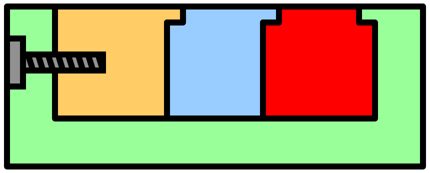
Design for product embedded disassembly

Shingo Takeuchi and Kazuhiro Saitou
Department of Mechanical Engineering
University of Michigan, Ann Arbor



Outline

- Introduction
- Related work
- Method
- Case study
- Summary
- Future work

Introduction

- **Throwaway society**

Introduction

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Introduction

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Introduction

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Introduction

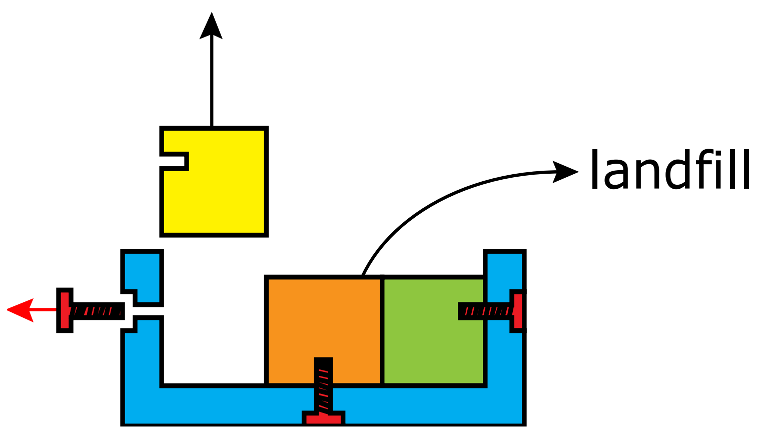
- **Throwaway society – why?**
  - Lack of economical incentive for eco-friendly products
  - Lack of customer awareness
  - Lack of government regulation
- **All these are changing....**
  - Limited resource: From throw away society to sustainable society
  - Eco-friendliness became an factor of customer preference
  - Increased government regulation on eco-responsibility
  - Improved recycling/reuse technology

Introduction

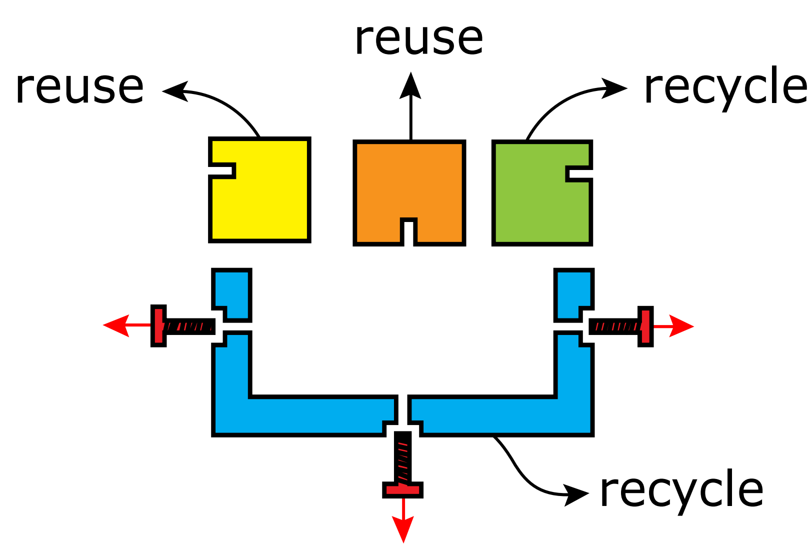
- **Reduce, recycle, reuse (R^3)**

Introduction

- **End-of-life (EOL) scenario: economical or environmental?**



vs.



Economically

Environmentally

Economically

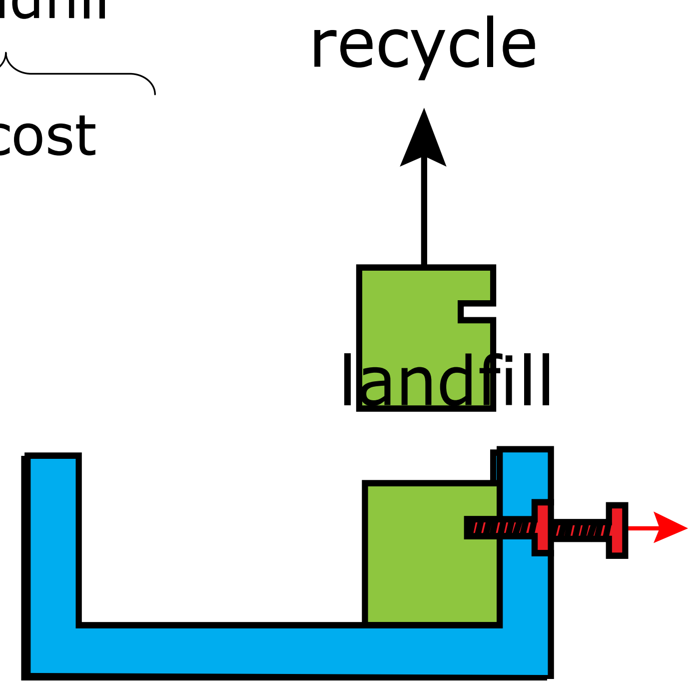
Environmentally

Introduction

- **Recycle or landfill: which is more economical?**

$$\underbrace{\text{revenue - cost}}^{\text{Recycle}} \gtrless \underbrace{\text{- cost}}^{\text{Landfill}}$$

- separation
- cleaning
- shredding
- ⋮
- disassembly

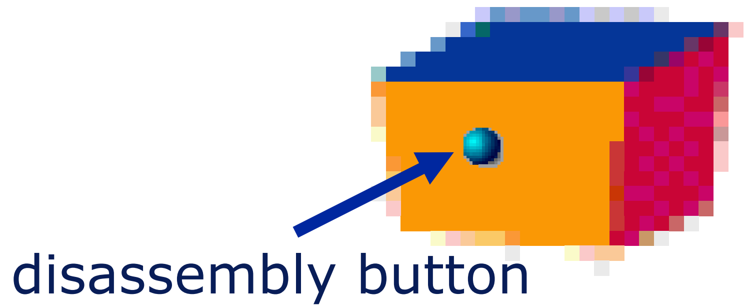


Introduction

- **Disassembly**
  - Not all parts are precious: “gold mining”
  - Should stop if labor cost > revenue
  - Labor intensive – cost depends on
    - Disassembly sequence
    - Spatial configurations of components
    - Spatial configurations and types of fasteners

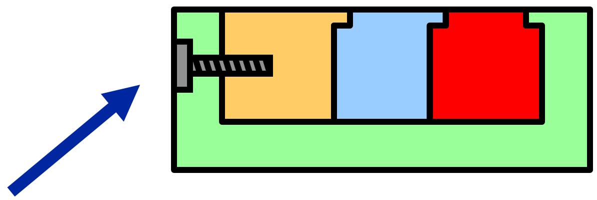
Introduction

- **Product embedded disassembly: idea**
  - Design products with a built-in disassembly means and activate when disassembly is necessary
  - Can reduce disassembly labor cost – just activate it!
  - No need to know which part to remove first – just activate it!



Introduction

- **Product embedded disassembly: embodiment**
  - Utilization of locators (e.g., catches, tracks) integral to components
  - Self-disintegration of the assembly, much like a domino effect
  - Can dramatically reduce the number of fasteners



“disassembly button”

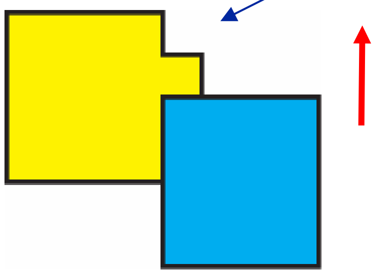
Related work

- **Design for Disassembly**
  - Navinchandra et al. (1991), Boothroyd et al (1992), Harjula et al. (1996), Kroll et al. (1996), Hiroshige et all (1997), Matsui et al. (1999), O'Shea et al. (1999), Das et all (2000, 2002), Reap and Brass (2002), Desai et all (2003), Sodhi et all (2004), Nizar et al (2004)
- **(Dis)assembly Sequence Planning**
  - de Fazio et al (1987), dé Mello et al (1990, 1991), Lee et all (1990), Baldwin et al (1991), Subramani et all (1991), Woo et al (1991, 1995), Zussman et all (1994), Kaufman et al (1996), Chen et al (1997), Lambert (1997), Kuo (2000), Srinivasan et all (2001), Dini et al (2001), Seo et al (2001), Li et al (2002), Chung et al (2005)
- **Configuration Design Problem**
  - Corcoran et al (1992), Fujita et al (1996), Kolli et al (1996), Grignon (1999), Jain et al (1998), Fadel et al (2001), Grignon (2004), Grangeon et al (2005)
- **Life Cycle Assessment**
  - Aanstoos et al (1998), Goggin et al (2000), Rose et al (2001), Caudill et al (2002), Williams et al (2003), Kuehr et al (2003), Hula et al (2003), Kuo et al (2005)

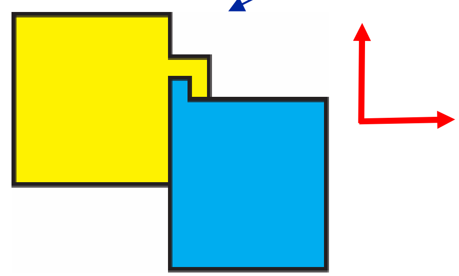
Method

- **Locators**
  - Geometric feature of a component for constraining its relative DOF in an assembly

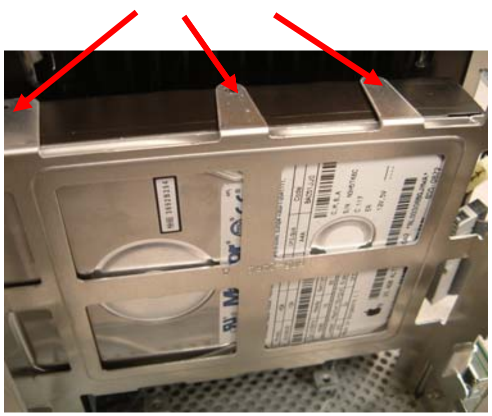
catch



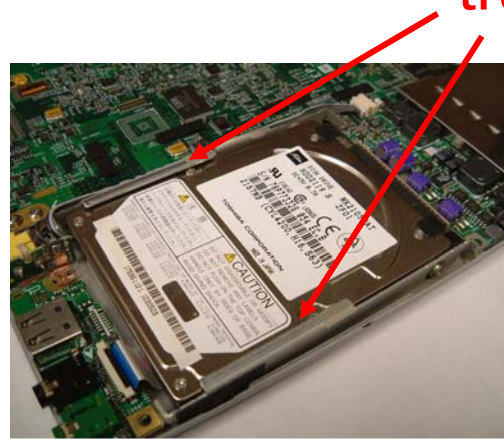
track



catch



track

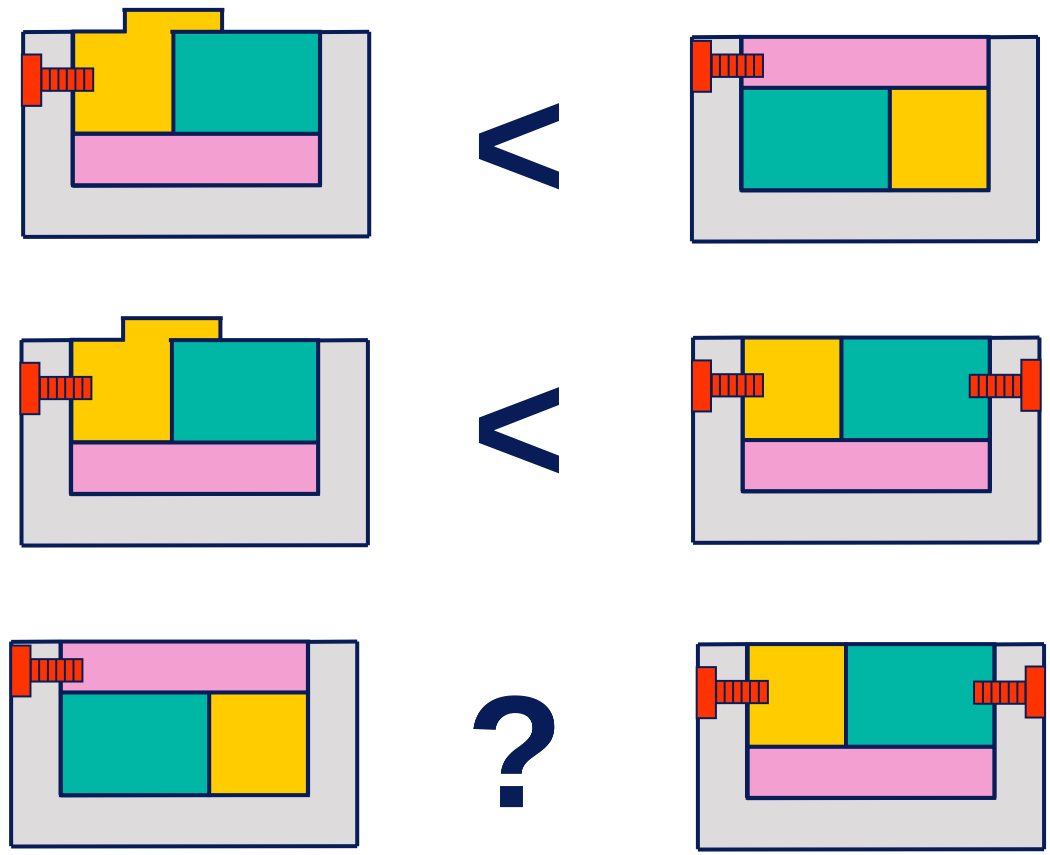


Method

- **Cost of disassembly depends on:**
  - Spatial configurations of components in a bin
  - Spatial configurations and types of locators on each component
  - Spatial configurations of fasteners (assume as unique type)
- **Bad news:**
  - They depend on each other! → need simultaneous decision to minimize disassembly cost

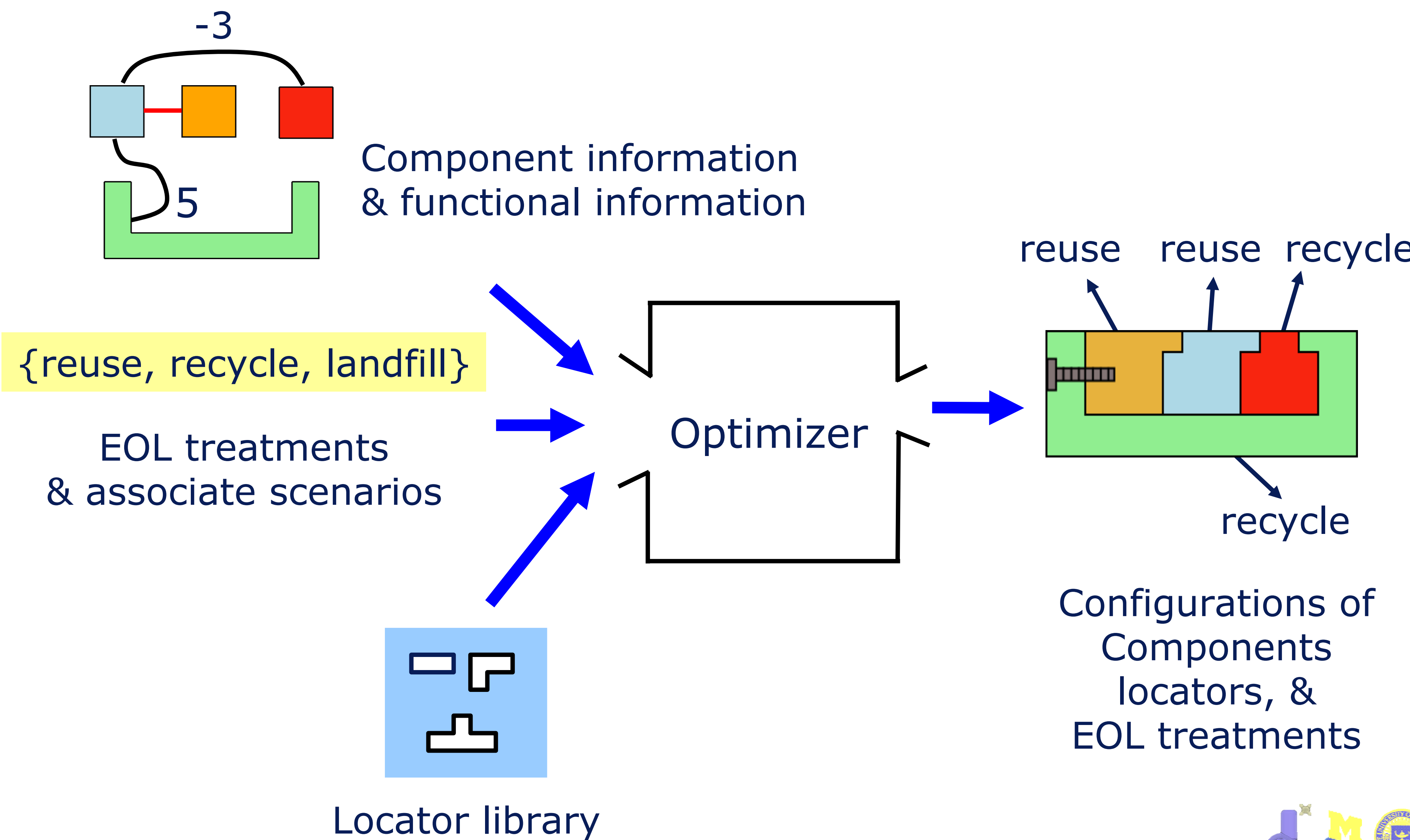
Method

- **Cost of disassembly**
  - Depends on configuration of component, locators, & fasteners
  - If  is valuable and  is toxic (must retrieve),



Method

Overview

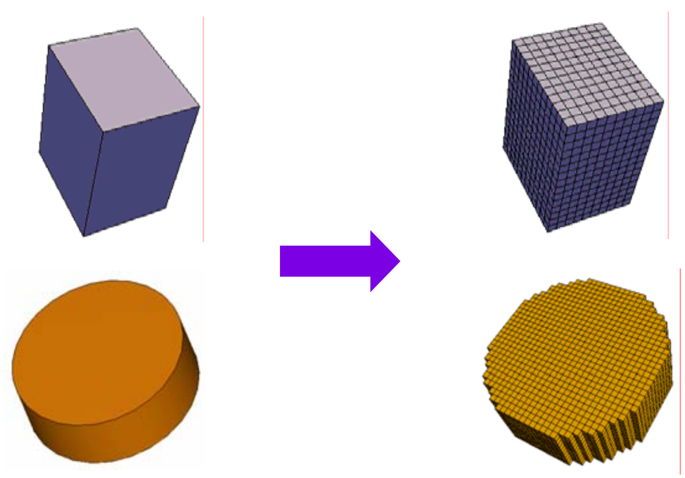


Method

- **Given:**
  - Component information, Contact & Distance specifications, Components to be retrieved, Locator library, and EOL treatments & associate scenarios
- **Find:**
  - Spatial configurations of components, locators and fasteners
  - EOL treatments
- **Subject to:**
  - No overlap among components, No unfixed component prior to disassembly, Satisfaction of contact specification, Assemblability of components
- **Minimizing:**
  - Violation of distance specification among components
  - Manufacturing difficulty increased by adding locators
  - Environmental Impact of EOL scenario
- **Maximizing:**
  - Profit of EOL scenario

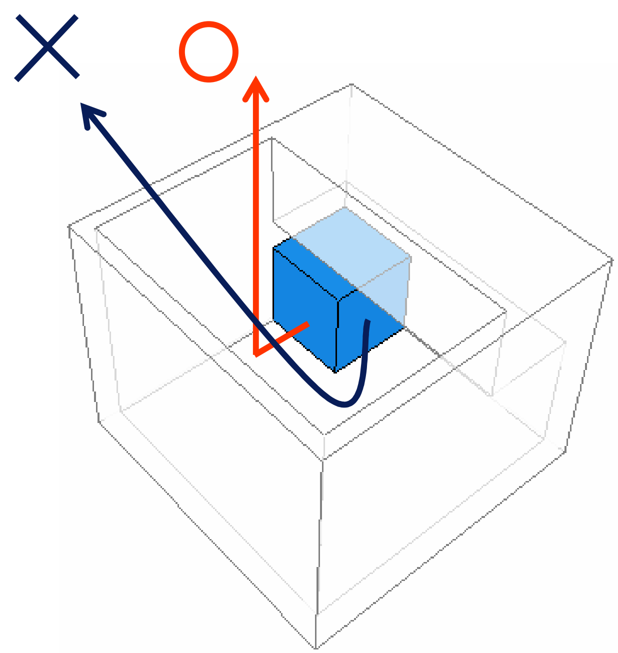
Method

- **Inputs**
  - Component information
    - Geometry (voxel representation)
    - Weights
    - Materials
    - Reuse values
    - Translations (±x, ±y, ±z) only, no rotation during disassembly



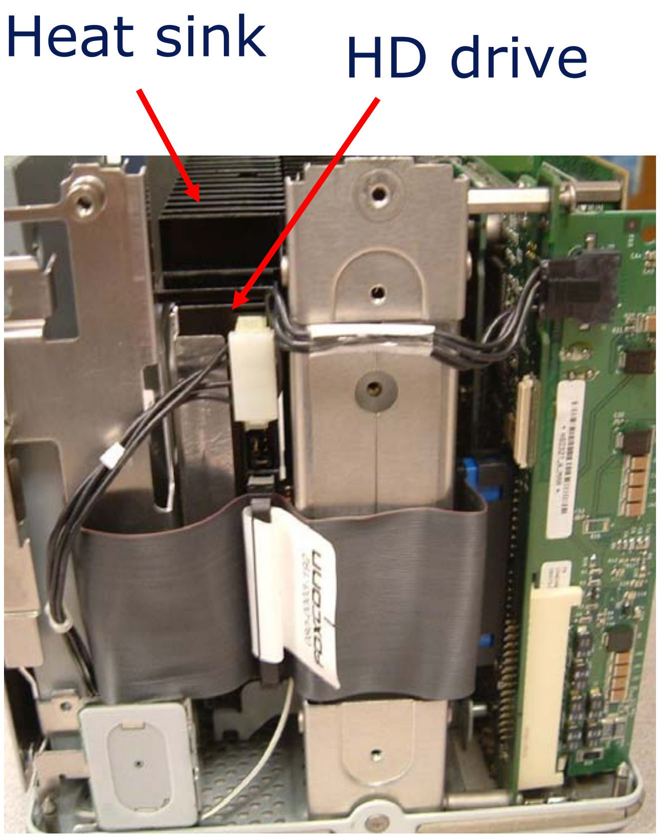
CAD data

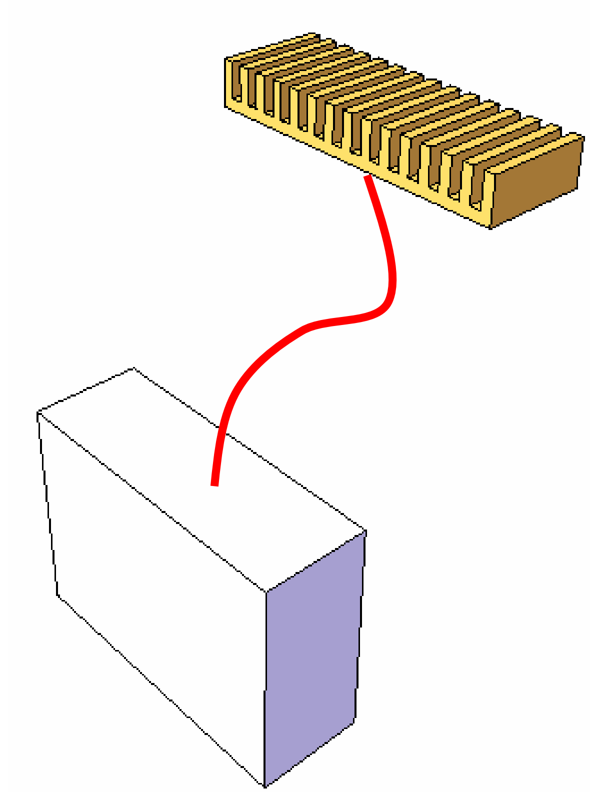
voxelized data



Method

- **Inputs**
  - Contact specification
    - A set of pairs of components requiring adjacency to each other



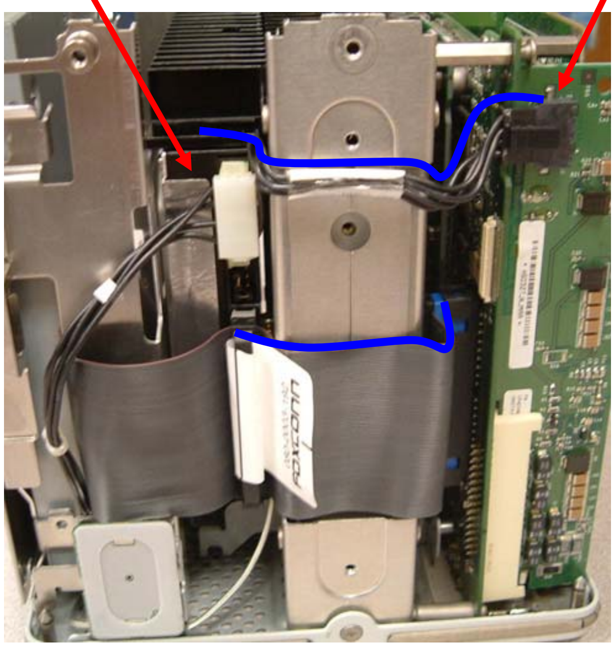


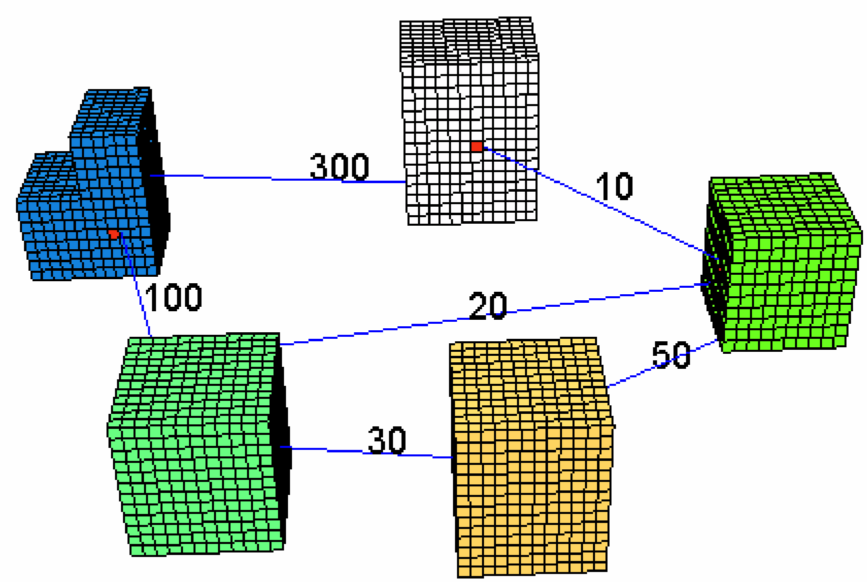
Method

- **Inputs**
  - Distance specification
    - A set of the weights of importance for the distances between two components for product function

HD drive

Mother board





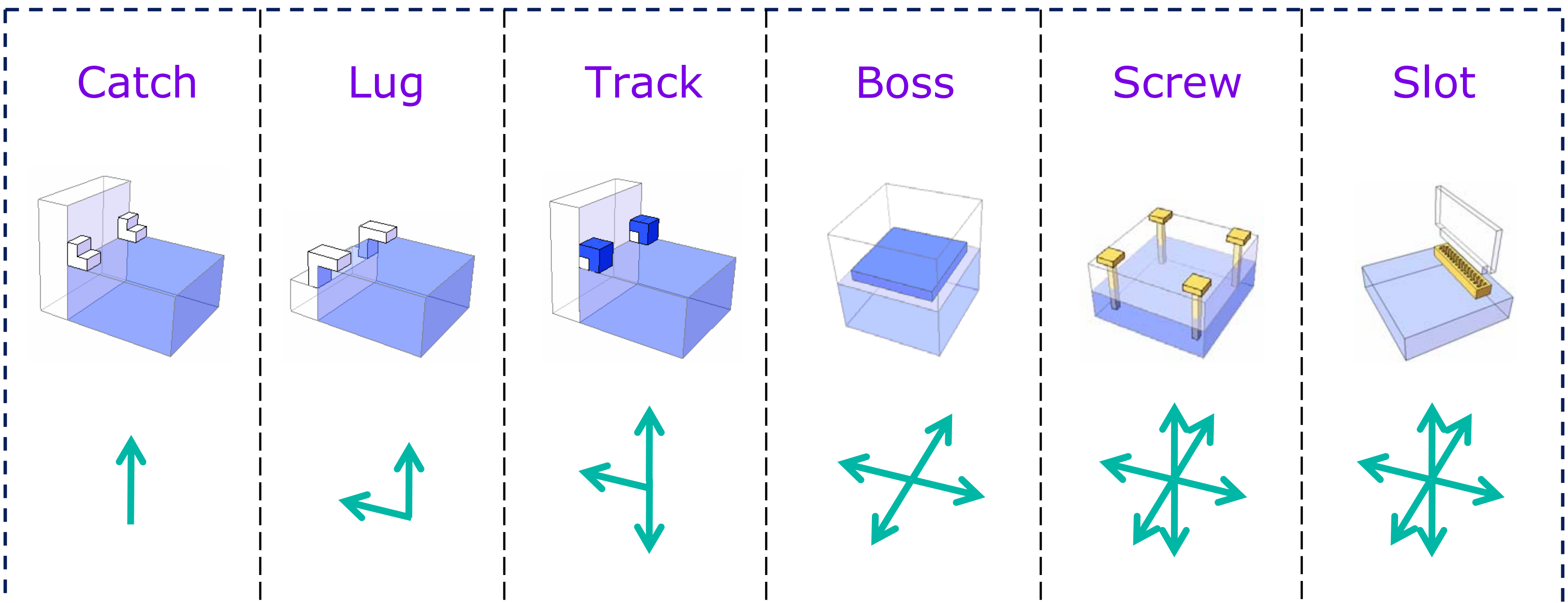
Method

- **Inputs**
  - Components to be retrieved
    - Regulated components that must be retrieved

Method

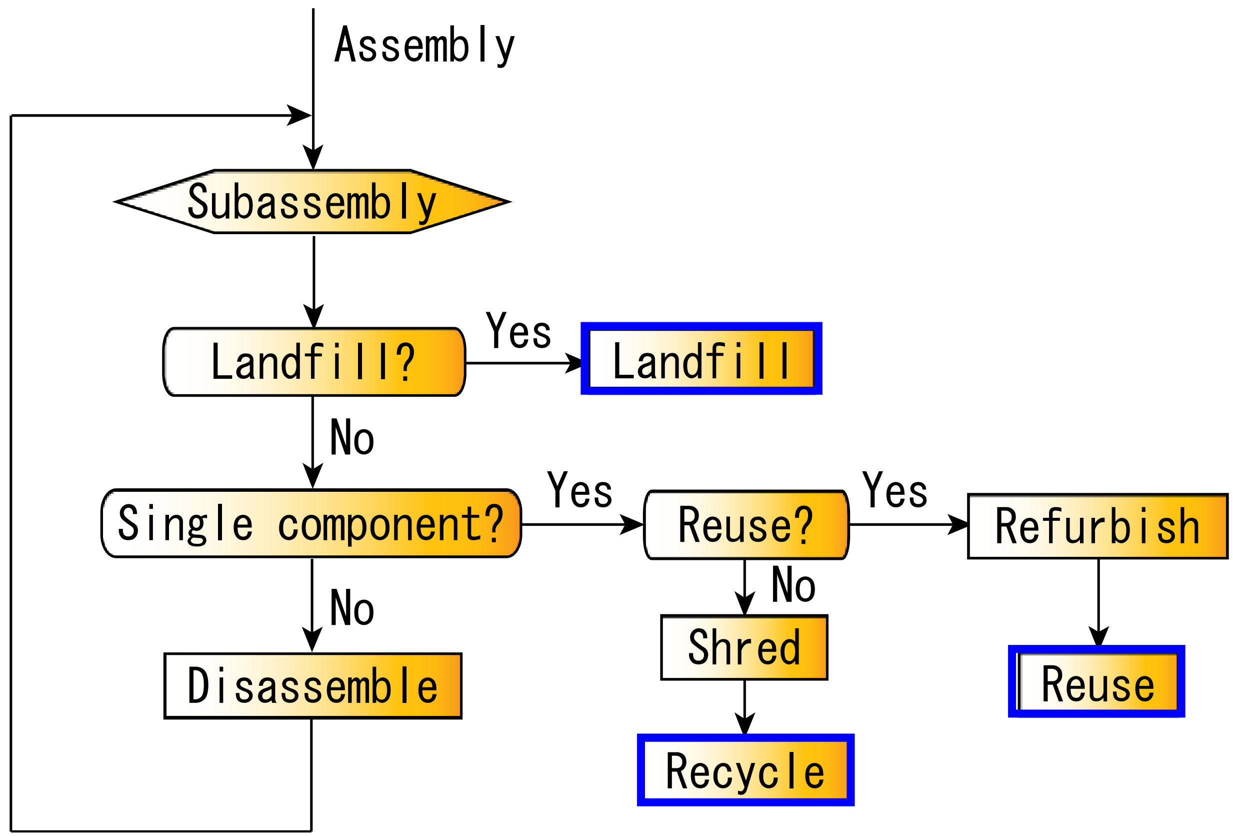
Locator library

- Id
- Parametric geometry
- Attachment rules
- Constraining direction wrt local coordinates



Method

- **Inputs**
  - EOL treatments & associated scenarios



Method

Design variables

$$\boldsymbol{x} = (x_0, x_1, \ldots, x_{n-1})$$
$$x_i = (t_i, r_i, \boldsymbol{d}_i)$$
$$\boldsymbol{d}_i = (d_0, d_1, \ldots, d_{f-1})$$

- t_i = translation of the *i*-th component wrt a global reference frame
- r_i = rotation of the *i*-th component wrt a global reference frame
- d_j = offset values of the *j*-th face of the *i*-th component in the normal direction

Method

- **Design variables**

$$\boldsymbol{y} = (\boldsymbol{y}_0, \boldsymbol{y}_1, \ldots, \boldsymbol{y}_{m-1})$$
$$\boldsymbol{y}_i = (CD_i, p_i)$$

  - $m = n(n-1)/2$ = number of pairs of components in assembly
  - CD_i = set of directions in which component c_0 of the *i*-th pair (c_0, c_1) is to be constrained
  - p_i = sequence in which locators are tested during the construction of the *i*-th pair

Method

Design variables

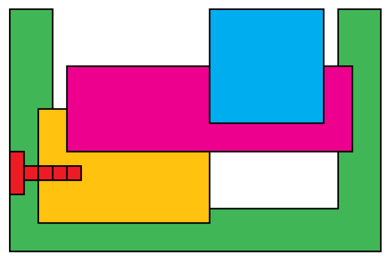
$$\mathbf{z} = (\mathbf{z}_0, \mathbf{z}_1, \ldots, \mathbf{z}_{n-1})$$

- z_i = end of life treatment {reuse, recycle, landfill} of the *i*-th component

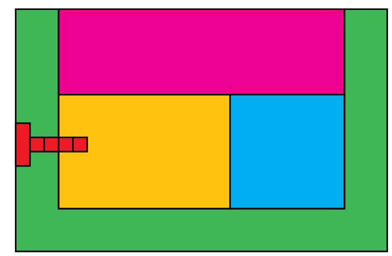
Method

Constraints

- No overlap among components

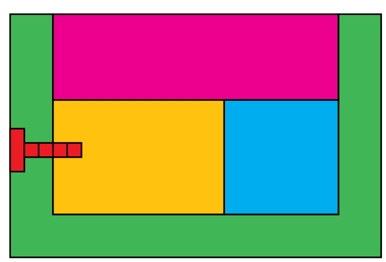


infeasible

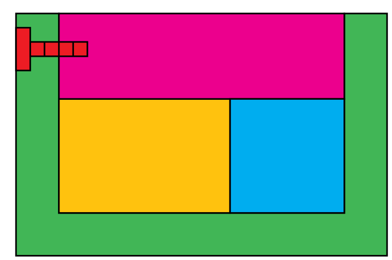


feasible

- No unfixed component prior to disassembly



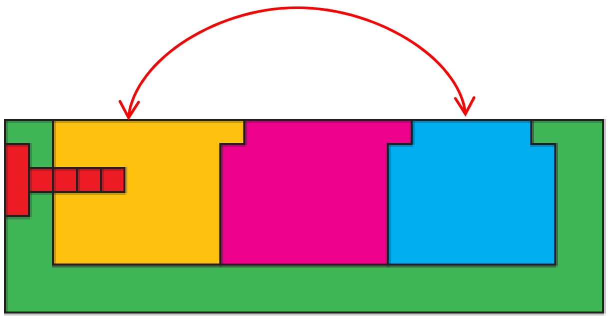
infeasible



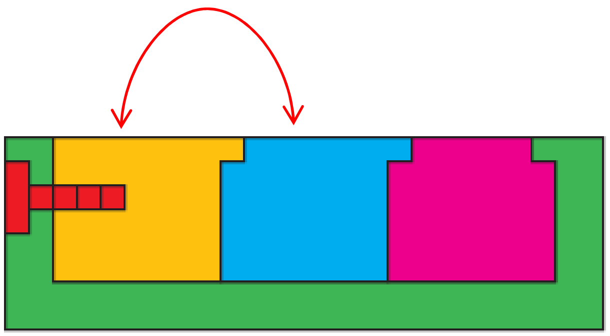
feasible

Method

- **Constraints**
  - Satisfaction of contact specification

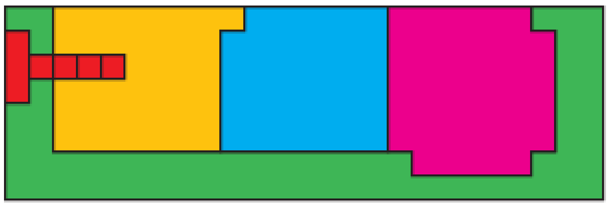


infeasible

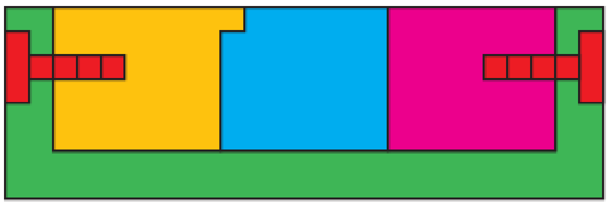


feasible

  - Assembleability of components



infeasible



feasible

Method

Objective functions

- Violation of distance specification (to be minimized)

$$f_{distance}(\mathbf{x}, \mathbf{y}) = \sum_i w_i \times \mathrm{distance}_i$$

- Manufacturing difficulty of locators (to be minimized)

$$f_{difficulty}(\mathbf{x}, \mathbf{y}) = \sum_i c_i$$

- Profit of EOL scenario (to be maximized)

$$f_{profit}(\mathbf{x}, \mathbf{y}, \mathbf{z}) = \sum_{i=0}^{n-1} p_i(z_i) - c^*(\mathbf{x}, \mathbf{y}, \mathbf{z})$$

- Environmental impact of EOL scenario (to be minimized)

$$f_{env}(\mathbf{z}) = \sum_i e_i(z_i)$$

Method

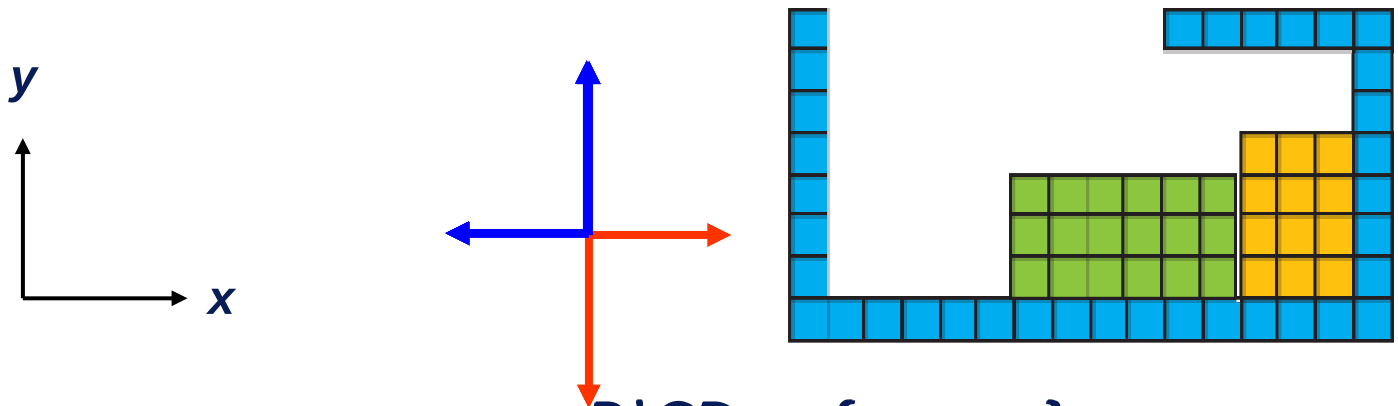
- **Disassembly cost**

  $c(x, y, z)$ = labor cost [$/h] * disassembly time [h]

- **Disassembly time is estimated based on:**
  - Number and accessibility of fasteners
  - Disassembly motion
    - Number of orientation changes
    - Total traveling distance
  - Disassembly time = ∞ if not 2-disassembleable

Method

- **2-disassemblability check (Beasley et at., 1993)**
  - Six translational motions {±x, ±y, ±z} only, no rotational motions during disassembly
  - Illustration with 2D: D = {-x, +x, -y, +y}

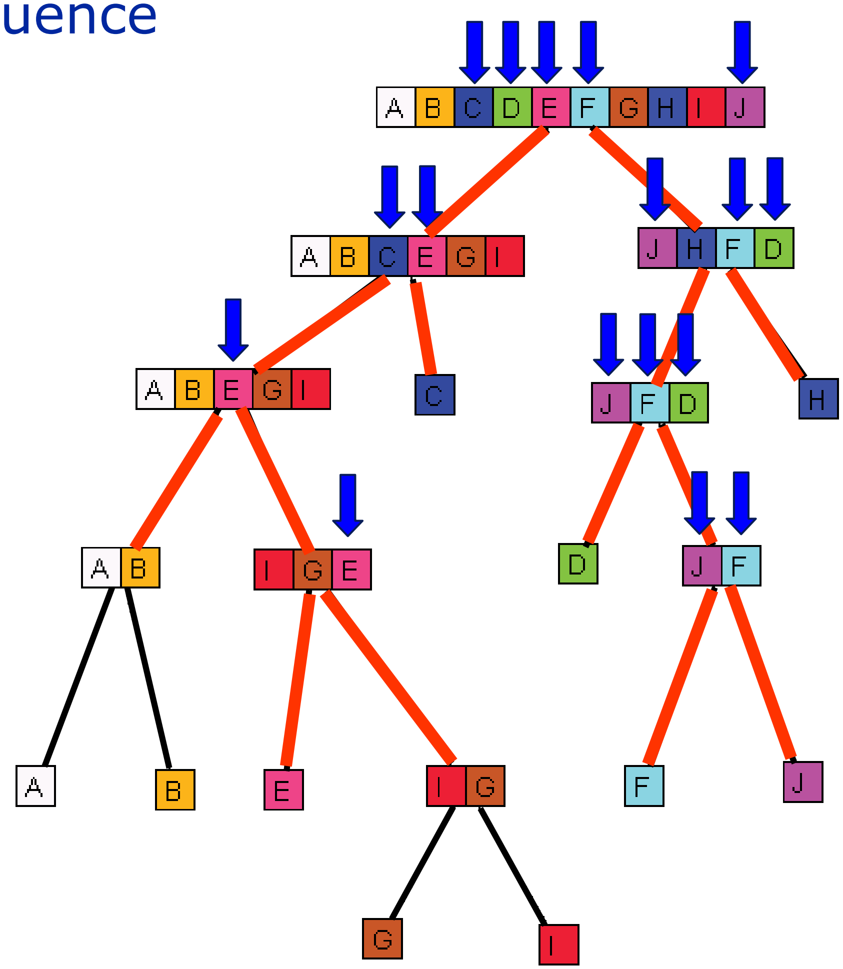


$D \backslash CD = \{+x, +y\}$

return TRUE (2-disassemblable)

Method

- **Minimum disassembly cost (c*(x, y, z))**
  1. Construct AND/OR graph (2-disassemblability criterion)
  2. Find the most efficient sub-sequence for each sequence
  3. Choose the best sub-sequence
- **Example:**
  - A, B, G, H, I → landfill
  - C, E → reuse
  - D, F, J → recycle



Method

- **Environmental impact of EOL scenario**
  - Energy consumption as the indicator for environmental impact (Hula et al., 2003)
  - Profit

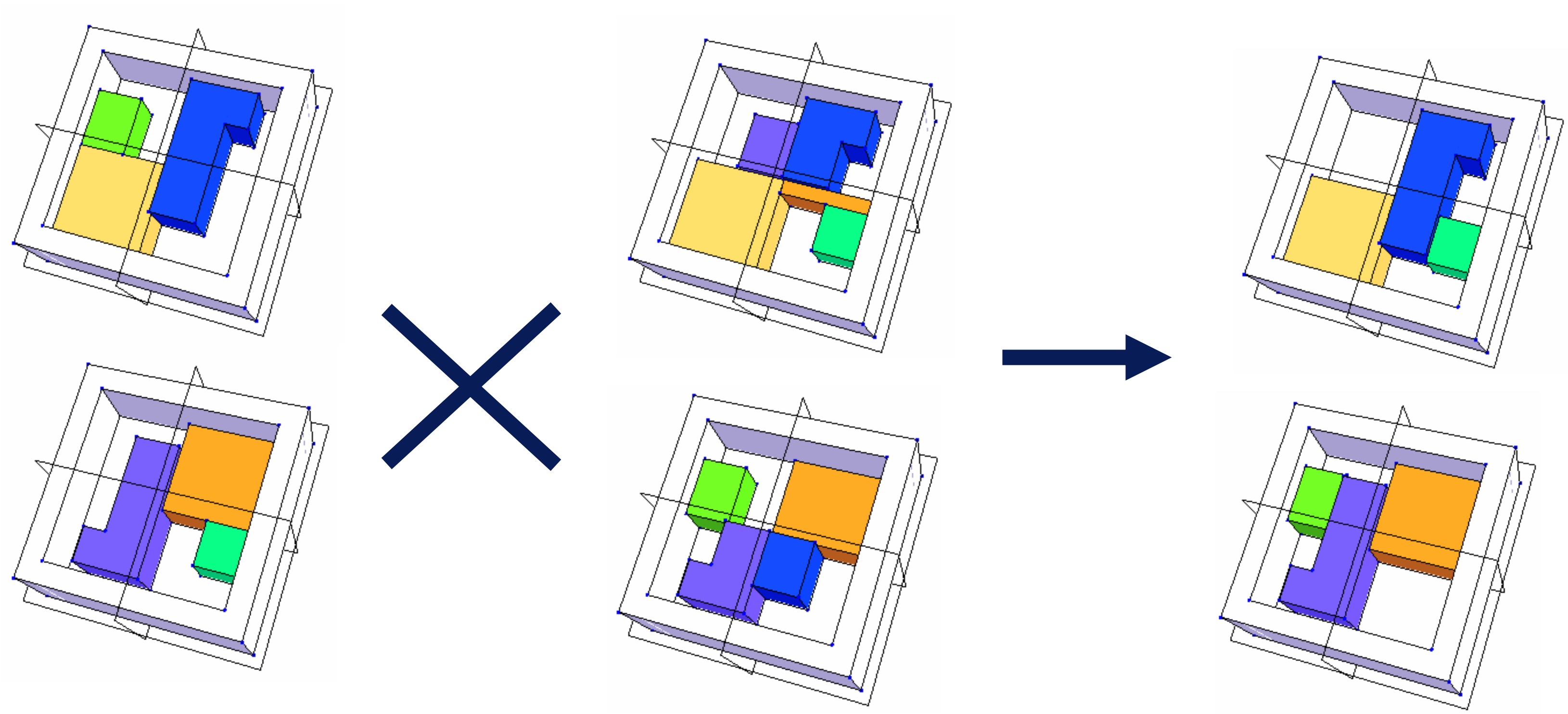
$$p_i(z_i) = \begin{cases} r_i^{reuse} - c_i^{trans} - c_i^{refurb} & \text{if } z_i = \text{reuse} \\ r_i^{recycle} - c_i^{trans} - c_i^{shred} & \text{if } z_i = \text{recycle} \\ -c_i^{trans} - c_i^{landfill} & \text{if } z_i = \text{landfill} \end{cases}$$

  - Energy consumption

$$e_i(z_i) = \begin{cases} e_i^{reuse} + e_i^{trans} + e_i^{refurb} & \text{if } z_i = \text{reuse} \\ e_i^{recycle} + e_i^{trans} + e_i^{shred} & \text{if } z_i = \text{recycle} \\ e_i^{landfill} + e_i^{trans} & \text{if } z_i = \text{landfill} \end{cases}$$

Method

- **Optimization algorithm**
  - NSGA-II with geometry-based crossover

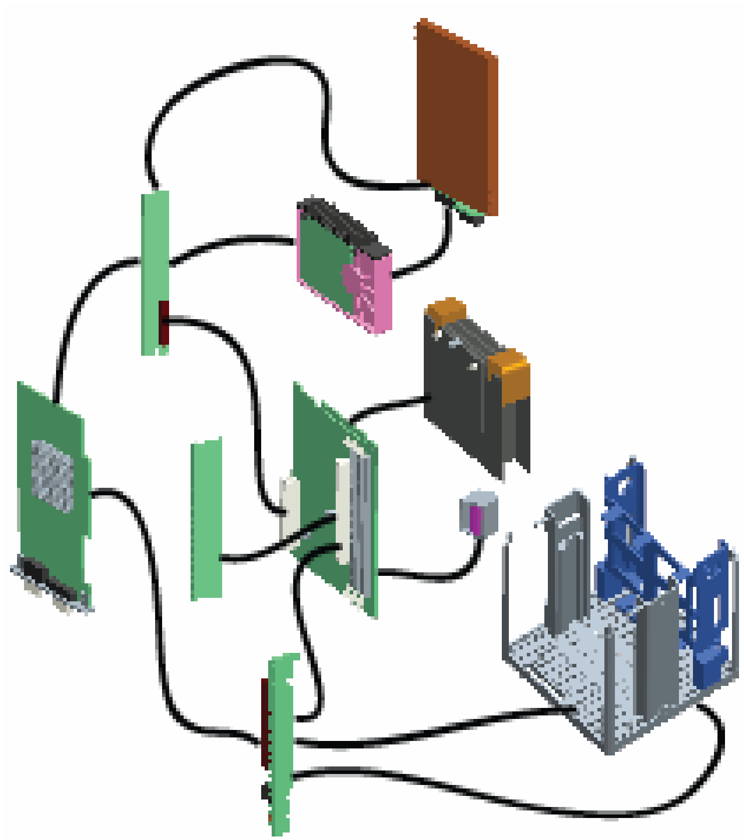


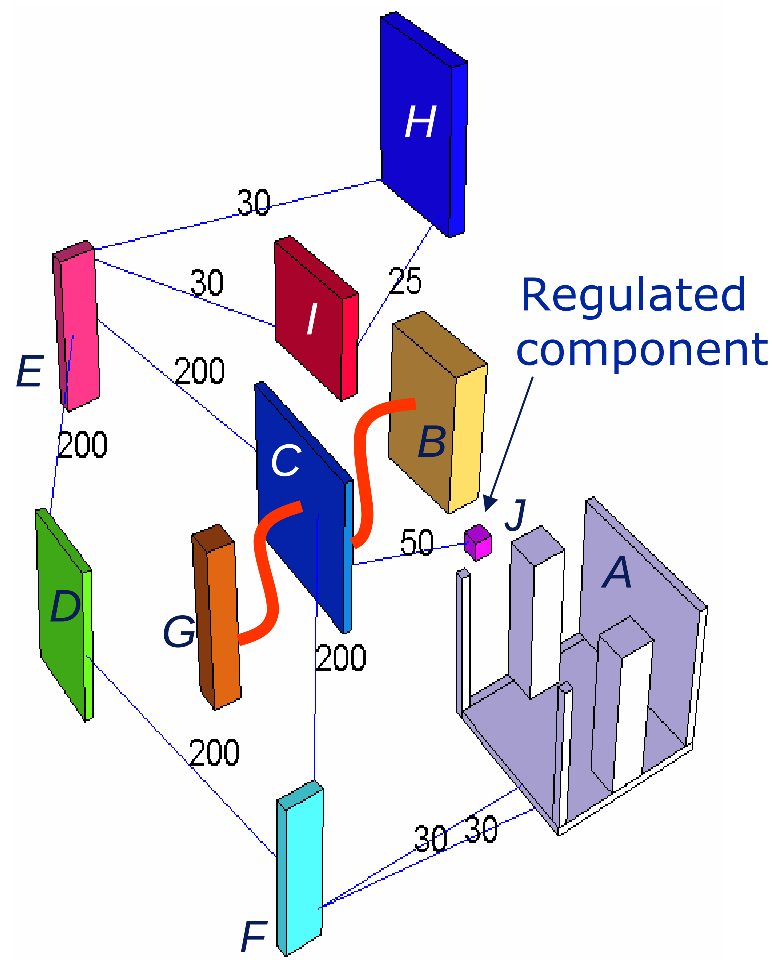
Case study

- **Power Mac G4 cube ®**

Case study

- **Component information**





Case study

Material composition [kg]

Component	Al	Steel	Cu	Gold	Silver	Tin	Lead	Cobalt	Li	Total
A (frame)	1.2	0	0	0	0	0	0	0	0	1.2
B (heat sink)	0.6	0	0	0	0	0	0	0	0	0.60
C (circuit board)	1.5e-2	0	4.8e-2	7.5e-5	3.0e-4	9.0e-3	6.0e-3	0	0	0.30
D (circuit board)	1.0e-2	0	3.2e-2	5.0e-5	2.0e-4	6.0e-3	4.0e-3	0	0	0.20
E (circuit board)	4.0e-3	0	1.3e-2	2.0e-5	8.0e-5	2.4e-3	1.6e-3	0	0	8.0e-2
F (circuit board)	5.0e-3	0	1.6e-2	2.5e-5	1.0e-4	3.0e-3	2.0e-3	0	0	0.10
G (RAM)	2.0e-3	0	6.4e-3	2.0e-5	4.0e-5	1.2e-3	8.0e-4	0	0	4.0e-2
H (CDD)	0.25	0.25	0	0	0	0	0	0	0	0.50
I (HDD)	0.10	0.36	6.4e-3	1.0e-5	4.0e-5	1.2e-3	8.0e-4	0	0	0.50
J (battery)	8.0e-5	0	1.4e-3	0	0	0	0	3.3e-3	4.0e-3	2.0e-3

Case study

Material information

Material	Energy intensity [MJ/kg]	Recovered energy [MJ/kg]	Material value [$/kg]
Aluminum	2.1e2	1.4e2	0.98
Steel	59	19	0.22
Cupper	94	85	1.2
Gold	8.4e4	7.5e4	1.7e4
Silver	1.6e3	1.4e3	2.7e2
Tin	2.3e2	2.0e2	6.2
Lead	54	48	1.0
Cobalt	8.0e4	6.0e4	38
Lithium	1.5e3	1.0e3	7.5

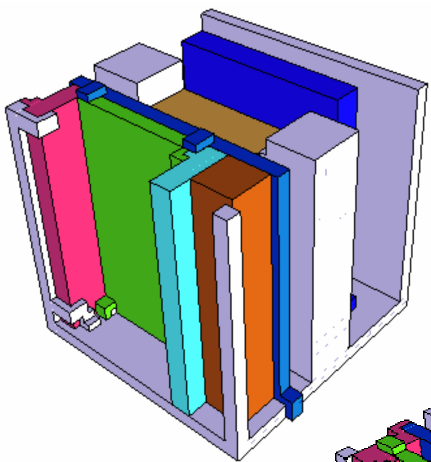
Case study

- **Revenue [$], cost [$] and energy consumption [MJ]**

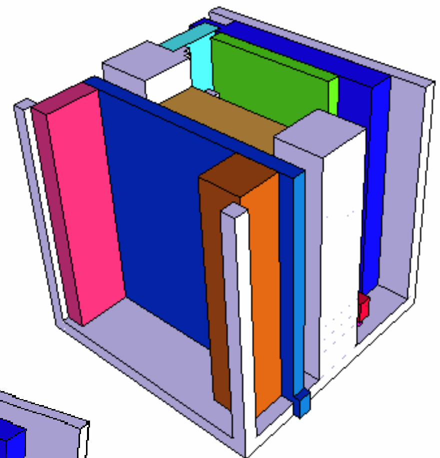
	A (frame)	B (heat sink)	C (circuit board)	D (circuit board)	E (circuit board)	F (circuit board)	G (RAM)	H (CDD)	I (HDD)	J (batt.)
r_i^{reuse}	N/A	N/A	3.5e2	80	1.3e2	39	57	40	60	5.0
$r_i^{recycle}$	1.2	0.60	1.5	1.0	0.39	0.49	0.36	0.30	0.37	0.12
c_i^{trans}	0.25	0.12	6.2e-2	4.1e-2	1.7e-2	2.1e-2	8.3e-3	0.10	0.10	4.1e-3
c_i^{refurb}	N/A	N/A	1.8e2	40	65	20	29	20	30	2.5
c_i^{shred}	0.14	7.2e-2	3.6e-2	2.4e-2	9.6e-3	1.2e-2	4.8e-3	6.0e-2	6.0e-2	2.4e-3
$c_i^{landfill}$	2.4e-2	1.2e-2	6.0e-3	4.0e-3	1.6e-3	2.0e-3	8.0e-4	1.0e-2	1.0e-2	4.0e-4
e_i^{reuse}	-2.6e2	-1.3e2	-17	-12	-4.5	-5.6	-3.1	-68	-45	-2.6e2
e_i^{trans}	1.4	0.70	0.35	0.23	9.4e-2	0.12	4.7e-2	0.59	0.59	2.3e-2
e_i^{refurb}	2.7	1.3	0.66	0.44	0.18	0.22	8.8e-2	1.1	1.1	4.4e-2
$e_i^{recycle}$	-170	-84	-14	-9.5	-3.8	-4.8	-2.7	-40	-23	-2.0e2
e_i^{shred}	1.2	0.60	0.30	0.20	8.0e-2	0.10	4.0e-2	0.50	0.50	2.0e-2
$e_i^{landfill}$	2.4e4	1.2e4	6.0e3	4.0e3	1.6e3	2.0e3	8.0e2	1.0e4	1.0e4	4.0e2

Case study

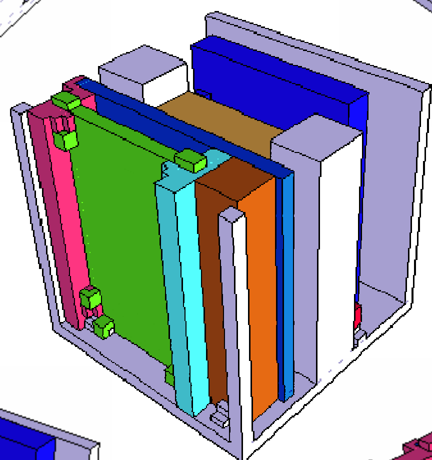
- **Representative optimal designs R1 – R5**



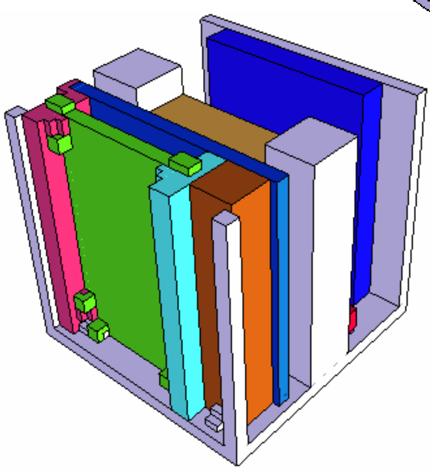
R_1



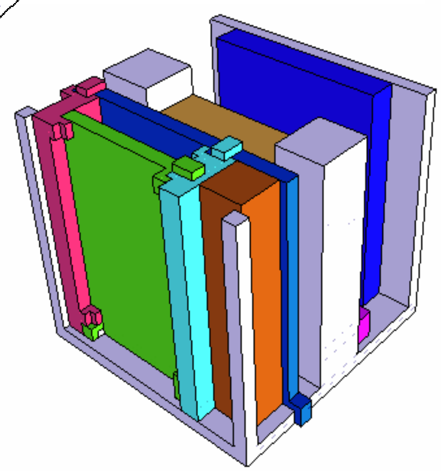
R_2



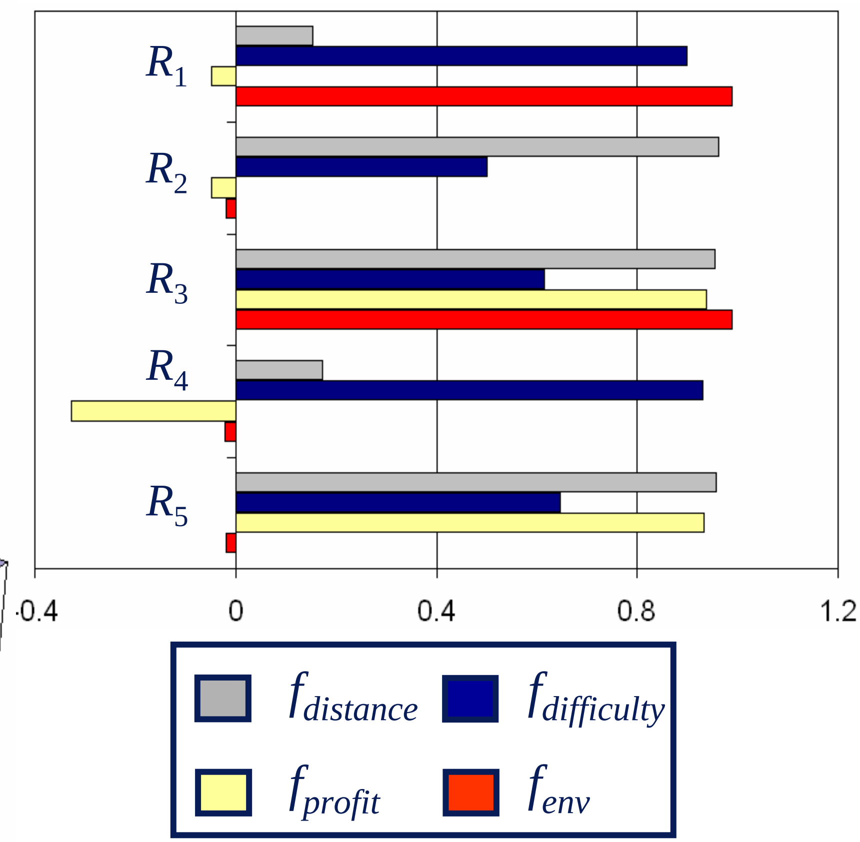
R_3



R_4

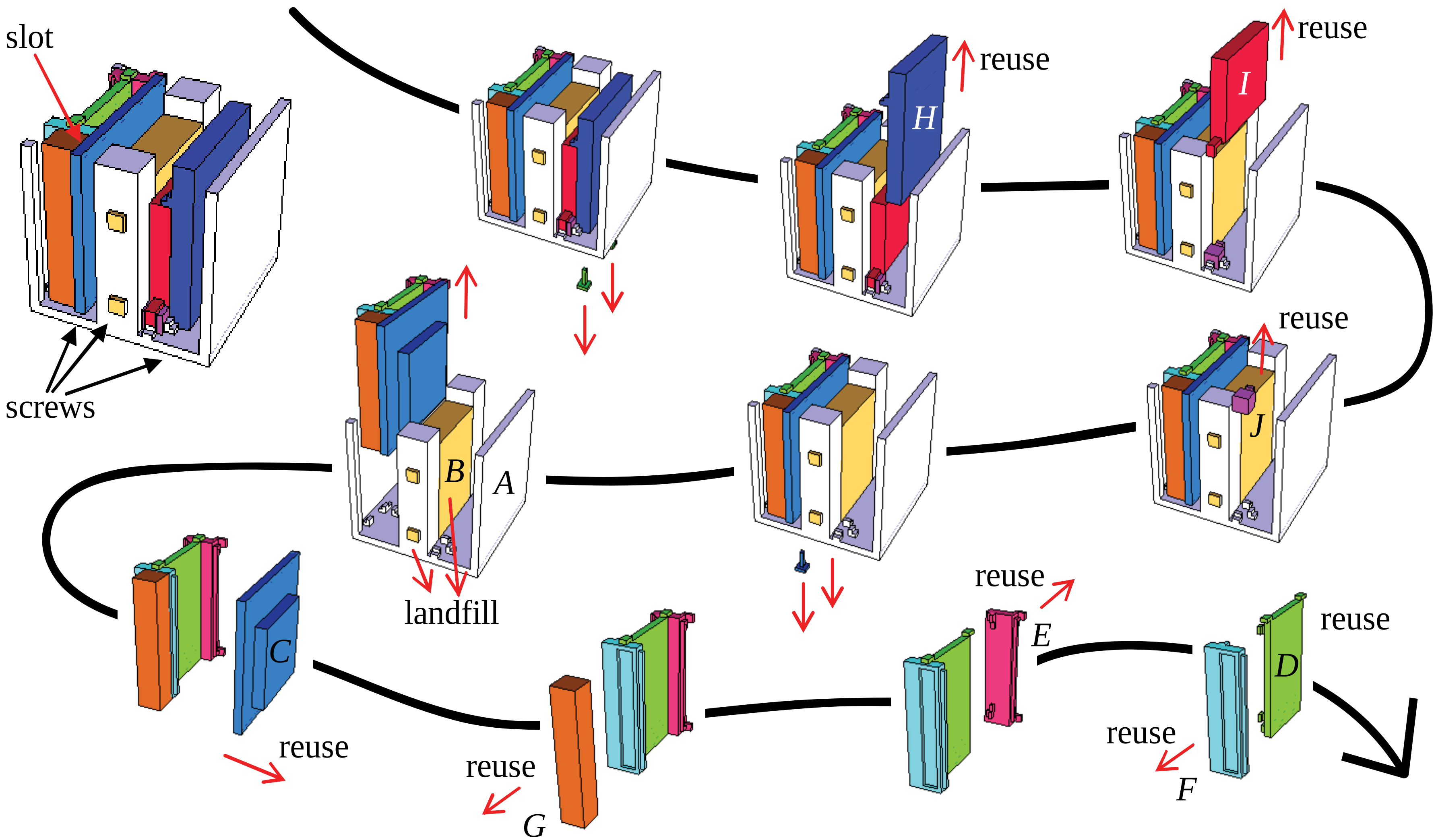


R_5



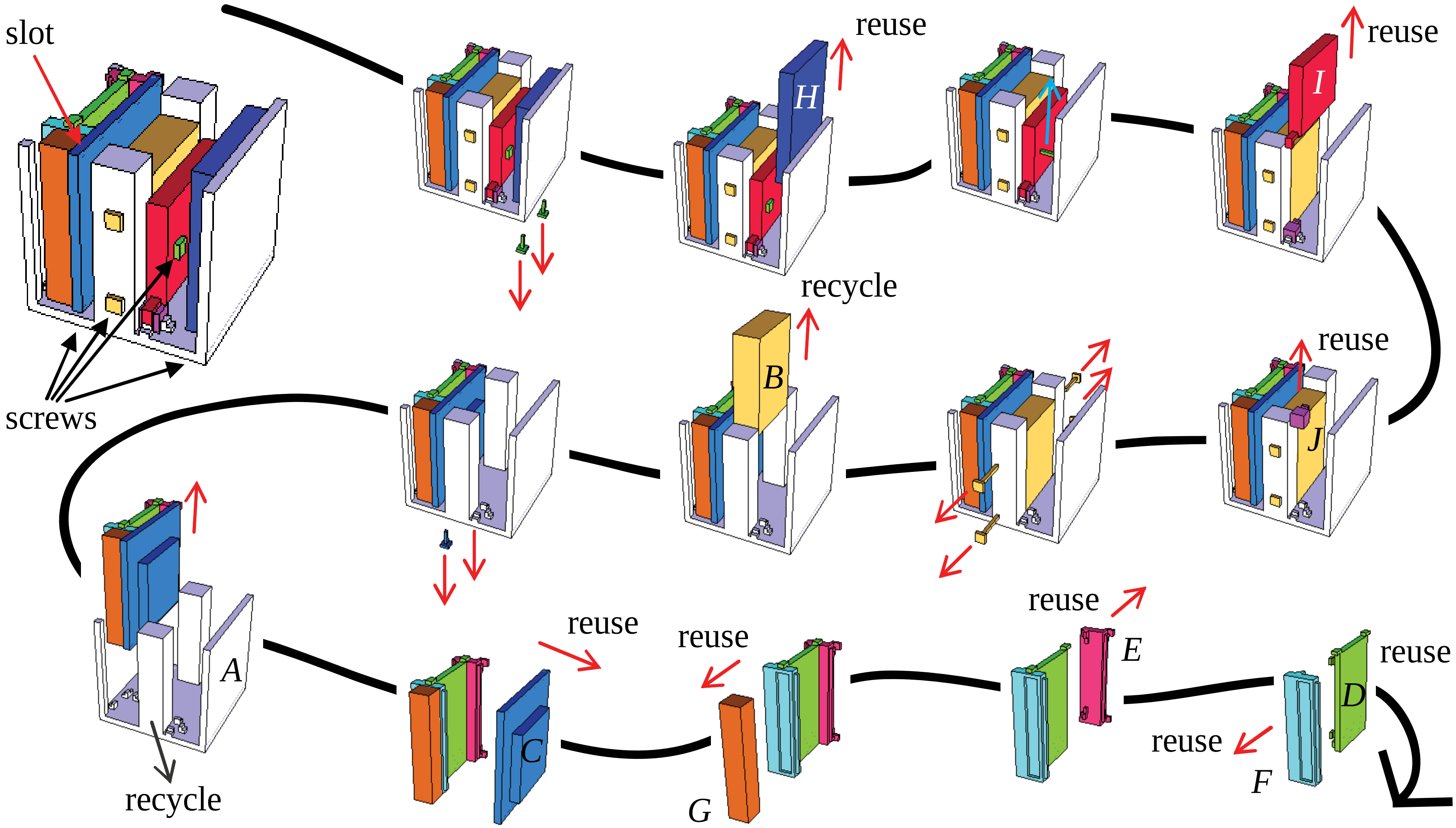
Case study

- **Optimal sequence of R3 with EOL treatments**



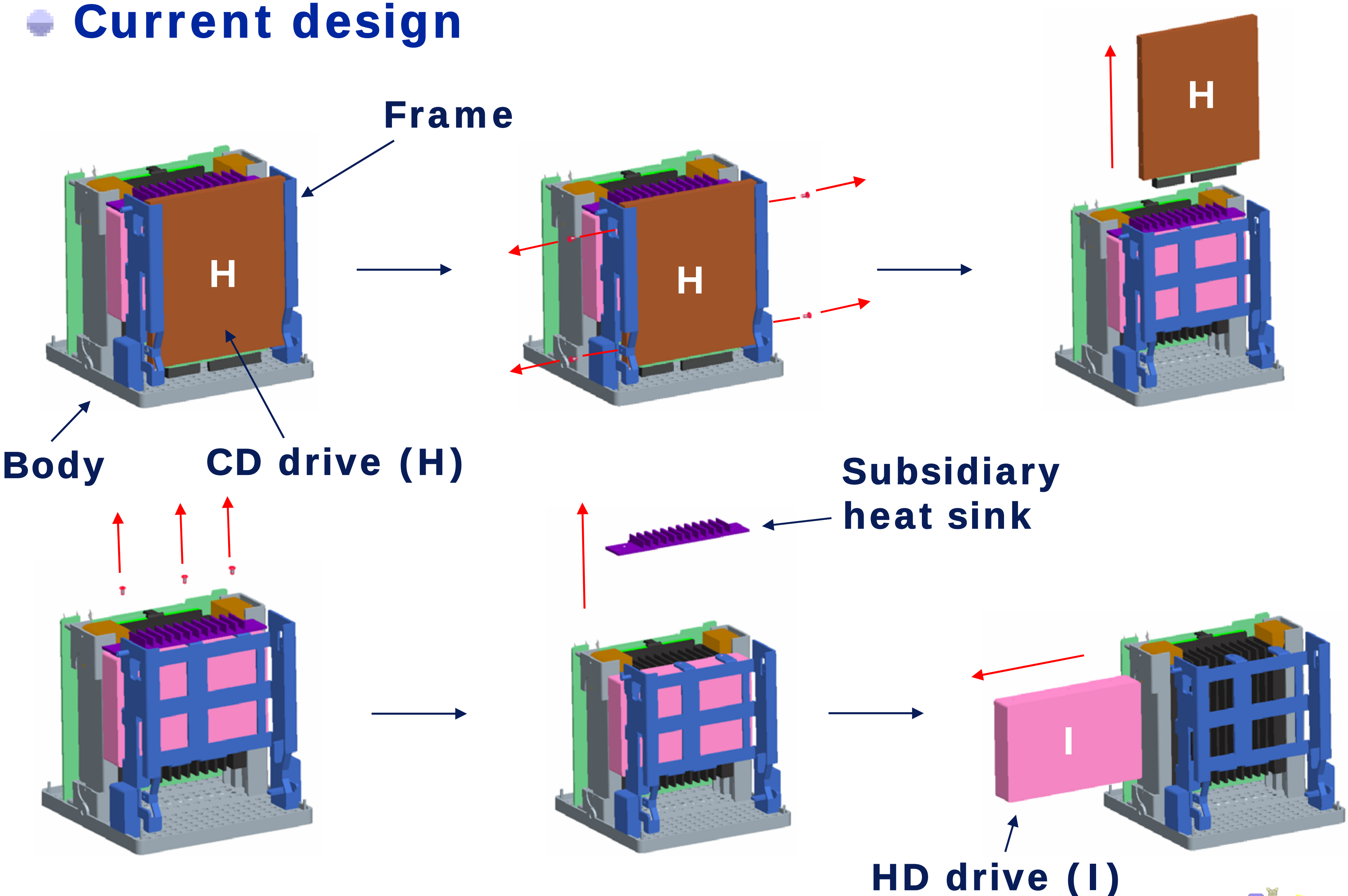
Case study

- **Optimal sequence of R5 with EOL treatments**



Case study

- **Current design**

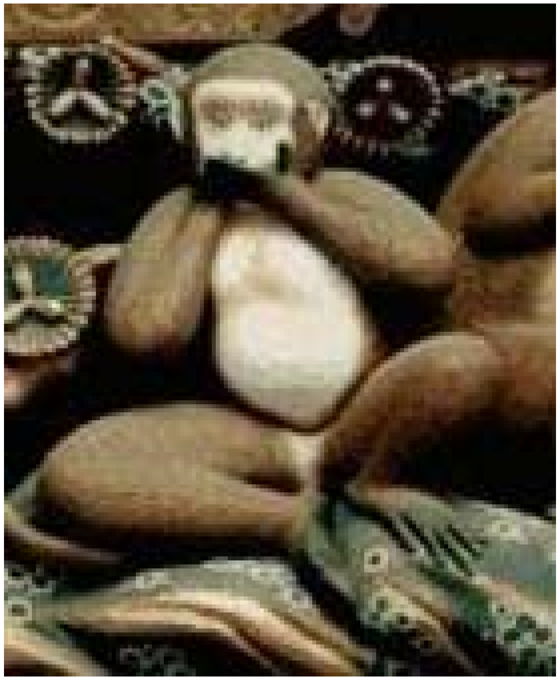


Summary

- **Design for optimal end-of-life via product embedded disassembly**
  - Integral locators to constrain parts
  - Domino-like self-disintegration
  - Energy consumption as an indicator for environmental impact
  - Design spatial configurations and EOL treatments
  - Trade-offs between profit and environmental impact

Future work

- **Results take too long (~2 weeks w/ one PC)**
  - Representation
  - Algorithm
  - implementation/parallelization
- **Only simple end-of-life scenario considered**
  - More detailed scenarios
  - LCA with accurate data
- **Only geometry considered**
  - Thermal
  - Stiffness
  - Impact
  - Safety

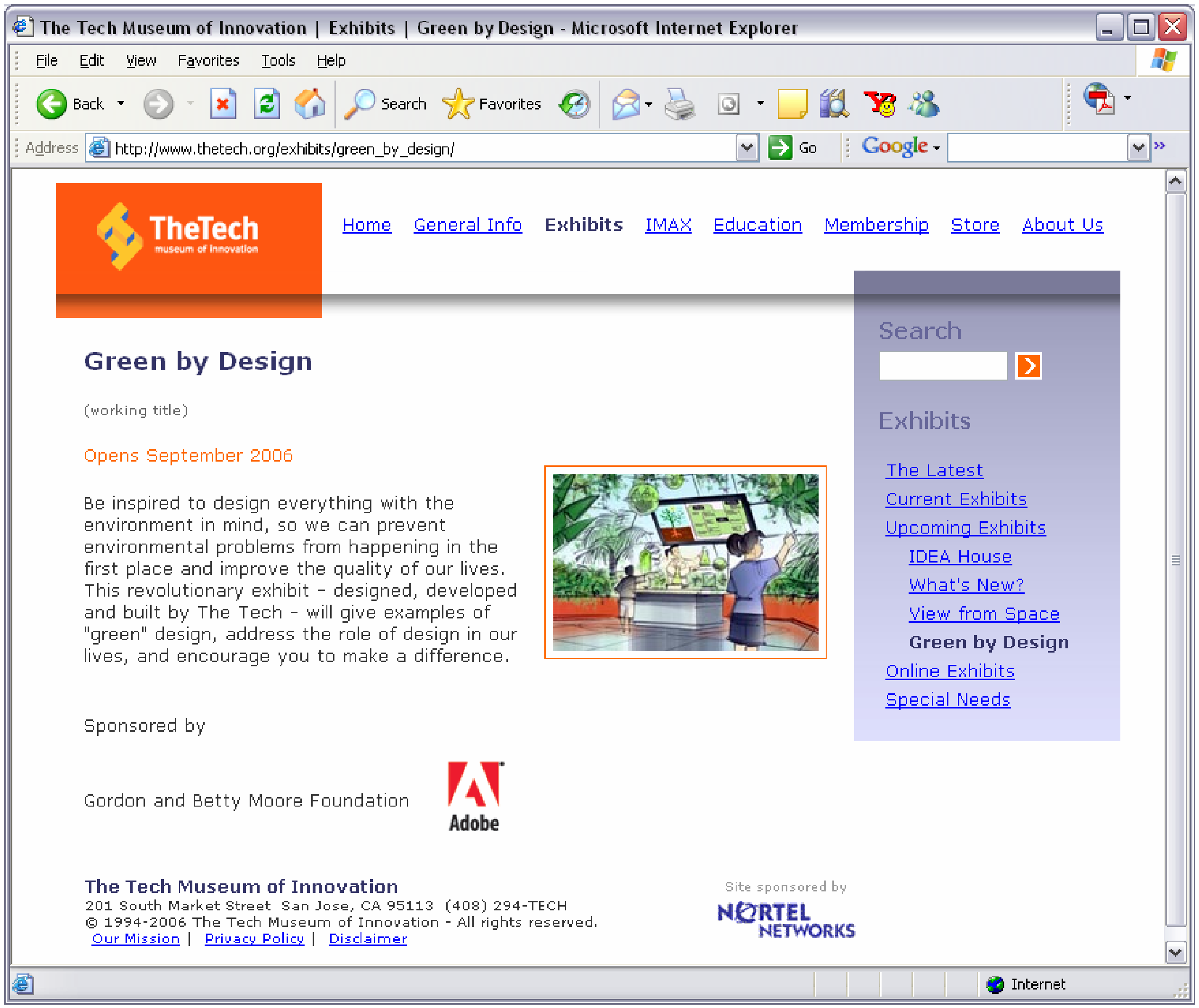


Acknowledgements

- **Powered by….**

Closure

- **Green by Design@TheTech (www.thetech.org)**



Closure

- **For more information:**
  - http://www.engin.umich.edu/~kazu
  - kazu@umich.edu