INTRODUCING DYNAMICS IN TRANSPORT NETWORK RESEARCH USING COMPUTATIONAL APPROACHES

EXAMPLES FROM THE DUTCH ROMAN LIMES
Project aim: Studying the development of the cultural landscape of the Dutch Roman *limes* through spatial dynamical modelling

Subproject aim: Reconstructing and analysing the cultural landscape (settlement patterns and transport networks) in relation to the natural environment
WHAT DO WE KNOW OF TRANSPORT?
WHAT DO WE KNOW OF TRANSPORT?

- Most evidence on regional to imperial scale
- Very little evidence for local transport
- How was transport for the Roman army organised?

Methodological questions:
- How do we model transport networks?
- How do we validate the results?
NATURAL PALAEOGEOGRAPHY

Palaeogeography through combining various source datasets:

- Soil maps
- Geomorphological maps
- Channel belt palaeogeography
- LIDAR elevation data
- Archaeological research
NATURAL PALAEOGEOGRAPHY
NATURAL PALAEOGEOGRAPHY
CULTURAL PALAEOGEOGRAPHY

Legend
- Castellum
- Civil settlement
- Military sites
- Post-built settlement and military site
- Post-built settlement
- Stone-built settlement
- Other

Legend
- Palaeogeography
  - Water
  - Low levee
  - Residual gully
  - High levee
  - High floodplain
  - Moderately high levee
  - Low floodplain

0  2.5  5  10 km
TRANSPORT COST ESTIMATION

\[
V = \sqrt[ ]{\frac{M - 1.5 \, W - 2 \, (W + L) \, \left(\frac{L}{W}\right)^2}{1.5 \, \eta \, (W + L)}}
\]

- \( V \) = velocity (m/s)
- \( M \) = metabolic rate (W)
- \( W \) = subject weight (kg)
- \( L \) = carried load (kg)
- \( \eta \) = terrain coefficient
# TRANSPORT COST ESTIMATION

<table>
<thead>
<tr>
<th>Terrain</th>
<th>Terrain coefficient</th>
<th>Time over 50m (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>20.0</td>
<td>159.8</td>
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<tr>
<td>Military road</td>
<td>1.0</td>
<td>35.7</td>
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<tr>
<td>High levee</td>
<td>1.1</td>
<td>37.5</td>
</tr>
<tr>
<td>Moderately high levee</td>
<td>1.1</td>
<td>37.5</td>
</tr>
<tr>
<td>Low levee</td>
<td>1.2</td>
<td>39.1</td>
</tr>
<tr>
<td>Residual gully</td>
<td>1.5</td>
<td>43.8</td>
</tr>
<tr>
<td>High floodplain</td>
<td>1.5</td>
<td>43.8</td>
</tr>
<tr>
<td>Low floodplain</td>
<td>1.8</td>
<td>47.9</td>
</tr>
<tr>
<td>Fen woodlands</td>
<td>1.8</td>
<td>47.9</td>
</tr>
<tr>
<td>Reed and sedge fields</td>
<td>1.8</td>
<td>47.9</td>
</tr>
<tr>
<td>High Pleistocene sands</td>
<td>1.5</td>
<td>43.8</td>
</tr>
<tr>
<td>Cover sand</td>
<td>1.2</td>
<td>39.1</td>
</tr>
</tbody>
</table>

Legend:
- **Palaeogeography**
  - Water
  - High levee
  - Low levee
  - Moderately high levee
  - Residual gully
  - High floodplain
  - Low floodplain
  - Fen woodlands
  - Reed and sedge fields
  - High Pleistocene sands
  - Cover sand
TRANSPORT NETWORK RECONSTRUCTION

Legend
- <15 minutes
- <30 minutes
- <45 minutes
- <1 hour
- <2 hours
- <3 hours
- <4 hours
- >4 hours
NETWORK ANALYSIS

Legend

Palaeogeography

- Water
- High levee
- Moderately high levee
- Low levee
- Residual gully
- High floodplain
- Low floodplain
- Fen woodlands
- Reed and sedge fields
- Cover sand
- High Pleistocene sands

0 2.5 5 10 km
NETWORK ANALYSIS

Walking without load

Walking with 40 kg load

Ox cart

Mule cart
Network analysis is often applied on the complete network.

Results can be dependent on complete network structure.

Can we test the robustness of the results?
## Robustness of Network Measurements: Key Site Selection

<table>
<thead>
<tr>
<th>ID</th>
<th>Toponym</th>
<th>Site type</th>
<th>W0_B rank</th>
<th>W40_B rank</th>
<th>MC_B rank</th>
<th>OC_B rank</th>
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<tbody>
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<td>110</td>
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<td>23</td>
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<td>48</td>
<td>20</td>
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<td>5</td>
<td>84</td>
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<td>64</td>
<td>18</td>
<td>7</td>
<td>32</td>
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</table>
ROBUSTNESS OF NETWORK MEASUREMENTS: RANDOM NETWORK EMERGENCE
Type A1:
- Early rise in betweenness centrality
- Convex break in percentual rank increase
- Early stabilisation in percentual rank
Type C1:

> Early rise in betweenness centrality
> Convex break in percentual rank increase
> No stabilisation in percentual rank but converging towards it
ROBUSTNESS OF NETWORK MEASUREMENTS: RESULTS

Type C2:

- Early rise in betweenness centrality
- Convex break in percentual rank increase
- No stabilisation in percentual rank
Robust betweenness centrality (stable percentual rank)

- Occurs ~60% in key sites across all networks
- Betweenness centrality is an inherent property of the site’s location
- Location could be the result of ‘natural evolution’ in transport networks
75% of sites that are in the top 10% of their network have a stabilising percentual rank trend.

Eight out of 24 sites show stabilisation in all networks, indicating a robust position in all transport networks as the result of ‘natural evolution’.

This includes two *horrea* sites.
Convergence towards stable percentual rank

> Betweenness centrality is partly an inherent property of the site’s location
> Besides advantageous location in transport network, other factors could also have played a role (e.g. political/military in Roman *castellum*)
No percentual rank stabilisation

> Betweenness centrality is dependent on the presence of the entire network
> Site location is not the result of ‘natural evolution’ in transport networks
> Site location is determined by other factors (suitability for farming, animal husbandry or perhaps of political/military nature such as Roman *castella*)
Chronological information is attached to site as a whole, often based on the archaeologist’s judgement.

- No variance in likelihood of presence or site size during individual periods.

- Not all chronological information on same level of detail.

- Can we treat (uncertainty in) chronology of sites more dynamically?
INTRODUCING CHRONOLOGICAL DYNAMICS: SITE DATABASE CHRONOLOGY

Site database chronology on three levels:

<table>
<thead>
<tr>
<th>Iron Age (IA)</th>
<th>Roman Period (RP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Iron Age (LIA)</td>
<td>Early Roman Period (ERP)</td>
</tr>
<tr>
<td></td>
<td>E. Roman Period A (ERPA)</td>
</tr>
<tr>
<td>until 12 BC</td>
<td>12 BC – AD 25</td>
</tr>
</tbody>
</table>
INTRODUCING CHRONOLOGICAL DYNAMICS: REINTERPRETING CHRONOLOGICAL INFORMATION

- Finds are associated with sites in the database
- Each find entry has individual chronological information
- Based on this information each period is given a value of 0 or 1
- A weight is added based on the level of chronological detail
- Per site, the weighted values for all finds and periods are summed
- The summed values are scaled to 1 to arrive at site likelihood values per period

<table>
<thead>
<tr>
<th>Find begin date</th>
<th>Find end date</th>
<th>LIA</th>
<th>ERPA</th>
<th>ERPB</th>
<th>MRPA</th>
<th>MRPB</th>
<th>LRPA</th>
<th>LRPB</th>
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<td>1</td>
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<td>ERPB</td>
<td>MRPB</td>
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<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>3</td>
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<tr>
<td>MRPA</td>
<td>MRPB</td>
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<td>0</td>
<td>0</td>
<td>1</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>3</td>
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</table>

<table>
<thead>
<tr>
<th>LIA</th>
<th>ERPA</th>
<th>ERPB</th>
<th>MRPA</th>
<th>MRPB</th>
<th>LRPA</th>
<th>LRPB</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>3</td>
<td>4</td>
<td>7</td>
<td>13</td>
<td>10</td>
<td>2</td>
<td>41</td>
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Site likelihood:

<table>
<thead>
<tr>
<th>LIA</th>
<th>ERPA</th>
<th>ERPB</th>
<th>MRPA</th>
<th>MRPB</th>
<th>LRPA</th>
<th>LRPB</th>
<th>Total</th>
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<tr>
<td>0.07</td>
<td>0.10</td>
<td>0.17</td>
<td>0.32</td>
<td>0.24</td>
<td>0.05</td>
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INTRODUCING CHRONOLOGICAL DYNAMICS: TESTING GLOBAL NETWORK MEASUREMENTS
INTRODUCING CHRONOLOGICAL DYNAMICS: RESULTS

Number of nodes

W0_B, LIA
W0_B, ERPA
W0_B, ERPB
W0_B, MRPA
W0_B, MRPB
W0_B, LRPA
W0_B, LRPB
INTRODUCING CHRONOLOGICAL DYNAMICS: RESULTS

Average clustering coefficient

Graph showing the average clustering coefficient over time for various categories.
INTRODUCING CHRONOLOGICAL DYNAMICS: RESULTS

Characteristic path length

- W0_B, LIA
- W0_B, ERPA
- W0_B, ERPB
- W0_B, MRPA
- W0_B, MRPB
- W0_B, LRPA
- W0_B, LRPB
Reinterpreted dataset matches archaeological expectations.

Change in global network measurements often related to change in number of nodes.

For all Roman periods, most global network measurements remain stable until site likelihood values of 0.14-0.16, even though number of nodes decreases.
INTRODUCING CHRONOLOGICAL DYNAMICS: IDEAL SITE LIKELIHOOD THRESHOLD?

> Network is robust despite declining number of nodes

> First break in number of nodes at site likelihood value of 0.09

> Last point at which most global network measurements are stable at 0.14

> Ideal site likelihood value for network modelling between 0.09 and 0.14
Combining least-cost path approaches and network analysis is a useful exercise to archaeologically study (models of) local transport networks, also considering the increasing amount of data available.

We should validate the results to make a stronger archaeological case; one such way is to apply random network emergence to test the robustness of measured values and thus their archaeological interpretation.

Issues like chronological uncertainty in your dataset should be taken into account when modelling in general and analysing transport networks in particular.