Measuring Social Infrastructure Service Burden

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1. INTRODUCTION TO SOCIAL INFRASTRUCTURE SERVICE BURDEN

Social Infrastructure Service Burden (abbr. *Social Burden*) is defined as the burden to a population for attaining services needed from infrastructure.

Infrastructure services represent opportunities to acquire things that people need, such as food, water, healthcare, financial services, etc. Accessing services requires effort, disruption to schedules, expenditure of money, etc. Social Burden represents the relative hardship people experience in the process of acquiring needed services. Social Burden is comprised of several components. One component is the effort associated with travel to a facility that provides a needed service. Another component of burden is the financial impact of acquiring resources once at the providing location.

We are applying Social Burden as a resilience metric by quantifying it following a major disruption to infrastructure. Specifically, we are most interested in quantifying this metric for events in which energy systems are a major component of the disruption. We do not believe this is the only such use of the Social Burden metric, and therefore we will also be exploring its use to describe blue-sky conditions of a society in the future.

Furthermore, while the construct can be applied to a dynamically changing situation, we are applying it statically, directly following a disruption. This notably ignores recovery dynamics that are a key capability of resilient systems. This too will be explored in future research.

2. CALCULATION OF SOCIAL BURDEN METRIC

We have developed the following mathematical formulation for Social Burden:

$B_{n,m} = \frac{E_{n,m}}{A_n}$, where: (1)

- $B_{n,m}$ = Social Burden, a matrix over discrete space (**n**) and infrastructure services (**m**)
- $E_{n,m}$ = Attainment Effort, or how hard people have to work to attain their infrastructure needs, also an **n x m** matrix
- A_n = Attainment Ability, or the resource people have at their disposal for attaining their infrastructure service needs, not dependent on the type of service, a vector length **n**

Because *A* is a vector, while *E* is a matrix, division is applied element-wise across the **m** (services) dimension of *E*. In matrix notation, this can be formulated as ***A" E***, where *A"* is a diagonal **n x n** matrix of $1/A_n$.

Effort (*E*) is a function of the individual "pairwise efforts" between each spatial element and each point that provides an infrastructure service, as follows:

$E_{n,m} = \frac{1}{\sum_l \frac{S_{l,m}}{I_{n,l}}}$, where: (2)

- $S_{l,m}$= Infrastructure to Service relationship, a matrix of over infrastructure points (**l**) and infrastructure services (**m**)
- $I_{n,l}$= Individual pairwise efforts between spatial elements (**n**) and infrastructure points (**l**).

This function for effort is essentially the reciprocal of the sum of the S-weighted reciprocal pairwise efforts. The reciprocal of pairwise effort can be thought of as the "level of service" that each infrastructure point provides each spatial element. Therefore, equation (2) can also be written:

$$E_{n,m} = \frac{1}{\sum_l G_{n,l} S_{l,m}}, \text{ where:} \quad (3)$$

$G_{n,l}$ is the reciprocal of $I_{n,l}$. In matrix notation this can be written $\boldsymbol{E} = \frac{\boldsymbol{1}}{\boldsymbol{G}\,\boldsymbol{S}}$. With this formulation, we are assuming that adding a new infrastructure point to the system will decrease the effort for everyone in that system, even the far-away spatial elements. However, overall effort will be dominated by the lowest pairwise efforts in this function. The pairwise efforts (I) are a function of distance and properties of the infrastructure points. We assume a linear increase in pairwise effort with distance between spatial element and infrastructure point (therefore, an asymptotic decrease in service level with distance), as follows:

$$I_{n,l} = J_l + D_{n,l} M_l, \text{ where:} \quad (4)$$

- J_l = The zero-distance effort associated with each infrastructure point (**l**)
- $D_{n,l}$ = Pairwise distance between spatial elements (**n**) and infrastructure points (**l**)
- M_l = The slope of effort with distance away from each infrastructure point (**l**).

The matrix notation for equation (4) is written as: $\boldsymbol{I} = \boldsymbol{J} + \boldsymbol{DM}$, where the vector J_l is replicated across the **n** dimension to form J, an **n x l** matrix, and the vector M_l should be placed on the diagonal to form M, which is an **l x l** matrix.

3. EXAMPLE APPLICATION OF SOCIAL BURDEN

Work with the island of Puerto Rico has served as a test case for this metric. We have assessed alternative microgrid portfolios from a set of 159 potential microgrid locations. We selected census block groups provided by the US Census as our spatial resolution – which provide data such as household income, age, and disability status for the attainment ability term, A_n in equation (1).

For any given portfolio of microgrids, we can calculate Social Burden by census block group. Figure 1 graphically depicts Social Burden for a randomly selected portfolio of 80 microgrids across the island, using median household income for the attainment factor. The Social Burden of any given census block group is the burden aggregated over all service types in the analysis, though we can also look at the Social Burden for individual service types.

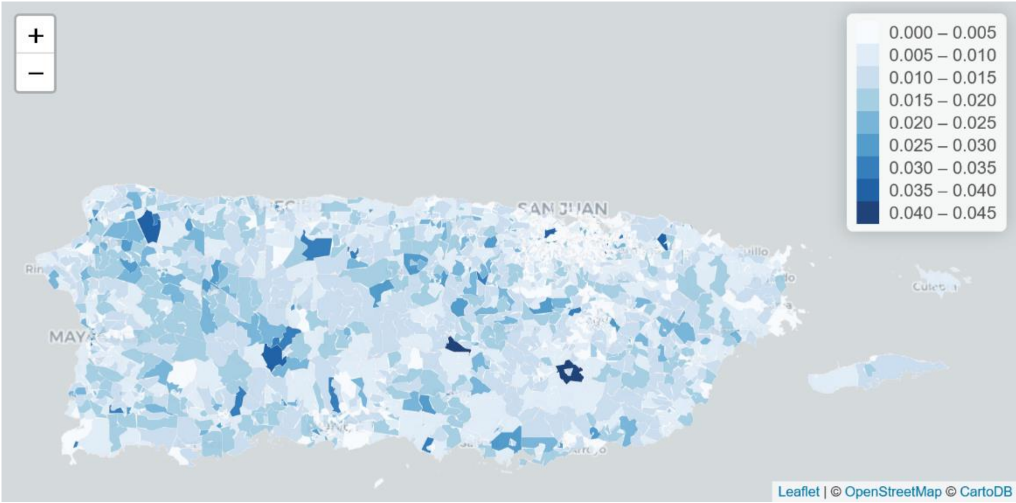

Figure 1. Social Burden by Census Block Group for Randomly Selected Portfolio of Microgrids.

Compare this to a map of just the effort component of the metric for the same set of 80 microgrids across the island in Figure 2. Leaving out the attainment factor essentially reduces the equation to the distance between the census block group centroids and the location of services. By comparing these two figures, it becomes apparent how much adding in an equity proxy (in this case household median income), impacts potential resilience and investment decisions.

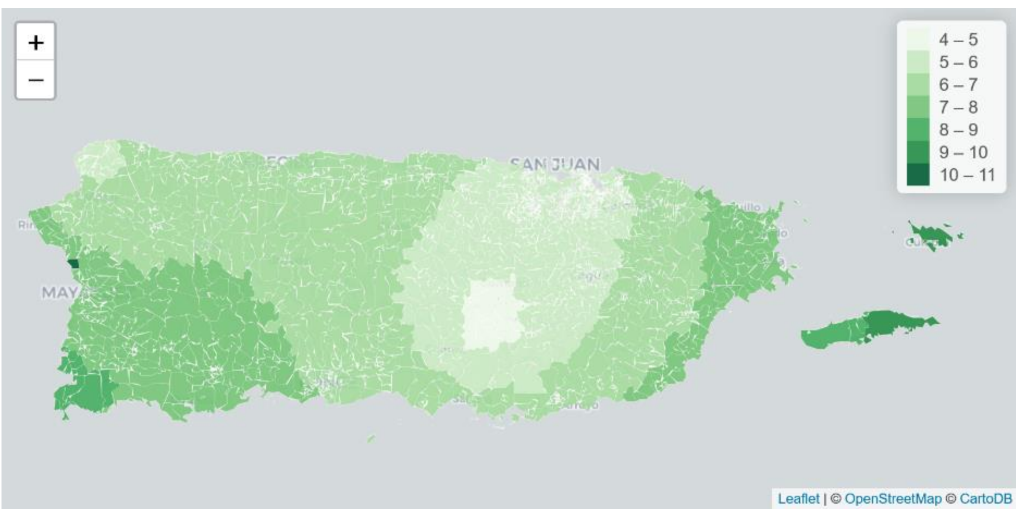

Figure 2. Effort by Census Block Group for Randomly Selected Portfolio of Microgrids.

In practice, Social Burden considerations are balanced against investment costs. At one end of the extreme, a community can choose to not invest in resilience measures (such as microgrids) for a cost of zero, but with a maximum burden to residents. At the other extreme, a community can choose to invest in the most microgrids and resilience measures possible to reduce Social Burden, but with an associated exorbitant cost. Between those two extremes are many other investment options that tradeoff between Social Burden and cost.

A sample Pareto frontier is shown in Figure 3 to illustrate a solution set. All the potential solutions are Pareto-optimal in that each solution minimizes Social Burden for a given cost level and vice versa. While no solution is mathematically "better" than others, we tend to focus on solutions where Social Burden is lowered significantly but costs remain relatively low. Portfolio 3 (third solution from the left) in Figure 3 is a good example of a solution that would be explored in-depth.

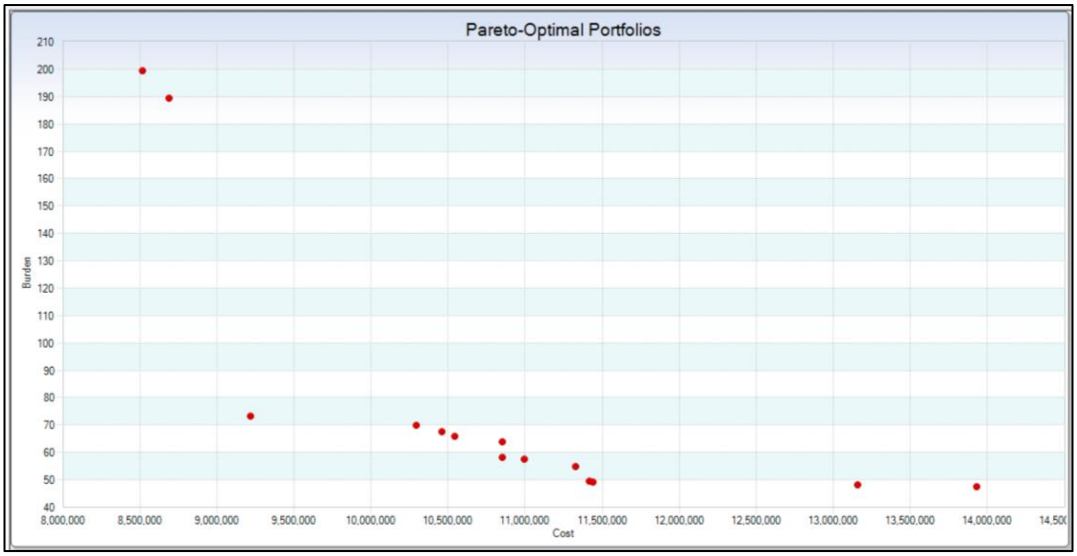

Figure 3. Example of Pareto-Optimal Solution Minimizing Both Burden and Cost.

4. CONCLUSION

Overall, Social Burden can be used to understand not just where services are located within a community, but how residents access them and their ability to acquire them once at the location. Including measures of equity can significantly change optimal investment options and help stakeholders better understand the unique socio-economic characteristics of their communities.

Social Burden is a stand-alone calculation but can also be used in resilience analysis tools. It is currently being used in the Resilient Node Cluster Analysis Tool (ReNCAT) developed by Sandia National Laboratories, as an optimization objective to optimally locate microgrids within communities.

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