25th anniversary
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Studying Flexible Design and Management Decision-Making in Engineering Systems Using Simulation Games

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Strategic Engineering Laboratory

- Funding
  - SGD $2.0M (CDN $1.8) over last 4 years (excluding current PhD student scholarships)
- Projects
  - 8 ongoing projects, funded by external (SMART, SEC, NRF-CREATE) and internal sources (NUS)
  - Collaboration with local companies/agencies
- Manpower
  - 8 post-doc fellows and research associates, 5 PhD students, > 20 undergraduate theses

SMART
Singapore-MIT Alliance for Research and Technology

NATIONAL
RESEARCH
FOUNDATION

(SEC) SINGAPORE-ETH
CENTRE

NUS
National University
of Singapore

Mission

- To **develop theory** of **real options and flexibility in the engineering design**, evaluation, and management of complex systems

- To **develop**, **evaluate**, and **test systematic procedures** for engineering design and management under uncertainty

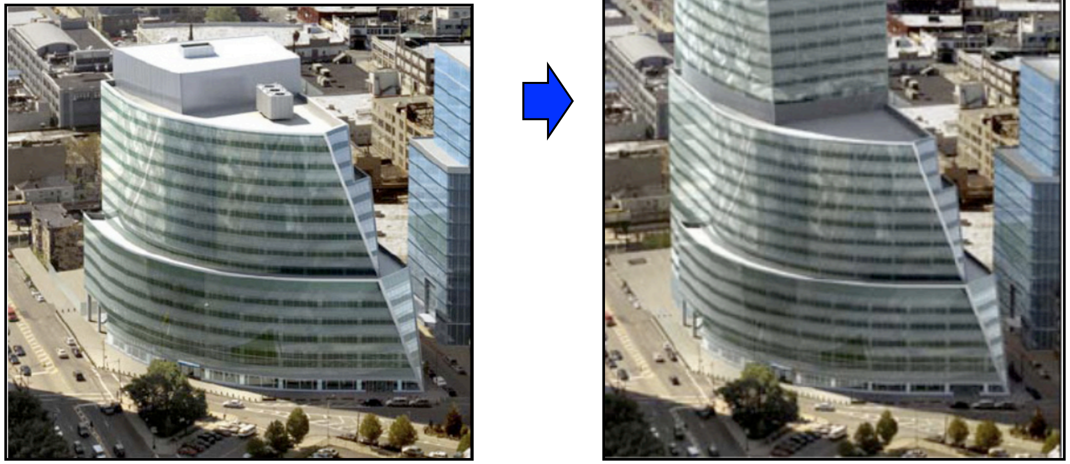
- To **improve lifecycle performance of complex engineering systems and products** compared to standard design and project evaluation approaches

What is Flexibility?

- Provides "right, **but not obligation**, to change system easily in face of uncertainty"
  - Abandon
  - Defer
  - Expand/contract
  - Phase
  - Switch
  - Etc.

- Also known as Real Option
  - "In" system: requires engineering design considerations
  - "On" system: from managerial standpoint

City Group Building, NYC

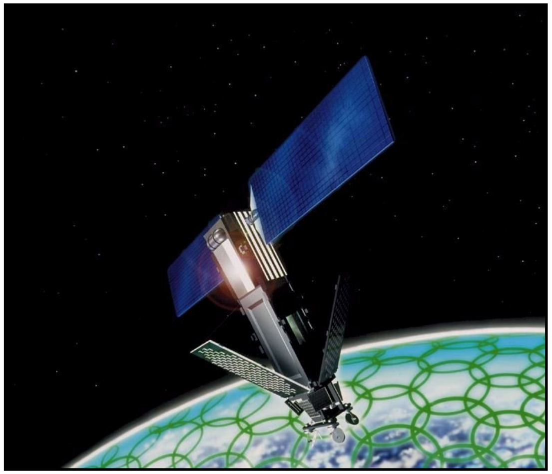


Source: Guma et al., 2009

Why Flexibility in Systems Matters?

- Engineering discipline increasingly complex
  - Need socio-technical considerations
- Uncertainty affects lifecycle performance
  - Markets volatile, regulations change, technology evolve
- Flexibility **can improve performance by 10%-30%** compared to standard design and project evaluation approaches
  - Protects from downsides (e.g. insurance)
  - Position for upsides (e.g. stock option)
  - **Net effect: better expected performance!**
- Design **rigidity** may lead to system failure or under performance
  - Iridium satellite/cell phone system
  - Convair B-58 Hustler

Source: www.comlinks.com



Iridium System:

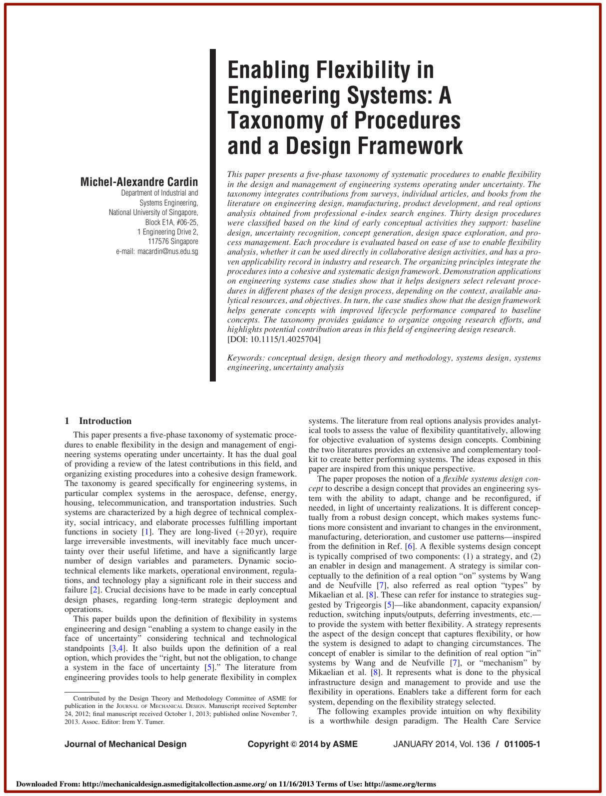
Demand forecast over optimistic, too much capacity deployed at once ➔ filed for bankruptcy (de Weck et al., 2004)

Source: en.wikipedia.org

B-58 Hustler:

No contingency for Soviet surface-to-air missiles ➔ quickly obsolete, only 10 years of service (Saleh and Hastings, 2000)

RESEARCH OVERVIEW



Enabling Flexibility in Engineering Systems: A Taxonomy of Procedures and a Design Framework

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This paper presents a five-phase taxonomy of systematic procedures to enable flexibility in the design and management of engineering systems operating under uncertainty. The taxonomy integrates contributions from surveys, individual articles, and books from the literature on engineering design, manufacturing, product development, and real options analysis obtained from professional e-index search engines. Thirty design procedures were classified based on the kind of early conceptual activities they support: baseline design, uncertainty recognition, concept generation, design space exploration, and process management. Each procedure is evaluated based on ease of use to enable flexibility analysis, whether it can be used directly in collaborative design activities, and has a proven applicability record in industry and research. The organizing principles integrate the procedures into a cohesive and systematic design framework. Demonstration applications on engineering systems case studies show that it helps designers select relevant procedures in different phases of the design process, depending on the context, available analytical resources, and objectives. In turn, the case studies show that the design framework helps generate concepts with improved lifecycle performance compared to baseline concepts. The taxonomy provides guidance to organize ongoing research efforts, and highlights potential contribution areas in this field of engineering design research.
[DOI: 10.1115/1.4025704]

Keywords: conceptual design, design theory and methodology, systems design, systems engineering, uncertainty analysis

1 Introduction

This paper presents a five-phase taxonomy of systematic procedures to enable flexibility in the design and management of engineering systems operating under uncertainty. It has the dual goal of providing a review of the latest contributions in this field, and organizing existing procedures into a cohesive design framework. The taxonomy is geared specifically for engineering systems, in particular complex systems in the aerospace, defense, energy, housing, telecommunication, and transportation industries. Such systems are characterized by a high degree of technical complexity, social intricacy, and elaborate processes fulfilling important functions in society [1]. They are long-lived (+20 yr), require large irreversible investments, will inevitably face much uncertainty over their useful lifetime, and have a significantly large number of design variables and parameters. Dynamic socio-technical elements like markets, operational environment, regulations, and technology play a significant role in their success and failure [2]. Crucial decisions have to be made in early conceptual design phases, regarding long-term strategic deployment and operations.

This paper builds upon the definition of flexibility in systems engineering and design "enabling a system to change easily in the face of uncertainty" considering technical and technological standpoints [3,4]. It also builds upon the definition of a real option, which provides the "right, but not the obligation, to change a system in the face of uncertainty [5]." The literature from engineering provides tools to help generate flexibility in complex systems. The literature from real options analysis provides analytical tools to assess the value of flexibility quantitatively, allowing for objective evaluation of systems design concepts. Combining the two literatures provides an extensive and complementary toolkit to create better performing systems. The ideas exposed in this paper are inspired from this unique perspective.

The paper proposes the notion of a *flexible systems design concept* to describe a design concept that provides an engineering system with the ability to adapt, change and be reconfigured, if needed, in light of uncertainty realizations. It is different conceptually from a robust design concept, which makes systems functions more consistent and invariant to changes in the environment, manufacturing, deterioration, and customer use patterns—inspired from the definition in Ref. [6]. A flexible systems design concept is typically comprised of two components: (1) a strategy, and (2) an enabler in design and management. A strategy is similar conceptually to the definition of a real option "on" systems by Wang and de Neufville [7], also referred as real option "types" by Mikaelian et al. [8]. These can refer for instance to strategies suggested by Trigeorgis [5]—like abandonment, capacity expansion/reduction, switching inputs/outputs, deferring investments, etc.—to provide the system with better flexibility. A strategy represents the aspect of the design concept that captures flexibility, or how the system is designed to adapt to changing circumstances. The concept of enabler is similar to the definition of real option "in" systems by Wang and de Neufville [7], or "mechanism" by Mikaelian et al. [8]. It represents what is done to the physical infrastructure design and management to provide and use the flexibility in operations. Enablers take a different form for each system, depending on the flexibility strategy selected.

The following examples provide intuition on why flexibility is a worthwhile design paradigm. The Health Care Service

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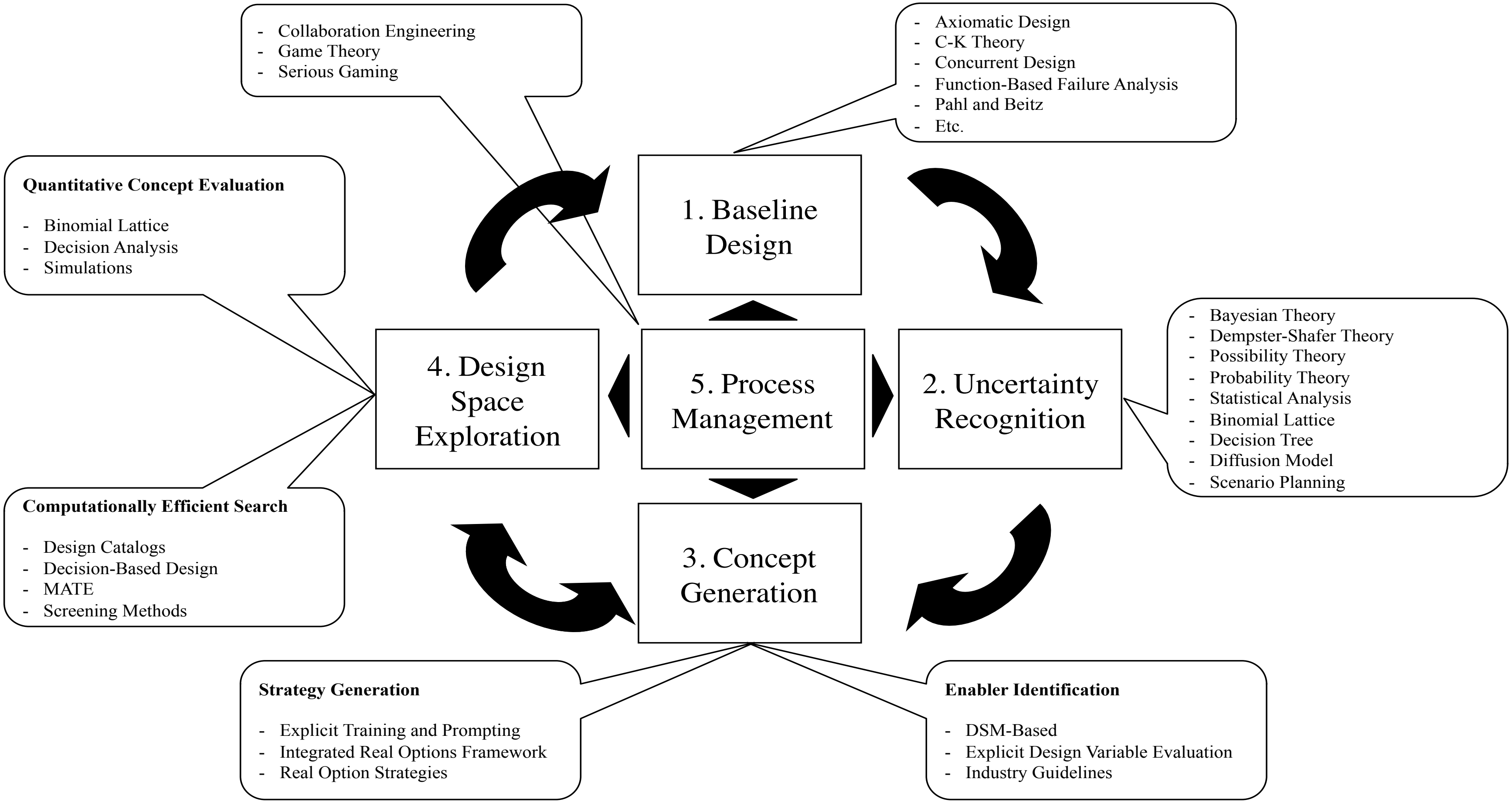
Taxonomy and Design Framework



- Collaboration Engineering
- Game Theory
- Serious Gaming

- Axiomatic Design
- C-K Theory
- Concurrent Design
- Function-Based Failure Analysis
- Pahl and Beitz
- Etc.

Quantitative Concept Evaluation

- Binomial Lattice
- Decision Analysis
- Simulations

1. Baseline Design

2. Uncertainty Recognition

3. Concept Generation

4. Design Space Exploration

5. Process Management

- Bayesian Theory
- Dempster-Shafer Theory
- Possibility Theory
- Probability Theory
- Statistical Analysis
- Binomial Lattice
- Decision Tree
- Diffusion Model
- Scenario Planning

Computationally Efficient Search

- Design Catalogs
- Decision-Based Design
- MATE
- Screening Methods

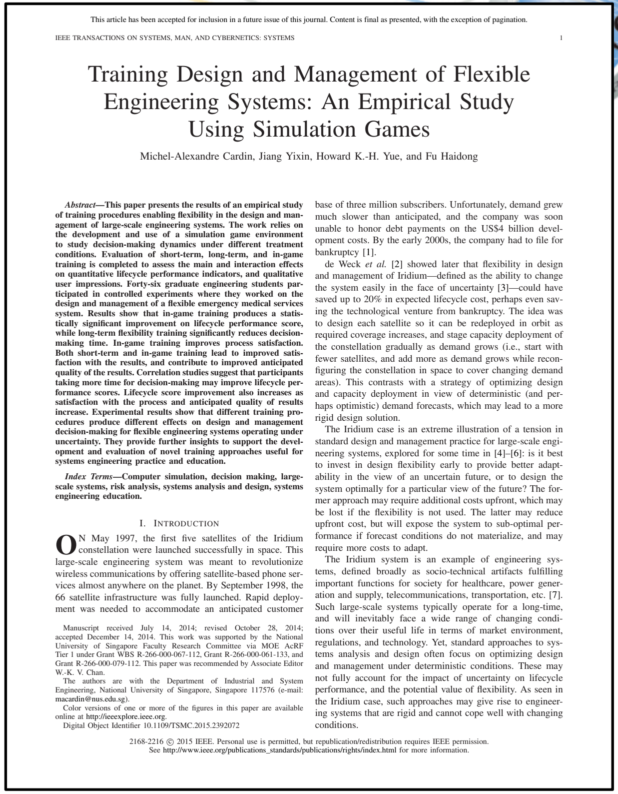
Strategy Generation

- Explicit Training and Prompting
- Integrated Real Options Framework
- Real Option Strategies

Enabler Identification

- DSM-Based
- Explicit Design Variable Evaluation
- Industry Guidelines

PHASE 5: PROCESS MANAGEMENT



IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS: SYSTEMS 1

Training Design and Management of Flexible Engineering Systems: An Empirical Study Using Simulation Games

Michel-Alexandre Cardin, Jiang Yixin, Howard K.-H. Yue, and Fu Haidong

Abstract—**This paper presents the results of an empirical study of training procedures enabling flexibility in the design and management of large-scale engineering systems. The work relies on the development and use of a simulation game environment to study decision-making dynamics under different treatment conditions. Evaluation of short-term, long-term, and in-game training is completed to assess the main and interaction effects on quantitative lifecycle performance indicators, and qualitative user impressions. Forty-six graduate engineering students participated in controlled experiments where they worked on the design and management of a flexible emergency medical services system. Results show that in-game training produces a statistically significant improvement on lifecycle performance score, while long-term flexibility training significantly reduces decision-making time. In-game training improves process satisfaction. Both short-term and in-game training lead to improved satisfaction with the results, and contribute to improved anticipated quality of the results. Correlation studies suggest that participants taking more time for decision-making may improve lifecycle performance scores. Lifecycle score improvement also increases as satisfaction with the process and anticipated quality of results increase. Experimental results show that different training procedures produce different effects on design and management decision-making for flexible engineering systems operating under uncertainty. They provide further insights to support the development and evaluation of novel training approaches useful for systems engineering practice and education.**

Index Terms—**Computer simulation, decision making, large-scale systems, risk analysis, systems analysis and design, systems engineering education.**

I. INTRODUCTION

ON May 1997, the first five satellites of the Iridium constellation were launched successfully in space. This large-scale engineering system was meant to revolutionize wireless communications by offering satellite-based phone services almost anywhere on the planet. By September 1998, the 66 satellite infrastructure was fully launched. Rapid deployment was needed to accommodate an anticipated customer base of three million subscribers. Unfortunately, demand grew much slower than anticipated, and the company was soon unable to honor debt payments on the US$4 billion development costs. By the early 2000s, the company had to file for bankruptcy [1].

de Weck *et al.* [2] showed later that flexibility in design and management of Iridium—defined as the ability to change the system easily in the face of uncertainty [3]—could have saved up to 20% in expected lifecycle cost, perhaps even saving the technological venture from bankruptcy. The idea was to design each satellite so it can be redeployed in orbit as required coverage increases, and stage capacity deployment of the constellation gradually as demand grows (i.e., start with fewer satellites, and add more as demand grows while reconfiguring the constellation in space to cover changing demand areas). This contrasts with a strategy of optimizing design and capacity deployment in view of deterministic (and perhaps optimistic) demand forecasts, which may lead to a more rigid design solution.

The Iridium case is an extreme illustration of a tension in standard design and management practice for large-scale engineering systems, explored for some time in [4]–[6]: is it best to invest in design flexibility early to provide better adaptability in the view of an uncertain future, or to design the system optimally for a particular view of the future? The former approach may require additional costs upfront, which may be lost if the flexibility is not used. The latter may reduce upfront cost, but will expose the system to sub-optimal performance if forecast conditions do not materialize, and may require more costs to adapt.

The Iridium system is an example of engineering systems, defined broadly as socio-technical artifacts fulfilling important functions for society for healthcare, power generation and supply, telecommunications, transportation, etc. [7]. Such large-scale systems typically operate for a long-time, and will inevitably face a wide range of changing conditions over their useful life in terms of market environment, regulations, and technology. Yet, standard approaches to systems analysis and design often focus on optimizing design and management under deterministic conditions. These may not fully account for the impact of uncertainty on lifecycle performance, and the potential value of flexibility. As seen in the Iridium case, such approaches may give rise to engineering systems that are rigid and cannot cope well with changing conditions.

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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Motivation

- **Assuming flexibility exists, how to best manage in operations?**

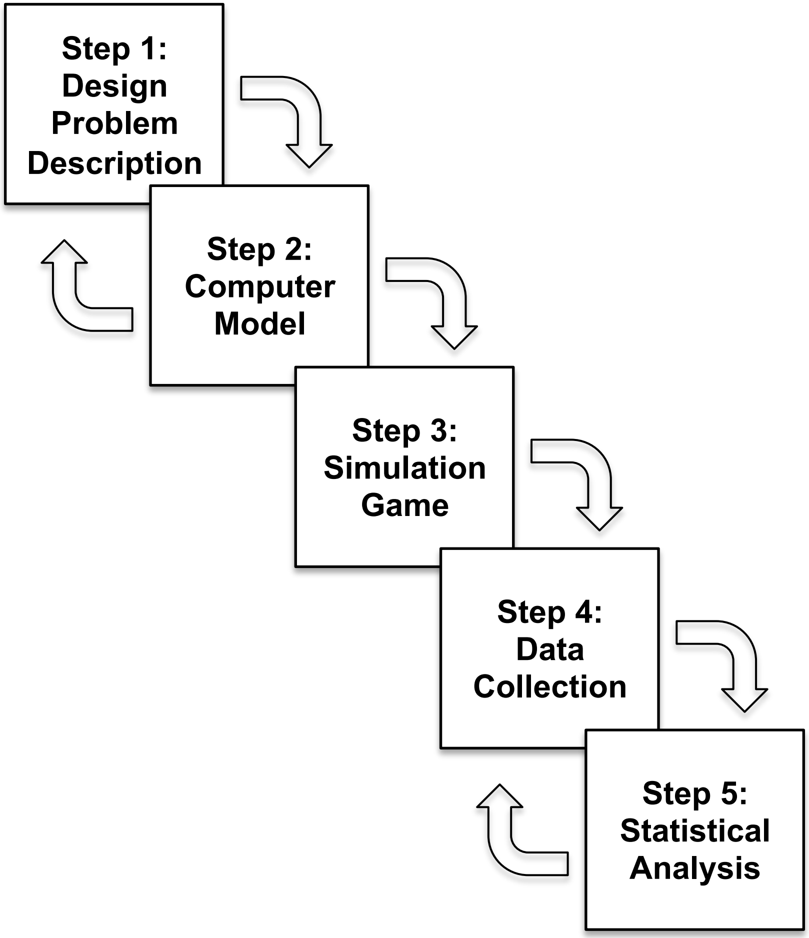
- Emergency Medical Services (EMS) systems very flexible:
  - Station allocation and timing
  - Resource allocation/reallocation
  - Abandonment of unused capacity

- Singapore collaborating agency relying on deterministic heuristics for design, planning and operations

- Can training help better manage flexible engineering systems?
  - What procedures are best?
  - What is the impact on quantitative lifecycle performance, and qualitative user impressions?

Experimental Methodology (Generic)

1. Design Problem Description
2. Computer Model
3. Simulation Game
4. Data Collection
5. Statistical Analysis



Step 1: Design Problem Description

Step 2: Computer Model

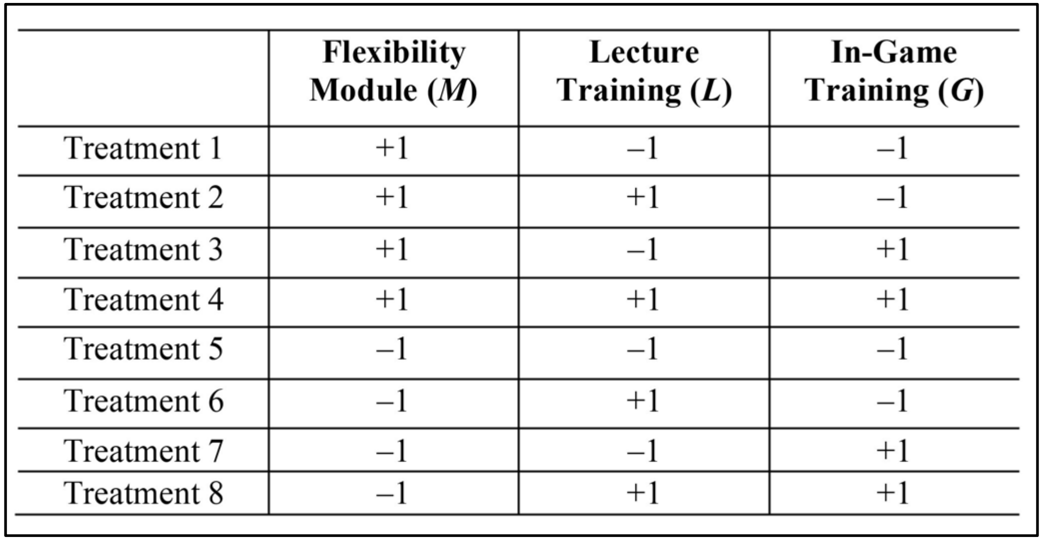
Step 3: Simulation Game

Step 4: Data Collection

Step 5: Statistical Analysis

Preliminary Setup

- 2^3 factorial design



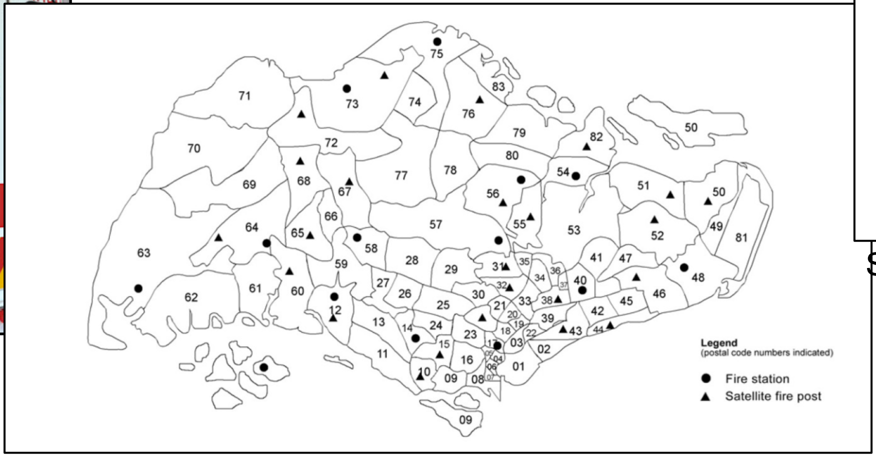
	Flexibility Module (*M*)	**Lecture Training (*L*)**	**In-Game Training (*G*)**
Treatment 1	+1	–1	–1
Treatment 2	+1	+1	–1
Treatment 3	+1	–1	+1
Treatment 4	+1	+1	+1
Treatment 5	–1	–1	–1
Treatment 6	–1	+1	–1
Treatment 7	–1	–1	+1
Treatment 8	–1	+1	+1

- Participants
  - 46 NUS graduate students
    - 7 (Treatment 1), 5 (Treatments 2-4), 6 (Treatments 5-8)
  - 57% > 25 years old, 85% have Bachelor only, 48% > 1 year work experience in industry

Step 1: Design Problem: Emergency Services

- Simplified version of realistic EMS system in Singapore
  - Focused on medical (i.e. hospitals, station/fire posts, ambulances)
  - Model developed in collaboration with Singapore Civil Defence Force
- Quantitative performance-based metric (response time, lost calls)
- Described benchmark design (initial station/ambulance deployment)
- Explained task to improve existing benchmark design

Source: livinginsingaporetoday.com

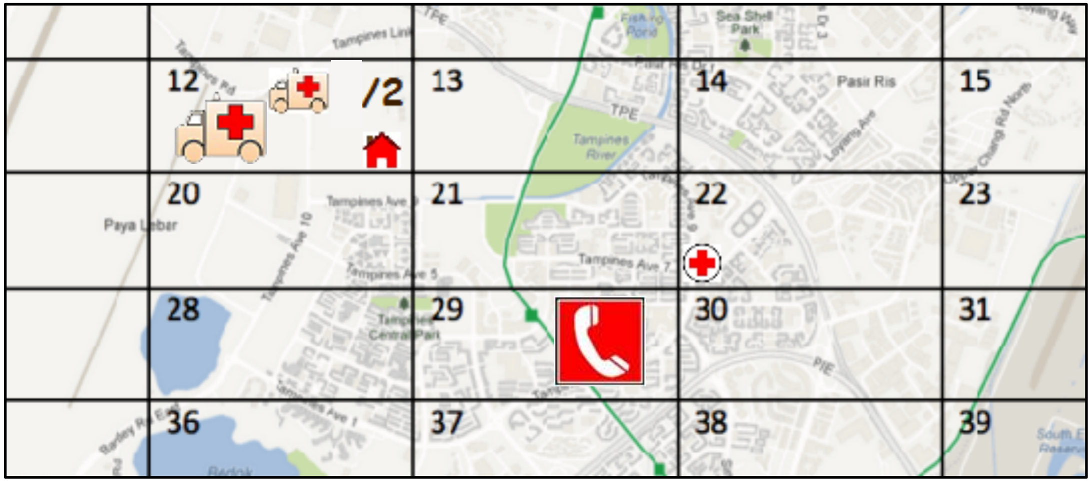


Source: Ong et al., 2009

SCDF
The Life Saving Force

Source: therealsingapore.com

Step 2: Computer Model: Discrete Event Simulation



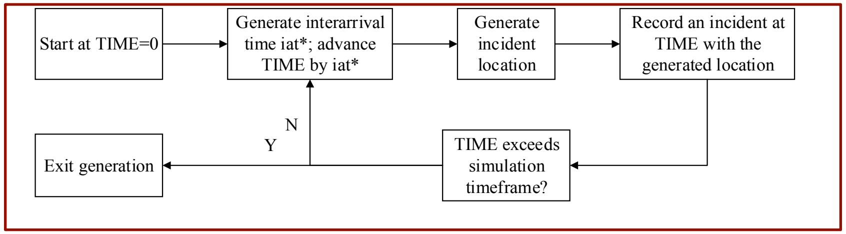
Timeline:

Activation Time → Station to scene time → Scene Time → Scene to hospital time → Hospital Time → Hospital to station time

Activation Time + Station to scene time = Response time

Incident Generation

- Flow diagram



Start at TIME=0

Generate interarrival time iat*; advance TIME by iat*

Generate incident location

Record an incident at TIME with the generated location

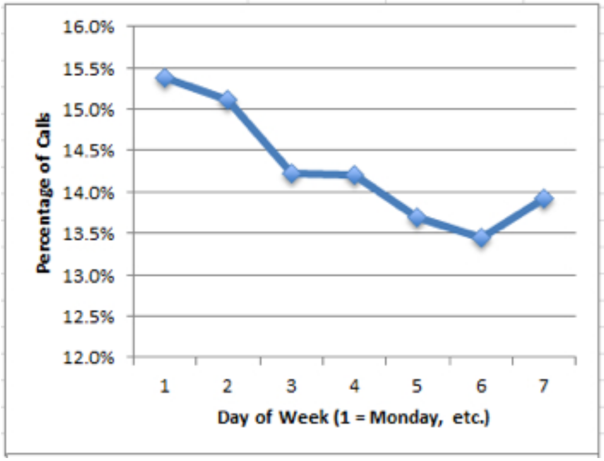
TIME exceeds simulation timeframe?

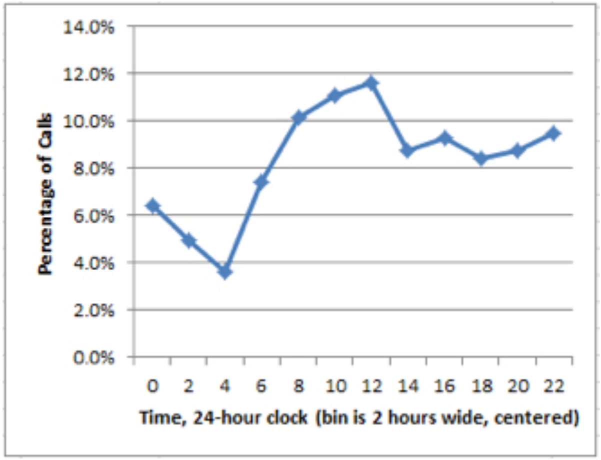
N

Y

Exit generation

- Inter-arrival times modeled from historical data

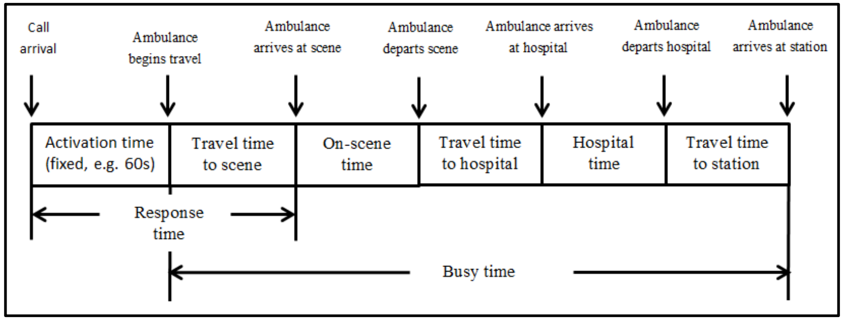




$$IAT_{ij} = -\ln\frac{(1-rand)}{\lambda_{ij}}$$

Incident Handling

- Nearest ambulance dispatched
- Cannot respond until previous call resolved



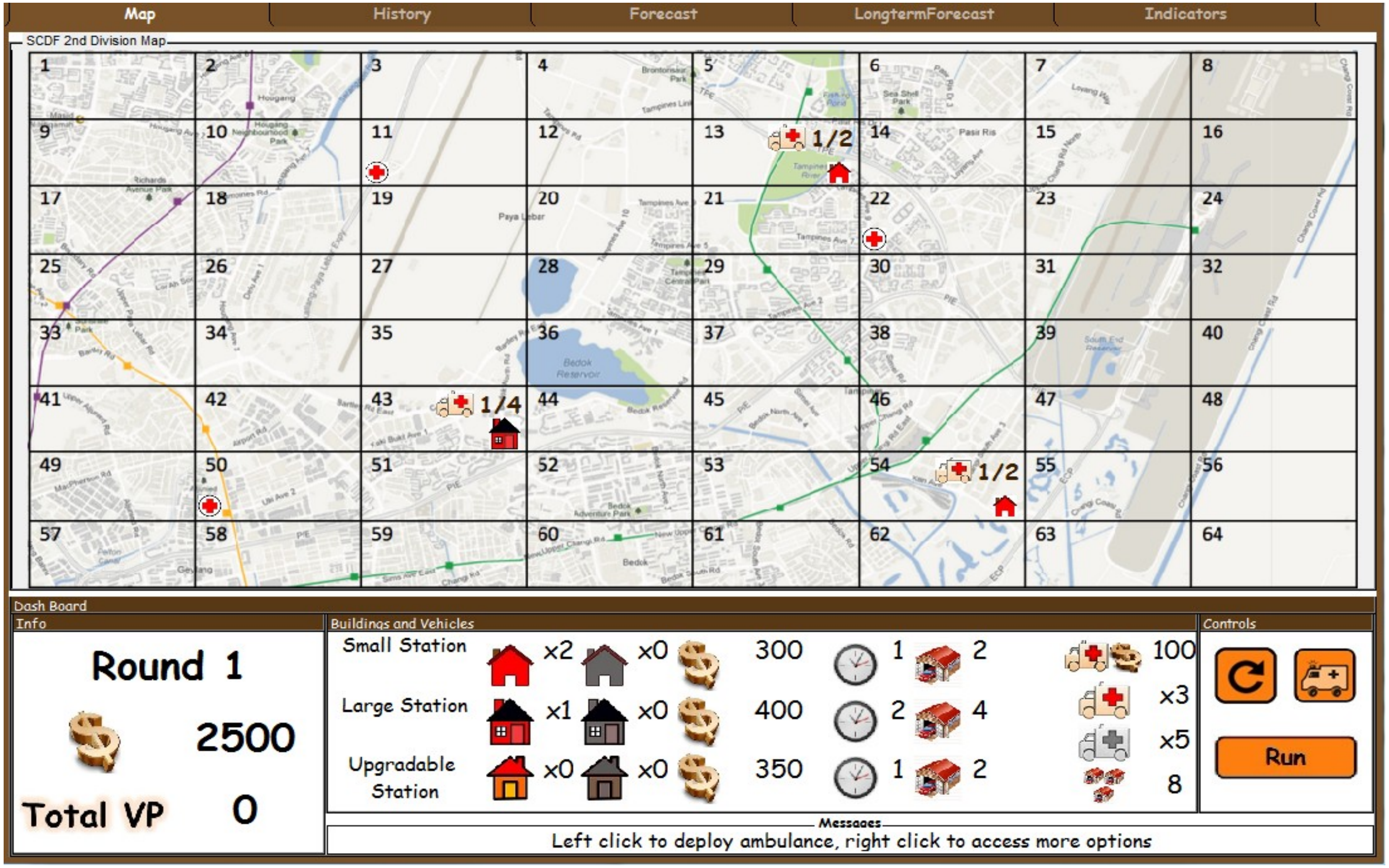
- Performance
  - Fast response rate, Lost incident rate, operating cost:

$$P_t = \frac{nR_t}{N_t} \times 100 \qquad L_t = \frac{nL_t}{N_t} \times 100 \qquad C_t = \frac{(nFS_t \times C_{FS} + nA_t \times C_A - OC_{\min})}{OC_{\max} - OC_{\min}} \times 100$$

  - Lifecycle performance:

$$S_t = a_1 P_t + a_2 L_t + a_3 C_t$$

Step 3: Simulation Game



Round 1

2500

Total VP 0

Small Station	x2	x0	300	1	2
Large Station	x1	x0	400	2	4
Upgradable Station	x0	x0	350	1	2

100

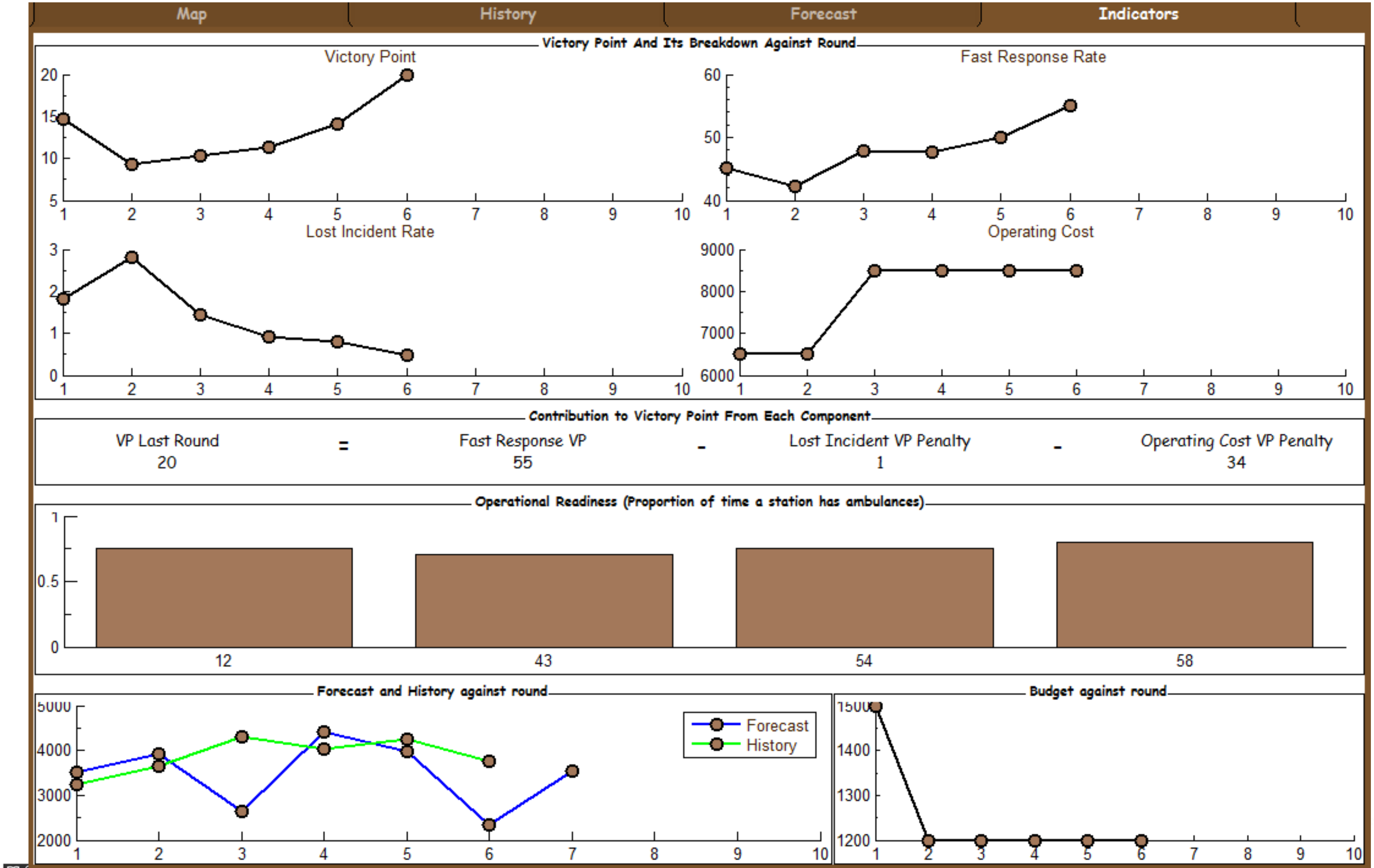
x3

x5

8

Left click to deploy ambulance, right click to access more options

Performance Measurements



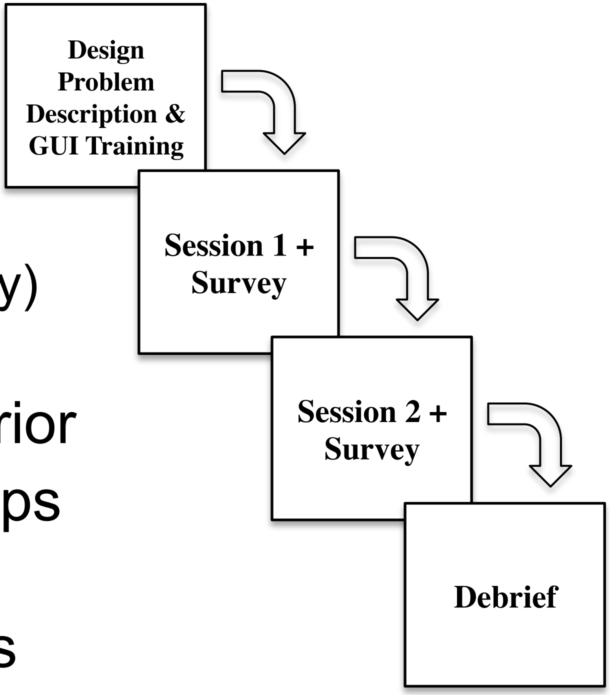
Contribution to Victory Point From Each Component

VP Last Round 20 = Fast Response VP 55 - Lost Incident VP Penalty 1 - Operating Cost VP Penalty 34

Step 4: Data Collection

- Factorial experiments designed to measure "Δ" pretest-posttest response improvement between Sessions 1 and 2: Δy = y2 – y1

$$\Delta y(x_1, x_2, \ldots, x_n) = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j>i}}^{n} \beta_{ij} x_i x_j + \varepsilon$$


Design Problem Description & GUI Training

Session 1 + Survey

Session 2 + Survey

Debrief

- Here y = *S*, can be others
  (e.g. time, satisfaction with process, results, quality)

- Controls for inherent creativity levels and prior knowledge of design procedure within-groups

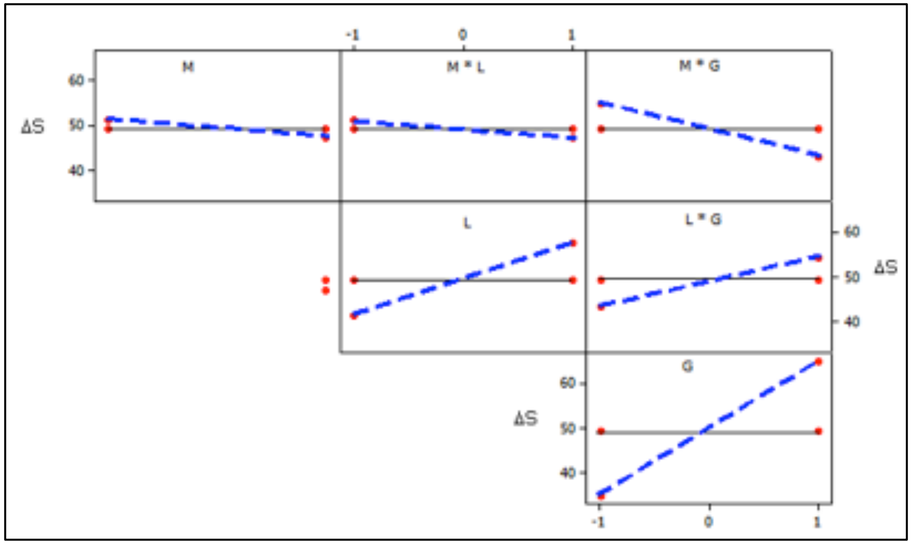
- Improves between-groups vs. within-groups variability comparison, internal validity of results (Campbell and Stanley, 1966)

Step 5: Effects on Lifecycle Performance Score (ΔS)

- GLM response

$$\Delta S = 49.7 - 1.51M + 7.9L + 14.6G - 2.0ML - 5.5MG + 6.1LG - 2.8MLG$$

- Significant main effects for in-game training ($G = +1$)
  - $\beta_G = 14.6$, $t = -2.0$, $p \leq 0.05$
- Interpretation
  - In-game training had main effect on ΔS vs. benchmark



Summary

- Short **in-game training valuable tool to improve lifecycle performance** of complex systems by means of flexibility
- Also **improves user satisfaction with process** – promotes user acceptability
- Short **lecture has main effects on results satisfaction and anticipated quality of results**
- Experimental approach allows quantification of **relationships between quantitative performance and qualitative user impressions**
- Study demonstrates that **short-term training tools valuable to improve design and management decision-making** in complex engineering systems under uncertainty

Conclusions

- **Standard design and practice may not account well for uncertainty and flexibility** in design and management of complex systems

- Explicit **considerations of uncertainty and flexibility shown to improve lifecycle performance** significantly

- Enabling/using flexibility challenging; **need R&D** for systematic design and training procedures

- **Need new quantitative analytical tools** to assess lifecycle performance impact on decision-making, and to assess impact on **qualitative indicators of user impressions**

- **Need empirical work** to determine which procedures are most suitable for real-world use

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  - Keppel Offshore and Marine Technology Centre (KOMTech)
  - Singapore Civil Defence Force (SCDF)

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