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Portfolio Decision Analysis for the Cost-Efficiency Evaluation of Weapon Systems

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Finnish Defense Forces

- Key statistics
  - Annual budget about $2.8 billion
  - About 1.3% of GNP (in the US about 4.5%)
  - Peacetime strength
    - » 13,000 regulars
    - » 27,000 conscripts
    - » 30,000 reservists trained annually
  - Wartime strength 430,000 soldiers
    - » Population of Finland 5.2 million
- Tasks
  - Provide territorial surveillance
  - Safeguard territorial integrity
  - Defend national sovereignty in all situations

Background

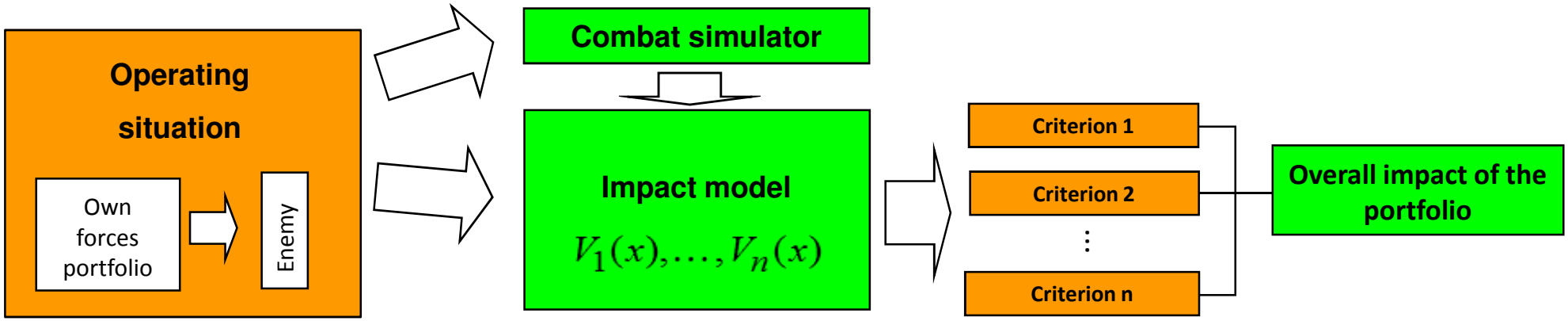
- Budgets for weapons system under growing pressure
- Combat simulators provide information about expected impacts in specific operating situations
- How can this information be used in the cost-efficiency evaluation of weapon systems?
- Methodological results from a research project funded by the Scientific Advisory Board for Defense (MATINE)

Concerns in Evaluating Weapon Systems

- Different kinds of impacts
  - Human casualties, loss of own systems, damage to enemy systems, targets
- Impacts are context dependent
  - Mission targets (attack/defense), weather, choice of tactical strategies
- There are interactions among weapon systems
  - Radar, for instance, enhances the capabilities of anti-aircraft guns
  - These interactions should be accounted for in cost-efficiency evaluation
  - Much of earlier research has focused on individual systems
- Impacts are often non-linear
  - 16 artillery guns may not be twice as effective as 8 guns

Estimates from Sandis Combat Simulator

- Operating situation defined by pre-specified conditions
  (own forces, enemy forces, terrain, weather, choice of tactics)
- Some of own forces kept constant while others are varied
- Simulations with different portfolios of selected weapon systems
- Simulation results extended by interpolation



A Formal Model of Weapon Systems

- Weapon system portfolio $x = (x_1, x_2 \ldots x_m) \in \mathbb{N}^m$

  m = Number of different weapon systems

  x_j = Number of weapon systems of the j^{th} type in portfolio x

  $C(x)$ = Total cost of portfolio x

- Feasible portfolios $X_F \subseteq \mathbb{N}^m$ satisfy relevant constraints
  - Resource constraints, logical constraints (incompatibilities etc.)

- Impact assessment criteria
  - Portfolios evaluated with regard to n different impact criteria (casualties to own systems, to enemy systems, attainment of objectives)
  - Overall impacts approximated by an additive value function

$$V(x,w) = \sum_{i=1}^{n} w_i V_i(x), \quad w \in S_w^0 = \{w \in \mathbb{R}_+^n \mid \sum_{i=1}^{n} w_i = 1\}$$

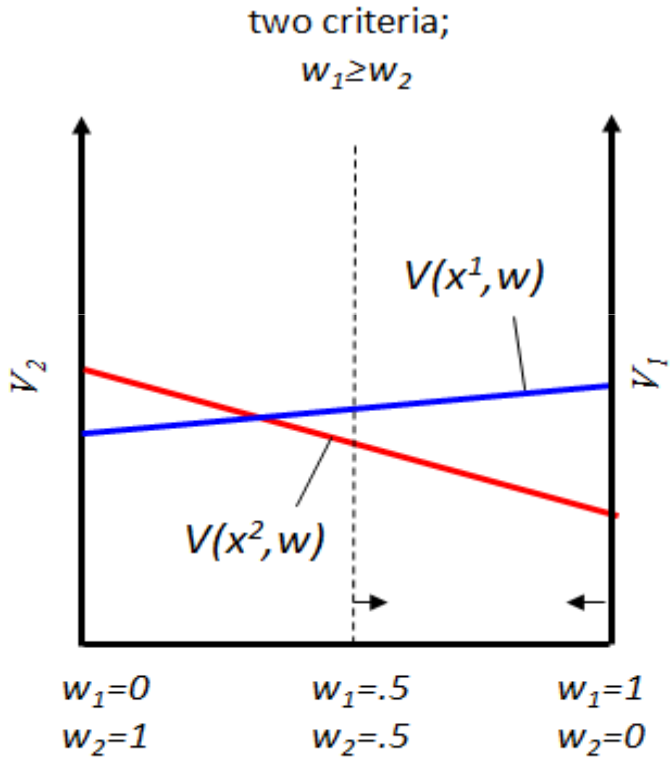
Incomplete Information and Dominance

- A set of feasible weights $S_w \subseteq S_w^0$ instead of exact weights
  - E.g. rank-ordering of criteria based on importance

$$S_w = \{w \in S_w^0 \mid w_1 \geq w_2 \geq \ldots \geq w_n\}$$

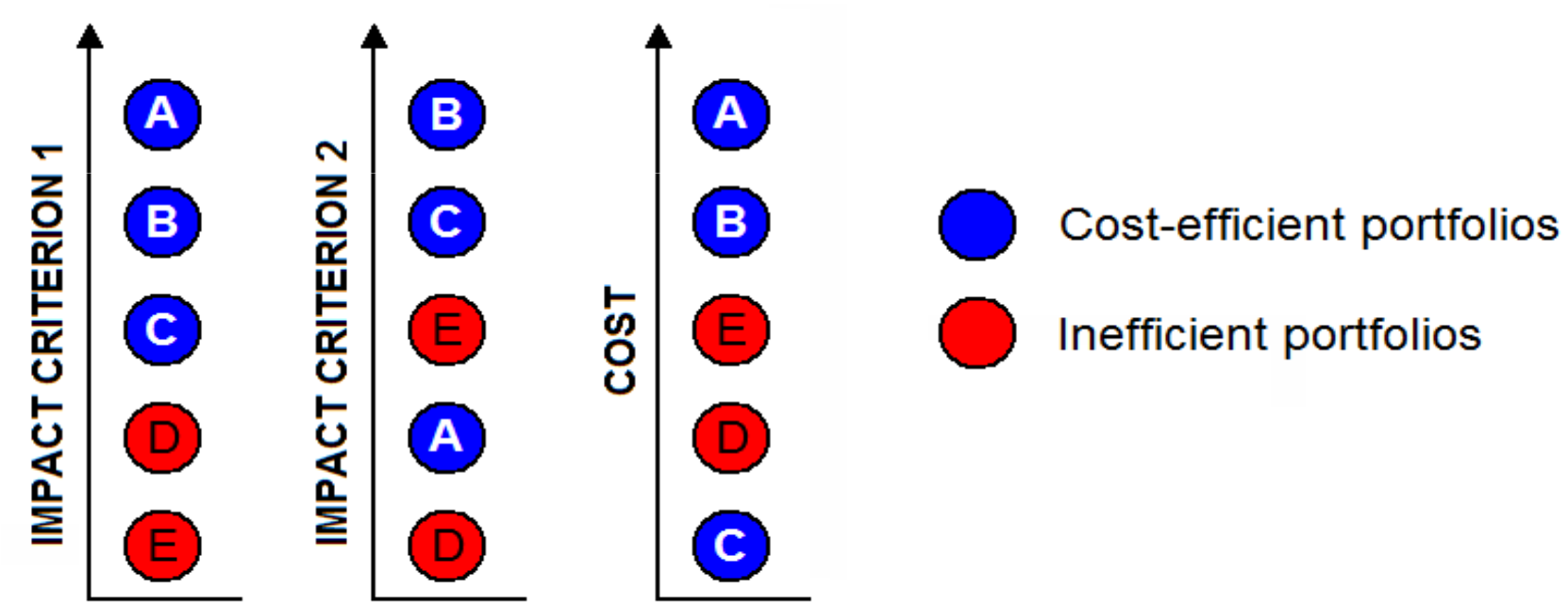
- Portfolio x^1 dominates x^2 if it has greater or equal overall impact for all feasible weights

$$\begin{cases} V(x^1, w) \geq V(x^2, w) \text{ for all } w \in S_w \\ V(x^1, w) > V(x^2, w) \text{ for some } w \in S_w \end{cases}$$



Cost-Efficient Portfolios

- Feasible portfolios are not dominated by any other portfolio that is of less or equal cost



Numerical Example Based on Realistic Data

- Three weapon systems

  $x_1 \in \{0,1,\ldots,24\}$ $x_2 \in \{0,1,\ldots,8\}$ $x_3 \in \{0,1\}$

  – Total portfolio cost derived from units costs through $C(x) = \sum_{j=1}^{3} c_j x_j$

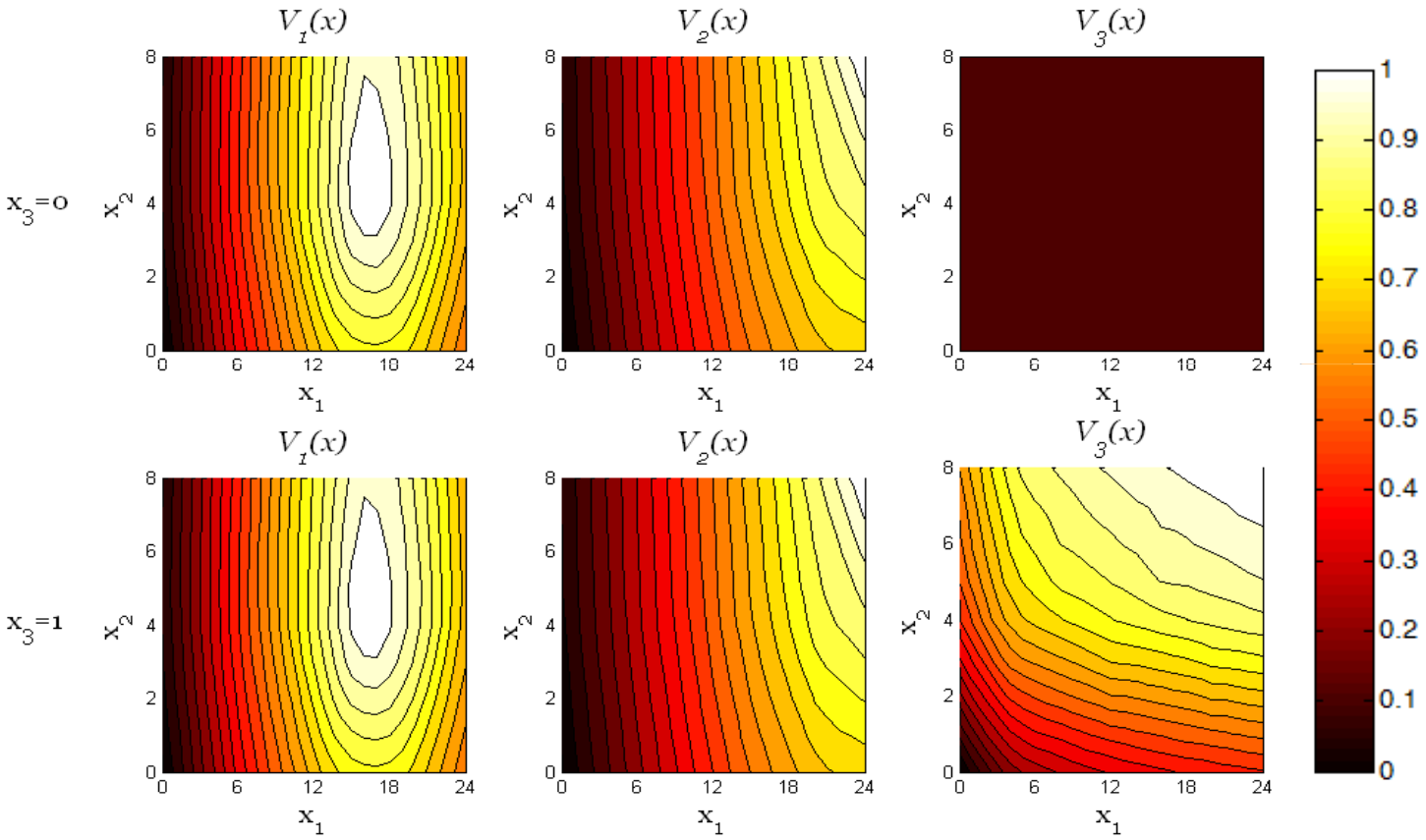
- Three impact criteria measuring different types of enemy casualties

- Incomplete information on the value (i.e. relevance) of impacts

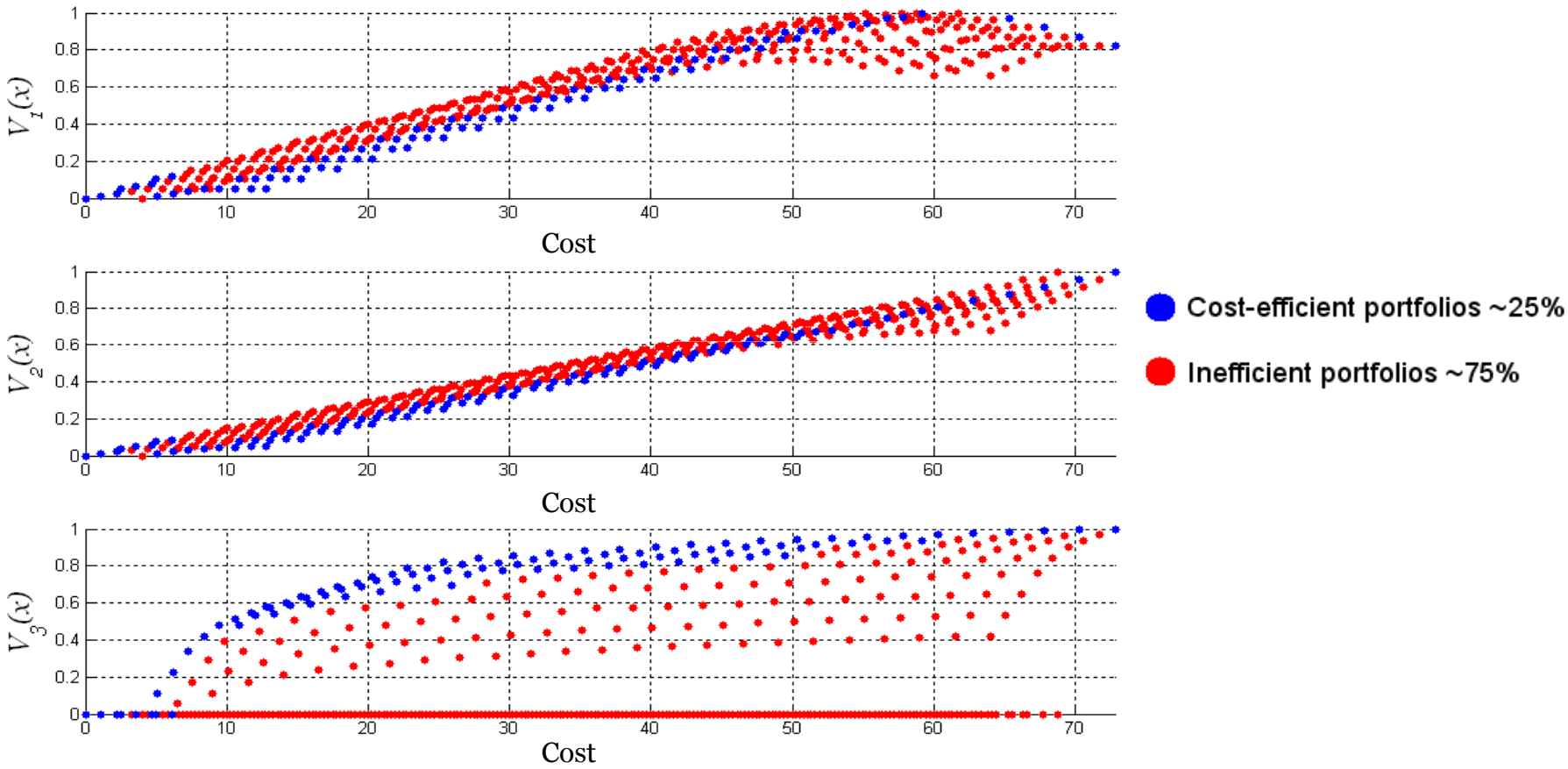
  $S_w = \{w \in S_w^0 \mid w_3 \geq w_1 \geq w_2\}$

- Analyze different cost levels with a focus on cost-efficient portfolios

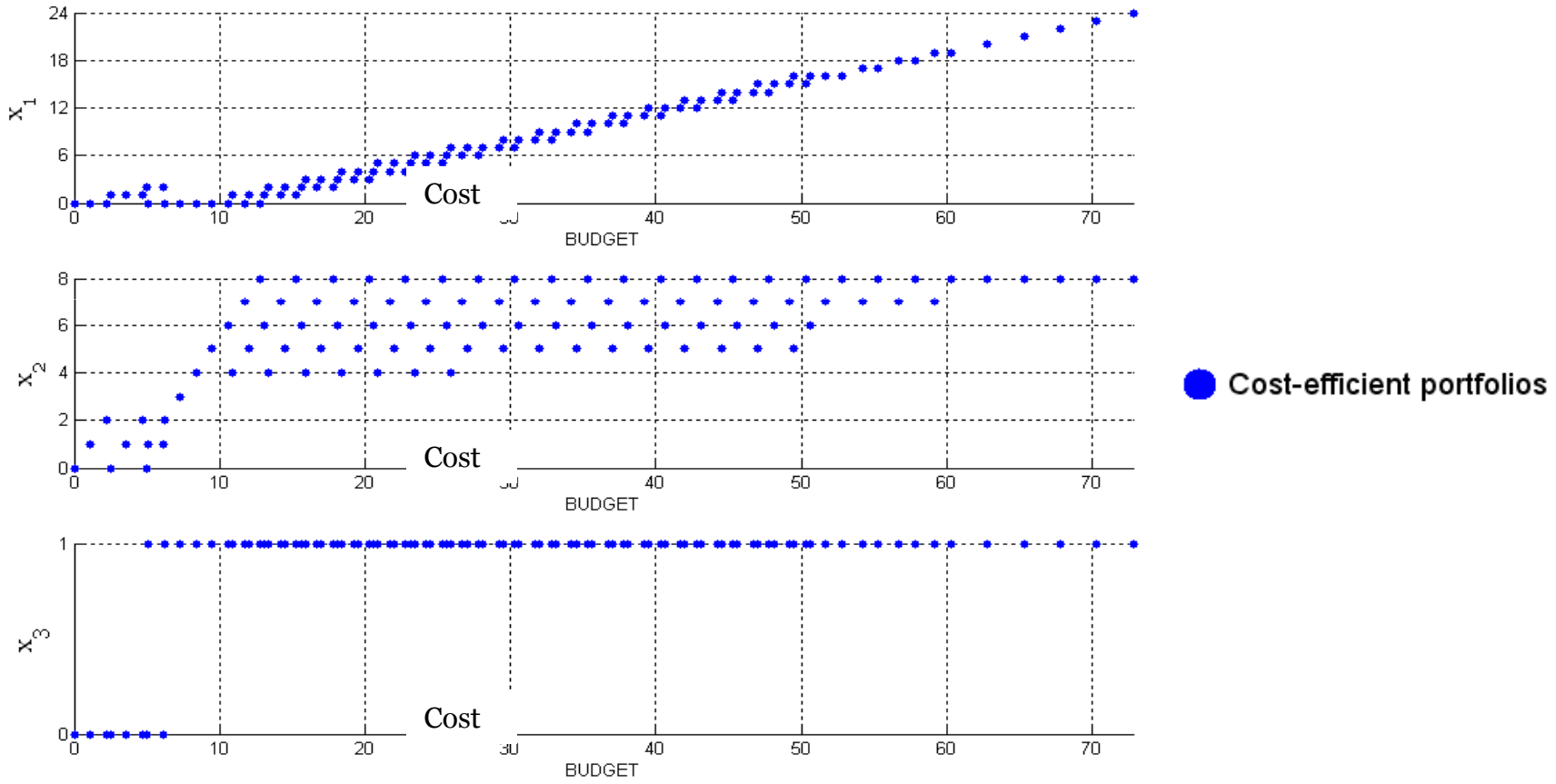
Simulated and Interpolated Impact Functions



Impacts of Weapon System Portfolios



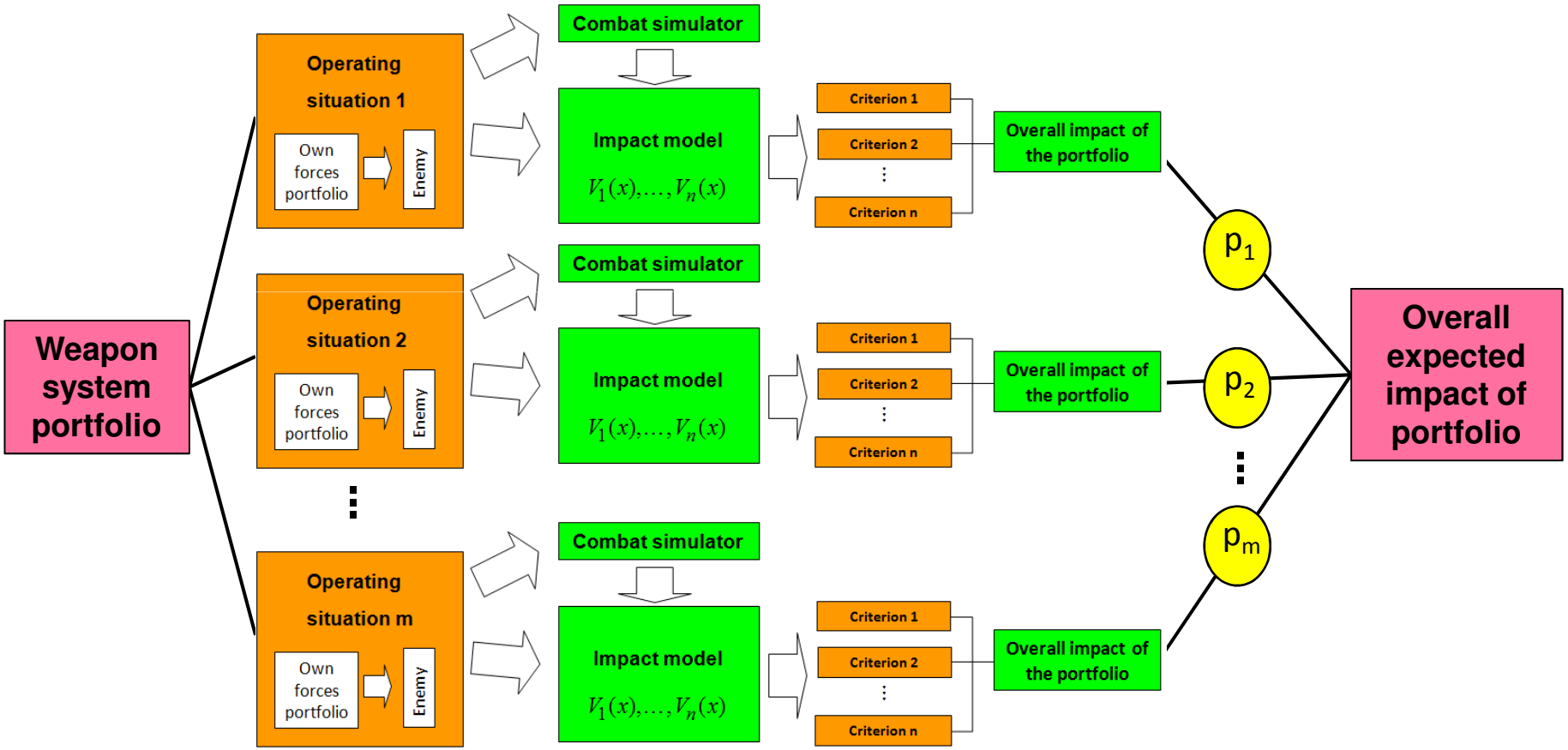
Composition of Cost-Efficient Portfolios



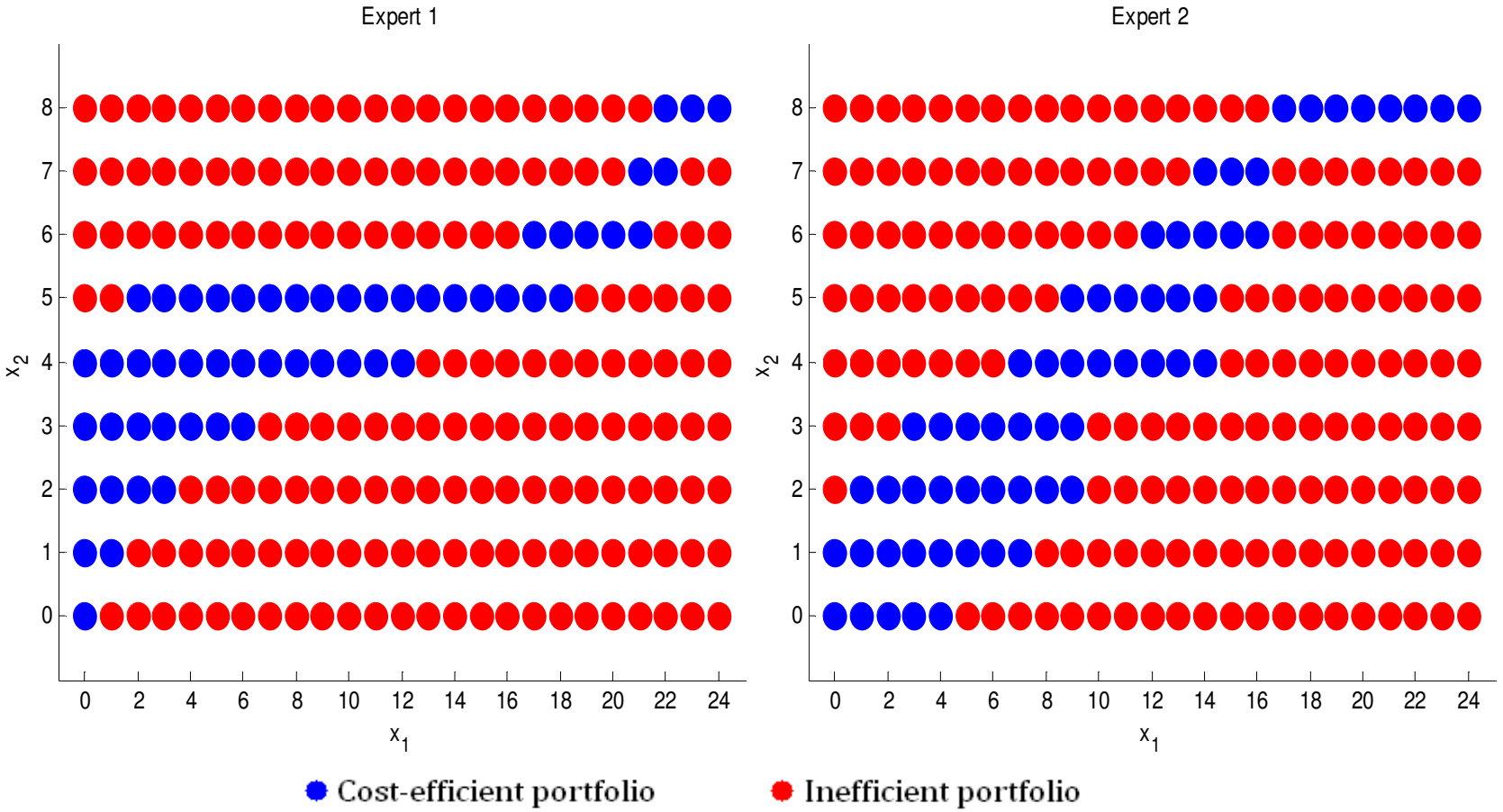
Multiple Operating Situations and Expert Judgments

- Cost-efficiency results are context dependent
  - Multiple operating situations need to be accounted for
  - This can be done by attaching probabilities to operating situations (cf. Liesiö and Salo, 2012)
- Simulations can be augmented or replaced by expert assessments
  - Assessments elicited from military experts in workshops using questionnaires
  - This approach is quicker than the development and use of simulation models
  - Comparison of results based on different assessments yields insights
- Assessing the robustness of cost-efficiency results
  - What is the share of operating situations where a portfolio is cost-efficient?

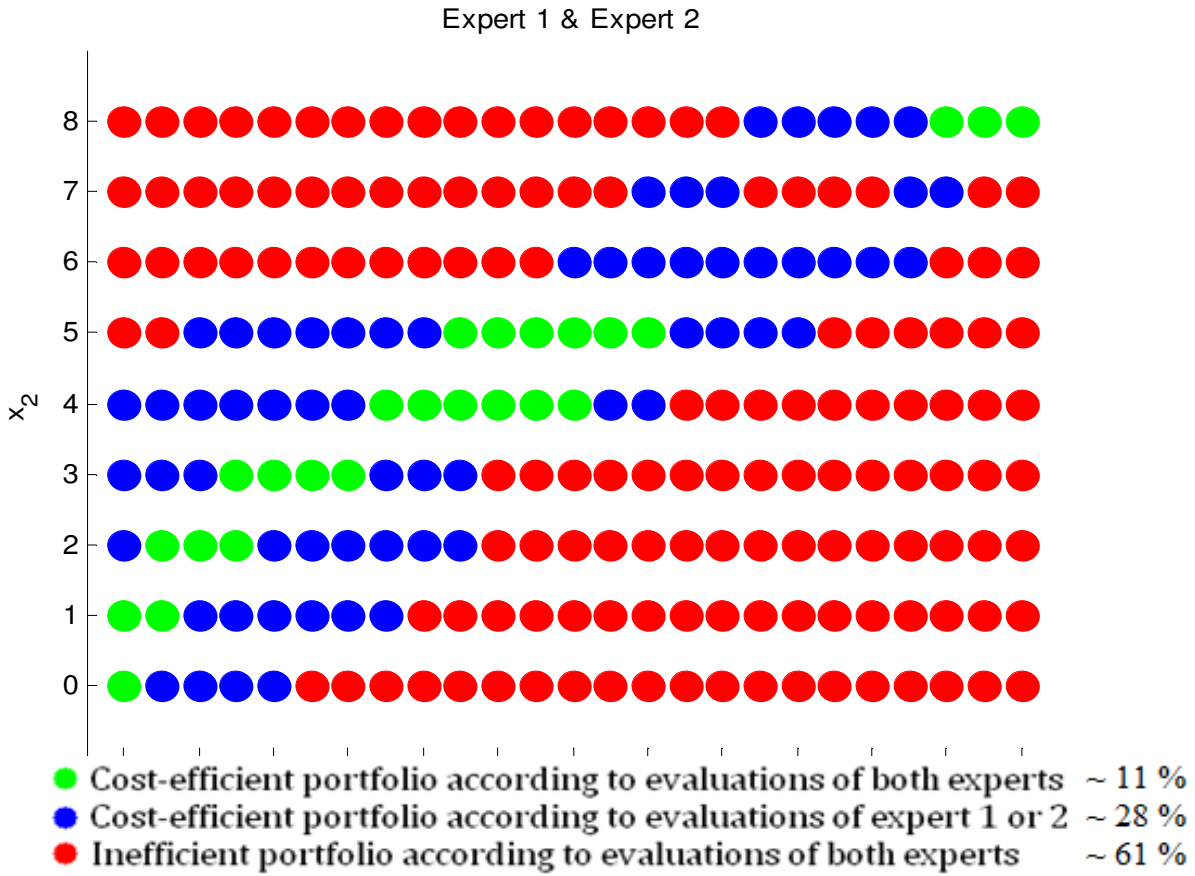
Multiple Operating Situations



Cost-Efficiency Using Core Indices 1/2



Cost-Efficiency Using Core Indices 2/2



Conclusions

- Portfolio approach motivated by strong interactions among systems
  - Evaluation of individual systems in isolation neglects these
- These interactions can be captured by combat simulators
- Multi-criteria model serves to aggregate impact dimensions
  - Contextual importance of impacts accounted for with incomplete weight information
- Cost-efficiency depends on both impacts and costs
  - ➔ At what cost levels can targeted impacts be achieved?
  - ➔ At what costs levels are individual systems cost-efficient?
- Project recognized as one of the most influential MATINE projects

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