Complex Systems Analytics: a Promising Enabler for Sustainable Design and Manufacturing

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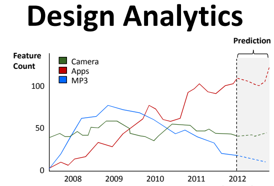
Overview

Predictive Systems Design Analytics



Flu Spread Pattern

User-Generated Contents

Product Life Cycle

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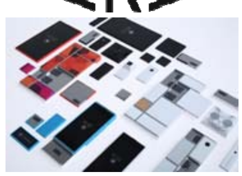
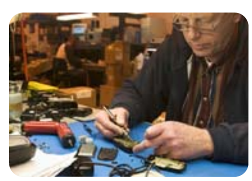
Let's envision ….

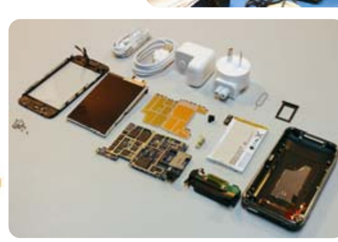
- Manufacturers can predict when a product will reach its end of life and the condition of the returned product based on the product attributes and customer demographic data at the moment a consumer purchases a product.
- Is it better to keep my phone as long as it lasts?
- "I am a green farmer. I would like to keep my harvester as long as I can."

Let's envision ….

- Even at the early stages of product design, the manufacturer can predict which component will be reused, recycled, remanufactured, or replaced with a new component; and, in turn, modularize platforms (i.e., better design) for easy, profitable end-of-life recovery operations.







Let’s envision ….

- Manufacturers can design a variety of products that are targeted for the new product market, as well as the remanufactured product market in a simultaneous manner for a better market coverage and higher profit.

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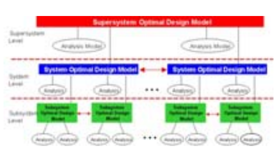
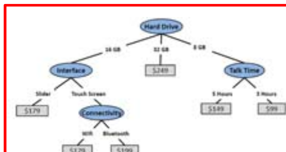
Research Contributions – Predictive Design and Analytics



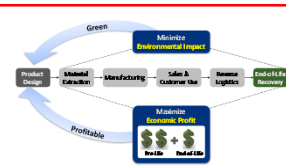
Multidisciplinary Design Optimization – Analytical Target Cascading (ATC)

Kim, et al. 2003 *Trans. ASME*



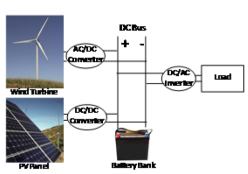
Trend Mining Design

Tucker & Kim 2008, 2009 *Trans. ASME*
Ma & Kim 2014 *Trans. ASME*



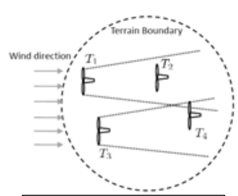
Green Profit Design

Kwak & Kim 2010, 2012 *Trans. ASME*
Kwak, Ma & Kim 2014 *J Cleaner Prod.*



Hybrid, Renewable Energy Generation

Lu & Kim 2010 *Trans. ASME*



Wind Farm Layout Design

Lu & Kim 2014 *Eng. Opt. J.*

Energy Distribution

Kannan, Shanbhag & Kim 2012
Opt. Mtd. & Software

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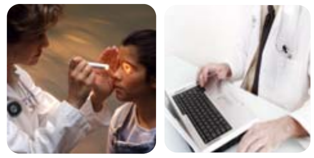
How does CDC detect influenza epidemic?

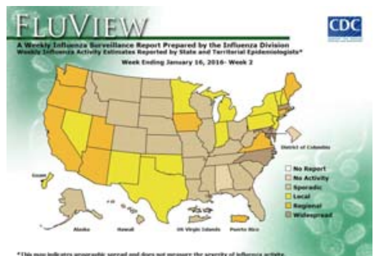
Visit



Report

Patients with **Influenza-Like Illness** (ILI) visit physicians.

Physician visits are reported to CDC on regular basis.



CDC analyzes the collected data and publishes a report on ILI.

It takes one week to detect influenza epidemics.

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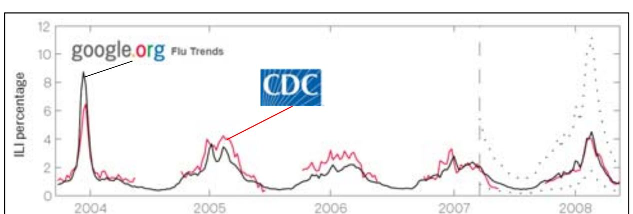
How does Google detect influenza epidemics?

Search

Submit

google.org Flu Trends



[Source] Ginsberg et al., 2009, "Detecting influenza epidemics using search engine query data," *Nature* 457(19).

Can estimate current flu activity around the world in near real-time.

For product design, can we utilize user-generated data like this?

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Are these waste (or opportunities)?

Management of Used and End-Of-Life Electronics in 2009 (Source: EPA)				
	Ready for End-of-Life Management (million of units)	Disposed (million of units)	Collected for Recycling (million of units)	Rate of Collection for Recycling (by weight)
Computers	47.4	29.4	18	**38%**
Televisions	27.2	22.7	4.6	**17%**
Mobile Devices	141	129	11.7	**8%**

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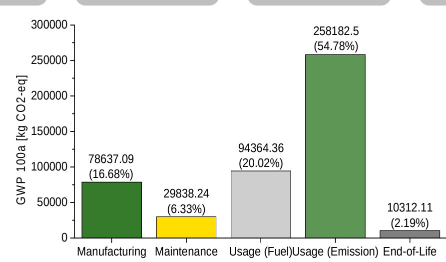
A product lives a life and causes environmental issues throughout the life (especially in usage phase).

- Natural resource depletion
- Climate change
- Toxic chemical releases
- Waste and land management

⋮

Product Design → Material Extraction → Manufacturing → Sales & Customer Use → Reverse Logistics → End-of-Life



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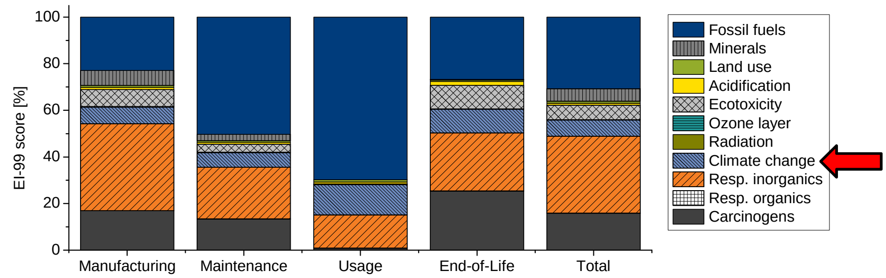
For example, a machine generates…



Global Warming Potential (kg CO_2e)

824 Tons CO2e	=	11,800x	9.4x	0.5x

Kwak et al. (2012) "Life Cycle Assessment of Complex Heavy Duty Off-Road Equipment," ASME ISFA.

A major obstacle is that there exists a time gap between *design* and *end-of-life*.

Remember one week delay for flu case?

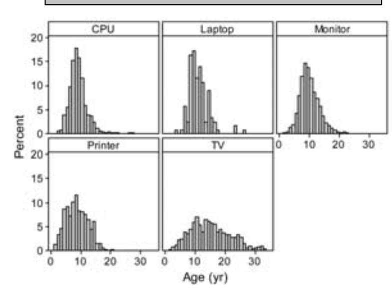
18 months

4 years

14 years

20 years (20,000 hrs)

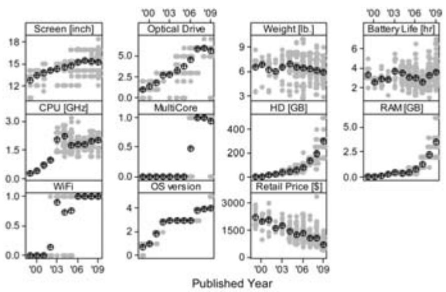
Age Distribution of EOL Products



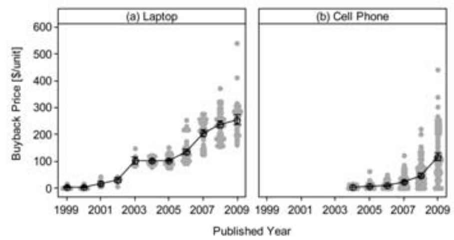
Kwak, M., Behdad, S., Zhao, Y., Kim, H. M. and Thurston, D. "E-waste Stream Analysis and Design Implications," *Journal of Mechanical Design*, Vol. 133, No. 10, 2011.

A major obstacle is that there exists a time gap between *design* and *end-of-life*.

Product Specification Trends (Laptop)



Market Value of EOL Products



Can we make recovery profitable?
How to overcome the obsolescence ?

Kwak, M., Kim, H. M. and Thurston, D. "Formulating Second-Hand Market Value as a Function of Product Specifications, Age, and Condition," *Journal of Mechanical Design*, 2011.

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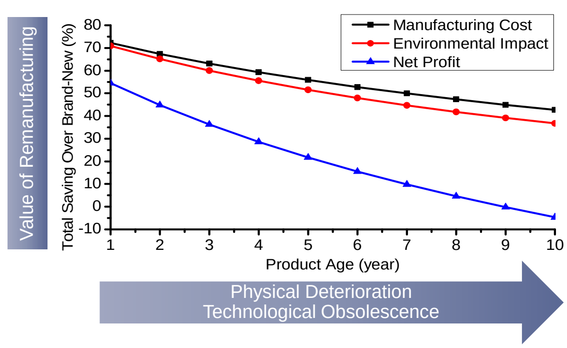
Green profit of reman changes over time!

A model for assessing the time-varying advantages of remanufacturing can

- Compare the remanufactured and brand-new versions of a product,
- Clarify how the nature of the product influences the time-varying value,
- Provide a multi-dimensional assessment tool (cost, impact, and net profit).



Kwak, M. and Kim, H. M., "Assessing Time-Varying Advantages of Remanufacturing: A Model for Products with Physical and Technological Obsolescence," ICED15, Milan, Italy, 2015.

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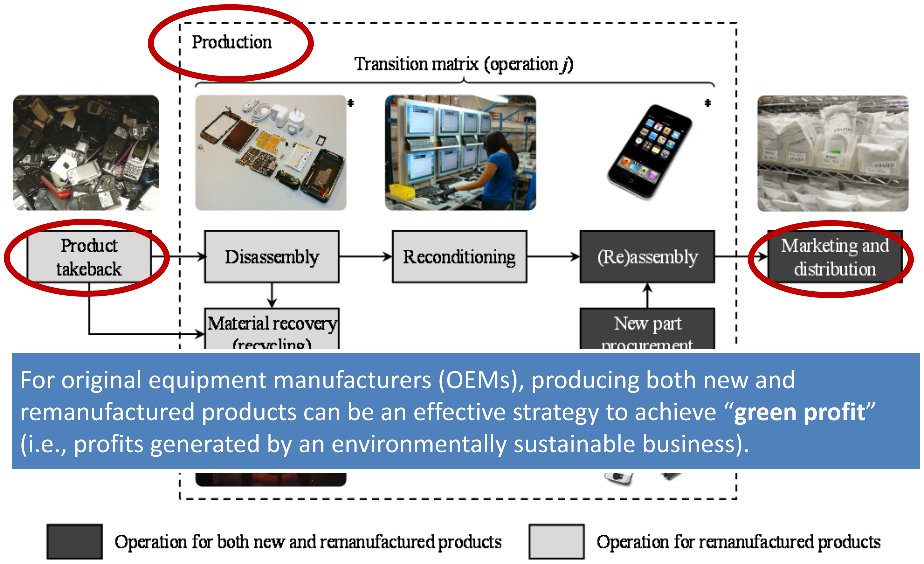
Reman is composed of three sequential activities.



For original equipment manufacturers (OEMs), producing both new and remanufactured products can be an effective strategy to achieve "**green profit**" (i.e., profits generated by an environmentally sustainable business).

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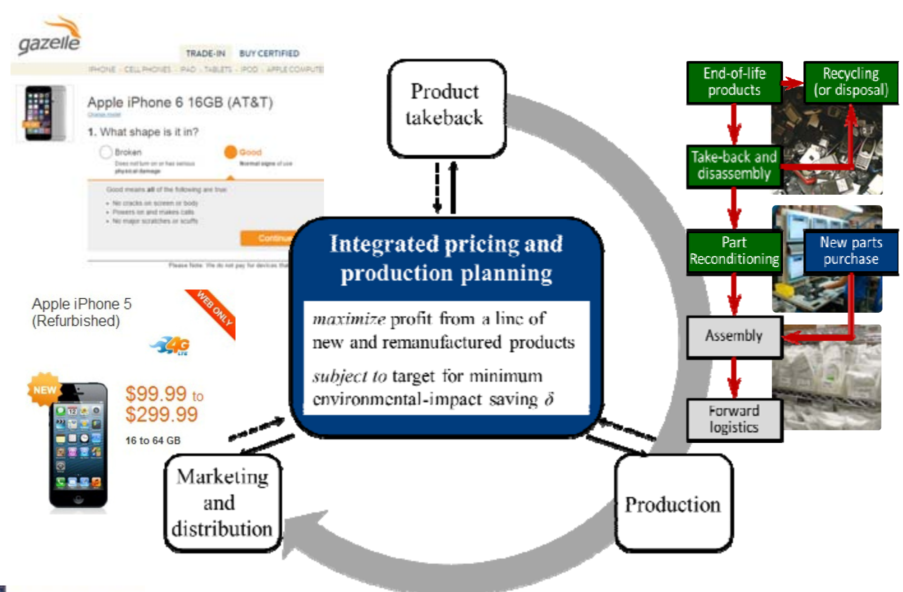
There is strong interdependence among the activities.



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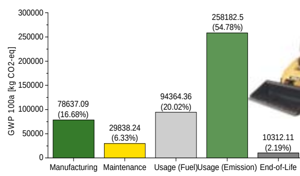
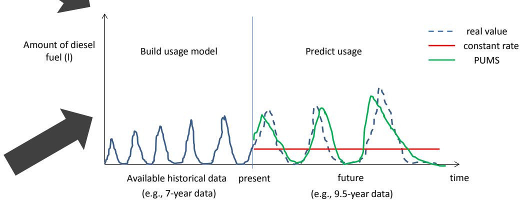
Let's see how these can be integrated for analytics.

Design Analytics

Life Cycle Design

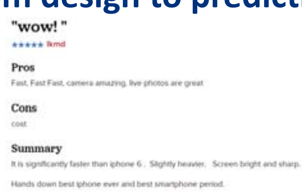


Predictive Design Analytics



User-generated contents and advanced telematics help establish the link from design to predictive analytics.

Customer Choice & Review


"wow! "
★★★★★ lkmd

Pros
Fast, Fast Fast, camera amazing, live photos are great

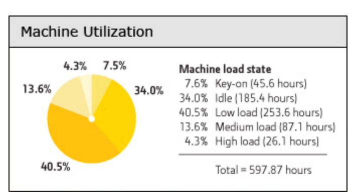
Cons
cost

Summary
It is significantly faster than iphone 6 . Slightly heavier. Screen bright and sharp.

Hands down best iphone ever and best smartphone period.

Type	Doors	Cylinders	HP	RPM	MPG	Price	Income	Age	Gender	Choice
Standard	2	4	288	4900	31	45400	46816	40	Female	Toyota
Standard	4	4	262	5100	30	41315	66590	54	Male	Chevrolet
Standard	4	4	207	5000	35	37028	97504	39	Male	Honda

Customer Usage Pattern



[Source] http://deere.com

Mining customer trends

- Tucker, C. and Kim, H. M. "Trend Mining for Predictive Product Design," *Journal of Mechanical Design*, Vol. 133, No. 11, 2011.
- Tucker, C. and Kim, H.M., "Predicting Emerging Product Design Trend by Mining Publicly Available Customer Review Data," *ICED*, 2011.
- Ma, J. and Kim, H. M. "Predictive Usage Mining for Life Cycle Assessment" Transportation Research - Part D, Vol. 38, pp. 125-143, July 2015.

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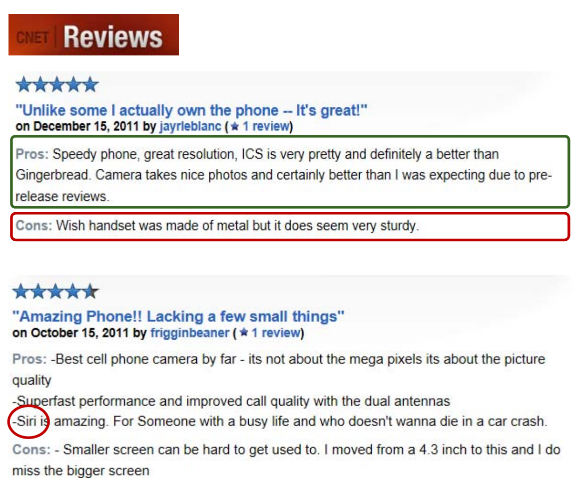
Customer review mining

Review Text Retrieval

Product Feature Text Mining

Counting and Prediction



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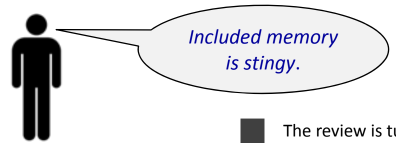
Customer review mining

Review Text Retrieval

Product Feature Text Mining

Counting and Prediction



The review is turned into a sequence with Part Of Speech* tags.

⟨{included, VB}{memory, NN}{is, VB}{stingy, JJ}⟩

⟨{included, VB}{$feature, NN}{is, VB}{stingy, JJ}⟩

Eric Brill. A simple rule-based part of speech tagger. In Proceedings of the Third Conference on Applied Natural Language Processing, pages 152–155, 1992.

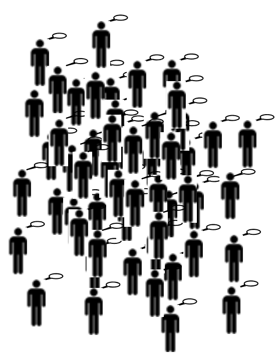
Customer review mining

Review Text Retrieval

Product Feature Text Mining

Counting and Prediction

Unstructured Data



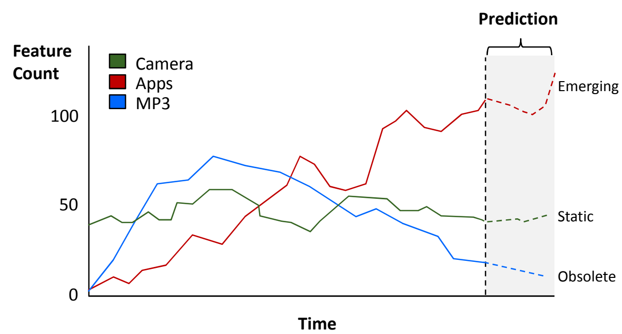
Text Tagging

Structured Data

Date	Feature	Count	Type
Jan 31	Screen	5	Cons
Feb1	Camera	9	Pros
Feb1	Apps	15	Pros
Feb1	Keypad	4	Pros
Feb1	Weight	7	Pros
Feb1	MP3	3	Pros
Feb1	WiFi	8	Cons
Feb1	Color	4	Cons
Feb1	Screen	7	Cons
Feb2	Camera	8	Pros
Feb2	Apps	14	Pros
Feb2	Keypad	2	Pros

Customer review mining

Review Text Retrieval → Product Feature Text Mining → Counting and Prediction



e.g., **Holt-Winters Forecasting** $\hat{y}_t(k) = L_t + kT_t + I_{t-s+k}$

Level: $L_t = \alpha(y_t - I_{t-s}) + (1-\alpha)(L_{t-1} + T_{t-1})$

Trend: $T_t = \gamma(L_t - L_{t-1}) + (1-\gamma)T_{t-1}$

Season: $I_t = \delta(y_t - L_t) + (1-\delta)I_{t-s}$

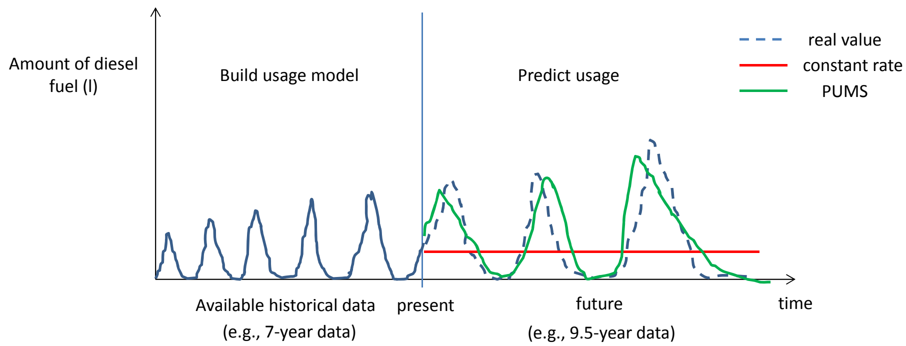
Large-scale sensor data from telematics system

- Companies such as Caterpillar (PRODUCT Link^{TM}) and John Deere (JD Link^{TM}) have developed telematics systems for their machinery.
- Operational data can be gathered in real time for various purposes: asset utilization monitoring, location tracking, fleet management, machine health prognostics, etc.

source : http://www.equipmentworld.com/

Engineering design scenario: combine harvesters

Estimate environmental impacts of product life cycle (e.g., 10 years or 20 years) with a usage model from sensor data



Ma, J. and Kim, H.M. "Predictive Usage Mining for Life Cycle Assessment," *Transportation Research – Part D*, Vol. 38, pp. 125-143, 2015.

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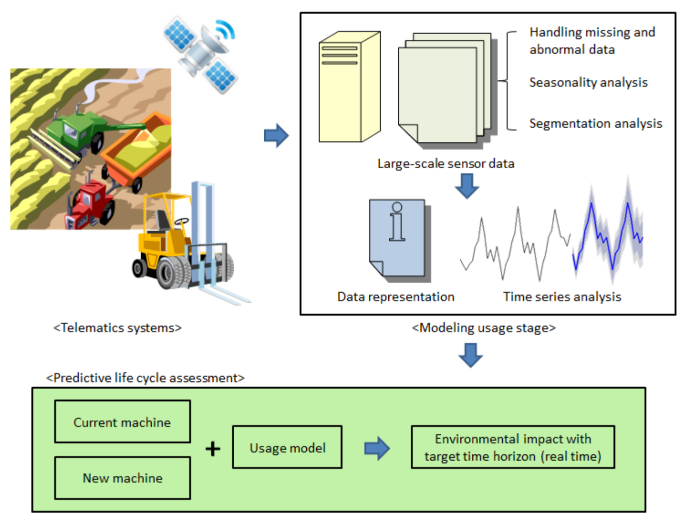
Predictive Usage Mining for Sustainability (PUMS)



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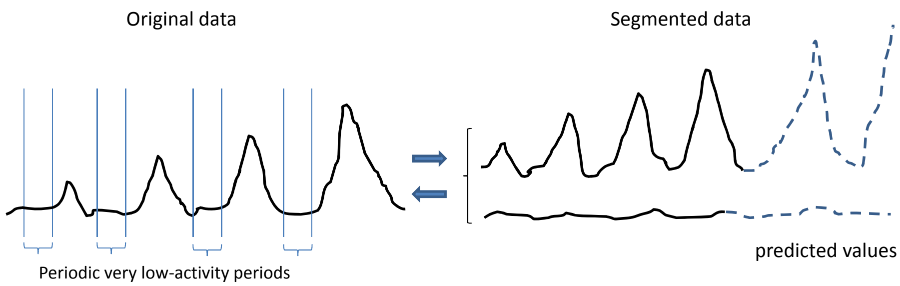
(Infrequent) Usage modeling

- Automatic segmentation
  - Detect periodic low-activity periods and group them separately
  - Magnify important patterns and make predictions
  - Combine the results and maintain the time stamp



Usage modeling

- Time series models
  - PUMS-ets

Smoothing factor, $0 < \alpha < 1$

observed time series

$$\hat{y}_{t+1} = \hat{y}_t + \alpha(y_t - \hat{y}_t)$$

forecast error

$$\begin{aligned}\hat{y}_{t+1} &= \alpha y_t + (1-\alpha)[\alpha y_{t-1} + (1-\alpha)\hat{y}_{t-1}] \\ &= \alpha y_t + \alpha(1-\alpha)y_{t-1} + (1-\alpha)^2\hat{y}_{t-1}.\end{aligned}$$

Trend Component		Seasonal Component N (None)	A (Additive)	M (Multiplicative)
N	(None)	N,N	N,A	N,M
A	(Additive)	A,N	A,A	A,M
A_d	(Additive damped)	A_d,N	A_d,A	A_d,M
M	(Multiplicative)	M,N	M,A	M,M
M_d	(Multiplicative damped)	M_d,N	M_d,A	M_d,M

  - PUMS-arima

autoregressive model, AR(p)

integration, I(d)

$$(1 - \phi_1 B - \cdots - \phi_p B^p)(1 - \Phi_1 B^m - \cdots - \Phi_P B^{Pm})(1-B)^d(1-B^m)^D\, y_t$$
$$= c + (1 + \theta_1 B + \cdots + \theta_q B^q)(1 + \Theta_1 B^m + \cdots + \Theta_Q B^{Qm})e_t$$

observed time series

moving average model, MA(q)

[Ref.] Hyndman et al. (2008)

Being green can be profitable?

Obstacles to making green profit

- OEM remanufacturer's concerns:
  - Unbalance b/w supply of cores and demand for reman products
  - Unproven environmental sustainability of remanufacturing
  - Cannibalization of new product sales

- Relevant literature:
  - **Pricing**: Focused on pricing from the economic perspective w/ little design and process consideration.
    Guide et al. (2003), Ferrer et al. (2010), Vadde et al. (2011)
  - **Production planning**: Pricing was separated from production planning.
    Mangun and Thurston (2002), Kwak and Kim (2010), Jayaraman (2006), Franke et al. (2006)
  - **Environmental assessment of remanufacturing**: Mostly Life Cycle Assessments (LCAs) comparing new and reman products for the sake of product evaluation not decision-making.
    Smith and Keoleian (2004), Goldey et al. (2010)

Let's consider economics together with environment.

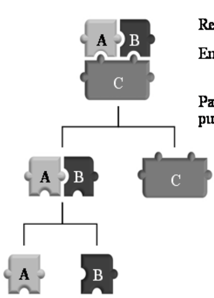
- For OEM remanufacturers, the new model considers **joint pricing and production planning** to develop an **optimal portfolio of new and remanufactured products**.
- Two objectives:

$$\text{Maximize [total profit } f_1\text{, total environmental saving } f_2\text{]}$$

- Decision variables:
  - p_u, x_u : buy-back price and take-back quantity of the end-of-life product
  - p_n, x_n : selling price and the production quantity of the new product
  - p_r, x_r : selling price and the production quantity of the reman product

Transition matrix

Transition matrix represents the **relationship between product design and remanufacturing operations** in a matrix form, such that the impact of product design can be mathematically reflected in the production planning.



	Item i		Operation j: 1	2	3	4	5	6	7	8	9
Remanufactured product	1	Product ABC (R)									1
End-of-life product	2	Product ABC (EOL 1)	-1								
	3	Product ABC (EOL 2)		-1							
Part (w/ or w/o external purchase availability)	4	Subassembly AB (R)								1	-1
	5	Subassembly AB (W)	1	0.6	-1						
	6	Subassembly AB (N)		0.4		-1					
	7	Component A (R)					1			-1	
	8	Component B (R)						1		-1	
	9	Component C (R)							1		-1
	10	Component A (W)			1	0.7	-1				
	15	Component C (N)		0.2							

Operations 1–4: Disassembly; 5–7: Reconditioning; 8–9: Reassembly

$$\text{Input}_i + \sum_{j \in J} T_{ij} \cdot Y_j = \text{Output}_i$$

Mathematical model (1/2)

The objective is to **maximize the total profit** from the sales of new and remanufactured products, while **achieving environmental-impact saving *δ*.**

Profit from the new product: $(P_n - C_n)\cdot Z_n$; Profit from the remanufactured product: $P_r \cdot Z_r - (\ldots)$

$$\max.\ (P_n - C_n)\cdot Z_n + P_r \cdot Z_r - \left(\sum_{i\in I} c_i^M \cdot M_i + \sum_{k\in K} P_k \cdot X_k + \sum_{j\in J} c_j \cdot Y_j + \sum_{i\in I} c_i^N \cdot N_i + c_d \cdot Z_r\right)$$

Cost of recycling; Cost of takeback; Cost of production; Cost of spare parts; Cost of reassy and sales

$g_1 : X_k \le A_k \cdot s_k(P_k) \quad \forall k \in K$ Take-back availability of end-of-life products, given buy-back price

$g_2 : Z_n \le \sum_{l\in L} Q_l \cdot d_{n,l}(P_n, P_r)$

$g_3 : Z_r \le \sum_{l\in L} Q_l \cdot d_{r,l}(P_n, P_r)$

(g_2, g_3) Production quantity not exceeding the demand, given selling price

$g_4 : Z_r \le X_k$ Upper limit for remanufacturing

$$g_5 : \sum_{k\in K} (e_w - e_k)\cdot X_k + \left\{E_n \cdot Z_r - \left(\sum_{i\in I} e_i^M \cdot M_i + \sum_{j\in J} e_j \cdot Y_j + \sum_{i\in I} e_i^N \cdot N_i + e_d \cdot Z_r\right)\right\} \ge \delta$$

Environmental-impact saving exceeding the target δ

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Mathematical model (2/2)

Constraints for the Input-output flow balance

$h_1 : X_k + \sum_{j\in J} T_{ij} \cdot Y_j - M_i = 0 \quad \forall i$ corresponding to the end-of-life product $k (\forall k \in K)$

$h_2 : N_i + \sum_{j\in J} T_{ij} \cdot Y_j - M_i = 0 \quad \forall i$ corresponding to a part with external purchase availability

$h_3 : \sum_{j\in J} T_{ij} \cdot Y_j - M_i = 0 \quad \forall i$ corresponding to a part without external purchase availability

$h_4 : \sum_{j\in J} T_{ij} \cdot Y_j - Z_r = 0 \quad \forall i$ corresponding to the remanufactured product

$h_5 : N_i = 0 \quad \forall i \notin$ part with external purchase availability

$h_6 : M_i = 0 \quad \forall i$ corresponding to the remanufactured product

Variable conditions

$X_k, Y_j, Z_n, Z_r, N_i \ge 0$ and integer $\quad \forall i \in I, \forall j \in J, \forall k \in K$

$P_k, P_n, P_r, M_i \ge 0 \quad \forall i \in I, \forall k \in K$

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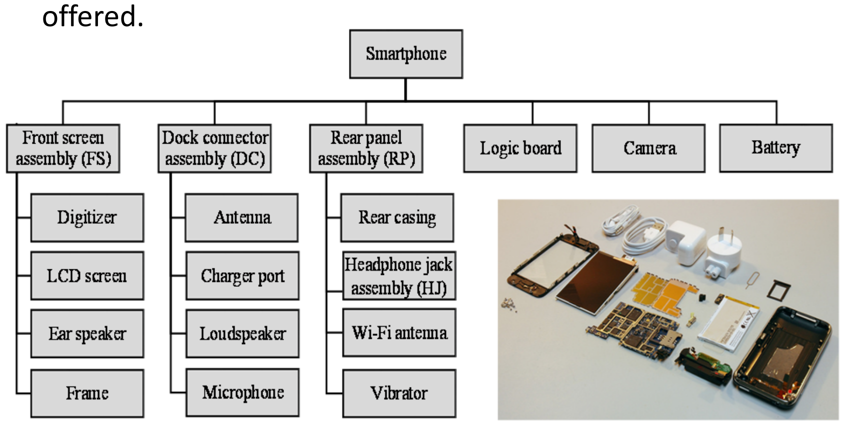
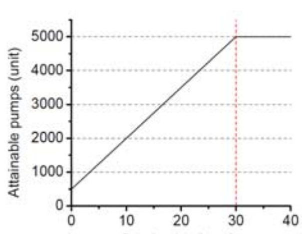
Example: smartphone

- **Baseline case:** New only. No takeback is conducted.
- **Target case:** Both new and remanufactured products are offered.



Example: engine water pump

Suppose that an OEM manufacturer of engine water pumps is considering starting their own remanufacturing business.



Current market status (baseline)

Attribute	New pump	Competitor
Price	$100	$50
Brand	OEM	Third-party
Condition	New	Reman
Market share	45%	55%

Assumptions on market conditions

Parameter	Value
Available cores in the market	5,000 units
Attainable cores at p_u=0	500 units
Buy-back price for 100% take-back	$30

Customer preference in the market

- Total market size: 3,000 units
- Customers prefer a new product w/ lower price and OEM brand.

Customer preference assumption

Attribute	Utility factor (β)	Ideal	Critical
Price	0.8	$0	$100
Brand	0.2	OEM	Third-party
Condition	0.45	New	Reman

Utility of product j: $U_j = [1-\beta_{cond}\cdot(1-y_{j,cond})]\cdot(\beta_{price}\cdot y_{j,price}+\beta_{brand}\cdot y_{j,brand})$

where

$$y_{j,cond} = \begin{cases} 0 & \textit{if} \text{ remanufactured product} \\ 1 & \textit{else} \text{ (new product)} \end{cases} \qquad y_{j,brand} = \begin{cases} 0 & \textit{if} \text{ remanufactured by third-party} \\ 1 & \textit{else} \text{ (OEM)} \end{cases}$$

$$y_{j,price} = 1 - p_j \big/ p_j^{critical}$$

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Bi-objective problem: ε-constraint approach

Using the ε-constraint approach, the model can incorporate the trade-offs between profit and environmental saving.

$$\max_x \ [f_1(x), f_2(x)]$$
subject to
$$g_l(x) \le 0 \quad l = 1,2,\cdots,L$$
$$h_m(x) = 0 \quad m = 1,2,\cdots,M$$

$$\max_x \ f_1(x)$$
subject to
$$g_l(x) \le 0 \quad l = 1,2,\cdots,L$$
$$h_m(x) = 0 \quad m = 1,2,\cdots,M$$
$$f_2(x) \ge \varepsilon$$
$$\varepsilon = f_2(x_1^*) + (f_2(x_2^*) - f_2(x_1^*))\cdot\delta$$
$$0 \le \delta \le 1$$

max f_2

Lower bound for f_2
(f_2 under max f_1)

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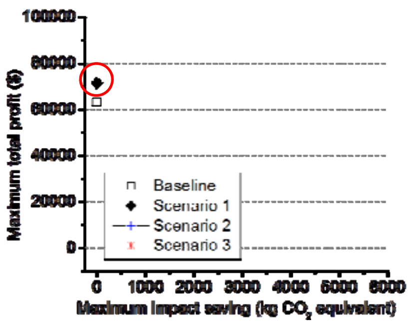
Case study: Scenario 1 (new production only)

- The company optimizes the selling price and quantity of the new pump. No remanufacturing is conducted.



	Baseline	Scenario 1
Selling price ($)	100.00	89.40
Market share	45%	66%
Pumps collected (unit)	0	0
Total cost ($)	71676.42	104831.41
Total profit ($)	63223.58	71547.25
Impact saving (kg CO_2e)	0.00	0.00

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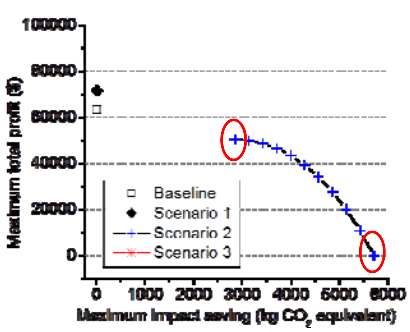
Case study: Scenario 2 (remanufacturing only)

- For this period, closed-loop production is conducted. The company produces only remanufactured pumps. The selling price and production quantity for the remanufactured pump are optimized.



	Max. profit	Max. impact saving
Selling price ($)	86.82	50.85
Market share	37%	74%
Buyback price ($)	4.93	13.23
Pumps collected (unit)	1240	2482
Total cost ($)	46761.31	114209.64
Total profit ($)	50440.20	6.24
Impact saving (kg CO_2e)	2853.18	5710.96

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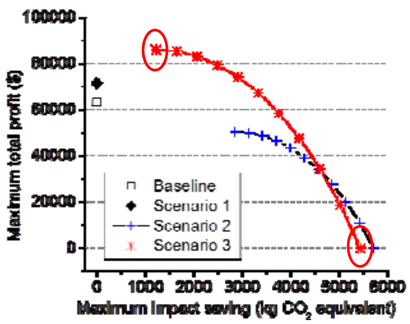
Case study: Scenario 3 (new and reman together)

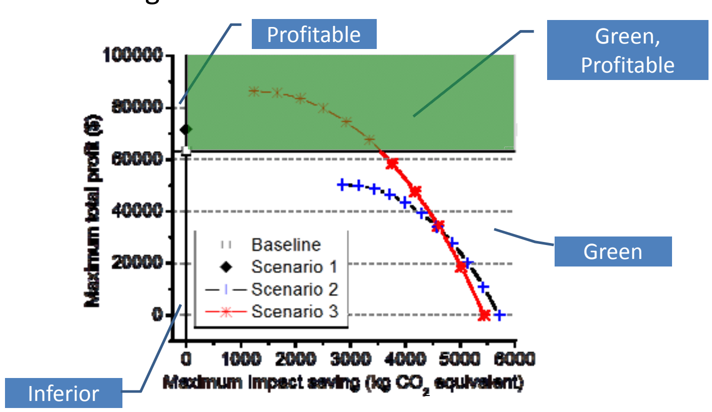
- The company optimizes and sells both the new and remanufactured products.



	Max profit		Max impact saving	
	New	Reman	New	Reman
Selling price ($)	93.46	91.77	99.99	41.34
Market share	48%	17%	13%	71%
Buyback price ($)	0.64		12.44	
Pumps collected (unit)	596		2366	
Total cost ($)	95553.02		127796.32	
Total profit ($)	86130.97		0.00	
Impact saving (kg CO_2e)	1226.70		5442.50	

Efficient frontier: Pareto-optimal solutions

The results shows an opportunity to increase profit and environmental saving at the same time.

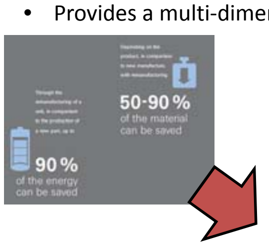


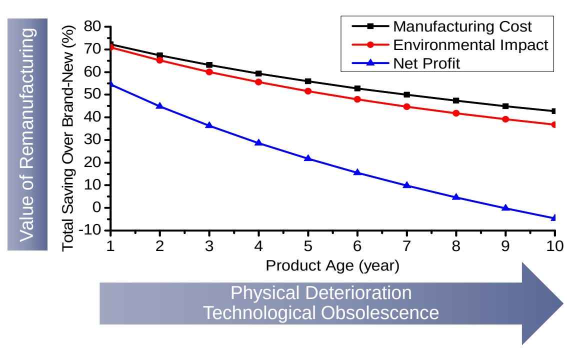
Reman product should be cheaper.

Green profit of reman changes over time!

A model for assessing the time-varying advantages of manufacturing is developed. The model:

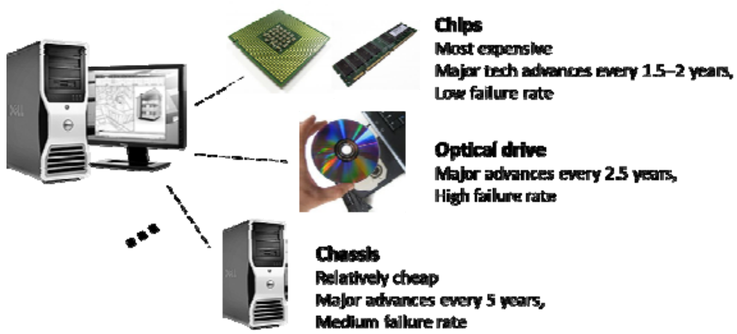
- Compares the remanufactured and brand-new versions of a product,
- Clarifies how the nature of the product influences the time-varying value,
- Provides a multi-dimensional assessment tool (cost, impact, and net profit).





Products w/ physical and technological obsolescence

Each part has its own lifecycle characteristics, in terms of cost, technological obsolescence, and physical deterioration.



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Products w/ physical and technological obsolescence

Each part has its own lifecycle characteristics, in terms of cost, technological obsolescence, and physical deterioration.

Probability that a part is reusable both **physically** and **technologically** can be modeled as:

$$w_i(t) \cdot \sum_{n=0}^{\delta_i^{target} - \delta_i(0)} f_i(n,t)$$

the maximum change in part generation allowed for *t* years to satisfy customer requirement

where

- $w(t)$: reusability of part *i* after *t* years of use
- n : change in the part generation over *t* years
- $f_i(n,t)$: the probability that a total of *n* generations of part *i* will appear in [0, *t*]

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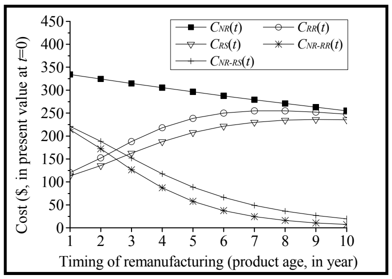
Cost advantage of a remanufactured product

Proposition 1. The **cost advantage** of remanufacturing over producing the equivalent brand-new product is formulated as $C_{NR\text{-}RR}(t)$.

$$C_{NR-RR}(t) = \sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n,t) \cdot \left(C_{i,\text{target}}^{new}(t) - C_i^{recond}(t) - V_i^{matl}(t) \right) \right]$$

Probability that a part is reusable both **physically** and **technologically**

Cost saving from reusing a part



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- NR: Production of brand-new products w/ responsible take-back and recycling
- RR: Remanufacturing w/ recycling; RS: Remanufacturing w/ *part resale* and recycling

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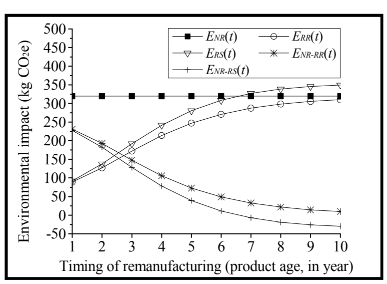
Environmental advantage of a reman product

Proposition 2. The **environmental advantage** of a remanufactured product over its equivalent brand-new is formulated as $E_{NR\text{-}RR}(t)$.

$$E_{NR-RR}(t) = \sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n,t) \cdot \left(E_{i,\text{target}}^{new}(t) - E_i^{recond}(t) + E_i^{matl}(t) \right) \right]$$

Probability that a part is reusable both **physically** and **technologically**

Avoided impact by reusing a part



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- NR: Production of brand-new products w/ responsible take-back and recycling
- RR: Remanufacturing w/ recycling; RS: Remanufacturing w/ *part resale* and recycling

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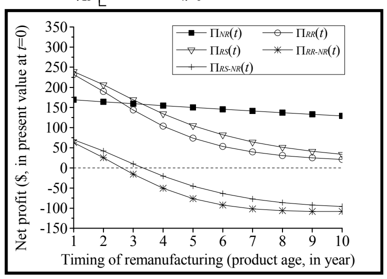
Net profit advantage of a reman product

Proposition 3. Let β be the price ratio of the remanufactured product to the equivalent brand-new. Then, the advantage of remanufacturing from the **net-profit** perspective is given as $\Pi_{RR\text{-}NR}(t)$.

$$\Pi_{RR-NR}(t) = (P_R - C_{RR}) - (P_N - C_{NR})$$
$$= (\beta - 1)\cdot P_N + \sum_{i\in I}\left[w_i(t)\cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} f_i(n,t)\cdot\left(C_{i,\text{target}}^{new}(t) - C_i^{recond}(t) - V_i^{matl}(t)\right)\right]$$



(β=0.7)

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- NR: Production of brand-new products w/ responsible take-back and recycling
- RR: Remanufacturing w/ recycling; RS: Remanufacturing w/ *part resale* and recycling

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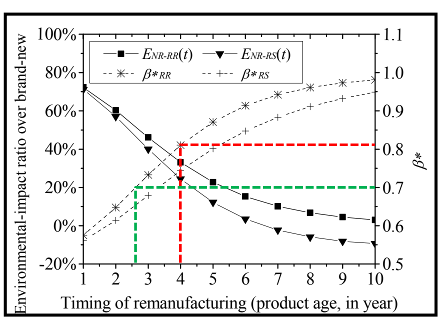
Net profit advantage of a reman product

Corollary 1. The range of β where the remanufacture product becomes more profitable than the brand-new is $\beta \geq \beta^*$, where β^* is*:*

$$\beta^*_{RR-NR} = 1 - (1/P_N)\cdot\sum_{i\in I}\left[w_i(t)\cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} \left(C_{i,\text{target}}^{new}(t) - C_i^{recond}(t) - V_i^{matl}(t)\right)\cdot f_i(n,t)\right]$$



Remanufacturing is more profitable only if consumers are willing to pay more than β^* of new price.

Let t=4. Remanufacturing (RR) makes sense if consumers are willing to pay more than 81% of new price on a REMAN product.

If beta is known as 0.7, a reasonable strategy is to remanufacture (RR) until t=2.5 and to choose new production afterwards.

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- NR: Production of brand-new products w/ responsible take-back and recycling
- RR: Remanufacturing w/ recycling; RS: Remanufacturing w/ *part resale* and recycling

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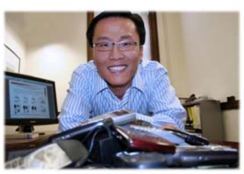
CONCLUSION

Where is this research heading?



Chicago Tribune USA TODAY

Consider cell phones' fate when designing them.

NSF CATERPILLAR JOHN DEERE

Acknowledgement of support: NSF CAREER award, Engineering Design and Innovation Program grant, GOALI grant, CAT, Deere.

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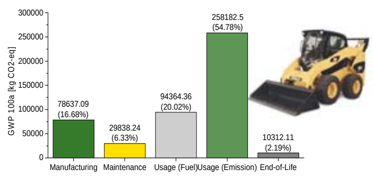
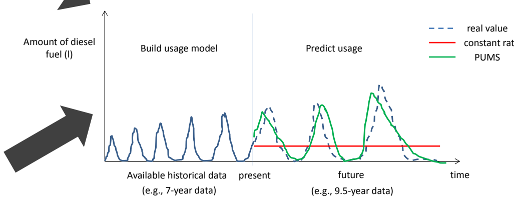
Summary

Design Analytics

Life Cycle Design



Predictive Design Analytics



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Being green can be sustainable by carefully linking predictive analytics with design and manufacturing.

Well-designed products enable more profitable, sustainable end-of-life product take-back and recovery.

A quantitative model can close the loop of pre-life, usage life and end-of-life of products for sustainability.

Predictive design analytics enables integrated approach to design, manufacturing, and sustainability.

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