Collective Utility in Hierarchical Structures of Collective Adaptive Systems: an Application in Transportation Systems

M. Bitsaki[1], M. Dramitinos[2], George Koutras[1], Dimitrios Plexousakis[1], Alina Psycharaki[1]

[1]Transformation Services Laboratory
University of Crete
Heraklion, 70013, Greece

[2]Department of Informatics
Athens University of Economics and Business
Athens, 10434, Greece

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The ALLOW Ensembles Model

- **Collective Adaptive Systems** (CAS) comprise heterogeneous entities (virtual & physical) collaborating towards the achievement of their own objectives, and the overall objective of the collective
  - Example: urban mobility system
- **Entities** collaborate with each other to fulfill specific goals in the scope of ensembles
  - Entities' individual goals can impact other's satisfaction
  - Examples: Bus Driver, Passenger, Route Manager, FlexiBus Manager
- **Cells** encapsulate a functionality that the entity offers to the system
  - Examples: Passenger Trip Booking, Credit Card Payment, Route Control
- **Ensemble** is a set of cells from different entities collaborating with each other to fulfill some of the goals of the entities
  - Example: Route

Contributions

- Define the collective utility of an ensemble
- Propose a hierarchical structure to calculate the collective utility
  - Suitable in environments of incomplete information
  - Facilitates computations
- Apply collective utility in urban mobility system for making decisions
  - Maximization problems

Collective Utility

- The ***utility*** of an entity is a measure of satisfaction experienced by the entity for using a service
  - Entities make choices to maximize their utility
- The **collective utility** of an ensemble is a measure of the welfare of <u>all</u> entities that participate in the ensemble

$$v_E(a, w_1, \dots, w_k) = f_1(w_1, \dots, w_k)u_1(a, w_1) + \cdots + f_k(w_1, \dots, w_k)u_k(a, w_k)$$

a: utility parameters

w_i: entity i preferences

u_i: individual utility for entity i

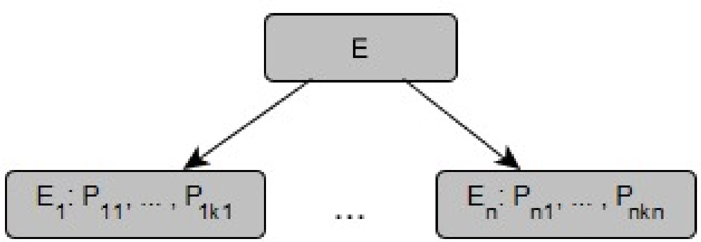
f_i: weight for entity i

Why Collective Utility is Important

- Evaluate ensembles
- Make collective decisions
- Improve the performance of service systems

A Utility Model for Ensemble Hierarchies

- A hierarchy of ensembles considers smaller ensembles being part of larger ensembles in terms of management and operation
- Accordingly, we consider a hierarchy of the utilities of the ensembles of the various levels in order to manage the required information in a scalable way



- $v_i = g_i(u_{i1}, \ldots, u_{ik_i}),\ i = 1, \ldots, n$
- $v = g(v_1, \ldots, v_n)$

u_{ij}: utility of entity *ij*

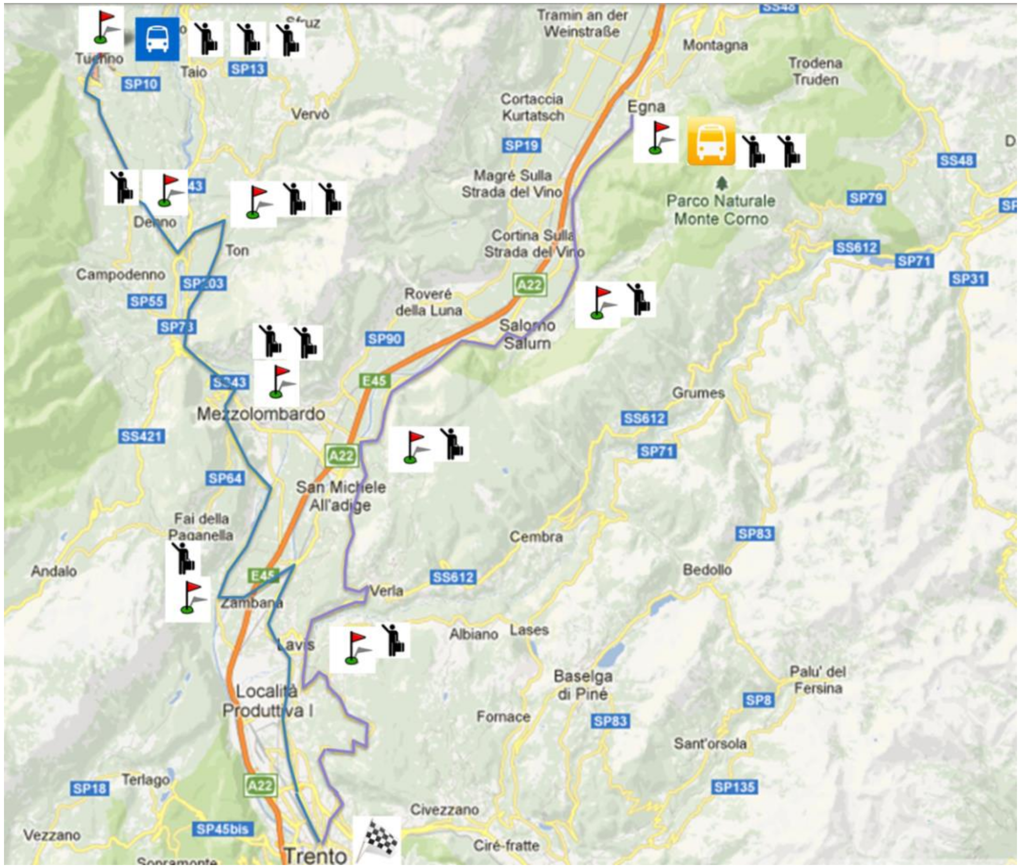
g_i, g: aggregation functions

Complementarities among Entities

- A factor that plays an important role in the <u>determination</u> of functions g, g_i is the existence of complementarities between the sets of the entities of the ensembles in the lower levels
  - entities collaborate with more than one ensembles in the lower level
  - each entity collaborates with only one ensemble in the lower level
  - all entities collaborate with all ensembles in the lower level

Smart City

- Passengers
  - Objectives
  - Preferences
- Buses
  - Fixed Capacity
- Dynamic Routes
  - Based on bookings
  - Context
- Environmental Changes
  - Traffic
  - Breakdowns
- Urban Mobility System
  - High service quality
  - Cost Optimization
  - Eco friendly



Urban Mobility System

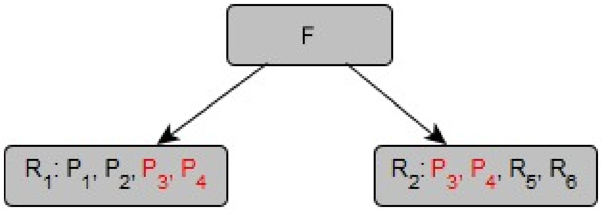
- A multi-modal transport system
  - Supervises various means of transportation: Regular bus, FlexiBus, Car pooling, etc.
  - Smart services
    - provide the passengers with a universal tool for planning complex trips involving more than one means
    - create integrated notification and support system
    - exploit related services on the go (ticket purchase, car pool reservation, …)

FlexiBus Scenario: Entities

- **Passengers**
  - Make requests specifying origin, destination, desired arrival time and other preferences
- **Bus driver**
  - is assigned a precise route
  - communicates with an assigned **Route Manager** to ask for the next pick-up point and to communicate information
- **FlexiBus Manager**
  - collects necessary information (i.e. traffic, closed roads, events, etc.) and available resources (i.e. available buses)
  - generates alternative routes

First Case: Multiple Routes for a Destination

- We consider a FlexiBus company that provides two routes for transporting passengers from pick-up point A to B and B to C respectively



$$u_i(t) = e^{\left(-\frac{k_i t}{w_i}\right)}$$

$$v_1 = \frac{w_1 u_1 + w_2 u_2 + w_{31} u_3 + w_{41} u_4}{w_1 + w_2 + w_{31} + w_{41}}$$

$$v_2 = \frac{w_5 u_5 + w_6 u_6 + w_{32} u_3 + w_{42} u_4}{w_5 + w_6 + w_{32} + w_{42}}$$

$$v = \frac{|S_1'|}{|S_1' \cup S_2'|} v_1 + \frac{|S_2'|}{|S_1' \cup S_2'|} v_2$$

w_i: maximum travel time of passenger *i*

k_i: risk tolerance

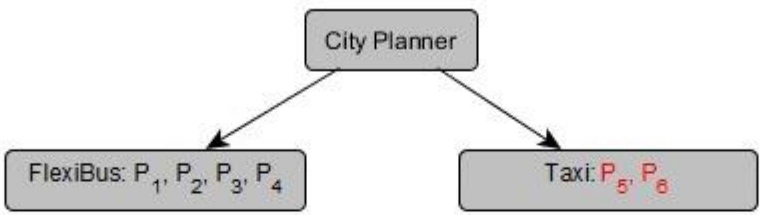
u_i: utility

S_j: set of passengers in route R_j

$S_1' = S_1 - (S_1 \cap S_2)$ and $S_2' = S_2 - (S_1 \cap S_2)$

Second Case: Multiple Passengers with the Same Goal

- We consider a city planner who coordinates the transportation of many passengers from <u>different origins</u> to the <u>same destination</u> at the same arrival time (e.g. to attend a concert) with different modes of transportation



w_i^1: maximum travel time of passenger i

w_i^2: preference of passenger i for taking the FlexiBus

u_i: utility of passenger *i*

S_1: set of passengers in FlexiBus

$$u_i = w_i^2 u_i^F + (1 - w_i^2) u_i^T$$

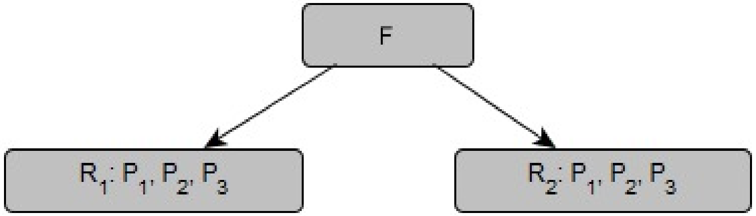
$$v_1 = \frac{w_1^1 u_1 + w_2^1 u_2 + w_3^1 u_3 + w_4^1 u_4}{w_1^1 + w_2^1 + w_3^1 + w_4^1}$$

$$v_2 = \frac{w_5^1 u_5 + w_6^1 u_6}{w_5^1 + w_6^1}$$

$$v = \frac{|S_1|}{|S_1 \cup S_2|} v_1 + \frac{|S_2|}{|S_1 \cup S_2|} v_2$$

Third Case: FlexiBus Failure

- We consider a FlexiBus company that provides a route for transporting passengers from point A to B. At some point, a failure occurs and the FlexiBus manager searches for alternatives



$$v_1 = \frac{w_1 u_1 + w_2 u_2 + w_3 u_3}{w_1 + w_2 + w_3}$$

$$v_2 = \frac{w_1 u_1' + w_2 u_2' + w_3 u_3'}{w_1 + w_2 + w_3}$$

$$v = \max\{v_1, v_2\}$$

Decision Making in First Scenario

- Consider that the FlexiBus Manager has received a number of requests for trip A to B, a number of requests for trip B to C and a number of requests for trip A to C (path passengers)
- <u>Decision</u> to be made: which passengers to serve so that the collective utility is maximized

Maximization Problem

$$\max_{K \subseteq N} u_K$$

$$s.t. |N_1 \cup N_3| \leq C_1$$
$$|N_2 \cup N_3| \leq C_2$$

$$w_{i1} + w_{i2} \leq w_i \; for \; each \; i \in N_3$$
$$T_1 \leq w_i \; for \; each \; i \in N_1$$
$$T_2 \leq w_i \; for \; each \; i \in N_2$$
$$T_1 + T_2 \leq w_i \; for \; each \; i \in N_3$$

u_K: collective utility of set of passengers K

$N = N_1 \cup N_2 \cup N_3$ set of all passengers

C_1, C_2 bus capacities

w_i: maximum travel time

$T_i, i = 1,2$ expected travel time

Hierarchical Approach

- We consider that the FlexiBus manager has access only to path requests which then forwards to the lower level route managers with the additional information of how to split the preference w_i for each such request
- Each route manager has access to the information related to the requests made for his own route
- Each route manager solves the above mathematical problem considering only passengers of his own route
  - some passengers that want both routes may be accepted by route 1 but may not be accepted by route 2
  - path passengers that have won in both links are accepted. The available seats are offered to single route passengers provided that overall collective utility is maximized

Experiments

- Route characteristics

	Route 1	Route 2
Start time	8:00	9:00
Travel time (min)	[30,40]	[20,30]
Capacity	20	20

- Passenger profile

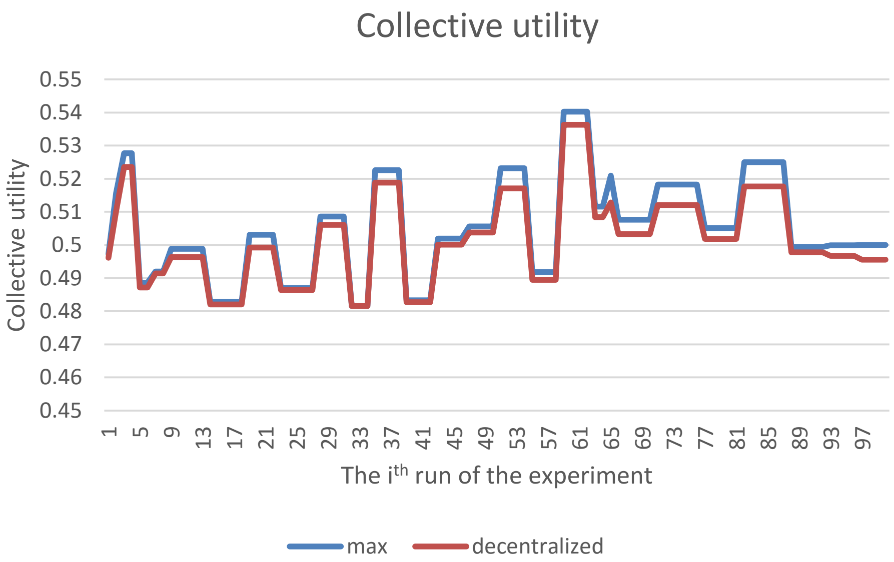
Preference	Type 1	Type 2	Type 3
Desired travel time (min)	[35, 45]	[25, 35]	[80, 100]
Risk tolerance	[0.5, 0.8]	[0.5, 0.8]	[0.2, 0.4]

Utility Functions

- $u(t) = e^{\left(-\frac{\mathrm{k}t}{t_{max}}\right)}$
- $U_1 = \sum_{i \epsilon N_1} \frac{1}{n_1 + wn_3} u_i + \sum_{i \epsilon N_3} \frac{w}{n_1 + wn_3} u_i$
- $U_2 = \sum_{i \epsilon N_2} \frac{1}{n_2 + wn_3} u_i + \sum_{i \epsilon N_3} \frac{w}{n_2 + wn_3} u_i$
- $U = \sum_{i \epsilon N_1} \frac{1}{n_1 + n_2 + wn_3} u_i + \sum_{i \epsilon N_2} \frac{1}{n_1 + n_2 + wn_3} u_i + \sum_{i \epsilon N_3} \frac{w}{n_1 + n_2 + wn_3} u_i$
- where w denotes the weight given to path passengers

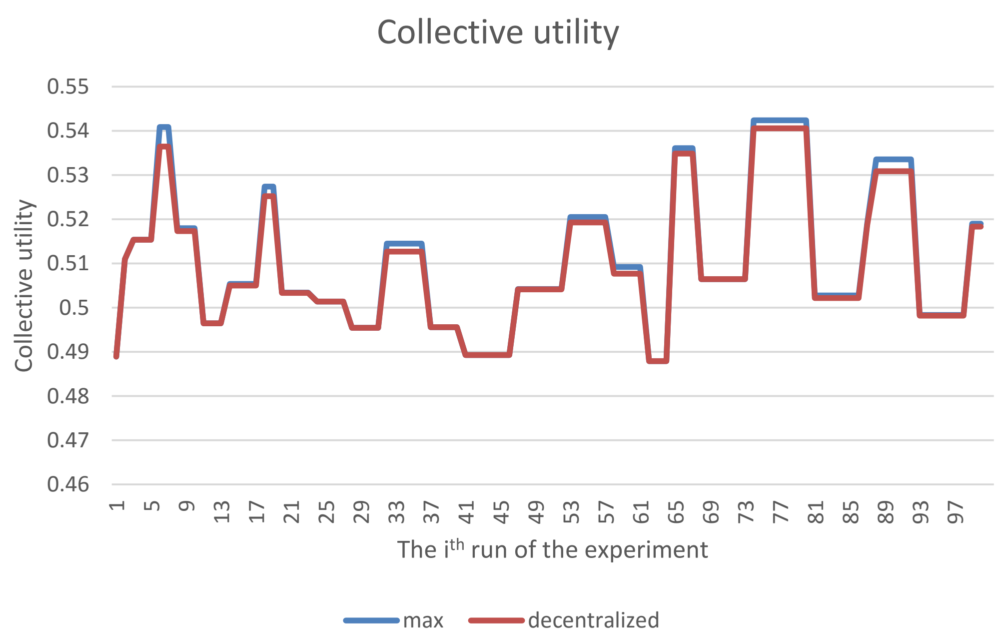
Results (I)

Comparison of hierarchical and central approaches for $w = 1.1$



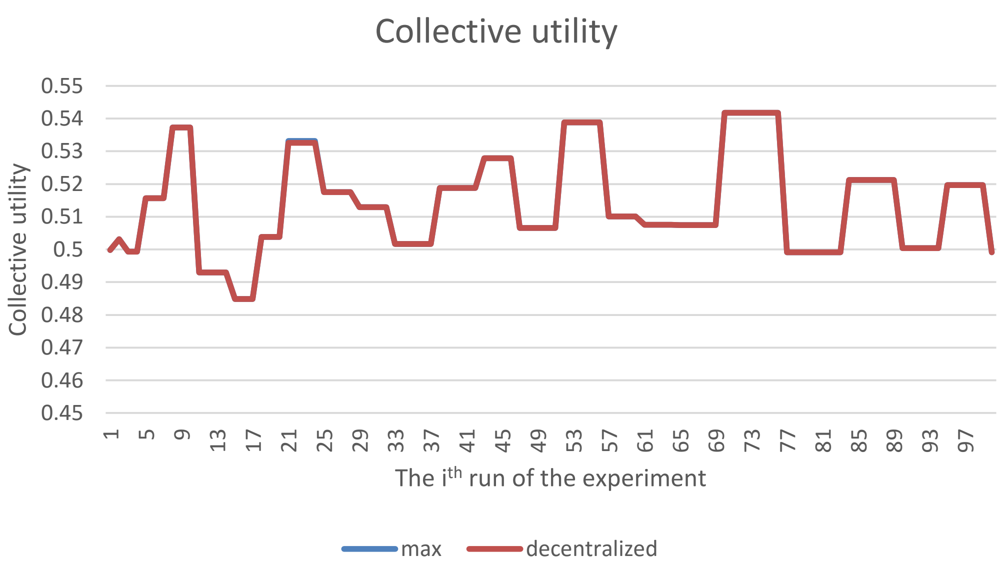
Results (II)

Comparison of hierarchical and central approaches for $w = 1.2$



Results (III)

Comparison of hierarchical and central approaches for $w = 1.3$



Conclusions

- In this paper, we provided models for calculating the collective utility of an ensemble and hierarchical structures for calculating upper level utilities from lower level utilities
- The success of this approach depends on
  - the way utility functions are selected (so that preferences of entities are appropriately represented)
  - how well the consecutive levels in the hierarchy coordinate to take into account complementarities, interdependencies and knowledge aggregation so that a scalable model is built.