SUPPLEMENTAL MATERIAL

Visualizing Interaction Effects for Combinatorial Cost-Benefit Analysis

Contents

SUP-1. Review of Visualization Techniques

In the context of our data and task abstractions, we conducted an assessment of visualization techniques that are relevant to the representation and comparison of interaction effects. Our review was structured in two stages: first, we examined techniques that depict individual two- and three-way interactions; second, we explored methods for comparing interaction effects across multiple action sets. This collection is not exhaustive but represents an opportunistic sample of visualization techniques identified in related work across various domains and use cases. Some approaches align more closely with our data characteristics and task requirements (see Tasks T1-T4), while others offer complementary perspectives. The techniques use a range of visual encoding channels, and many can be adapted or extended through interactivity, annotations, or other refinement to better support specific analytical tasks. A detailed summary of these techniques and their alignment with task requirements is provided in Figure 1.

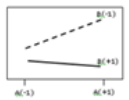
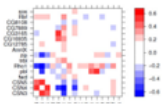
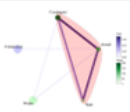
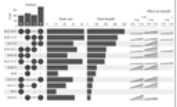
Thumbnail	Technique	Description	*Tasks* T1: Detect	T2: Characterize	T3: Estimate	T4: Compare	Support for set comparisons (total costs, total benefits)
	**Interaction plot** (also referred to as factorial plot or main effects plot)	Multi-series line chart displaying outcome curves for different conditions on the same axes, commonly used in factorial analysis. Third variable can be shown in side-by-side chart or using stroke style.	2-way; 3-way	Yes (seen directly from the chart)	Yes (seen directly from the chart)	Limited (only as small multiples)	No (costs are not integrated into the same view and require additional visual encoding)
	**Bubble chart**	Position encodes two continuous variables (cost and benefit), and bubble size encodes a third (e.g., cost-benefit ratio). Overlapping circles can lead to additional challenges.	2-way; 3-way	Yes (possible through relative size differences but imprecise)	Limited (rough estimations are possible but may need detailed comparison with set members)	Limited (may be difficult if interaction effects do not differ significantly between sets)	Yes (allows quick identification of sets with optimal cost-benefit trade-offs)
	**3D surface plot**	Two variables are represented on the x- and y-axes, while the outcome variable is mapped to the z-axis.	2-way	Yes (curvature of the plane)	Limited (detailed estimation requires gridlines or annotations)	Limited (only as small multiples)	No (costs are not integrated into the same view and require additional visual encoding)
	**Cube plot**	Used in factorial designs, where each vertex of the cube represents a combination of factor levels or variables. The outcome is encoded as labels, color, or size at each vertex.	2-way; 3-way	Yes (visible through patterns in vertex values)	Limited (rough estimation possible from visual vertex encodings but detailed comparisons may be cumbersome)	Limited (only as small multiples)	No (costs are not integrated into the same view and require additional visual encoding)
	**Heatmap**	Rows and columns represent individual actions and their possible combinations, while cell fills encode the outcome. Users can identify patterns by observing variations across different action combinations.	2-way	Yes (visible through color gradients and patterns across the grid)	Limited (rough estimations are possible but precise values cannot be determined from color gradients alone)	Yes (all action sets can be represented on the axes)	No (costs are not integrated into the same view and require additional visual encoding)
	**Concentric circles**	Similar to a heatmap, but actions and their combinations are arranged in a concentric ring layout, where each ring represents a different level of combination, and color encodes the outcome.	2-way; 3-way	Yes (visible through color gradients and patterns across the rings)	Limited (rough estimations are possible but precise values cannot be determined from color gradients alone)	Limited (only as small multiples)	No (costs are not integrated into the same view and require additional visual encoding)
	**Node-link diagram**	Each variable is represented as a node, and pairwise interactions are shown as connecting edges. Node size and luminance increase with variable importance, while edge width and color encode the strength of variable interactions.	2-way	Yes (visible through edge thickness and color intensity)	Limited (relative strength can be estimated but precise values require annotations)	Limited (only as small multiples)	No (costs are not integrated into the same view and require additional visual encoding)
	***[Proposed technique]*** **Multi-attribute set ranking with word-scale visualization**	A ranking-based visualization based on the UpSet technique, where set attributes are encoded as bar charts and word-scale inline visualizations support the analysis of interaction effects.	2-way; 3-way	Yes (visible through word-scale representations of interaction effects)	Yes (visible through word-scale representations of interaction effects)	Yes (supports direct comparison of multiple sets within a single view)	Yes (allows quick identification of sets with optimal cost-benefit trade-offs from the bar charts)

Figure 1. Reviewed visualization techniques for analyzing interaction effects in combinatorial cost-benefit analysis: interaction plot, bubble chart, 3D surface plot, cube plot, heatmap, concentric circles, node-link diagram, and our proposed multi-attribute set visualization.

SUP-2. Preliminary Comparative Evaluation

In this section, we present instructions given to participants in our study, along with screenshots of the visual encodings.

After providing consent and completing an attention check, participants were asked to rate their familiarity with a set of visualization types (see example in Fig. 2).

Figure 2. Example visualization type: Participants rate their experience with box plots on a scale from 1 (no experience) to 5 (extensive).

Participants were then presented with an introduction and instructions for completing the task.

Introduction

Imagine the following: You are a decision maker at a company that produces bricks. Due to climate change, you have decided to establish new measures (so-called "actions") in your factory to reduce CO_2 emissions. You have four different actions that can be applied in combination to reduce emissions. The amount of emissions reduced by the actions is referred to as the total benefit.

The four actions are labeled as follows:

- **Action A (Act. A)**
- **Action B (Act. B)**
- **Action C (Act. C)**
- **Action D (Act. D)**

To reduce emissions, it is possible to implement a combination of one to three actions (but not all four actions). Importantly, the different actions do not affect emission reduction (total benefit) in isolation. Instead, the total benefit of a combination of multiple actions might be greater or smaller than the sum of the total benefits if the individual actions were applied separately. Thus, it is important to carefully consider how the different actions affect each other to make an informed decision.

As a decision maker, you have the following goals:

- Understand how different actions affect the overall emission reduction (total benefit).
- Select the combination of actions that results in the highest reduction of emissions.

To achieve these goals, the data science team at your company has prepared visualizations of the effects of the different actions on emission reduction.

Instructions

The following visualization shows the effects of different actions on emission reduction (total benefit). Please take some time to carefully inspect the plot.

The next section contains several questions about the plot. You will be asked to answer these questions as accurately and swiftly as possible. The costs of different actions are not relevant for your decision. Focus only on the (total) benefit of the different actions.

The plot will be also shown on the next page, so you do not have to memorize the plot. Please give your best effort to answer the following questions as accurately and swiftly as possible. Click "Continue" when you feel ready.

Depending on their randomly assigned group (visualization technique), participants answered multiple questions related to interaction effects (see example in Fig. 3). Screenshots of alternative techniques are shown in Fig. 4, Fig. 6, and Fig. 7.

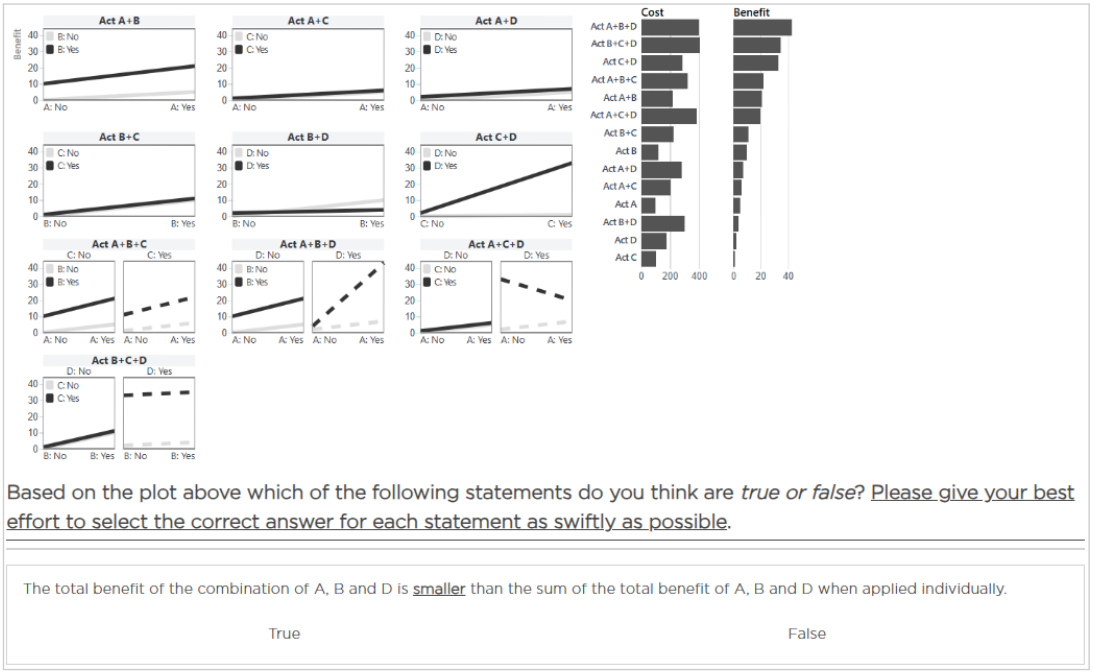


Figure 3. Participants answer questions related to interaction effects. One group is assigned to interaction plots to respond based on the visualized data.

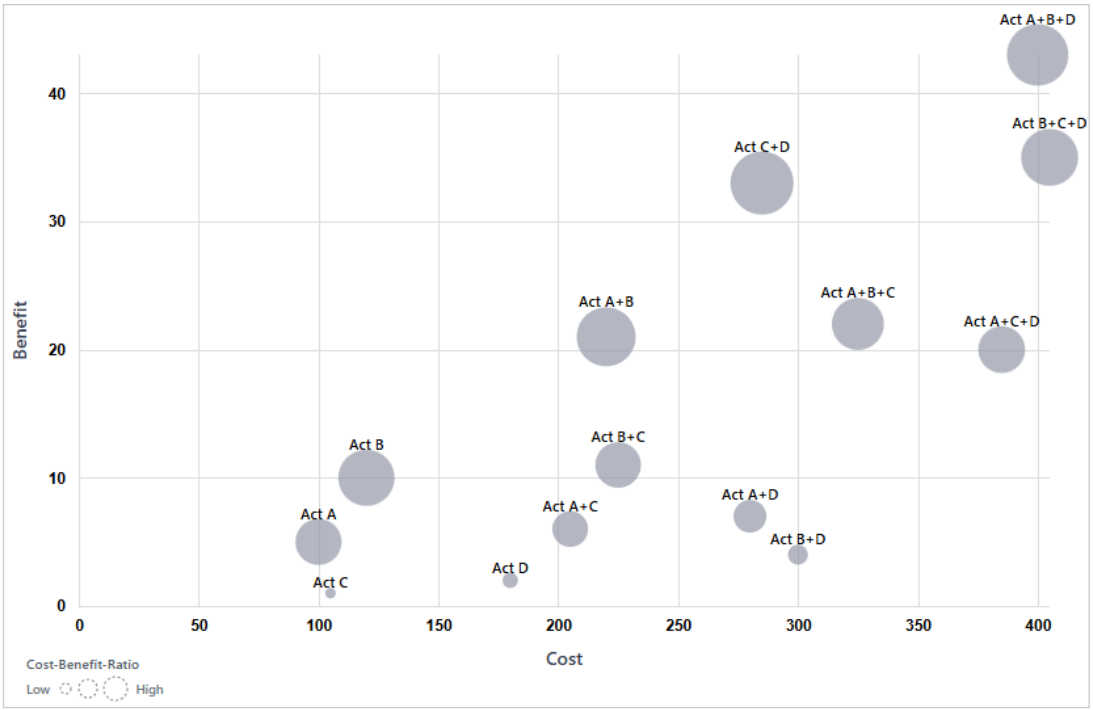


Figure 4. Bubble chart visualizing individual actions and their combinations. The x-axis represents cost, the y-axis represents benefit, and the circle size is scaled based on the cost-benefit ratio.

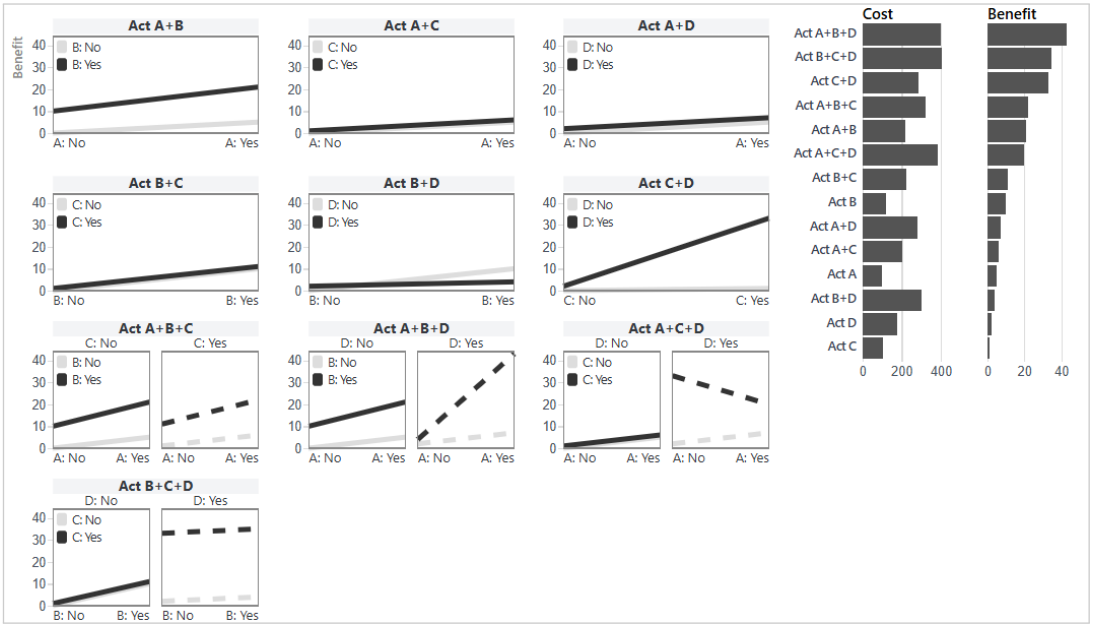


Figure 5. *Left*: Interaction plots depicting the effect of two and three-way interactions. The y-axis represents the continuous outcome variable (benefit), while the x-axis indicates whether the first variable is active. Line color encodes the second variable. For three-way interactions, a side-by-side display is used, where the left column shows results with an inactive third variable and the right column with an active third variable. *Right*: Bar charts ranking alternative action sets based on their costs and benefits.

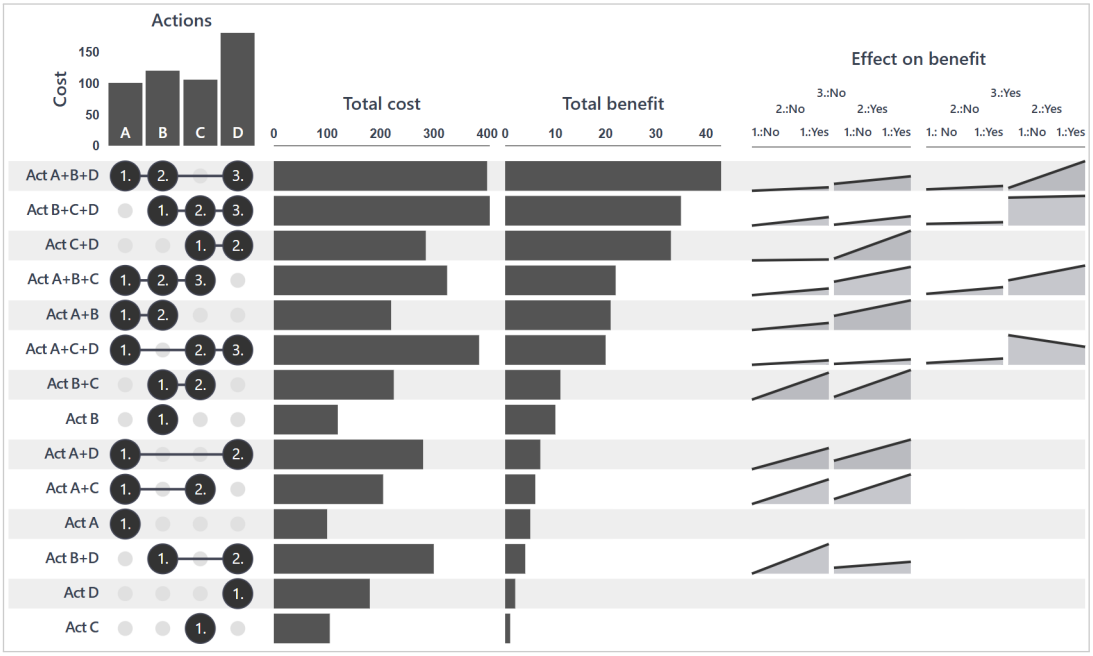


Figure 6. Proposed adaptation of the UpSet technique for ranking alternative sets of actions. *Left*: Combinatorial matrix representing action set memberships. *Center*: Bar charts displaying the total cost and benefit of all combinations. *Right*: Word-scale visualizations (juxtaposed areas) supporting the analysis of interaction effects, similar to interaction profiles but without color coding for the second variable, which is instead shown side by side.

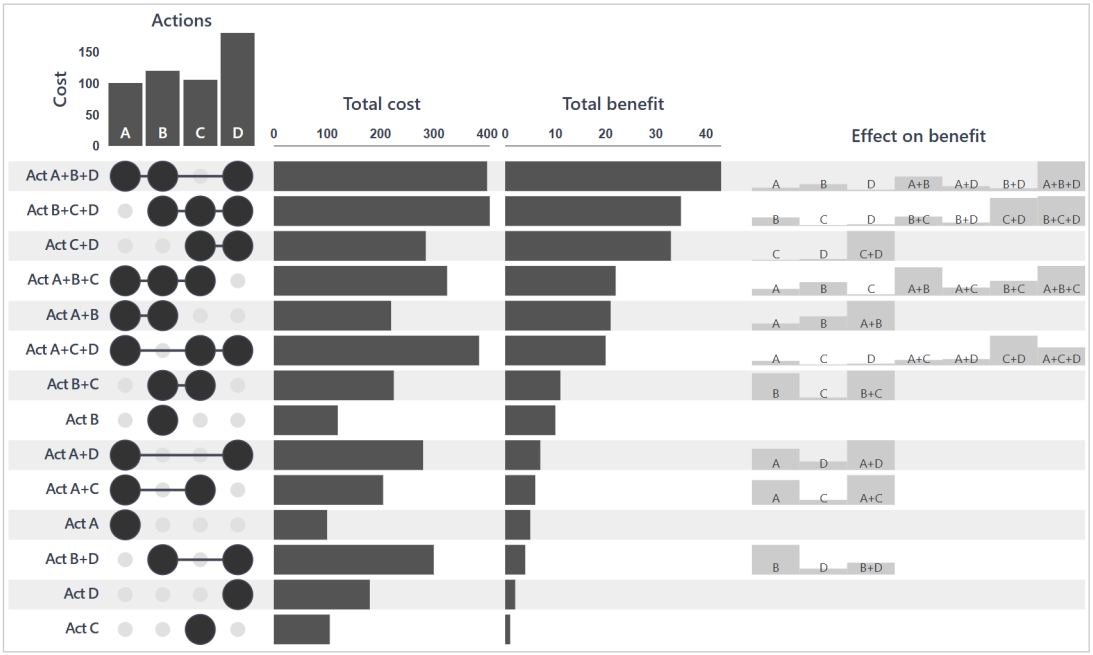


Figure 7. Alternative variant of the ranking-based visualization tested in our study (see Fig. 6). Instead of juxtaposed areas, the right side displays column bars for direct outcome comparisons. For each set (e.g., A+B), the bars show the individual outcomes of A and B alongside their combined effect to support the analysis of interaction effects.

Participants answered a set of questions about their experience, subjective performance (see Fig. 8, and the perceived usefulness of the visualization. At the end, they provided demographic information.

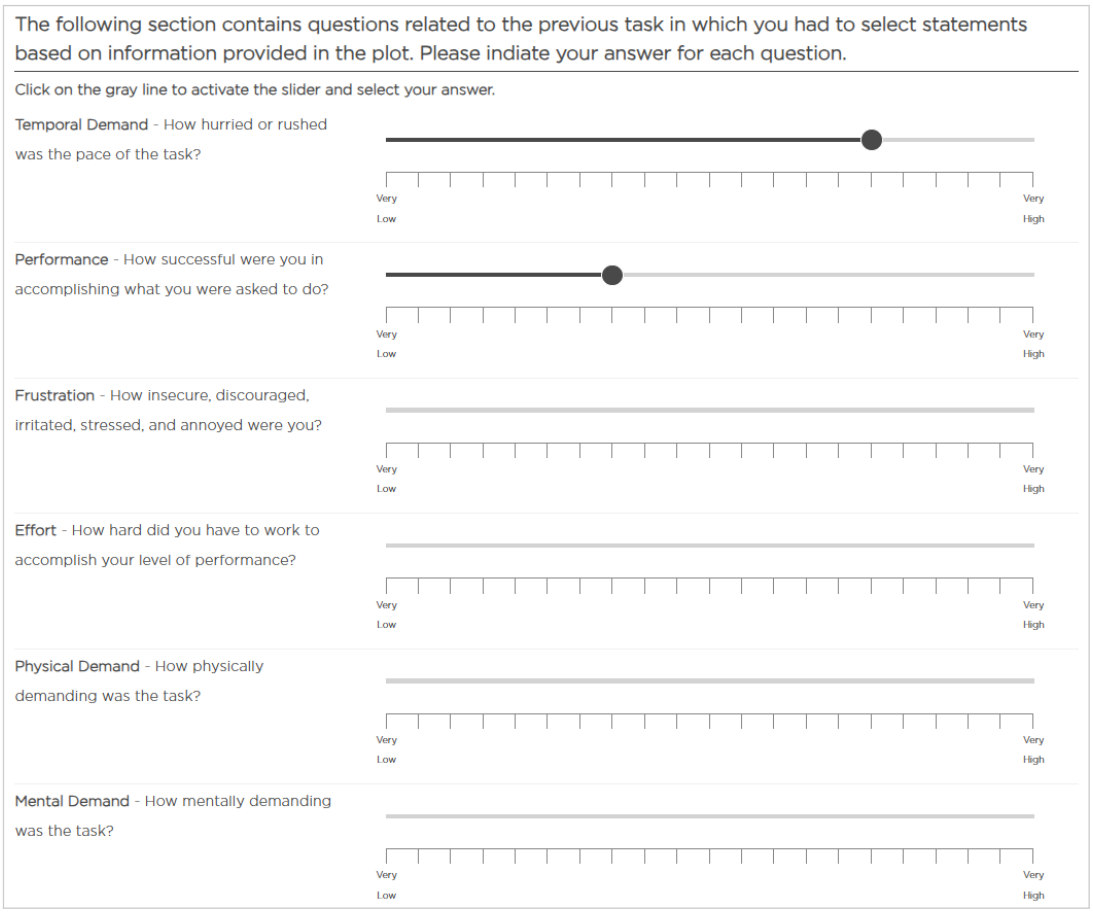


Figure 8. Participants rated their experience and subjective performance for the given task.