Sustainability Optimisation with Multiple Criteria and Multiple Stakeholders

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- Definitions and fundamental concepts
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What is Operational Research?

- The science of better.
- The science of *making* better *decisions* *(my additions)*.
- Operational research (O.R.) is the discipline of applying advanced analytical methods to help make better decisions.
- Centre for Operational Research and Logistics www.port.ac.uk/corl

UK Operational Research Society
www.orsoc.org

Multiple conflicting criteria?

- A **criterion** is one dimension by which the goodness of a given solution to a problem may be measured. (Jones and Tamiz, 2010)
  - Cost, time, environmental impact, customer satisfaction, patient throughput, average queuing time, student satisfaction, ...
- An **objective** is a criterion plus a direction.
  - Minimise cost, maximise customer satisfaction

Multi-Criteria Decision Making

- Decisions with multiple measurement criteria are termed MCDM problems

Car Choice problem?
Binary choice

Criteria
Acceleration, cost, number of passengers, prestige,...

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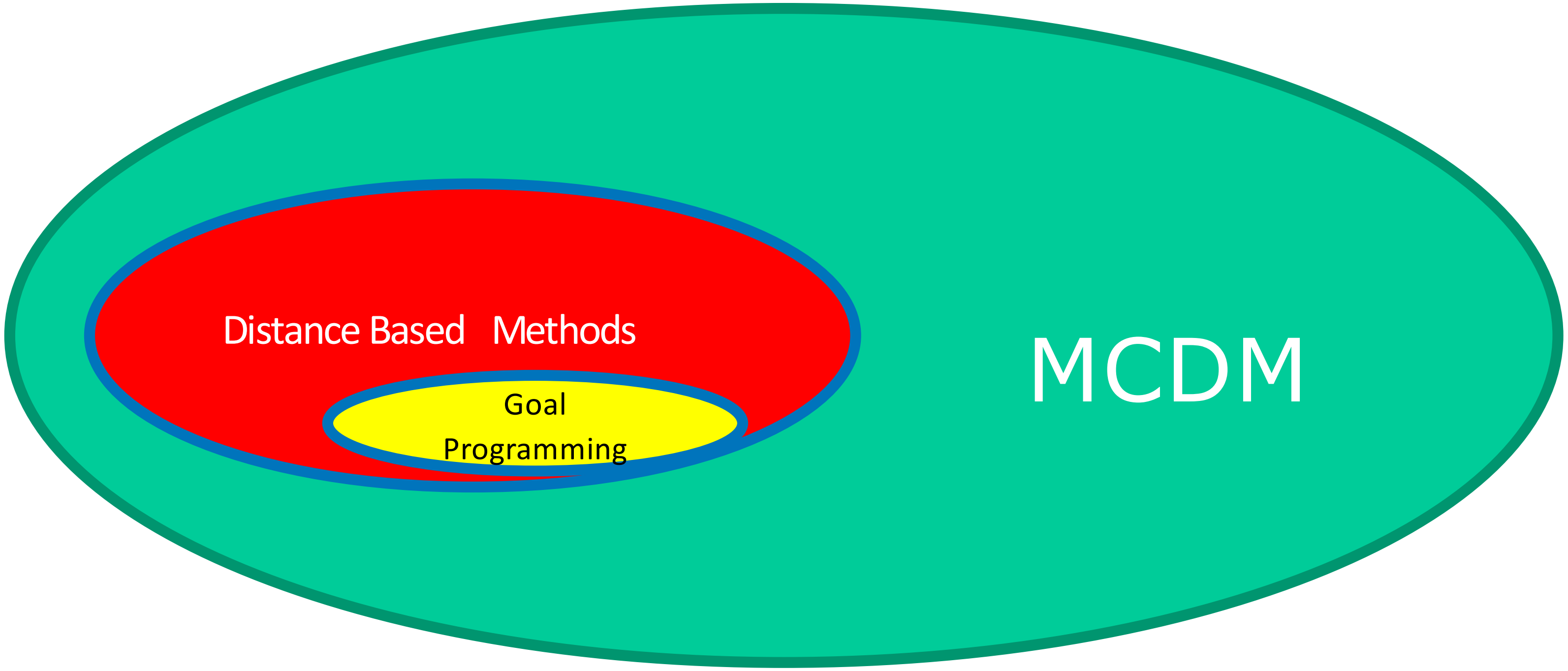
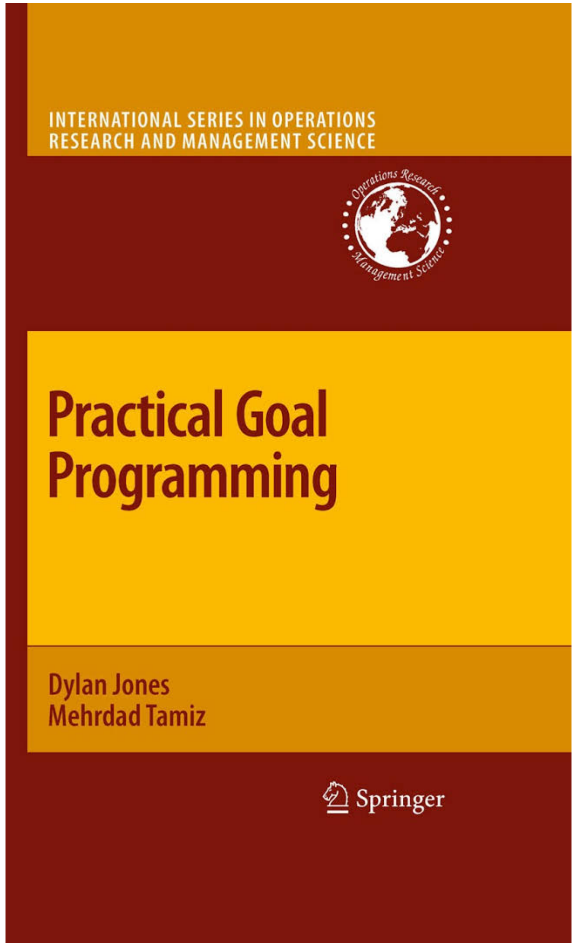
Multi-Criteria Decision Making



Goal Programming

- A **criterion** is one dimension by which the goodness of a given solution to a problem may be measured. (Jones and Tamiz, 2010)
  - Cost, time, environmental impact, customer satisfaction, patient throughput, average queuing time, student satisfaction, ….
- An **objective** is a criterion plus a direction.
  - Minimise cost, maximise customer satisfaction
- A **goal** is a criterion, a direction, plus a numerical target value.
  - Achieve a total cost of less than £10,000,000
- **Goal programming** is a satisficing mathematical technique for achieving a set of goals as closely possibly in the presence of multiple, conflicting criteria.



Jones and Tamiz 2010

Satisficing?

- Herbert Simon (1916-2001)
- Bounded rationality
- Satisficing: Satisfy + Suffice
- Organisations make decisions by aiming to reach a set of defined goals rather than by the theoretical "ideal" of optimising all objectives
- Satisficing Vs Optimising

Source: The Nobel Foundation

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Generic form of a weighted goal programme (Q goals)

$$Min\ \boldsymbol{a} = \sum_{q=1}^{Q} \left(\frac{u_q n_q}{k_q} + \frac{v_q p_q}{k_q} \right)$$

Subject to:

$$f_q(\underline{\boldsymbol{x}}) + n_q - p_q = b_q \qquad q = 1, \dots Q$$

$$\underline{x} \in F$$

$$n_q, p_q \geq 0 \qquad q = 1, \dots, Q$$

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Distance Metric based MCDM methods

- A distance-metric based MDCM method utilises one or more distance metrics to achieve a solution in accord with the decision maker(s) preferences
  - Goal programming: Minimise distance between a set of decision maker specified targets and the set of achieved values (Charnes and Cooper, 1955, 1961)
  - Compromise programming: Minimise distance between the set of ideal values and the set of achieved values (Yu and Zeleny, 1973).
- The Lp distance metric is most frequently used:

$$Min\ L_p = \left[\sum_{i=1}^{Q} \left(\frac{u_i n_i}{k_i} \right)^p + \sum_{i=1}^{Q} \left(\frac{v_i p_i}{k_i} \right)^p \right]^{1/p}$$

- Weighted goal programming: p=1
- Lexicographic goal programming: series of p=1
- Chebyshev goal programming (Flavell, 1976): p=∞
- Extended goal programming (Romero, 2004): p=1 and p=∞
- Meta goal programming (Rodriguez *et al.*, 2002): p=0, p=1 and p=∞

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Goal programming variants

'Distance' Variant

Lexicographic
Weighted
Chebyshev

Classical

Meta
Extended
Extended Network
Multi-Choice

Recent

+

'Decision/Goal' Variant

Integer
Binary
Fractional
Non-linear
Stochastic

Decision

Fuzzy
Chance Constrained
Interval
Non-Standard Preference

Goal

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Extended Goal Programming (Non-Lexicographic) – Romero 2001,2004

$$Min\ a = \alpha\lambda + (1-\alpha)\sum_{i=1}^{q}\left(\frac{u_i n_i}{k_i} + \frac{v_i p_i}{k_i}\right)$$

Balance

Optimisation

Subject to,

$$f_i(\underline{x}) + n_i - p_i = b_i \quad i = 1,\ldots,q$$

$$\frac{u_i n_i}{k_i} + \frac{v_i p_i}{k_i} \leq \lambda \qquad i = 1,\ldots,q$$

$$n_i, p_i \geq 0 \quad i = 1,\ldots,q \quad \lambda \geq 0$$

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Extension to a network of decisions

- Consider a network with L layers.
- Each network layer $l = 1, \ldots, L$ consists of j^l nodes
- Each node has k objectives, with associated function $f_k^{j^l}(\underline{x})$, a target value $b_k^{j^l}$ and deviational variables $n_k^{j^l}$ and $p_k^{j^l}$

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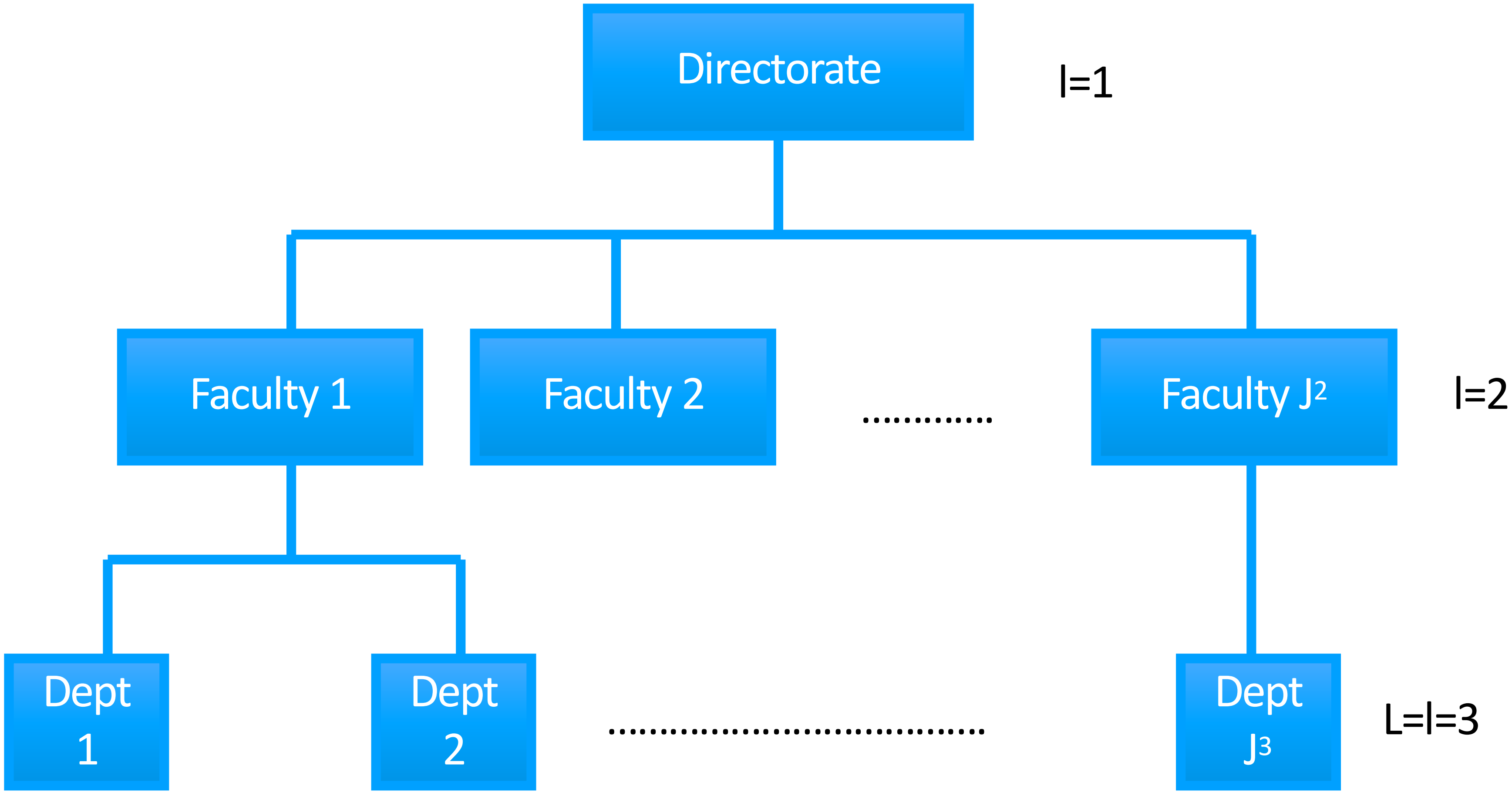
Example – A University



Research output, student numbers, student satisfaction ,….

Extended goal programming network model (part 1)

$$Min\ a = w_1 \left[\alpha^{j^1} \lambda^{j^1} + (1 - \lambda^{j^1}) \left(\sum_{k=1}^{K} \frac{u_k^{j^1} n_k^{j^1}}{b_k^{j^1}} + \frac{v_k^{j^1} p_k^{j^1}}{b_k^{j^1}} \right) \right]$$

$$+ \sum_{l=2}^{L} w_l \left[\beta_l D_l + (1 - \beta_l) \sum_{j^l=1}^{J^l} \left\{ \alpha^{j^l} \lambda^{j^l} + (1 - \alpha^{j^l}) \left(\sum_{k=1}^{K} \frac{u_k^{j^l} n_k^{j^l}}{b_k^{j^l}} + \frac{v_k^{j^l} p_k^{j^l}}{b_k^{j^l}} \right) \right\} \right]$$

Subject to,

$$f_k^{j^l}(\underline{x}) + n_k^{j^l} - p_k^{j^l} = b_k^{j^l} \quad k = 1, \dots, K; \quad j^l = 1, \dots, J^l; \quad l = 1, \dots, L$$

Extended Goal Programming Network Model (part 2)

$$\sum_{k=1}^{K} \frac{u_k^{j^l} n_k^{j^l}}{b_k^{j^l}} + \frac{v_k^{j^l} p_k^{j^l}}{b_k^{j^l}} \leq \lambda^{j^l} \qquad k = 1, \dots, K; \quad j^l = 1, \dots, J^l; \quad l = 1, \dots, L$$

$$\sum_{j^l=1}^{J^l} \left\{ \alpha^{j^l} \lambda^{j^l} + (1 - \alpha^{j^l}) \left(\sum_{k=1}^{K} \frac{u_k^{j^l} n_k^{j^l}}{b_k^{j^l}} + \frac{v_k^{j^l} p_k^{j^l}}{b_k^{j^l}} \right) \right\} \leq D_l \quad j^l = 1, \dots, J^l; \quad l = 1, \dots, L$$

$$\underline{x} \in F$$

$$n_k^{j^l}, p_k^{j^l} \geq 0 \quad k = 1, \dots, K; \quad j^l = 1, \dots, J^l; \quad l = 1, \dots, L$$

$$\lambda^{j^l} \geq 0 \quad j^l = 1, \dots, J^l; \quad l = 1, \dots, L; \quad D_l \geq 0 \quad l = 1, \dots, L$$

Important Parameters

w_l is the relative level of importance given to network level l

α^{j^l} gives the level of consideration of balance versus optimisation amongst **objectives** at node j^l at network level l.

β_l gives the level of consideration of balance versus optimisation amongst **stakeholders** scores at network level l.

Multiple Criteria in Sustainability

Source, Rochester Institute of Technology, US and United Nations

Sustainable:

- Energy
- Agriculture
- Cities
- Tourism
- Development
- Finance
- Healthcare
- Transportation
- Logistics and Supply Chain Management
- ……….

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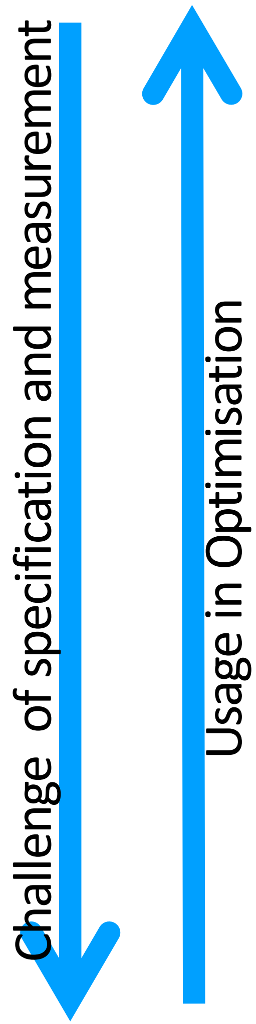
Multi-criteria Sustainability

- Over 2000+ articles combining multiple criteria and sustainable keywords
  - 178 combining goal programming and sustainable keywords
  - Some recent examples:
- Sustainable Indian Economic growth and development (Gupta *et al., 2018)*
  - *Fuzzy goal programming model*
- Sustainable Portuguese agriculture (Xavier *et al*., 2018)
  - *Extended goal programming model*
- Sustainable tourism evaluation (Blancas *et al.,* 2018)
  - *Weighted goal programming with multiple sub-criteria (indices)*
- Sustainable biomass supply chain network (Petridis *et al.*, 2018)
  - *Mixed integer weighted goal programming model*
- Sustainable forestry management (Belavenutti *et al.,* 2018)
  - *Survey include multiple goal programming variants and AHP*
- Sustainable remanufacturing processes (Shakourloo, 2017)
  - *Stochastic goal programming model*

Sustainability criteria

- Technical
  - Is solution able to cope with future demands and conditions (deterministic or stochastic)?
    - Capacity goals, production goals, design goals
- Economic
  - Is solution financially viable on a long-term basis?
    - Cost goals, profit goals, efficiency goals
- Environmental
  - Is solution environmental beneficial and does not cause damage?
    - Emissions goals, ecological goals, pollution goals
- Social
  - Is the solution socially beneficial and equitable
    - Employment goals, equity goals, provision goals, impact goals, access to services goals



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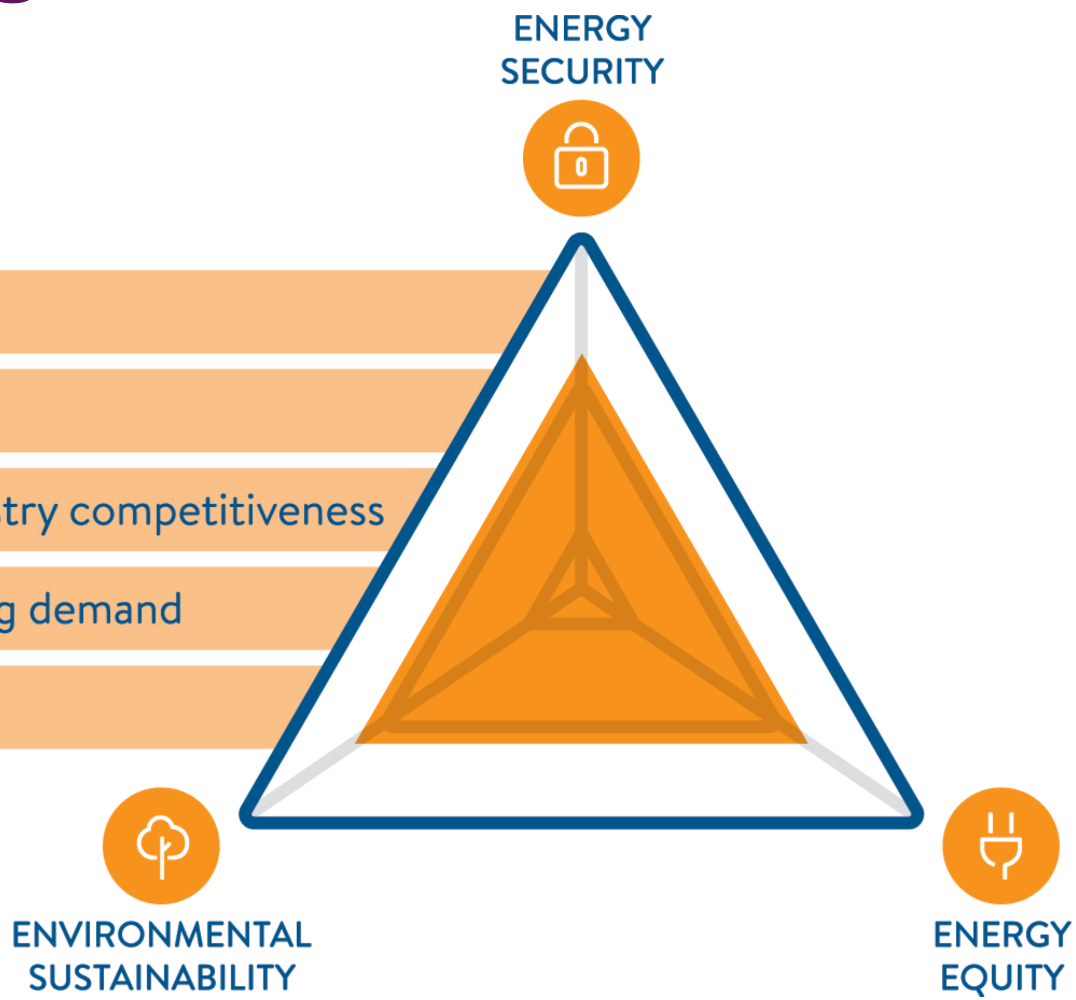
Multiple Criteria in Sustainable Energy Planning

Energy Trilemma

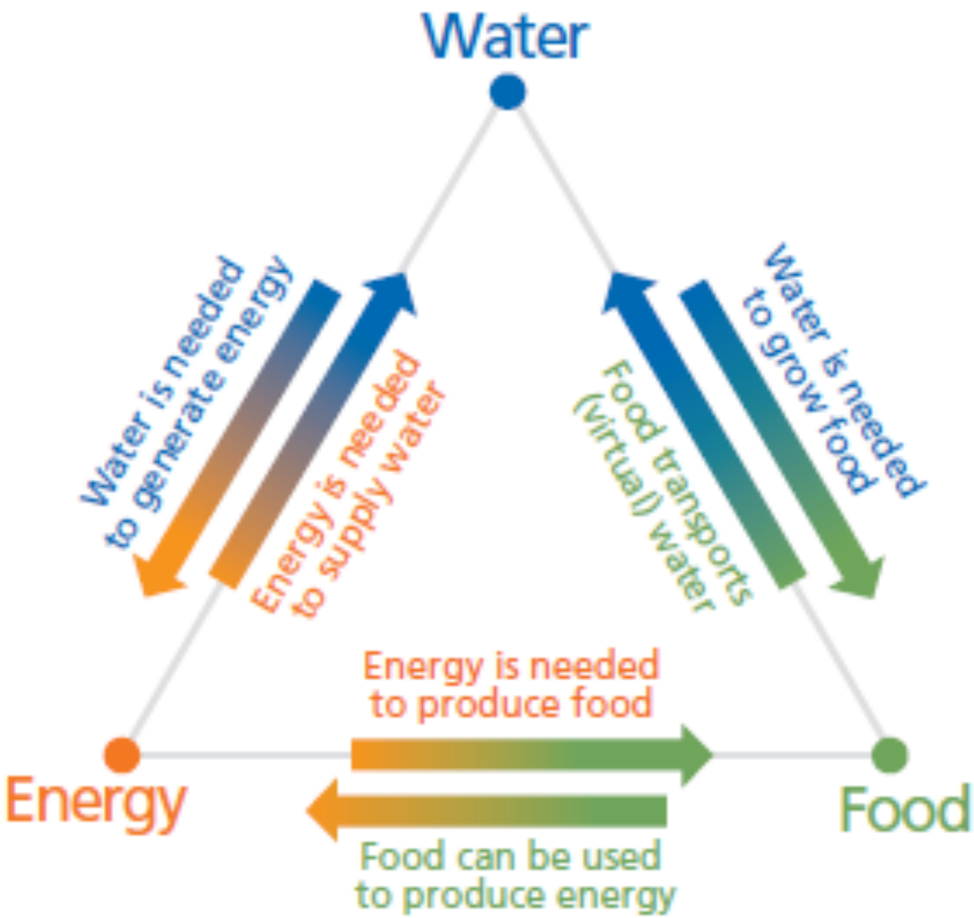
1. Transforming energy supply
2. Advancing energy access
3. Enabling consumer affordability and industry competitiveness
4. Improving energy efficiency and managing demand
5. Decarbonising the energy sector



Source: World Energy Council

Multiple Criteria in Sustainable Development

Nexus



Source: United Nations University

Application: Sustainable Container routing in Spain

- Decision problem: Quantity of container traffic to route through 12 key ports on the Southern-Western Atlantic and Mediterranean Coasts
  - 83% of Spanish container total, approx. 15 million TEUs, 5% future increase

Model Characteristics

- The extended network goal programming variant (Jones *et al*., 2016) is utilized as the decision involves multiple geographical regions and stakeholders.
- Aim is to try and allocate future container growth in a socially sustainable manner

Different objectives:

- Economic → Container transportation costs and port costs
- Social → Youth unemployment and youth employment rate
- Environmental → Carbon dioxide emissions and air quality index (AQI)
- Technical → The allowed vessel size

Stakeholders:

- Spanish Government, regional governments, logistics providers

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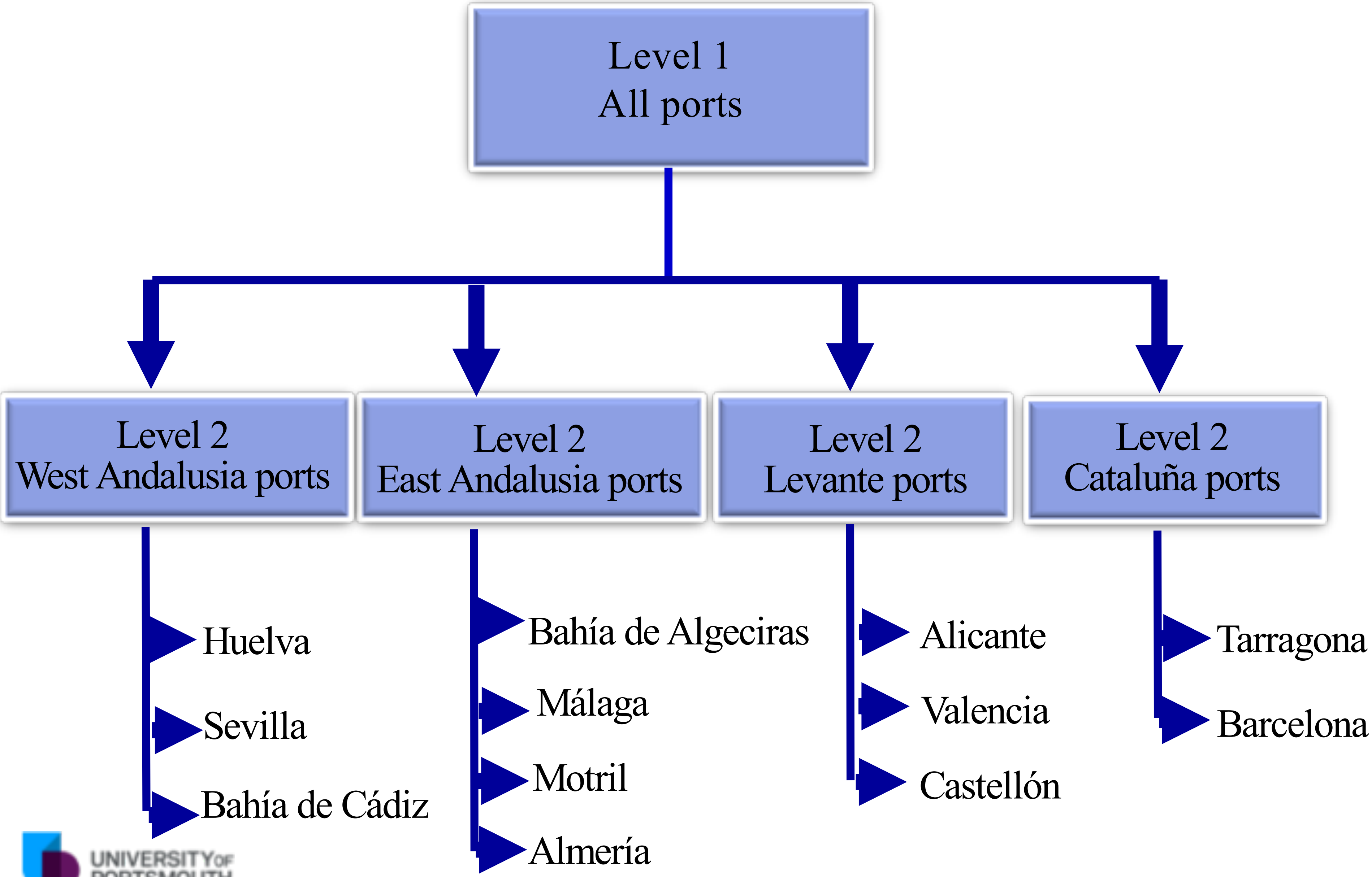
Network of Ports



Goal programming parameters

Decision variables		• Amount of TEUs in each port in the future $x_i \quad i = 1, \ldots, 12$
Goals	Economic	• Minimise container transportation costs TC • Minimise port costs PC
	Social	• Minimise the youth unemployment rate YU • Maximise the youth employment rate YE
	Environmental	• Minimise carbon dioxide emissions $CO2$ • Maximise the air quality index (AQI) of the port AQI
	Technical	• Maximise the allowed vessel size VS
Fixed restrictions		• Limits on TEUs required by each city • Ensure all future TEUs assigned to a port • Minimum and maximum value of the decision variables

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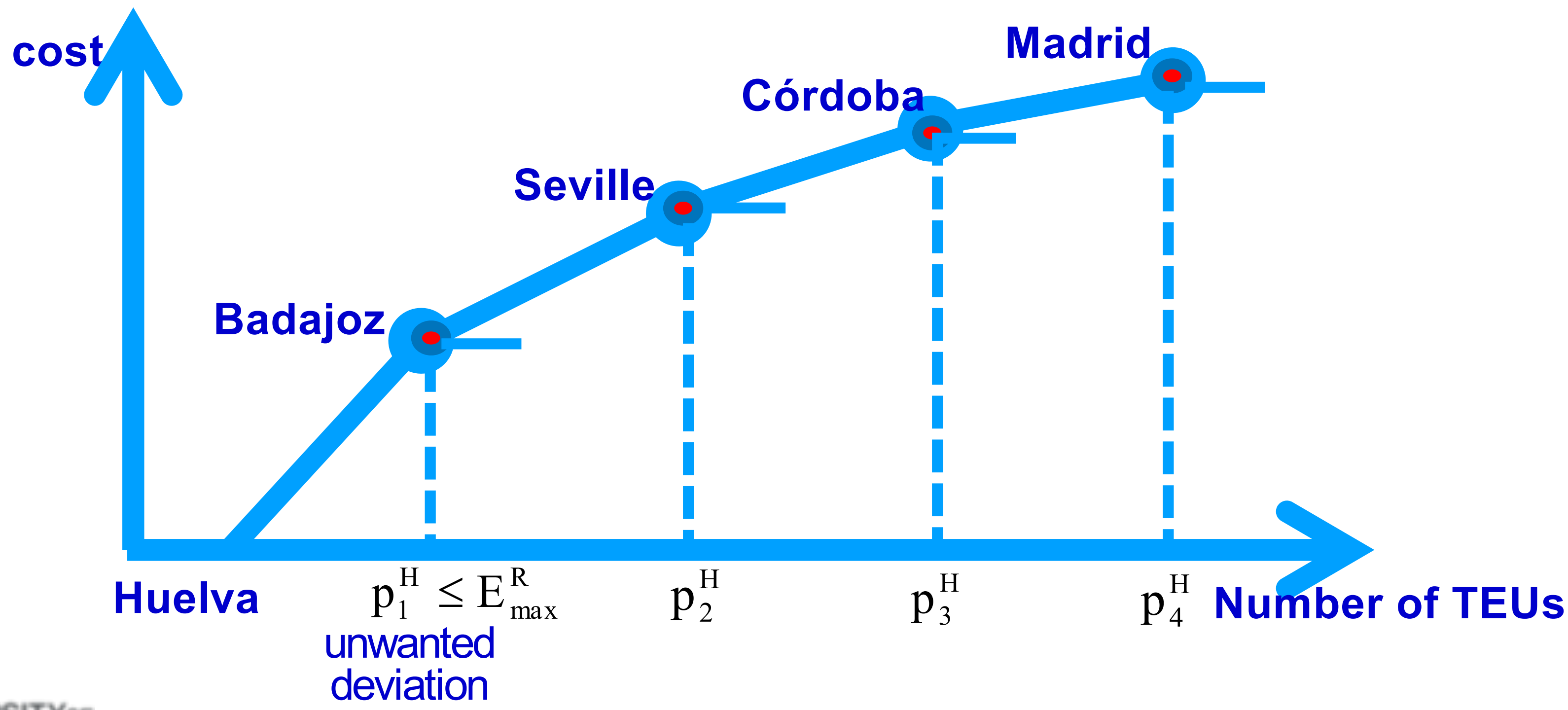
Transportation cost modelling

- Penalty function approach: approximation based on container flows to major cities

$$\sum_{k=1}^{4}\sum_{i=1}^{12} TC_{ki} \cdot p_{ki} + n_1^G - \underline{p_1^G} = TC_G$$



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Port cost modelling

Port i	Port cost (€) (31/12/15)	TEUs	Port cost (€/TEU)
Huelva	38,341,808.4	47,571.87	805.98
Sevilla	26,639,049.5	229,153.08	116.25
B. Cádiz	21,542,450.2	36,631.07	588.09
B. Algeciras	76,333.6	37,149.18	2.05
Málaga	20,701,539.7	178,910.84	115.71
Motril	8,603,547.9	17,734.65	485.13
Almería	16,031,933.4	59,701.12	268.54
Alicante	13,793,370.3	104,756.02	131.67
Valencia	128,860,408.3	303,483.71	424.60
Castellón	21,219,461.2	70,359.40	301.59
Tarragona	48,216,994.6	63,957.07	753.90
Barcelona	145,351	777,216	**0.19**

Source: Profit and loss accounts (BOE, 2015)

$$PC_i = \frac{\text{total port cost (€)}}{\text{number TEUs}}$$

$$\sum_{i=1}^{12} PC_i x_i + n_2^G - \underline{p_2^G} = PC_G$$

Target value PC_G

Smallest PC_i x Total future TEUs (increase 5%)

0.19 * 2,022,955

Youth unemployment modelling

Port i	Youth unemployed people (Dic 2016)	Youth working-age population (Dic 2016)	Youth unemployment rate %
Huelva	5,672	18,300	30.99
Sevilla	21,613	62,200	34.75
B. Cádiz	16,023	33,200	**48.26**
B. Algeciras	16,023	33,200	**48.26**
Málaga	15,089	45,500	33.16
Motril	8,919	28,100	31.74
Almería	5,477	24,400	22.45
Alicante	10,755	59,900	17.95
Valencia	13,862	93,000	14.91
Castellón	3,409	18,100	18.83
Tarragona	4,166	25,900	16.08
Barcelona	18,439	194,300	9.9

Source: SEPE statistics

Source: INE statistics

$$\sum_{i=1}^{12} YU_i x_i + n_3^G - \underline{p_3^G} = YU_G$$

Target value YU_G

Maximum YU_i x Total future TEUs (increase 5%)

0.48 * 2,022,955

$$YU_i = \frac{\text{number of unemployed 15 – 24 year - olds}}{\text{working - age population 15 - 24 year - olds}} \cdot 100$$

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Youth employment modelling

Port i	Youth employed people (Dic 2016)	Youth population (Dic 2016)	Youth employment rate %
Huelva	12,628	54,846	23.02
Sevilla	40,587	207,743	19.54
B. Cádiz	17,177	133,123	**12.90**
B. Algeciras	17,177	133,123	**12.90**
Málaga	30,411	165,827	18.34
Motril	19,181	100,796	19.03
Almería	18,923	77,248	24.50
Alicante	49,145	180,216	27.27
Valencia	79,138	244,334	32.39
Castellón	14,691	55,616	26.42
Tarragona	21,734	77,093	28.19
Barcelona	175,861	522,673	33.65

Youth working-age population – youth unemployment

Source: INE statistics

$$\sum_{i=1}^{12} YE_i x_i + \underline{n_4^G} - p_4^G = YE_G$$

Target value YE_G

Minimum YE_i x Total future TEUs (increase 5%)

0.129 * 2,022,955

$$YE_i = \frac{\text{number of employed people 15 - 24 years - old}}{\text{total population 15 - 24 years - old}} \cdot 100$$

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Carbon emissions modelling

Port i	CO_2 (tons) verified in 2015	Rank
Huelva	3,282,033	9
Sevilla	60,204	4
B. Cádiz	0	1
B. Algeciras	3,906,065	10
Málaga	1,381,532	8
Motril	173,219	5
Almería	0	1
Alicante	1,442	2
Valencia	12,530	3
Castellón	1,319,617	7
Tarragona	4,259,503	11
Barcelona	1,107,019	6

Source: Observatorio de la Sostenibilidad Report

$CO2_i$

$$\sum_{i=1}^{12} CO2_i x_i + n_5^G - \underline{p_5^G} = CO2_G$$

- Main CO_2 emitting installations
- Installations are located less than 15 km from the port

Target value $CO2_G$

Minimum rank x Total future TEUs (increase 5%)

1 * 2,022,955

Air quality modelling

Port i	AQI value (31/12/16)
Huelva	48
Sevilla	44.8
B. Cádiz	46
B. Algeciras	56
Málaga	47.33
Motril	60
Almería	52
Alicante	34
Valencia	39.6
Castellón	30
Tarragona	41.33
Barcelona	46.55

Source: AQI statistics Spain.
Ecologistas en Acción

AQIi

$$\sum_{i=1}^{12} AQI_i x_i + n_6^G - \underline{p_6^G} = AQI_G$$

Target value AQIG

Biggest good value in levels of health x Total future TEUs (increase 5%)

50 * 2,022,955

AQI colour code guide

AQI values	Levels of Health	Colour
0-50	Good	Green
51-100	Moderate	Yellow
101-150	Unhealthy for sensitive group	Orange
151-200	Unhealthy	Red
201-300	Very Unhealthy	Purple

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Vessel size modelling

Port i	Basin length in commercial docks (m)	Rank
Huelva	4,298	7
Sevilla	4,714	6
B. Cádiz	2,392	11
B. Algeciras	6,776	4
Málaga	2,938	10
Motril	2,369	12
Almería	3,320.7	8
Alicante	3,099.07	9
Valencia	12,462	2
Castellón	6,388	5
Tarragona	8,981	3
Barcelona	15,229.7	1

Source: Puertos del Estado. Annual reports

VS_i

$$\sum_{i=1}^{12} VS_i x_i + \underline{n_7^G} - p_7^G = VS_G$$

Target value VS_G

Smallest rank x Total future TEUs (increase 5%)

1 * 2,022,955

Second level (regional) modelling

- To calculate economic, social, environmental and technical goals by region

Example: Minimise port costs by region (Goal 2 Level 2)

West Andalusia ports #3

$$\sum_{i=1}^{3} PC_i x_i + n_2^{R_1} - \underline{p_2^{R_1}} = PC_1$$

Region 1

East Andalusia ports #4

$$\sum_{i=4}^{7} PC_i x_i + n_2^{R_2} - \underline{p_2^{R_2}} = PC_2$$

Region 2

Levante ports #3

$$\sum_{i=8}^{10} PC_i x_i + n_2^{R_3} - \underline{p_2^{R_3}} = PC_3$$

Region 3

Cataluña ports #2

$$\sum_{i=11}^{12} PC_i x_i + n_2^{R_4} - \underline{p_2^{R_4}} = PC_4$$

Region 4

Target values PC_j

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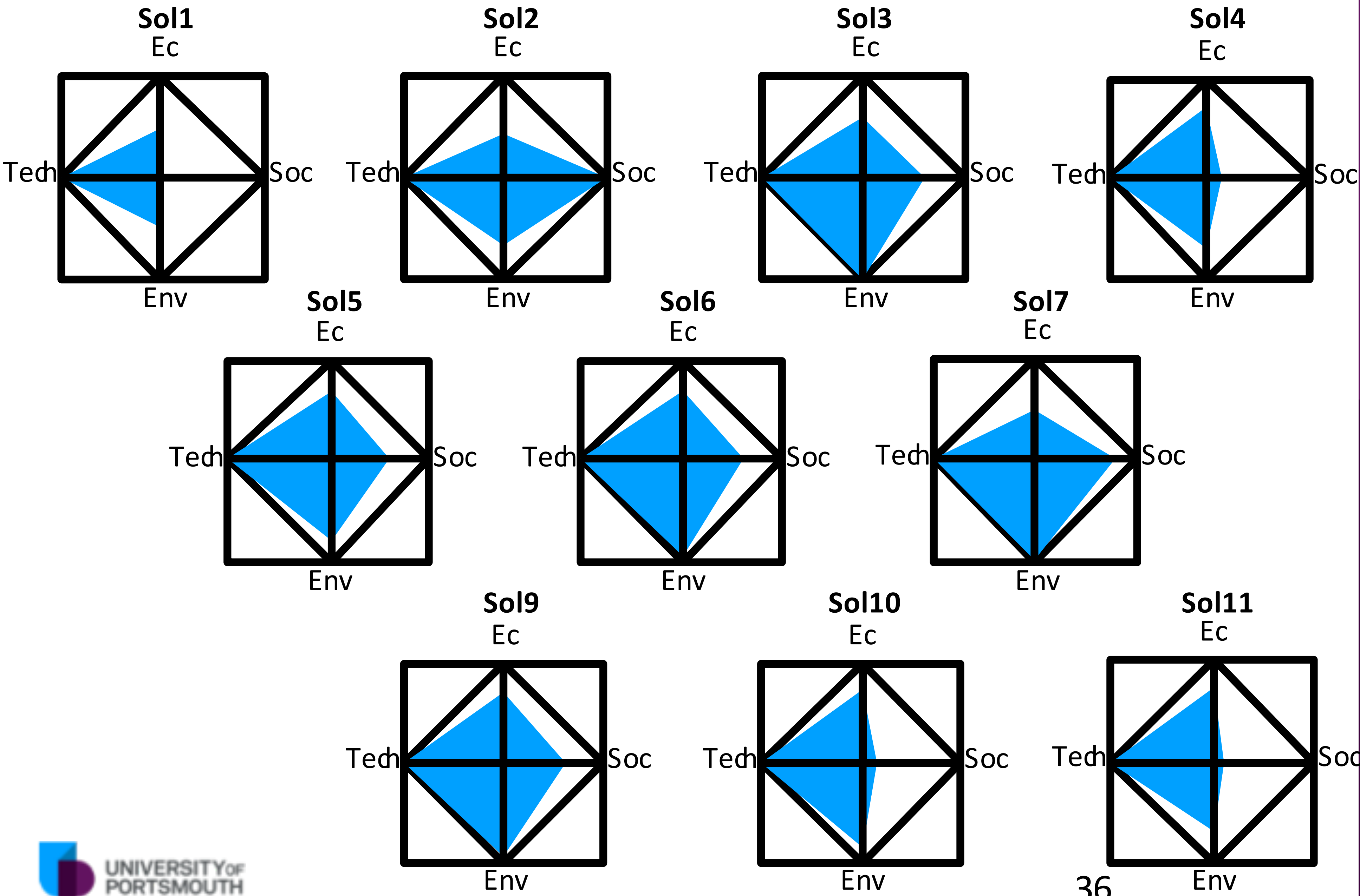
Extended network goal programming achievement function

$$Min\, w\left[\alpha^G D^G + (1-\alpha^G)\left(\frac{v_1^G p_1^G}{TC_G} + \frac{v_2^G p_2^G}{PC_G} + \frac{u_1^G n_3^G}{YUR_G} + \frac{v_4^G p_4^G}{YER_G} + \frac{v_5^G p_5^G}{CO2_G} + \frac{v_6^G p_6^G}{AQI_G} + \frac{u_2^G n_7^G}{LP_G}\right)\right] +$$

$$(1-w)\left[\beta D^R + (1-\beta)\sum_{j=1}^{4}\left(\alpha^{R_j} D^{R_j} + (1-\alpha^{R_j})\left(\frac{v_1^{R_j} p_1^{R_j}}{TC_j} + \frac{v_2^{R_j} p_2^{R_j}}{PC_j} + \frac{u_1^{R_j} n_3^{R_j}}{YUR_j} + \frac{v_4^{R_j} p_4^{R_j}}{YER_j} + \frac{v_5^{R_j} p_5^{R_j}}{CO2_j} + \frac{v_6^{R_j} p_6^{R_j}}{AQI_j} + \frac{u_2^{R_j} n_7^{R_j}}{LP_j}\right)\right)\right]$$

- Normalization criteria: Dividing each unwanted deviation variable between their target (percentage normalisation).
- Sensitivity analysis (Jones, 2011) employed to elicit criterion trade-offs
- Models solved by LINGO software

Solutions by sustainability criteria



Sample Solution in Decision Space

Decision variables	Sol 10	
	TEU's	% change
x_1: Huelva port	45,952.12	-5%
x_2: Sevilla port	222,882.94	-5%
x_3: Bay of Cádiz port	35,628.76	-5%
x_4: Bay of Algeciras port	5,705.16	25%
x_5: Málaga port	17,4015.44	-5%
x_6: Motril port	5,749.8	-5%
x_7: Almeria port	58,067.56	-5%
x_8: Alicante port	134,065.34	25%
x_9: Castellón port	388,394.36	25%
x_{10}: Valencia port	68,434.21	-5%
x_{11}: Tarragona port	62,207.06	-5%
x_{12}: Barcelona port	821,852.25	3%

Marine renewable energy planning: OR for sustainable energy

- 2OM Project (2012-2015)
  - 5 partner, €1.8million UK-France
  - Offshore wind farm maintenance and supply chain planning
- Channel MOR Project (2014-2015)
  - 12 partner, €1million UK-France
  - Marine renewable energy mapping
- Leanwind Project (2013-2017)
  - 31 partner, €10million Europe wide
  - Offshore wind efficiency (all aspects)
- Research visits to Brazil (2012-2016)

European Regional Development Fund
The European Union, investing in your future

Fonds européen de développement régional
L'Union européenne investit dans votre avenir

Offshore wind efficiency?

"Offshore wind to power £17.5bn investment boom as costs halve

Only a few years ago sceptics scoffed at claims that offshore wind power could be generated for a third less within a decade; this week the industry **cut its costs by half in less than three years**. This will mean cheaper energy bills for British households. But it could also establish the UK as a world leader in the green technology, as turbines are built along the coast."

True

Daily Telegraph, 11th September 2017

"Wind power has failed to deliver what it promised. The wind-power industry is expensive, passes costs on to the consumer and does not create many jobs in return"

Was True

Daily Telegraph View, 15th June 2013

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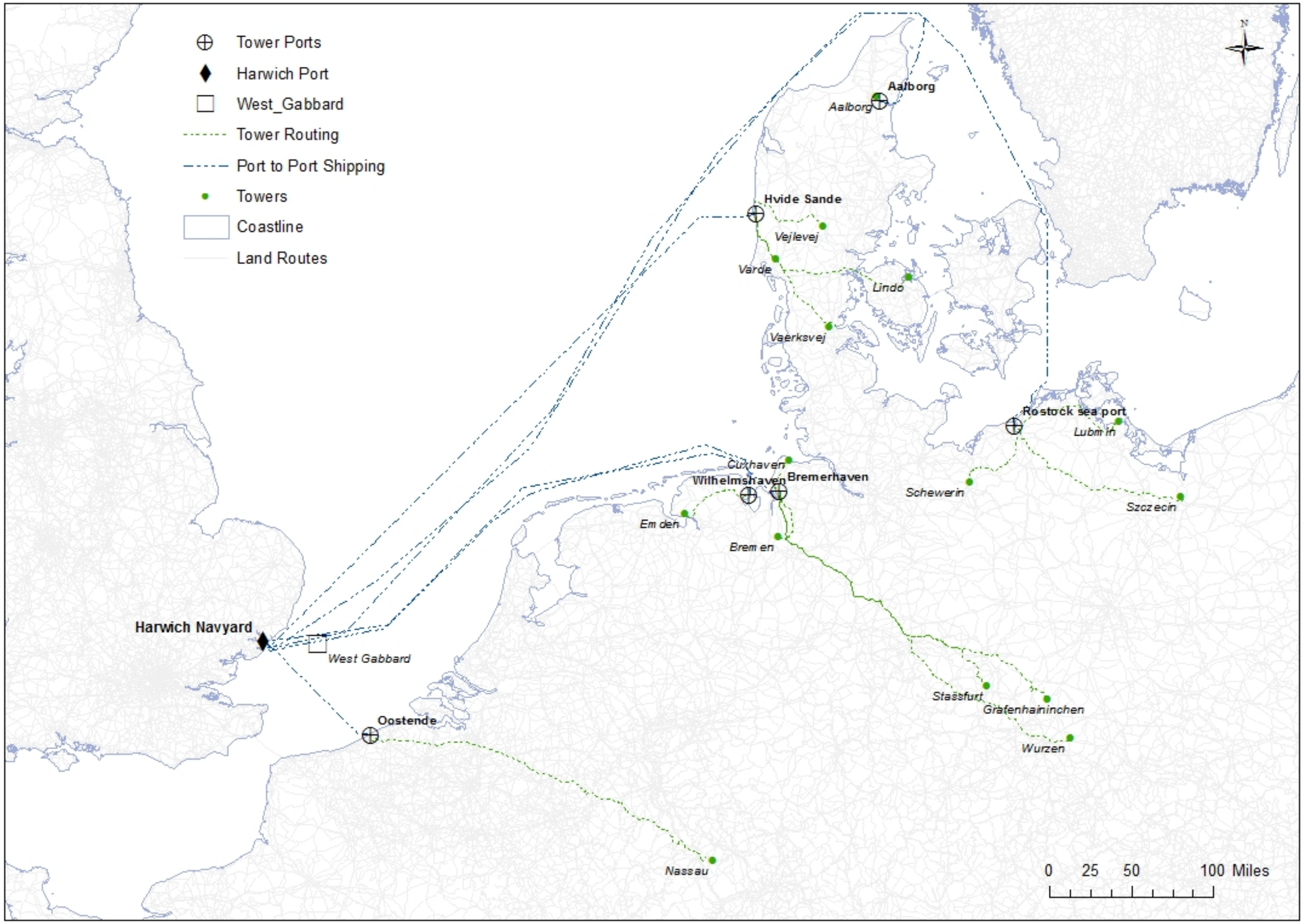
Proposed routing - construction



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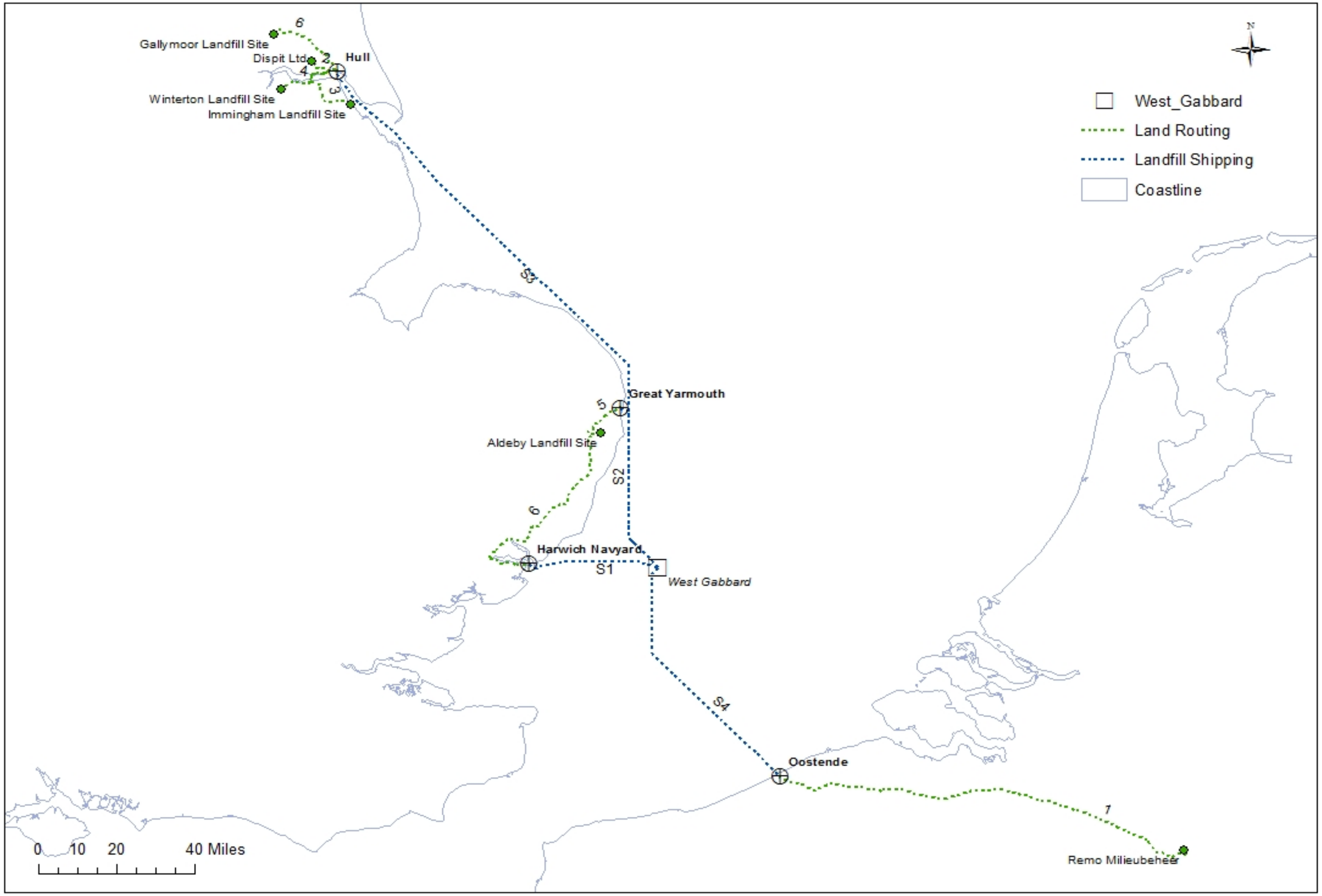
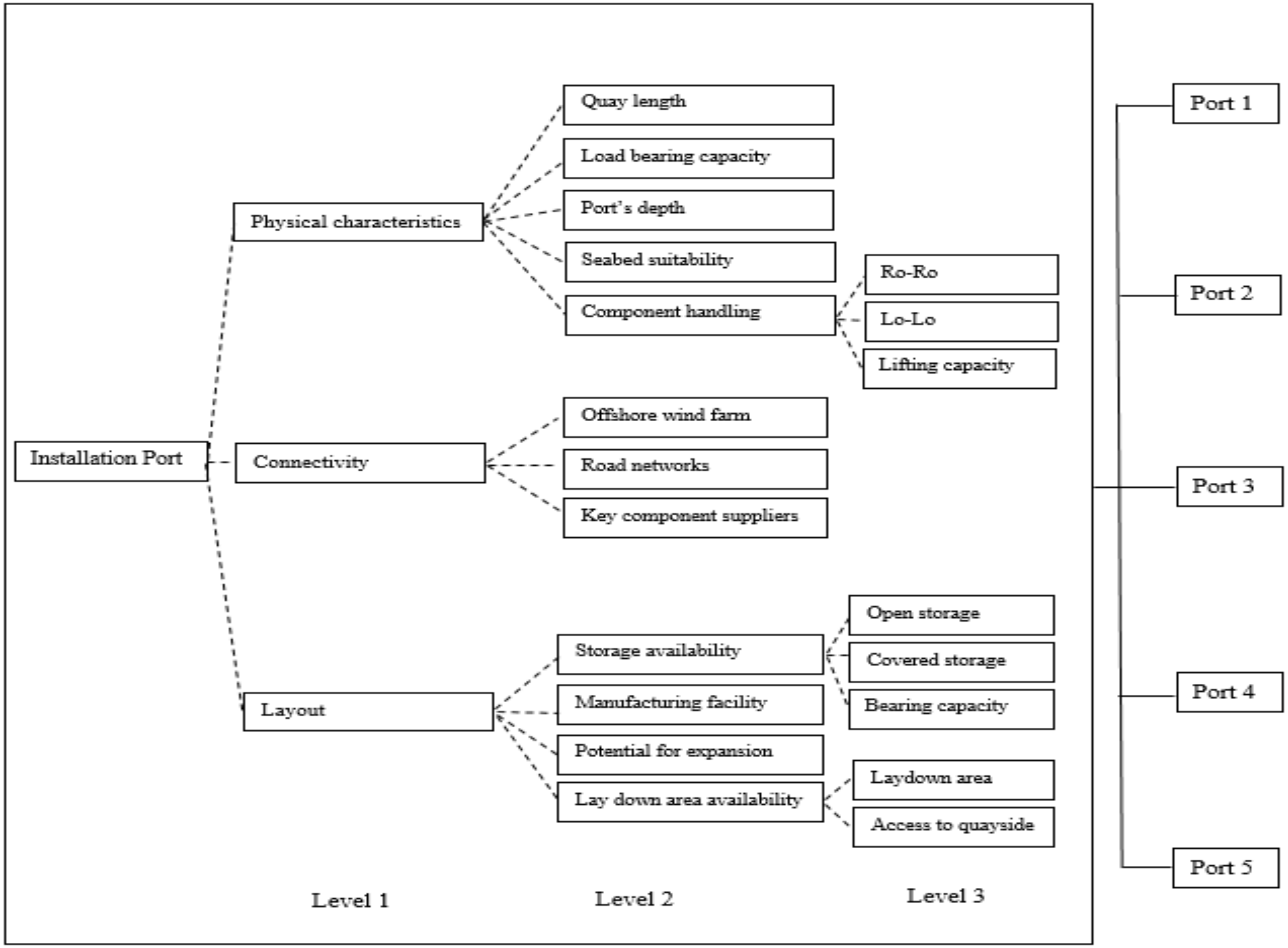
Proposed routing – Decommissioning



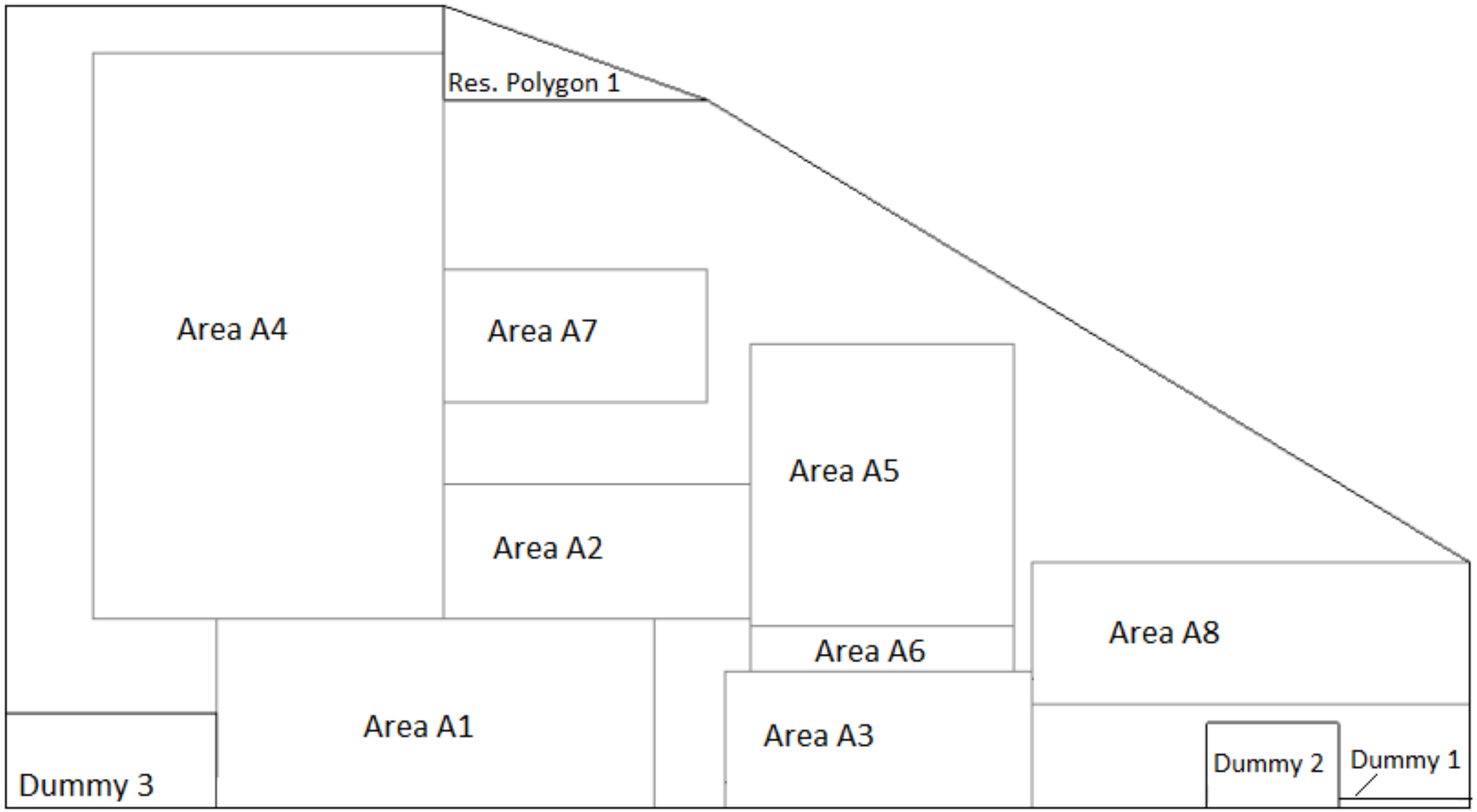
How to choose the ports?



Analytical Hierarchy Process (AHP)

Akbari, Irawan, Jones and Menachof (2017)

How to layout the ports?



Irregular shape packing – Irawan, Song, Jones, Akbari (2017)

Offshore wind site selection

Round 3 Sites

Jones and Wall, 2016

Where to build wind farms?

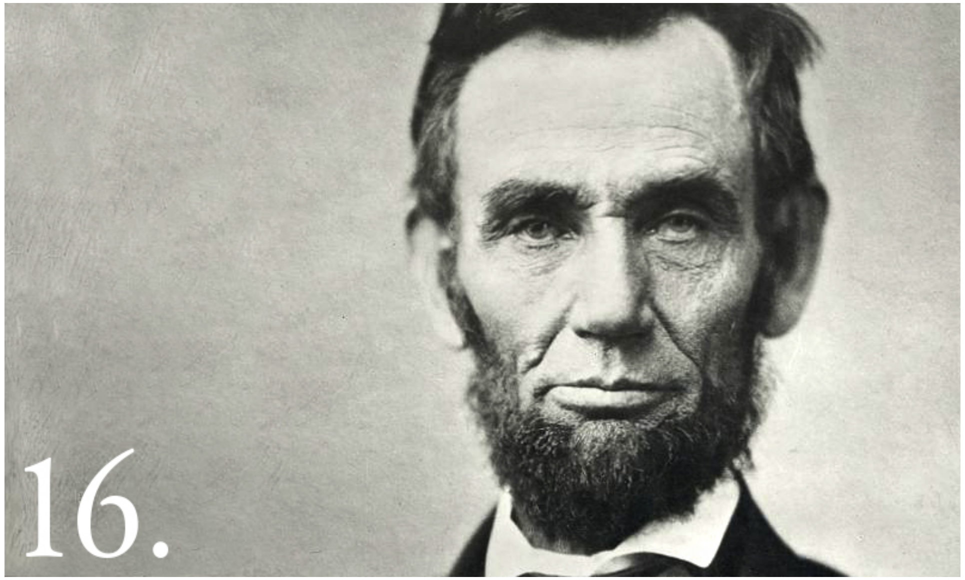
- Decision Owner: Crown Estate, Operators
  - Where to progress wind farms from a set of possible offshore locations ($x_i = 0$ if not progressed, $x_i = 1$ if progressed)
- Stakeholders:
  - Manufacturers
  - Operators
  - Governmental Authorities
  - Ports
  - Logistics Providers
  - Other Maritime Stakeholders: Leisure Community, Local Community, Environmentalists, Fishing Community.

Multi-stakeholder multi-criteria decision problem

"You can please some of the people all of the time, you can please all of the people some of the time, but you can't please all of the people all of the time"

A. Lincoln (apocryphal),

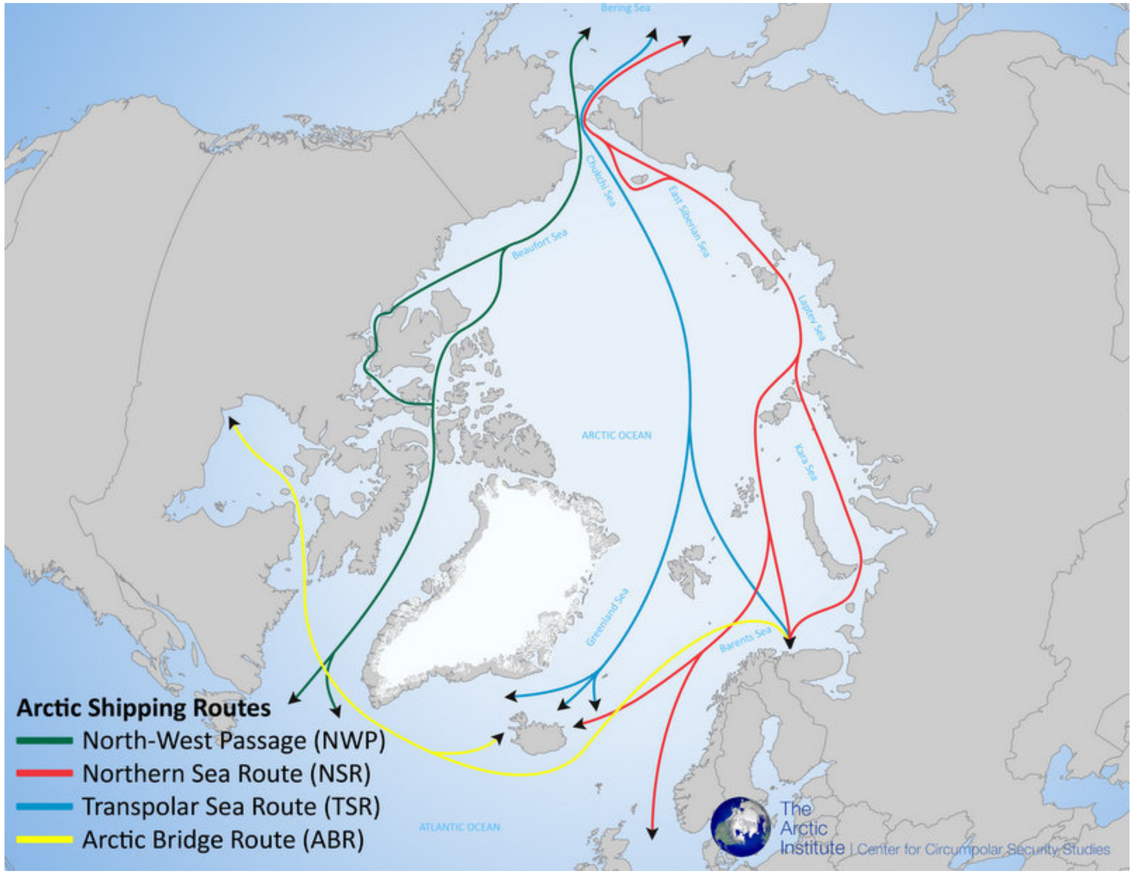
J. Lydgate (postulated)



Source: Whitehouse.Gov

Future Applications - Arctic shipping and tourism

- Potential gains in time, cost, distance
- Location and scheduling of search and rescue facilities
- Protection of environment and indigenous communities



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Future Application – Smart Lights Concept (SLIC)

- Assessment of smart lighting solutions in France, Belgium and the Netherlands

- Multiple sustainability criteria
  - Environmental pollution
  - Safety
  - Cost of Implementation

- Project timescale 2018-2021

Interreg
EUROPEAN UNION
2 Seas Mers Zeeën
SLIC
European Regional Development Fund

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Conclusions

- There is a natural synergy between multiple criteria decision making and sustainability
- Goal programming is an appropriate technique for the investigation of trade-offs between the attainment of conflicting sustainability goals
- The field of multiple criteria sustainability optimisation spans many, diverse current and future fields of application
- There exist challenges in accurate quantitative modelling of social (and sometimes other) sustainability criteria

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Thank you for attending

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