Multi-modal spatial availability: a research proposal

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Overview

1. Accessibility measures and multi-modal applications
2. Explaining spatial availability within multi-modal analysis
3. Policy scenario planning application: low emission zones in Madrid
4. Implications: the changes in spatial availability of opportunities, active mobility, GHG emissions

Multi-modal accessibility measures

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Gravity-based accessibility (Hansen-type) - no competition

$$A_i^m = \sum_j O_j f(c_{ij})^m$$

- i is a set of origin locations
- j is a set of destination locations
- O_j is the number of opportunities at location j
- $f(\cdot)$ is an impedance function of c_{ij} (cost of moving between i and j) for each mode m; if binary, the measure if *cumulative opportunities*

E.g., used in *(Tahmasbi et al., 2019)* to calculate A_i^m (per mode). Variations on how it is combined across modes.

Suffers from the same interpretability issues *(Handy and Niemeier, 1997; Miller et al., 2018)*.

Does not include competition (demand:supply, mass effect) *(Shen, 1998; Merlin and Hu, 2018)*.

Multi-modal accessibility measures

Competitive accessibility (Shen-type) - no proportional allocation

Shen (1998) modified Hansen-type accessibility; popularized as the two-step floating catchment area (2SFCA) method by *(Luo and Wang, 2003)*

$$S_i^m = \sum_j \frac{O_j f(c_{ij})^m}{\sum_m D_j^m}$$

with:

$$D_j^m = \sum_i P_i^m f(c_{ij})^m$$

- S_i^m is Shen-type accessibility for each mode m
- D_j^m is the demand at j from P_i using each mode m

Generalized multi-model competition:

$$S_i = \sum_m \left(\frac{P_i^m}{P_i}\right) \sum_j \frac{O_j f(c_{ij})^m}{\sum_m \sum_i P_i^m f(c_{ij})^m}$$

E.g., used by *Tao et al., 2020*.

However, the resulting value is an accessibility *score* so interpretation is obfuscated *(Soukhov et al., 2023)*.

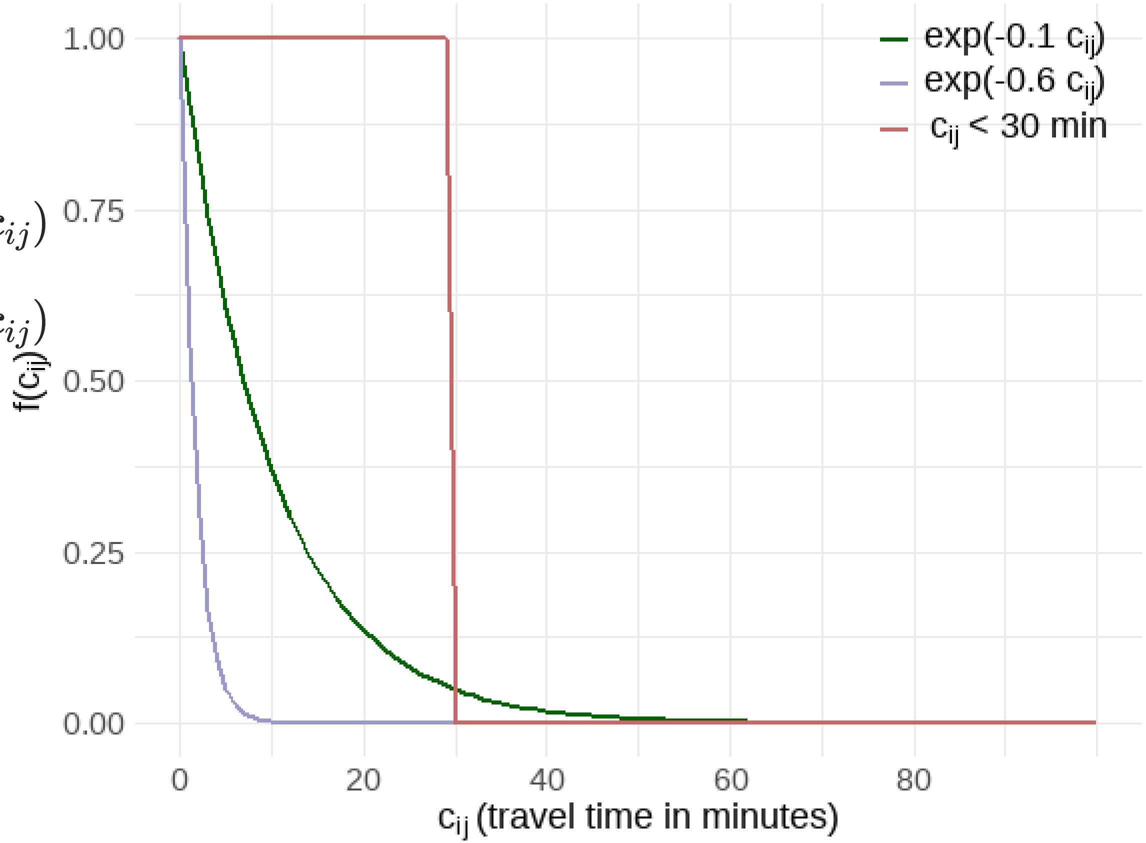
Impedance functions - quantifying how subsets of people travel

$f(c_{ij})^m$ is a function of the cost of moving between i and j for modes m.

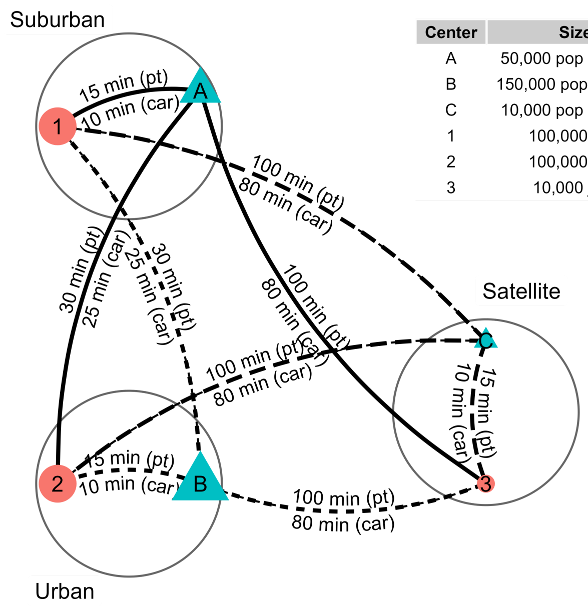
$$f(c_{ij})^{\text{t.behav.1}} = \exp(-0.1 \cdot c_{ij})$$

$$f(c_{ij})^{\text{t.behav.2}} = \exp(-0.6 \cdot c_{ij})$$

$f(c_{ij}) = 1$ if $c_{ij} \leq 30$
else $f(c_{ij}) = 0$



Simulated example - Hansen-type accessibility (no competition or proportional allocation consideration)



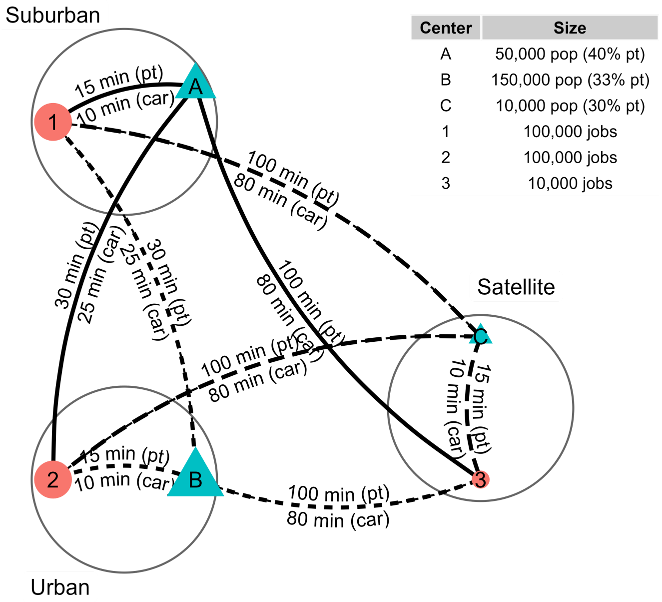
Center	Size
A	50,000 pop (40% pt)
B	150,000 pop (33% pt)
C	10,000 pop (30% pt)
1	100,000 jobs
2	100,000 jobs
3	10,000 jobs

$$A_i^m = \sum_j O_j f(c_{ij})^m$$

Impedance function:
$f(c_{ij})^{\text{car}} = f(c_{ij})^{\text{pt}} = exp(-0.1 \cdot c_{ij})$;

i	m	A
A	car	44999.80
A	pt	27292.18
B	car	44999.80
B	pt	27292.18
C	car	3745.89
C	pt	2240.38

Synthetic example - Shen-type accessibility (no proportional allocation consideration)



$$S_i = \sum_m \left(\frac{P_i^m}{P_i}\right) S_i^m$$

i	S
A	1.32
B	0.89
C	0.99

Spatial availability - competitive *and* proportional allocation

- Spatial availability considering multi-modes:

$$V_i^m = \sum_j^J O_j \, F_{ij}^{t,m}$$

- The proportional allocation factor combines two aspects of the problem, population and cost:

$$F_{ij}^{t,m} = \frac{F_i^{pm} \cdot F_{ij}^{cm}}{\sum_{m=1}^{M} \sum_{i=1}^{N} F_i^{pm} \cdot F_{ij}^{cm}}$$

- Where $F_i^{p,m}$ is population allocation factor:

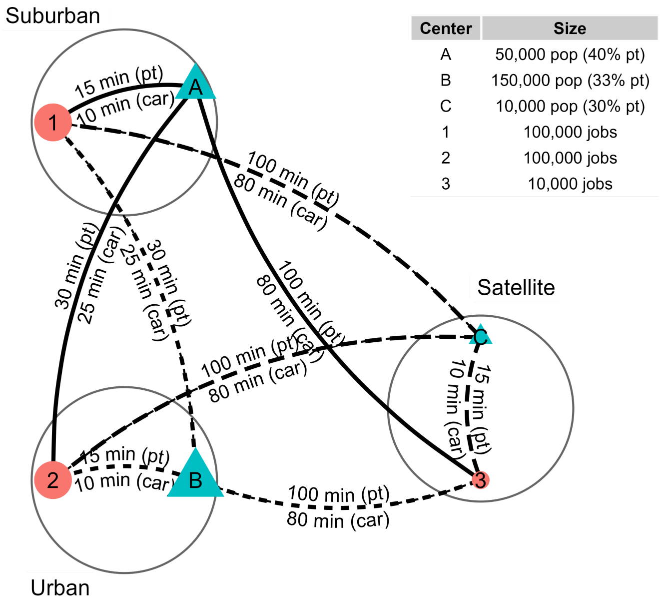
$$F_i^{p,m} = \frac{P_i^m}{\sum_i P_i^m}$$

- And the $F_{ij}^{c,m}$ is a cost allocation factor:

$$F_{ij}^{c,m} = \frac{f(c_{ij})^m}{\sum_i f(c_{ij})^m}$$

- Total spatial availability: $V_i = \sum_m^M V_i^m$
  - Considers competition and proportionally allocates opportunities (singly-constrained: $O = \sum_j O_j$)
- Total spatial availability per capita: $v_i = \sum_m \frac{V_i^m}{P_im}$
  - Equivalent to Shen-style accessibility

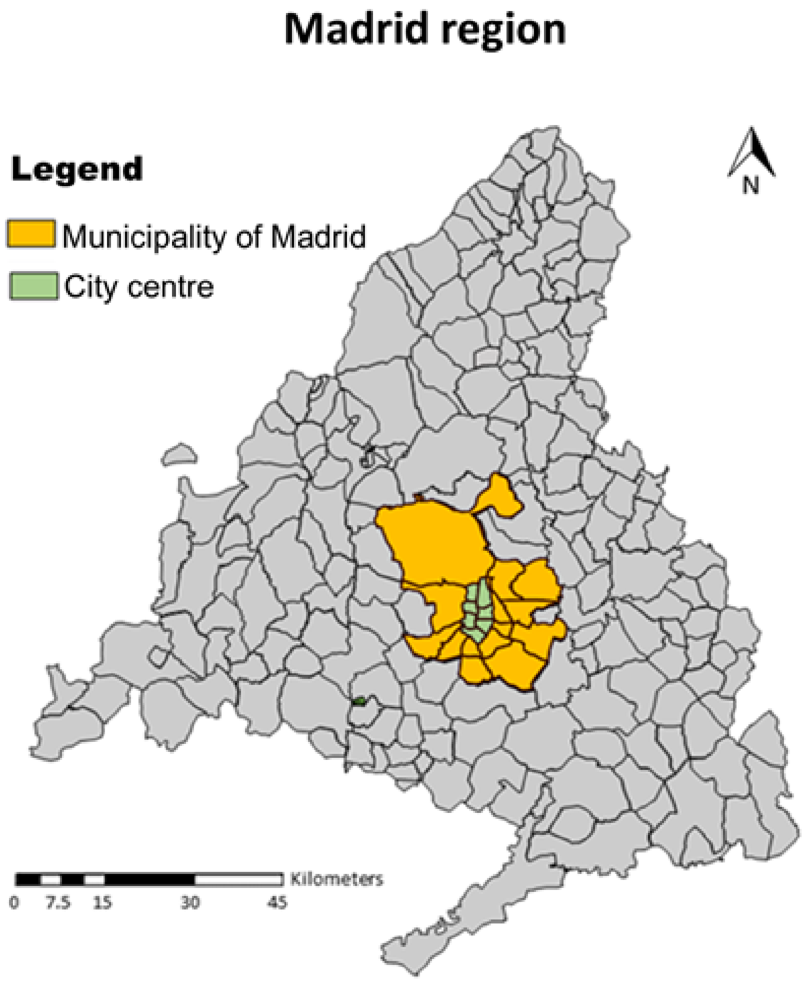
Spatial availability - competitive *and* proportional allocation



S_i (eqv. to v_i) and $V_i = \sum_{m=1}^{M} V_i^m$

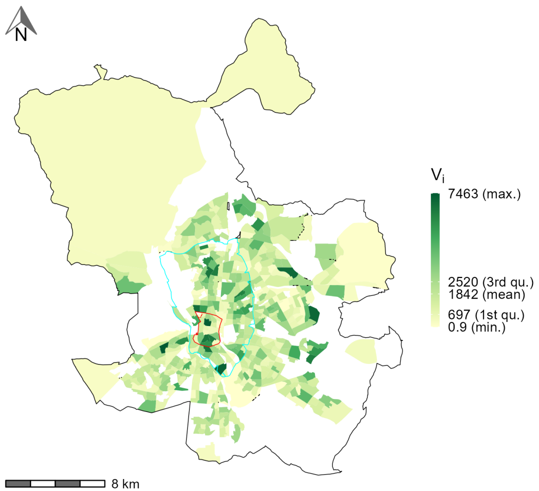
S	V
1.32	65918.81
0.89	134209.03
0.99	9872.16

Madrid's low emission zones - a policy of modal discrimination

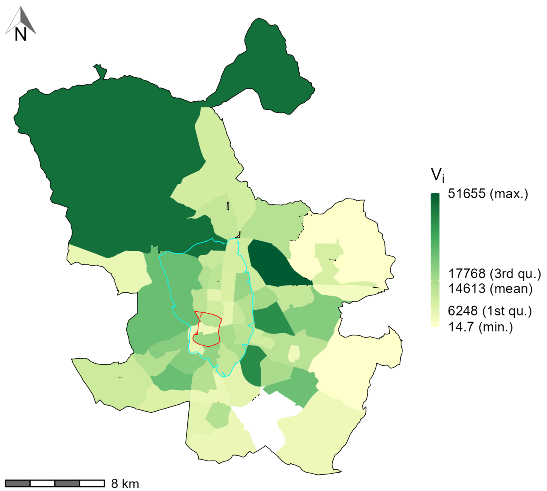


- November 2018 - LEZ Centro
- 2023 - LEZ within M-30
- 2024 - LEZ within Madrid Municipality

Multi-modal home-to-work accessibility in Madrid: 2018 travel survey

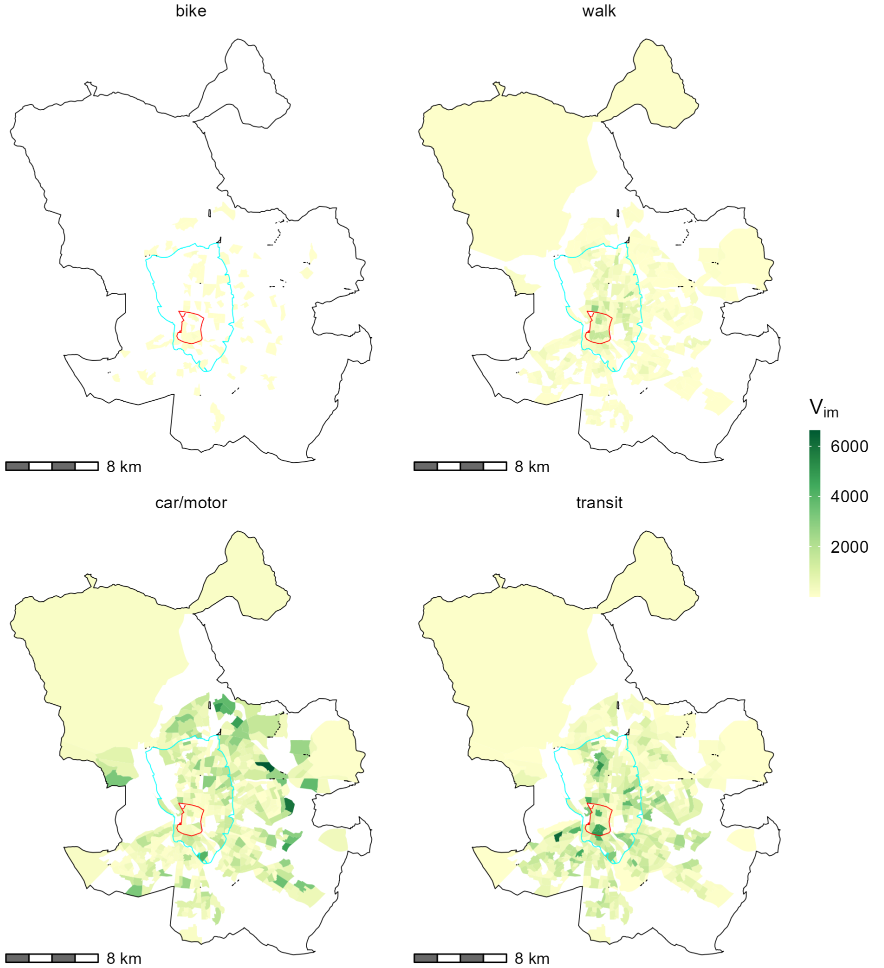


Spatial Availability V_i at resolution Zona 1259



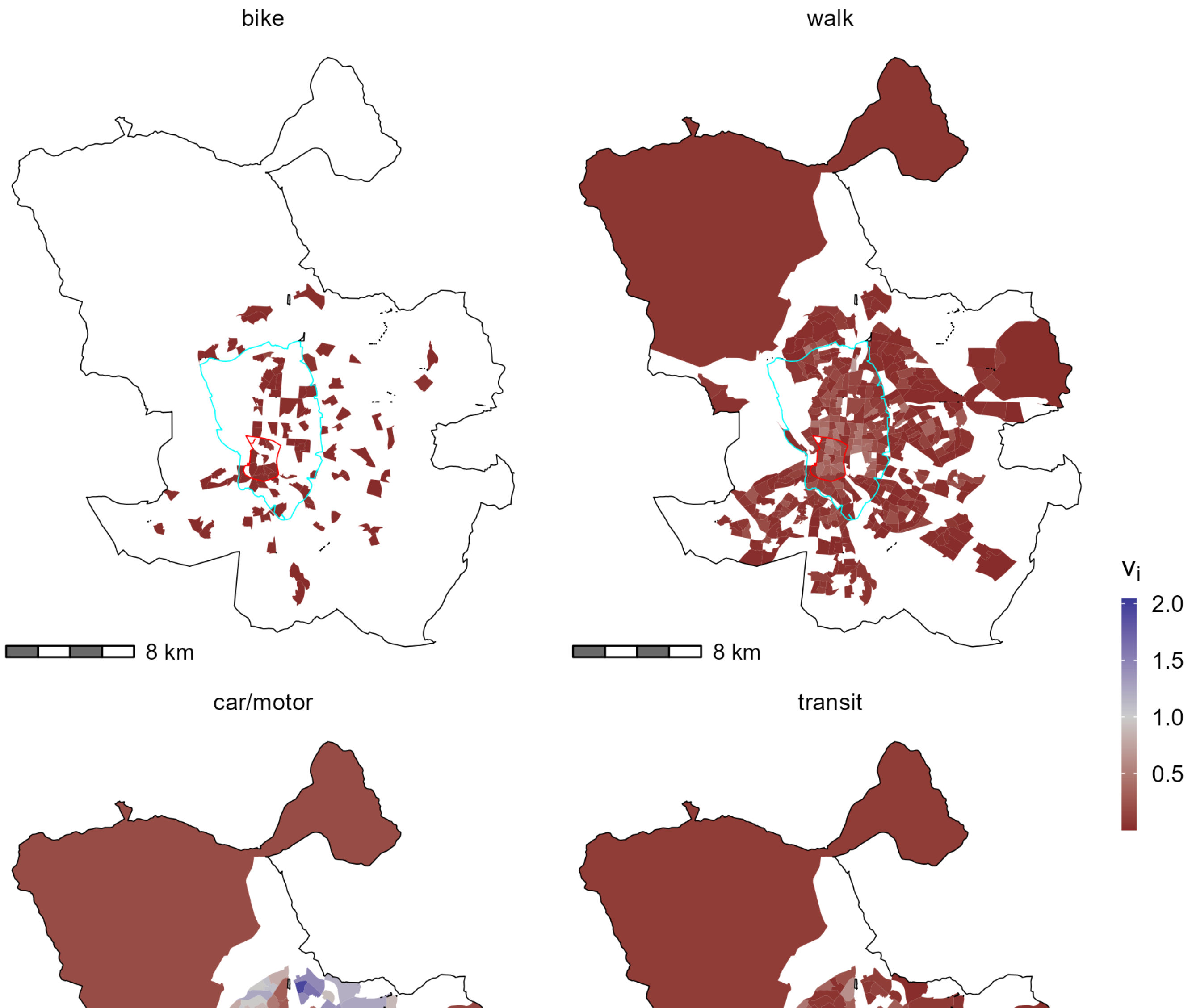
Spatial Availability V_i at resolution Zona 208

Multi-modal home-to-work accessibility in Madrid: 2018 travel survey



Spatial Availability V_i^m at resolution Zona 1259

Multi-modal home-to-work accessibility in Madrid: 2018 travel survey



Acknowledgments

MOBILIZING JUSTICE

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Any questions? Remarks?

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Spatial availability paper:

Extra slides

Proof: Spatial availability cancels out into Shen-style accessibility

Population allocation factor: $F_{ij}^{p} = \frac{P_{i\in r}^{\alpha}}{\sum_{i}^{K} P_{i\in r}^{\alpha}}$

$$F_{A}^{p} = \frac{P_{A}^{\alpha}}{P_{A}^{\alpha}+P_{B}^{\alpha}+P_{C}^{\alpha}}$$

Cost allocation factor: $F_{ij}^{c} = \frac{f(c_{ij})}{\sum_{i=A}^{K} f(c_{ij})}$

$$F_{A1}^{c} = \frac{f(c_{A1})}{f(c_{A1})+f(c_{B1})+f(c_{C1})} \; F_{B1}^{c} = \frac{f(c_{A2})}{f(c_{A2})+f(c_{B2})+f(c_{C2})} \; F_{C1}^{c} = \frac{f(c_{A3})}{f(c_{A3})+f(c_{B3})+f(c_{C3})}$$

Now let's put it together with P, and see how the denominators end up cancelling out:

$$v_i = \sum_j \frac{O_j}{P_{i\in r}^{\alpha}} \frac{\frac{P_{i\in r}^{\alpha}}{\sum_{i}^{K} P_{i\in r}^{\alpha}} \cdot \frac{f(c_{ij})}{\sum_{i}^{K} f(c_{ij})}}{\sum_{i}^{K} \frac{P_{i\in r}^{\alpha}}{\sum_{i}^{K} P_{i\in r}^{\alpha}} \cdot \frac{f(c_{ij})}{\sum_{i}^{K} f(c_{ij})}}$$

$$v_A = \frac{O_1}{P_A^\alpha}\left(\frac{\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{A1})}{f(c_{A1})+f(c_{B1})+f(c_{C1})}}{\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{A1})}{f(c_{A1})+f(c_{B1})+f(c_{C1})}+\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{B1})}{f(c_{A1})+f(c_{B1})+f(c_{C1})}+\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{C1})}{f(c_{A1})+f(c_{B1})+f(c_{C1})}}\right)+$$

$$\frac{O_2}{P_A^\alpha}\left(\frac{\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{A2})}{f(c_{A2})+f(c_{B2})+f(c_{C2})}}{\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{A2})}{f(c_{A2})+f(c_{B2})+f(c_{C2})}+\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{B2})}{f(c_{A2})+f(c_{B2})+f(c_{C2})}+\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{C2})}{f(c_{A2})+f(c_{B2})+f(c_{C2})}}\right)+$$

$$\frac{O_3}{P_A^\alpha}\left(\frac{\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{A3})}{f(c_{A3})+f(c_{B3})+f(c_{C3})}}{\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{A3})}{f(c_{A3})+f(c_{B3})+f(c_{C3})}+\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{B3})}{f(c_{A3})+f(c_{B3})+f(c_{C3})}+\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{C3})}{f(c_{A3})+f(c_{B3})+f(c_{C3})}}\right)$$

First, notice how the denominator on the denominator is the same across the summation? Let's simplify it:

$$v_A = \frac{O_1}{P_A^\alpha}\left(\frac{\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{A1})}{f(c_{A1})+f(c_{B1})+f(c_{C1})}}{\frac{P_A^\alpha\cdot f(c_{A1})+P_A^\alpha\cdot f(c_{B1})+P_A^\alpha\cdot f(c_{C1})}{(P_A^\alpha+P_B^\alpha+P_C^\alpha)\cdot(f(c_{A1})+f(c_{B1})+f(c_{C1}))}}\right)+\frac{O_2}{P_A^\alpha}\left(\frac{\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{A2})}{f(c_{A2})+f(c_{B2})+f(c_{C2})}}{\frac{P_A^\alpha\cdot f(c_{A2})+P_A^\alpha\cdot f(c_{B2})+P_A^\alpha\cdot f(c_{C2})}{(P_A^\alpha+P_B^\alpha+P_C^\alpha)\cdot(f(c_{A2})+f(c_{B2})+f(c_{C2}))}}\right)+\frac{O_3}{P_A^\alpha}\left(\frac{\frac{P_A^\alpha}{P_A^\alpha+P_B^\alpha+P_C^\alpha}\cdot\frac{f(c_{A3})}{f(c_{A3})+f(c_{B3})+f(c_{C3})}}{\frac{P_A^\alpha\cdot f(c_{A3})+P_A^\alpha\cdot f(c_{B3})+P_A^\alpha\cdot f(c_{C3})}{(P_A^\alpha+P_B^\alpha+P_C^\alpha)\cdot(f(c_{A3})+f(c_{B3})+f(c_{C3}))}}\right)$$

See how the denominator of the denominator is the same as the denominator of the numerator's denominator for each J (J=1, J=2, and J=3)? Let's cancel those out and simplify:

$$v_A = \frac{O_1}{P_A^\alpha}\left(\frac{P_A^\alpha\cdot f(c_{A1})}{P_A^\alpha\cdot f(c_{A1})+P_A^\alpha\cdot f(c_{B1})+P_A^\alpha\cdot f(c_{C1})}+\frac{O_2}{P_A^\alpha}\frac{P_A^\alpha\cdot f(c_{A2})}{P_A^\alpha\cdot f(c_{A2})+P_A^\alpha\cdot f(c_{B2})+P_A^\alpha\cdot f(c_{C2})}+\frac{O_3}{P_A^\alpha}\frac{P_A^\alpha\cdot f(c_{A3})}{P_A^\alpha\cdot f(c_{A3})+P_A^\alpha\cdot f(c_{B3})+P_A^\alpha\cdot f(c_{C3})}\right)$$

Next, see how we can cancel out the P_A^α? Let's do that.

$$v_A = O_1(\frac{f(c_{A1})}{P_A^\alpha \cdot f(c_{A1}) + P_B^\alpha \cdot f(c_{B1}) + P_C^\alpha \cdot f(c_{C1})} + O_2 \frac{f(c_{A2})}{P_A^\alpha \cdot f(c_{A2}) + P_B^\alpha \cdot f(c_{B2}) + P_C^\alpha \cdot f(c_{C2})} + O_3 \frac{f(c_{A3})}{P_A^\alpha \cdot f(c_{A3}) + P_B^\alpha \cdot f(c_{B3}) + P_C^\alpha \cdot f(c_{C3})})$$

Shen's accessibility:

$$S_i = \sum_j \frac{O_j f(c_{ij})}{\sum_k P_k f(c_{jk})}$$