Combinatorial Civic Crowdfunding with Budgeted Agents: Welfare Optimality at Equilibrium and Optimal Deviation

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February, 2023

37^{th} AAAI Conference on Artificial Intelligence **(AAAI 2023)**

Overview

1. Introduction
2. State-of-the-Art
3. Combinatorial Civic Crowdfunding (CCC)
    - Budget Surplus
    - Budget Deficit
    - Optimal Deviation is NP-Hard
    - Welfare and Agent Utility Trade-off
    - Looking Forward

Introduction

- **Civic Crowdfunding.** process of raising voluntary contributions towards the funding of a *public* project
  - Libraries
  - Parks

(a) Wooden Pedestrian Bridge in Rotterdam

(b) Solar Panels Installation in Memphis

Civic Crowdfunded Projects

Introduction: Lack of Incentives

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Challenge

Strategic agents require proper incentives to contribute!

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Refund Bonus Schemes

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- In PPR, if the project is not funded by the deadline, the agents get additional refund – along with their contributions!
- Formally, the agent utilities are,

$$\sigma(\cdot) = \mathbb{1}_{C \geq T} \cdot \underbrace{(\theta - x)}_{Funded(\sigma^F)} + \mathbb{1}_{C<T} \cdot \underbrace{\frac{x}{C} \cdot B}_{Unfunded(\sigma^U)}$$

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- PPR introduces a particular form of refund bonus scheme
- Damle *et al.* [2] show that if the refund bonus scheme is increasing w.r.t. contribution, the project is funded at equilibrium
- This condition on the refund bonus is also referred to as **Contribution Monotonicity** (CM)

Limitations: PPR and Related Work

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- PPR, and subsequent works [2, 3, 4, 5], focus on a single project
- These works also assume agents have *sufficient* budgets to pay their equilibrium contributions
- One can easily create instances with *budget-constrained* agents where equilibrium may not exist!

Our Focus: Combinatorial Civic Crowdfunding

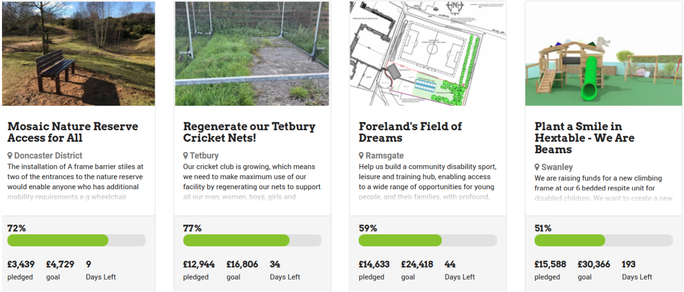

Figure: Combinatorial Civic Crowdfunding (CCC). Notice that agents may be interested to contribute to more than one project (especially if they are similar in type). Credit: `spacehive.com`.

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Socially Efficient Equilibrium

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- As agents are budget-constrained, only a subset of projects can be funded
- It may be desirable that such a subset is welfare-maximizing within the overall budget
- We refer to the funding of the socially welfare optimal subset at equilibrium as *socially efficient equilibrium* (SEE)

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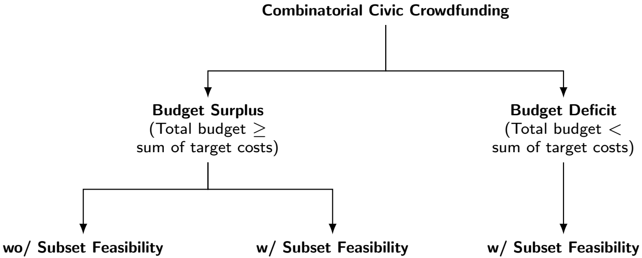
Combinatorial Civic Crowdfunding: Overview



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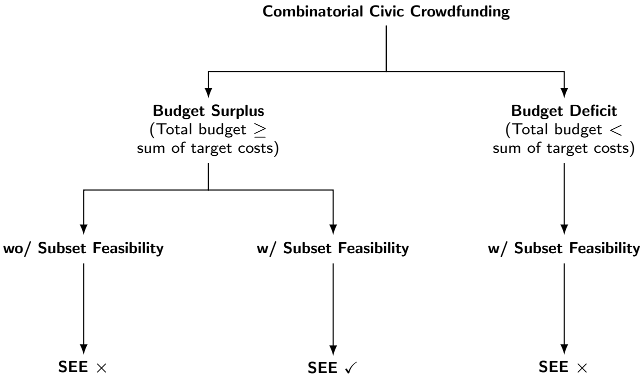

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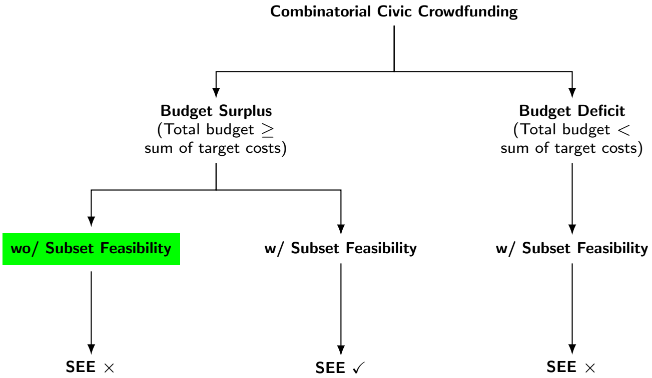
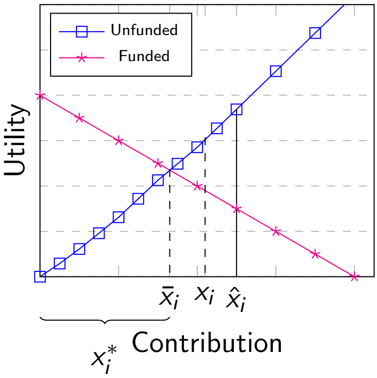


Impossibility

Theorem

Given a vector of refund schemes $(R_j)_{j \in P}$, which satisfy CM, there are Budget Surplus game instances of $\mathcal{M}_{CC}$ such that there is no equilibrium. That is, the set of equilibrium contributions may be empty.

Proof Intuition



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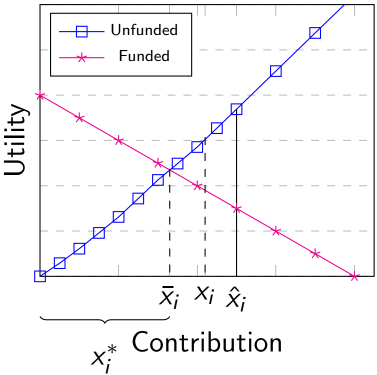

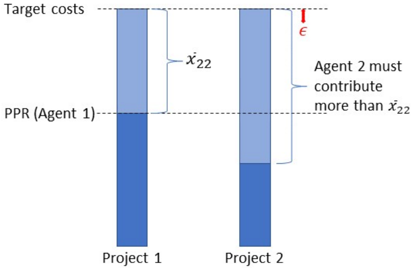

Subset Feasibility

Definition (Subset Feasibility for M (SF_M))

Given an instance of $\mathcal{M}_{CC}$ with $(R_j)_{j\in P}$ satisfying, Subset Feasibility for M, $M \subseteq P$, is satisfied if, $\forall i \in N$,

$$\gamma_i \geq \sum_{j\in M} \bar{x}_{ij}, \tag{1}$$

where $\theta_{ij} - \bar{x}_{ij} = R_j(\bar{x}_{ij}, B_j, \cdot)$.

Informally, if each agent i has enough budget to contribute $\bar{x}_{ij}$ for $j \in M$, $M \subseteq P$, then Subset Feasibility is satisfied for M.

Combinatorial Civic Crowdfunding: Overview

- **Combinatorial Civic Crowdfunding**
  - **Budget Surplus** (Total budget $\geq$ sum of target costs)
    - **wo/ Subset Feasibility**
      - **SEE** $\times$
    - **w/ Subset Feasibility**
      - **SEE** $\checkmark$
  - **Budget Deficit** (Total budget $<$ sum of target costs)
    - **w/ Subset Feasibility**
      - **SEE** $\times$

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Funding Guaranteed

Theorem

Given $\mathcal{M}_{CC}$ and $(R_j)_{j \in P}$ such that SF_P is satisfied, at equilibrium all the projects are funded, i.e., $C_j = T_j,\ \forall j \in P$. If $B_j \leq \vartheta_j - T_j,\ \forall j \in P$, then the set of PSNEs are
$\left\{ (x_{ij}^*)_{j \in P} \mid \sigma_{ij}^F(x_{ij}^*; \cdot) \geq \sigma_{ij}^U(x_{ij}^*; \cdot), \forall j \in P,\ \forall i \in N \right\}$.

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Proof intuition: simultaneous PPR

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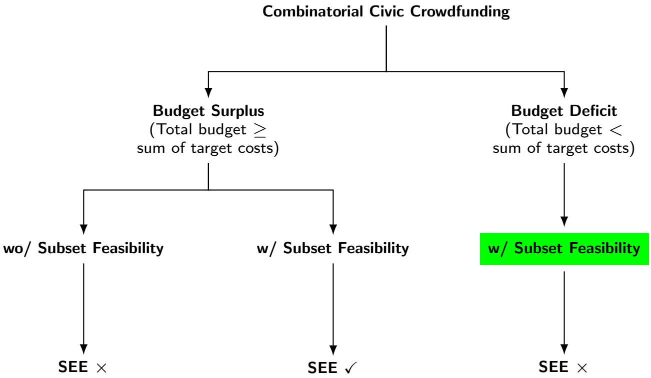

CCC with Budget Deficit

- Naturally, in this scenario only a subset of projects can be funded.
- To analyze agents' equilibrium behavior and funding guarantees, we focus on the subset of projects that maximizes the social welfare, i.e., $P^\star$.

Impossibility even with Subset Feasibility

Theorem

Given an instance of $\mathcal{M}_{CC}$, a unique $P^\star$ may not be funded at equilibrium even with Subset Feasibility for $P^\star$, $SF_{P^\star}$, for any set of $(R_j)_{j\in P}$ satisfying CM.

Proof Intuition

Algorithm Instance

Consider $P = \{1, 2\}$, $N = \{1, 2\}$ and fixed $R(\cdot)$

1: **procedure** GenerateValues($R(\cdot)$)
2: $T_1 \leftarrow \mathbb{R}_+$
3: Choose θ_{11} s.t. $\bar{x}_{11} < T_1 < \theta_{11}$ based on $R_1(\cdot)$
4: Choose θ_{21} s.t. $\bar{x}_{21} := T_1 - \bar{x}_{11}$
5: Set $T_2 = \bar{x}_{21}$, $\theta_{12} = 0$ and choose θ_{22} s.t. $\theta_{21} < \theta_{22} < \theta_{11} + \theta_{21} - x^*_{11}$ ▷ $P^\star = \{1\}$
6: Set $\gamma_1 := \bar{x}_{11}$ and $\gamma_2 := \bar{x}_{21}$ ▷ *Satisfying* $SF_{P^\star}$
7: **return** θ's, γ's, and T's ▷ s.t. Agent 2 deviates
8: **end procedure**

- Proof by construction where one of the agents has an incentive to deviate when $P^\star$ is funded

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  return θ's, γ's, and T's ▷ s.t. Agent 2 deviates

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- Proof by construction where one of the agents has an incentive to deviate when $P^\star$ is funded
- We also show that constructing such an instance is always possible for any refund scheme satisfying CM

Mixed Integer Program for Optimal Deviation

$\mathcal{Q}$. Given the total contribution by $N \setminus \{i'\}$ agents towards each project j, can the agent i' compute its optimal strategy?

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$$\max_{(x_{i'j})_{j \in P}} \sum_{j \in P} z_{i'j} \cdot (\theta_{i'j} - x_{i'j}) + (1 - z_{i'j}) \cdot R(x_{i'j}, \cdot)$$

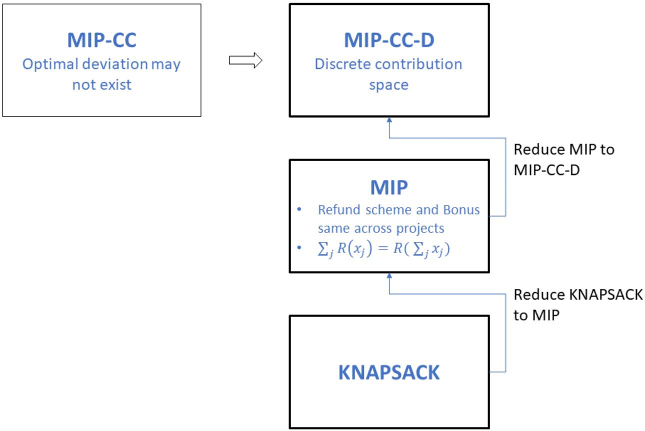
$$\textbf{s.t.} \sum_{j \in P} x_{i'j} \leq \gamma_{i'} \text{// Budget Constraint}$$

$$x_{i'j} \leq T_j - C_j, \forall j \text{// Remaining Contribution}$$

$$\left.\begin{aligned} &(x_{i'j} - T_j + C_j) \cdot z_{i'j} \leq 0, \forall j \\ &x_{i'j} - T_j + C_j < z_{i'j}, \forall j \\ &z_{i'j} \in \{0, 1\}, \forall j \end{aligned}\right\} \text{// Defining Indicator Variable}$$

Figure: MIP-CC: Mixed Integer Program to calculate Agent i''s optimal strategy given the contributions of the remaining agents $N \setminus \{i'\}$

Optimal Deviation is NP-Hard: Proof Intuition



Welfare and Agent Utility Trade-off

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- In Budget Deficit, we see that funding of welfare optimal subset at equilibrium may be impossible
- We show that finding an agent's optimal deviation is NP-Hard
- We propose certain heuristics and observe the trade-off between the welfare generated vs. agent utilities

Experimental Setup: Heuristics

1. Symmetric: Contribute equally to all projects

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5. OptWelfare: Contribute $\bar{x}$ to all projects in $P^\star$, equally distribute the remaining budget to $P \setminus P^\star$

Experimental Setup: Measures

- *Normalized Social Welfare* (SW_N). Ratio of the welfare obtained and the welfare from $P^\star$

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Experimental Setup: Measures

- *Normalized Social Welfare* (SW_N). Ratio of the welfare obtained and the welfare from $P^\star$
- *Normalized Agent Utility* (AU_N). Ratio of the agent utility obtained w.r.t. to the utility when each agent has enough budget to play $\bar{x}$ for each project $j \in P$

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Results

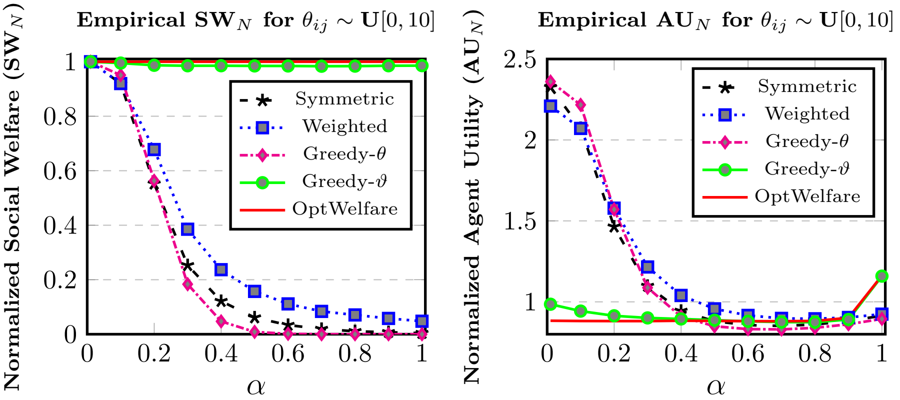

Figure: Empirical SW$_N$ and AU$_N$ for $\theta_{ij} \sim \mathbf{U}[0, 10]$

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Future Work

- Other solution concepts: Bayesian-NE, ϵ-NE

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- Heuristics with improved trade-off
- Randomized/Round-robin algorithms

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Thank You!

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