Revealing Spatial and Diurnal Dynamics in Urban Spatial Networks

A Case Study of Singapore

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Presentation Outline

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- Degree Correlation
- Page Rank
- Community Detection

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- Degree Distribution
- Degree Correlation
- Page Rank
- Community Detection

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- Scale-Free Networks
- Uncertainty
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- Conclusion

1. BACKGROUND & MOTIVATION

Motivations

Despite relatively comprehensive information available on land use and transport in Singapore, knowledge gaps exist –

Why spatial and diurnal dynamics?

- Master Plan 2019 gives greater emphasis on:
  - Amenity co-location; Greater flexibility in repurposing land (especially in industrial estates)
  - Polycentricity: building the second CBD, grooming specialized regional centres/new growth areas e.g. Woodlands
- **How do the new emphasis influence activity patterns and spatial interaction networks?**

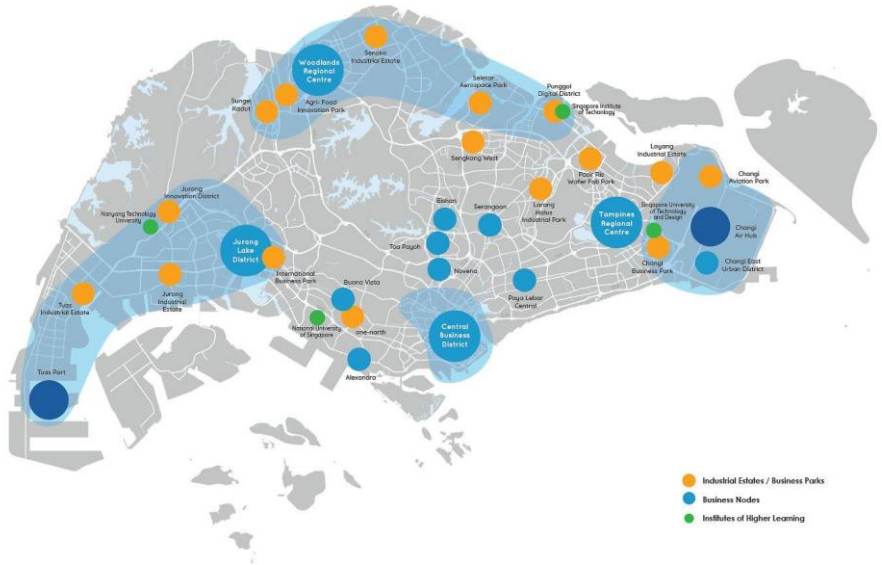
Why network science approach?

- Applications of complex network analysis in spatial data mining: **how the methods may aid our understanding of urban spaces and what are the challenges?**

Long-term interest on urban systems

- How does the urban system work? Keywords from complex systems: **hierarchy, self-organization, emergence, network dynamics, system resilience & robustness**

New Growth Areas Highlighted in MP19



Research Questions

- This project is positioned as **an exploratory study** to investigate **spatial and temporal (diurnal) changes in Singapore's urban spatial interaction networks**.
- Specifically, the project seeks to find out:
  1. Network characterization – based on the network topology and properties, what type of network is this?
  2. Spatial and temporal analysis of network topology and diurnal dynamics – what do the networks tell us about urban space and activity patterns?
  3. Uncertainty in network analysis – how does uncertainty manifest in a network?

Study Area: Singapore

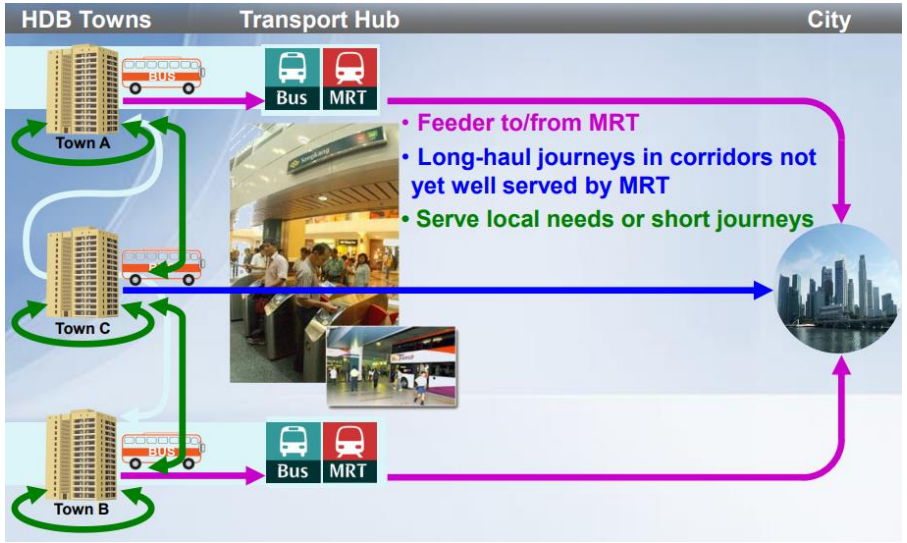
Characterised by extensive public transport networks and high public transport ridership

*The LTA planned for a system with defined roles for each mode of transport. The **MRT network** would form the backbone of Singapore's public transport system, serving the heavy transit corridors primarily for long-haul travel. This would be supported by the **buses and the Light Rapid Transit (LRT)** which serve lighter corridors and provide intra-town feeder services to connect residential towns to MRT stations and bus interchanges. This concept is known as the "**Hub-and-Spoke**" model.*

Centre for Liveable Cities, Land Transport Authority (2013)

*Our public transport system is of a **hub-and-spoke** design, which is an **efficient** model to bring commuters to a transport hub and then onwards to their destination. Transfers are an integral part of this system.*

Ministry of Transport (n.d.)



2. DATA & METHODOLOGY

Data Sources

Data obtained from LTA Data Mall

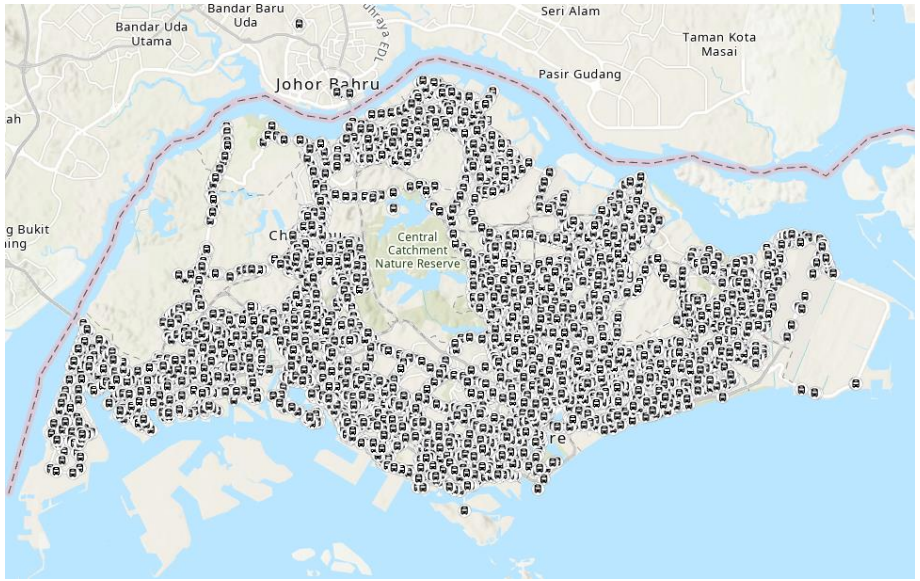
Passenger Volume by Bus Stop OD (.csv)

January 2021

YEAR_MONTH	DAY_TYPE	TIME_PER_HOUR	PT_TYPE	ORIGIN_PT_CODE	DESTINATION_PT_CODE	TOTAL_TRIPS
2020-12	WEEKEND	12	BUS	93201	92111	2
2020-12	WEEKDAY	12	BUS	93201	92111	5
2020-12	WEEKEND	23	BUS	59019	60179	1
2020-12	WEEKEND	13	BUS	1239	3059	1
2020-12	WEEKDAY	13	BUS	1239	3059	13

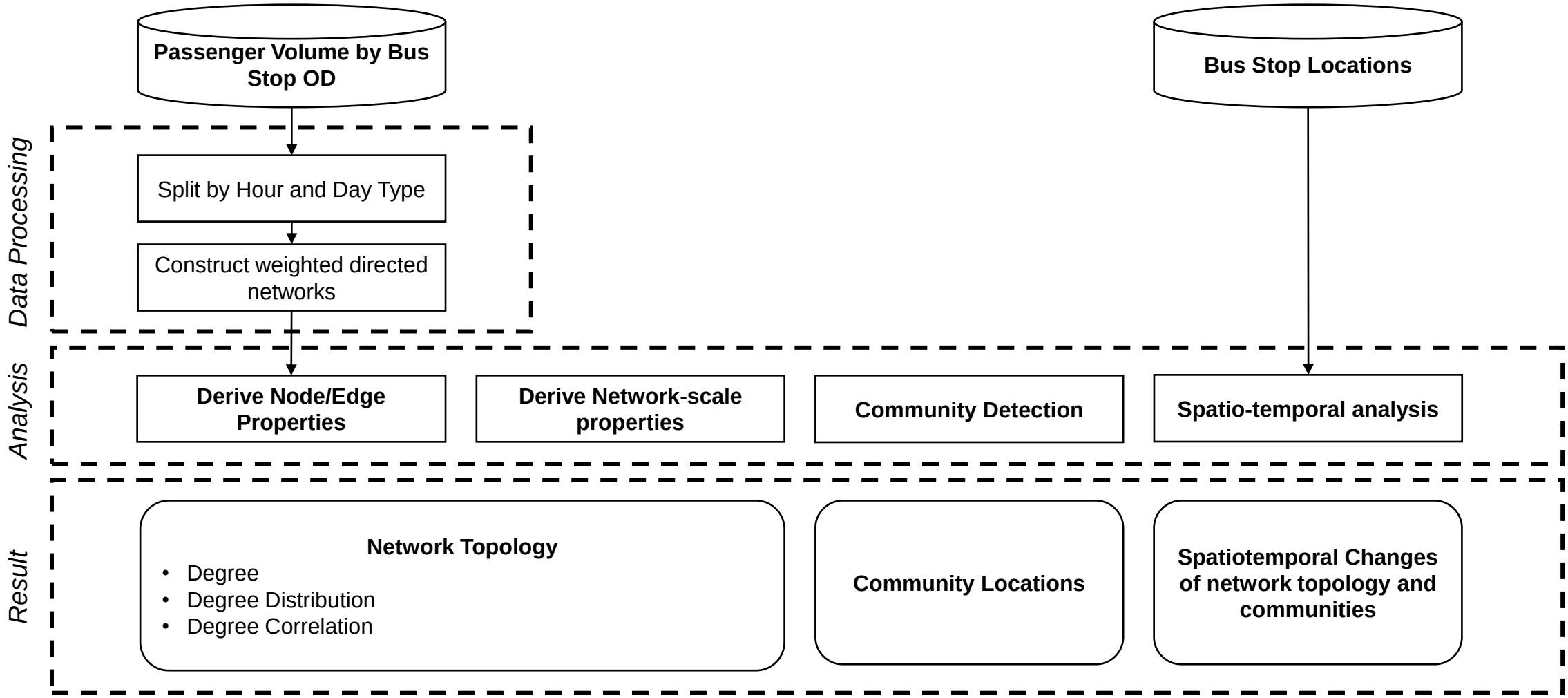
Bus Stop Locations (.shp)

Updated as of Dec 2020



BUS_STOP_N	BUS_ROOF_N	LOC_DESC
63359	B01	HOUGANG SWIM CPLX
64141	B13	AFT JLN TELAWI
83139	B07	AFT JOO CHIAT PL
55231	B02	OPP SBST EAST DISTRICT
55351	B03	OPP FUDU WALK P/G
92089	B10	CHIJ KATONG CON

Overview of Methodology



Define & Construct Networks

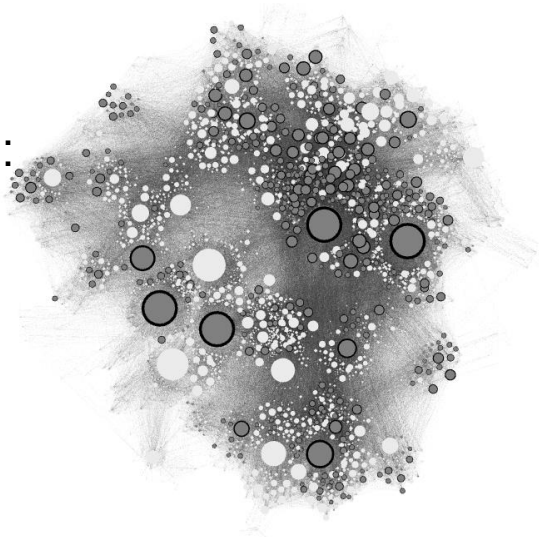
Source Target Weight

YEAR_MONTH	DAY_TYPE	TIME_PER_HOUR	PT_TYPE	ORIGIN_PT_CODE	DESTINATION_PT_CODE	TOTAL_TRIPS
2021-01	WEEKDAY	8	BUS	91099	92091	23
2021-01	WEEKEND	8	BUS	91099	92091	4
2021-01	WEEKDAY	22	BUS	10499	10191	1
2021-01	WEEKEND	7	BUS	31051	44009	5
2021-01	WEEKEND	10	BUS	1211	83111	1
2021-01	WEEKEND	15	BUS	14171	14369	1
2021-01	WEEKDAY	15	BUS	75009	83059	25
2021-01	WEEKEND	15	BUS	75009	83059	5

Edge Table

Source	Target	Weight
52279	07569	2
52279	17161	1
52279	52149	2
52279	52239	2
52279	52291	7
52279	52009	31
52279	11171	1
52279	52169	1
52279	52259	4
52279	09111	1
52279	09219	1
52279	50038	1
52279	11079	2
52279	11029	2
52279	52281	7
52279	52501	9

- Each edge represents **trips from the same pair of O/D**: start at tap-in transit node, end at tap-out transit node
- Final outcome: **spatial interaction network**



Construct Weighted Directed Network

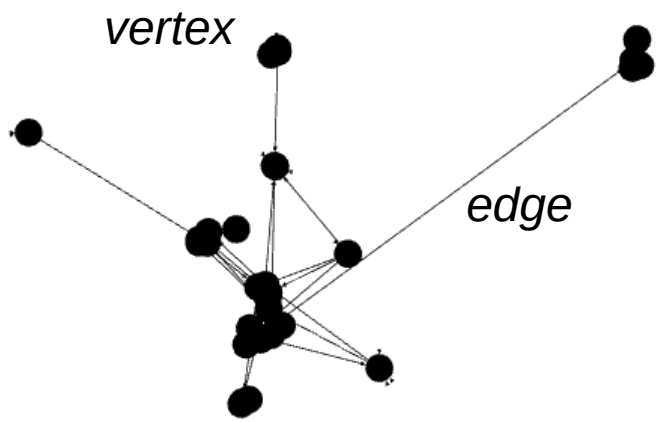
G ≡ {V,E,W}

Characterise Network Topology

Node-based properties

Local Properties ⟷ *Global Properties*

Degree
Number of links a node has to other nodes
In-Degree: number of links coming in to the node
Out-Degree: number of links coming out from the node

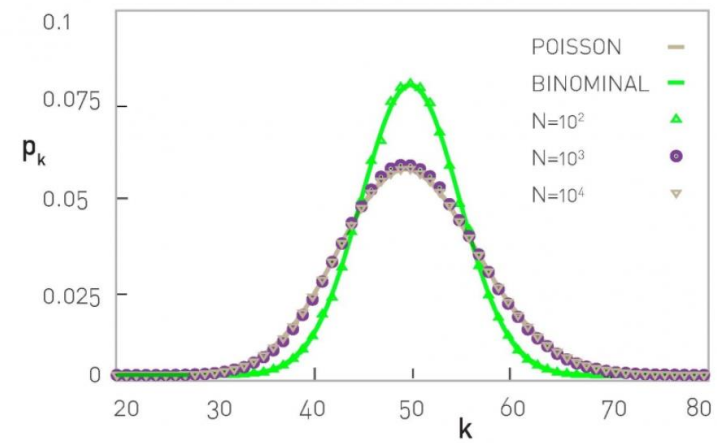


Average Degree: Number of edges over the number of nodes

$$\langle k^{in} \rangle = \frac{1}{N}\sum_{i=1}^{N} k_i^{in} = \langle k^{out} \rangle = \frac{1}{N}\sum_{i=1}^{N} k_i^{out} = \frac{L}{N}$$

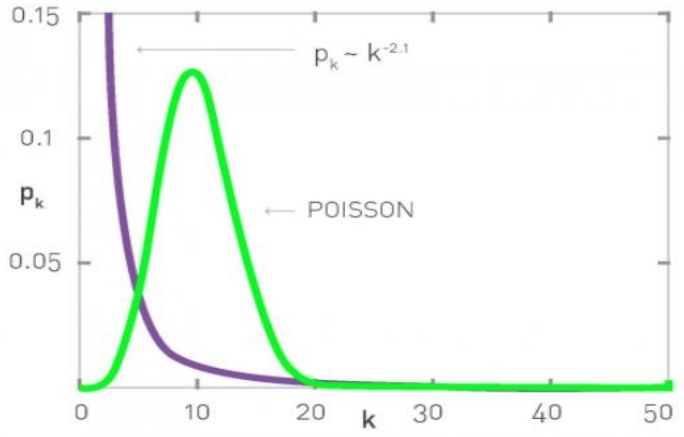
Degree Distribution p_k: Probability of a randomly selected node in the network with degree k. Degree distribution is independent of the network size.

Random network



Each node pair is connected with probability p.

Scale-free network



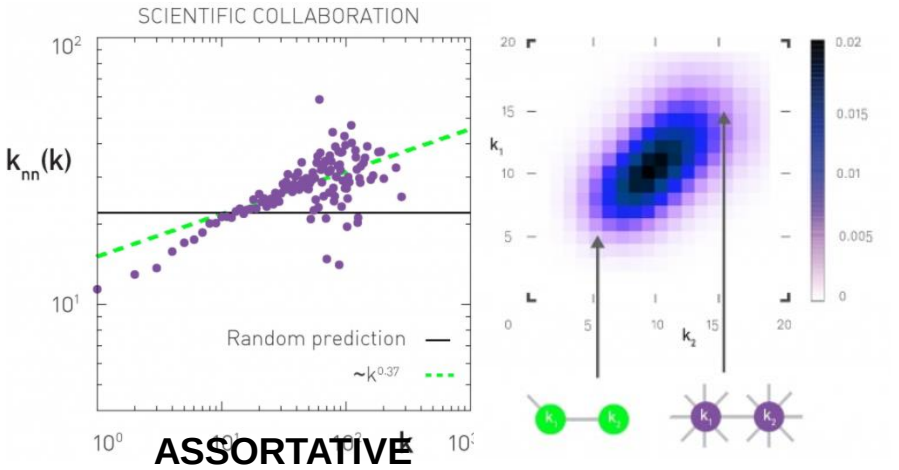
Degree distribution follows a power law (approximately)

Barabasi (2016)

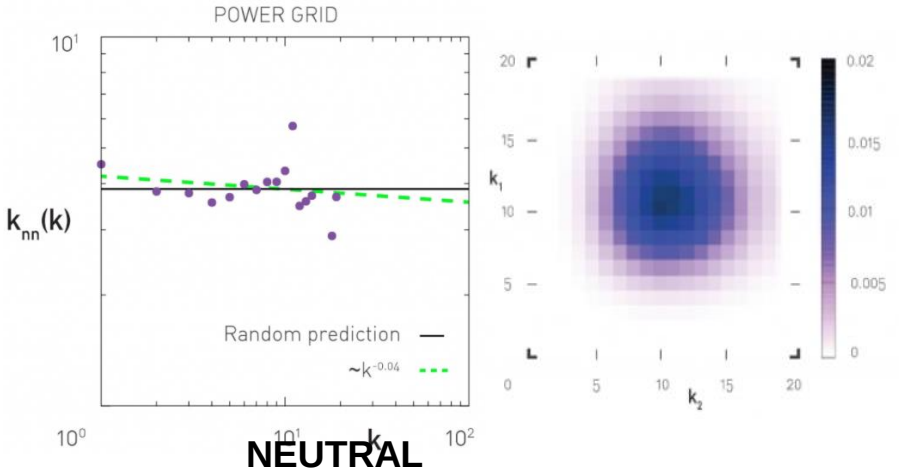
Characterise Network Topology

Node-based properties

Local Properties ⟷ *Global Properties*



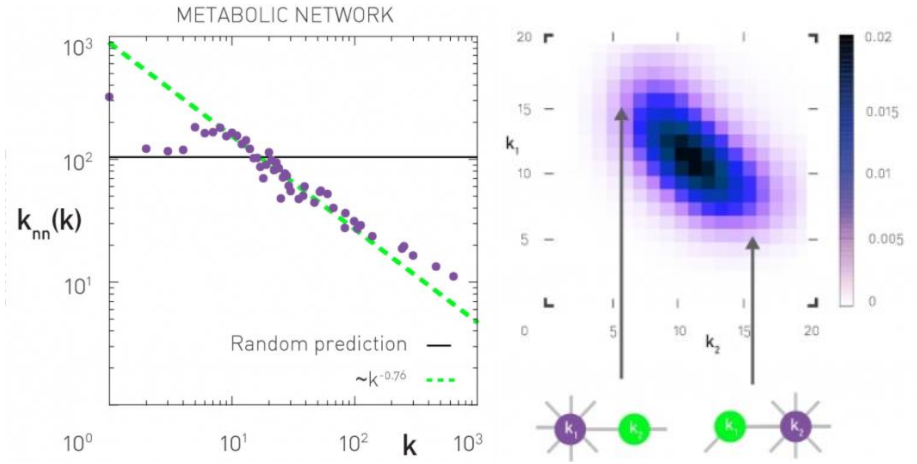
ASSORTATIVE



NEUTRAL

Degree Correlation: Likelihood of a node links to nodes of similar or dissimilar nodal degrees

- $k_{nn}(k)$: Average Degree of neighbours of all degree-k nodes
- *Joint Degree Distribution*: Correlation of degrees of two nodes in all edges in a network



DISASSORTATIVE

Barabási (2016)

Compute Other Network Statistics

PageRank (PR)

A link-analysis algorithm used first by Google Search to rank web pages in their search engine results; a measure of "importance" or "quality" of elements in the network.

How does the PageRank algorithm work?

- A hyperlink to a page (a link to a node) counts as a vote of support
- PR of the page/node is defined recursively depending on the number and PageRank metric of all pages that link to it
- High PR: linked to by many pages also with high PR → **importance in the network** → inferred to be authoritative/central in the network

$$PR(A) = (1-d) + d\,(PR(T1)/C(T1) + \ldots + PR(Tn)/C(Tn))$$

Note that the PageRanks form a probability distribution over web pages, so the sum of all web pages' PageRanks will be one.

Where:

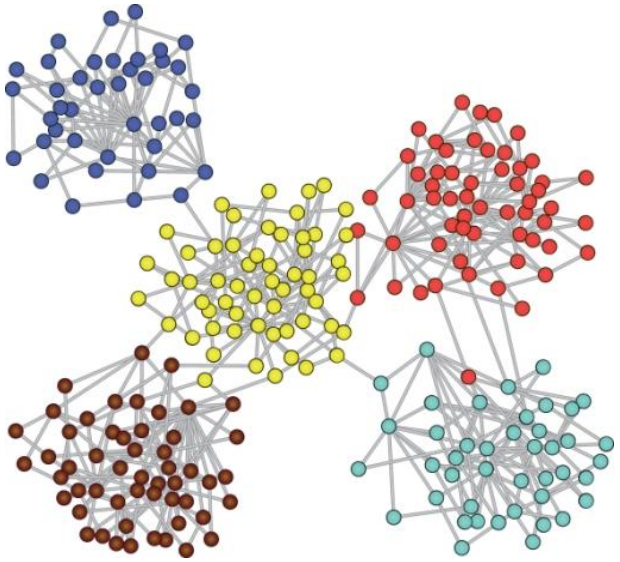
- d is the dampening factor between 0 and 1
- $C(A)$ is the number of links going out from page A
- T_i is a page that points to page A

Sum of PR of all nodes in a network will be 1

Brin & Page (1998)

Source: https://www.google.com/search/howsearchworks/algorithms/

Network Community Detection



Community: a group of nodes that have a higher likelihood of connecting to each other than to nodes from other communities.

Communities in a spatial interaction network: Clusters of places where people are more likely to travel among, than to places outside

$$Q = \frac{1}{2m} \sum_{ij} \left[A_{ij} - \frac{k_i k_j}{2m} \right] \delta(c_i, c_j),$$

where

- A_{ij} represents the edge weight between nodes i and j;
- k_i and k_j are the sum of the weights of the edges attached to nodes i and j, respectively;
- m is the sum of all of the edge weights in the graph;
- c_i and c_j are the communities of the nodes; and
- δ is Kronecker delta function ($\delta(x, y) = 1$ if $x = y$, 0 otherwise).

Algorithm used: Louvain Modularity

Quality function to be optimized: modularity (-0.5 – 1) to measure the **density of links** inside communities compared to links between communities → outcome: non-overlapping communities

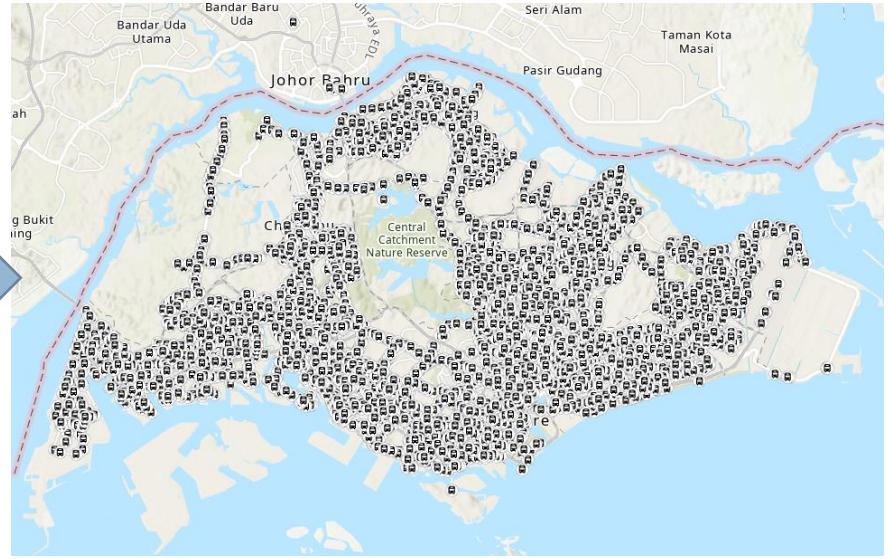
1. Each node starts with its own community; modularity score calculated for the initial state
2. Iteratively move each node to a community of its neighbours, and recalculate modularity score, and place the node into a community that will result in the greatest increase in modularity score
3. Formulate a new network using communities as nodes and repeat the process until no further increase in modularity score can be achieved

Blondel et al. (2008)

Spatial Analysis

BusStopId	indegree	outdegree	Degree	weighted indegre	weighted outdegr	Weighted Degree	modularity_class	pageranks	closness centrality	harmonicclosnesscentra	betweeness centrality	Authority	Hub	clustering	eigencentrality
44259	101	184	285	2393	4464	6857	8	0.00	0.38	0.42	191239.50	0.02	0.02	0.06	0.18
44521	15	14	29	346	195	541	8	0.00	0.29	0.31	166.28	0.00	0.00	0.28	0.02
21681	62	3	65	337	268	605	0	0.00	0.30	0.32	515.20	0.01	0.00	0.15	0.11
44589	8	5	13	209	333	542	8	0.00	0.29	0.31	21.56	0.00	0.00	0.52	0.01
28451	81	63	144	758	882	1640	0	0.00	0.31	0.33	14952.02	0.01	0.00	0.13	0.22
46531	70	7	77	938	529	1467	3	0.00	0.31	0.33	8503.05	0.01	0.00	0.11	0.13
44041	71	44	115	590	466	1056	8	0.00	0.32	0.34	23346.73	0.01	0.00		
45469	9	11	20	157	460	617	8	0.00	0.24	0.24	644.56	0.00	0.00		
43429	41	33	74	736	772	1508	4	0.00	0.32	0.34	5619.88	0.01	0.00		
14169	129	116	245	719	2461	3180	5	0.00	0.37	0.40	56225.54	0.03	0.03		
44149	75	78	153	726	1343	2069	8	0.00	0.34	0.37	100162.72	0.02	0.01	0.09	0.17
21379	81	32	113	1039	1789	2828	0	0.00	0.33	0.35	37680.44	0.01	0.00	0.12	0.13
44009	259	268	527	19342	10585	29927	8	0.00	0.41	0.45	1060867.85	0.03	0.04	0.04	0.40
28091	96	49	145	16419	5853	22272	0	0.00	0.31	0.33	26125.31	0.01	0.00	0.11	0.16
18049	45	30	75	518	157	675	5	0.00	0.33	0.35	1600.58	0.01	0.01	0.19	0.07
45131	70	16	86	717	911	1628	3	0.00	0.31	0.33	31445.90	0.01	0.00	0.12	0.12
44871	8	8	16	282	529	811	8	0.00	0.29	0.31	22.26	0.00	0.00	0.41	0.01
43449	26	38	64	161	1055	1216	4	0.00	0.33	0.35	2136.42	0.01	0.00	0.21	0.06
22009	477	465	942	39971	37259	77230	0	0.01	0.43	0.48	3017672.43	0.04	0.05	0.02	0.62
17129	41	61	102	314	1201	1515	5	0.00	0.35	0.37	3178.22	0.01	0.02	0.20	0.06

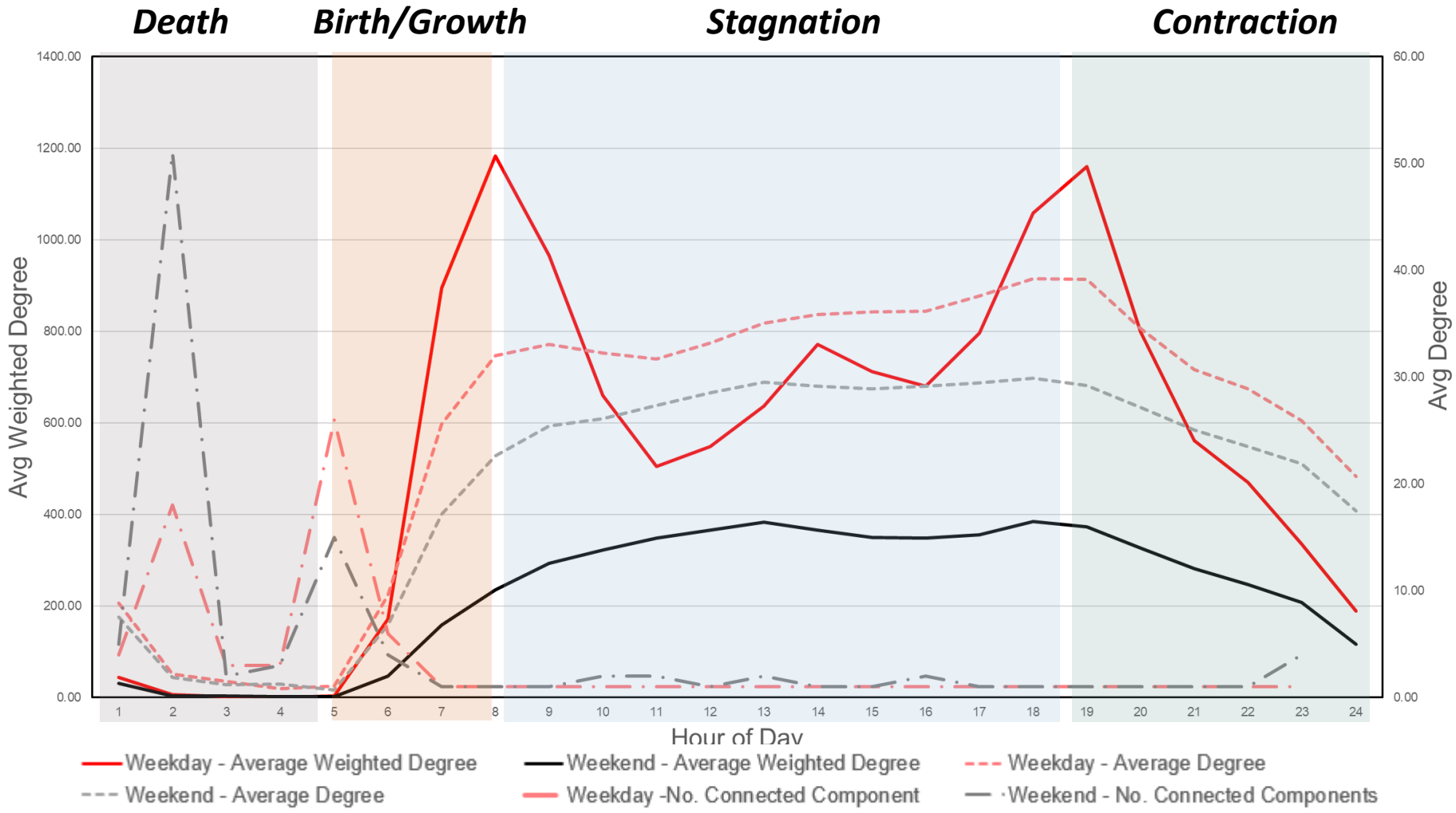
Join By Bus Stop Code



- Kernel density → from point to surface
- Zonal statistics → summarise attributes in an area
- 2D / 3D visualisation

3. RESULTS

Diurnal Evolution of Networks



Generally follows the intensity of urban activities

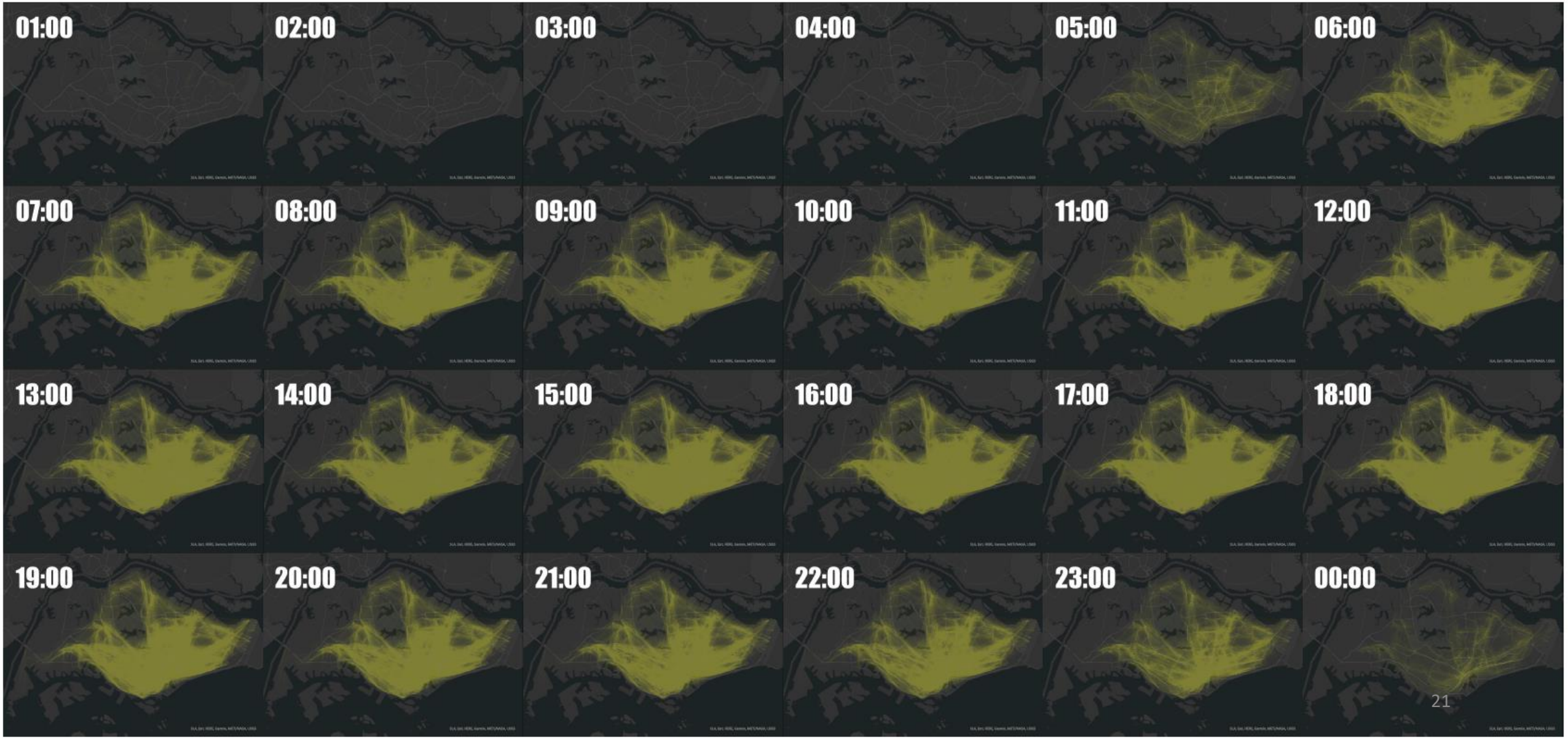
Birth/Growth

- Rapid increase of number of nodes & edges → increase in average degree and average weighted degree
- Forming 1 connected component

Contraction & Death

- Decrease in no. of active nodes and edges
- Breaking down into many components→ disconnected network

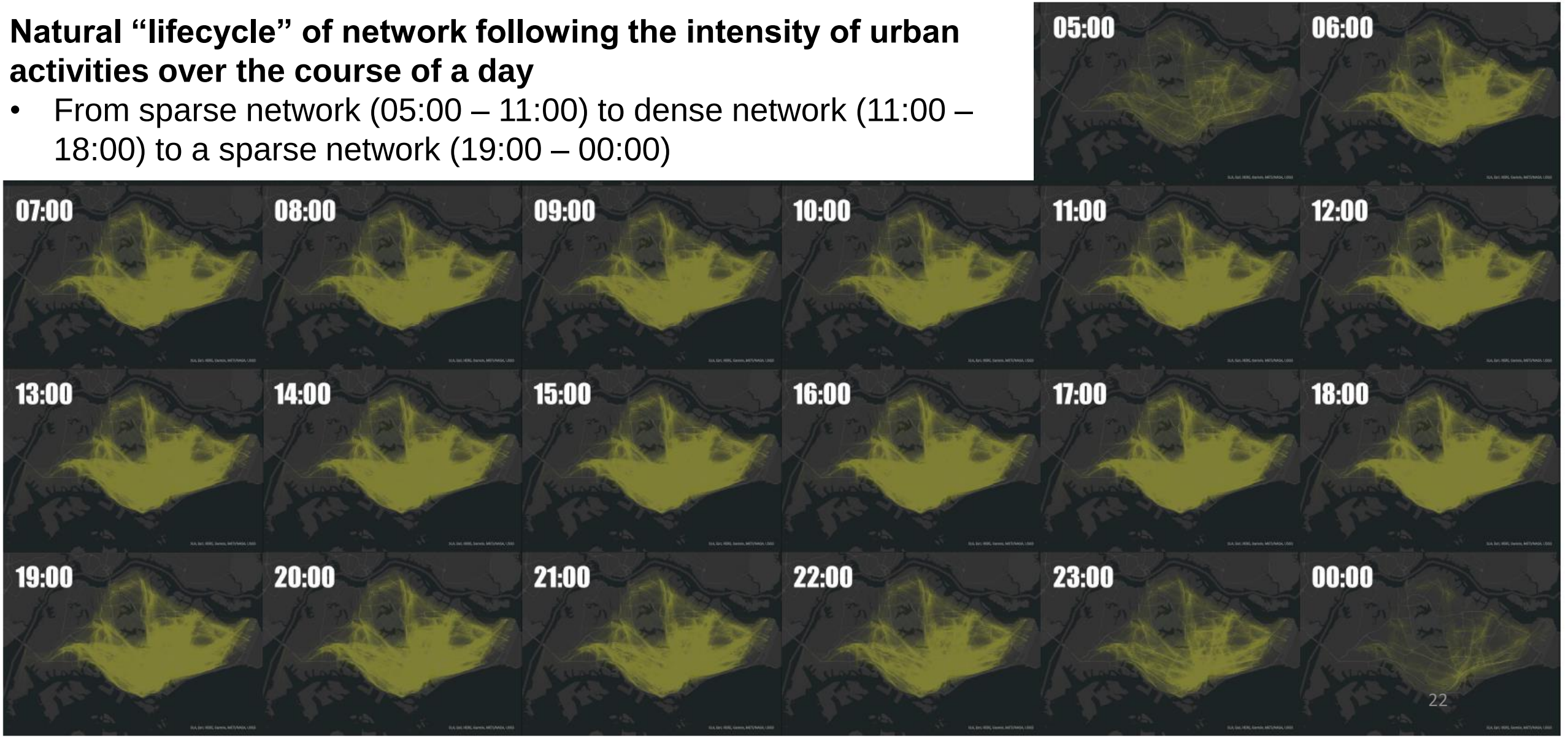
ON A TYPICAL WEEKDAY



ON A TYPICAL WEEKDAY

Natural “lifecycle” of network following the intensity of urban activities over the course of a day

- From sparse network (05:00 – 11:00) to dense network (11:00 – 18:00) to a sparse network (19:00 – 00:00)



ON A TYPICAL WEEKDAY

Disconnected components observed in late night hours

- Fewer trips made; disconnected network
- Both neighbourhood and long-range trips are observed
- Will be excluded from community detection and network-scale topology analysis (e.g. knn average degree, degree correlation)

WEEKDAY

WEEKEND/HOLIDAY

Visual Assessment

- Both follow a similar evolution lifecycle
- Generally weekend networks show lower density of edges and a delayed growth period

(Spatial) Degree Distribution

High-degree nodes are mostly major transit hubs

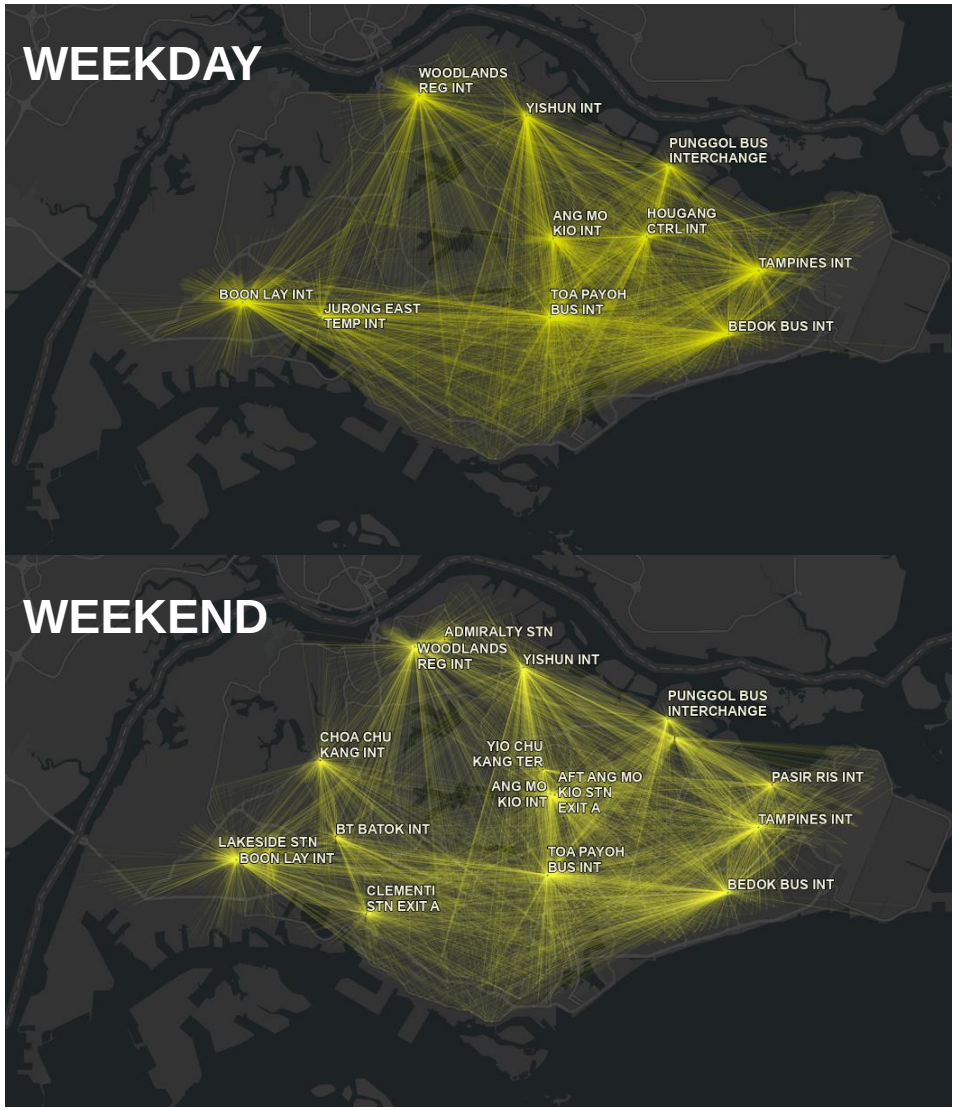
Top 10 nodes with the highest degrees on a <u>weekday</u> from 07:00 – 00:00

- Bedok Bus Int
- Toa Payoh Bus Int
- Tampines Int
- Boon Lay Int *Highest weighted degree*
- Woodlands Reg Int
- Yishun Int
- Ang Mo Kio Int
- Hougang Ctrl Int
- Jurong East Temp Int
- Punggol Bus Interchange

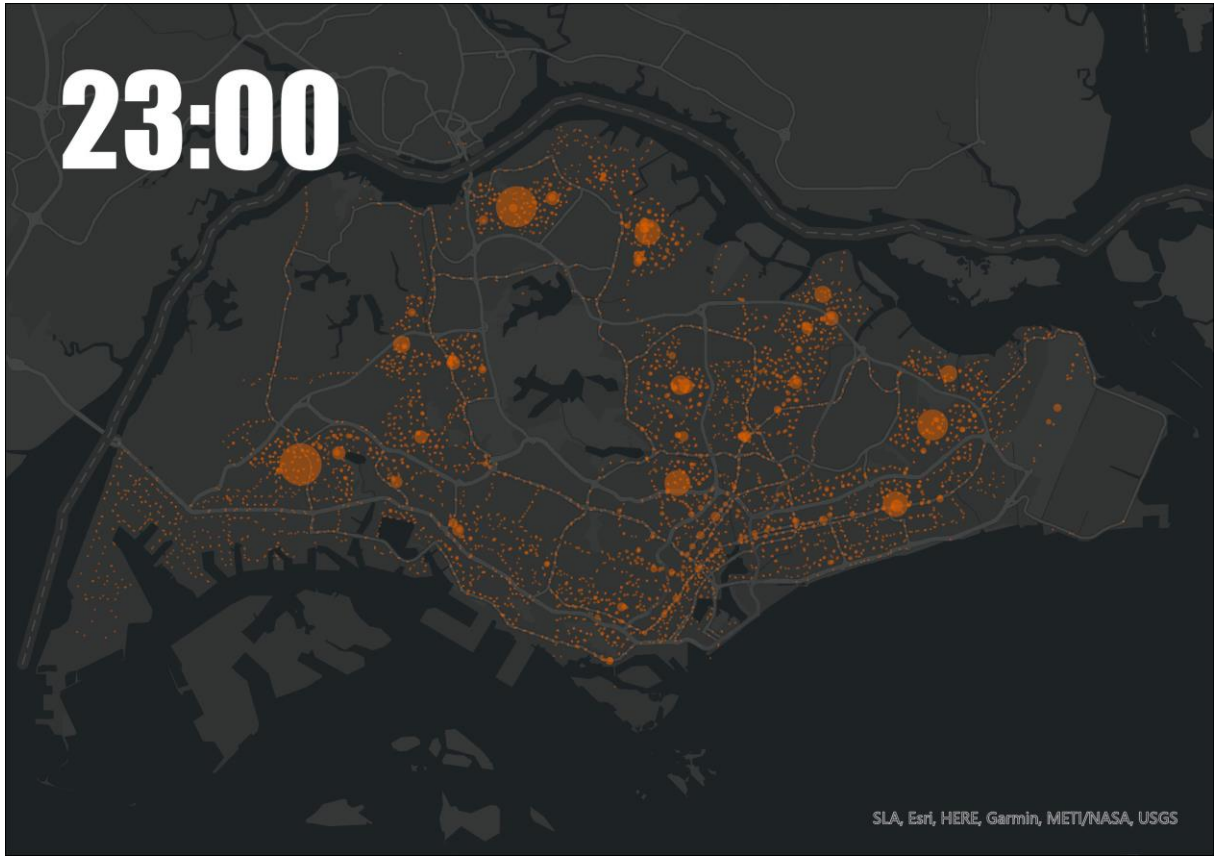
Additional nodes with highest degrees on a <u>weekend</u> from 07:00 – 00:00

- Yio Chu Kang Terminal
- Aft Ang Mo Kio Stn Exit A
- Pasir Ris Int
- Admiralty Stn
- Choa Chu Kang Stn
- Lakeside Stn
- Bt Batok Stn
- Clementi Stn Exit A

Where is the city centre?
Where is the CBD?

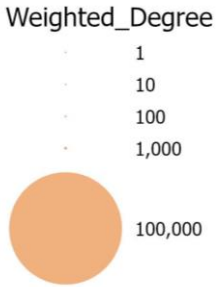


(Temporal) Degree Distribution



Visual observations

1. Distinct temporal “pulse” of weighted degree changes
2. Locations of nodes that show significant increase in weighted degrees – periphery first, centre later
3. Distinct groups of nodes with weighted degrees that change with different temporal pulses
   - Some have high weighted degrees throughout the day
   - Some show short “bursts” of high weighted degrees

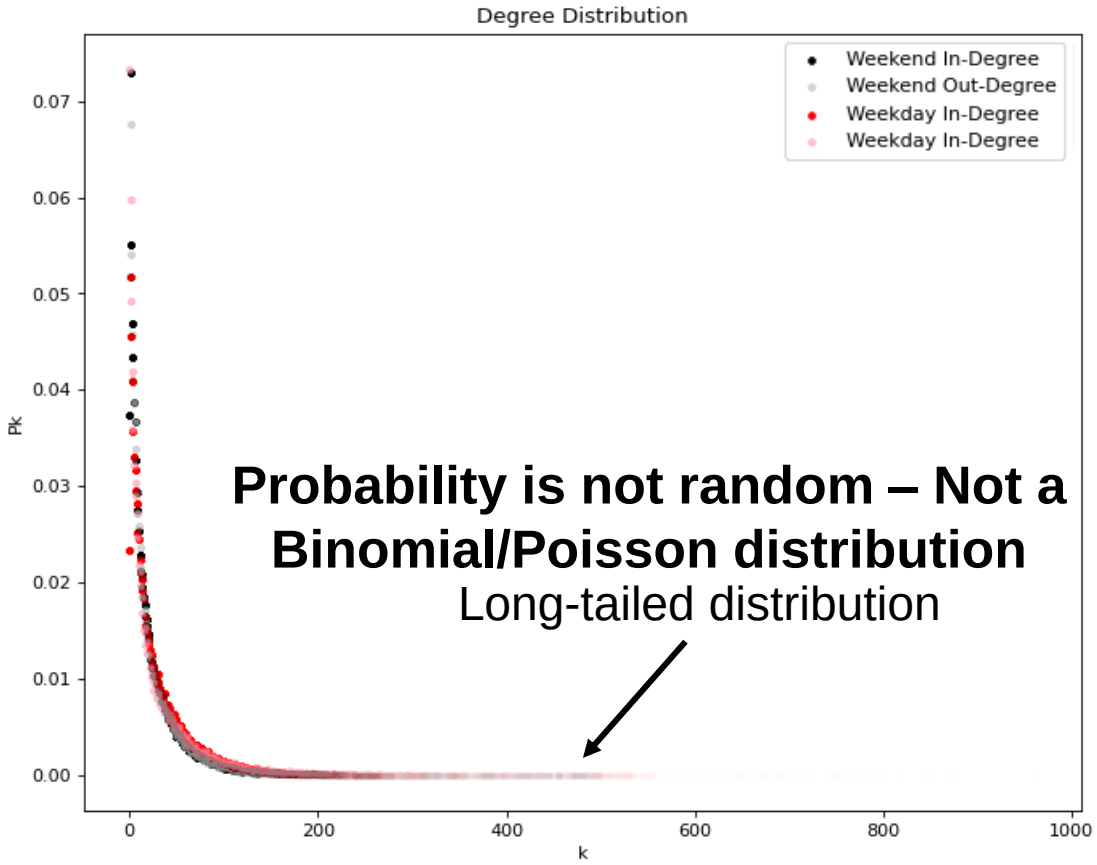


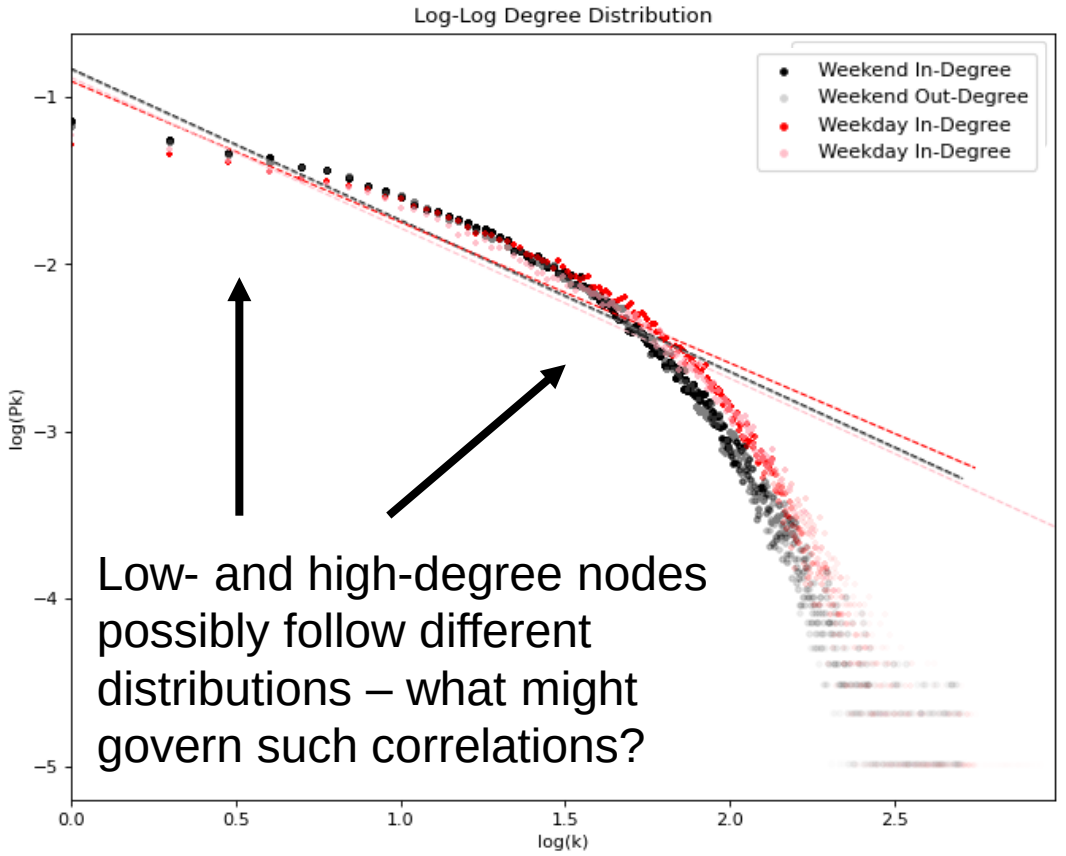
For further consideration

- Profiling of transit nodes based on temporal patterns of degree changes → different roles played in the network
- Traffic demand catchments/neighbourhoods of transit nodes
- Land use/activity type/trip purposes

Degree Distribution

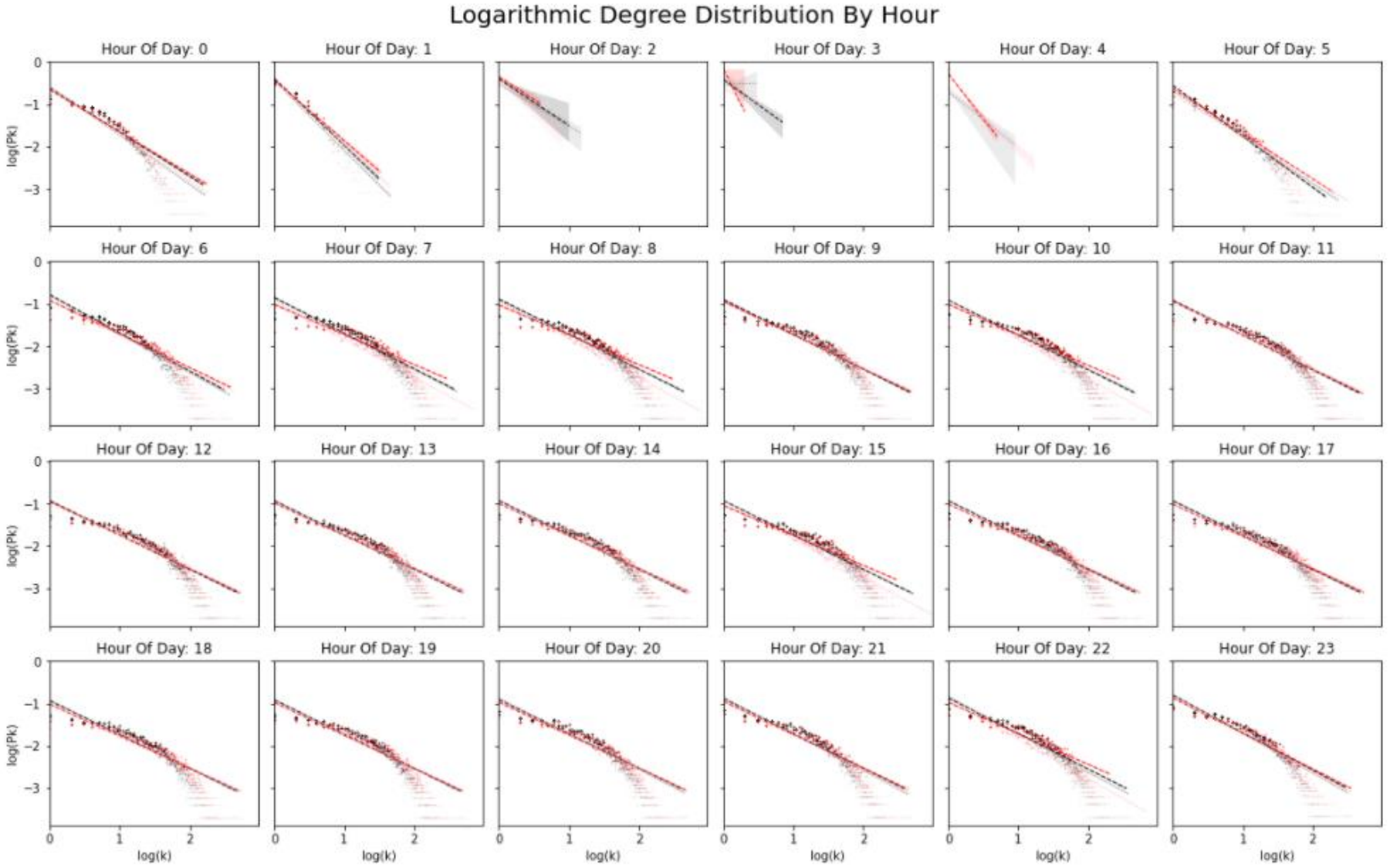
Weekday k_{in}: y = **-0.84**x - 0.90
Weekday k_{out}: y = **-0.90**x - 0.88
Weekend k_{in} : y = **-0.91**x- 0.83
Weekend k_{out} : y = **-0.91**x - 0.84



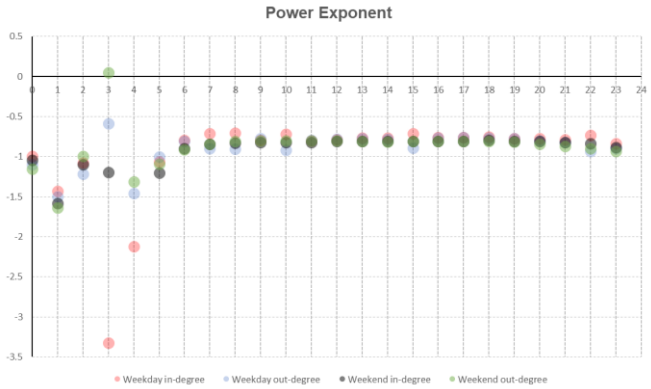


- Degree distribution approximately follows **power law**: few nodes with high degree, many nodes with small degree
- Assuming a distribution of $\mathbf{p_k = a\ k^{-b}}$, fitted into a linear regression → **0 < b < 1**

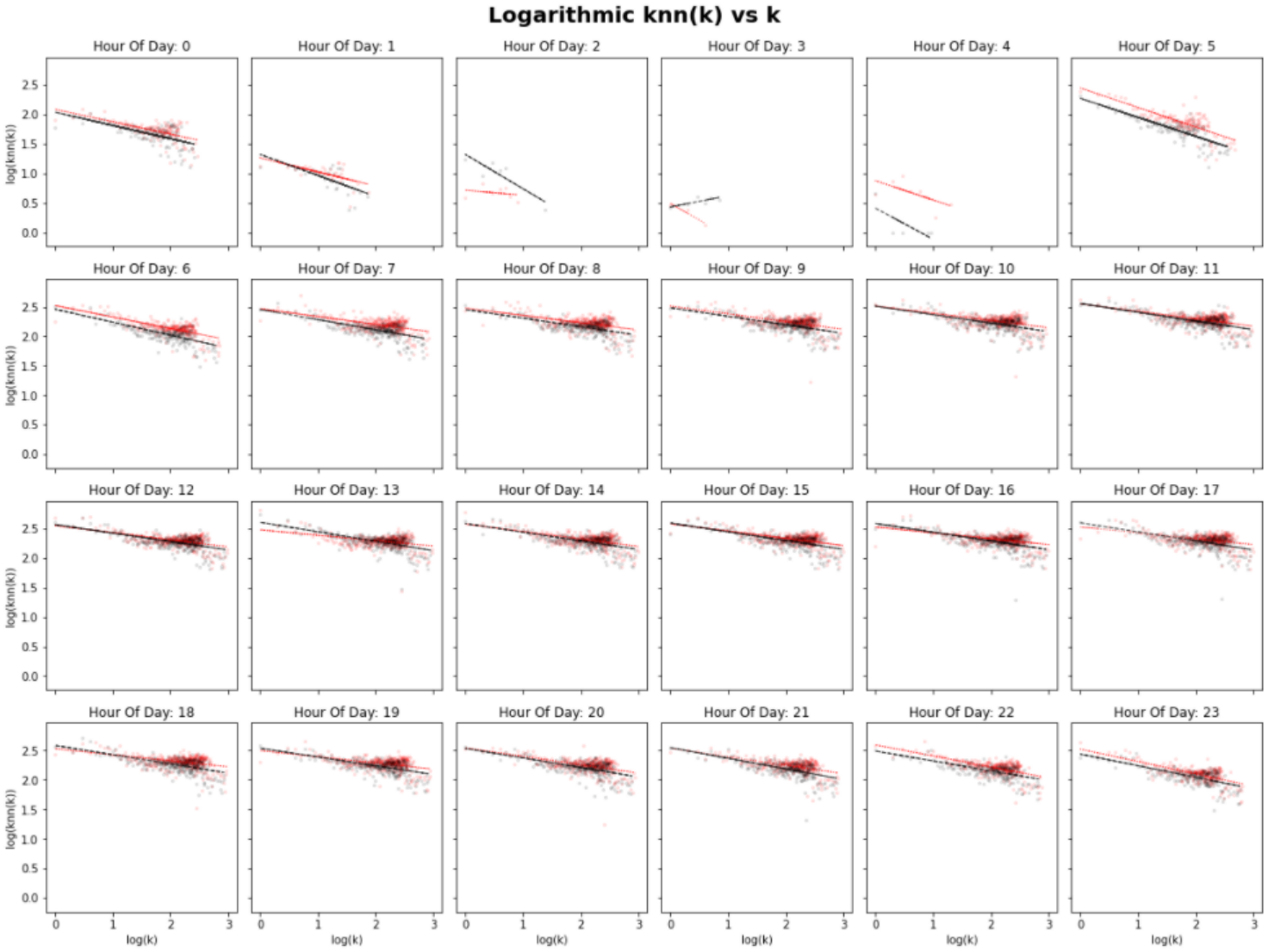
Remarkable consistency of degree distribution across different hours of the day and between weekdays and weekends



- As the network evolves, **the degree distribution remains scale-free.**
- Power exponent ≈ -0.9



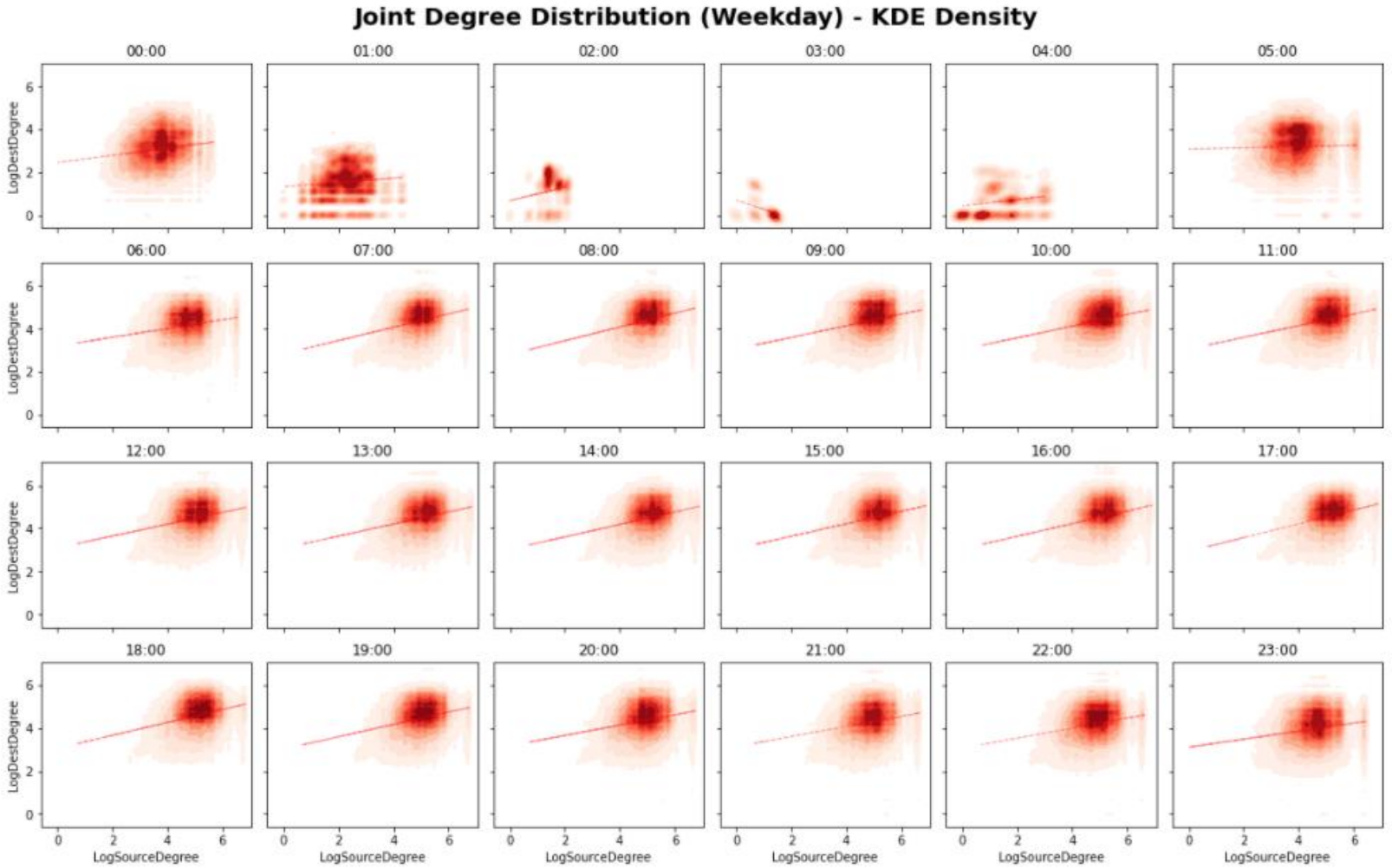
Degree Correlation



Negative gradients from $k_{nn}(k)$ suggests that these networks are **disassortative networks**:

- High-degree nodes tend have neighbours of lower degree
- Suggests possible hierarchical arrangements

Degree Correlation



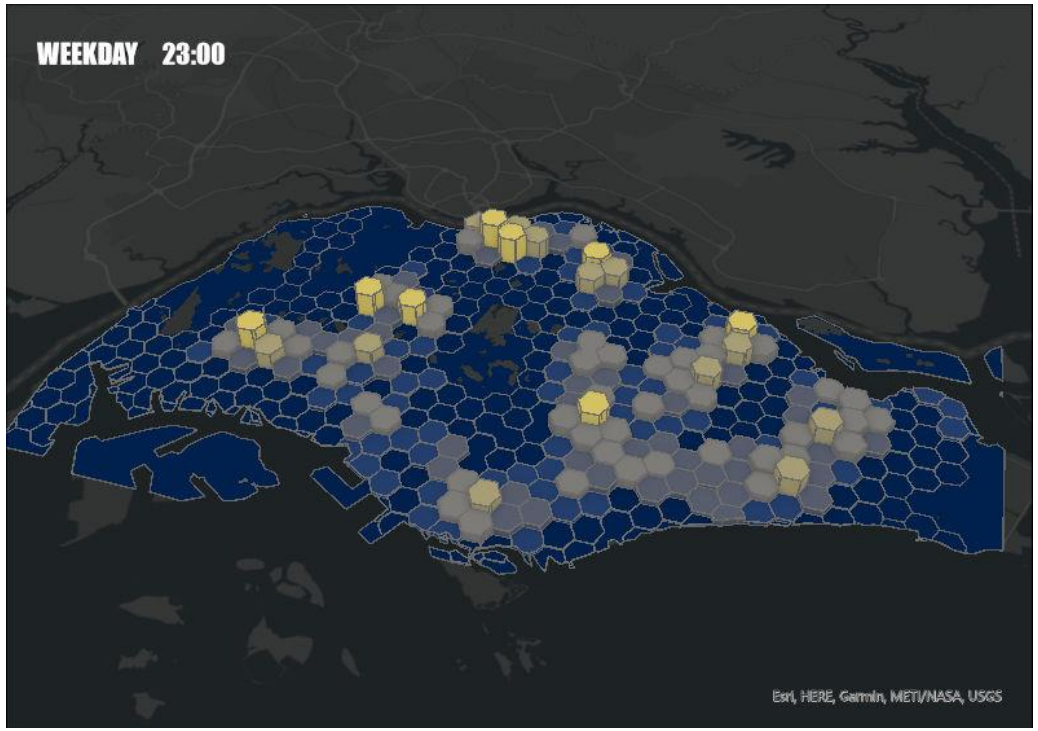
Contradictory result from Joint Degree Distribution

- For every pair of nodes – higher degree nodes tend to also link with higher degree neighbours: assortative networks
- Weak correlation observed from a wide distribution: weakly assortative to neutral
- Require further investigation and statistical tests

PageRank Measures

PageRank value answers the question:

- Where are the “important” nodes in each timeframe?
- Do nodes stay “important” over the course of a day?



Visual Observations

1. Spatial variations of PageRank values
2. Not all high-PageRank nodes are high-degree nodes: e.g. **city centre nodes** at 09:00 – 11:00
3. In some timeframes, multiple high-PageRank nodes are seen: polycentricity?

➔ Possibly a function of local land use/activities and time AND connectivity to other important nodes

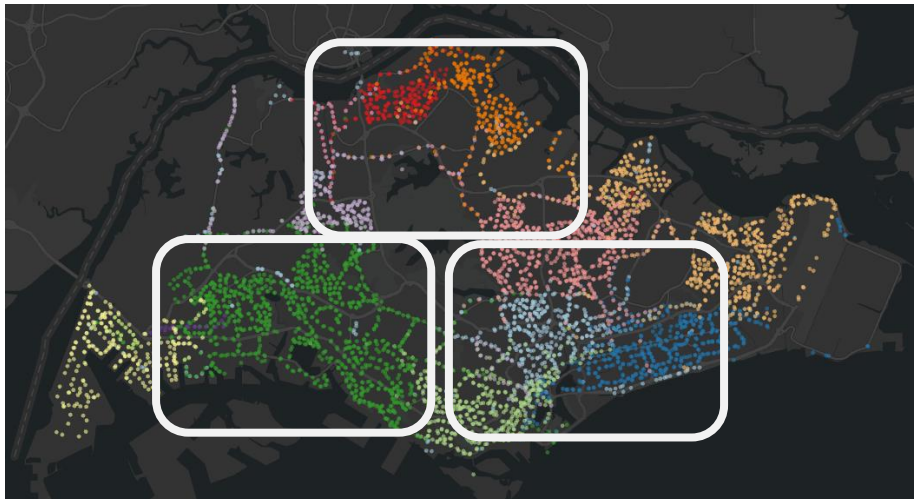
- Hexagon size is determined with incremental spatial autocorrelation of peak distance at which clustering of high PageRank values manifest
- Height of each hexagon block represents the mean of page rank kernel density of the area within the timeframe
- PR values cannot be used to compare across timeframes due to structural differences in network compositions

Diurnal Changes in Community Structures

WEEKDAY 08:00

WEEKDAY 12:00

WEEKDAY 18:00



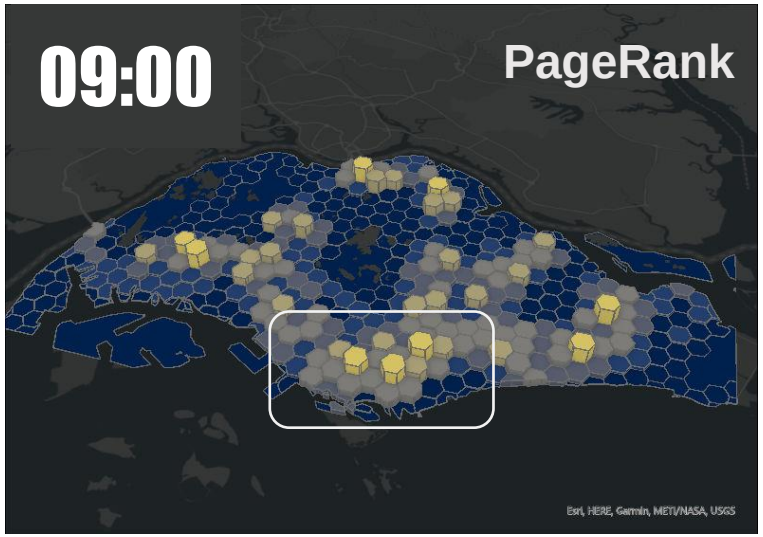
Based on network topology, **community membership changes over the hours**: indication of different travel patterns for different purposes at different hours

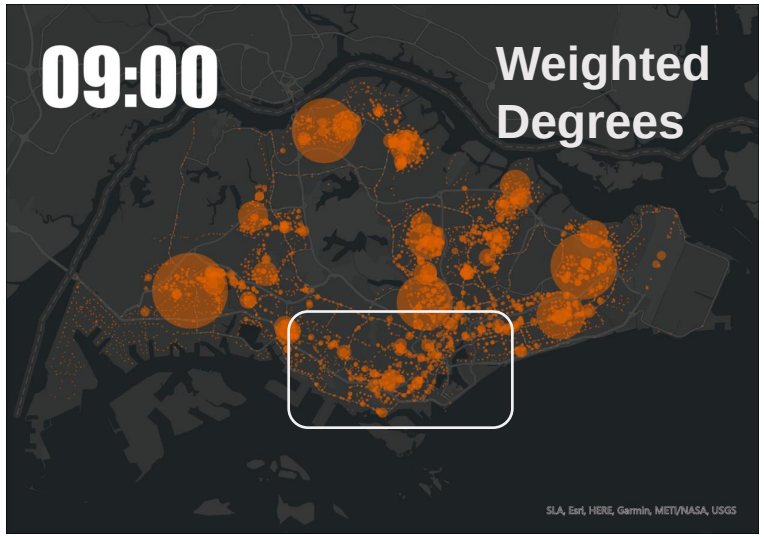
Summary of Results

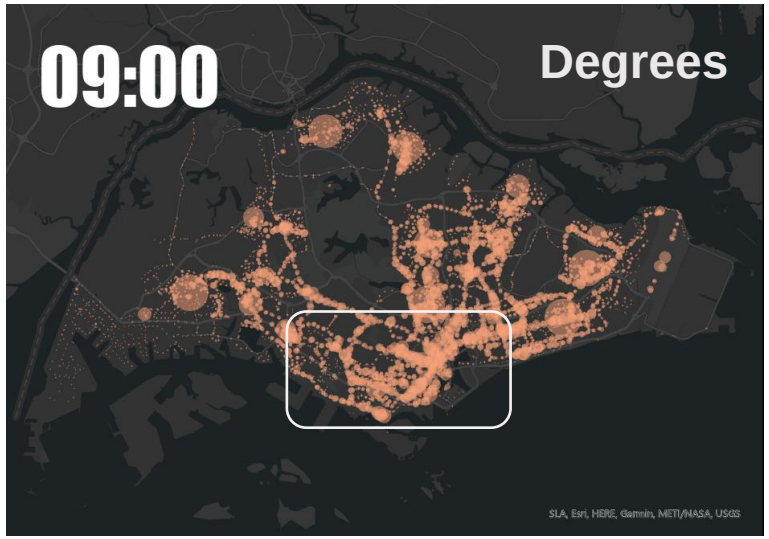
1. **What type of network is this?**
   - Consistently scale-free
   - Weakly disassortative (contradictory findings)
2. **What do the networks tell us about urban space and activity patterns?**
   - A clear diurnal lifecycle observed from temporal changes in average degrees and average weighted degrees, following intensity of urban activities
   - Places matter: spatial variations in the temporal evolution of node degrees and PageRank
   - Time matters: polycentric urban forms and community structure evolve over the course of a day
3. **How does uncertainty manifest in a network?**
   - To be discussed

4. DISCUSSION & CONCLUSION

Local vs Network Properties







Degrees/Weighted Degrees may have been attributed to local properties

- Local interventions e.g. presence of bus interchanges, number of bus services

PageRank accounts for network properties of the nodes

- High PR value indicates connectivity to nodes of high importance
- A measure of importance IN the network → highlighted city centres
- Better explained by network properties than local properties

Reflection on the definition of city centre beyond local properties

- Morphological definition e.g. concentration of employment opportunities, land use types may not be sufficient
- Good to incorporate functional definition: importance in a network, contribution of flows

Local Rules to Global Emergence

Individual Trip Data

Manifestation of activities and actual usage of urban spaces based on a myriad of considerations

Spatial Interaction Networks

Emergence of general patterns from collective decision making

Urban System

Spatial organisation, hierarchy, efficiency & optimisation

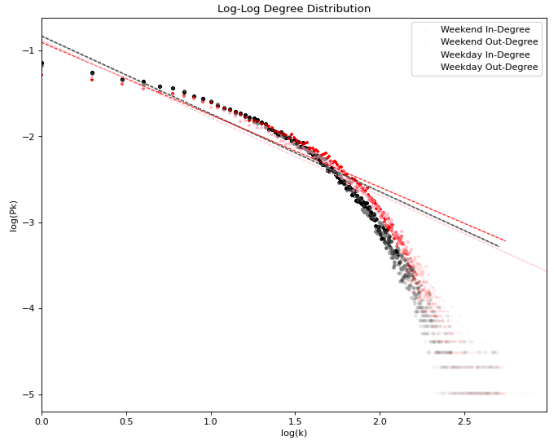
Exploratory study using a data-driven approach to develop preliminary findings for further investigations

- Individuals make decisions based on respective considerations
  - Where to buy house/where to work
  - Mode of travel
  - Time of travel
  - Bus services to take/transfers to make
  - …
- Formation of spatial interaction networks: just the sum of individual trips? WITH emergent patterns
- Networks reveal the overall organisation of the entire urban system with spatial implications
  - Non-adjacent nodes that belong to the same community
  - Consistent degree distribution
  - Possible self-organisation of urban activities

Scale-Free Network

Definition: *a network whose degree distribution follows a power law*

- **No internal scale**: the characteristics (degree distribution, underlying structure etc.) remain true regardless of network size
- Very few nodes with high degrees – serve as the "hubs" in network; Many nodes with few degrees; accounts for observations of 80-20 rules
- Hierarchical organisation: robustness to failure
- Self-organisation



Barabasi & Albert (1999): Scale-free networks arise from:

- *Growth*: As network grows, new vertices are continuously added
- *Preferential Attachment*: New vertices attach preferentially to vertices that are already well connected

In the context of spatial interaction networks:

- The network grows as passengers from more bus stops commence their trips
- Choice of trip destination is preferential: more likely to be bus stops that are already well-connected

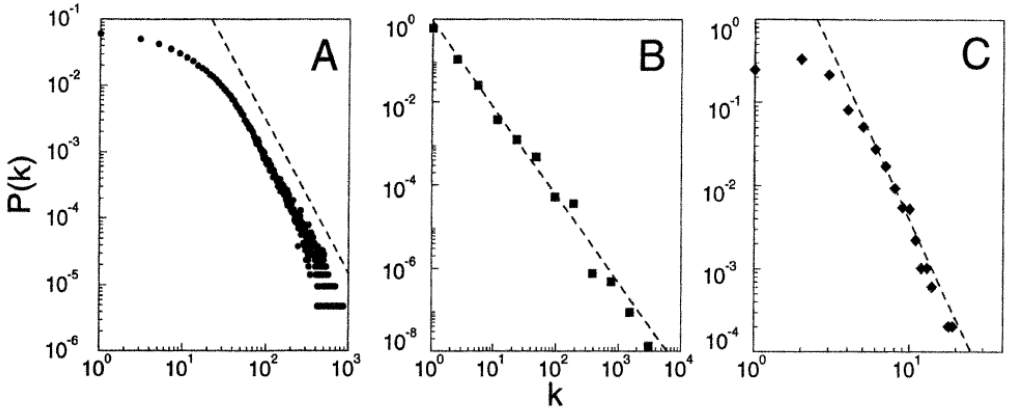
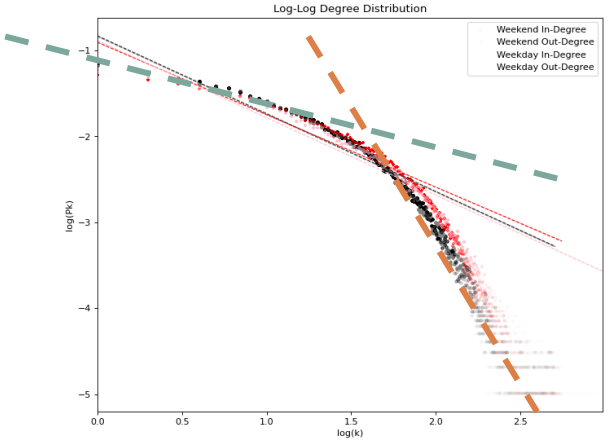


Fig. 1. The distribution function of connectivities for various large networks. (**A**) Actor collaboration graph with $N = 212{,}250$ vertices and average connectivity $\langle k \rangle = 28.78$. (**B**) WWW, $N = 325{,}729$, $\langle k \rangle = 5.46$ (*6*). (**C**) Power grid data, $N = 4941$, $\langle k \rangle = 2.67$. The dashed lines have slopes (A) $\gamma_{actor} = 2.3$, (B) $\gamma_{www} = 2.1$ and (C) $\gamma_{power} = 4$.

Barabasi & Albert (1999)

Scale-Free Network: Some Cautions



Different Basis/Assumptions

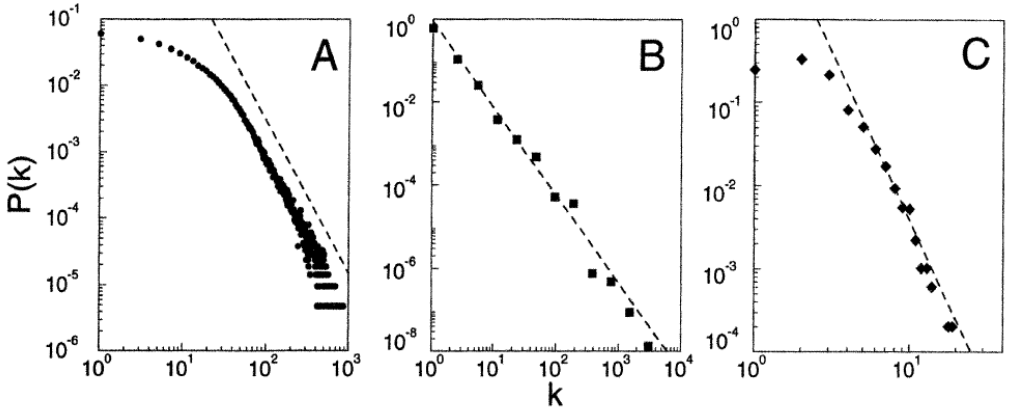
- Barabasi & Albert (1999)'s findings were reported on open networks: assuming continuous growth over the lifetime.
- The diurnal spatial interaction network show a complete lifecycle: are our observations sufficient to extend the findings to the whole network lifecycle?
- Worth testing on long-term spatial interaction networks

Constraints/Limit to Growth

- Linear model may not be the best fit for power exponent: Possibly point to the existence of constraints/limiting factors for nodes with higher degrees

Statistical Proofs

- How do we statistically prove that the distribution follows power law? → An area of active academic debate and research that is related to uncertainty.



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Barabasi & Albert (1999)

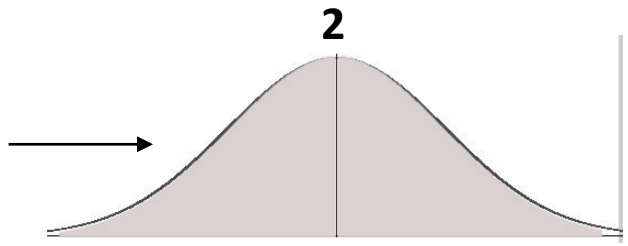
Manifestation of Uncertainty

YEAR_MONTH	DAY_TYPE	TIME_PER_HOUR	PT_TYPE	ORIGIN_PT_CODE	DESTINATION_PT_CODE	TOTAL_TRIPS
2020-12	WEEKEND	12	BUS	93201	92111	2
2020-12	WEEKDAY	12	BUS	93201	92111	5
2020-12	WEEKEND	23	BUS	59019	60179	1
2020-12	WEEKEND	13	BUS	1239	3059	1
2020-12	WEEKDAY	13	BUS	1239	3059	13

Uncertainty from simplification

- From LTA: On **a typical weekday** of January 2021, from 1200hrs to 1259hrs, the total number of trips that travelled from Bus Stop **93201**, Victoria School, to Bus Stop **92111**, Opposite Roxy Square, is 2. Exact method used to derive the value is not known.

Probable full distribution of trip numbers within the hourly timeframe



How does this uncertainty arise?

- Simplification deemed necessary to reduce the massive individual tap-in/tap-out data to an “expected count” within hourly timeframes for public sharing

Implications

1. Loss of granularity in the exact temporal distribution of trip timing
2. Loss of precision in the temporal analysis result

How is uncertainty handled in the project?

- Insufficient information is given to reconstruct the temporal distribution
- Work with the existing temporal resolution (hourly timeframes + day types) for analysis to keep it consistent

Limitations

Trips vs Journeys

- Trips are defined by each pair of tap-in/tap-out: heavily influenced by the design of bus service routes and do not represent actual origin/destination of one journey
- Available public data is anonymised and aggregated: unable to chain trips into a journey
- May have over-estimated the influence of bus interchanges/high-degree nodes

Only bus data is considered

- Heavily influenced by the hub-and-spoke bus service design model
- Potential to conceptualise multi-layer networks (from multi-modal transport data) to mitigate the hub-and-spoke design effect, especially in deriving urban centres and studying polycentric forms

Challenges and Future Research

- **Theoretical/Conceptual**: Interpretation of findings in the context of urban space studies
  - How do the relevant concepts (e.g. communities, degree distribution, degree correlation) and findings translate into knowledge of urban space?
  - How do geographical concepts (e.g. distance, scale, neighbourhoods) apply in networks (at all)?
  - The mechanics of forming the spatial interaction networks and scale-free state, e.g. individual location decision choices
- **Technical: Fitting and definition of a power law**
  - An active field of research with significant challenges;
  - This project has resorted to visual observation and approximation; requires more rigorous statistical proofs

Conclusion

- Initial exploration of the spatial interaction networks from bus passenger data
- Inter-disciplinary research: requires conceptual and theoretical grounding to support the result interpretation and explanation of the mechanics
- Future research possibilities
  - Multi-layer networks
  - Community detection
  - Contextualise networks in geography – interpretation of results
  - Network evolution and phase transition

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Thank You

Software & technologies used

- Gephi 0.9.2: network analysis
- Python networkx/pandas/numpy package: network analysis & community detection & statistical analysis
- ArcGIS Pro: visualization