Decomposition Strategy for the Dynamic Synthesis/Design and Operational/Control Optimization of Complex Systems

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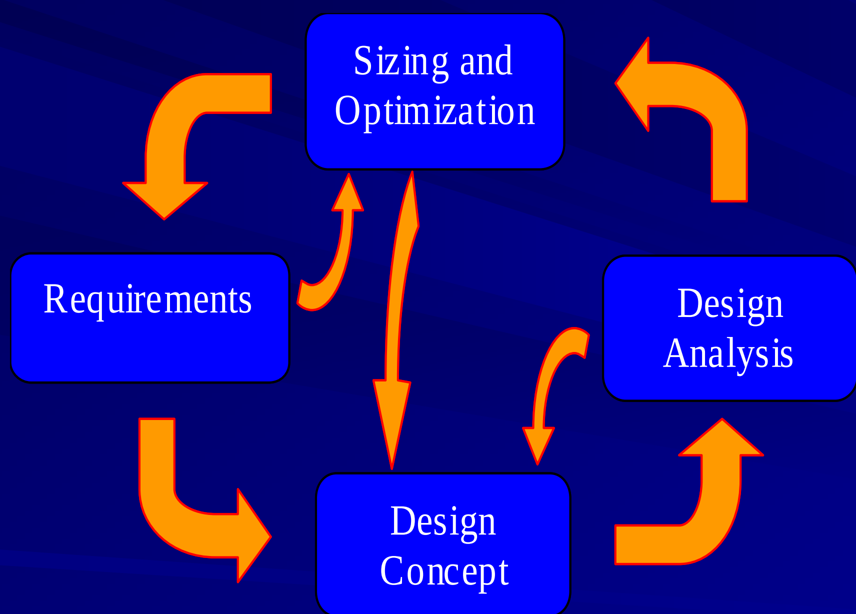
Outline

- Issues of applying large-scale optimization and how one can address them effectively to the development and operation of highly complex and dynamic systems (transportation and stationary) even when high fidelity models and large numbers of optimization degrees of freedom are in play.

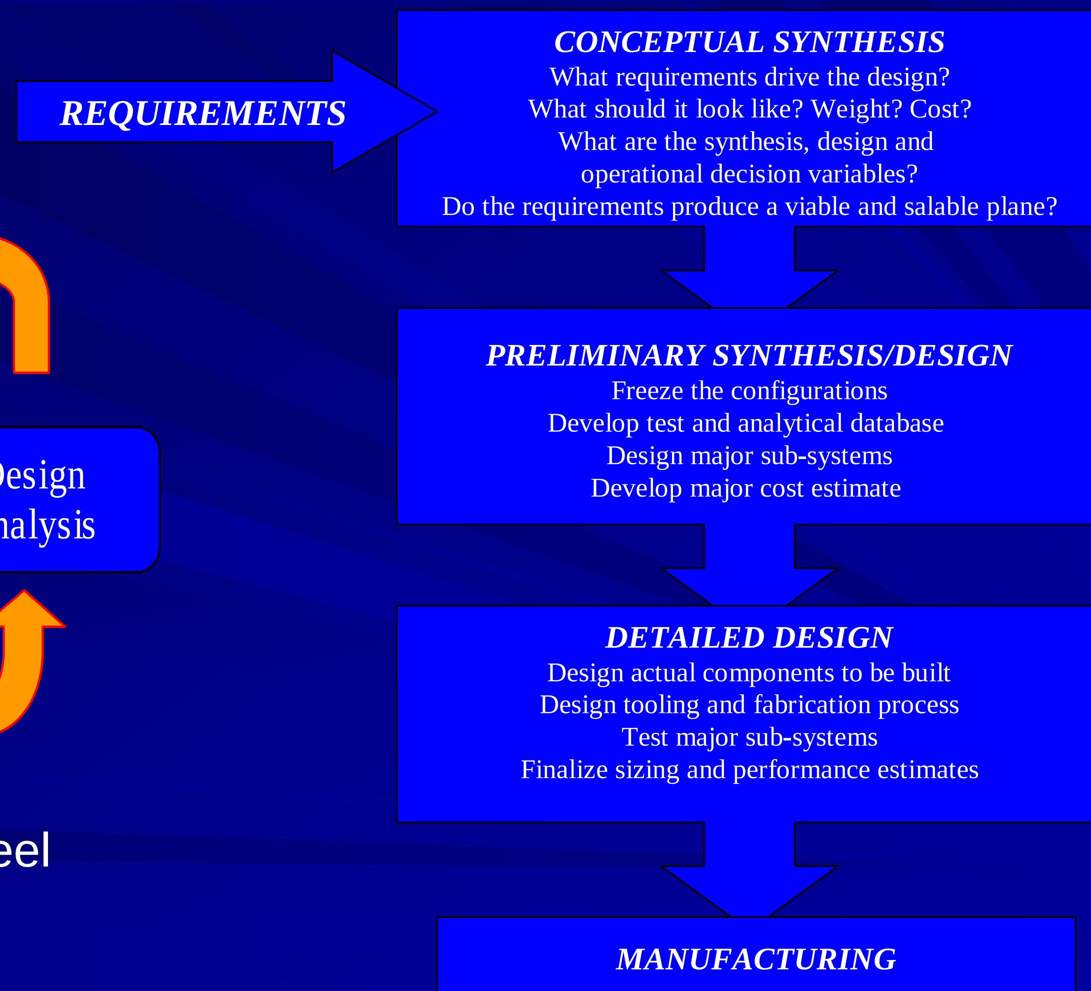
- Systems may even consist of a mix of systems some of which can be viewed in the traditional sense of an energy conversion process and others which cannot.

- With effective decomposition strategies, it is possible to optimize system and component level structures, i.e. *synthesize*, while simultaneously optimizing component *designs*, *operation*, and *control* over an entire load spectrum.

Synthesis/Design



The synthesis/design wheel



Three phases of system synthesis/design

Large scale optimization and the use of decomposition strategies

Synthesis/Design and operational/control optimization challenge

Synthesis/Design Variables $\{x\}$

- *Geometry* (e.g., length, width of a HX)
- Design *Thermodynamic* Variables (e.g., pressure ratio, bypass ratio)
- Integer Variables related to *configuration* (e.g., existence / nonexistence of component)

Operational/Control Variables $\{y_i\}$

- Flow rates
- Throttle settings
- *Integer* Variables (component on-off)
- Sell/ Buy products

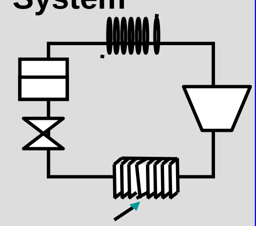
Dynamics

- multiple load segments
- complex load
- transient effects

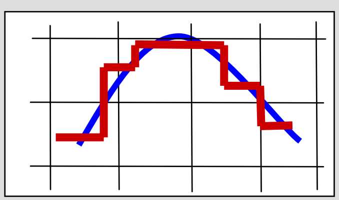
Subsystems

- Multiple
- Energy and non-energy
- Component level detail

System



Load / Environment



Time

$$\text{Minimize}_{\{x,y_i\}} \; C_T = \sum_i C_i$$

Problem:
Too many variables/
The complexity of the problem is too high

Dynamic Mixed Integer Non-linear Programming (MINLP) Problem

Optimization strategy

Single-level optimization approach

- **Models**
- **Simulators**
- **Analyzers**

→

- **Optimization**
- **Algorithms:**
- **Gradient-based**
- **Heuristics**
- **AI**

Mathematical / Computational Drawbacks

- The resulting DMINLP is very difficult and expensive to solve
- The number of independent (decision) variables may grow to be very large
- Software compatibility issues and data exchange need to be solved

Cultural Drawbacks

- A single analyst, who has expertise in every discipline / technology involved, is needed
- Different groups are usually assigned parts of the overall design. These groups may be geographically dispersed
- Every group would prefer to carry out its own optimizations
- Technology and software proprietary issues may also arise

Multi-level optimization approach

Multi-level approach

- Models
- Simulators
- Analyzers

Interface

Multi-level optimization:

- Physical decomposition (LGO, ILGO & DILGO)
- Conceptual decomposition
- Time decomposition

Optimization algorithms:

- gradient-based
- heuristic
- AI

Traditional single-level approach

Multi-level optimization approach: Decomposition

✓ **Advantage is that the size of each unit- or system-level optimization problem is smaller than the overall single-level problem**

Conceptual Decomposition

Divides the problem into two separate problems: synthesis/design and operation

- Captures synthesis / design compromises due to operation at off-design

Physical Decomposition

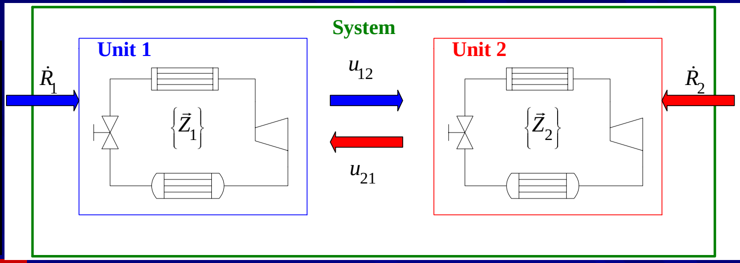
- Divides the problem into unit and system-level optimizations
  - Must be able to optimize each unit locally and independently
  - Must account for the interactions at the system-level
  - Should converge to the same or nearly the same single-level system optimum
- Local-Global Optimization (LGO), Iterative Local Global Optimization (ILGO), and Dynamic Iterative Local Global Optimization (DILGO)

Time Decomposition

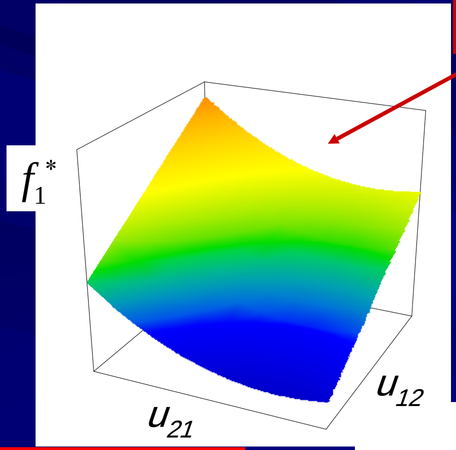
- Divides the problem into discrete time segment optimizations
  - Assumes quasi-stationary operation

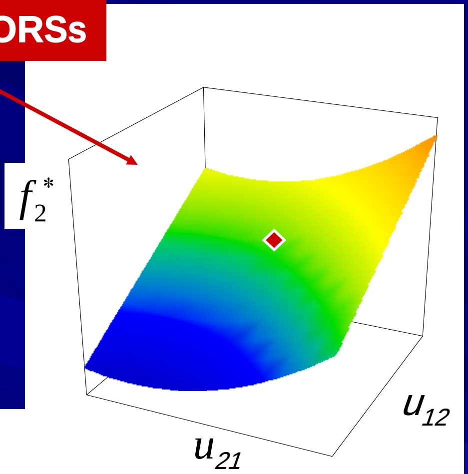
Physical decomposition: LGO & ILGO

Fundamental idea of LGO: Obtain local (unit-level) optima for various combinations of values of the coupling functions and then find the best of these combinations

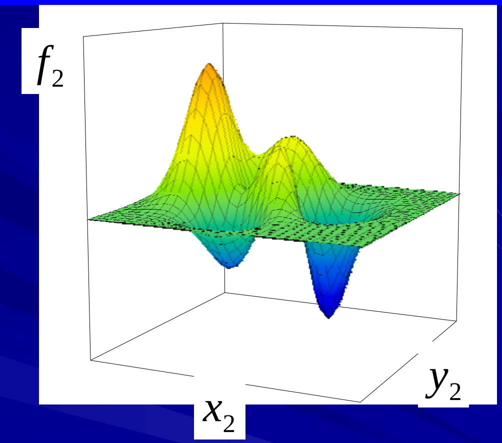


Unit-Level ORSs

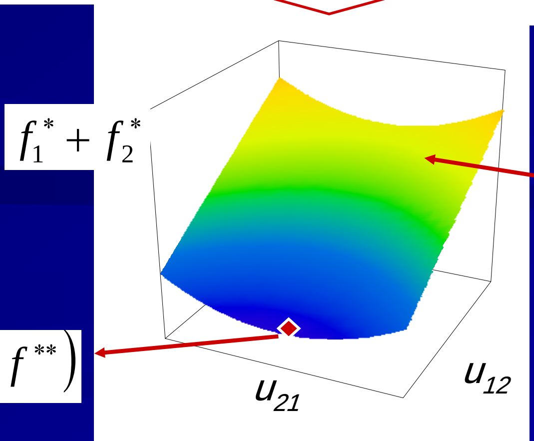




Unit- Level Optimization



Fundamental idea of ILGO: Move along the system-level ORS using shadow price information.



System-level ORS (Optimum response surface)

System-level optimization

Applications

- Supersonic aircraft with 493 optimization degrees of freedom synthesized/designed and operated over an entire mission with multiple subsystems including the airframe-aerodynamics

- Fully dynamic synthesis/design and operational/control optimization of a 5 kWe SOFC APU for stationary applications (183 optimization degrees of freedom and multiple subsystems)

- 250 kW PEMFC total energy system for residential applications and 1.5 MWe Hybrid SOFC-GT system.

Conclusion

- It is *very possible* to do the integrated dynamic synthesis/design and operational /control optimization of very complex systems!