PICMET

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Challenges in designing and Implementing Large Systems

-- Implications on Social and Technological Innovations --

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Thank you for the invitation to speak.

You have made singular contributions to the development of the field of management of technology.

Congratulations on the 25th Anniversary of PICMET.

Two specific questions related to *"Innovations"*:

***1. Social Innovation*:**

The "ranking" of many universities does not change. ***Why?***

***2. Technical* Innovation:**

Some development projects cannot achieve their goals on *schedule* and within the *original cost estimate.* ***Why*?**

Conclusions first:

In both cases, the root causes of the problem may be the following:

1. Not defining a right set of FRs for the system

2. "Coupling" of functional requirements (FRs) of the system.

We will address the issues related to technical systems first, since it is easier to support the conclusion.

Technological Innovations

Boeing 747 (Joe Sutter, 1921-2016)

Finished this project in 29 months

(The NY Times, Sept 1, 2016)

Lockheed Martin's F-35 Fighter Airplane

F-35 Fighter Airplane

- (D. Francis, The Fiscal Times, 7/31/2014)

"… the seemingly never-ending list of problems with the Pentagon's next-generation F-35 fight jet, from cost overruns of $160 billion to technical problems that have plagued the plane's development. …"

Berlin Brandenburg Willy Brandt Airport (BER)
"**Germany's most expensive construction site**"

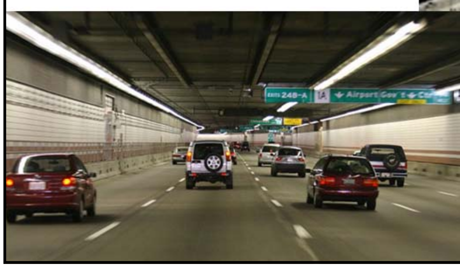
New Berlin Airport

- **"How Berlin's Futuristic Airport Became a $6 Billion Embarrassment"**

(Bloomberg Business, Joshua Hammer, July 25, 2015)

- Opening originally scheduled for 2012 has been delayed to 2017 with cost exceeding the original budget by ten-fold (10x)

Boston’s Underground Central Artery Highway



“Big Dig”
(Boston’s underground central artery highway)

- Original budget of $2 billion ballooned to $18 billion and delayed its opening (32 years in planning and 12 years in construction)

$4 billion World Trade Center Transportation Hub in NY (cost overrun ~$1.8 billion, 12 years to complete)

On-Line Electric Vehicle (OLEV)
(Developed at KAIST in about 2 years)

Question?

How could

Boeing 747 be developed in 29 months

and

OLEV in 24 months

when it took so long to complete other projects and often with major cost over-runs?

Lockheed Martin, GM, Bechtel, etc. are highly sophisticated leading technological companies in the world.

- **They attract highly educated, intelligent, and smart engineers and managers.**
- **Their engineers and scientists do mathematical modeling, simulation, etc.**
- **These companies have rich experience in developing large systems.**
- **Many engineers and scientists are highly motivated to work on these exciting projects – once in a life time projects.**

Yet, they often repeat design/build/test cycles to correct the mistakes made in design and construction of the system.

After repeated corrections, they may eventually converge on an acceptable system after repeated trial-and error processes.

Why?

What are the root causes of these mistakes?

Social Innovation: Universities

- On September 6, 2016, QS published a new ranking of universities world-wide.
- **The ranking of most universities has not changed much. Why?**
- Is the root cause of the problems universities are facing different from those faced by industrial firms in their product development?

Most Probable Causes of the Problem

in developing both technological and social innovations are:

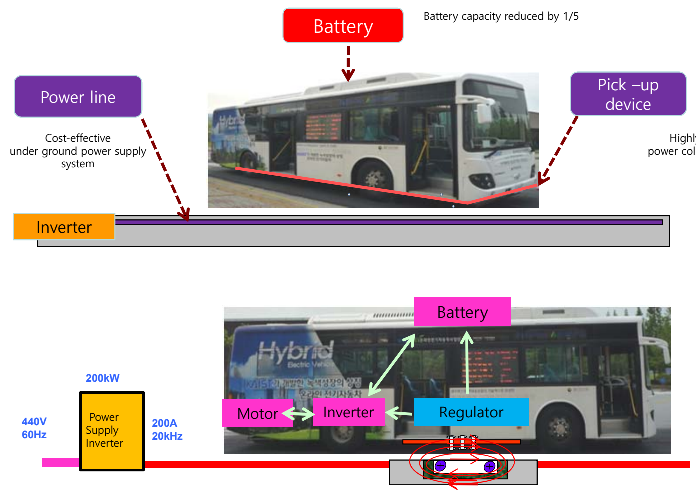
- **Not having defined FRs (goals)**
- **Coupling of FRs**

OLEV (On-Line Electric Vehicle)

- Goal: Replace IC engines with electric motor to prevent global warming.
- Electric vehicle (EV) “without battery”
- Receives electric power wirelessly from underground cable

- Project started in 2009 and made operational in 2011
- Three cities in have been running it commercially.
- Forth city has decided to adopt it.
- Quiet
- Cheapest transportation (U of M study)
- Being applied to high speed trains

Concept of OLEV



※ KAIST is demonstrating the core technology by using both power supply system under ground and power collection system attached to bus.

Basic Wireless Power Transfer Technology

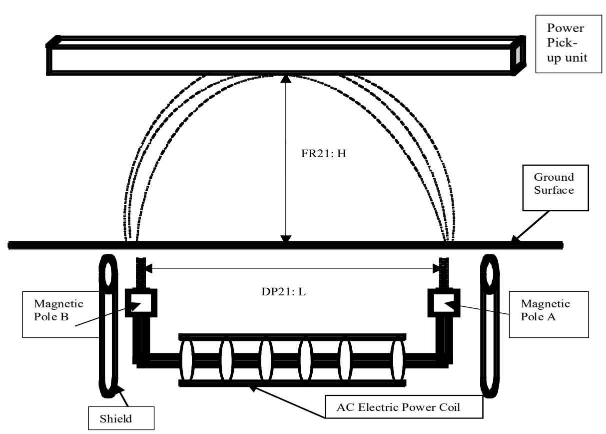
SMFIR (Shaped Magnetic Field in Resonance)

Three FRs of SMFIR:

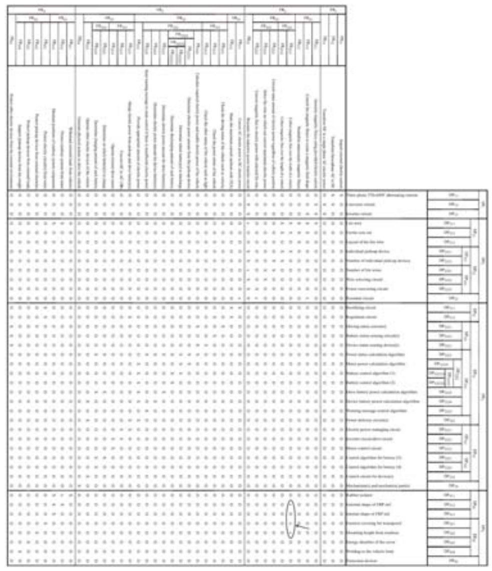
FR1 = Generate magnetic field above the ground

FR2 = reach the bottom of the vehicle

FR3 = pick up the power.



Role of System Architect:
Create and Monitor Design Matrix (DM)
DM for OLEV (Hong and Park, 2010)

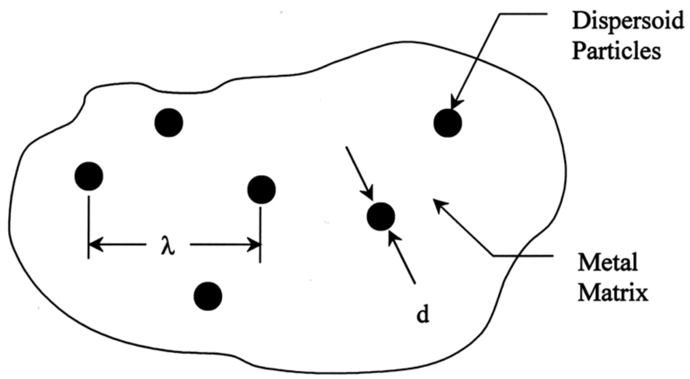


OLEV Bus in Gumi City (Design to Implemenation: ~2 yrs from design to implementation)

Mixalloy
(TiB_2 Dispersion strengthened Cu)

- Concept to manufacturing (no laboratory experiments) in about three years. Lost 6 months because of the coupled design intentionally included.
- The functional requirements (FRs) of Mixalloy:
  - FR1 = High strength at high operating temperatures = τ_s
  - FR2 = High elongation and toughness = K_c
  - FR3 = High electrical and thermal conductivity = ϕ

Mixalloy to Illustrate Effect of Coupling of FRs



Microstructure of the alloy with hard ceramic particle in a metal matrix

Mixalloys - Design of the Process

Mapping from the Physical domain to the Process Domain

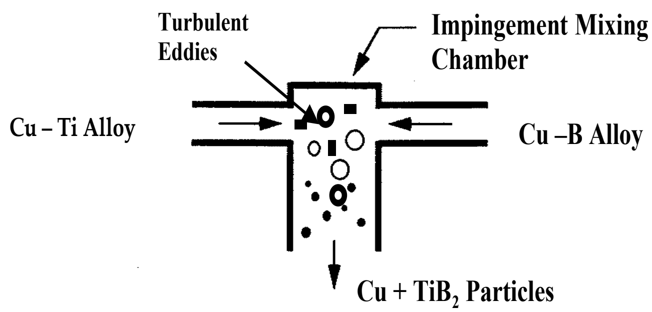
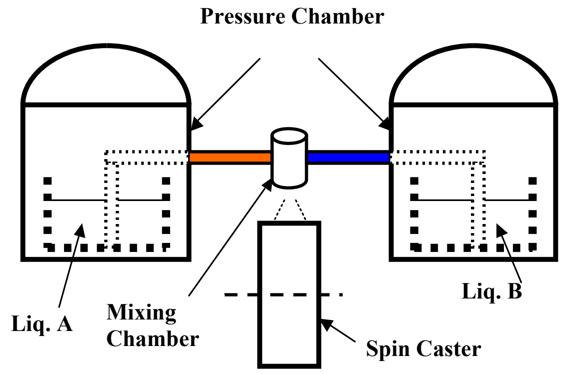


Figure 7.5 Mixalloy process for making dispersion strengthened alloys. This figure shows impingement mixing of Cu/Ti liquid solution with Cu/B liquid solution to form a pure copper phase with nano-scale titanium diboride particles. (Courtesy of Sutek Corporation, Hudson, MA)

Intentional coupled design delayed the project and incurred major cost.



A schematic drawing of the Mixalloying equipment. The metal was melt using induction heating. The equipment was about 15 feet high and occupied about 20 feet by 20 feet area, excluding auxiliary equipment such as power supply, water tank, metal chip collectors, etc. (Courtesy of Sutek Corporation)

From Just an Idea to Commercialization in 3 years

We designed production machine without having done laboratory experiments.

We made the first Mixalloy using the original equipment.

We shipped our product to Chrysler, GM, and other automotive companies in about three (3) years.

On Development of Universities

- The U.S. and the world ranking of many universities have not changed much for years. Why?

First Steps in Social Innovation:

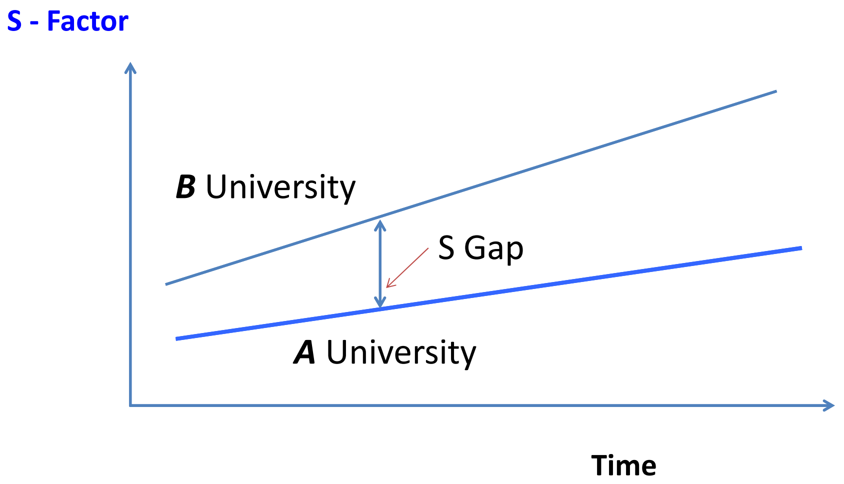
- **Identification of the problem**
- **Defining the problem**
- **Defining the goal for innovation**
- **Then, *DESIGN***

defining FRs for the organization and without violating the independence of FRs of a university.

Examples of Social Innovation:

- **MIT-Industry Polymer Processing Program**
- **MIT Laboratory for Manufacturing and Productivity**
- **NSF Engineering Directorate**
- **Engineering Research Centers**
- **KAIST (The Korea Advanced Institute of Science and Technology)**

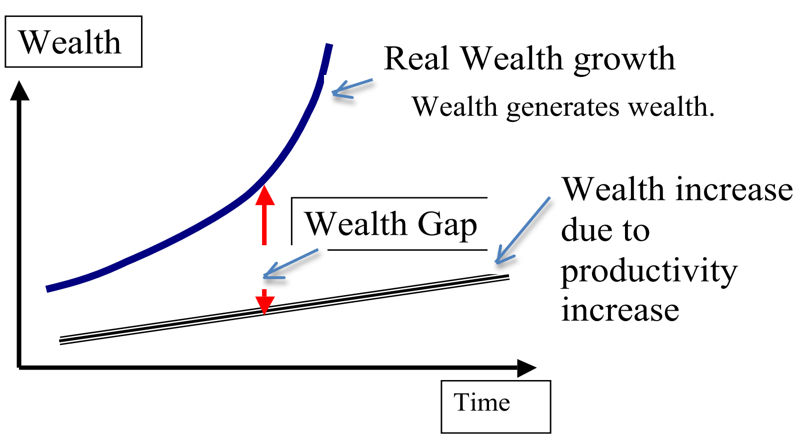
Divergence of University Development: the S-Curve



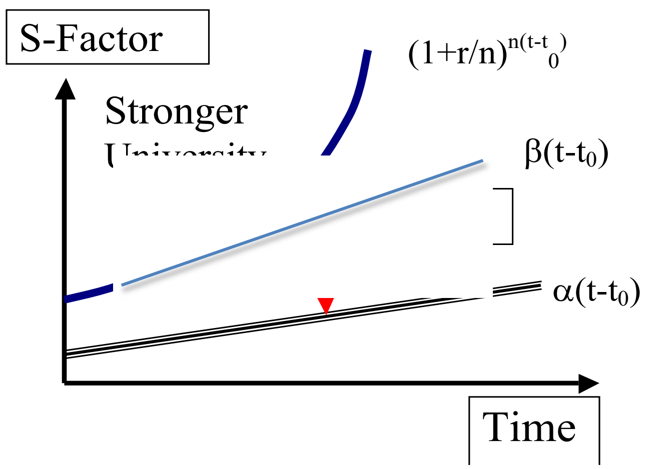
The Piketty Curve

"The rate of capital return in developed countries is persistently greater than the rate of economic growth, and that this will cause wealth inequality to increase in the future.

(T. Piketty, *Capital, 2013*)

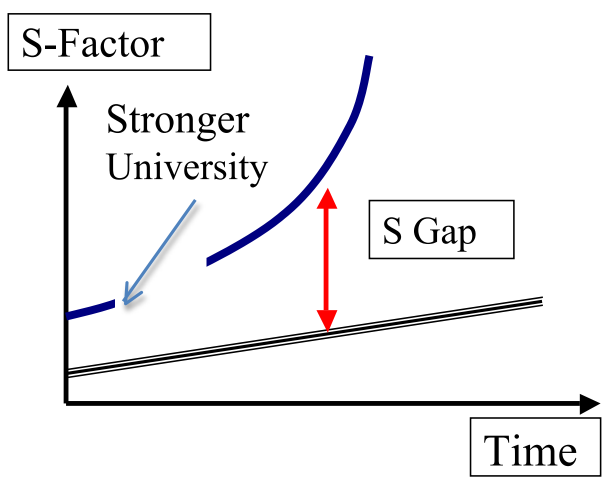


$$S = S_0(\alpha - \beta)(t - t_0) + S_0(1 + r/n)^{n(t - t_0)}$$



The S-Curve

The S Gap Increases like a "compound interest" with time unless corrective actions are taken.



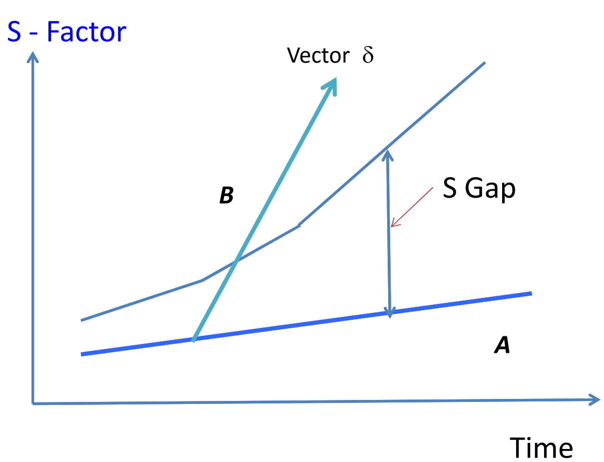
The Root Causes of the S-Gap

Root Causes of the S Gap

- More competitive students and faculty go to the leading universities.
- Resource concentration (financial gifts, funds, etc.).
- Faster growth of wealth (e.g., outstanding faculty, students, facilities, repuration, etc.) by existing wealth (ref. Capital, Piketty, 2013).
- Safety factor – joining a successful enterprise is assumed to be safe.
- Quality of life is better at richer institutions.
- More opportunities.

To become one of the best universities: Leap frogging from *A* to *B*

Vector δ Actions that may change the **history** of a university.



Two Different Examples: Vector δ

KAIST

- Strengthened the tenure system.
- Strengthened faculty by hiring 350 new young professors (from 400 in 2006) irrespective of departmental affiliation based on quality of the candidate.
- Created an inter-disciplinary research structure.
- Selected important research area in EEWS (energy, environment, water, sustainability).
- Undertook innovative projects to solve problems of the 21st century → OLEV & Mobile Harbor.
- Adopted English as the language of instruction.
- Globalized faculty and students.
- Provided opportunities to disadvantaged students.

KAIST
(The Korea Advanced Institute of Science and Technology)

- **Results**
  - **Among the top 10 most innovative university in the world**
  - **Rapid rise in ranking to 43 from 197 (?), in engineering top 20**
  - **New research direction, e.g., OLEV (On-Line Electric Vehicle), EEWS, KI**
  - **Major increase in budget and research funding**
  - **14 new buildings**
  - **Stronger faculty (to 650)**

Two Different Examples: Vector δ

MIT Mechanical Engineering

- Transformed the department for the 21st engineering, moving away from the then traditional mechanical engineering that was created to deal with automotive and power engineering.
- Hired a large number of professors who received their PhD in other disciplines (today more than 50% of the ME faculty came from other disciplines) in order to forge new mechanical engineering disciplines.
- Created new laboratories and new disciplines.
- Encouraged students to combine traditional ME with other fields.
- Raised major gifts.

Today at MIT, Mechanical Engineering Department has the largest enrollment in engineering.

Theorems

- *Coupling of the functional requirements (FRs) of the system under development is the root cause of cost-over-runs and project delays.*
- *Coupling of the functional requirements (FRs) of "social systems", e.g., universities, is the root cause of slow or no change in quality of institutions.*

Conclusions

- One of the tasks in management of technology is "system innovation and development" through ***design***.
- For aspiring research universities, the same logic used for technological innovation can be applied to make major improvements.
- The cost over-run and the long development time associated with many technology development projects can be avoided.

Thank you.

MIT-Industry Polymer Processing Program

- Identification of the problem
  - Not teaching Polymer Processing
  - Lack of research funding
  - Need industrial input on problems that need to be solved
- Defining the problem
  - Need industrial input and cooperation of a multi-disciplinary faculty team
- Defining the goal for innovation
  - Create cooperative research program with industry

MIT-Industry Polymer Processing Program

- Results
  - Industrial consortium
  - 14 companies paying up to $150K/year
  - Professors from five departments collaborating
  - A large number of graduate students, getting SM and PhD degree
  - Strong polymer related research in the ME Dept
  - NSF support

MIT Laboratory for Manufacturing and Productivity

- **Identification of the problem**
  - US Trade balance (negative)
  - No teaching and limited research in mfg
  - No teaching programs in mfg
- **Defining the problem**
  - Lack of science base in mfg and design
  - Strong competition from overseas
  - Lack of organization
- **Defining the goal for innovation**
  - Create science base for design and mfg
  - Establish a strong inter-departmental effort

NSF Engineering Directorate

- **Identification of the problem**
  - Lack of clear goals and mission
  - Not fulfilling the mission given by the U.S. NSF Act
  - Support for past excellence
  - No support for young researchers
  - No programs for emerging areas
  - Small budget
  - Poor visibility for ENGINEERING in Washington
- **Defining the problem**
  - Wrong direction and programs
- **Defining the goal for innovation**
  - New direction and new programs

NSF Engineering Directorate

- Results
  - New direction
  - New programs
  - Increased funding
  - Support for young people
  - ERC
  - Merit based funding
  - Support for new fields
  - Etc.

Impact of MIT and KAIST Research

- Basic design research – Axiomatic Design
- Solving important problems of humanity
- EEWS
- Systems research
- Example: OLEV (On-Line Electric Vehicle)

Examples of Technical Systems with Problems of Cost Over-runs and Delays:

Having taught many engineers in some of these companies indicate that they execute the projects, including design and implementation, based on their experience, followed by modeling and optimization afterwards.

- If they ***create a coupled system*** in making design decisions at any level of design hierarchy, modeling and optimization techniques will not create a reliable and robust system.

Examples of some Highly Innovative Technical Systems that were completed on time and within budget.

Example of Coupling of FRs

Suppose the system you are designing must satisfy three (3) functional requirements, FR1, FR2, FR3.

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} A_{11} A_{12} A_{13} \\ A_{21} A_{22} A_{23} \\ A_{31} A_{32} A_{33} \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix}$$

Is anything wrong with this design?

Yes, it is a coupled design if all of the off-diagonal elements of the design matrix are non-zero.

Things get worse if the highest level design has to be decomposed.

Suppose you came up with a design that requires a second-level decomposition, e.g., FR1 as follows:

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \end{Bmatrix} = \begin{bmatrix} abc \\ def \\ ghi \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \end{Bmatrix}$$

Is anything wrong with this design?

Example of Uncoupled FRs

If you design the system where FRs are independent from each other, by choosing DPs properly, i.e.,

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} a00 \\ 0b0 \\ 00c \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix}$$

This design is much simpler to implement and thus, the product becomes highly reliable, because it satisfies the Independence Axiom.

The Independence Axiom:
Maintain the independence of FRs