Using graphical models to explore relationships between variables underlying community energy initiatives

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Exploratory Analysis

Special characteristics of exploratory analysis

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- multiple research questions and multiple theories = large data sets.
- in such cases, traditional methods such as correlation tables can become overwhelming.

Solution: use graphical models.

Illustration: Community Energy Initiatives

Buurkracht

- Community energy initiatives aim to enhance sustainable energy behaviours together with people in the neighbourhood.
- A sole focus in individual level factors would not do justice to its collective nature.
- Energy behaviours may not merely depend on the personal factors, but also on factors related to a wider social context.
- Understanding relationships between personal factors and factors related to the social context is of key interest.

Buurkracht: Variables in the study

Personal factors Values, Environmental self-identity, Need to be unique, Need to belong, Personal importance of sustainable energy behaviour.

Factors related to the social context Neighbourhood identification, Neighbourhood homogeneity, Neighbourhood interaction, Neighbourhood environmental identity, Neighbourhood importance of sustainable energy behaviour.

Opinions on energy companies and the government

Sustainable energy intentions and behaviour Household sustainable energy intentions, Communal sustainable energy intentions, Self-reported sustainable energy behaviour.

Initiative membership

Buurkracht: Complex data set

- $N_1 = 303$ initiative participants, $N_2 = 265$ right-door-neighbours.
- Data on 23 variables (69 items).

Table 1: Correlation Table

Variable	Collective energy intentions	Collective social intentions	Individual energy intentions	Past energy behavior	Neighbourhood environmental Identity	Neighbourhood identification	Interaction with neighbourhood	Neighbourhood energy norms
Collective energy intentions	1.00000000	0.6390336	0.56026244	0.24256324	0.26128522	0.26406099	0.32140762	0.21066918
Collective social intentions	0.63903364	1.0000000	0.36729872	0.10425862	0.31630553	0.40339008	0.49867650	0.23367956
Individual energy intentions	0.56026244	0.3672987	1.00000000	0.23314600	0.24894755	0.17690290	0.16196666	0.24896600
Past energy behavior	0.24256324	0.1042586	0.23314600	1.00000000	0.09197581	0.03708332	0.12008185	0.05020820
Neighbourhood environmental Identity	0.26128522	0.3163055	0.24894755	0.09197581	1.00000000	0.55058979	0.43753365	0.72491279
Neighbourhood identification	0.26406099	0.4033901	0.17690290	0.03708332	0.55058979	1.00000000	0.63985185	0.44801862
Interaction with neighbourhood	0.32140762	0.4986765	0.16196666	0.12008185	0.43753365	0.63985185	1.00000000	0.34279254
Neighbourhood energy norms	0.21066918	0.2336796	0.24896600	0.05020820	0.72491279	0.44801862	0.34279254	1.00000000
Homogeneity in neighbourhood	0.19467858	0.2600740	0.10921831	0.03583985	0.54429975	0.53305900	0.47070184	0.34363351
Interaction in neighbourhood	0.22130219	0.4009412	0.12549407	0.10834558	0.46691304	0.58005561	0.74029528	0.37281798
Personal outcome efficacy	0.32100115	0.1945755	0.44567571	0.10663851	0.24123467	0.23442091	0.10382692	0.25771833
Environmental self-identity	0.31943122	0.1874234	0.44027773	0.21426490	0.30911594	0.21364688	0.13202947	0.25414659
Need to belong	0.21962533	0.1925099	0.15727089	0.02442656	0.12447547	0.19690322	0.14237600	0.10098592
Personal energy norms	0.34212444	0.2006219	0.49022096	0.23317881	0.22206718	0.17901679	0.10983320	0.25581094
Need to be unique	0.15267051	0.1604475	0.14744928	0.02753044	0.12256944	0.17052380	0.12356217	0.12956822
Altruistic values	0.12961027	0.1612056	0.20266378	0.02049821	0.15458137	0.20002051	0.15525014	0.23955023
Biospheric values	0.24041313	0.1707479	0.34692902	0.10736618	0.22036405	0.19765067	0.12072176	0.24860420
Egoistic values	0.10770679	0.1404754	0.04411716	0.02247897	0.18083903	0.12393510	0.09799483	0.10564643
Hedonic values	0.03940645	0.1303561	0.16683208	-0.03421703	0.18464782	0.16325892	0.13251616	0.18070173
Initiative outcome efficacy	0.36156690	0.2737526	0.33329037	0.12128486	0.18820580	0.20210600	0.12236583	0.20602148
Group based anger	0.19406773	0.1726725	0.25503296	0.08285380	0.10256582	0.09169922	0.12841881	0.11315825
Membership	0.46843376	0.1727777	0.21963212	0.18239490	0.05613682	0.05099886	0.10980202	-0.03169963

Variable	Homogeneity in neighbourhood	Interaction in neighbourhood	Personal outcome efficacy	Environmental self-identity	Need to belong	Personal energy norms	Need to be Unique
Collective energy intentions	0.19467858	0.22130219	0.32100115	0.31943122	0.21962533	0.3421244399	0.15267051
Collective social intentions	0.26007402	0.40094118	0.19457546	0.18742340	0.19250994	0.2006219418	0.16044750
Individual energy intentions	0.10921831	0.12549407	0.44567571	0.44027773	0.15727089	0.4902209610	0.14744928
Past energy behavior	0.03583985	0.10834558	0.10663851	0.21426490	0.02442656	0.2331788077	0.02753044
Neighbourhood environmental Identity	0.54429975	0.46691304	0.24123467	0.30911594	0.12447547	0.2220671824	0.12256944
Neighbourhood identification	0.53305900	0.58005561	0.23442091	0.21364688	0.19690322	0.1790167945	0.17052380
Interaction with neighbourhood	0.47070184	0.74029528	0.10382692	0.13202947	0.14237600	0.1098331967	0.12356217
Neighbourhood energy norms	0.34363351	0.37281798	0.25771833	0.25414659	0.10098592	0.2558109448	0.12956822
Homogeneity in neighbourhood	1.00000000	0.49161655	0.12979653	0.10653511	0.14136437	0.1176761764	0.10328674
Interaction in neighbourhood	0.49161655	1.00000000	0.09195050	0.06097901	0.08992959	0.0975888640	0.13570542
Personal outcome efficacy	0.12979653	0.09195050	1.00000000	0.45131906	0.27035087	0.4786019558	0.30660001
Environmental self-identity	0.10653511	0.06097901	0.45131906	1.00000000	0.28202024	0.6477628635	0.22147656
Need to belong	0.14136437	0.08992959	0.27035087	0.28202024	1.00000000	0.1689773819	0.21027384
Personal energy norms	0.11767618	0.09758886	0.47860196	0.64776286	0.16897738	1.0000000000	0.15420764
Need to be unique	0.10328674	0.13570542	0.30660001	0.22147656	0.21027384	0.1542076400	1.00000000
Altruistic values	0.06580532	0.06555907	0.32010121	0.34239841	0.17022704	0.3367708582	0.14870098
Biospheric values	0.07010359	0.03170766	0.43515463	0.59633459	0.15800904	0.5335121674	0.17897009
Egoistic values	0.13670806	0.06090379	0.12108427	0.07024787	0.21419307	0.0009960042	0.29019426
Hedonic values	0.11835347	0.12888791	0.18471539	0.07484992	0.02885437	0.1261308561	0.21571150
Initiative outcome efficacy	0.08496818	0.08156286	0.43309802	0.37438405	0.24419689	0.3783477161	0.19822020
Group based anger	0.04901652	0.06838383	0.22230287	0.28576971	0.05551032	0.3026101380	0.06844315
Membership	0.05331512	0.02340664	0.08744412	0.17042929	0.11485875	0.1430674074	-0.10058317

Variable	Altruistic values	Biospheric Values	Egoistic Values	Hedonic Values	Initiative outcome efficacy	Group based anger	Membership
Collective energy intentions	0.12961027	0.24041313	0.1077067899	0.03940645	0.36156690	0.19406773	0.46843376
Collective social intentions	0.16120564	0.17074786	0.1404753860	0.13035605	0.27375256	0.17267252	0.17277768
Individual energy intentions	0.20266378	0.34692902	0.0441171566	0.16683208	0.33329037	0.25503296	0.21963212
Past energy behavior	0.02049821	0.10736618	0.0224789667	-0.03421703	0.12128486	0.08285380	0.18239490
Neighbourhood environmental Identity	0.15458137	0.22036405	0.1808390324	0.18464782	0.18820580	0.10256582	0.05613682
Neighbourhood identification	0.20002051	0.19765067	0.1239351000	0.16325892	0.20210600	0.09169922	0.05099886
Interaction with neighbourhood	0.15525014	0.12072176	0.0979948290	0.13251616	0.12236583	0.12841881	0.10980202
Neighbourhood energy norms	0.23955023	0.24860420	0.1056464312	0.18070173	0.20602148	0.11315825	-0.03169963
Homogeneity in neighbourhood	0.06580532	0.07010359	0.1367080649	0.11835347	0.08496818	0.04901652	0.05331512
Interaction in neighbourhood	0.06555907	0.03170766	0.0609037910	0.12888791	0.08156286	0.06838383	0.02340664
Personal outcome efficacy	0.32010121	0.43515463	0.1210842686	0.18471539	0.43309802	0.22230287	0.08744412
Environmental self-identity	0.34239841	0.59633459	0.0702478723	0.07484992	0.37438405	0.28576971	0.17042929
Need to belong	0.17022704	0.15800904	0.2141930661	0.02885437	0.24419689	0.05551032	0.11485875
Personal energy norms	0.33677086	0.53351217	0.0009960042	0.12613086	0.37834772	0.30261014	0.14306741
Need to be unique	0.14870098	0.17897009	0.2901942550	0.21571150	0.19822020	0.06844315	-0.10058317
Altruistic values	1.00000000	0.58455020	0.0721484855	0.27335131	0.21723805	0.24125127	0.01566498
Biospheric values	0.58455020	1.00000000	0.1091704887	0.25833228	0.30708446	0.33870125	0.02527026
Egoistic values	0.07214849	0.10917049	1.0000000000	0.33392851	0.04752937	-0.05578699	0.01933417
Hedonic values	0.27335131	0.25833228	0.3339285149	1.00000000	0.07447555	0.04394986	-0.03085452
Initiative outcome efficacy	0.21723805	0.30708446	0.0475293678	0.07447555	1.00000000	0.17292748	0.16252979
Group based anger	0.24125127	0.33870125	-0.0557869904	0.04394986	0.17292748	1.00000000	0.03684433
Membership	0.01566498	0.02527026	0.0193341714	-0.03085452	0.16252979	0.03684433	1.00000000

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Collective social intentions	0.63903364	1.0000000	0.36729872	0.10425862	0.31630553	0.40339008
Individual energy intentions	0.56026244	0.3672987	1.00000000	0.23314600	0.24894755	0.17690290
Past energy behavior	0.24256324	0.1042586	0.23314600	1.00000000	0.09197581	0.03708332
Neighbourhood environmental Identity	0.26128522	0.3163055	0.24894755	0.09197581	1.00000000	0.55058979
Neighbourhood identification	0.26406099	0.4033901	0.17690290	0.03708332	0.55058979	1.00000000
Interaction with neighbourhood	0.32140762	0.4986765	0.16196666	0.12008185	0.43753365	0.63985185
Neighbourhood energy norms	0.21066918	0.2336796	0.24896600	0.05020820	0.72491279	0.44801862
Homogeneity in neighbourhood	0.19467858	0.2600740	0.10921831	0.03583985	0.54429975	0.53305900
Interaction in neighbourhood	0.22130219	0.4009412	0.12549407	0.10834558	0.46691304	0.58005561
Personal outcome efficacy	0.32100115	0.1945755	0.44567571	0.10663851	0.24123467	0.23442091
Environmental self-identity	0.31943122	0.1874234	0.44027773	0.21426490	0.30911594	0.21364688
Need to belong	0.21962533	0.1925099	0.15727089	0.02442656	0.12447547	0.19690322
Personal energy norms	0.34212444	0.2006219	0.49022096	0.23317881	0.22206718	0.17901679
Need to be unique	0.15267051	0.1604475	0.14744928	0.02753044	0.12256944	0.17052380
Altruistic values	0.12961027	0.1612056	0.20266378	0.02049821	0.15458137	0.20002051
Biospheric values	0.24041313	0.1707479	0.34692902	0.10736618	0.22036405	0.19765067
Egoistic values	0.10770679	0.1404754	0.04411716	0.02247897	0.18083903	0.12393510
Hedonic values	0.03940645	0.1303561	0.16683208	-0.03421703	0.18464782	0.16325892
Initiative outcome efficacy	0.36156690	0.2737526	0.33329037	0.12128486	0.18820580	0.20210600
Group based anger	0.19406773	0.1726725	0.25503296	0.08285380	0.10256582	0.09169922
Membership	0.46843376	0.1727777	0.21963212	0.18239490	0.05613682	0.05099886

Variable	Interaction with neighbourhood	Neighbourhood energy norms	Homogeneity in neighbourhood	Interaction in neighbourhood	Personal outcome efficacy	Environmental self-identity
Collective energy intentions	0.32140762	0.21066918	0.19467858	0.22130219	0.32100115	0.31943122
Collective social intentions	0.49867650	0.23367956	0.26007402	0.40094118	0.19457546	0.18742340
Individual energy intentions	0.16196666	0.24896600	0.10921831	0.12549407	0.44567571	0.44027773
Past energy behavior	0.12008185	0.05020820	0.03583985	0.10834558	0.10663851	0.21426490
Neighbourhood environmental Identity	0.43753365	0.72491279	0.54429975	0.46691304	0.24123467	0.30911594
Neighbourhood identification	0.63985185	0.44801862	0.53305900	0.58005561	0.23442091	0.21364688
Interaction with neighbourhood	1.00000000	0.34279254	0.47070184	0.74029528	0.10382692	0.13202947
Neighbourhood energy norms	0.34279254	1.00000000	0.34363351	0.37281798	0.25771833	0.25414659
Homogeneity in neighbourhood	0.47070184	0.34363351	1.00000000	0.49161655	0.12979653	0.10653511
Interaction in neighbourhood	0.74029528	0.37281798	0.49161655	1.00000000	0.09195050	0.06097901
Personal outcome efficacy	0.10382692	0.25771833	0.12979653	0.09195050	1.00000000	0.45131906
Environmental self-identity	0.13202947	0.25414659	0.10653511	0.06097901	0.45131906	1.00000000
Need to belong	0.14237600	0.10098592	0.14136437	0.08992959	0.27035087	0.28202024
Personal energy norms	0.10983320	0.25581094	0.11767618	0.09758886	0.47860196	0.64776286
Need to be unique	0.12356217	0.12956822	0.10328674	0.13570542	0.30660001	0.22147656
Altruistic values	0.15525014	0.23955023	0.06580532	0.06555907	0.32010121	0.34239841
Biospheric values	0.12072176	0.24860420	0.07010359	0.03170766	0.43515463	0.59633459
Egoistic values	0.09799483	0.10564643	0.13670806	0.06090379	0.12108427	0.07024787
Hedonic values	0.13251616	0.18070173	0.11835347	0.12888791	0.18471539	0.07484992
Initiative outcome efficacy	0.12236583	0.20602148	0.08496818	0.08156286	0.43309802	0.37438405
Group based anger	0.12841881	0.11315825	0.04901652	0.06838383	0.22230287	0.28576971
Membership	0.10980202	-0.03169963	0.05331512	0.02340664	0.08744412	0.17042929

Variable	Need to belong	Personal energy norms	Need to be Unique	Altruistic values	Biospheric Values	Egoistic Values
Collective energy intentions	0.21962533	0.3421244399	0.15267051	0.12961027	0.24041313	0.1077067899
Collective social intentions	0.19250994	0.2006219418	0.16044750	0.16120564	0.17074786	0.1404753860
Individual energy intentions	0.15727089	0.4902209610	0.14744928	0.20266378	0.34692902	0.0441171566
Past energy behavior	0.02442656	0.2331788077	0.02753044	0.02049821	0.10736618	0.0224789667
Neighbourhood environmental Identity	0.12447547	0.2220671824	0.12256944	0.15458137	0.22036405	0.1808390324
Neighbourhood identification	0.19690322	0.1790167945	0.17052380	0.20002051	0.19765067	0.1239351000
Interaction with neighbourhood	0.14237600	0.1098331967	0.12356217	0.15525014	0.12072176	0.0979948290
Neighbourhood energy norms	0.10098592	0.2558109448	0.12956822	0.23955023	0.24860420	0.1056464312
Homogeneity in neighbourhood	0.14136437	0.1176761764	0.10328674	0.06580532	0.07010359	0.1367080649
Interaction in neighbourhood	0.08992959	0.0975888640	0.13570542	0.06555907	0.03170766	0.0609037910
Personal outcome efficacy	0.27035087	0.4786019558	0.30660001	0.32010121	0.43515463	0.1210842686
Environmental self-identity	0.28202024	0.6477628635	0.22147656	0.34239841	0.59633459	0.0702478723
Need to belong	1.00000000	0.1689773819	0.21027384	0.17022704	0.15800904	0.2141930661
Personal energy norms	0.16897738	1.0000000000	0.15420764	0.33677086	0.53351217	0.0009960042
Need to be unique	0.21027384	0.1542076400	1.00000000	0.14870098	0.17897009	0.2901942550
Altruistic values	0.17022704	0.3367708582	0.14870098	1.00000000	0.58455020	0.0721484855
Biospheric values	0.15800904	0.5335121674	0.17897009	0.58455020	1.00000000	0.1091704887
Egoistic values	0.21419307	0.0009960042	0.29019426	0.07214849	0.10917049	1.0000000000
Hedonic values	0.02885437	0.1261308561	0.21571150	0.27335131	0.25833228	0.3339285149
Initiative outcome efficacy	0.24419689	0.3783477161	0.19822020	0.21723805	0.30708446	0.0475293678
Group based anger	0.05551032	0.3026101380	0.06844315	0.24125127	0.33870125	-0.0557869904
Membership	0.11485875	0.1430674074	-0.10058317	0.01566498	0.02527026	0.0193341714

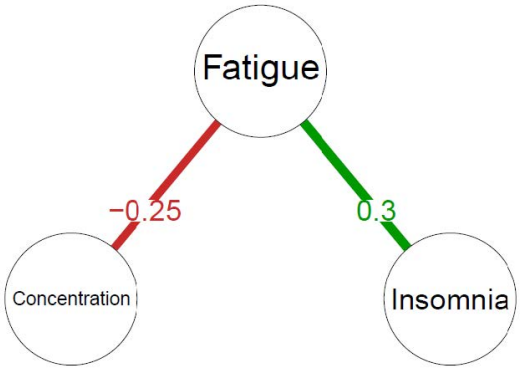
Variable	Hedonic Values	Initiative outcome efficacy	Group based anger	Membership
Collective energy intentions	0.03940645	0.36156690	0.19406773	0.46843376
Collective social intentions	0.13035605	0.27375256	0.17267252	0.17277768
Individual energy intentions	0.16683208	0.33329037	0.25503296	0.21963212
Past energy behavior	-0.03421703	0.12128486	0.08285380	0.18239490
Neighbourhood environmental Identity	0.18464782	0.18820580	0.10256582	0.05613682
Neighbourhood identification	0.16325892	0.20210600	0.09169922	0.05099886
Interaction with neighbourhood	0.13251616	0.12236583	0.12841881	0.10980202
Neighbourhood energy norms	0.18070173	0.20602148	0.11315825	-0.03169963
Homogeneity in neighbourhood	0.11835347	0.08496818	0.04901652	0.05331512
Interaction in neighbourhood	0.12888791	0.08156286	0.06838383	0.02340664
Personal outcome efficacy	0.18471539	0.43309802	0.22230287	0.08744412
Environmental self-identity	0.07484992	0.37438405	0.28576971	0.17042929
Need to belong	0.02885437	0.24419689	0.05551032	0.11485875
Personal energy norms	0.12613086	0.37834772	0.30261014	0.14306741
Need to be unique	0.21571150	0.19822020	0.06844315	-0.10058317
Altruistic values	0.27335131	0.21723805	0.24125127	0.01566498
Biospheric values	0.25833228	0.30708446	0.33870125	0.02527026
Egoistic values	0.33392851	0.04752937	-0.05578699	0.01933417
Hedonic values	1.00000000	0.07447555	0.04394986	-0.03085452
Initiative outcome efficacy	0.07447555	1.00000000	0.17292748	0.16252979
Group based anger	0.04394986	0.17292748	1.00000000	0.03684433
Membership	-0.03085452	0.16252979	0.03684433	1.00000000

Solution: use graphical models.

Methods : The Gaussian graphical model

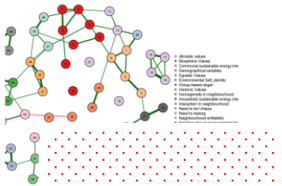
The Gaussian graphical model: Just the basics

- Nodes represent items or variables.
- Lines represent partial correlation coefficients

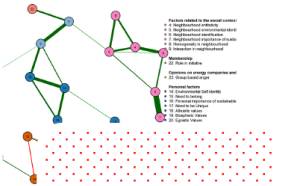


The Gaussian graphical model: An Exploratory analysis tool

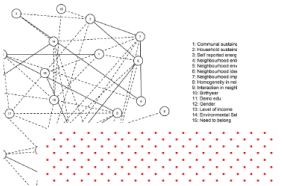
A systematic approach to initial data analysis.



item level analysis



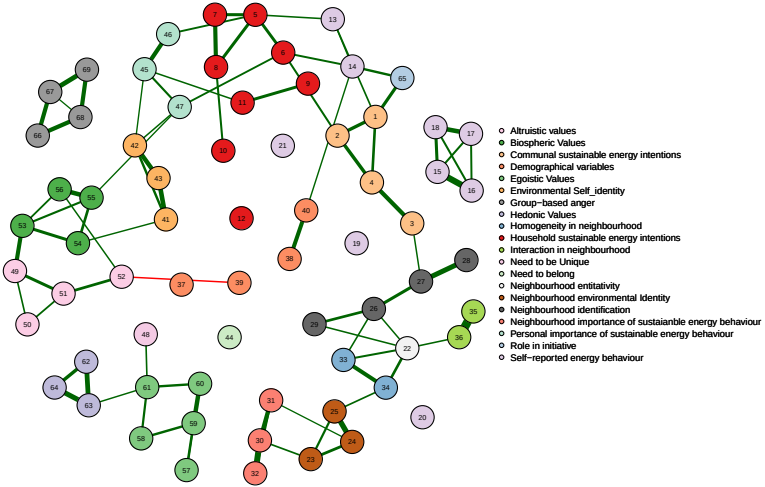
scale level analysis



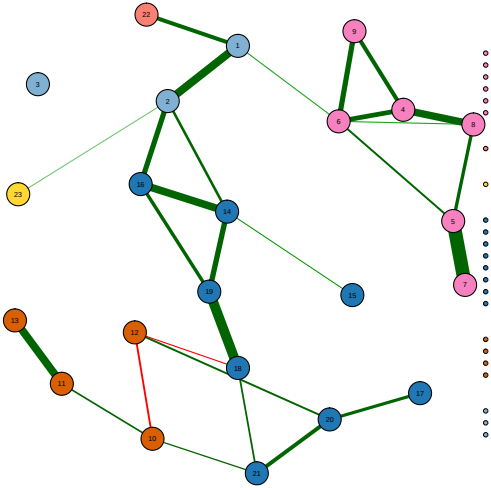
compare subgroups

Results

Buurkracht: Item level analysis



Buurkracht: Scale level analysis



Factors related to the social context
- 4: Neighbourhood entitativity
- 5: Neighbourhood environmental identity
- 6: Neighbourhood identification
- 7: Neighbourhood importance of sustainable energy behaviour
- 8: Homogeneity in neighbourhood
- 9: Interaction in neighbourhood

Membership
- 22: Role in initiative

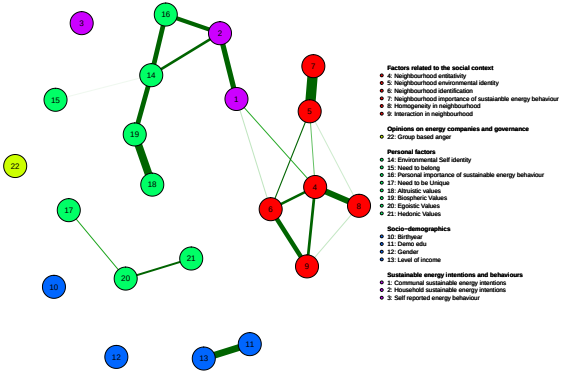
Opinions on energy companies and governance
- 23: Group based anger

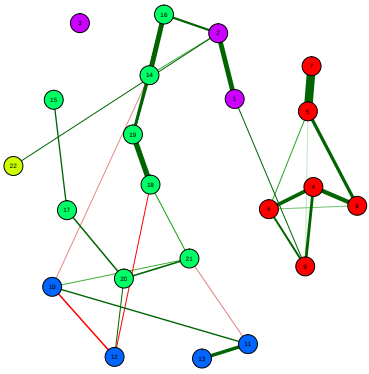
Personal factors
- 14: Environmental Self identity
- 15: Need to belong
- 16: Personal importance of sustainable energy behaviour
- 17: Need to be Unique
- 18: Altruistic values
- 19: Biospheric Values
- 20: Egoistic Values
- 21: Hedonic Values

Socio-demographics
- 10: Birthyear
- 11: Education level
- 12: Gender
- 13: Level of income

Sustainable energy intentions and behaviours
- 1: Communal sustainable energy intentions
- 2: Household sustainable energy intentions
- 3: Self reported energy behaviour

Buurkracht: Comparing members and non-members





Conclusions

Buurkracht: Summary

When incorporating variables from multiple theories not studied together before, a systematic hypothesis-free search is useful.

Exploratory analyses through GGM reveal:

- All used scales seem to be reliable.
- Small differences in graphs of members and non-members.
- Several relationships are in line with theory.

(in prep.) N. Bhushan, F. Mohnert, D. Sloot, L. Jans, C. J. Albers, L. Steg. *The value of Gaussian graphical models to explore relationships between environmental psychological constructs.*

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Thank you!

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Thank you!

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(please contact me for technical details underlying these models)

Graphical Model: Just the basics

- A marriage of graph theory & probability theory.
- Insight into properties of the model, e.g. Conditional Independence can be obtained by inspection of the graph.

$$X \sim N(\mu, \Sigma)$$

- Σ, the variance-covariance matrix encodes *all* information about how variables relate to each other.
- It also encodes *all* conditional relationships .
- This is captured in the precision matrix $K = \Sigma^{-1}$.
- The standardised precision matrix is known as the Gaussian graphical model[1].

[1] Also termed “network“ models

In addition..

Graphical models are also useful for:

- Confirmatory analysis using the GGM.
- Identifying causal effects when experiments are not feasible.
- Estimating bounds on causal effects.
- Exploratory search for causal relations.
- Easy to use R packages (GGM is also in JASP).

With these models, we improve our understanding of factors influencing energy use behaviour and effects of community energy initiatives to promote energy savings.

Further reading – Graphical Models

- Lauritzen, S.L. (1996). *Graphical Models*. Oxford University Press.
- Spirtes, P., Glymour, C., Scheines, R. (2000). *Causation, prediction, and search* (2nd ed.). Cambridge, MA: MIT Press.
- Pearl, J. (2009). *Causality: Models, reasoning, and inference* (2nd ed.). Cambridge: Cambridge University Press.