ASME® 2021 IDETC-CIE
International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
CONFERENCE Aug 17–20, 2021
Online, Virtual

Robust Design of Complex Socio-Technical Systems using Complex Networks
CIE 2021 Graduate Research Poster

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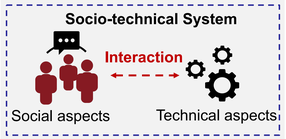
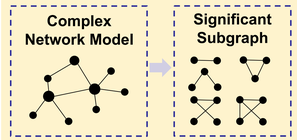
Introduction and Background



- Design parameters
- Uncontrollable noise effects (e.g., seasonal changes)



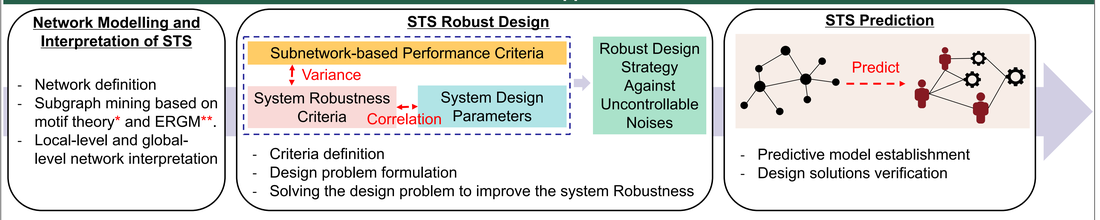
- Network definition
- Significant subgraph identification
- Interplays between local-level and global-level networks

Because of the increasing internal interconnections and unpredictable social behaviors, the robust design of a **socio-technical system (STS)** is challenging. Network-based STS robust design provides a pathway to model social behaviors and capture the relationships between local-level and global-level systems. This network modeling is important in support of developing a novel bottom-up robust design method that not only emphasizes the robustness of the entire system but also maintains the functionality of the local service systems.

Research Questions

- **RQ1:** How to model the local service structures of STS and evaluate their impacts on the global system performance based on network theories?
- **RQ2:** What is the relationship between the local-level structures and the system-level performance, and how can it be used to support STS robust design against uncontrollable perturbations?
- **RQ3:** How to verify and validate the effectiveness of an STS robust design approach?

Research Approach



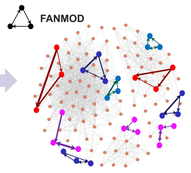
*: Network motifs are underlying nonrandom subgraphs within a complex real-world network, and it can be identified by tools like FANMOD and mfinder.
**: ERGM (exponential random graph model) is a stochastic network model that can model network structural effects beyond simply modeling nodal attribute effects and relational attribute effects.

Application Context

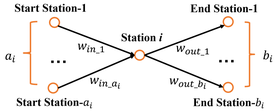
Bike-sharing System (BSS)

- ***Nodes***: bike stations
- ***Directed Links***: trip from one station to another station
- ***Weights***: trip times happened in one month

BSS Trip Network and Trip Motifs



Rebalance Performance Criteria of Global-level Trip Network



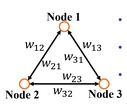
$$c_i = \sum_{j=1}^{ai} w_{in\_j} - \sum_{j=1}^{bi} w_{out\_j}$$

- > 0: return problem
- < 0: rental problem
- $= 0$: no rebalance problem

$$\alpha = \frac{1}{M}\sum_{i=1}^{M}|c_i| \qquad \beta = \frac{1}{N}\sum_{i=1}^{N}|c_i|$$

M: **the number of stations with rental problem**
N: **the number of stations with return problem**

Rebalance Performance Criteria of Local-level Trip Motif



- For Node 1: $c_1 = (w_{21} + w_{31}) - (w_{12} + w_{13})$
- For Node 2: $c_2 = (w_{12} + w_{32}) - (w_{21} + w_{23})$
- For Node 3: $c_3 = (w_{13} + w_{23}) - (w_{31} + w_{32})$

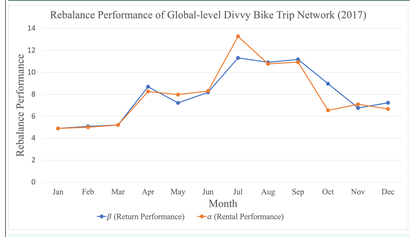
- An example: if $c_1 > 0, c_2 > 0, c_3 < 0$,

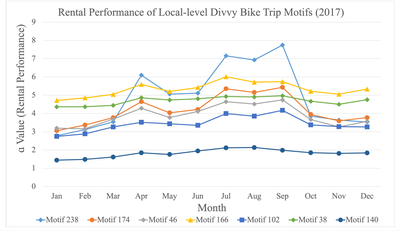
$$\alpha_g = c_3 \qquad \beta_g = \frac{1}{2}(c_1 + c_2)$$

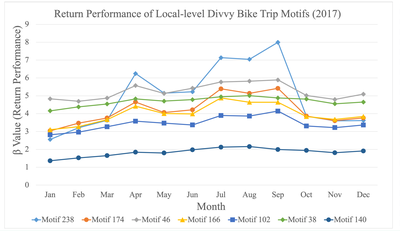
- Assuming we have K motif g in network G,

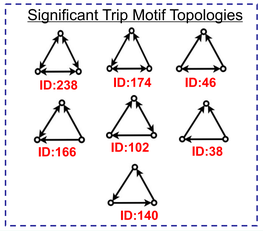
$$\bar{\alpha}_g = \frac{1}{K}\sum_{j=1}^{K}\alpha_{g,j} \quad \bar{\beta}_g = \frac{1}{K}\sum_{j=1}^{K}\beta_{g,j}$$

Global-level and Local-level Rebalance Performance of Divvy Bike Trip Network and Significant Trip Motifs







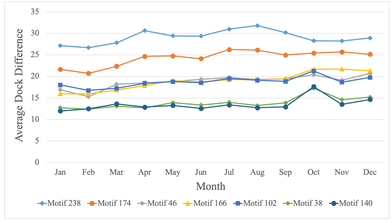


- Both global-level and local-level trip networks have more serious rebalance issues in warmer seasons than those in colder seasons.
- During the warmer season, global-level trip networks have both return and rental issues. However, most local-level trip motifs only have either return or rental issues, and just motif 238 and motif 174 obviously have both issues.

- **Seasonal robustness criterion**: yearly variance of motif rebalance score (i.e., α and β).

Divvy Bike Robust Design Against Seasonal Effects

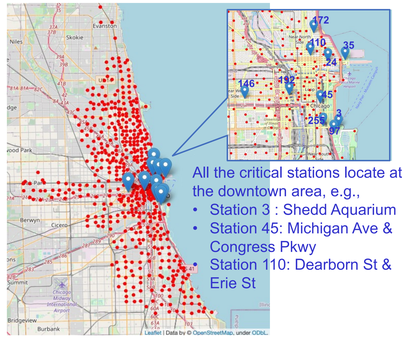
Capacity Planning Criterion of Significant Trip Motifs



Correlation coefficient (dock difference vs seasonal robustness criterion)	2014	2015	2016	2017
	0.9037	0.9305	0.9227	0.9258

- **Imbalanced capacity**, i.e., large dock difference, could weaken the robustness of BSS local-level trip motif rebalance performance to make it sensitive to seasonal changes.
- Motif 238 has the worst rebalance performance, so its capacity should be optimized.
- Motif 238s with the highest dock difference values in each month are identified and check which stations constructed these motifs.

Critical Stations Identification



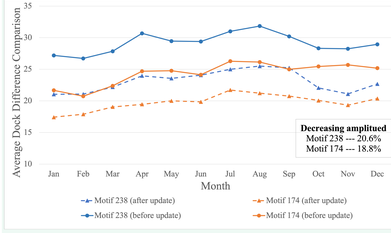
Identification rules:

- Among twelve months, stations that appear in the most numbers of months to construct the critical motif 238s should be changed dock numbers.
- Stations that appear most in each month to construct the critical motif 238s should be changed the dock numbers.
- Critical station set: {3,24,35,45,97,110,146,172,192,255}

Updating Result of BSS Capacity Design

Station ID	3	24	35	45	97	110	146	172	192	255
Original dock num	55	15	47	15	55	23	11	11	47	39
Add/delete num	-28	8	-24	8	-32	0	12	12	-24	-16
New dock num	27	23	23	23	23	23	23	23	23	23

- Based on the identified critical stations. A **multi-objective optimization problem** is formulated, and its goal is to minimize the dock difference of critical motif 238s but not increase other motifs' dock differences.
- This nonlinear integer optimization problem is solved by using **genetic algorithm**, *ga* function in MATLAB (2020). The result is shown in the above table.



- After optimization, the dock difference of motif 238 and 174 are decreased **by 20.6% and 18.8%**. With such a decrease, the enhance of the system robustness against seasonal effects is expected to be achieved effectively.

Future Work

1. Developing an interpretation model of STS based on ERGM
2. Developing a predictive model of STS based on network embedding technique and then applying the developed model to verify the applicability of the proposed design method.
3. Developing an improved robust design method for STS against multiple noise effects.

References

1. Hassannezhad, M., Cantamessa, M., Montagna, F. and Clarkson, P.J., 2019. Managing Sociotechnical Complexity in Engineering Design Projects. *Journal of Mechanical Design*, *141*(8).
2. Xiao, Y. and Sha, Z., 2020, August. Towards Engineering Complex Socio-Technical Systems Using Network Motifs: A Case Study on Bike-Sharing Systems. In *ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers Digital Collection.

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