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INSMART

Integrative Smart City Planning

Report on the Multi-criteria methodology, the process and the results of the decision making – Nottingham

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Executive summary	
This report presents the optimal ranking of future energy scenario alternatives considered for the City of Nottingham in the framework of task 5.3. The various impacts (criteria values) of different energy scenarios (results generated by TIMES models) are assessed using the MultiCriteria Decision Aid (MCDA) software Visual PROMETHEE v.1.4.0.0 combined with a systematic methodology (Hinkle's method) to determine the weights of the objective function. The MCDA problem is solved using the PROMETHEE software by means of a hierarchical optimization set-up for processing the databases of available pairs of actions and criteria towards the ranking of actions which satisfy and/or compromise preferences and constraints extracted by multiple stakeholders.	
Keywords	MultiCriteria Decision Aid (MCDA); PROMETHEE; Ranking of urban energy upgrading actions; Stakeholders' preferences; Decision-making; Hinkle's method; Deliberative MultiCriteria Evaluation (DMCE) methodology

Table of Contents

Acronyms and Definitions

CHP – Combined Heat and Power

CUK – Climate UK

ESM – Energy City Model

MCDA – Multi Criteria Decision Analysis

NCC – Nottingham City Council

PROMETHEE – Preference Ranking Organization METHod for Enrichment of Evaluations

PV – Photovoltaic

RES – Renewable energy sources

SG – Stakeholder Group

TIMES – The Integrated MARKAL-EFOM System

1. Introduction

An application of the innovative city planning method, developed within the EU FP7 project InSMART, was applied to the municipality of Nottingham in the UK. A multi-model approach was used to explore and rank alternative scenarios (combinations of actions and measures) for the sustainable development of the municipality, with a particular focus on the residential and transport sectors.

A technology-explicit model of the city referred to as the Nottingham ESM was designed to be used as a test bed for exploring the evolution of energy-environmental variables in the urban area. A mid-term projection, to 2030, of the reference scenario for the city was calculated and then compared against seven future energy scenarios representing alternative sustainable-oriented planning hypotheses. Using the dynamic responses of the urban system model results for each scenario, a multi-criteria method was used to determine the ranking of the alternative scenarios, evaluated against a set of elements (technological, social, environmental, economic), and on the basis of local stakeholders' preferences.

Key city stakeholders participated in the design of the city's future energy scenarios, in the definition and evaluation of the criteria, and of the responses of the tool (results of multi-criteria analysis). Two formal workshops were held during the process described in this report. An initial scenario design workshop was held in March 2016 and a MCDA workshop was held in September 2016. Appendix I provides details of the MCDA workshop agenda and list of delegates who attended. This report describes the main components of the multi criteria decision analysis – MCDA - (alternatives, criteria, weights) and the results of the process.

The goal of this activity is to evaluate the potential future energy scenarios against key criteria in conjunction with local stakeholders. The primary aim is to shortlist one (or few) options which can be deeper explored and analysed in the framework of the preparation of the sustainable energy action plan for the city in work package 6.

2. Problem structuring – Future energy scenarios

2.1. Problem structuring

Due to the complexities of urban decision making processes, the diversity of impact of the large scale energy projects, and the multiple stakeholders involved, a participatory multi-criteria approach was required. Local stakeholders have been engaged and involved in the key stages of the MCDA process; from the design of the future energy scenarios, the definition of the criteria against which those scenarios are evaluated, and in the selection of the preferences (weights) on those criteria.

The first step to involve stakeholders in the scenario definitions was undertaken through two workshops. An initial brainstorming session was held in December 2015 with representatives of the relevant municipal directorates (e.g. energy services, transport, housing, capital projects, etc.). The results of this session were used to develop an initial draft set of scenarios which were then reviewed and updated by the stakeholder group. A formal workshop to review and finalise the scenario design was held in March 2016 with an extended group including representatives from other key city stakeholders including community groups, large employers and service providers. The outcome of this workshop was the identification of five future energy scenarios to 2030 for Nottingham. These were:

- **Reference** – Projection to 2030 of the original 2014 energy model. Acts as the baseline against which to compare the other scenarios
- **No investment** – Assumes lower than expected income and spending on energy improvements compared to the reference scenario
- **Local leadership (LL)** – Local authority and city stakeholders are engaged with the need to reduce energy consumption and carbon emissions.

- **Green Governance (GG)** – National focus on the green agenda with the introduction of a carbon tax and increased subsidies for energy efficiency schemes and low carbon energy generation options.
- **Green Growth** – Ultra high investment scenario that goes beyond the GG scenario and includes higher subsidies for low carbon energy project and energy efficiency schemes. Also includes more ambitious targets for energy and CO2 emissions reductions.

Subsequent discussions with E4SMA, the project partner developing the TIMES-based Nottingham ESM, excluded the two extreme scenarios (No investment and Green Growth) and led to the development of a number of sub-scenarios based on the LL and GG scenarios.

2.2. Presentation of the alternatives

The final set of seven scenarios, in addition to the reference scenario, were:

- **LL-Low cost** – Low municipal engagement. No subsidies for energy retrofits. Limited expansion of transport infrastructure (cycle network).
- **LL-Engaged** – Public sector focused with district heating expansion and public transport upgrades. Subsidies for residential retrofits.
- **LL-Full** – Includes all planned transport and energy projects (e.g. Go Ultra Low, District heating expansion, Community scale biomass CHP, etc.).
- **LL-Growth** – Highest level of local engagement with 'forced' inclusion of biomass fuelled CHP generation, plant scale PV and low carbon housing.

All GG scenarios were based on the LL-Full scenario with the addition of a national Carbon Tax and increased subsidies for low carbon energy generation systems. Different routes for an expanded tram network (NET phase 3) are the main difference between the GG scenarios.

- **GG-West** – Includes proposed extension of NET line 1 to Kimberley.
- **GG-East** – Includes proposed addition of NET Line 4 to Gedling.

- **GG-All** – Includes all proposed NET extensions (Kimberley, Gedling and link to HS2 at Long Eaton) and the inclusion of an Anaerobic Digestion plant to increase low carbon energy generation potential.

Table 1 provides details of the energy measures associate with each scenario.

Table 1: Energy measures associated with each future energy scenario for Nottingham

Scenario	Work from home & cycling infrastructure	Domestic PV and Solar thermal	Residential retrofits incl. rebound effect (R2-R5)	Electric buses and southern corridor	Solid wall insulation (R1)	District heating expansion	Go Ultra Low (electric vehicles, low carbon zone) & parking charge increase (LL2)	Community scale Biomass CHP schemes	NET Phase 3 - Kimberley	Carbon Tax	NET Phase 3 – Gedling	NET Phase 3 – All routes	Anaerobic Digester Plant	Plant scale PV at park and ride site	New Low carbon housing developments	Increased diffusion of electric vehicles [1]	Subsidies for Low carbon heating systems
LL – Low cost	X	X	X														
LL - Engaged	X	X	X	X	X	X											
LL2	X	X	X	X	X	X	X	X									
LL - Growth	X	X	X	X	X	X	X	X[2]						X[3]	X	X	
GG - West	X	X	X	X	X	X	X	X	X	X							X
GG - East	X	X	X	X	X	X	X	X		X	X						X
GG	X	X	X	X	X	X	X	X		X		X	X				X

[1] Agreed in discussions with E4SMA to use an additional 10% penetration of electric vehicles for this measure
[2] In this scenario the penetration of Community biomass CHP is to be 'forced' rather than left to the system
[3] In this scenario the plant scale PV sites at the two park and ride sites are to be included in the model irrespective of the economic case for their implementation

A more detailed description of the scenarios and the corresponding results from the Nottingham ESM are reported in the InSMART Report on optimum sustainability pathways for Nottingham [2].

3. Criteria Identification and Evaluation

3.1. Criteria

The expectation of any decision-maker is to identify a strategy that is optimal across all criteria at the same time. This is usually impossible as many criteria, are in conflict each with other. For example, low cost energy measures may not typically be able to produce as a large an energy reduction as a higher cost option. Options that maximise overall energy reduction or reduce carbon emissions may not be socially acceptable or may be technically or legally difficult to achieve. The objective of MCDA is thus to identify the best "compromise" decisions for the integrated urban-energy planning of Nottingham.

In order to explore sustainable energy planning for the city, ten criteria have been selected which aim to fully evaluate the pros and cons of each alternative configuration of the future urban-energy system. Half of the criteria are "quantitative" and can be directly derived by the outputs of the ESM model (and from the transport analysis), whilst the remaining five are "qualitative" (measured with a 5 point Likert scale). The inclusion of qualitative criteria gives additional space for a more holistic evaluation of the alternatives including both *hard* and *soft* measures.

Table 2 summarizes the criteria, the unit of measure chosen and the desirable and non-desirable states for each criteria. These states are integral to the Hinkle method of weighting the criteria described in section 3.2. C1-C5 are the quantitative criteria, C6-C10 are the qualitative criteria.

The criteria are formulated as to follow some basic characteristics:

- Understandability - decision makers well-know the actual meaning of the indicators
- Measurability - both quantitative and qualitative criteria are determined making use of analytic approach
- Non-redundancy - criteria should not be virtually over-weighted by presenting the same issue with more than one item
- Independence - there must be at least one variable of the alternative for which two criteria compete
- Completeness - number and types of criteria should be evaluated and selected in order to cover all the key aspects and complexities of the specific decision problem). If (or when) the above mentioned set of criteria is modified (by adding or removing criteria of the problem), the final ranking of alternatives may differ.

Table 2: List of criteria used in the MCDA process

Criteria	Code	Brief Description of the Criteria	Desirable state	Non-desirable state
Energy reduction potential (%)	C1	Energy reduction potential relating to the scenario.	Very high energy savings	Very low energy savings
Overall cost (£)	C2	Total cost associated with a scenario over the projected time horizon	Very low cost	Very high cost
Low carbon energy generation (TJ)	C3	Represents low carbon energy generated by the scenario	Very high energy generation	Very low energy generation
Cost efficiency (£/tonnes CO2)	C4	The cost efficiency of a scenario in terms of its decarbonisation potential.	Very cost effective decarbonisation	Very high cost decarbonisation
Reduction in CO2 emissions (tonnes CO2)	C5	Reduction in carbon (CO2) emissions associated with the scenario.	Very high CO2 reduction	Very low CO2 reduction
Technical constraints	C6	Scale of the technical issues associated with the scenario.	No technical difficulties	Major technical obstacles
Social acceptability	C7	Social acceptability of a scenario to local citizens	Very high societal acceptance	Very low societal acceptance
Legal issues	C8	Legal and regulatory concerns relating to the implementation of a scenario.	No legal issues	Major legal concerns
Economic impact	C9	Overall effect of the scenario on local economy including employment activity, business development and inward investment	Major improvement to economic development	Reduced economic development

Quality of Life Issues	C10	Represents the effect on the scenario on citizen's quality of life. For example, reduced traffic congestion, increased indoor thermal comfort, improved local environment	Major quality of life improvements	Decreased quality of life

3.2. Weights

The Hinkle method [1] using a "resistance to change grid" was employed for estimating criterion importance ranking or weighting. The rationale of the method is in the definition of two terms per each criterion, one expressing its most desirable outcome and the other expressing the least desirable outcome ("bipolar form"). The bipolar form for the criteria used for Nottingham were provided in Table 2. Figure 1 shows an example grid for evaluating the choice of buying a car based on five criteria; Price, Power, Fuel consumption, Space and comfort. The first three criteria are quantitative and the latter two are qualitative (rated on a 5 point Likert scale from Very Low – Very High)

	Price	Power	Consumption	Space	Comfort
Price		-	X	X	-
Power			X	X	-
Consumption				X	-
Space					-
Comfort					

Figure 1: Resistance to change grid example

The decision makers are then asked to explore the "bipolar" expression in a pairwise manner by filling a resistance to change grid like the one shown in Figure 1. Stakeholders compare each pair of criteria and identify which one is they are most reluctant to change from their desirable to the undesirable state. Using the example, a comparison price between and fuel consumption. Which of the pair would you rather change from their desirable to undesirable state? Would you trade a very high price for very high fuel consumption?

The resistance to change grid is completed by comparing each pair of criteria in this way:

- In the grid, an 'X' indicates that the criteria in the column resists change.
- A blank indicates that the criteria in the row resists change.
- In order to derive the scores of each criterion, all the blanks along the rows above the diagonal are added to all the corresponding 'X's in the columns to give the final score.

For the price vs consumption example an 'X' is shown in Figure 1 indicating that low fuel consumption was preferred over low price. Where the comparison between two criteria cannot be resolved using the approach described:

- If stakeholders cannot express a preference between the criteria, a 'I' is recorded in the grid to represent indifference to change
- If stakeholders conclude that a change in one of the criteria is reflected in a similar change to the compared criteria then an 'e' is recorded in the grid

The method was presented during at the MCDA workshop in Nottingham held in September 2016 to all the participants, the 'cars' example was shared with them to illustrate the weighting process and facilitate their work.

The results of applying the Hinkle method for weighting the InSMART criteria for Nottingham are given at the start of chapter 5.

4. MCDA Model Implementation

4.1. Quantitative criteria

The outputs of the Nottingham ESM and of the Nottingham InSMART transport model (set of results per scenario) are used to populate the values of the quantitative criteria using the multi-criteria software chosen, Visual PROMETHEE (VP). This is then used to determine the stakeholder's ranking of the scenarios. Table 3 shows the "quantitative outputs" of the two models which are used as "quantitative inputs" for the multi-criteria analysis exercise.

Table 3: Values for quantitative criteria generated by Nottingham ESM & Transport model

Scenario	% Energy reduction	Overall cost (£)	Low Carbon Energy (TJ)	Cost efficiency (£/tCO2)	Reduction in O2 emissions (tCO2[4])
LL-Low Cost	7.24	£319,875,681	375	£5,371.62	79,067
LL-Engaged	8.28	£517,546,084	564	£5,442.36	95,096
LL - Full	8.81	£767,110,984	564	£7,375.82	104,003
LL-Growth	9.34	£779,525,456	718	£6,649.88	117,224
GG - West	9.1	£1,024,860,522	1,260	£8,693.10	117,896
GG - East	9.3	£1,135,860,522	1,260	£9,636.10	117,876
GG - All	9.34	£1,403,928,483	1,227	£11,574.79	121,292

4.2. Qualitative criteria

Table 4: Nottingham qualitative criteria – final agreed values from MCDA workshop

[4] tCO2 = Tonnes CO2

Evaluations	Technical constraints	Social acceptability	Legal issues	Economic impact	Quality of Life Issues
LL-Low Cost	No technical difficulties (5)	Very high societal acceptance (5)	No legal issues (5)	No economic impact (2)	No effect on quality of life (2)
LL-Engaged	No technical difficulties (5)	High societal acceptance (4)	Minimal legal concerns (4)	Minor improvement to city economy (3)	Minor improvements to quality of life (3)
LL - Full	Minimal technical concerns (4)	Average societal acceptance (3)	Minor legal issues (3)	Minor improvement to city economy (3)	Significant improvements to quality of life (4)
LL-Growth	Minor technical concerns (3)	Average societal acceptance (3)	Minor legal issues (3)	Minor improvement to city economy (3)	Significant improvements to quality of life (4)
GG - West	Minor technical concerns (3)	Average societal acceptance (3)	Significant legal issues (2)	Minor improvement to city economy (3)	Significant improvements to quality of life (4)
GG - East	Significant technical issues (2)	Average societal acceptance (3)	Significant legal issues (2)	Significant improvement to city economy (4)	Significant improvements to quality of life (4)
GG - All	Significant technical issue (2)	Low societal acceptance (2)	Major legal or regulatory issues (1)	Significant improvement to city economy (4)	Significant improvements to quality of life (4)

The values assigned to the five qualitative criteria were initially defined by the UoN LUCAS research group during the dry run exercise of the MCDA process. These values were reviewed during the MCDA workshop by each of the four working groups as an additional exercise. The results from each of the four groups were discussed and a consensus set of final values for these criteria were developed, as shown in

Table 4. The cells highlighted in red show those that were changed from the initial default values. Note that altered criterion were only changed by one value on their respective scales.

4.3. Evaluation matrix

The full evaluation table taken from Visual Promethee is shown in Figure 2. It allows a visual comparison of the scenarios (rows) by criterion (column) and to immediately see the best performing (green) and the worst performing options (red) for each column. Although this is a mono-dimensional and simplified comparison (no weights are used), it makes clear the complex nature of the decision problem, as some alternatives perform very well on few criteria but are weak on other criteria. It also makes

evident that there is no alternative which dominates the others[5], as well as there is no alternative which is fully dominated, so that none of the options can be discharged "a priori". For instance, scenario 1 (LL-Low Cost) is the best option in five out of the ten criteria but it is also the worst for the other five criteria. In comparison, scenario 5 (GG-West) is the best option for only two out of the ten criteria but is not the worst for any of the remaining criteria. Solving the complexity of this problem for the municipality of Nottingham is the goal the MCDA process.

	consensus	Energy redu...	Overall cost	Low Carbon ...	Cost efficiency	CO2 emissio...	Technical co...	Social accept...	Legal issues	Economic im...	Quality of Lif...
	Unit	%	£	TJ	£/tonnes CO2	t	5-point	5-point	5-point	5-point	5-point
	Cluster/Group	●	◆	●	◆	●	■	■	■	◆	■
	Preferences										
	Statistics										
	Evaluations										
☑	LL-Low Cost	7.24	£319,875,681.	375.12	5371.62	79067.18	very good	very good	very good	bad	bad
☑	LL-Engaged	8.28	£517,546,084.	564.14	5442.36	95095.92	very good	good	good	average	average
☑	LL - Full	8.81	£767,110,984.	564.14	7375.82	104003.43	good	average	average	average	good
☑	LL-Growth	9.34	£779,525,456.	717.96	6649.88	117224.06	average	average	average	average	good
☑	GG - West	9.10	£1,024,860,52	1259.84	8693.10	117893.56	average	average	bad	average	good
☑	GG - East	9.30	£1,135,860,52	1259.84	9636.10	117875.52	bad	average	bad	good	good
☑	GG - All	9.34	£1,403,928,48	1227.24	11574.79	121291.90	bad	bad	very bad	good	good

Figure 2: Visual Promethee evaluation table for Nottingham

Figure 2 also shows the groupings for the criteria as defined in VP under the *Cluster/Group* row near the top of the evaluation table (represented by a coloured shape). The definitions of the criteria groups for the Nottingham MCDA model are:

● Energy = Energy Reduction Potential (C1)

◆ Economic = Overall Cost (C2), Cost Efficiency (C4), Economic Impacts (C9)

● Decarbonisation= Low carbon energy (C3), Reduction in CO2 emissions (C5)

■ Logistical = Technical Constraints (C6), Legal Issues (C8)

■ Social = Social Acceptability (C7), Quality of Life Issues (C10)

[5] When an option dominates the others (is better of the other alternatives against all the criteria), the decision problem does not exist or is probably not well structured.

4.4. Preference functions

In addition to the weighting of the criteria, Promethee uses preference functions and two threshold values; indifference (Q) and preference (P) in order to fully rank the alternatives (scenarios) against the criteria. It is beyond the scope of this report to provide a full technical explanation of the inner workings of the Promethee method as implemented in VP but details can be found in the VP Handbook [3] available online.

Preference functions and threshold values are designated in VP using a 'wizard' which asks the user a number of questions in order to assign the correct function and value for each criteria based on the value range for each criteria. The questions were presented to stakeholders as the final exercise at the Nottingham MCDA workshop held in September 2016. Appendix II lists the questions asked for each of the criteria to define their preference functions and threshold values.

Although not all groups were able to complete the exercise in the time available, there was enough overall results to reach a consensus for each of the criteria which was then input to the VP model and used to rank the scenarios. The results of this exercise are shown in Table 5.

Table 5: Results of the preference function and threshold definition exercise

Question	Criterion	Group 1	Group 2	Group 3	Group 4	Consensus
Q1	C1	Y	Y	Y	Y	**Y**
Q1	C2	N	N	N	N	**N**
Q1	C3	N	N	Y	N	**N**
Q1	C4	Y	Y	N	Y	**Y**
Q1	C5	Y	Y	N	Y	**Y**
Q1	C6	N	N	N	N	**N**
Q1	C7	Y	N	Y	Y	**Y**
Q1	C8	N	N	Y	N	**N**
Q1	C9	Y	Y	Y	Y	**Y**
Q1	C10	Y	Y	N	Y	**Y**
Q2	C1	X	X	X		**X**
Q2	C2	1	1	X		**1**
Q2	C3	2	1	X		**X**

Q2	C4	X	X	X		**X**
Q2	C5	X	X	X		**X**
Q2	C6	1	X	2		**X**
Q2	C7	X	X	2		**X**
Q2	C8	1	X			**X**
Q2	C9	1	2			**2**
Q2	C10	1	2			**2**
Q3	C1	1	1.5	0.89	1	**1.1**
Q3	C2	30000000	15000000	50000000		**31.67**
Q3	C3	50	80	306		**145.33**
Q3	C4	750	350	1807		**969**
Q3	C5	5000	6000	20312		**10437.33**
Q3	C6		1.5	1.5		**1.5**
Q3	C7		1.5	1.5		**1.5**
Q3	C8		1.5	1.5		**1.5**
Q3	C9		0.5	0.5		**0.5**
Q3	C10		0.5	0.5		**0.5**

5 MCDA Results

Twenty stakeholders attended the MCDA workshop. This led to the formation of four groups. The groups were predefined by colleagues from the city council in order to ensure a diverse representation in each working group. A UoN researcher was also present in each group to support the discussion process. The researcher role was only to facilitate discussion and explain the MCDA exercises if necessary. The researchers did not take an active role in the decision making processes. An external facilitator (from the group Climate UK[6]) was present to run the workshop.

MCDA results are presented by means of the total cost-function value (Phi value) obtained for each action and are further assessed using a PROMETHEE Rainbow chart. The considerations adopted to assess this type of chart are presented in Figure 3. The Rainbow diagram prioritizes the actions/interventions from the highest to the lowest Phi value in its scaled form in the range from -1 (worst solutions) to +1 (best solutions), meaning that

[6] CUK are a UK based non-profit Community Interest Company (CIC). They are a network of organisations and individuals supporting local action on climate change. CUK have a long standing relationship with NCC.

actions with positive Phi could be considered acceptable. Criteria with positive and negative contributions/flows (Phi+ and Phi-) for each action are illustrated in the rainbow's bars by means of their colour pre-set for criteria' categories; therefore, providing a clear view of the level of achievement of optimal values of criteria in relation to the preferences (weight, P and Q) defined for stakeholders.

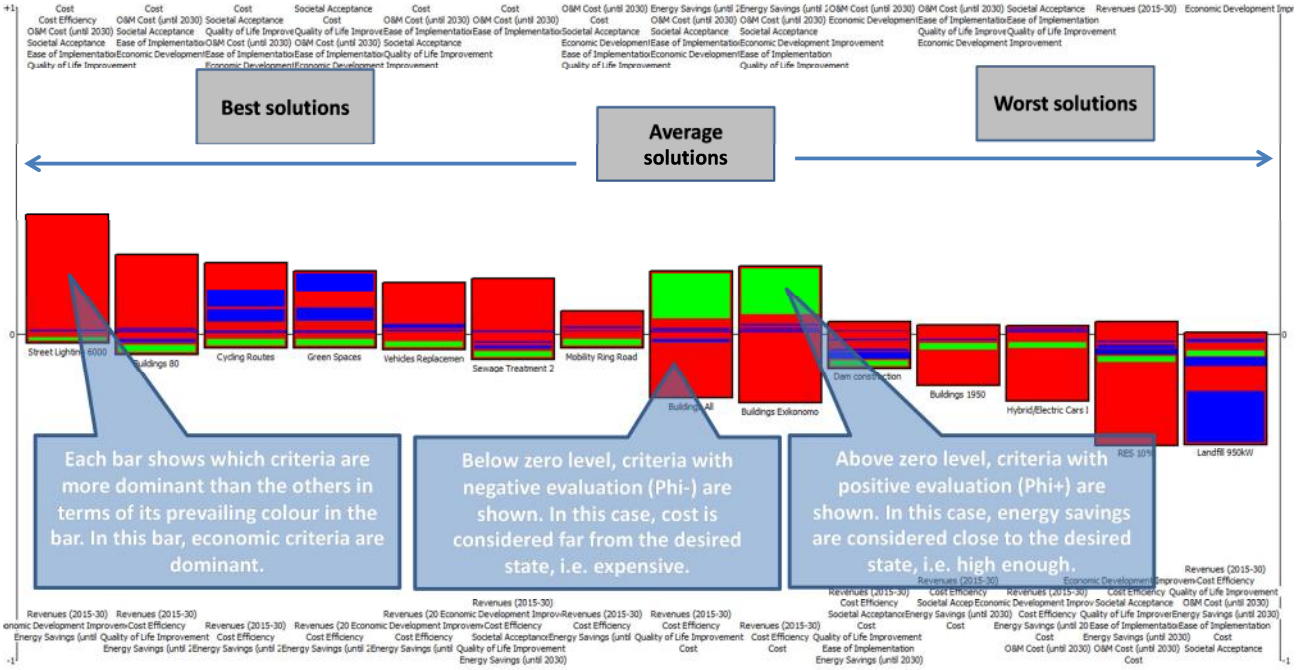

Figure 3: Considerations for assessing MCDA results using PROMETHEE Rainbow chart

5.1 Consensus solution

This section describes and discusses the results of the MCDA process based on the final consensus values for the criteria weighting, qualitative criteria values and preference functions and thresholds described in chapters 3 and 4.

The resistance to change grid for the consensus weighting result is shown in Table 6. The grids for each of the working groups are included in appendix IV.

Table 6: Completed resistance to change matrix for Nottingham (consensus)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	SCORE	**Weight**
C1		-	-	X	X	-	-	-	-	X	6	**13.3**
C2			-	X	X	-	-	-	X	X	4	**8.9**

C3				X	X	-	-	-	-	X	4	**8.9**
C4					-	-	-	-	-	X	8	**17.8**
C5						-	-	-	-	X	7	**15.6**
C6							X	-	X	X	1	**2.2**
C7								-	X	X	2	**4.4**
C8									X	X	0	**0.0**
C9										X	4	**8.9**
C10											9	**20.0**

The consensus solution among all stakeholders is presented in the following figures and tables generated by Visual PROMETHEE (Figure 4, Figure 5, Figure 6 and Table 7).

It should be noted that the consensus values used are not simply an average of the values provided by the four working groups. The consensus values were reached through a formal process with all stakeholders where the results from each group were compared and any differences were debated until a final value agreeable to the majority was reached. In almost all instances the consensus reached was unanimous. Only in a one or two cases was a majority only consensus value required.

Table 7: Table of Phi values for scenarios for the consensus solution

Scenario	Phi	Phi+	Phi-
LL-Growth	0.1624	0.2949	0.1325
GG - East	0.1198	0.297	0.1772
GG - West	0.1002	0.2564	0.1562
LL - Full	0.0535	0.2238	0.1703
GG - All	-0.0143	0.2729	0.2873
LL-Engaged	-0.0678	0.2757	0.3436
LL-Low Cost	-0.3538	0.2301	0.5839

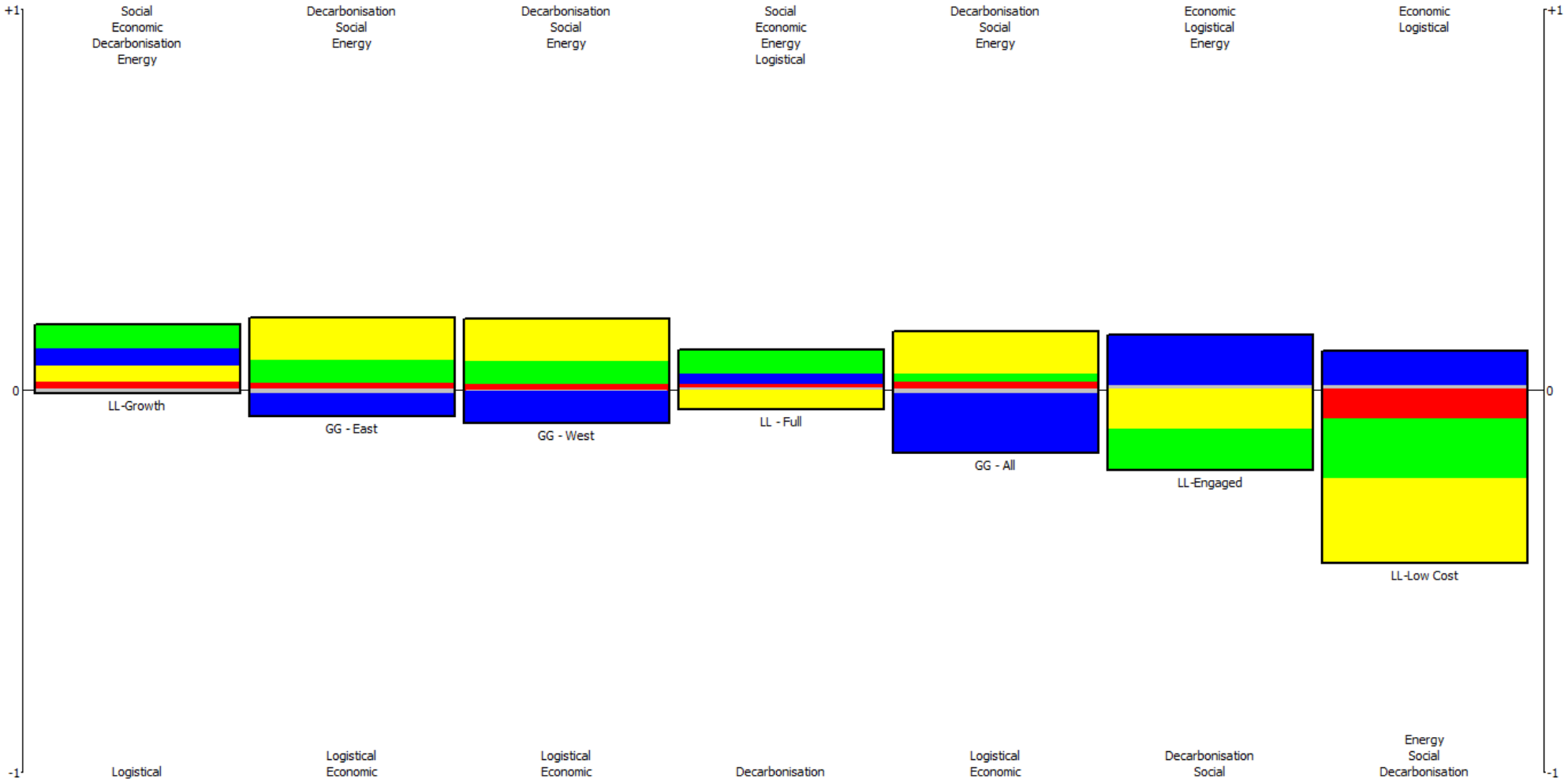

Figure 4: PROMETHEE Rainbow diagram for the consensus solution among Stakeholders.

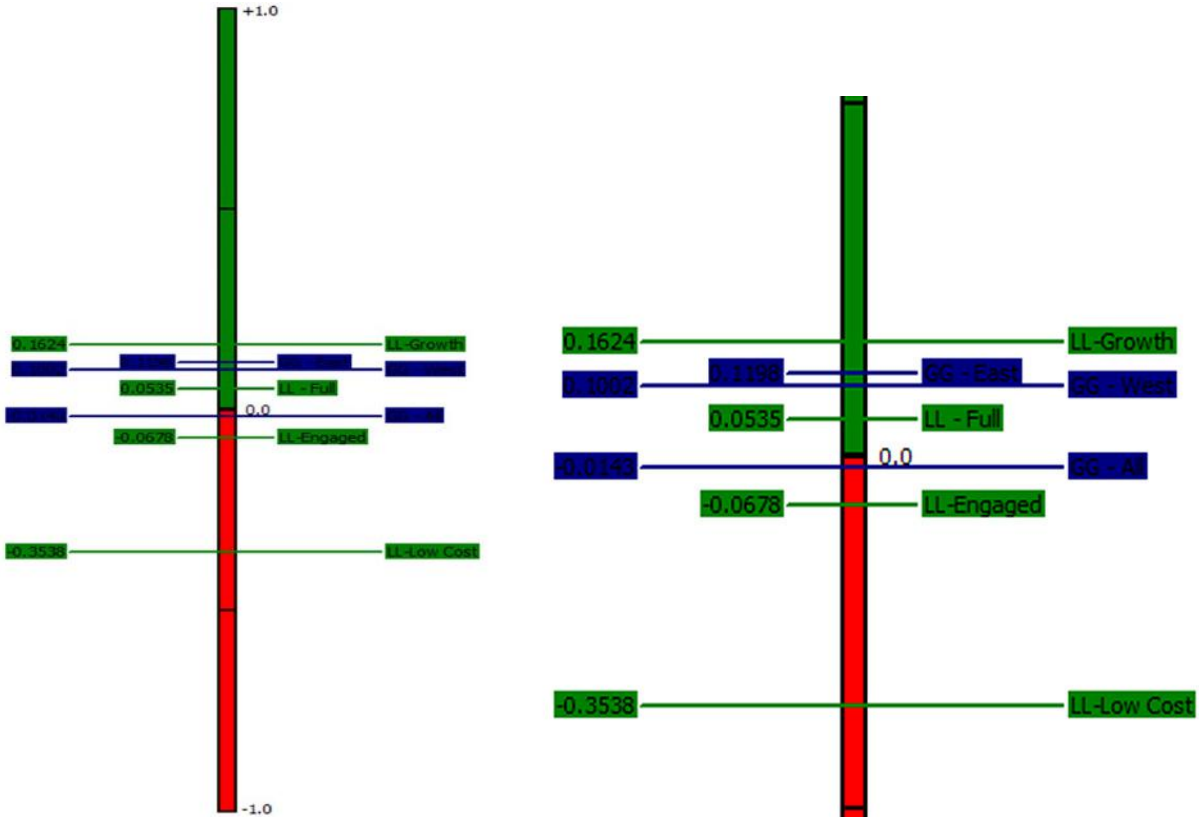

Figure 5: PROMETHEE II Complete ranking diagram [Left]Full, [Right]Zoomed version

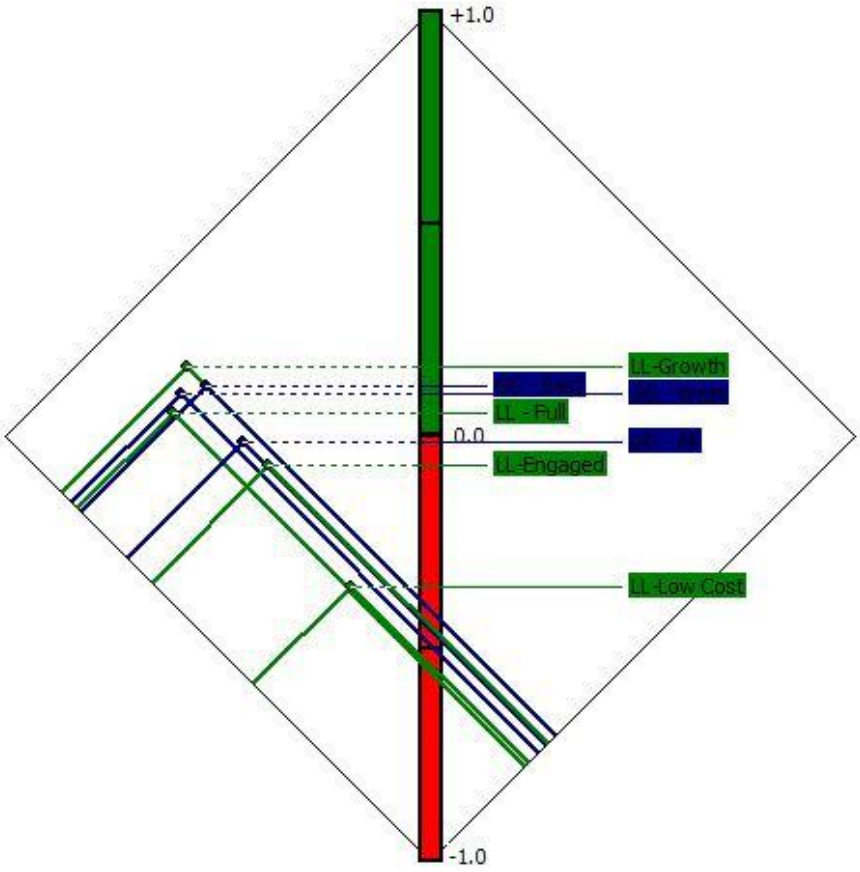

Figure 6: PROMETHEE Diamond chart for the consensus solution

Based on the data shown in the charts and tables shown, a number of conclusions can be made:

- LL-Growth is the highest ranked scenario and has the lowest scoring for negative impacts (Phi-). Positives (Phi+) are distributed across a number of criteria groups fairly evenly (illustrated by the blue, green and yellow coloured bars in the rainbow chart). LL-Growth's only negative impacts are logistical and of very small magnitude.
- GG-East has the highest positive scoring for any scenario but its negatives, particularly cost (shown in blue in the rainbow chart), significantly reduce its overall ranking (Phi).
- The solutions are clustered into three distinct groupings; the top four ranked scenarios, the mid ranked two scenarios (GG-All, LL-Engaged) and the bottom ranked scenario, LL-Low Cost, on its own. This is clearly evident in figures 6 and 7.
- The rankings of GG-East and GG-West are very similar. GG-East's slightly higher overall ranking is accounted for by it scoring one rank higher on the *Economic Impact* criterion C9 and having a slightly higher *Energy Reduction Potential* than GG-West.
- The significantly increased cost of the GG-All scenario in comparison to the other GG based scenarios does not offset the additional small reduction in energy use and CO2 emissions. This option therefore performs poorly compared to the other GG scenarios in the MCDA.
- LL-Engaged and LL-Low Cost are the worst performing scenarios mainly due to their low scoring in terms of social and decarbonisation criteria.

The multi-criteria decision analysis identified a combination of measures (planning hypothesis) that are ranked high in the preferences of the stakeholders in the city. These specific interventions will form the basis of a deeper explorations under the framework of WP6, and will feed the technical part of Sustainable Energy Action Plan for the city of Nottingham.

However, taking "final and definitive" decisions on the basis of the MCDA findings reported has the risk of being too simplistic. All can be suggested at

this stage, is that some combinations of measures deserve to be further examined and considered for the final preparation of the strategic energy action plan, while others look (much) less interesting and can be excluded from deeper investigations. Table 8 summarizes the findings of this analysis.

Table 8: Scenario ranking and options for future work

Rank	Scenario	Option
1	LL-Growth	Shortlisted
2	GG-East	Shortlisted
3	GG-West	Shortlisted
4	LL-Full	Right below the threshold
5	GG-All	Likely not of interest
6	LL-Engaged / LL-Low Cost	Discarded

Since LL-Full is wholly contained within LL-Growth (see Table 1), there will be no need to separately consider LL-Full in the next work package (WP6). Instead the focus on the techno-economic analyses in WP6 will concentrate on LL-Growth with some consideration of the promising elements of the GG-East/GG-West scenarios.

5.2 Sensitivity Analysis

In order to assess the sensitivity of the MCDA process to changes in criteria weighting, preference functions and threshold values the results for each working group are discussed in this section. PROMETHEE Rainbow charts for each of the working groups are provided in Appendix IV. Each group's MCDA results are based on the weights, preference functions and threshold values defined by that group rather than the final consensus values.

The results of the initial exercise of criteria weighting for all groups are shown in Figure 7. The normalised weighting for each criteria is shown for each working group along with the final consensus weighting values. It is clear that there are some significant differences between the weightings for some of the criteria.

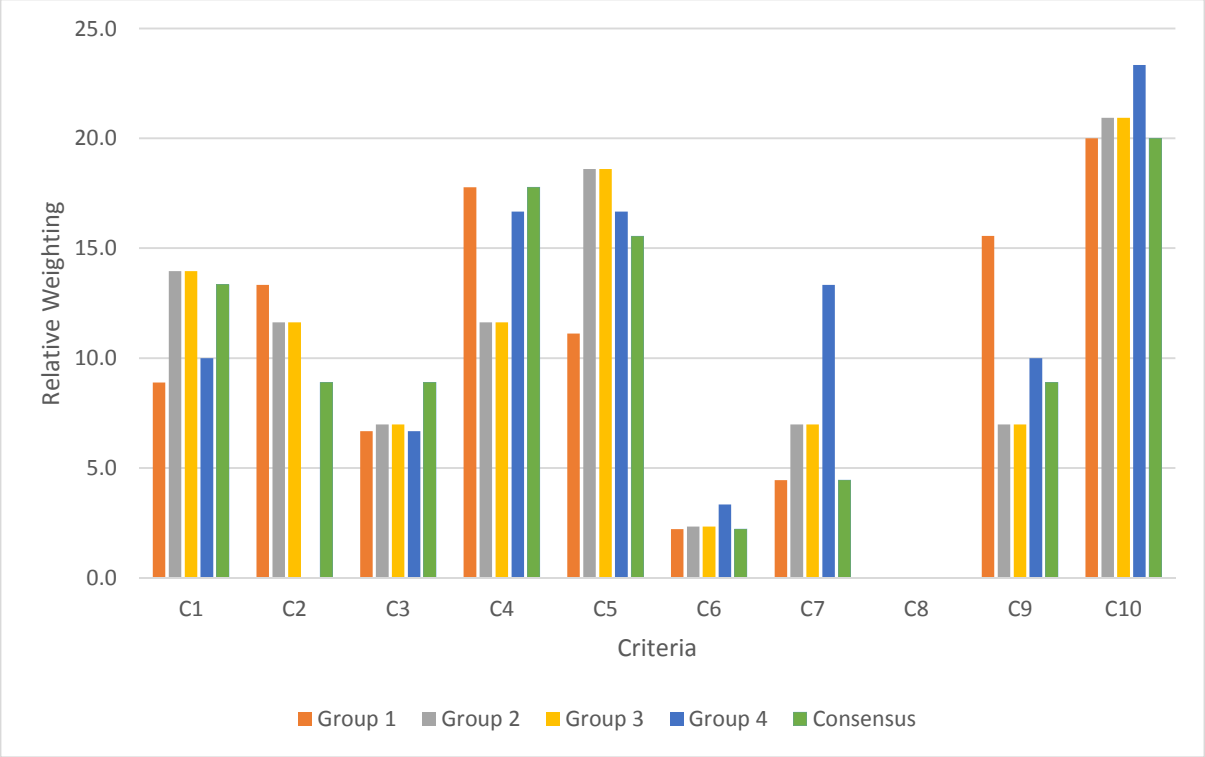

Figure 7: Chart showing results of the Hinkle method for each of the four working groups and the overall consensus weights for the criteria

The acceptable (Phi>0) and unacceptable alternatives for each working group together with the final solutions for the agreed consensus result are presented in Table 9 in descending order of Phi.

Table 9: Stakeholders' decision matrix.

Stakeholders' Decisions Matrix	Group 1	Group 2	Group 3	Group 4	Agreed Consensus
Acceptable solutions in descending order of Phi (Phi>0)	GG - East	LL-Growth	LL-Growth	GG - East	LL-Growth
	GG - West	GG - East	GG - East	LL-Growth	GG - East
	LL-Growth	LL - Full	GG - West	GG - West	GG - West
	GG - All	GG - West	LL - Full	LL - Full	LL - Full
	LL - Full				
Worst solutions in descending order of Phi (Phi<0)	LL-Engaged	GG - All	LL-Engaged	GG - All	GG - All
	LL-Low Cost	LL-Engaged	GG - All	LL-Engaged	LL-Engaged
		LL-Low Cost	LL-Low Cost	LL-Low Cost	LL-Low Cost

LL-Growth and GG-East are the top ranked scenarios across all the working groups and in the final consensus. GG-West and LL-Full are also deemed to be acceptable solutions across all groups with GG-All only being deemed acceptable to working group 1, due to that group's lower weighting of the *Total Cost* criterion.

In terms of the worst performing solutions, LL-Low Cost is the bottom ranked scenario across all groups with LL-Engaged and GG-All (excluding group 1) ranked slightly above it.

The group results show that although there are some differences to the overall order of ranking due to the differences in weights, preferences and thresholds, the scenarios suitable for shortlisting (Table 8) would remain the same.

In order to fully explore the sensitivity of the results, PROMETHEE results based on just applying the quantitative criteria was also investigated. The results of this are shown in Figure 8 and Table 10.

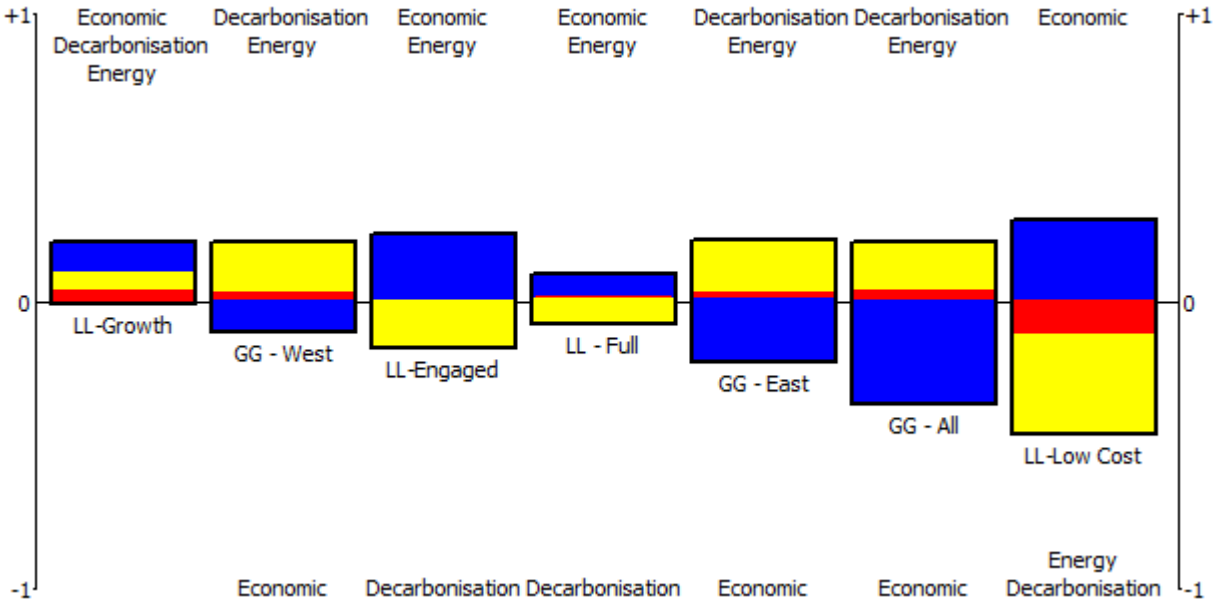

Figure 8: PROMETHEE Rainbow chart based on application of quantitative criteria only

Table 10: PROMETHEE Ranking table based on application of quantitative criteria only

Rank	action	Phi	Phi+	Phi-
1	LL-Growth	0.1886	0.3196	0.1310
2	GG - West	0.0920	0.2598	0.1677
3	LL-Engaged	0.0622	0.2789	0.2167
4	LL - Full	0.0082	0.2035	0.1953
5	GG - East	-0.0073	0.2306	0.2378
6	GG - All	-0.1583	0.2047	0.3630
7	LL-Low Cost	-0.1854	0.2715	0.4570

It is not meant to suggest that qualitative criteria should be excluded from the decision problem, rather it aims to test and show the sensitivity of the default ranking (robustness of the shortlist) when only the outputs of the modelling exercises undertaken in the previous WPs are used.

The changes generated by such assumption are now more significant, but some elements of robustness are still evident. LL-Growth is still the highest ranked scenario based on the quantitative criteria alone. However, GG-East (Due to the infrastructure cost related to the construction of the new tram line) is no longer an acceptable solution. However, GG-West remains an acceptable solution as that tram extension has a much reduced construction cost whilst still including the other decarbonisation benefits associated with the GG scenarios. Based solely on the quantitative criteria, LL-Engaged and LL-Full become acceptable solutions due to their low economic cost.

Even based on this more limited MCDA assessment, the two highest ranked alternatives match the shortlisting generated by the full MCDA approach.

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[1] Hinkle, D. (1965). *The change of personal constructs from the viewpoint of a theory of construct implications*. Ph.D. Dissertation, Ohio State University.

[2] InSMART (2016) InSMART Deliverable D5.1 *Report on optimum sustainability pathways – Nottingham*. Available online at http://www.insmartenergy.com/work-package-5/

[3] VPSolutions (2013) *Visual PROMETHEE 1.4 Manual*. Available online at http://www.promethee-gaia.net/assets/vpmanual.pdf [accessed 17/10/16]

Acknowledgements

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Appendix I – Nottingham MCDA workshop

WORKSHOP AGENDA

Time	Item	Lead
9.30	Arrival and refreshments	
9.45	Welcome and introductions	Mike Peverill, facilitator
9.55	Setting the scene – the wider context for this workshop	Jane Lumb, Nottingham City Council
10.05	Recap of the InSmart project	Andy Whitley, Nottingham City Council
10.10	Introduction to the first exercise (weighting the scenario criteria)	Gavin Long, University of Nottingham
10.35	Weighting exercise	In small groups
11.35	Break	
11.50	Comparing and consolidating results	Mike Peverill
12.30	Lunch	
1.15	Introduction to second exercise (scoring the scenarios) and multi-criteria decision making analysis	Gavin Long
1.40	Scoring exercise	In small groups
2.40	Comparing and consolidating results	Mike Peverill
3.00	Break (whilst scenarios are updated)	
3.15	Presentation of results	Gavin Long
3.35	Questions and discussion of results	Plenary
4.05	Reflections, conclusions, thanks and next steps	Jane Lumb
4.15	End	

WORKSHOP PARTICIPANTS

Name	Organisation
1. Anton Ianakiev	Nottingham Trent University
2. Alison Thomas	Nottingham City Council
3. Andy Allen	University of Nottingham
4. Andy Whitley	Nottingham City Council
5. Ben Purvis	University of Nottingham
6. Chris Keane	Nottingham City Council
7. Chris Pryke-Hendy	Nottingham Trent University
8. Darren Robinson	University of Nottingham
9. Elin Hultgren	Nottingham Energy Partnership
10.Gavin Long	University of Nottingham
11.Jane Lumb	Nottingham City Council
12.John Beardmore	T4S
13.Luke Jackson	Nottingham City Council
14.Mark Thomas	Nottingham City Council
15.Martin Oakes	University of Nottingham
16.Mike Peverill	Climate UK
17.Paul Chandler	T4S
18.Paul Flowers	Nottingham City Council
19.Rasita Chudasama	Nottingham City Council
20.Ricky Wright	Nottingham City Transport
21.Ruth Stallwood	Nottingham City Council
22.Sara Ball	Nottingham City Council
23.Siobhan Metcalfe	Nottingham City Council
24.Steve Tough	Nottingham City Council

Appendix II – MCDA Workshop Exercise 2B – defining preference functions and threshold values

2b. Q1
When comparing two actions on this criterion, do you feel that this difference is negligible?

C1. Energy reduction potential (%) – 0.12%
C2. Overall cost (£) - £90,000,000
C3. Low carbon energy generation (TJ) - 32.6 TJ
C4. Cost efficiency (£/tonnes CO2) - £70.74
C5. Reduction in CO2 emissions (tCO2) - 18 Tonnes CO2

C6 – C10. For these criteria, do you feel that a one level difference is very important?
C6. Technical constraints: Yes/No
C7. Social acceptability: Yes/No
C8. Legal issues: Yes/No
C9. Economic impact: Yes/No
C10. Quality of life issues: Yes/No

2b. Q2
Let us compare two actions A and B on this criterion. In each case indicate if case 1 or case 2 is much more important with a tick or add an 'X' if the cases are not so different.

C1.	Case 1: A = 6.84% - B = 6.25%
	Case 2: A = 9.21% - B = 8.62%
C2.	Case 1: A = £319,875,681 - B = £536,686,241
	Case 2: A = £1,187,117,922 - B = £1,403,928,483
C3.	Case 1: A = 552 TJ - B = 375 TJ
	Case 2: A = 1260 TJ - B = 1083 TJ
C4.	Case 1: A = £5,371 - B = £6,612
	Case 2: A = £10,334 - B = £11,575
C5.	Case 1: A = 87,512 tCO2- B = 79,067 tCO2
	Case 2: A = 121,292 tCO2 - B = 112,847 tCO2

For the qualitative criteria C6-C10 note that 1.00 is the negative extreme and 5.00 is the positive extreme for that qualitative criterion

C6.	Case 1: A = 1.80 - B = 1.00
	Case 2: A = 5.00 - B = 4.20
C7.	Case 1: A = 1.80 - B = 1.00
	Case 2: A = 5.00 - B = 4.20
C8.	Case 1: A = 1.80 - B = 1.00
	Case 2: A = 5.00 - B = 4.20
C9.	Case 1: A = 1.80 - B = 1.00
	Case 2: A = 5.00 - B = 4.20
C10.	Case 1: A = 1.80 - B = 1.00
	Case 2: A = 5.00 - B = 4.20

2b. Q3
For each criterion, please indicate what is the maximum value of that criterion you would be indifferent to? Suggested values, automatically generated by the Promethee software, are included to assist your decisions.

If you are happy with the automated values, add a tick. Otherwise write in an appropriate value for each criteria

C1. Energy reduction potential (%) – 0.89%
C2. Overall cost (£) - £264,000,000
C3. Low carbon energy generation (TJ) - 306 TJ
C4. Cost efficiency (£/tonnes CO2) - £1,807
C5. CO2 emissions (tonnes) - 20,312 Tonnes CO2
C6. Technical constraints: - 1.14
C7. Social acceptability: - 1.14
C8. Legal issues: - 1.14
C9. Economic impact: - 1.14
C10. Quality of life issues: - 1.14

Appendix III – Visual Promethee

Visual Promethee[7] is a multi-criteria decision aid (MCDA) software, designed to help the analyst to:

- evaluate several possible decisions or items according to multiple often conflicting criteria,
- identify the best possible decision,
- rank possible decisions from the best to the worst one,
- visualize decision or evaluation problems to better understand the difficulties in making good decisions,
- achieve consensus decisions when several decision-makers have conflicting points of view,
- justify or invalidate decisions based on "objective" elements.

The Promethee methods are designed to analyze data within a multi-criteria "table" including:

- a number of actions,
- several criteria

In mathematical terms the problem is the following:

$$\{F_1(a), F_2(a), \dots, F_k(a) | a \in A\}$$

where *A* is a finite set of *n* actions (or alternatives) and F_1 to F_k are *k* criteria. *Fj*(*a*) is the evaluation of action *a* on criterion *Fj*. If we suppose that all criteria have to be maximized, the multi-criteria table (or evaluation matrix) would look like as follows:

$$\begin{array}{cccccc} \cdot & F1 & F2 & \dots\dots & & F_k \\ a_1 & F_1(a_1) & F_2(a_1) & \dots\dots & & F_k(a_1) \\ a_2 & F_1(a_2) & F_2(a_2) & \dots\dots & & Fk(a2) \\ | \dots & \dots\dots & \dots\dots & \dots\dots\dots\dots & \dots\dots & | \\ \dots & & & & & \\ a_n & F_1(a_n) & F_2(a_n) & \dots\dots & & F_k(a_n) \end{array}$$

The objective of MCDA is thus to identify the best compromise decisions.

One very common way to try to solve multi-criteria decision problem is to aggregate all the criteria into a single summary score. This can be done in several ways. A good way to obtain solutions with a more balanced compromise is to use outranking methods.

[7] It is developed by Professor Bertrand Mareschal from the Solvay Brussels School of Economics and Management of the Université Libre de Bruxelles (ULB). The first implementation of the Promethee method dates back in the 1980's. In the following decades several software implementing the methodologies were developed: PromCalc, Decision Lab, and finally D-Sight (2010) and Visual Promethee (2012).

The basis of outranking methods is very simple: instead of trying to define what is good and what is bad, which can be very difficult especially when facing a new problem for which very few reference points are known, it is usually much easier to compare one solution to another. The first outranking method developed was **Electre**, back in the 1970s; other outranking methods were implemented: Promethee elaborates and improves Electre, introducing also a new graphical descriptive tool (Gaia).

To perform the pairwise comparison which is at the basis of the outranking methodology, implementation of **preference functions**, which take into account the differences existing between the two actions/alternatives being compared, is needed. For each criterion F_j, we have a preference function $\boldsymbol{P_j(a,b)}$ and a normalized weight $w_j > 0$.

A multicriteria preference index is computed as:

$$\pi(a, b) = \sum_{j=1}^{k} w_j P_j(a, b)$$

In the Promethee software there are a series of predefined preference functions, which can be used to shape the relative distance among the alternatives. With normalized weights, $\pi(a,b)$ is a number between 0 and 1. It expresses how much *a* is preferred to *b* taking into account all the criteria and their weights. For instance:

- if $\pi(a,b) = 0$, all the P_j (*a*,*b*) values are equal to 0, which means that *a* is never even slightly preferred to *b* on any criterion.
- if $\pi(a,b) = 1$, all the P_j (*a*,*b*) values are equal to 1, which means that *a* is strongly preferred to *b* on all the criteria.

The result of this procedure is a table hosting the **preference flows**. Three different types of preference flows are computed:

- **Positive** or leaving **flow**: it measures how much an action *a* is preferred to the other *n-1*, alternatives (in other words, how alternative *a* is outranking the others). It is a global measurement of the "strengths" of action *a*.

$$\Phi^{+}(a) = \frac{1}{n-1}\sum_{b \in A} \pi(a,b)$$

- **Negative** or entering **flow:** it measures how much the other n-1 alternatives *are* preferred to the action *a*. It is a global measurement of the "weakness" of action *a*.

$$\Phi^{-}(a) = \frac{1}{n-1}\sum \pi(b,a)$$

$$b \in A$$

- **Net flow**, which is the algebraic sum of the previous: it is a balance between the positive and negative preference flows, *thus it takes onto account and aggregates both strengths and weaknesses of the alternative into a single figure*.

$$\Phi(a) = \Phi^{+}(a) - \Phi^{-}(a)$$

The larger *Φ(a)* is, the better the alternative performs.

Pairwise comparison is based on the concept of deviation, or distance between alternatives: the larger the deviation, the larger the preference degree is.

The preference flows can be computed for each criterion separately (**uni-criterion flows**) and the **multi-criteria flow** is the sum of the uni-criterion flows weighted over the w_j given to each criterion:

$$\Phi(a) = \sum_{j=1}^{k} w_j \Phi_j(a)$$

With the uni-criterion net flow for the criterion j:

$$\Phi_j(a) = \frac{1}{1-n} \sum_{b \in A} \left[P_j(a,b) - P_j(b,a) \right]$$

By calculating this type of flows, preferences can be ranked from best to worse based on the partial rankings (considering *Phi+* and *Phi-*), and on the complete ranking taking into account the net *Phi*.

Appendix IV – MCDA results by group

Completed resistance to change grids for each of the four working groups

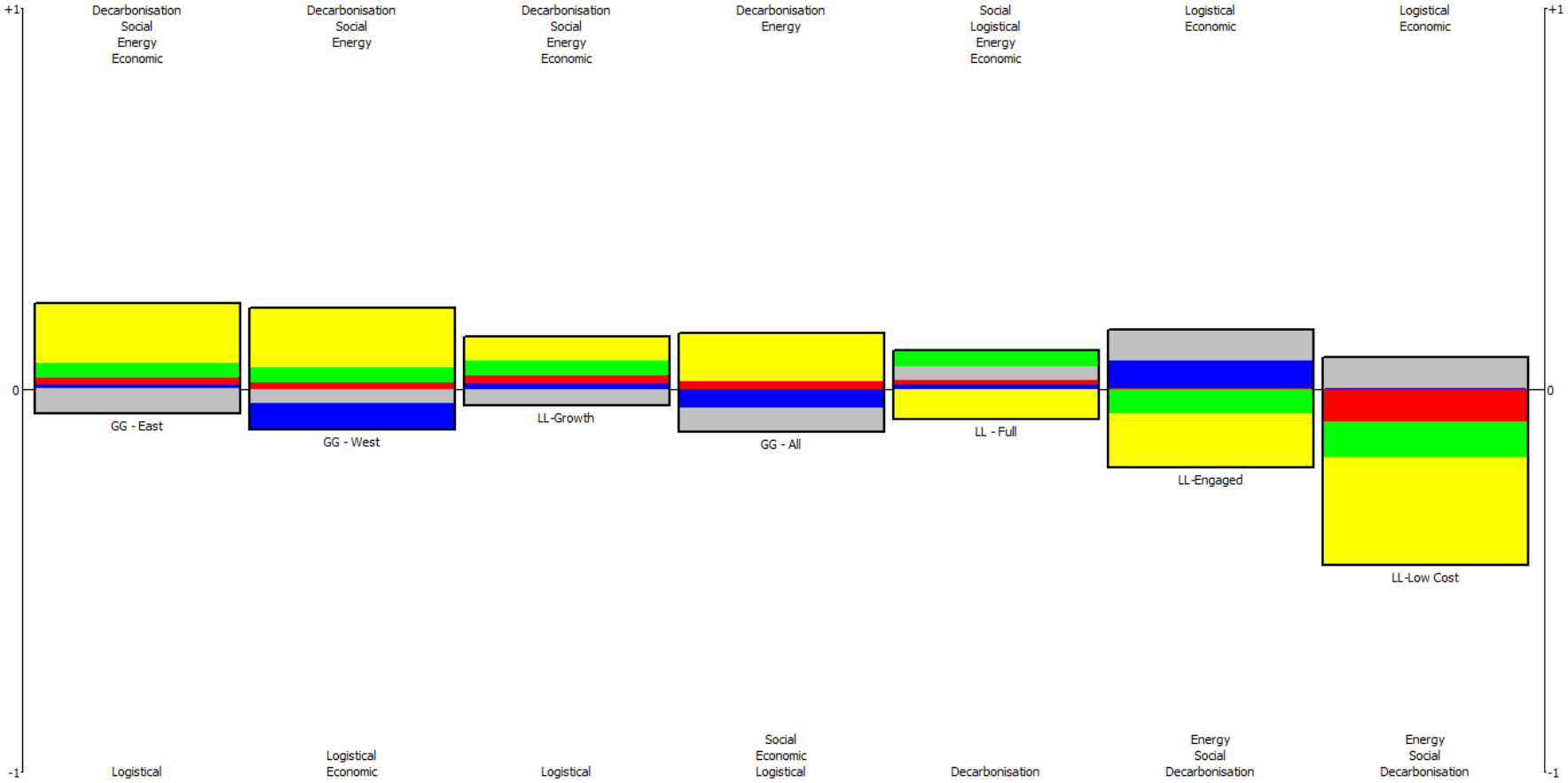
Group 1	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	SCORE	Weight
C1		X	-	X	X	-	-	-	-	I	5	11.6
C2			X	X	X	X	-	-	X	X	3	7.0
C3				I	X	-	-	-	I	-	5	11.6
C4					-	X	X	-	X	X	4	9.3
C5						-	-	-	-	-	8	18.6
C6							-	-	-	X	5	11.6
C7								-	X	X	2	4.7
C8									X	X	0	0.0
C9										X	5	11.6
C10											6	14.0

Group 2	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	SCORE	Weight
C1		X	-	X	X	-	-	-	X	X	4	8.9
C2			-	X	-	-	-	-	X	X	6	13.3
C3				X	X	-	-	-	X	X	3	6.7
C4					-	-	-	-	-	X	8	17.8
C5						-	-	-	X	X	5	11.1
C6							X	-	X	X	1	2.2
C7								-	X	X	2	4.4
C8									X	X	0	0.0
C9										X	7	15.6
C10											9	20.0

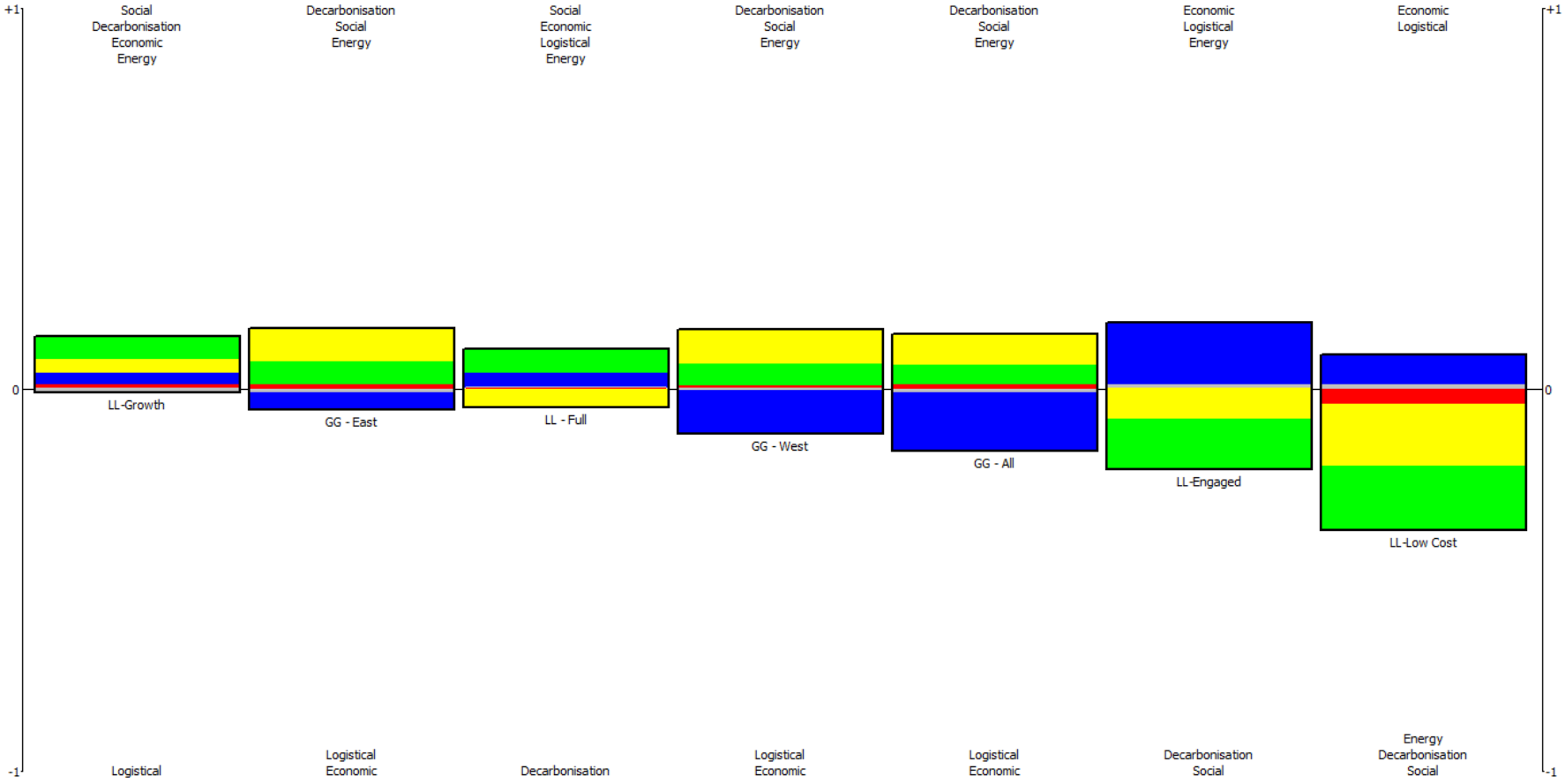
Group 3	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	SCORE	normalize
C1		-	-	I	X	-	-	-	-	X	6	14.0
C2			-	I	X	-	-	-	-	X	5	11.6
C3				X	X	-	X	-	-	X	3	7.0
C4					X	-	-	-	-	X	5	11.6
C5						-	-	-	-	X	8	18.6
C6							X	-	X	X	1	2.3
C7								-	X	X	3	7.0
C8									X	X	0	0.0
C9										X	3	7.0
C10											9	20.9

Group 4	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	SCORE	normalize
C1		-	-	I	X	X	I	I	-	X	3	10.0
C2			X	X	X	I	X	I	X	X	0	0.0
C3				X	E	-	I	I	I	X	2	6.7
C4					-	-	I	-	E/I	X	5	16.7
C5						-	I	-	-	I	5	16.7
C6							X	I	X	X	1	3.3
C7								-	-	I	4	13.3
C8									X	X	0	0.0
C9										X	3	10.0
C10											7	23.3

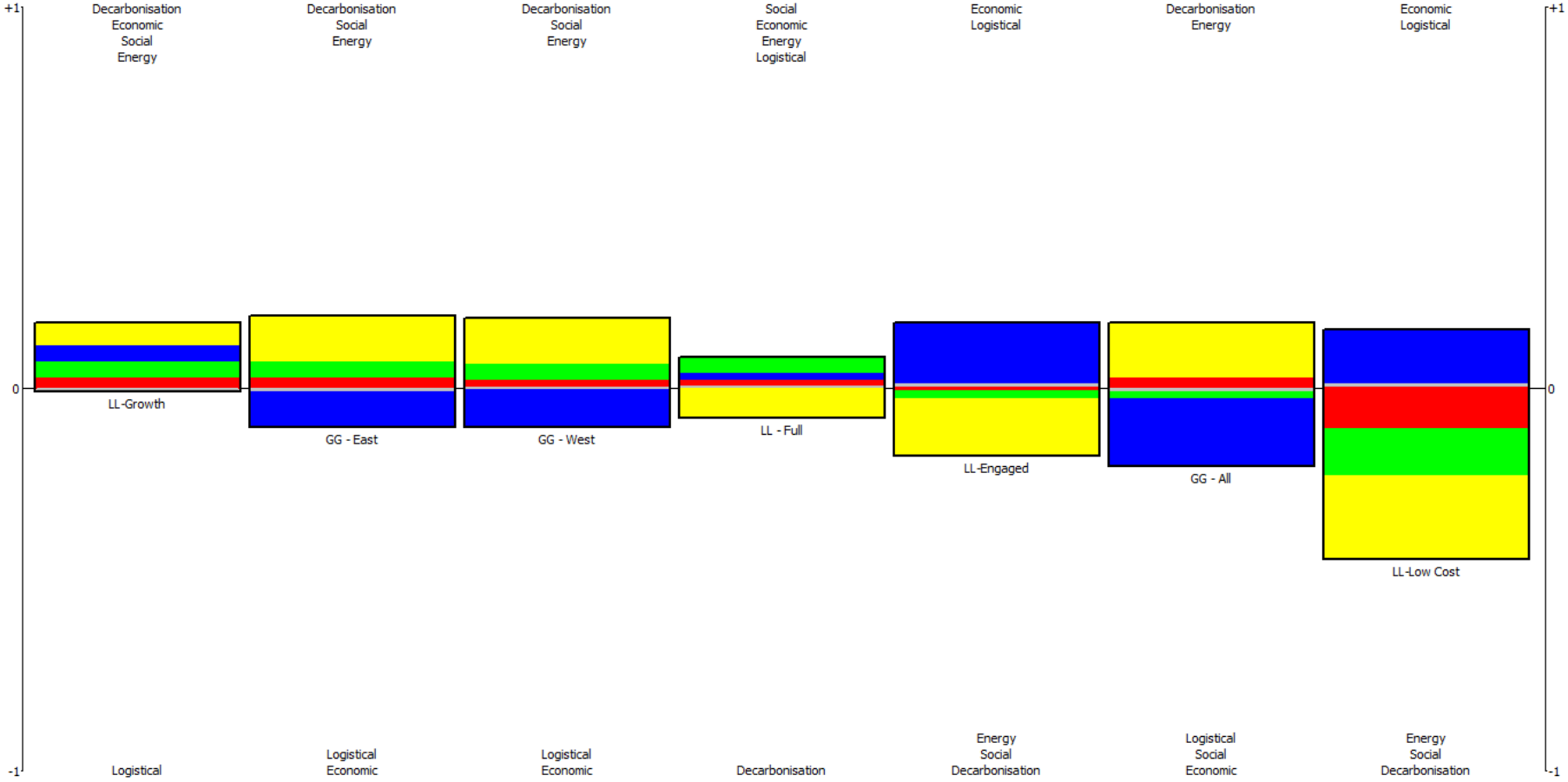
Rainbow diagram of MCDA results for working group 1.



Rainbow diagram of MCDA results for working group 2.



Rainbow diagram of MCDA results for working group 3.



Rainbow diagram of MCDA results for working group 4.