INTEGRATING SYSTEM DESIGN EVALUATION METHODOLOGY WITH THE SYSTEM ENGINEERING PROCESS

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Project Description

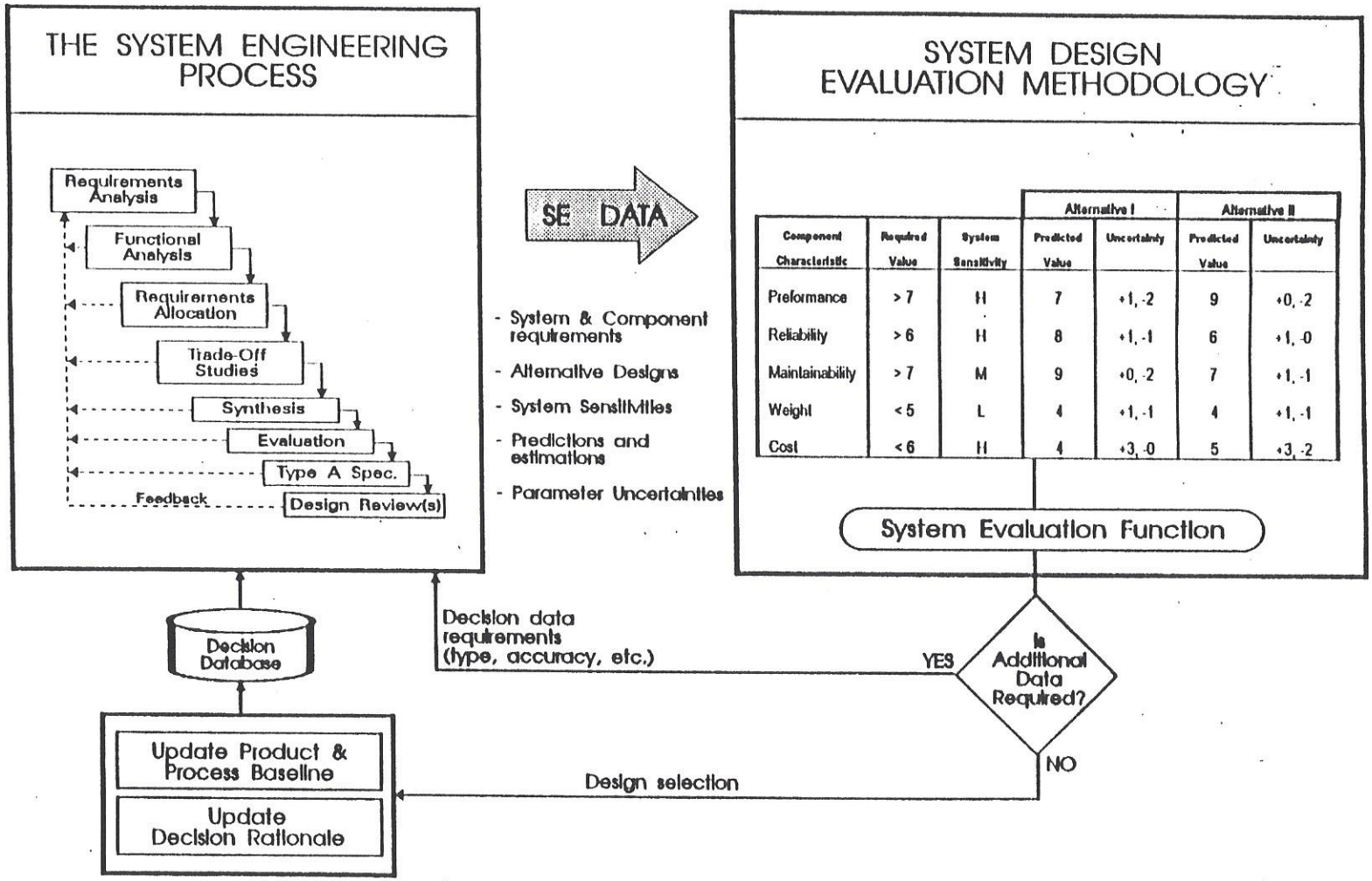
- Virginia Polytechnic Institute and State University (Virginia Tech), in cooperation with the Software Productivity Consortium (SPC), is pursuing an approach to advance the state of practice for developing complex systems based on previous research within Virginia Tech's Systems Engineering Design Laboratory (SEDL).

- The results of this project will provide benefits to SPC in support of its member companies, and to the broader base of industry within the Commonwealth of Virginia through Virginia Tech's off-campus graduate program in Systems Engineering.

Project Goal and Objectives

- **Advance the state of the practice of Systems Engineering by developing a systematic approach to design evaluation and trade-offs for complex system development.**
- **Specific project objectives include:**
  - Development of a design evaluation methodology fully integrated with the system engineering process, utilizing critical data produced by the process as an input, and generating critical design decision data to drive the process forward.
  - Extend the research conducted at Virginia Tech in this area by refining, documenting, and demonstrating the integration between design evaluation methodology and the systems engineering process.

System Design Evaluation Methodology Integration with the System Engineering Process



Component Characteristic	Required Value	System Sensitivity	Alternative I Predicted Value	Alternative I Uncertainty	Alternative II Predicted Value	Alternative II Uncertainty
Preformance	> 7	H	7	+1, -2	9	+0, -2
Reliability	> 6	H	8	+1, -1	6	+1, -0
Maintainability	> 7	M	9	+0, -2	7	+1, -1
Weight	< 5	L	4	+1, -1	4	+1, -1
Cost	< 6	H	4	+3, -0	5	+3, -2

Project Deliverables

- **A technical report describing the system design evaluation methodology and its application to one or more realistic examples (hard copy and electronic copy in standard format).**
- **A prototype computer-based implementation of the methodology which demonstrates its application to one or more realistic examples.**
- **As a minimum, these examples will include:**
  - Up-front system design trades associated with allocating functions to hardware and software and selecting a systems architecture, and
  - Downstream trades associated with re-engineering or modifying an existing system.

Technical Approach

- **This project builds upon extensive prior research completed within the Systems Engineering Design Laboratory (SEDL) at Virginia Tech.**
- **Results from prior research projects provide a logical framework for achieving the objectives herein. The project exhibits an integration and extension of existing elements.**
- **Specific (and supporting) research projects include:**
  - A recent project sponsored by Naval Surface Warfare Center - Dahlgren Division, involved the development of a system engineering process model. Results of this research are documented in *"Application of the System Engineering Process to Define Requirements for Computer-Based Design Tools"*, co-edited by Blanchard, Fabrycky, and Verma.

Technical Approach (cont.)

- **Specific (and supporting) research projects include (cont.):**
  - A research project supported by Northern Telecom resulted in the development of a Design Decision Support System (DDSS) described in *"Concurrent Embedded Systems"*, co-authored by Midkiff and Fabrycky. The primary emphasis was to develop a systematic computer-based approach to support design evaluation during early design trade-offs. Focus was on evaluating alternative systems' design architectures and associated allocation of functions to hardware, software, and firmware.
  - Development of the DDSS was based upon the unique Design Dependent Parameter (DDP) paradigm developed at Virginia Tech. This paradigm, presented in *"Indirect Experimentation for System Optimization: A Paradigm Based on Design Dependent Parameters"*, authored by Fabrycky, addresses the impact of significant design dependent parameters (such as reliability and maintainability) on the system life-cycle cost. A cost-effectiveness evaluation is enabled by the Design Evaluation Function (DEF) and a Design Evaluation Display (DED).

Technical Emphasis

- This project emphasizes the coordinated application of the system engineering process and the design evaluation methodology during new system acquisition, as well as for system redesign.

- Evaluation activities are shown to be iterative, but also continuously changing in scope and resolution with the progression of the system design and development process.

- The process is shown to serve as a good framework within which evaluation activities may be guided and conducted in an integrated manner.

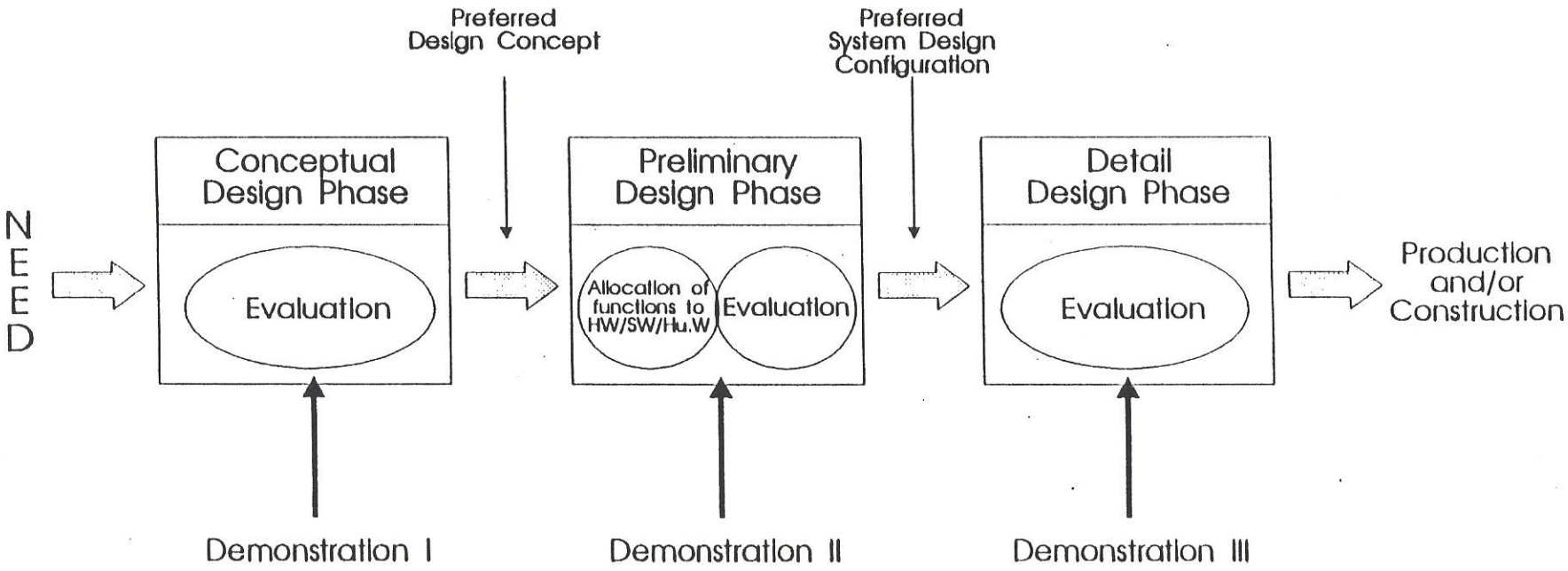
Technical Emphasis (cont.)

This project systematically addresses complex sets of interrelated criteria, the ability to make effective decisions which properly address the numerous factors, and will provide a centerpiece tightly integrated with the well defined system engineering process.

Major points of emphasis include, but are not limited to:

- How Technical Performance Measures (TPMs) and parameters are used as inputs from the process model to the demonstrator.
- How the impact of requirement changes and design parameter variation is addressed and incorporated as part of the evaluation methodology.
- How to accommodate uncertainty in input information through interactive "what-if" studies to minimize the need for unavailable data.
- How interaction between design alternatives and design requirements can be resolved to the mutual benefit of the producer and customer.

Application of Design Evaluation Methodology to Different Phases of the System Life Cycle

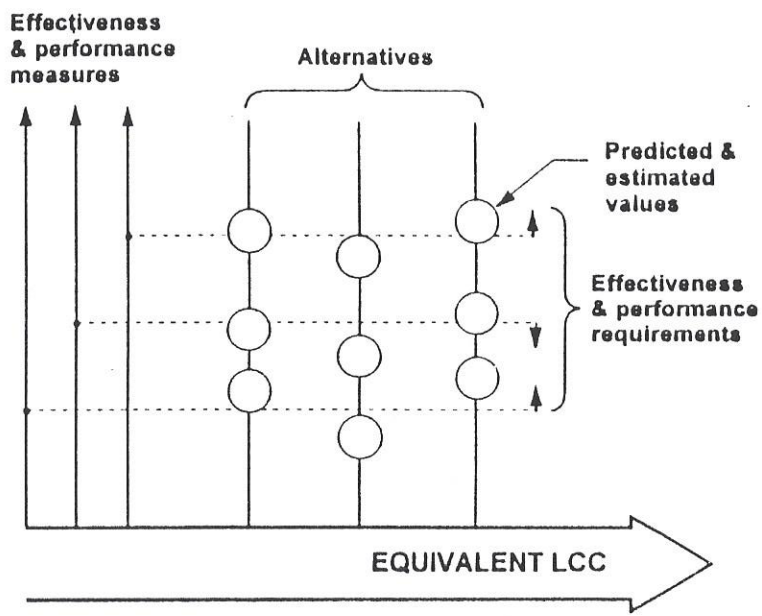


Optimization and Trade-Off

Design Evaluation Function

References	Funcational Form	Application
Churchman, Ackoff, & Arnoff (1957)	$E = f(x_i, y_j)$ E = system effectiveness x_i = variables under control y_j = variables not suubject to control	Operations
Banks & Fabrycky (1987)	$E = f(X, Y_d, Y_i);\ g(X, Y_d) \lesseqgtr C$ E = system effectiveness X = procurement level and procurement quantity Y_d = source dependent parameters Y_i = source independent parameters	Procurement Operations
Blanchard & Fabrycky, 1990 & Fabrycky & Blanchard, 1991	$E = f(X, Y_d, Y_i);\ g(X, Y_d) \lesseqgtr C$ E = evaluation measure X = design variables Y_d = design dependent parameters Y_i = design independent parameters	Design Optimization

Design Evaluation Display



Case Study Example

An organization needs a system to facilitate an interactive session/meeting between multiple members of a distributed system design team.

- This example was constructed over several meetings and brain-storming sessions between Dinesh Verma in Industrial and Systems Engineering and Scott Midkiff in the Bradley Department of Electrical Engineering at Virginia Polytechnic Institute and State University.
- Attempts were made to convey a sense of realism and complexity which may be encountered on an actual project.
- The process of constructing this example did not involve rigorous interaction with "real" customers having actual requirements and preferences.

Demonstrator Overview and Features

	CD	PD	DD	Tutorial	Tools	Biblio
Development packages:						
• Toolbook 3.0	✓	✓	✓	✓	-	-
• Acrobat Reader 2.0	-	-	-	-	✓	✓
Lines of code:	25k	0k	5k	-	-	-
Number of screens:	25	25	125	200	-	-
Number of items:	-	-	-	-	375	160
Number of documents:	2	2	2	-	-	-

Project Benefits

- **The project benefits SPC as a Virginia business and should benefit its member companies.**
  - Strengthen SPC's systems engineering capabilities to help SPC attract new members and improve its ability to assist its current members.
  - Many SPC member companies are located in Virginia.
  - Demonstrator may serve as a systems engineering training aid that can be used by SPC and its member companies.
- **The project benefits Virginia Tech's System Engineering off-campus graduate program.**
  - Program largely targeted to students working for Virginia companies.
  - Helps Virginia companies by improving their current work force.
  - As a starting point for projects and as a teaching tool in ENGR 5004.
- **The project benefits the VCOE.**
  - VCOE, with ARPA funding, may take the demonstrator and provide it to a broad range of firms, many in Virginia.

Applications and Extensions

The demonstrator serves as a prototype Systems Engineering entity that may be commercialized. Possible areas of extension are:

- Benchmarking best practices
- Systems engineering process and methods
- Demonstrator application and use by SPC member companies
- Tool commercialization testbed

Proposal Compliance

Key Tasks Identified in the Proposal	Status and Plans
Identify relevant past and on-going work performed in the area of design evaluation, trade-off analysis, and decision making (such as QFD, AHP, Kepner-Tregoe, and Taguchi Methods)	100 % Complete
Conduct a preliminary assessment of the state of the practice of system design evaluation and tradeoff methods (such as DSMC, NASA)	100 % Complete
Develop requirements for an effective design evaluation methodology including specific data requirements for each of the system engineering process activities.	100 % Complete
Develop the system design evaluation methodology which includes both heuristics and an underlying mathematical foundation	100 % Complete
Integrate this methodology with the system engineering process and the design decision support environment	80 % Complete
Apply the system design evaluation methodology, system engineering process, and design decision support environment, to reaslistic examples which include: • Upfront system design trades associated with allocating functions to hardware and software and selecting a systems architecture, and • Downstream design trades associated with re-engineering or modifying an existing system.	80 % Complete In addition to these examples identified in the proposal, an example to demonstrate system evaluation during the conceptual design phase has also been devleoped.
Develop a prototype computer-based implementation of the system design evaluation methodology integrated into the design decision support environment	70 % Complete
Demonstrate the application of the system design evaluation methodology to the examples listed above.	60 % Complete
Refine the system engineering process and the DDSS based on the integration with the methodology	50 % Complete
Document results in a technical report	20% Complete

CONCEPTUAL DESIGN DEMONSTRATION

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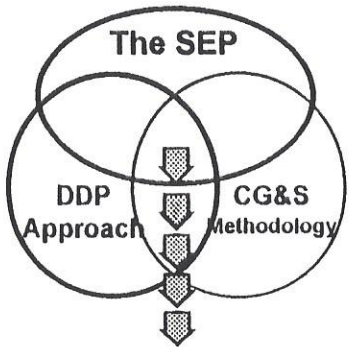
Framework and Approach

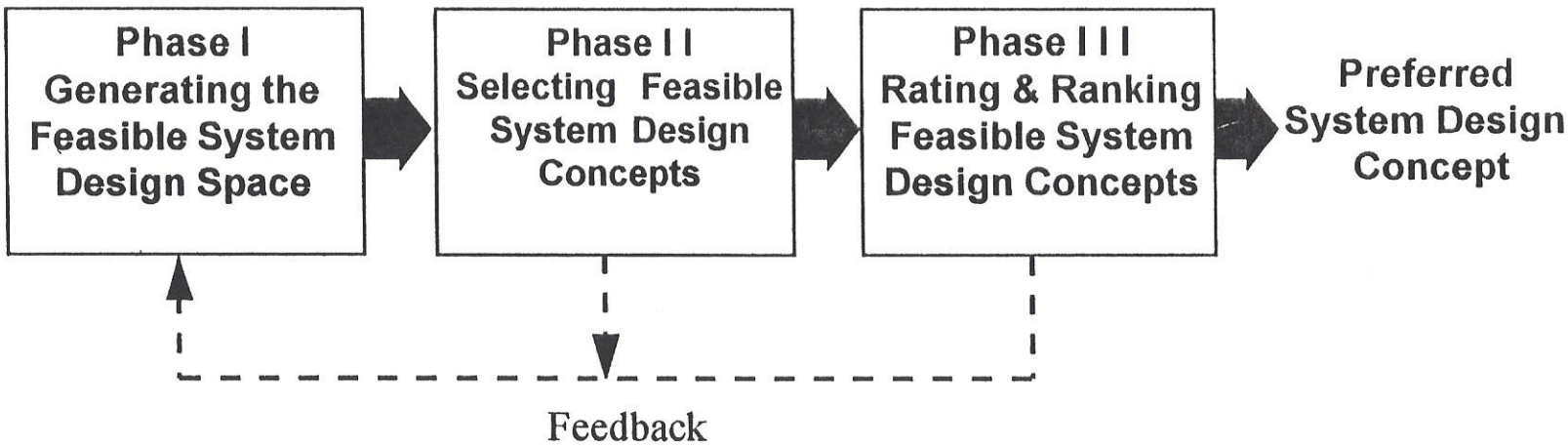
The conceptual system design evaluation methodology has been developed within the overall framework of:

- The System Engineering Process
- The Design Dependent Parameter Approach
- The Concept Generation and Selection Methodology



Conceptual System Design Evaluation Methodology

Conceptual System Design Analysis and Evaluation Process



Phase I: Generating the Feasible System Design Space

Identify functional need

↓

Identify customer requirements and the importance of these requirements

↓

Identify relevant design dependent parameters

↓

Correlate customer requirements and design dependent parameters

↓

Benchmark customer satisfaction levels

↓

Conduct technical assessment of existing facilities/systems

↓

Generate *IPN* index and *TOF* index values

↓

Delineate target values for the design dependent parameters
(i.e., identify design requirements or the feasible design space)

The Fuzzy QFD Mechanism

Hierarchy of Pertinent Design Dependent Parameters.
These are defined using the mechanism.

Hierarchy of Subjectively Stated Customer Requirements and their Importance.
Importances are defined using a linguistic scale with five linguistic labels.

Correlation Between Customer Requirements and the Relevant Design Dependent Parameters.
This is accomplished through the use of a linguistic scale with five linguistic labels.

Benchmarking Customer Perceptions Relative to Existing Capabilities
This is accomplished using a linguistic scale with five linguistic labels.

Assessment of Design Dependent Parameter Values for Existing Capabilities, their Importance, and Target Values for the on-going Design and Development Effort.

The *IPN* Index

- The Improvement Potential and Necessity (IPN) index provides designers with an indication of the improvement potential of a design dependent parameter (in terms of customer satisfaction levels), along with a necessity for this improvement.

- IPN is delineated by developing a matrix linking customer satisfaction levels and the correlation between customer requirements and design dependent parameters.

Rationale for the *IPN* Index

- The *IPN* index allows exploitation of the most prominent opportunities in order to gain a strategic advantage in the market place.
- Design effort can be focused towards avenues where improvements can be accomplished (in terms of overall customer satisfaction levels) in the most effective and efficient manner.
- IPN concept is very similar to the Pareto analysis used to delineate critical factors requiring the most attention.

The *TOF* Index

- For completeness of the design requirements process, it is necessary to define not only the required levels for the design dependent parameters, but also the associated tolerance levels.
- This information is conveyed through the development of an index called the *Tolerance of Fuzziness (TOF).*

Phase II: Selecting Feasible Conceptual Solutions

Generate Potential Conceptual Design Alternatives

↓

Predict and Estimate Relevant Design Dependent Parameter Values

↓

Setup Feasibility Thresholds for the Design Dependent Parameters

↓

Assess Feasibility Indices for all DDPs of every Potential Concept

↓

Select Feasible Conceptual Solutions

↓

Identify Opportunites for Effective & Efficient Design Improvements

Feasibility Index

The feasibilty index "allows" flexibility in setting different feasibility threshold levels for different design parameters as a function of their criticality. An adaptation of this mechnism is used in the ultimate rating and ranking of design concepts.

$$FI_{ddp_{ni}} = \frac{Projected\ overlap\ volume\ for\ the\ ith\ DDP\ of\ nth\ concept}{Total\ projected\ volume\ of\ anticipated\ profile\ for\ the\ ith\ DDP\ of\ nth}$$

Phase III: Rating and Ranking Feasible Conceptual Solutions

Compute Design Dependent Parameter Absolute Importances

↓

Compute Design Dependent Parameter Relative Importances

↓

Consolidate Design Dependent Parameter Relative Importances and Feasibility Indices for Every Feasible Design Concept

↓

Generate the Conceptual System Design Evaluation Display

↓

Select the Preferred Design Concept

PRELIMINARY DESIGN DEMONSTRATION

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Outline

- Objectives, status, and plans
- Evaluation methodology and ADARTS considerations
- Case study demonstration and completion plan

Objectives

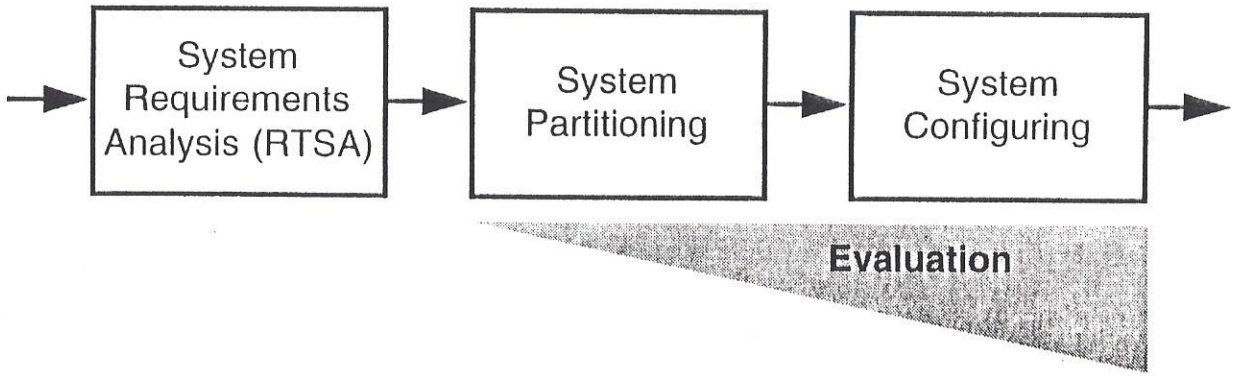
- Demonstrate the integration of evaluation methods with preliminary design activities for hardware/software systems
- Preliminary design based on system-level tasks in SPC's ADARTS process
  - System requirements analysis -- Real-time System Analysis (RTSA)
  - System partitioning
  - System configuring
- Evaluation methods
  - Analysis of requirements allocation
  - Design decision support for design alternatives
    - Demonstration focuses on hardware versus software implementation and selection of hardware and software "parts"
    - Methodology could be extended to other categories of alternatives

Status and Plans

- Current status
  - Interfaces with conceptual design and detailed design established
  - Concepts for integrating evaluation methods with ADARTS process understood (based on Webster's GLM, SDAT, ESTEVAL)
  - Partial implementation in Toolbook to illustrate demonstration approach
- Planned for January 15 delivery
  - Integration of basic evaluation methods
  - Toolbook-based demonstration of integration with limited flexibility
- Planned for May 15 delivery (with no-cost time extension)
  - Full investigation of integration of extended evaluation methods
  - Toolbook-based demonstration of the evaluation methods and full integration
- Future opportunities
  - Extension and increased coverage of evaluation methods, e.g. to evaluate alternative architectural styles
  - Increased demonstrator flexibility

Approach

- Preliminary design context
- Preliminary design activities -- ADARTS system-level activities
  - System requirements analysis (RTSA)
  - System partitioning
  - System configuring
- Evaluation tasks
  - Analysis of requirements allocation
  - Allocation to hardware/software implementation
  - Evaluation of alternative configurations



Preliminary Design Context

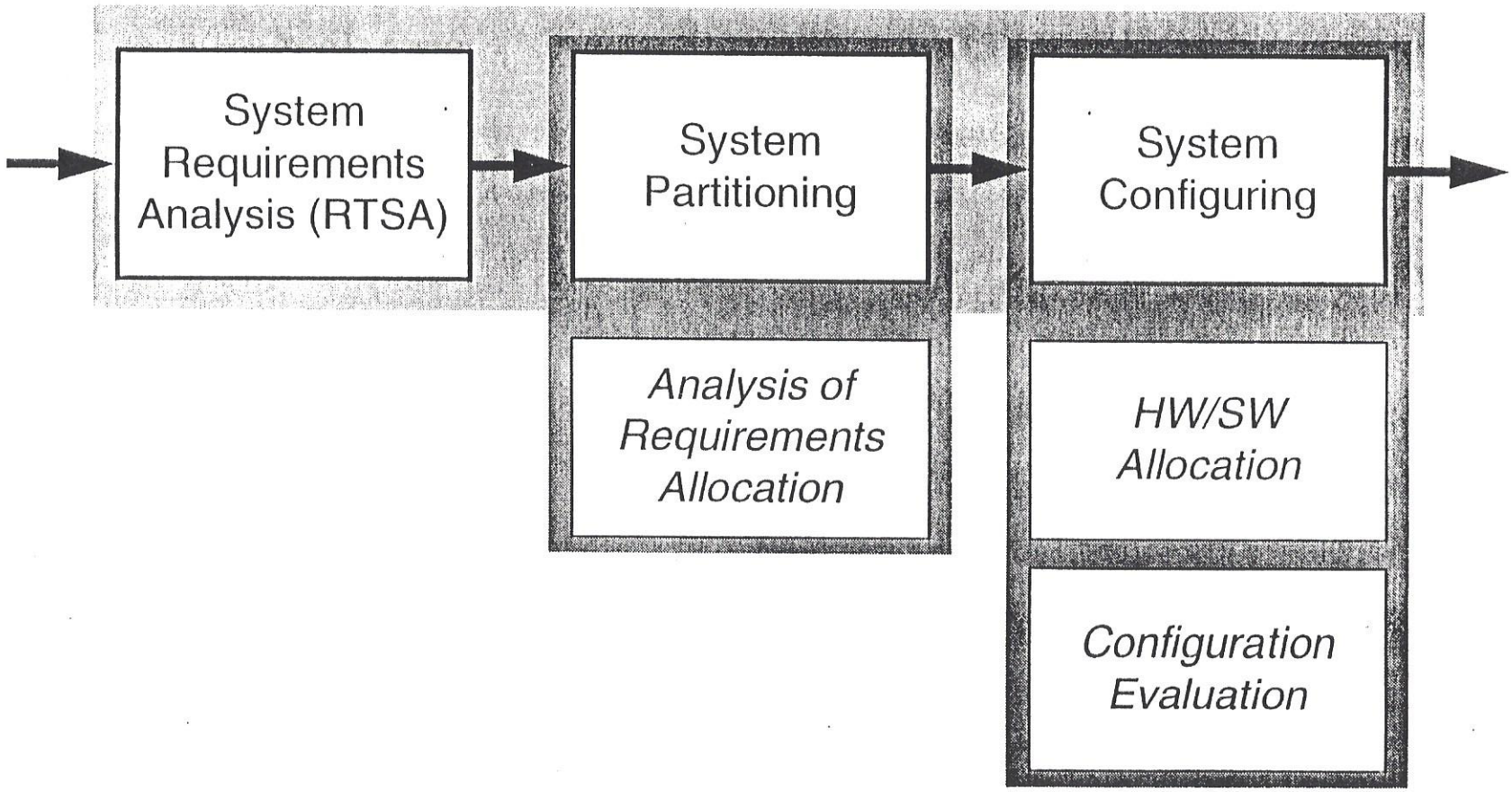
Inputs
- System design concept
- Customer requirements

Imply
- System capabilities
- Implementation constraints

Outputs
- System configuration
- Allocation to HW, SW
- Subsystem requirements

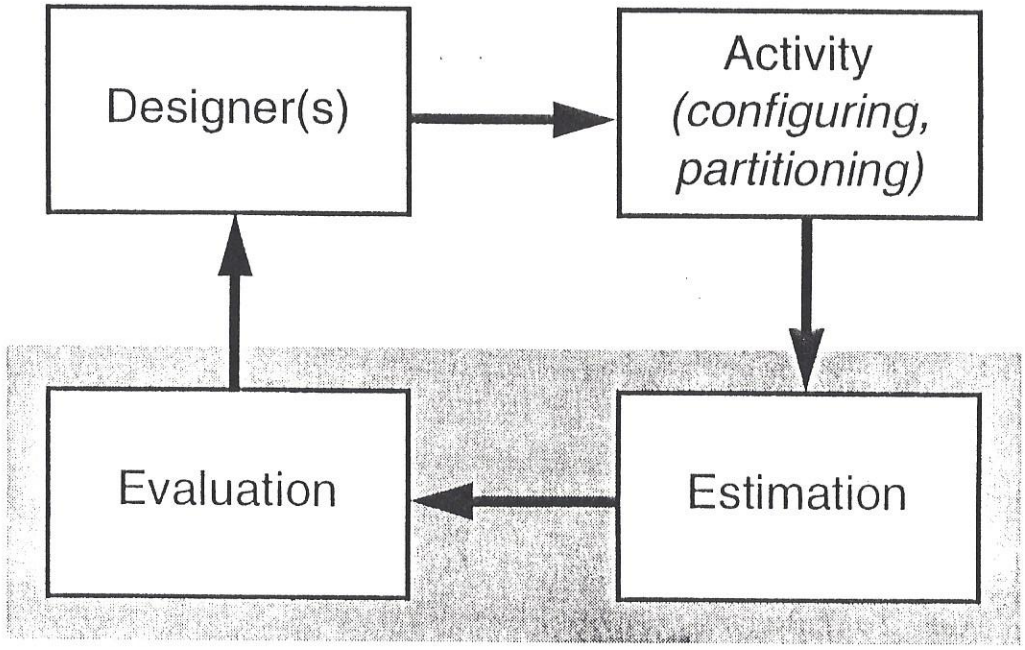
Trace to
- System capabilities
- Implementation constraints
- Design decisions

Evaluation Methods

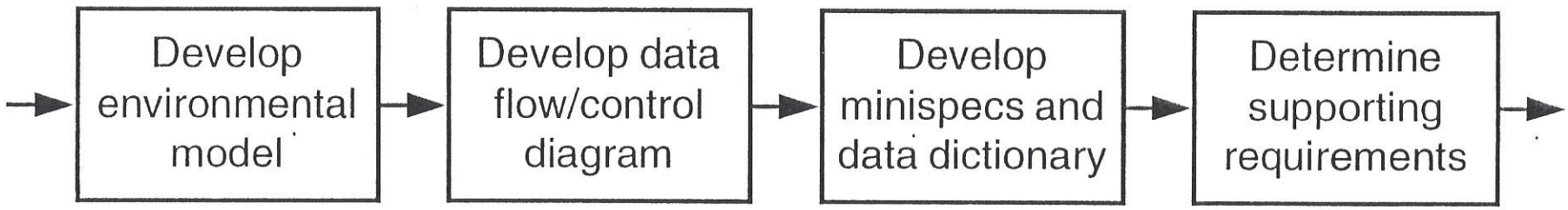


Evaluation Morphology

- Evaluation provides feedback to the designer(s) to enable iteration and design improvement
  - Iteration within a synthesis activity
    - System partitioning
    - System configuring
  - Identify need to return to an earlier activity to modify design decisions

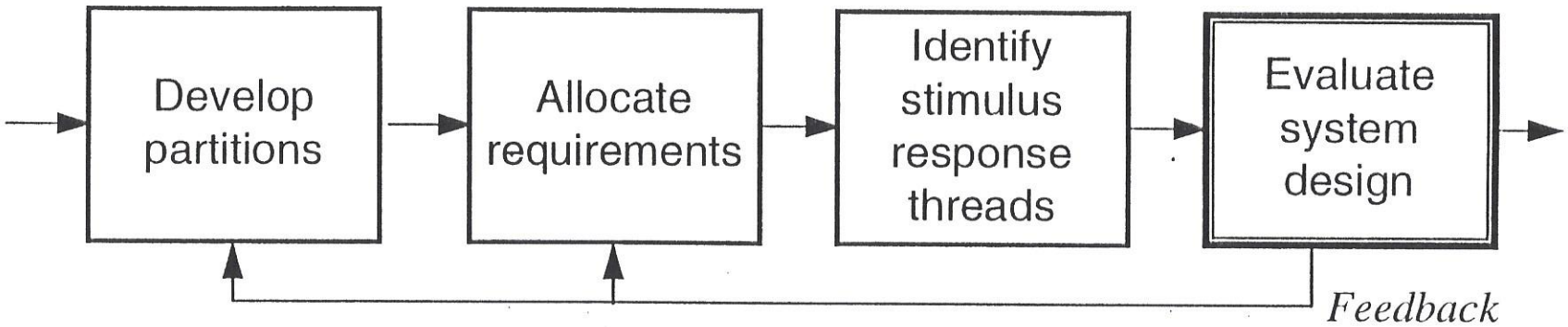


System Requirements Analysis



- Inputs (from conceptual design phase)
  - Definition of system function
  - System requirements
  - Customer needs and operational scenarios
  - System design concept
- Outputs (to system partitioning activity and beyond)
  - System context
  - Data/control flow diagrams
  - High-level specifications
  - Additional requirements

System Partitioning

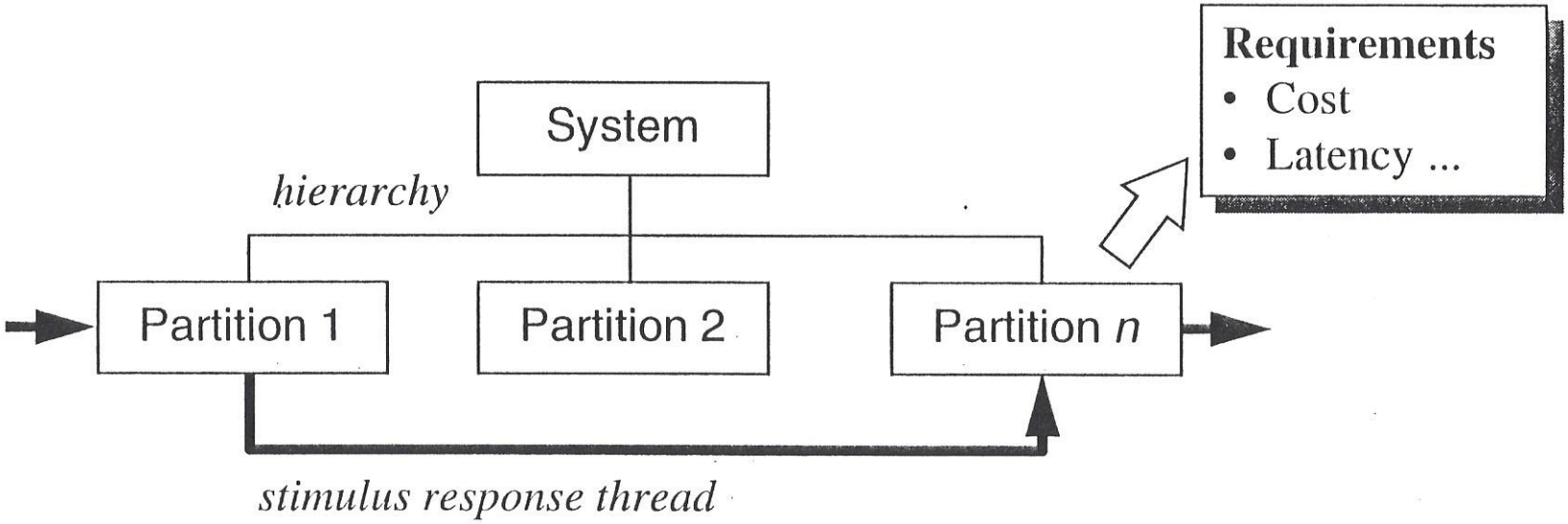


- Inputs
  - System context
  - Data/control flow diagrams
  - High-level specifications
  - Additional requirements
- Outputs
  - System partition
  - Partition specifications
  - Interface and message specifications

System Partitioning: Evaluation

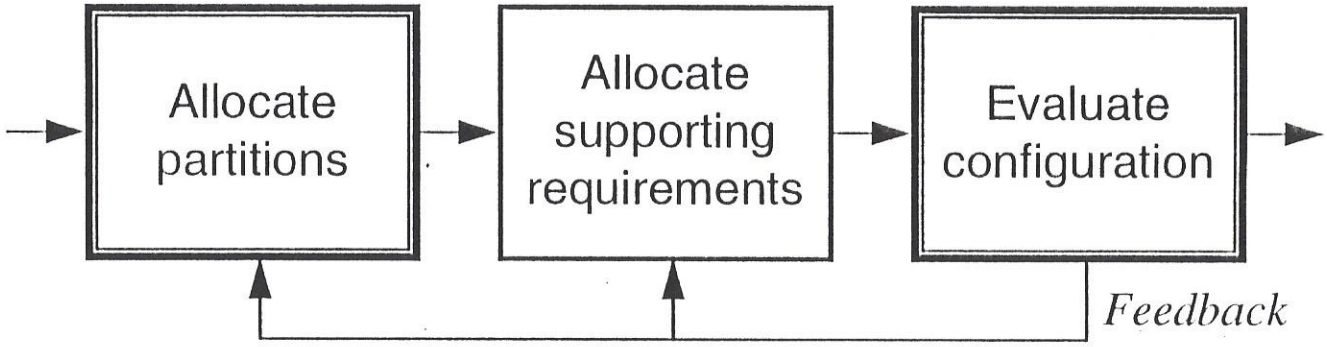
- Required evaluation methods
  - System-level verification of specifications
  - Performance analysis
- Performance analysis is application specific and will *not* be addressed in detail in this work
- System-level verification of specifications
  - Objective is to verify
    - Completeness
    - Consistency
  - Based on earlier work
    - System Design and Analysis Tool (SDAT)

SDAT Approach



- SDAT does system-level "roll-up" of requirements
  - Along system hierarchy, e.g. for cost
  - Along stimulus-response threads, e.g. for latency
- Evaluation metrics are design-dependent parameters
- Evaluation functions/estimation methods needed for each metric

System Configuring

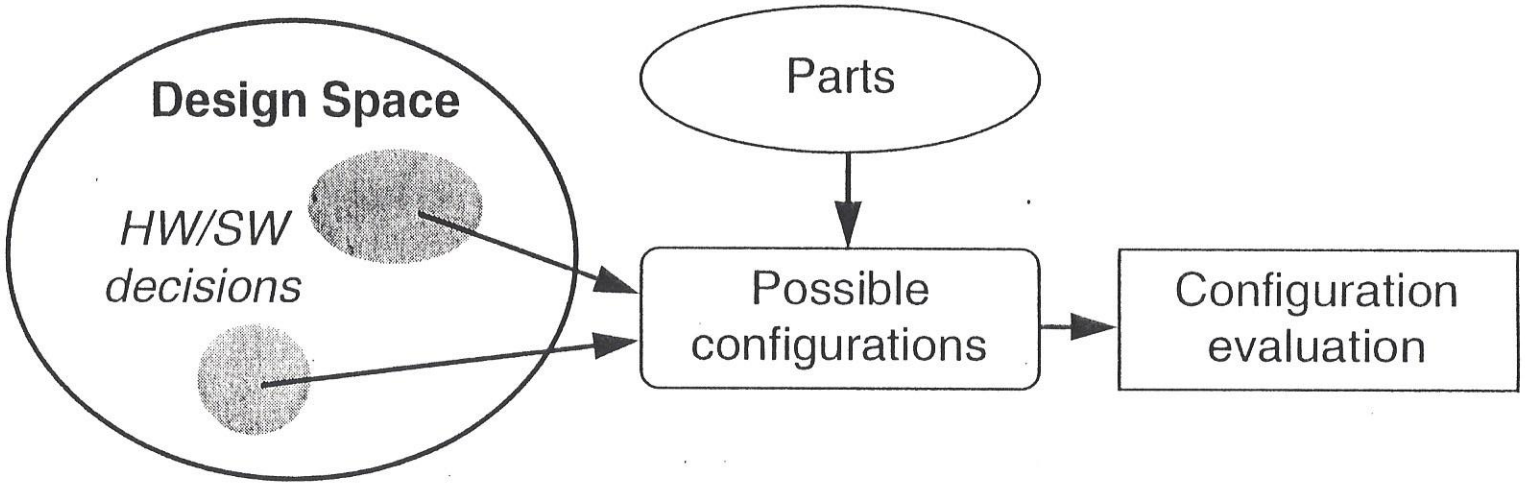


- Inputs
  - System partition
  - Partition specification
  - "Parts" specification
- Outputs
  - System decomposition
  - Subsystem requirements
  - System configuration (hardware/software allocation)

System Configuring: Evaluation

- Required evaluation methods
  - Design decision support for hardware/software allocation
  - System configuration evaluation
- Design decision support for hardware/software allocation
  - Objective is to suggest "goodness" of hardware versus software implementation
  - Based on earlier work
    - Webster's utilization of the General Linear Model (GLM)
    - Embedded in System Design and Analysis Tools (SDAT)
- System-level verification of specifications
  - Objective is to evaluate system-level compliance with requirements based on selection of specific "parts"
    - Parts include both software and hardware components
    - Specifications are known for existing parts and estimated for parts to be developed
  - Based on earlier work
    - Estimation/Evaluation (ESTEVAL) tool

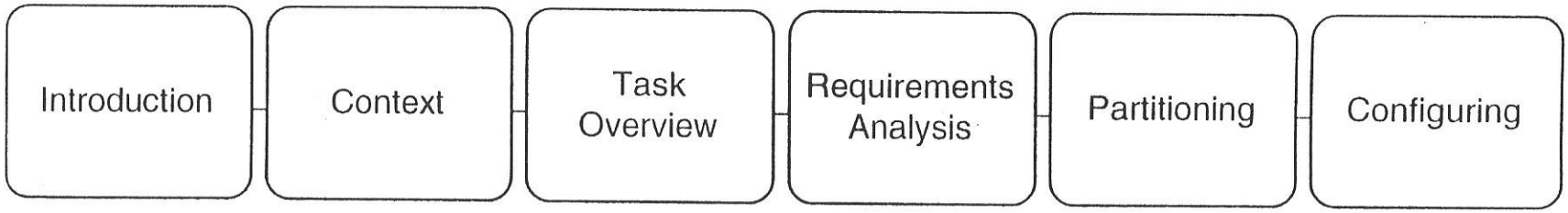
SDAT/ESTEVAL Approach for Configuring



- General Linear Model (GLM) in SDAT weights "goodness" of hardware versus software implementation as a function of partition requirement levels and properties of hardware and software implementation
- ESTEVAL uses a library of hardware and software parts to estimate system attributes versus requirements
- Permits
  - Design iteration
  - Decreasing granularity of design decisions

Case Study Demonstration

- Group videoconferencing system
  - Inputs traceable Conceptual Design Demonstration
  - Partial linkage to Detailed Design Demonstration
- General structure
  - Follows ADARTS activities, input criteria, exit criteria
  - Additional "depth" for case study and evaluation methods
- Status
  - Currently only a high-level framework is implemented
  - Basic functionality with limited flexibility to be delivered January 15
  - Full functionality and flexibility to be delivered May 15



DETAIL DESIGN DEMONSTRATION

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Detail Design Primary Objective

The objective of this demonstration is to illustrate how evaluation is implemented throughout the detail design phase of the system life cycle. In particular this involves:

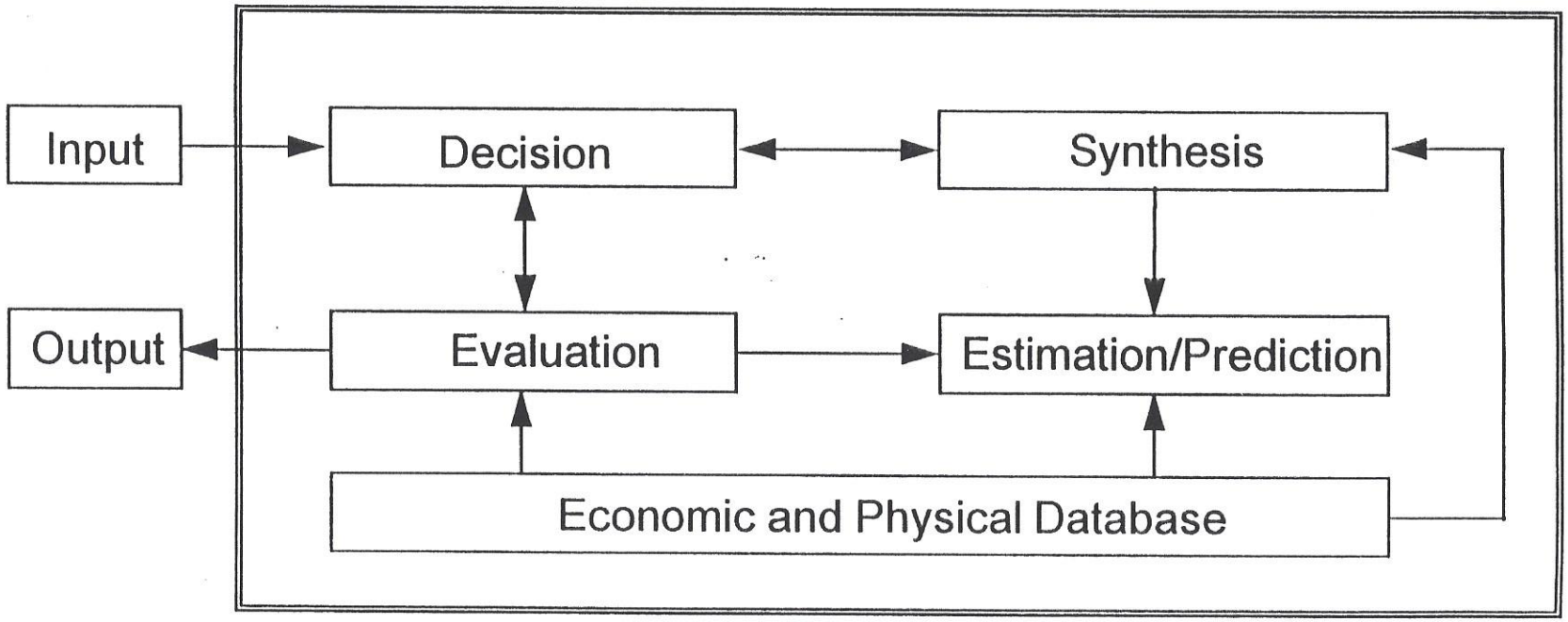
- Evaluation in the form of "ad hoc" assessment during the synthesis activities
- Evaluation in the form of comparison between the predicted performance of a current design against specifications
- Evaluation in the form of comparison between two or more candidate designs

Detail Design Secondary Objectives

Secondary objectives include discussion and demonstration of pertinent concepts such as:

- Design morphology
- Design Dependent Parameters (DDP)
- Role of optimization in system engineering process (ex. REPS-OPT)
- Function of system engineer(s) in detail design versus the design team

Design Morphology



Design Morphology Input

With the completion of preliminary design activities, the preferred concept which is output from conceptual design has been further defined into a preferred configuration. This serves as the input into detail design. It includes:

- A system hierarchy detailing structure of preferred configuration
- The design requirements detailing the desired performance, physical attributes, the "ilities", and other design considerations. (The specifications are also known as the TPM's or TPM rating)
- A system hierarchy with information on the allocation of system functions to hardware, software, and human functions.
- Design specifications detailing the desired performance, physical attributes, the "ilities", and other considerations. The specifications represent allocated requirements.

Design Morphology: Decision

Decision is manifested within the morphology as:

- Initial assessment and allocation of the requirements .
- "Ad hoc" intuitive decisions in the synthesis process.
- Comparison of predictions of candidate design performance to TPM's.
- Comparison between candidate designs, selection of final design, or a decision to return to a previous design phase for further work.

Design Morphology: Synthesis

- **Designers use CAE/CAD tools to develop prototype designs, based on allocated requirements. Supporting technical information is retrieved from economic and physical databases.**
- **Emphasis should be on:**
  - Rapid development iterations
  - "Ad hoc" intuitive decisions in the creation of initial prototypes

Design Morphology: Estimation and Prediction

The designers use modeling tools to predict system performance (design dependent parameters) and estimate cost parameters. These results are then evaluated against system requirements as a feasibility check. If the design proves:

- Deficient -- process returns to synthesis
- Acceptable -- design process progresses to analyze and trade-off evaluation

Design Morphology: Analysis and Evaluation

For each design, the design variables are optimized with respect to evaluation measure(s). Evaluation functions are then used to facilitate comparisons of design alternatives.

- Comparisons emphasize trade-offs between relative AELCC figures and respective system performance, as measured in TPM's
- The design evaluation display (DED) and associated tables are the primary tools for this task.

Design Morphology: Database

The design process is supported by:

- Economic databases, with actual and forecasted information on interest rates, cost data, labor rates, etc.
- Databases containing physical design data gathered from empirical experiments, technical references, and other outside sources.

Design Morphology: Output

There are three (3) possible outcomes:

- The desired result is actual plans for the final design and its attendant support functions.
- Return to preliminary design to re-examine the preferred configuration.
- In an extreme instance, the process may even return to the conceptual design phase.

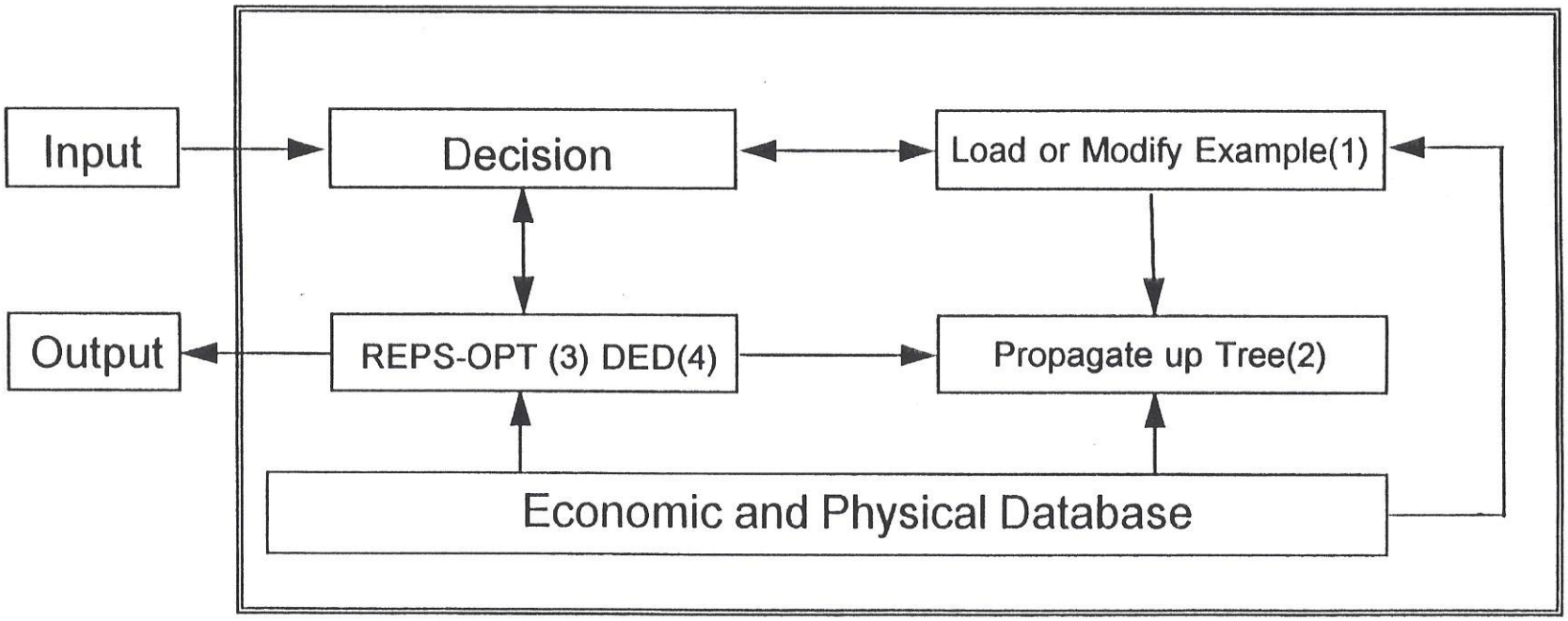
Detail Design Case Study

- **The detail design case study is based on design activities in the development of a remote conferencing system. Emphasis is placed on demonstrating how evaluation is implemented throughout the detail design phase of the system engineering process.**

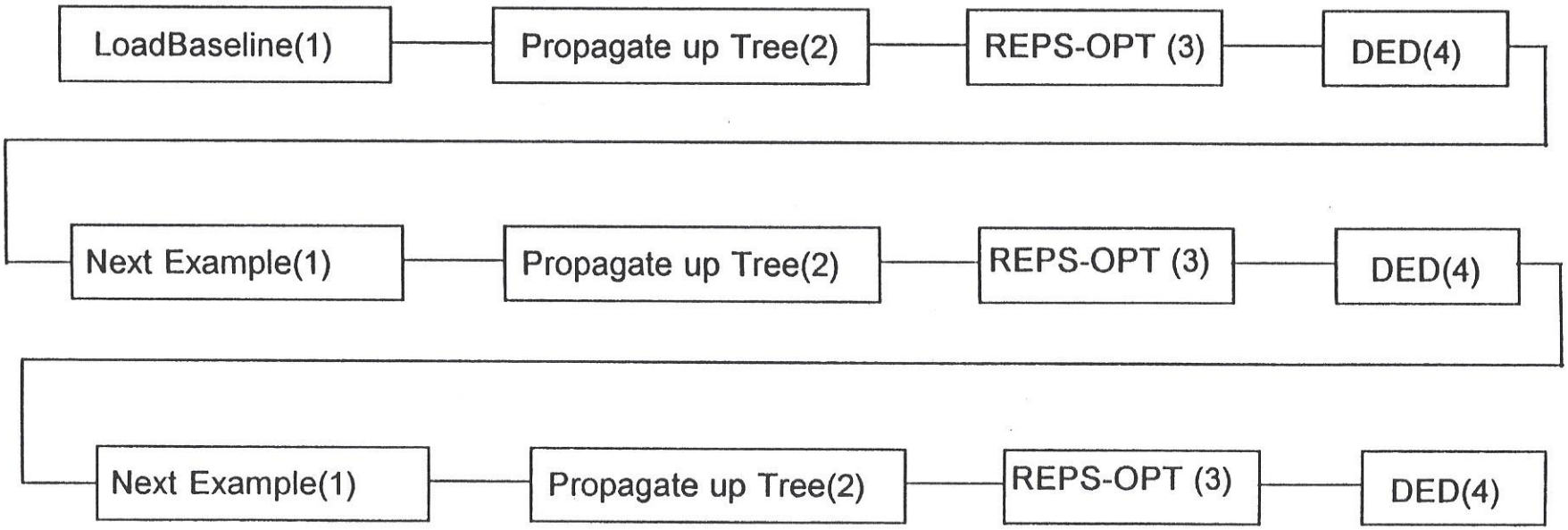
- **The user can :**
  - Follow a path using pre-loaded examples
  - Navigate between milestones, modify parameters, and "Experiment" in design iteration

Detail Design Case Study Design Iterations

Each "cycle" represents a design iteration



Detail Design Case Study Design Iterations



Current State of Detail Design Demonstrator

- **The basic framework is complete at this time. Each of the "milestones is in place, with varying amounts of additional supporting text required.**
  - Script and viewers for loading and modifying example data is complete
  - Script and viewers for "propagating" predictions up the hierarchical tree are complete
  - The REPS-OPT algorithm is functional
  - The Design Evaluation Display is in place and functioning
- **Need to complete/enhance:**
  - Case study overview
  - Example files
  - Supplementary viewers to "walk" new users through the case study
  - Viewers explaining evaluation of case study example in the DED
  - Bibliography