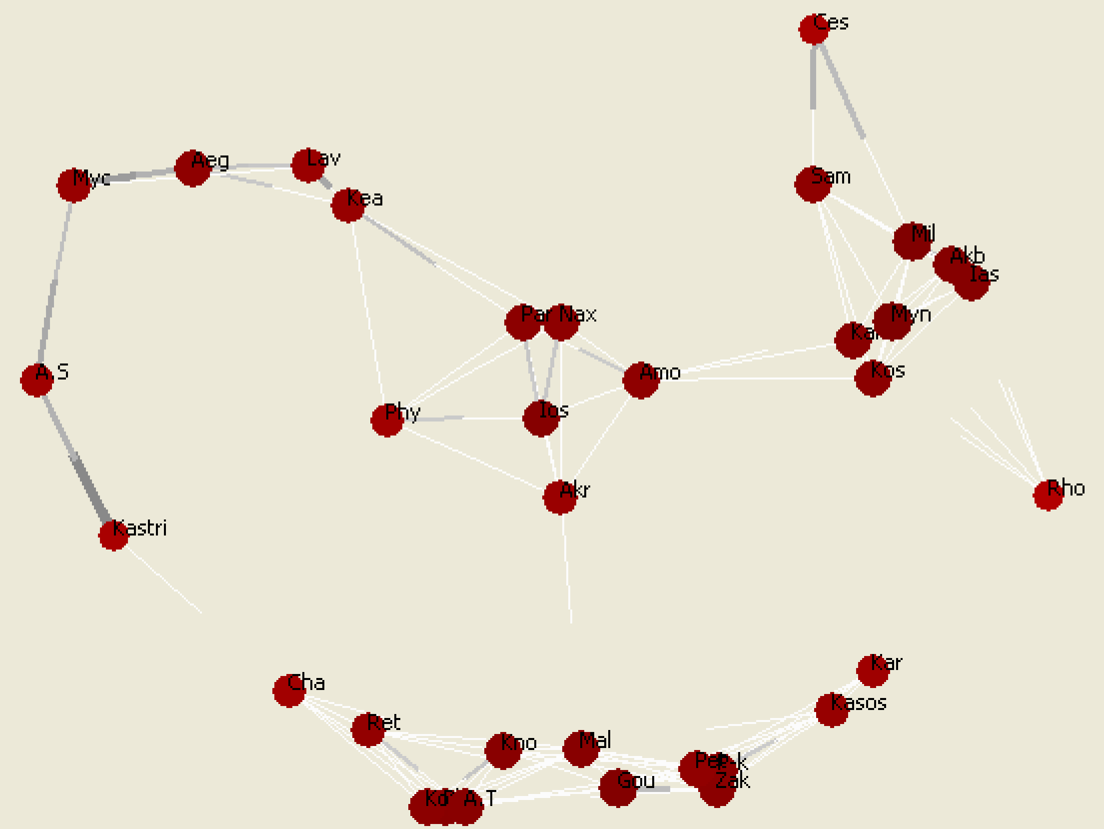
model number 1_3	Monte Carlo Update	Limits on Out Strength 1.0	max vertex value 5.0
mu 0.5	j 0.0	kappa 1.0	lambda 2.0
b 1.2	distance scale 100.0	short distance scale 5.0	metric number 5.0
beta 524288.0	Zero Colour Frac 0.01	Min. Colour Frac 0.2	Relative Vertex Display
Absolute Edge Display, Max 1.0	Influence Range 1.0 (prob=0.5)	sites by Size	

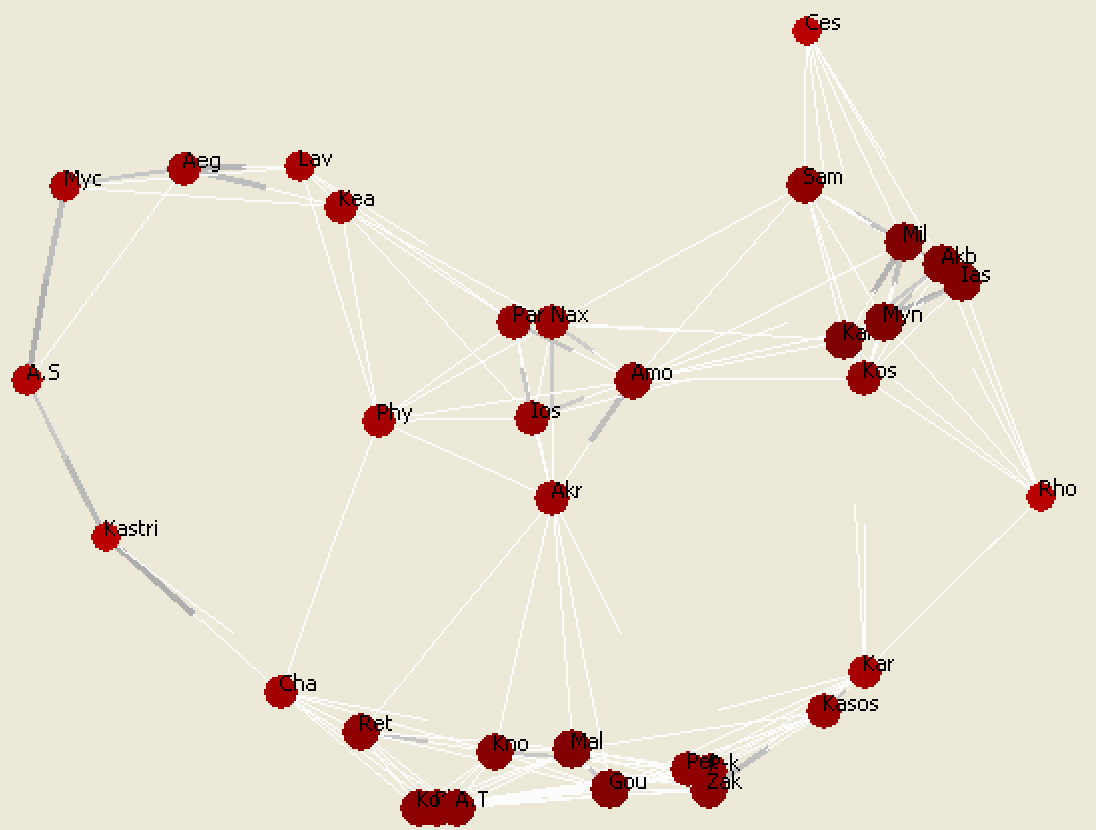


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	0.74	0.08	0.53	0.87
Site Out W.Strength	0.74	0.09	0.52	0.87
Edge Weight	0.02	0.06	0.0	0.46
Edge Value	0.03	0.08	0.0	0.79

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0
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 3.0
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	

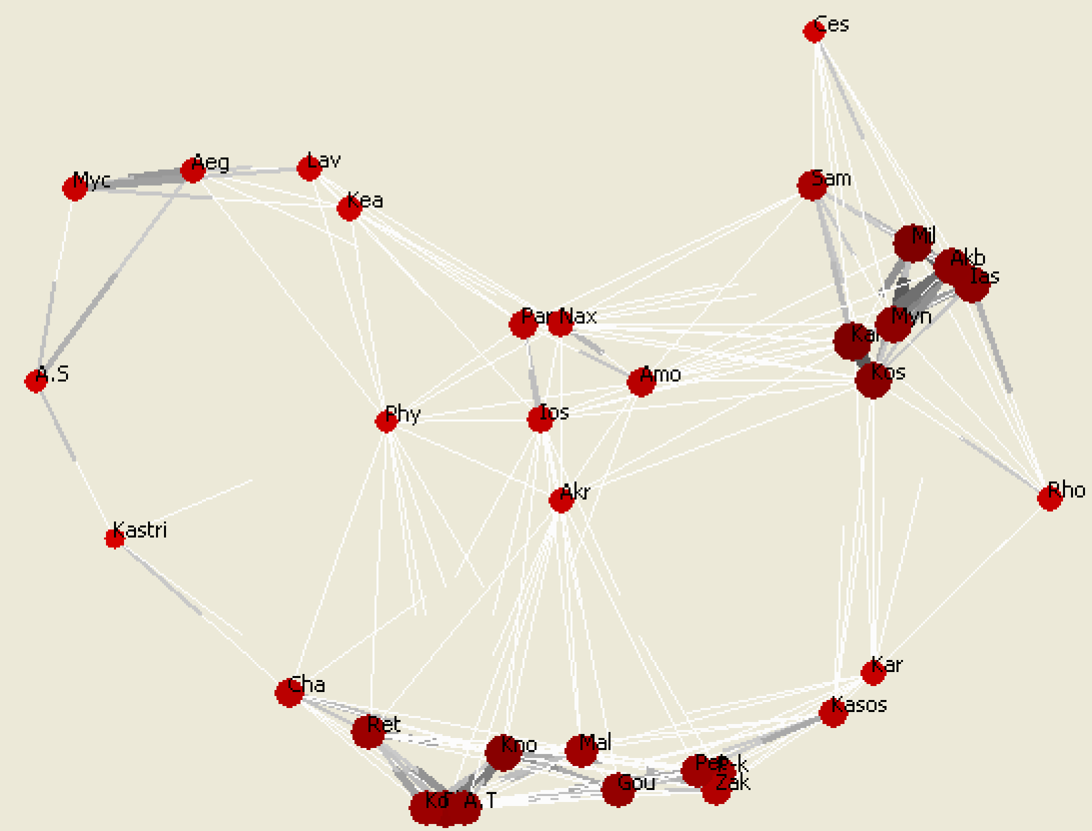


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	0.97	0.16	0.65	1.2
Site Out W.Strength	0.97	0.16	0.65	1.2
Edge Weight	0.03	0.06	0.0	0.32
Edge Value	0.03	0.06	0.0	0.49

aegean34 Ariadne Network Display iN060825

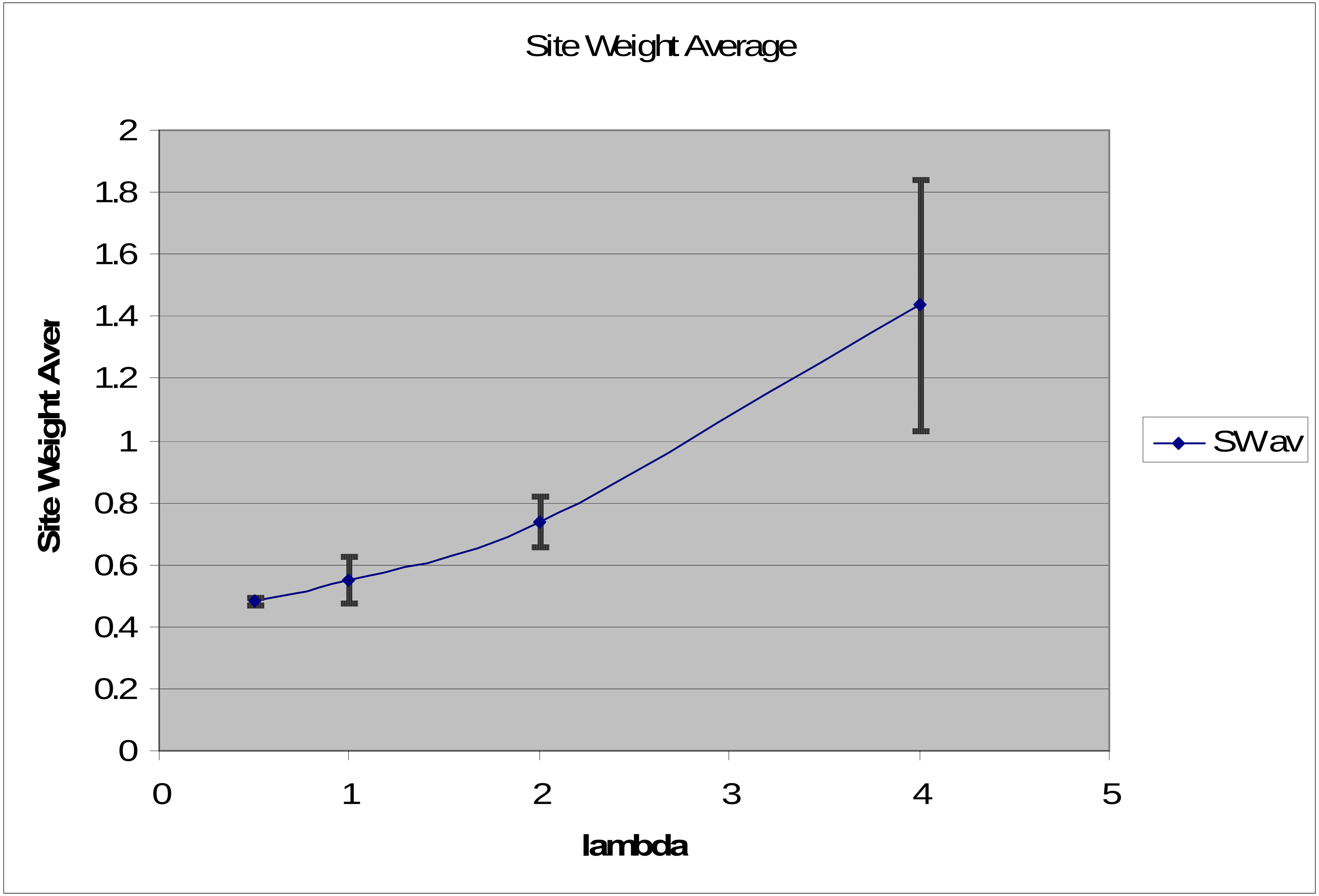
input file: aegean34
output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0
Model: Standard Hamiltonian+Gravity (source and target site in trade term)

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	



Quantity/Value	Average	Sigma	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

End of increasing λ sequence



Site Weight Average
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Site Weight Aver
0
1
2
3
4
5
lambda
SWav

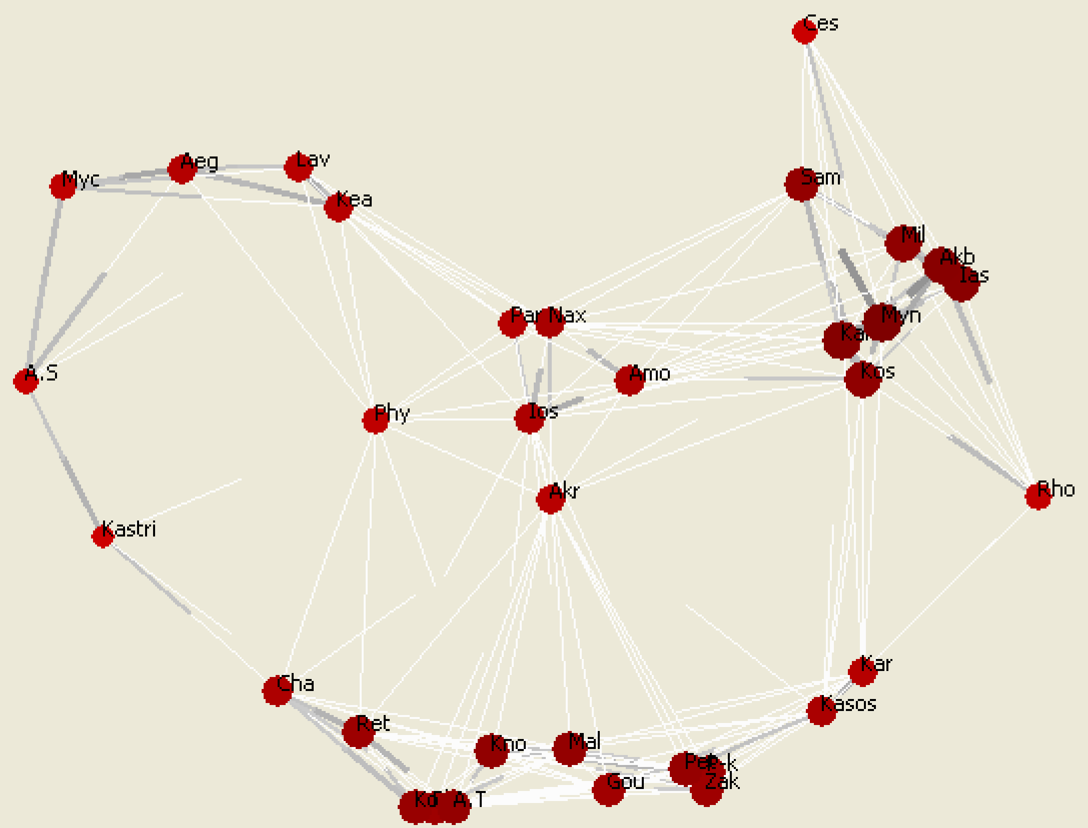
Statistical Variation Constant Values

- 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.

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0
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	

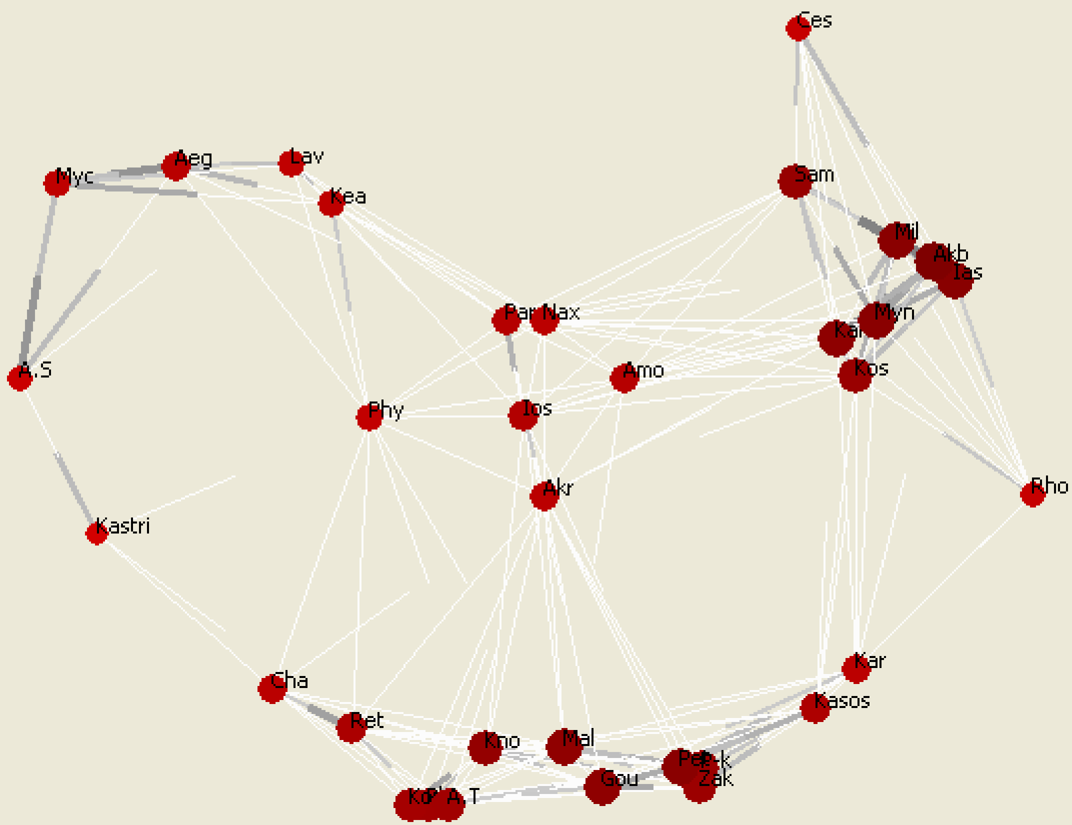


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.38	0.33	0.77	1.99
Site Out W.Strength	1.38	0.33	0.77	1.99
Edge Weight	0.04	0.08	0.0	0.42
Edge Value	0.03	0.06	0.0	0.38

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr1
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	

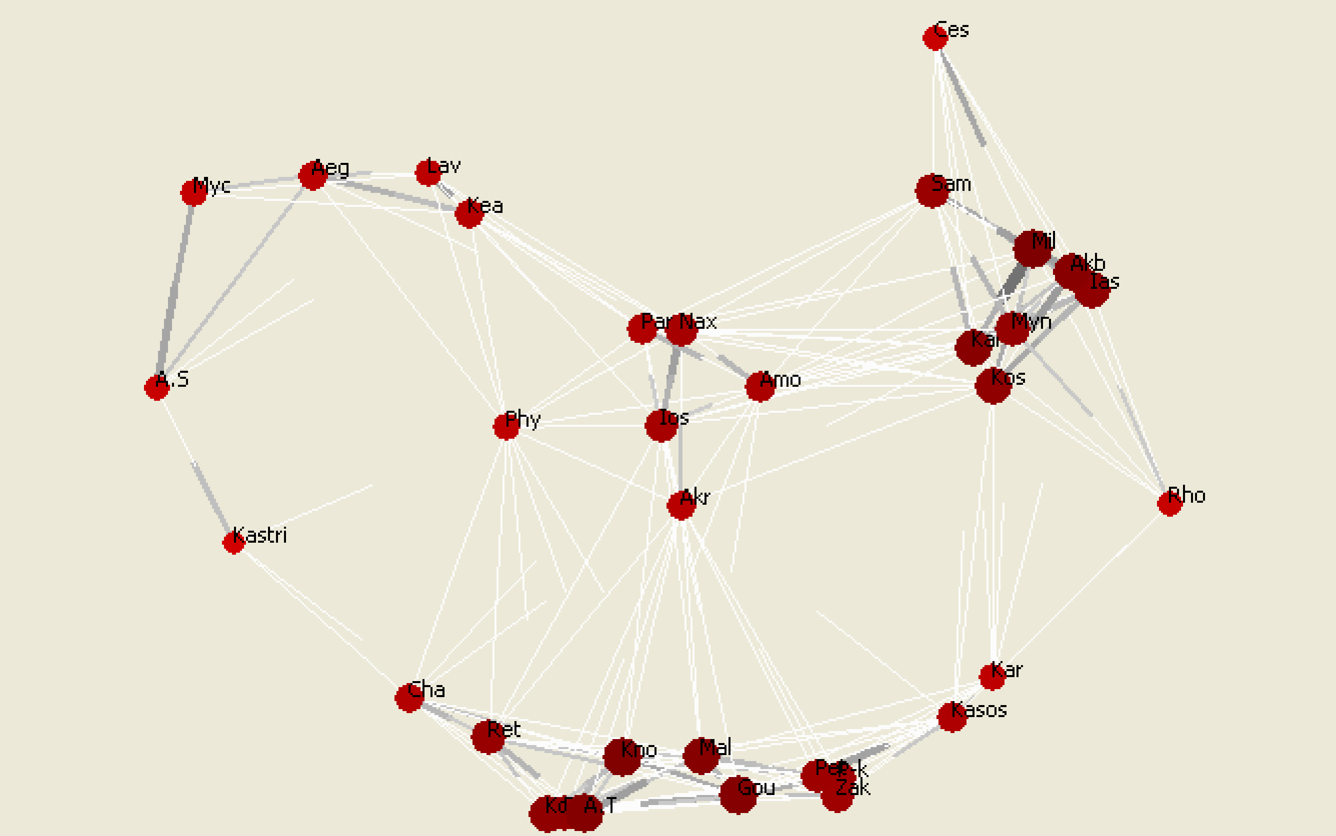


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.42	0.38	0.72	2.12
Site Out W.Strength	1.42	0.38	0.72	2.12
Edge Weight	0.04	0.08	0.0	0.49
Edge Value	0.03	0.06	0.0	0.48

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr2
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	

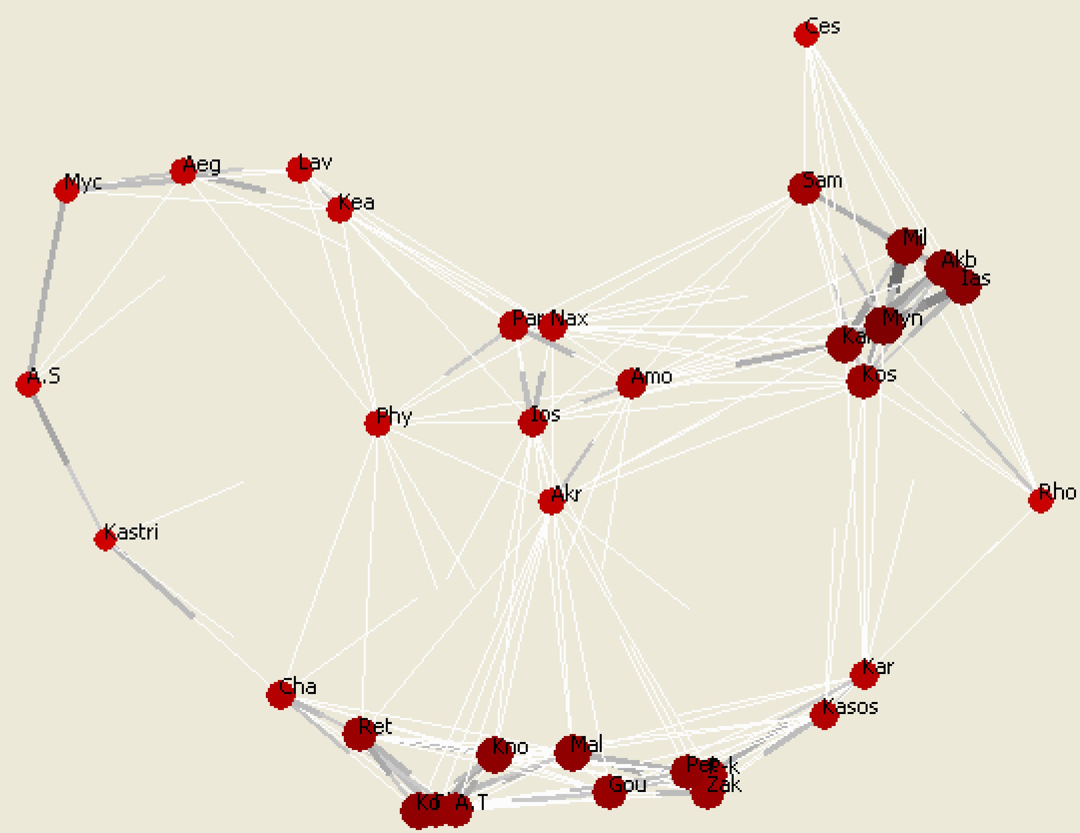


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.45	0.39	0.72	2.05
Site Out W.Strength	1.45	0.39	0.72	2.05
Edge Weight	0.04	0.08	0.0	0.55
Edge Value	0.03	0.06	0.0	0.4

aegean34 Ariadne Network Display iN060825

input file: aegean34
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	

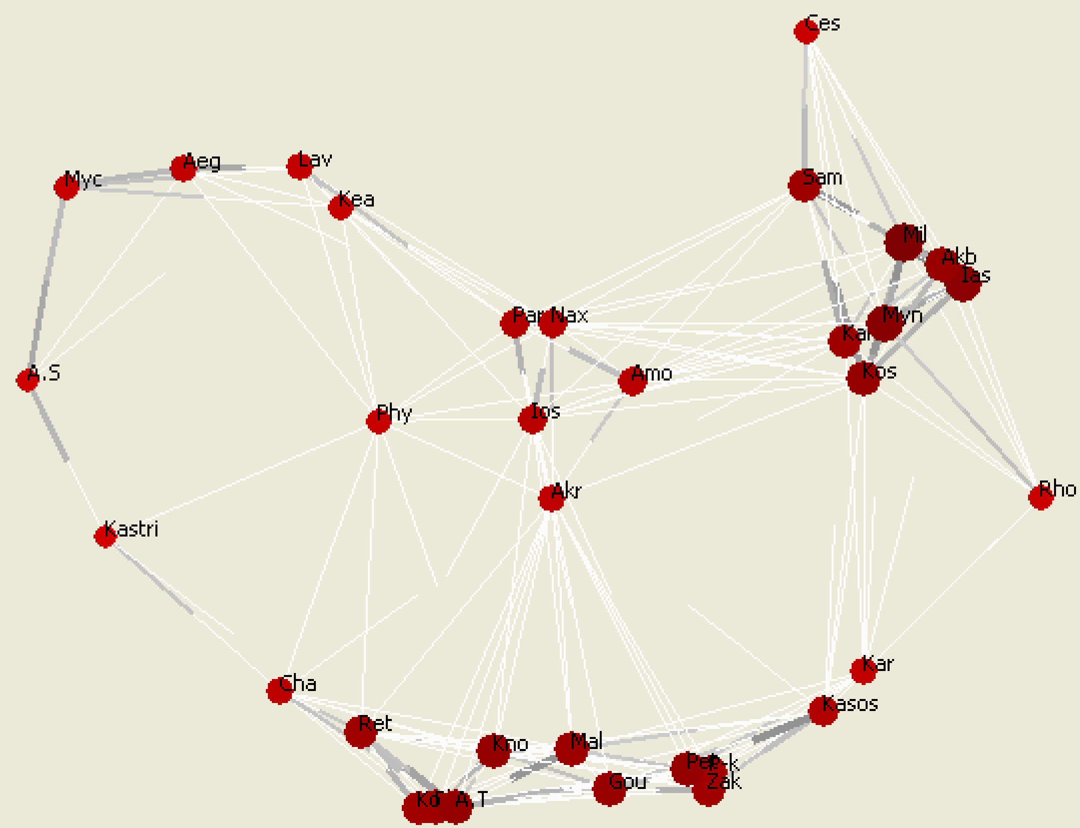


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.44	0.4	0.79	2.15
Site Out W.Strength	1.44	0.41	0.79	2.15
Edge Weight	0.04	0.08	0.0	0.56
Edge Value	0.03	0.06	0.0	0.41

aegean34 Ariadne Network Display iN060825

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	



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

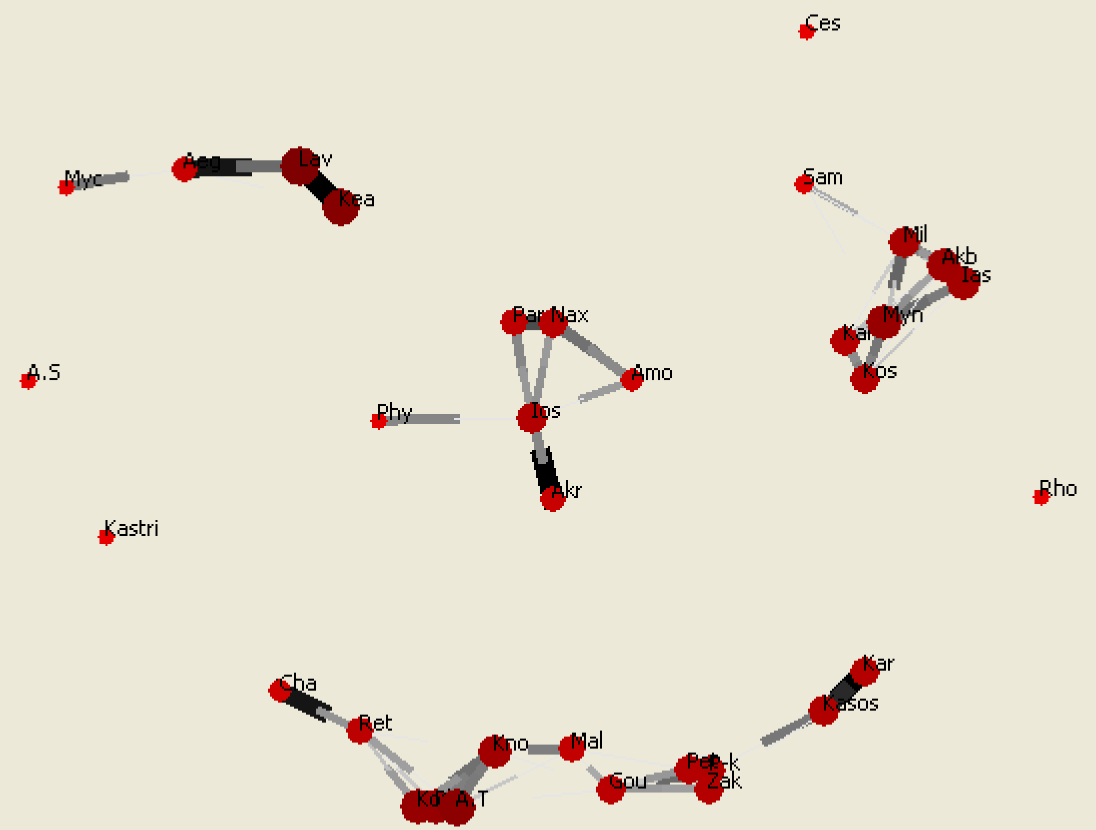
Range of Distance Scales (d)

- Next 4 slides

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s50.0MCr0
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 50.0	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	

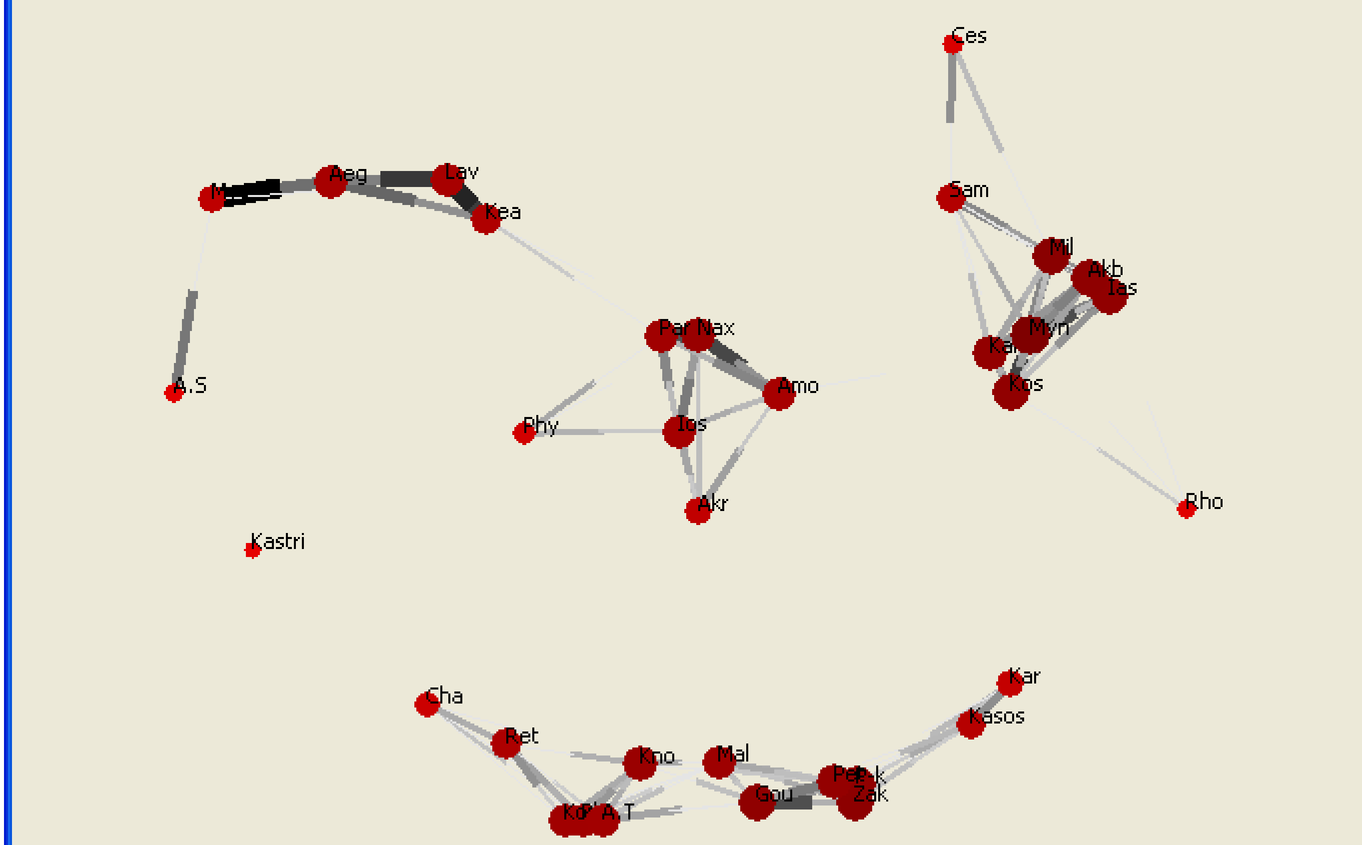


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.38	0.57	0.48	2.52
Site Out W.Strength	1.32	0.65	0.07	2.5
Edge Weight	0.04	0.16	0.0	2.29
Edge Value	0.03	0.1	0.0	0.97

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s75.0MCr0
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	

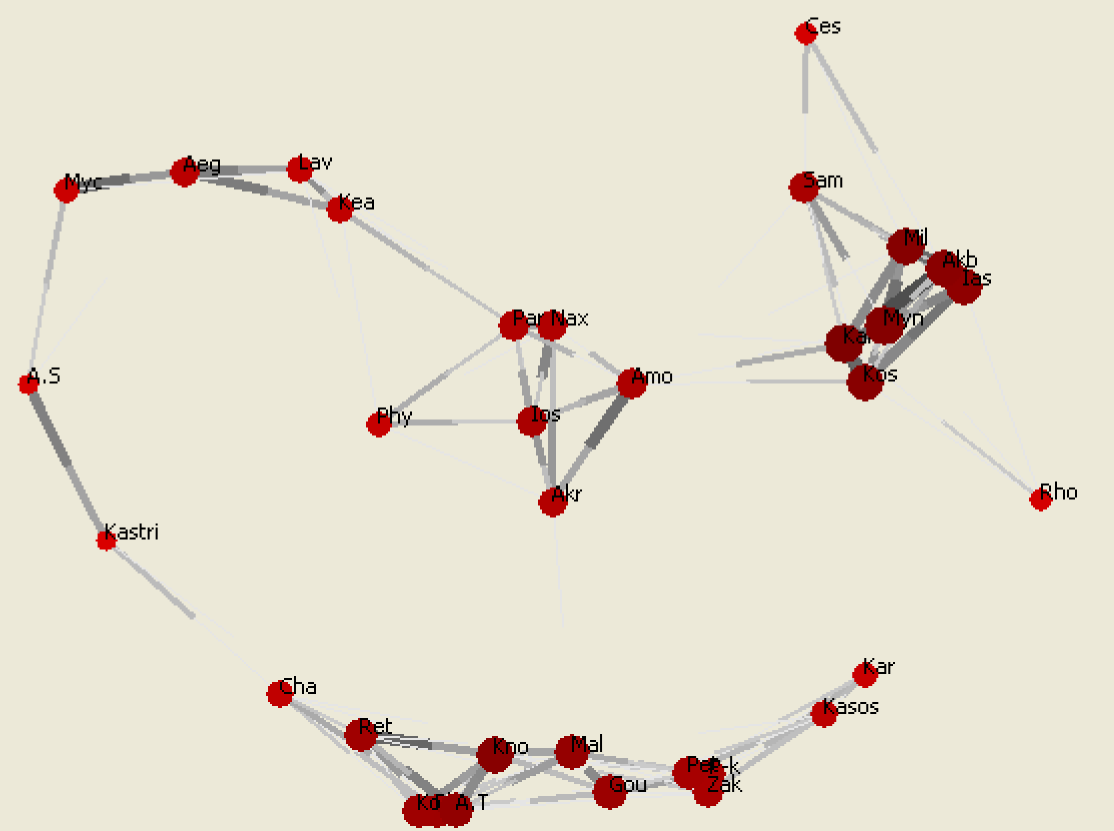


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.6	0.52	0.48	2.42
Site Out W.Strength	1.58	0.54	0.08	2.42
Edge Weight	0.05	0.13	0.0	1.03
Edge Value	0.03	0.08	0.0	0.96

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s100.0MCr0
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 0.1	Min. Colour Frac 0.2	Relative Vertex Display
Absolute Edge Display, Max 1.0	Influence Range 1.0 (prob=0.5)	sites by Size	

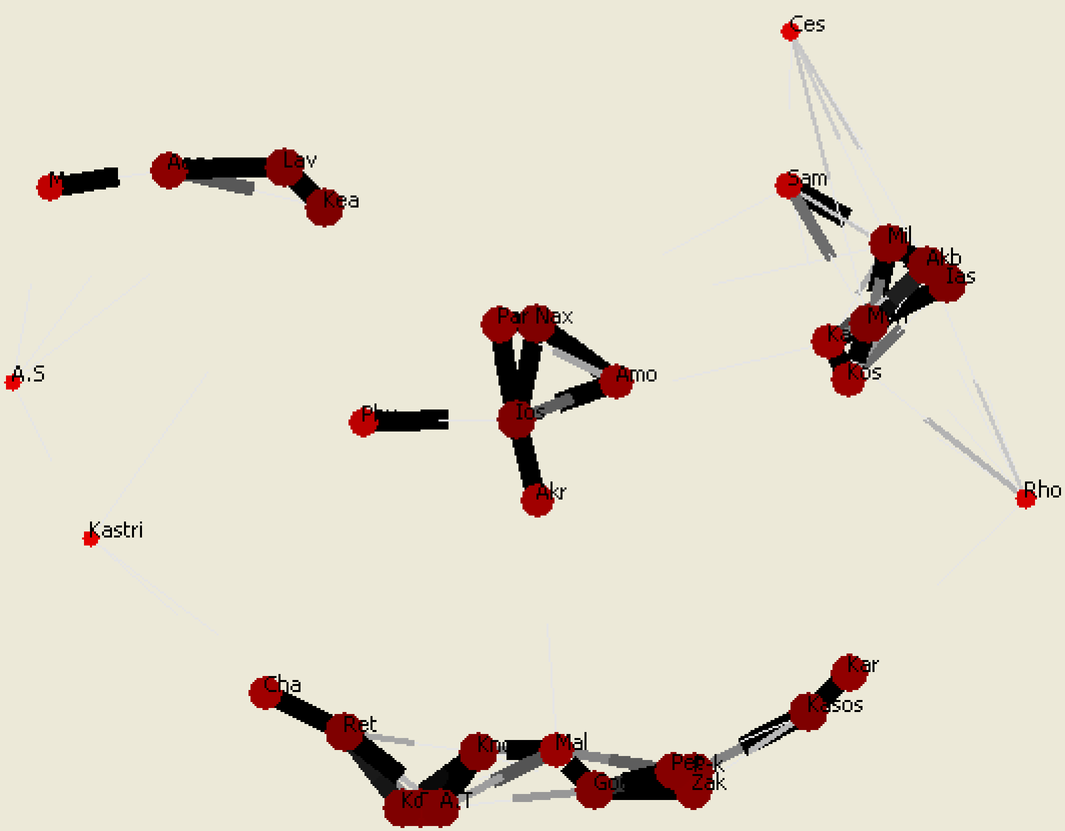


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.78	0.56	0.82	2.74
Site Out W.Strength	1.78	0.56	0.82	2.74
Edge Weight	0.05	0.12	0.0	0.69
Edge Value	0.03	0.07	0.0	0.57

aegean34 Ariadne Network Display iN060825

input file: aegean34
output files: output/aegean34_v1_3e-1.0m1.0j0.0k1.0b1.2s125.0MCr0
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	



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

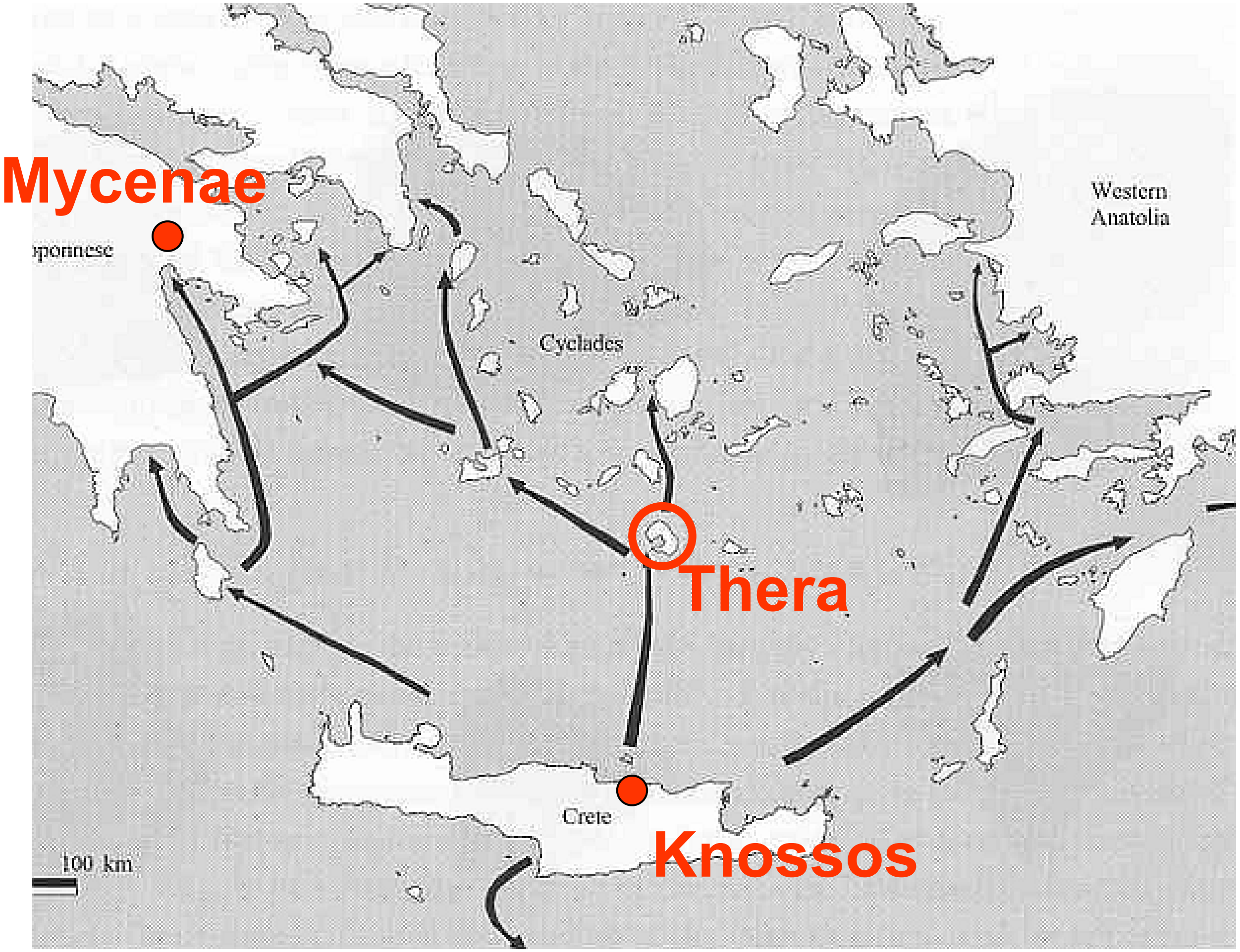
Network Description

- 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
  - » Site **Weight** (S_i v_i) = Site `*population*'
- e_{ij} Fractional Edge values $\boldsymbol{0 \leq \Sigma_j e_{ij} \leq 1}$
  - » 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?

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)

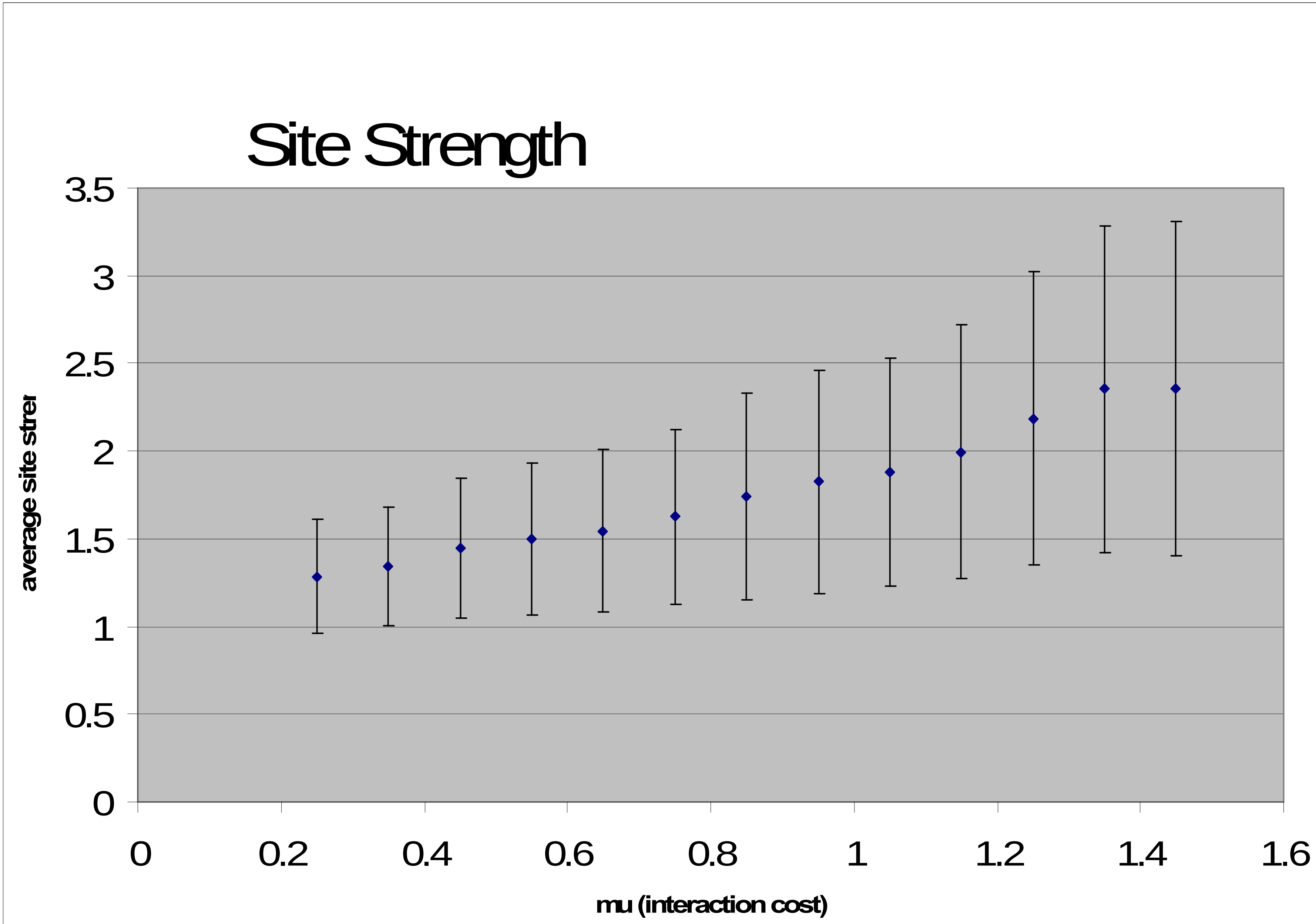
- **Scale of networks**
- **Uneven site size**
- **Length of links**
- **Directionality**

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'

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 strer
mu (interaction cost)
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