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ON THE ROLE OF DSM IN DESIGNING SYSTEMS AND PRODUCTS FOR CHANGEABILITY

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1 INTRODUCTION

Increasingly, systems and products are designed such that future configuration changes can be easily implemented. These systems often feature long lifecycles, significant and partially irreversible investments and large uncertainty in user needs. The Design Structure Matrix (DSM) can play a central role in designing such systems for changeability, by clearly identifying where changes occurred in the past and/or where they are likely to occur in the future. Specifically, this paper introduces the *Change-DSM* and the *ΔDSM* and illustrates their use in two automotive projects.

2 ΔDSM AND CHANGE-DSM

Research into changeability generally falls into two areas: Understanding reasons for and patterns of past and present change activity, see for example Eckert, Zanker and Clarkson [1] and designing future systems such that they are "easy" to change, see Fricke and Schulz [2]. In both cases, the DSM plays an important role in analyzing and visualizing which parts of the system are affected by change. While the *component-DSM*, where rows and columns represents objects (generally hardware and/or software components of the system), shows the relationship between components we have found two variants of the basic component-DSM to be particularly useful: the Delta-DSM (ΔDSM) and the Change-DSM. These are subtly different and are shown generically in Fig.1:

- The ΔDSM shows the *differences between a baseline system and a changed system.* The ΔDSM shows only the expected or actual changes relative to the baseline DSM.
- The Change-DSM shows the *change propagation paths* between components of the system by showing the initiating components as columns and the receiving ones as rows.

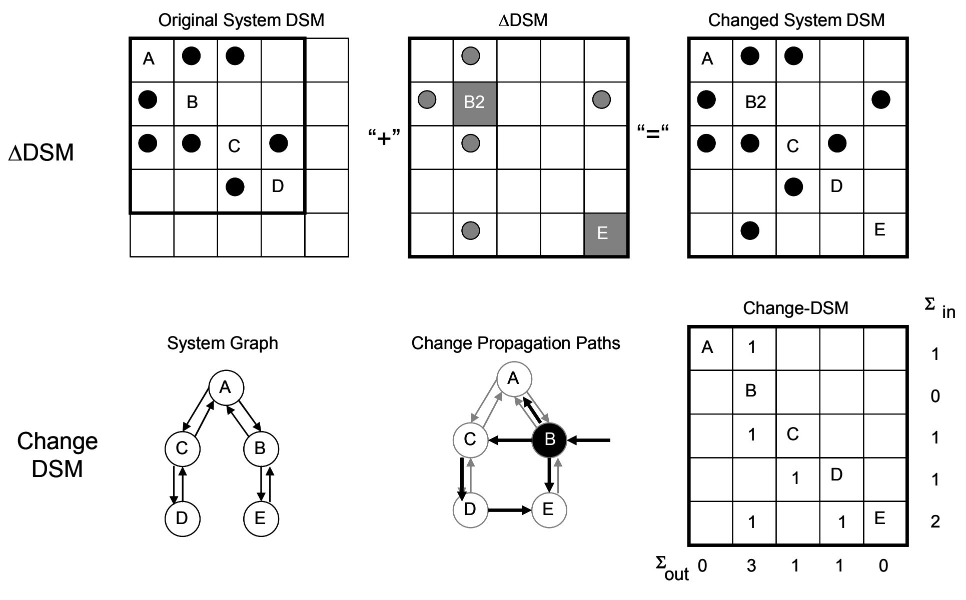

*Fig. **1**: DSM for Changeability: ΔDSM (top row), Change-DSM (bottom row)*

In Fig.1 (top row), we see a hypothetical baseline system with four components A, B, C and D. The interconnections between components are shown as black dots "●". The following changes are made to the baseline system: component B is replaced with B2, component E is added to the system, three existing interconnections are changed and two new interconnections are added. These changes are summarized in the ΔDSM. The final changed system configuration is a superposition of the baseline DSM and the ΔDSM. The bottom row of Fig.1 shows the concept underlying the Change-DSM. An existing system A, B, C, D, E is shown as a system graph. An externally initiated change is made to component B. Component B is therefore the "instigating" [1] component and changes radiate from B→A, B→C→D→E and B→E. These change propagation paths are shown in the Change-DSM by a "1" if a change propagates from one component to another. The row-sum shows the total number of inbound changes for each component, while the column-sum shows the number of outgoing changes.

3 INDUSTRIAL APPLICATIONS

2.1 Technology Infusion Analysis for a Hydrogen-Enhanced Engine (ArvinMeritor)

In [3] we demonstrated the application of the ΔDSM to a technology infusion problem. The ΔDSM was used to assess the invasiveness of a new technology, in this case a plasma fuel reformer for producing and injecting hydrogen-enriched gas into the inlet manifold of a conventional gasoline internal combustion engine. Fig. 2 shows the baseline DSM, with color-coded interconnections.

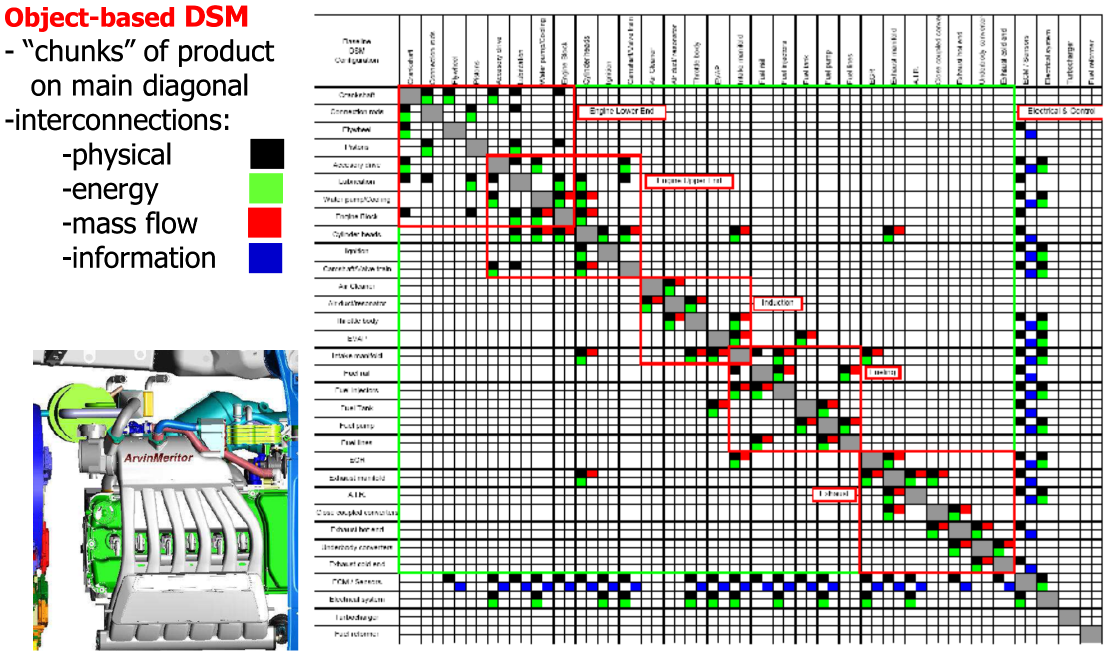

Fig.2: Baseline component-DSM of internal combustion engine (inline 6-cyl), [3], courtesy ArvinMeritor, engine shown as insert in lower left, baseline DSM shown on the right side

In order to capture the amount of redesign that would have to be done to accommodate the new fuel reformer technology, we recorded the following eight types of changes[1] relative to the baseline:

1. Change in the physical relationship between components
   a. Residing in the same module or sub-system
   b. Residing in a different module or sub-system
2. Change in energy flow between components
3. Change in material (mass) flow between components
4. Change in information flow between components (typical for control)
5. Change in design of a component (marked on the diagonal)
6. Addition of a component (marked on the diagonal)
7. Elimination of a component (marked on the diagonal)

The resulting ΔDSM is shown in Figure 3. The individual changes are color-coded appropriately.

[1] For physical relationship changes we distinguish between intra- and inter-module changes, because the latter are generally much more invasive and often require crossing of organizational boundaries.

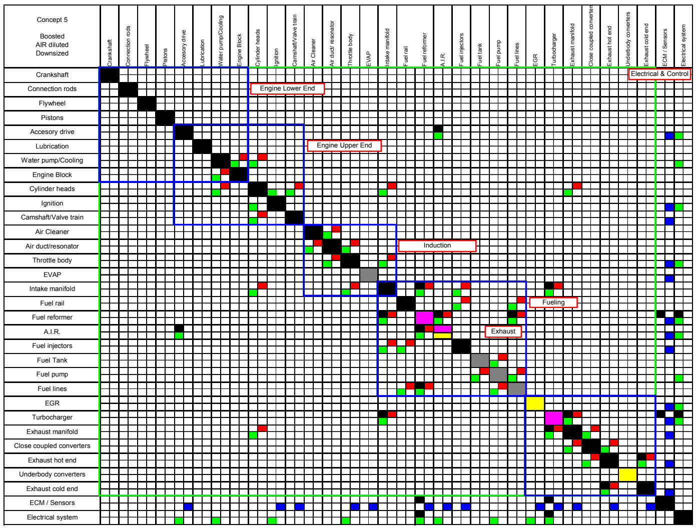

Fig.3: ΔDSM of internal combustion engine [3] with integrated plasma fuel reformer

2.2 Embedding Flexibility in Automotive Body-in-White Platforms (General Motors)

Fig.4 shows the use of Change-DSM to identify components in an automotive Body-in-White Platform that are likely to change if a length-change (=stretching) of the vehicle is required [4].

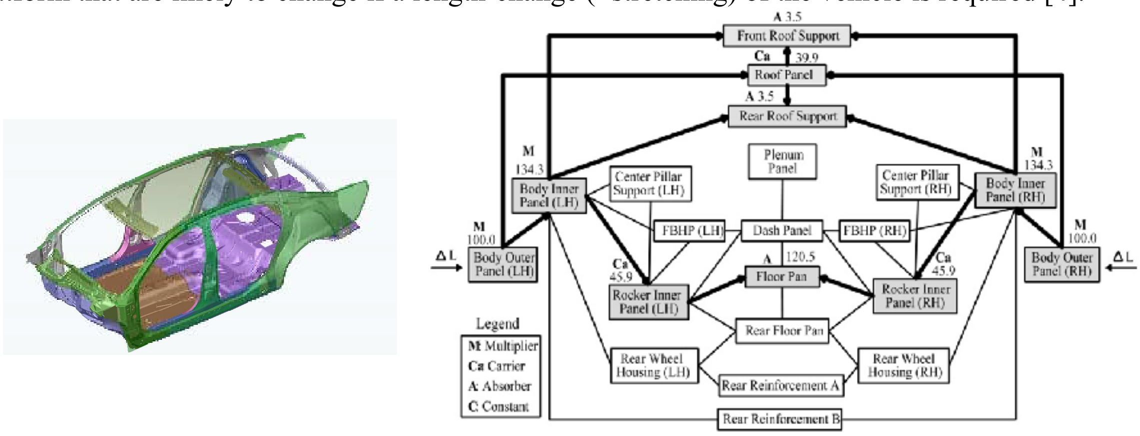

Fig.4: Automotive Body-in-White analysis for Changeability with Change-DSM [4]

4 CONCLUSIONS AND FUTURE WORK

Two variants of the component-DSM show promise for better management of changeability in complex systems and products: ΔDSM summarizes the differences between a baseline configuration and a new, changed configuration. The Change-DSM is helpful in identifying change propagation paths and pinpointing components that are likely to act as multipliers or absorbers of changes.

REFERENCES

[1] Eckert C., Clarkson P. and Zanker W., "Change and Customization in Complex Engineering Domains", Research in Engineering Design, 15 (2004): 1-21

[2] Fricke E., Schulz A. P., "Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle", Systems Engineering, (8)4, (2005): 342-359

[3] Smaling R., de Weck O., "Assessing Risks and Opportunities of Technology Infusion in System Design", Systems Engineering, 10 (1), (2007): 1-25

[4] Suh E.S., de Weck O.L., and Chang D., "Flexible Product Platforms: Framework and Case Study", Research in Engineering Design, 18 (2), August (2007): 69-87

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Design for Changeability

ON THE ROLE OF DSM IN DESIGNING SYSTEMS AND PRODUCTS FOR CHANGEABILITY

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IN COOPERATION WITH BMW GROUP
CAPITALIZE ON COMPLEXITY

Motivation

- Increasingly, systems and products are designed such that future configuration changes can be easily implemented.
- These systems often feature long lifecycles, significant and partially irreversible investments and large uncertainty in user needs.
- The Design Structure Matrix (DSM) can play a central role in designing such systems for changeability, by clearly identifying **where changes occurred in the past and/or where they are likely to occur in the future.**
- Specifically, this paper introduces the ***Change-DSM*** and the ***ΔDSM*** and illustrates their use in two automotive projects.

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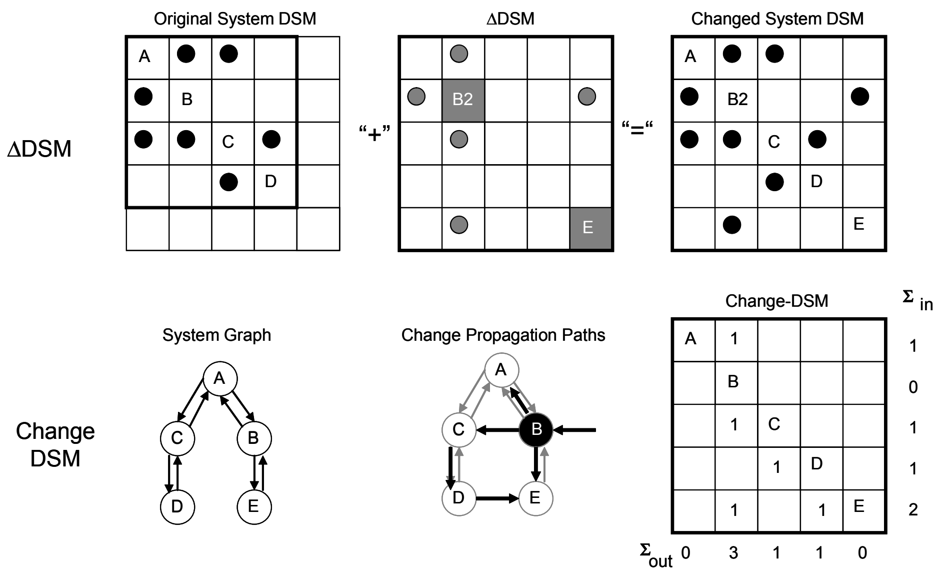
ΔDSM versus Change-DSM



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Part 1 - ΔDSM

ΔDSM and Technology Infusion Analysis

- Some blockbuster products are clean sheet designs
  - Even they typically reuse existing lower-level components
- However, most products evolve from predecessors
  - Infusion of new technologies over time
  - Increase value of product to customers and firm
  - Carefully manage resources and risks during R&D and transition of technology to full scale production
- Purpose of formal Technology Infusion Analysis
  - To assess the potential cost/performance trade-off of a new technology during conceptual design, before committing to invest significant research and development resources

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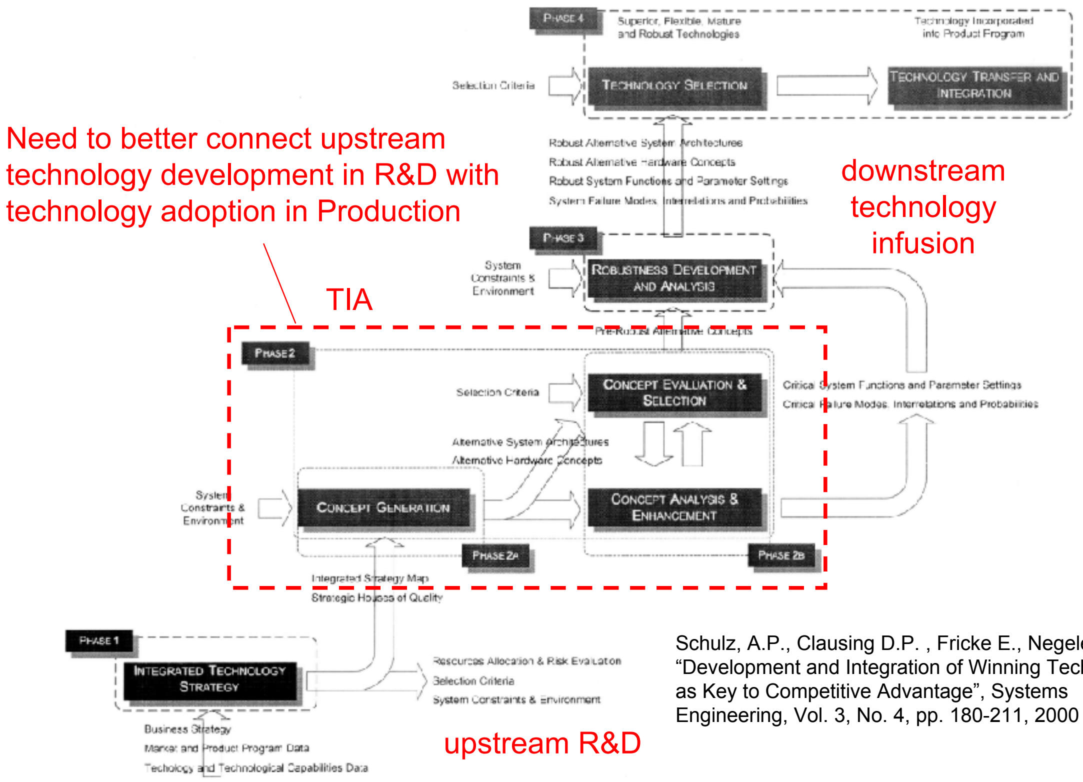
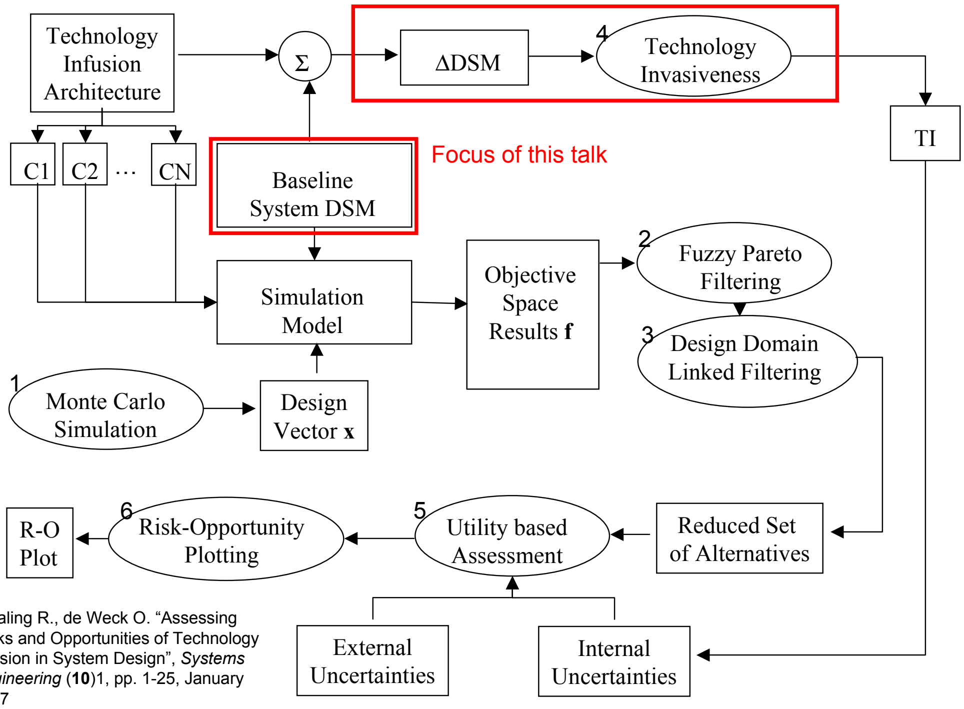


Schulz, A.P., Clausing D.P. , Fricke E., Negele H., "Development and Integration of Winning Technologies as Key to Competitive Advantage", Systems Engineering, Vol. 3, No. 4, pp. 180-211, 2000

Questions to answer

- What is the impact of the new technology on product performance, price and cost of ownership?
- How "disruptive" is the new technology to the existing baseline product?
  - changes required? R&D and integration effort?
  - This is the main step where DSM can help
- What are the risks and opportunities?
  - risk distribution of making it work reliably?
  - will the technology be worthwhile given exogenous uncertainties such as competition, regulations, customer preference shifts …?

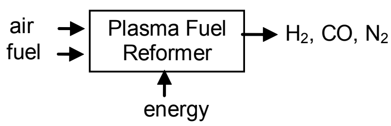
Technology Infusion Framework



Smaling R., de Weck O. "Assessing Risks and Opportunities of Technology Infusion in System Design", *Systems Engineering* (**10**)1, pp. 1-25, January 2007

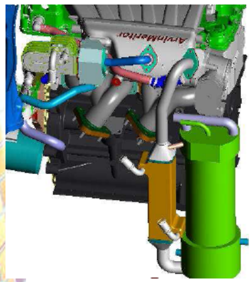
Example: Hydrogen Fuel Reformer

- Rising fuel prices
- Need for reducing toxic emissions
- Development of new technologies for cars and trucks
- Hydrogen Fuel Cells
  - broad adoption still decades away, challenges:
  - cost, H_2 on-board storage, distribution network for H_2
- Stepping Stone Technology: Hydrogen Fuel Reformer
  - Plasmatron, developed at MIT Plasma Fusion Center

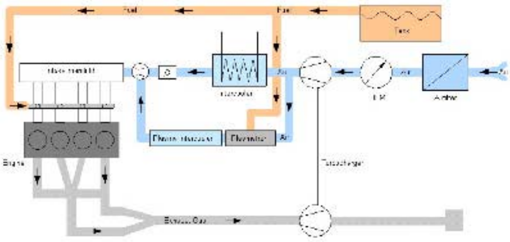


Integration on Test Vehicle

Source: Arvin Meritor



- Laboratory Testing (Plasmatron in Isolation)
- Test Integration in Vehicle:
  - Engine Compartment Physical Integration
  - Plasmatron Power (Electrical)
  - Supply Air & Fuel at Inlet
  - Route H_2-CO mixture to engine inlet manifold
- There are multiple concepts of how this can be done



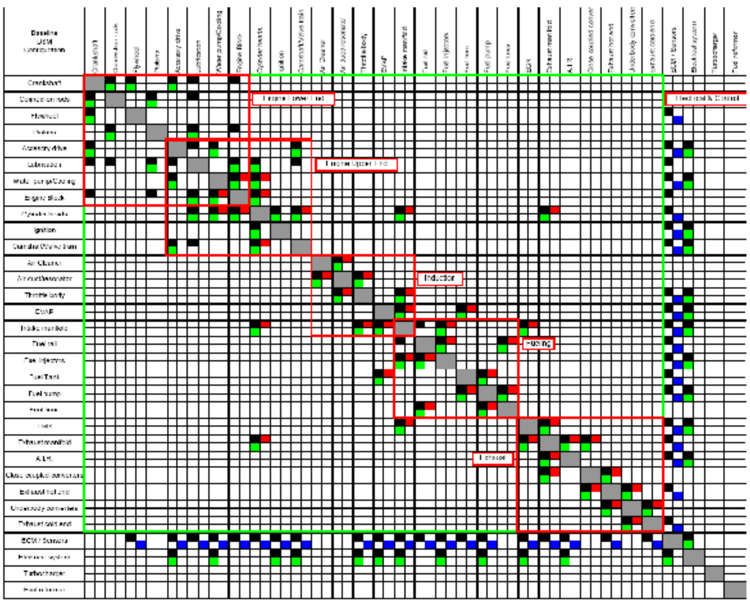
Baseline DSM

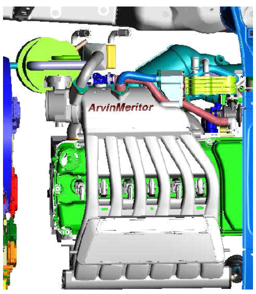
Object-based DSM

- "chunks" of product on main diagonal

-interconnections:

- -physical
- -energy
- -mass flow
- -information





Step 4.2: Record Changes

1. Change in the **physical relationship** between components
    a. Residing in the same module or sub-system
    b. Residing in a different module or sub-system
2. Change in **energy flow** between components
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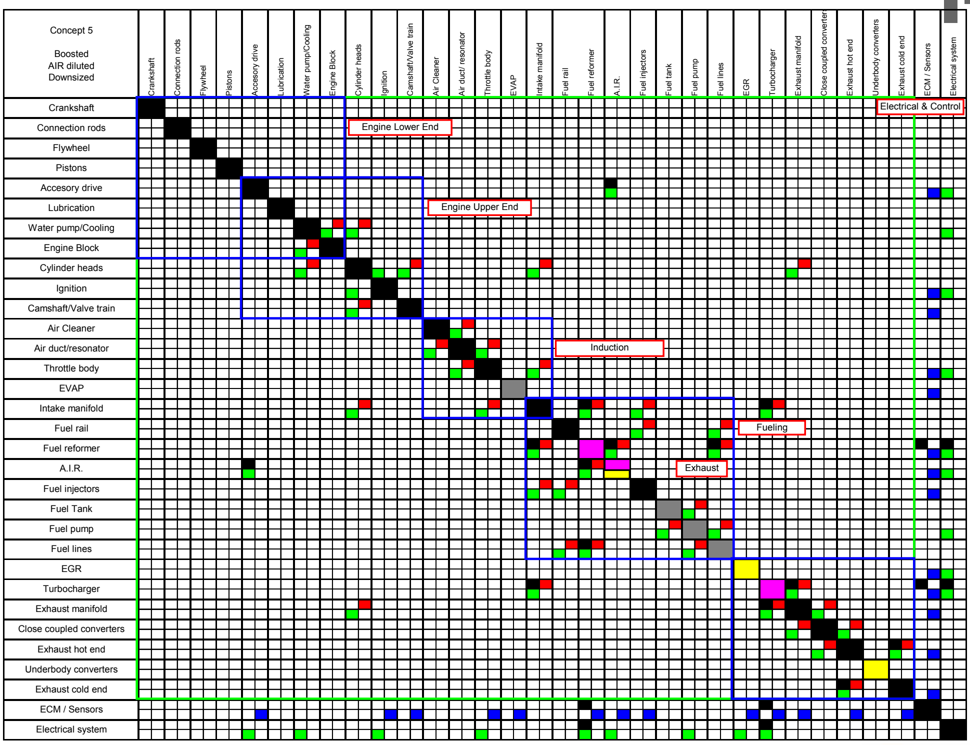
5. Change in **design of a component** (marked on the diagonal)
6. **Addition** of a component (marked on the diagonal)
7. **Elimination** of a component (marked on the diagonal)

Step 4.2 (cont.): ΔDSM



Step 4.3: Compute TI

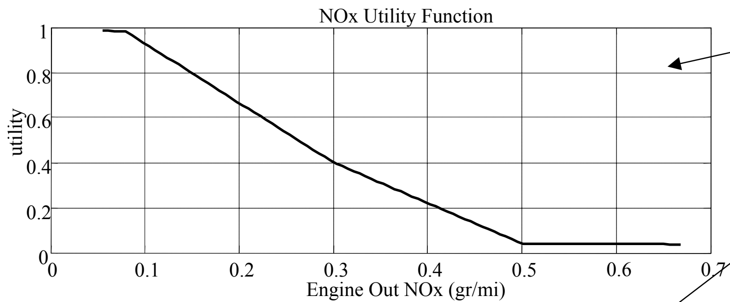
- Compute TI
- Sensitivity Analysis

$$TI_i = \sum_{j=1}^{8} w_j \sum_{k=1}^{N} \sum_{l=1}^{N} \Delta DSM^{i}_{j,k,l}$$

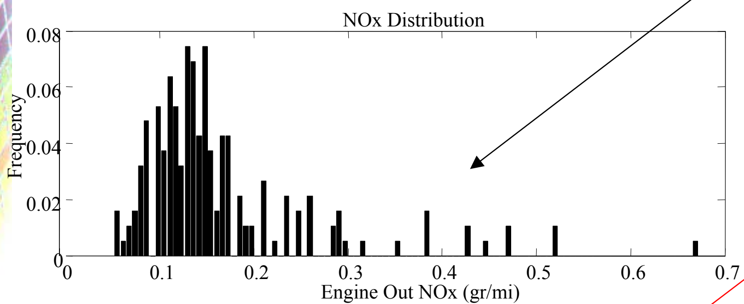
	Count	Weight	Multiplied
New component/subsystem	3	0.25	0.75
Eliminated component/subsystem	3	0.05	0.15
Component redesign	15	0.15	2.25
New inter-connection	7	0.15	1.05
New intra-connection	5	0.1	0.5
Change in mass flow	21	0.2	4.2
Change in energy flow	32	0.05	1.6
Change in controls	13	0.05	0.65
Invaseveness Index	11.15		

Alternative is to compute TI as the fraction of baseline DSM cells modified

Step 6: Compute Risk & Opportunity



Utility Curves from Scenarios



Distribution of Outcomes from Simulation

Risk

$$R_{pm} = \sum_i \left(pm(J_i)\left[U_{pm}(J_i) - U_{pm}(T_{pm})\right]\right)$$

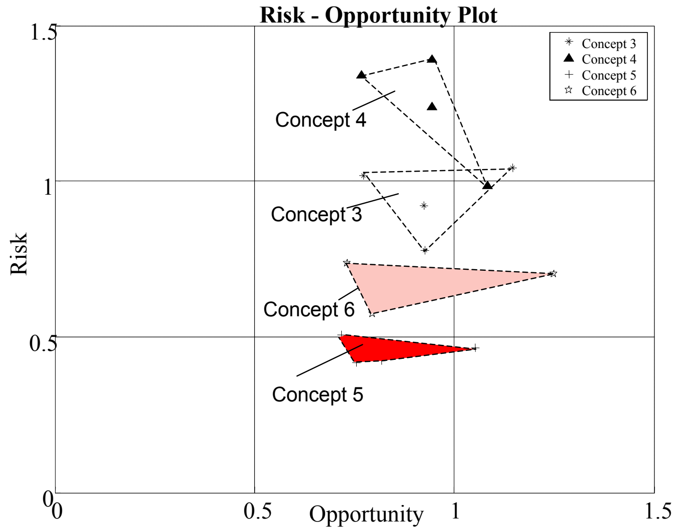
$$\forall J_i > T_{pm}$$

$$R_{Ci} = TI_i \cdot \sum_{j=1}^{k} w_j R_{pm,j}$$

Technology invasiveness influences risk

Step 6: Plot Risk vs. Opportunity

- Concepts 5 and 6 appear to be the most attractive
- Concepts 1 and 2 (naturally aspirated) were eliminated earlier
- Supports tech infusion decision making

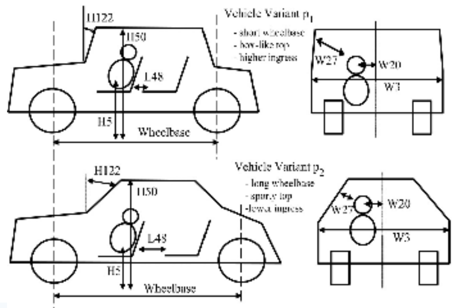


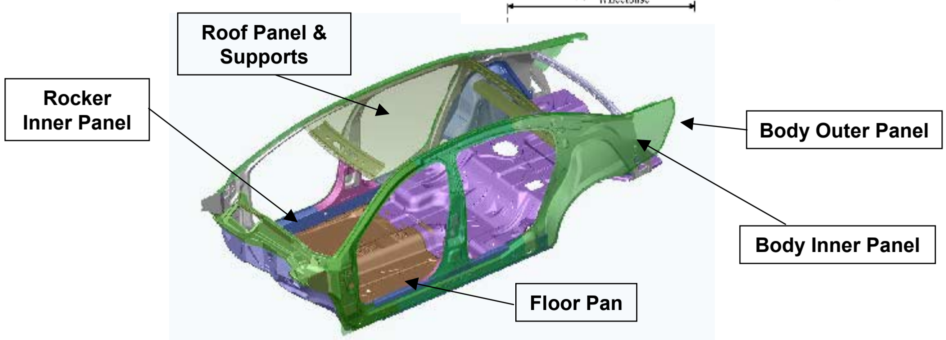
	T.I.	R_{FCI}	O_{FCI}	R_{NOx}	O_{NOx}	R_{CE}	O_{CE}	R_{TOT}	O_{TOT}
Concept 1	7.15	0.95	0.02	0.94	0.04	0.14	0.30	0.35	0.12
Concept 2	7.45	0.96	0.01	0.23	0.73	0.29	0.15	0.26	0.30
Concept 3	11.15	0.65	0.31	0.23	0.74	0.18	0.23	0.28	0.42
Concept 4	11.60	0.93	0.04	0.07	0.89	0.39	0.10	0.38	0.35
Concept 5	12.35	0.30	0.65	0.22	0.75	0.05	0.39	0.17	0.60
Concept 6	12.80	0.73	0.24	0.09	0.88	0.11	0.27	0.28	0.46

Vehicle Customization

Part 2 – Change–DSM

Suh E.S., de Weck O.L., and Chang D., "Flexible Product Platforms: Framework and Case Study", *Research in Engineering Design*, 18 (2), 67-89, August (2007)





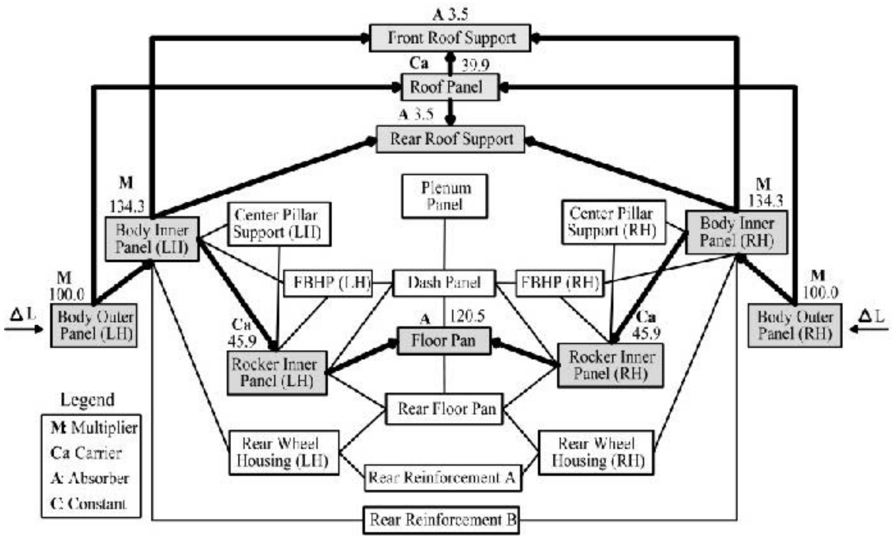
- Dimensions requiring differentiation = **H122, L48, W27, H50**
- Critical components identified through change propagation analysis*

Change-DSM

Component Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Change Received
Body Outer Panel (RH) ASM	1																						0
Body Outer Panel (LH) ASM	2																						0
Body Inner Panel (RH) ASM	3	1																					1
Body Inner Panel (LH) ASM	4		1																				1
Front Body Hinge Panel (RH) ASM	5																						0
Front Body Hinge Panel (LH) ASM	6																						0
Center Pillar Support (RH) ASM	7																						0
Center Pillar Support (LH) ASM	8																						0
Rocker Inner Panel (RH) ASM	9			1																			1
Rocker Inner Panel (LH) ASM	10				1																		1
Rear Wheel Housing (RH) ASM	11																						0
Rear Wheel Housing (LH) ASM	12																						0
Plenum Panel ASM	13																						0
Dash Panel ASM	14																						0
Front Floor Panel ASM	15									1	1												2
Rear Floor Pan ASM	16																						0
Rear Reinforcement A	17																						0
Rear Reinforcement B	18																						0
Roof Panel	19	1	1																				2
Front Roof Support	20			1	1															1			3
Rear Roof Support	21			1	1															1			3
Total Change Propagated Outwards (E_{out})		2	2	3	3	0	0	0	0	1	1	0	0	0	0	0	0	0	0	2	0	0	
CPI		2	2	2	2	0	0	0	0	0	0	0	0	0	0	-2	0	0	0	0	-3	-3	
Component Class		M	M	M	M					Ca	Ca					A				Ca	A	A	

BIW Change Propagation Network

- Identify:
  - change multipliers
  - components that are expensive to change



Conclusions

- Most products emerge through modifications to previous products and are not clean sheet designs
- **DSM**'s can be helpful in **mapping the changes** that are needed to:
  - Create a new variant of a product
  - Infuse a new technology into a product
  - Identify change propagation paths
- There are two change-related component-DSMs that have been developed in our research that are in industrial use:
  - **ΔDSM**
    - Shows only changes relative to a baseline component-DSM
    - Use to account for amount and type of change in a product
  - **Change-DSM**
    - Shows change propagation pathos from one component to another
    - Helpful to identify change multipliers and absorbers

More information at: http://strategic.mit.edu