Breaking Barriers between Product Lifecycle and Working Knowledge in Design

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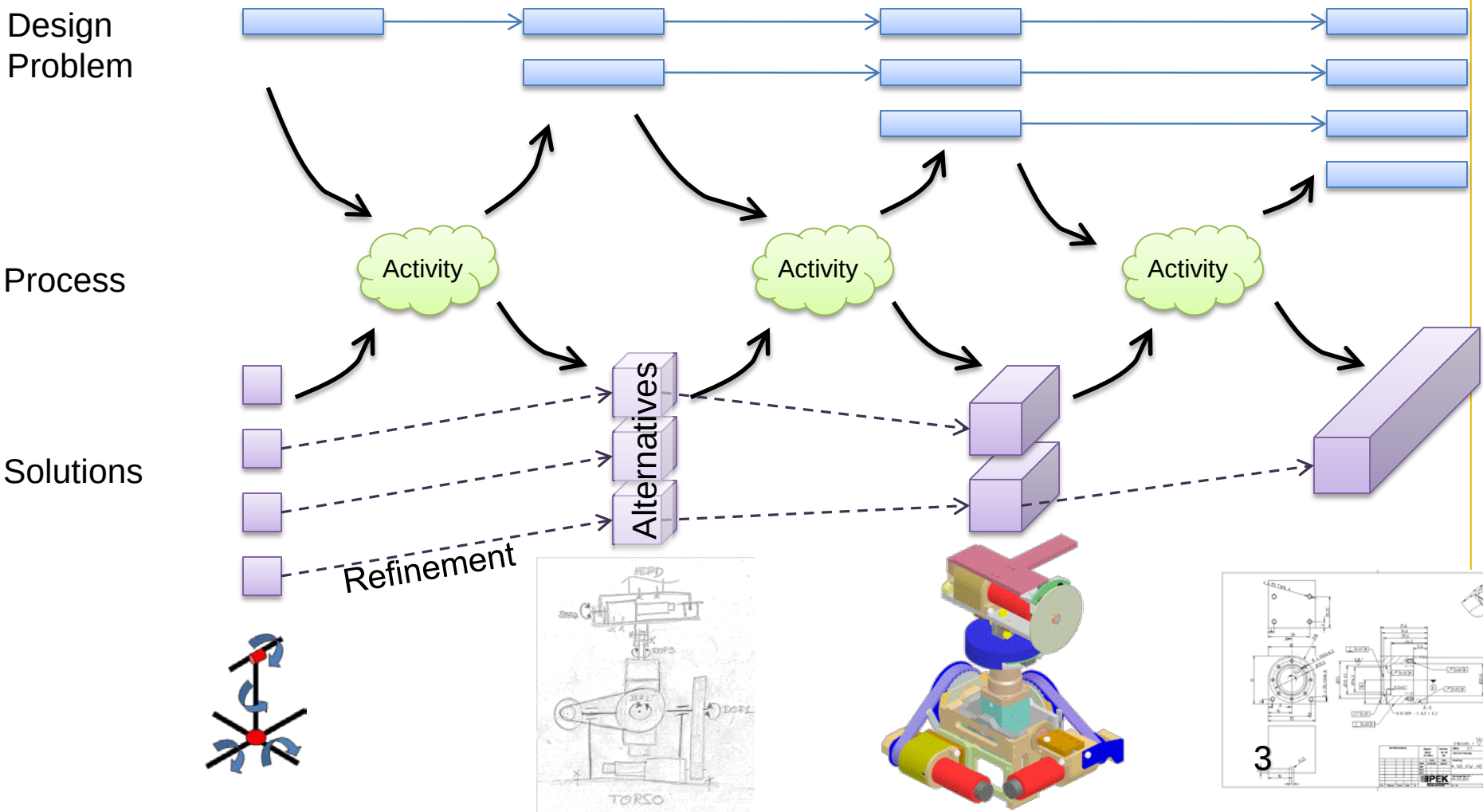
Introduction

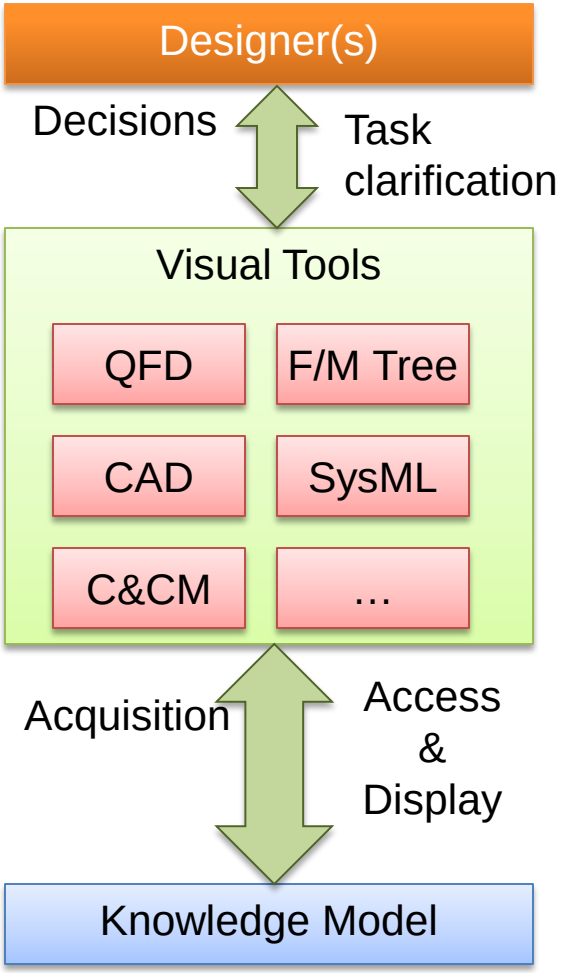
- Design has no *unique* solution, so *multiple alternatives* can exist (due to):
  - Several conflicting objectives
  - A requirement can be interpreted in several ways
  - Several solution principles / embodiments can achieve the same function
  - Different composition of multiple disciplines (For example, in mechatronic products)
- Moreover, each of these solutions can be described in *multiple levels* of *detail* and *abstraction*, for example
  - In the simplest case, an overall function broken into several simpler functions and so on
  - Overall geometry (assembly) described in detail through component models
  - The geometry of a single component can be described as a 2D sketch or a 3D drawing….

Design Process



Motivation

- Previous attempts to capture knowledge
  - Highly specialized tools
  - “Knowledge” engineer
  - Rationale management
  - Failed![1] – too much effort
- Tie visual tools to Knowledge Model
  - Already prevalent
  - No additional effort
  - *Need grammar for each visual*

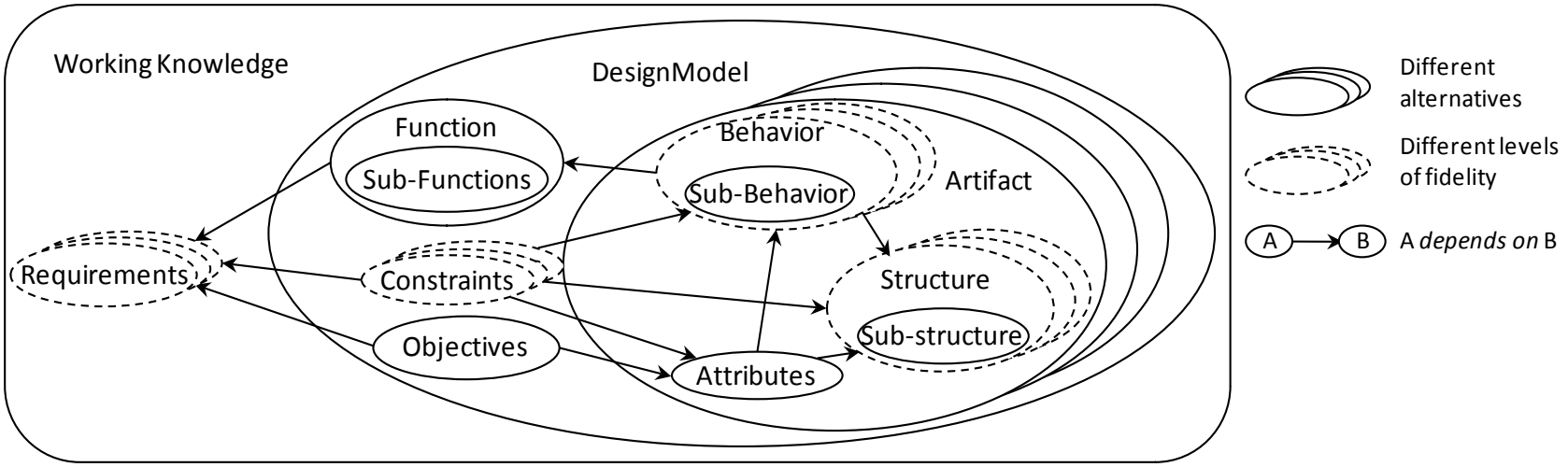


[1] P. Schütt, "The post-Nonaka Knowledge Management," *Journal of Universal Computer Science, vol. 9, pp. 451-462, 2003.*

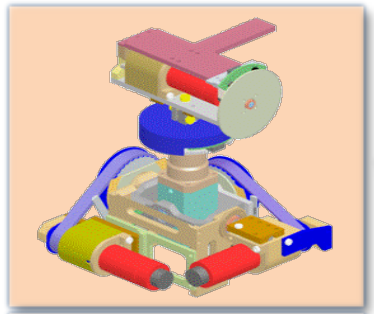
Working Knowledge

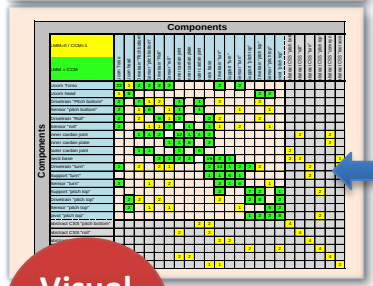
The working knowledge consists of:

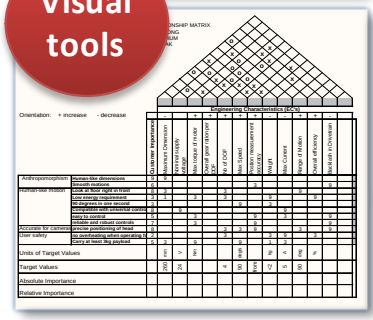
- Knowledge about function, form and behavior of the product being designed.
- Knowledge about constraints, objectives and requirements that the design should satisfy.
- The alternatives that exist at each stage in the design processed (expressed explicitly by the designer).
- Representation of these entities in different levels of abstraction



Vision







Visual tools

Current Work

PLM

←PDM

SLM→

Product Model

CAE Model

Analysis & Simulation tools

Finite Element Solver, etc.

WK Model

... Model

HoQ Model

Constraint problem

Constraint solver

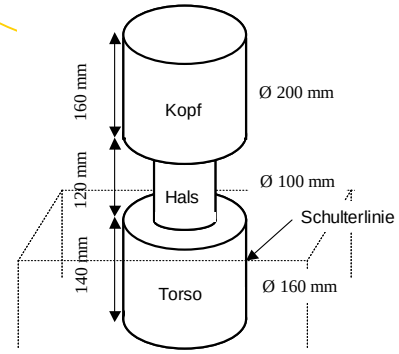
Optimization problem

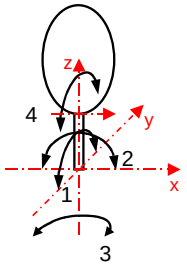
Optimizer

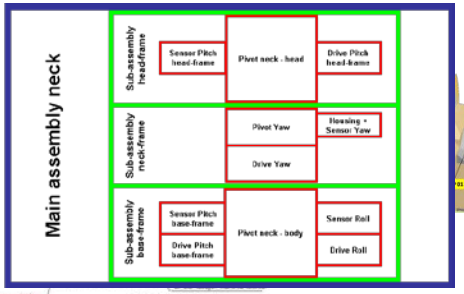
Decision support tools

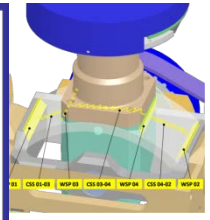
Future Work

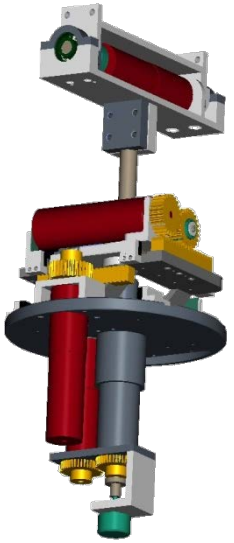
Visual Tools

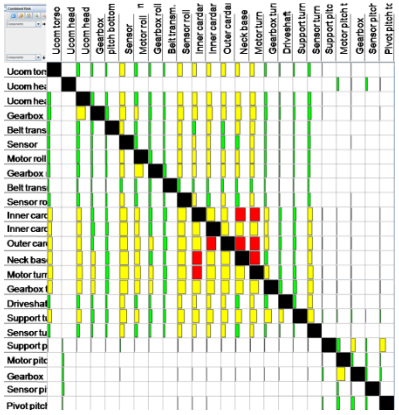




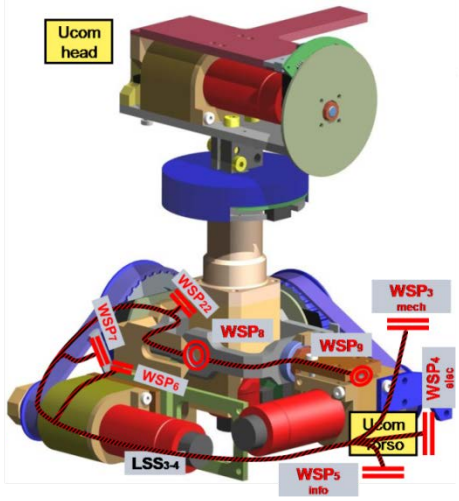


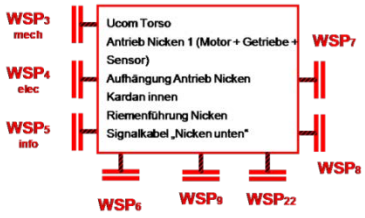


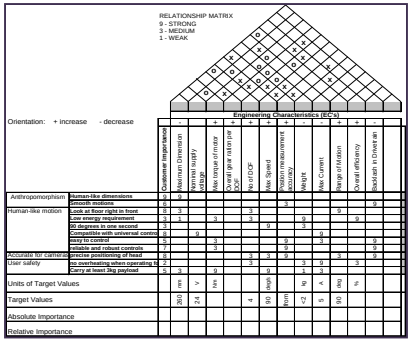


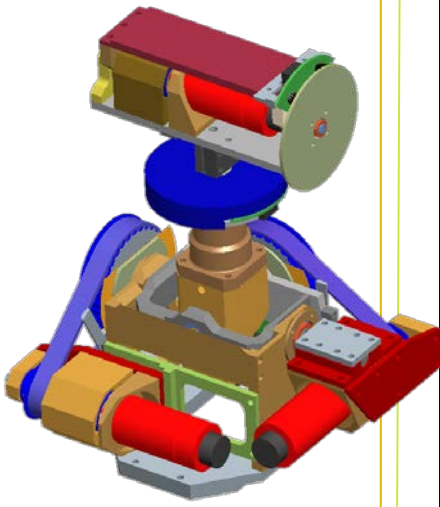


- Stage: operation
- Main function: Moving and positioning of robot head
- Sub-function: move head relative to torso / "pitch bottom"









Visual Tools

Established design characteristics	Typical visual tool used (from [3] and [20])	Additional visual representations / tools
Design Specification		*SysML requirements diagram*
Black box	Black box diagram	
Establish technological principles and sequence of operation		
T.P.1, T.P.2, T.P.n → Optimal technical process	Technical process diagram	
Group functions based on boundaries of technical processes	*QFD 1*	
F.S.1, F.S.2, F.S.n → Optimal function structure	Function-structure schematic	*Hierarchical Function structures*
Families of organs (function carriers); Combination and basic arrangement	*Morphological matrix*	
Con.1, Con.2, Con.n → Optimal organ structure	Organ structure • Conceptual sketch • *Conceptual schematic*	*AND-OR trees*
Parts, arrangement, rough form, some dimensions, material and manufacturing	QFD 2, Concept selection table	
P.L.1, P.L.2, P.L.n → Optimal preliminary layout	Component structure • *Preliminary layout sketch*	
Definitive arrangement, form, all dimensions; Material & manufacturing, partial tolerances;		*SysML parametric diagram for equations* Design sets visualization • Pareto fronts • Interval box representations • *Polytope approximation*
D.L.1, D.L.2, D.L.n → Optimal dimensional layout	Component structure • Dimensional layout (scale)	
Release for detailing		

Legend
T.P. – Technical Process
F.S. – Function Structure
Con. – Concept
P.L. – Preliminary Layout
D.L. – Dimensional Layout
Note: Visual tools implemented are indicated with *italics*.

Approach

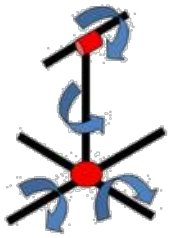
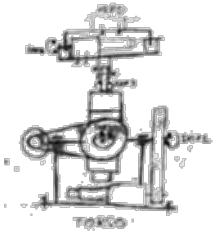
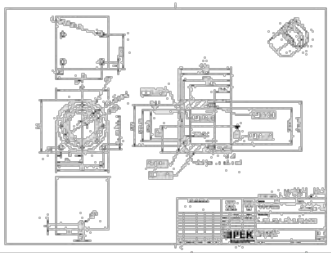
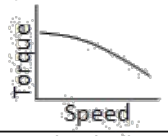
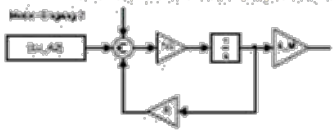
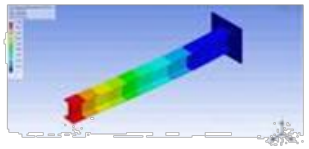
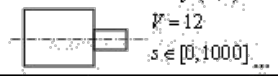
- What is working knowledge?
  - Need to understand the design process
- Develop a simple model of working knowledge using existing design concepts
- Connect the WKM to visual tools

Modeling Concepts

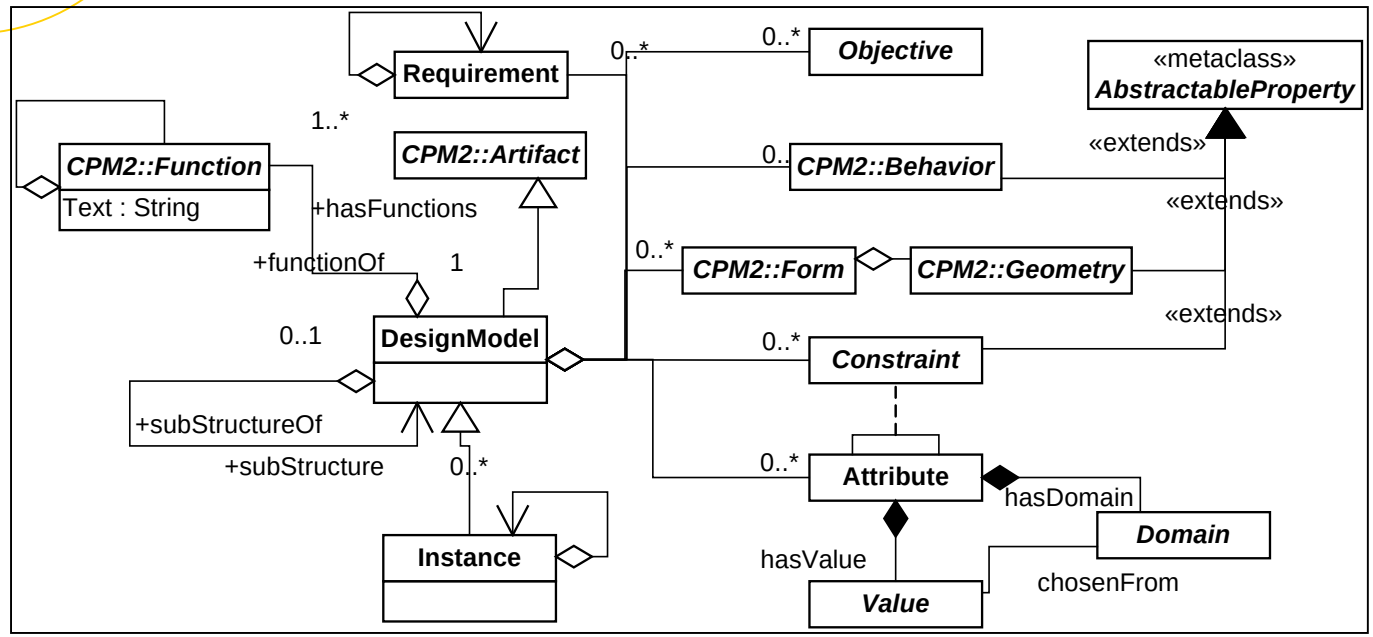
Legend
- ◆ Only a few
- ○ Many
- ⊙ Almost all

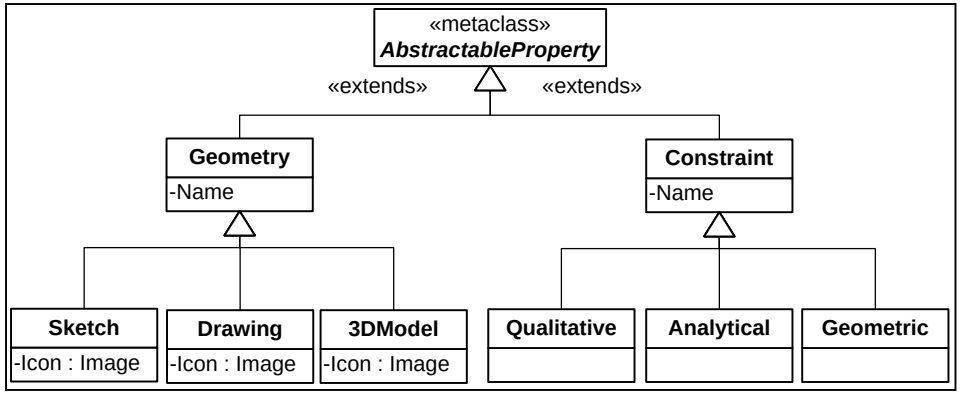
Concepts \ Models	Design Knowledge Models	Design Repositories	Individual Artifacts	PLM/PDM Systems	Hierarchical Synthesis	Configuration and Generative Design	Parametric Design	Working Knowledge Model
Requirements	○	○	◆	⊙				✓
Specifications		○	⊙				○	
Structure								
Architecture		⊙	⊙	⊙		○		✓
Topology	○	⊙	○			⊙	○	
Function								
Hierarchical Structure		○	○	◆	⊙			✓
Flow Structure		○	○		◆	○		
Rationale	⊙		◆	◆				
Constraints								
Numerical	◆		◆		◆	○	⊙	✓
Qualitative						◆		✓
Logical	○				○	○		✓
Semantic	⊙					⊙		
Geometry								
Assembly structure		○	○	⊙		◆	○	✓
Part Features			◆	◆				
Ports			◆			○	○	
Behavior	◆	◆	○			◆	⊙	
Hierarchical Behavior							○	
Objective	○				◆	○	⊙	✓
Alternative								
Architecture/Design		◆			⊙	⊙		✓
Geometries				⊙				✓
Constraints				○	○		○	✓
Abstractions								
Product				◆				✓
Geometry				○				✓
Constraints								✓
Behavior				◆			○	

Abstractions of concepts

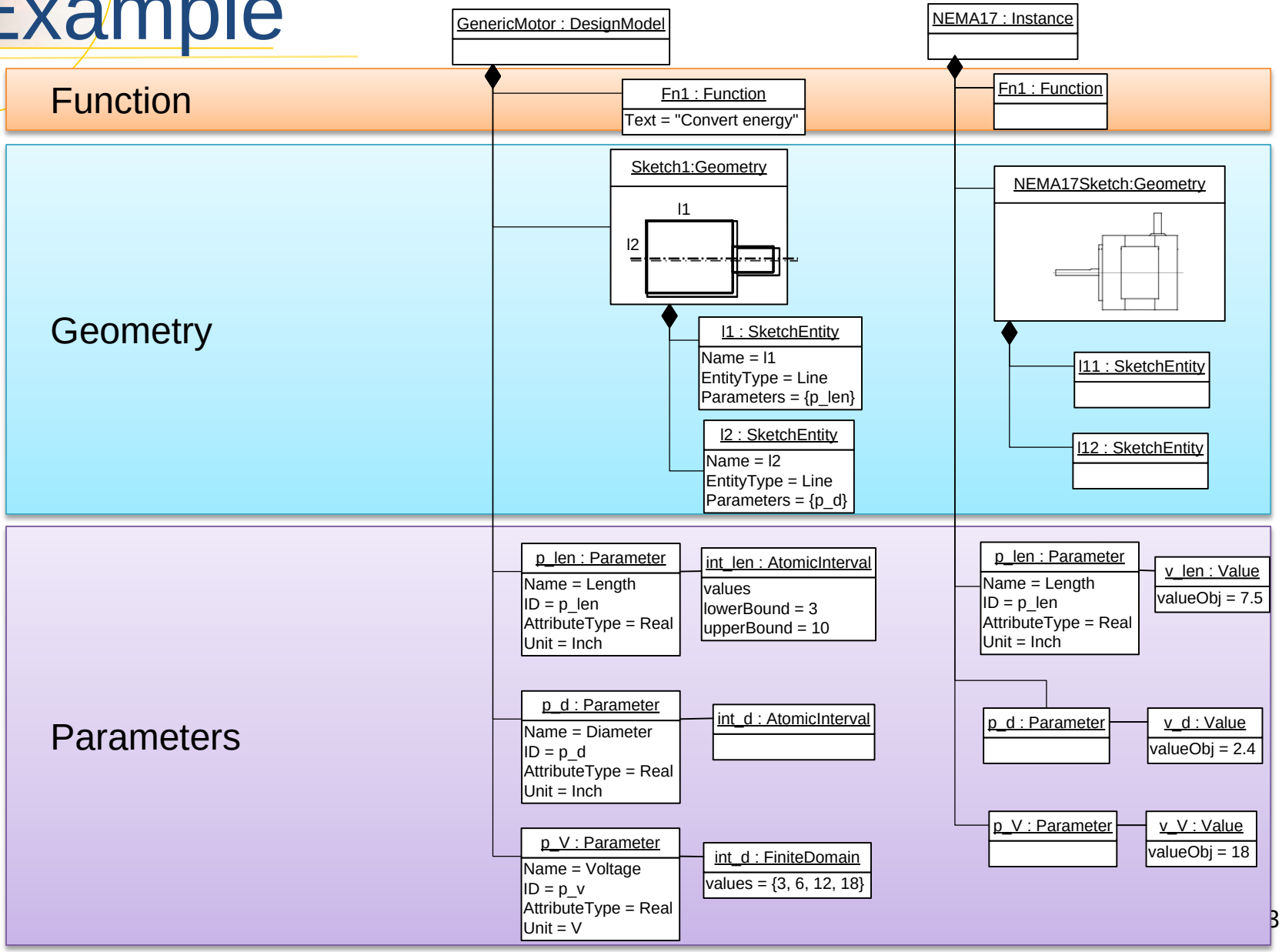
Element	Abstract → Level of Abstraction → Concrete				
Geometry	*Line diagrams* 	*Rough sketches* 	*2D Drawings*	*3D CAD Models* 	*Detailed manufacturing drawings* 
Function/ Behavior	*Qualitative descriptions* "converts electrical energy to mechanical energy"			*Charts and tables* 	*Detailed Simulation* 
Constraint / Analytical relationship	*Qualitative relationships* $l \xrightarrow{+} \delta$ and $h \xrightarrow{-} \delta$ (read as δ decreases monotonically with h)			*Simple algebraic calculations* $\delta = \frac{Wl^3}{8Eh}$	*Detailed analysis* 
Objective	*Qualitative words* Should be responsive				*Quantitative* $\max V$
Material	*Generic class* Metal	*Material class* Aluminum			*Specific material* AlZnCuMg1.5
Design Description	*Solution principle*	*Concept* A "motor" 			*Final artifact* A specific stepper motor model "NEMA 17 S91" 

Working Knowledge Model





Example

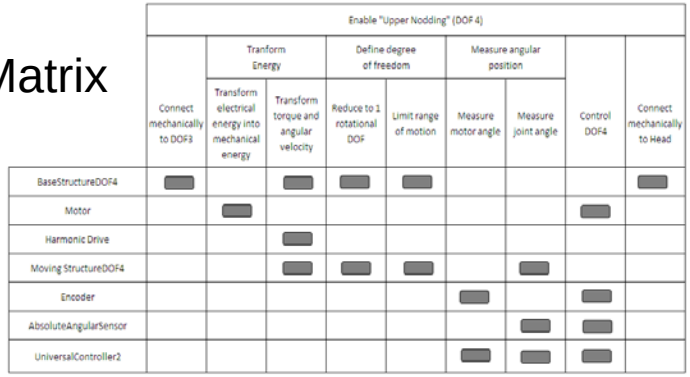

GenericMotor : DesignModel
NEMA17 : Instance
Function
Fn1 : Function
Text = "Convert energy"
Fn1 : Function
Geometry
Sketch1:Geometry
l1
l2
NEMA17Sketch:Geometry
l1 : SketchEntity
Name = l1
EntityType = Line
Parameters = {p_len}
l2 : SketchEntity
Name = l2
EntityType = Line
Parameters = {p_d}
l11 : SketchEntity
l12 : SketchEntity
Parameters
p_len : Parameter
Name = Length
ID = p_len
AttributeType = Real
Unit = Inch
int_len : AtomicInterval
values
lowerBound = 3
upperBound = 10
p_len : Parameter
Name = Length
ID = p_len
AttributeType = Real
Unit = Inch
v_len : Value
valueObj = 7.5
p_d : Parameter
Name = Diameter
ID = p_d
AttributeType = Real
Unit = Inch
int_d : AtomicInterval
p_d : Parameter
v_d : Value
valueObj = 2.4
p_V : Parameter
Name = Voltage
ID = p_v
AttributeType = Real
Unit = V
int_d : FiniteDomain
values = {3, 6, 12, 18}
p_V : Parameter
v_V : Value
valueObj = 18

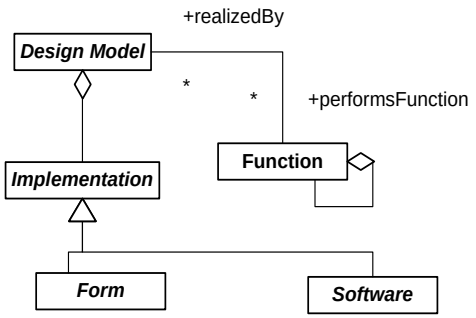
Visual tools and WKM

Concepts \ Visual tool	SysML Requirement Diagram	Hierarchical Function Structures	House of Quality 1	Morphological Matrix	2D Drawing	SysML Parametric Diagram	**Working Knowledge Model**
Requirements	✓(complete)		✓(complete)				✓
Structure							
Architecture				✓(as Means)			✓
Topology					✓(only Geometric)		✓(only Geometric)
Function							
Hierarchical Structure		✓(complete)	✓(as Requirement)	✓(complete)			✓
Flow Structure							
Constraints							
Numerical	✓(possible)		✓(as Targets)		✓(possible)	✓(only equality)	✓
Geometric					✓(complete)		✓
Qualitative			✓(in Roof)				✓
Logical							✓
Semantic	✓(possible)						
Geometry							
Assembly structure					✓(complete)		✓
Part Features					✓(complete)		
Objective	✓(possible)		✓(as Objective)				✓
Alternative							
Architecture/Design			✓(as Competition)	✓(as Means)			✓
Geometries							✓
Constraints							✓

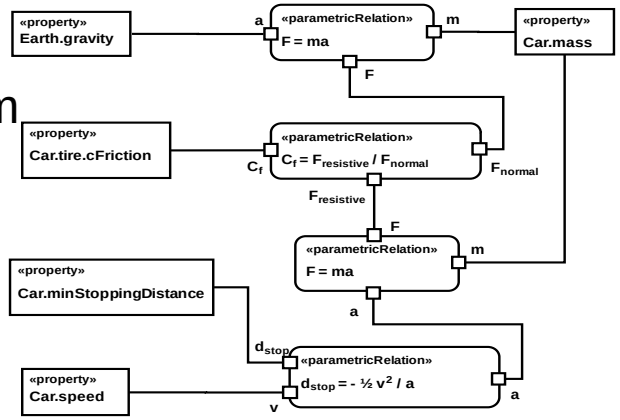
Visual Tool Grammar - examples

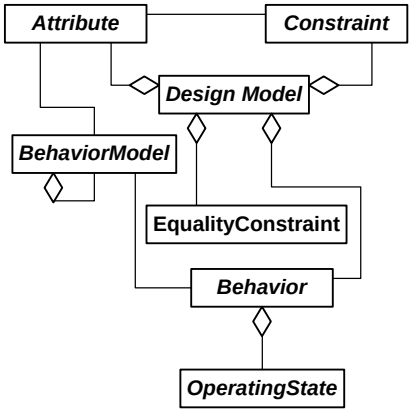
Function-Component Matrix





SysML Parametric Diagram





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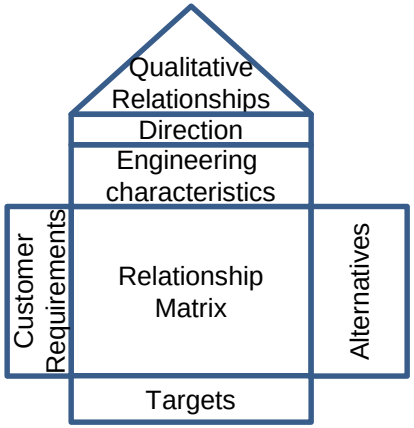
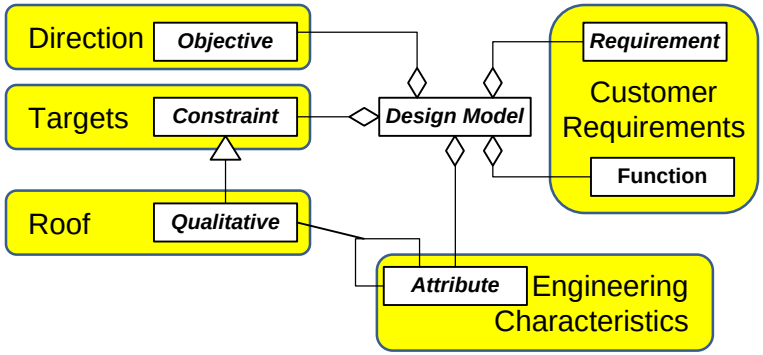
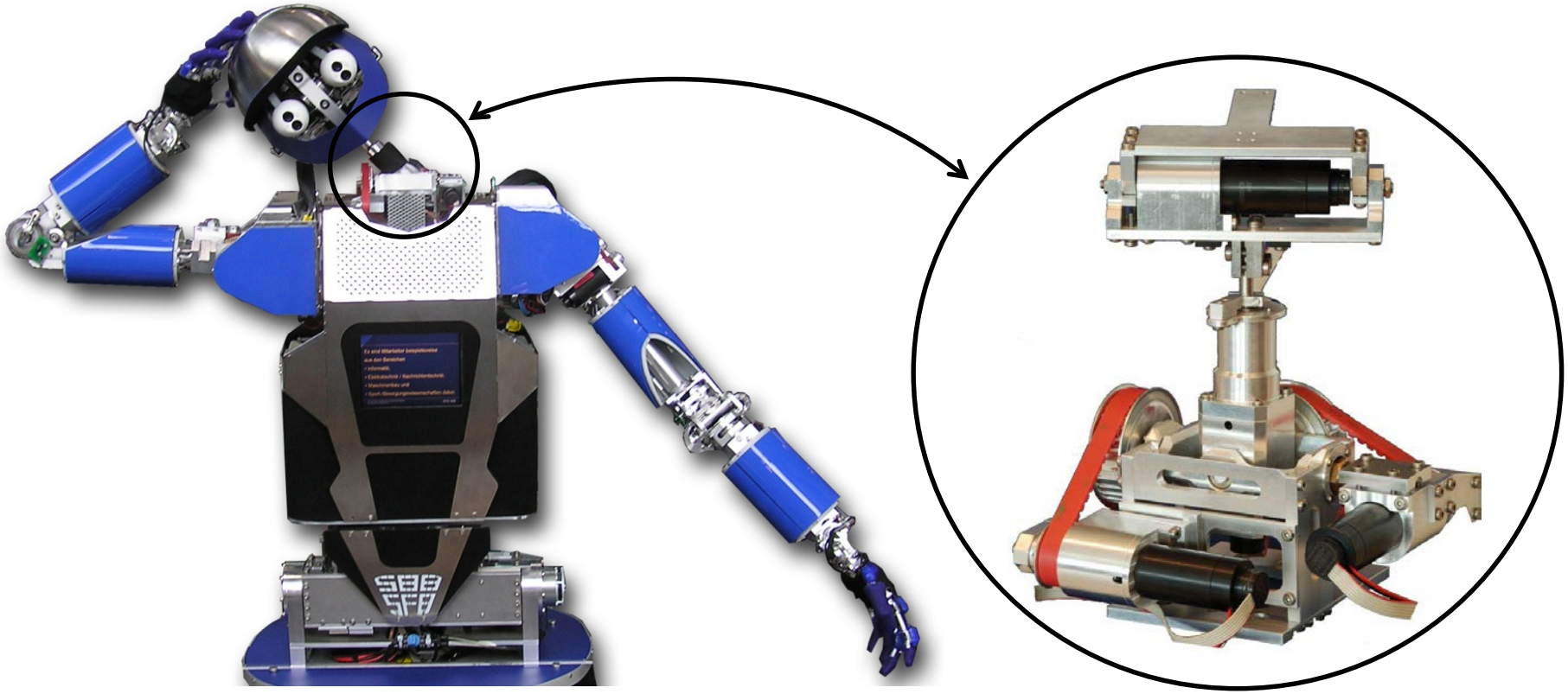
Visual Tool Grammar - examples

HoQ



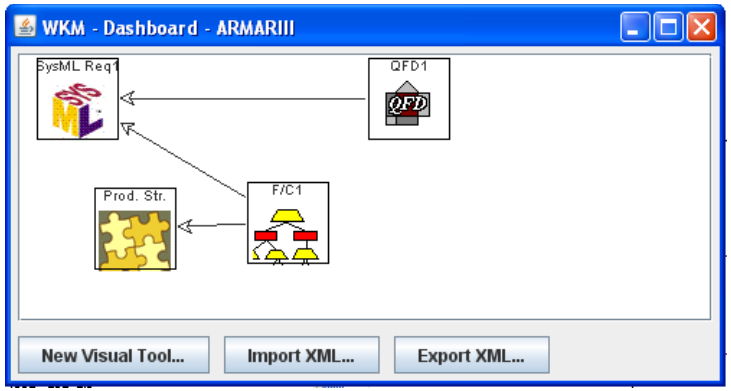


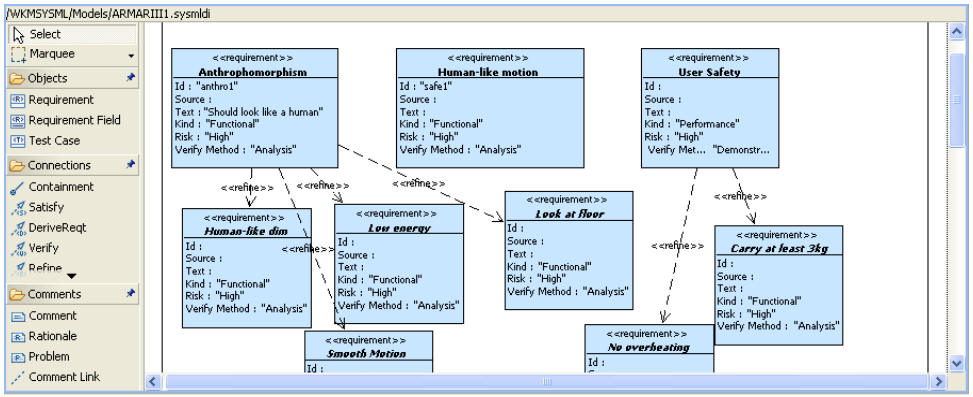
Case Study I



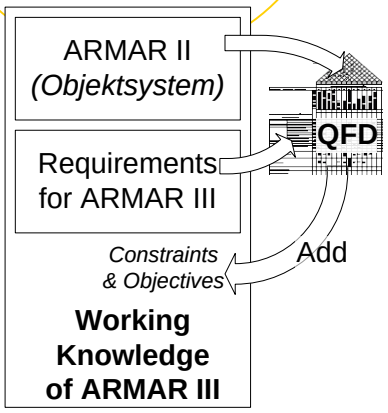
Humanoid Robot Neck – ARMAR III – Universität Karlsruhe, Germany

ARMAR III Case Study



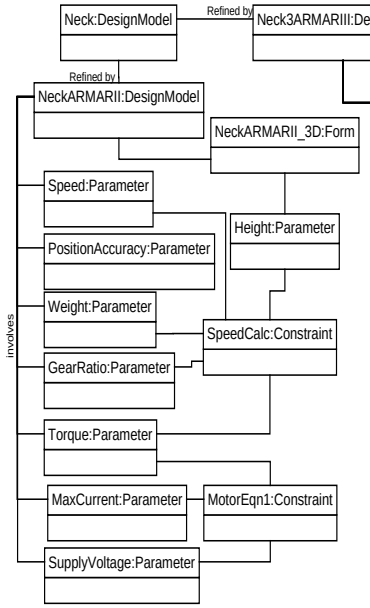


HoQ of ARMAR III

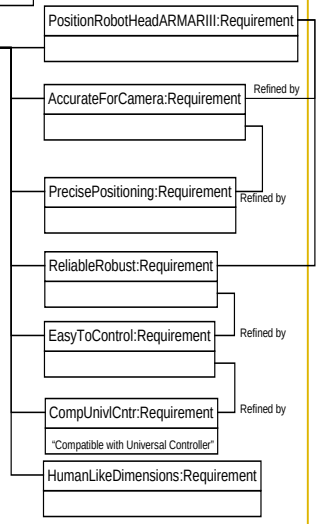


House of Quality - HoQ1

Requirement \ Parameter		Max. Dim	Supply. Volt.	Max. Torque	Gear Ratio	No. DOF	Max Speed	Pos. Acc.	Weight	Max. Curr.	Motion Range	Efficiency	Backlash
Direction		-		+	+	+	+	+	-	-	+	+	-
Human-like dim	9	9											
Smooth Motion	6							3					9
Look at floor	8	3				3					9		
Low energy	3	1		3		3				9		9	
90deg per sec	3						9			3			
Universal Contr.	8		9										
Easy to control	5			3				9					9
Reliable and robust	7			3				9					9
Precise positioning	8					3	3	9			3		9
No overheating	2					3			3			3	
Carry at least 3kg	5	3		9			9		1				
Constr/Tgt		60	24			4	90		<2	5	90		
Unit		nm	V	Nm			°/s		kg		de	%	

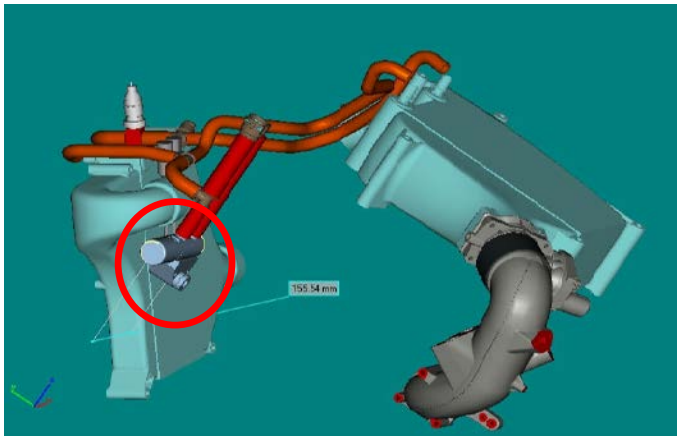


Partial instance of ARMARII neck

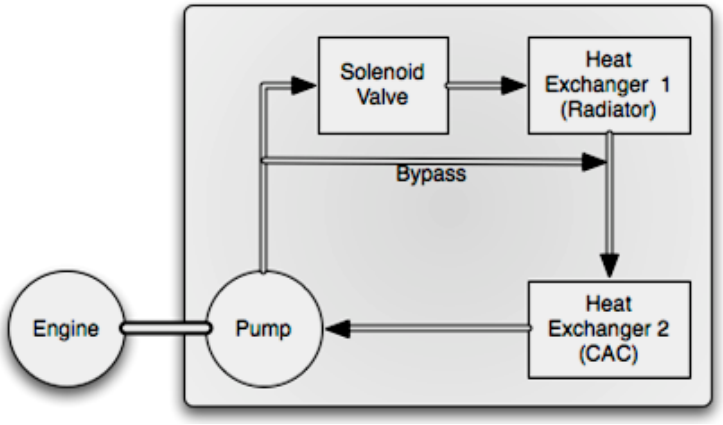


Partial listing of ARMAR III requirements

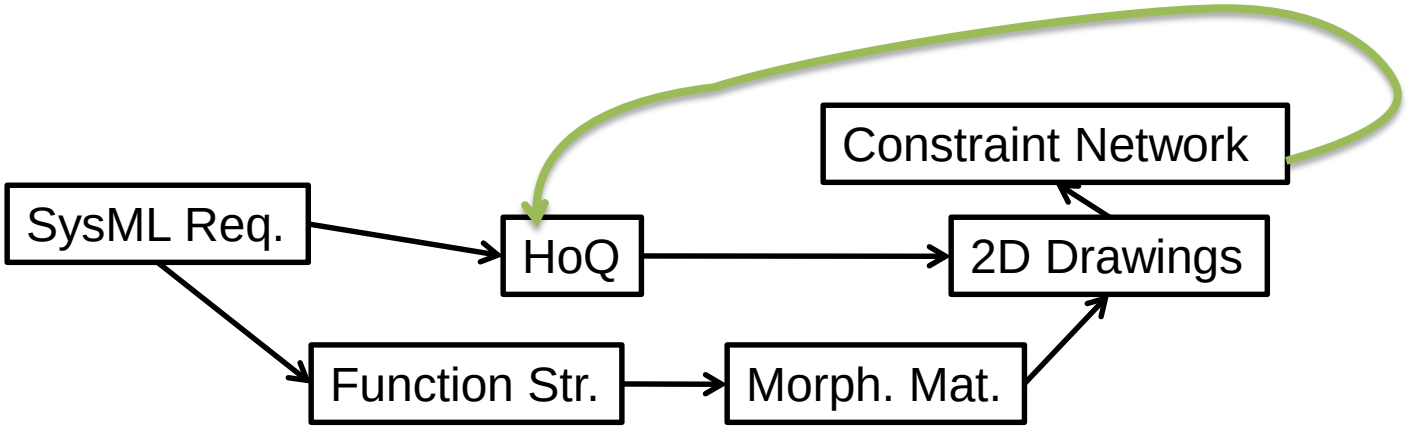
Case study II



Coolant valve for IC engine

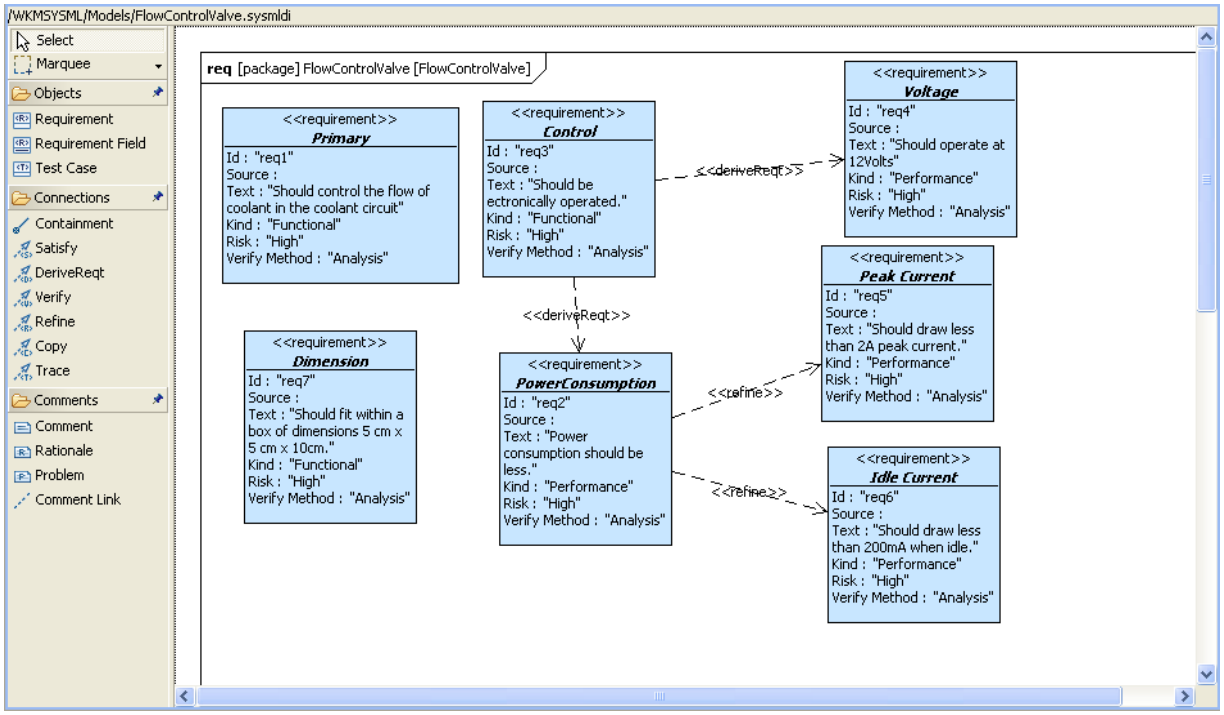


Schematic

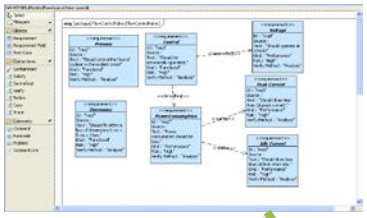


Coolant Valve Requirements

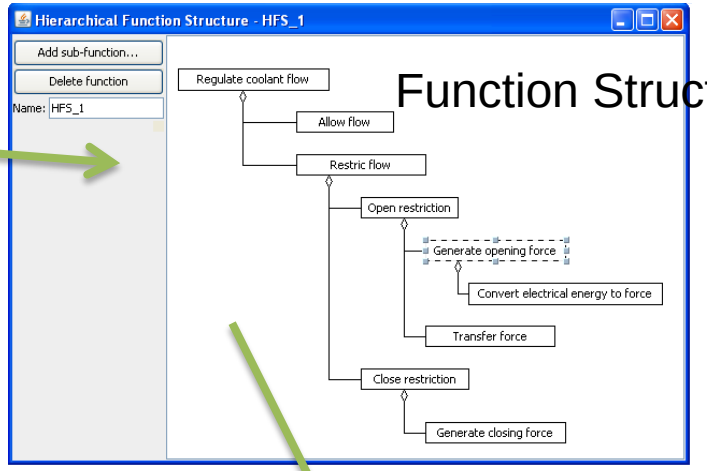
SysML Requirements diagram



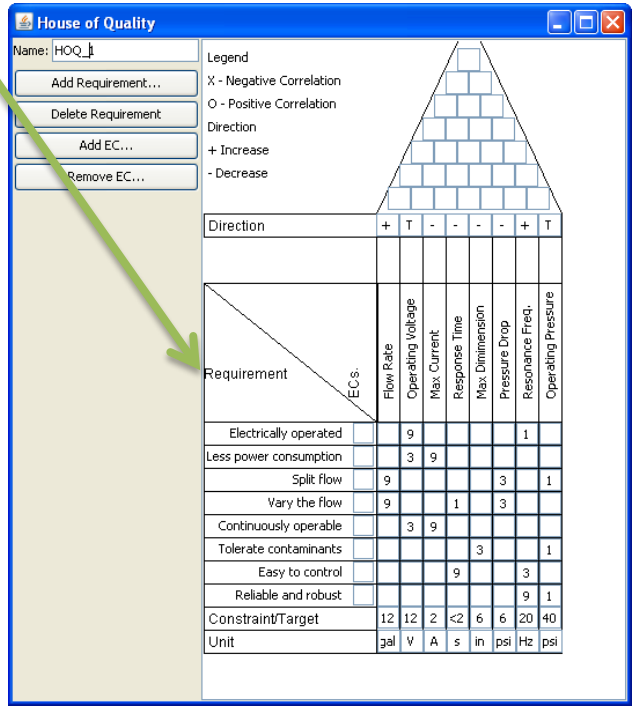
Coolant Valve Design

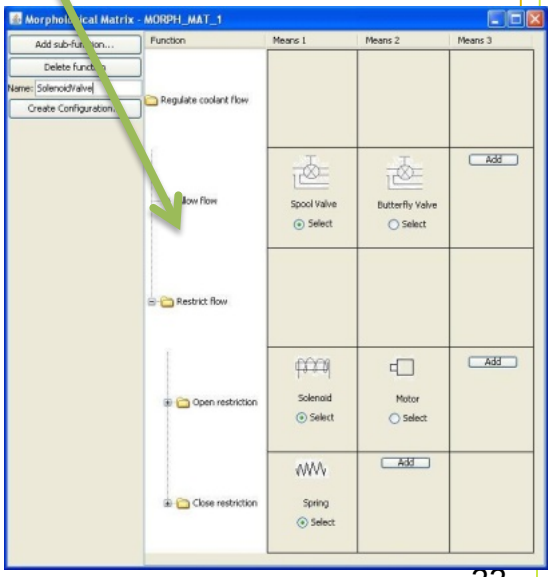


Function Structure



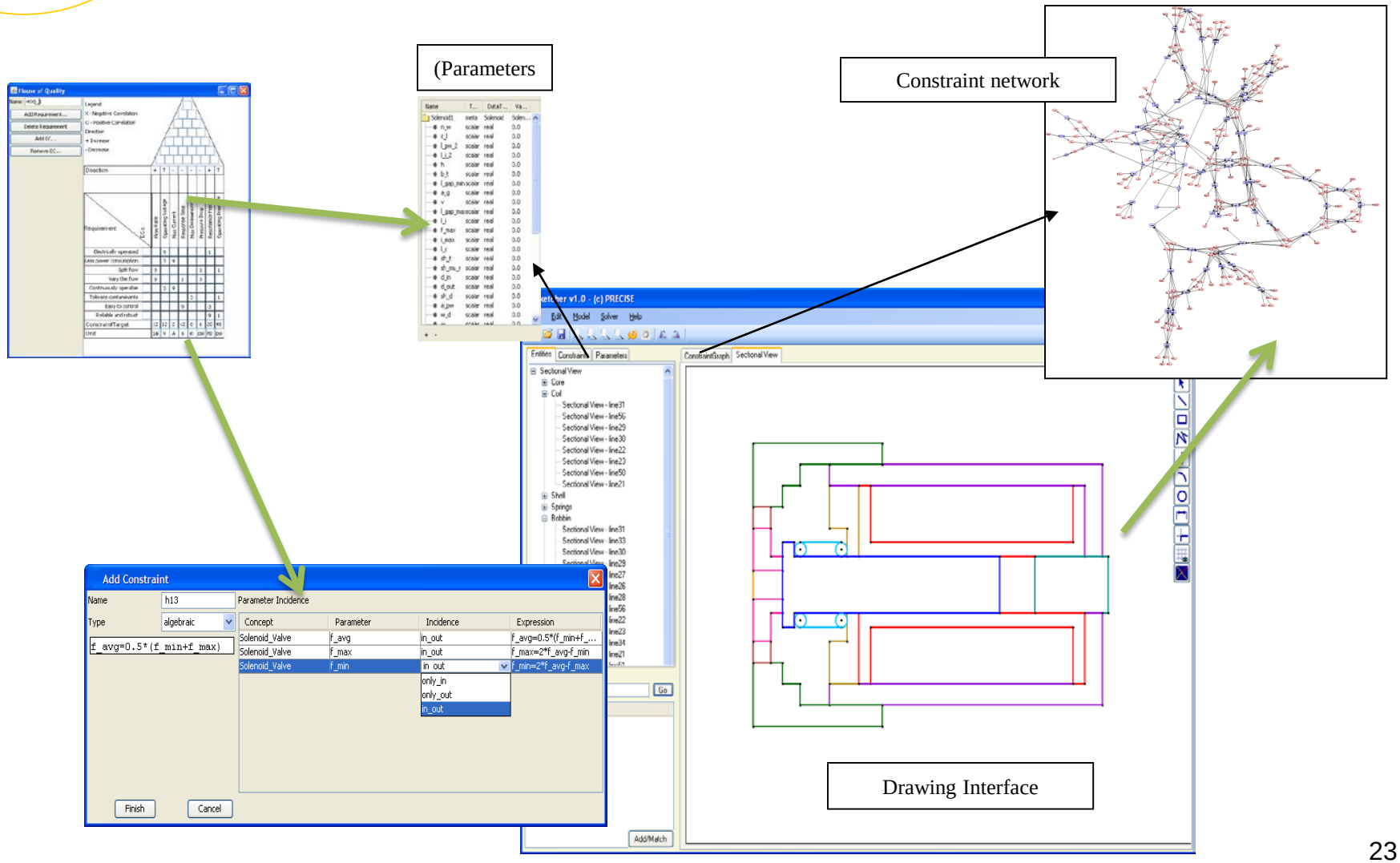
House of Quality



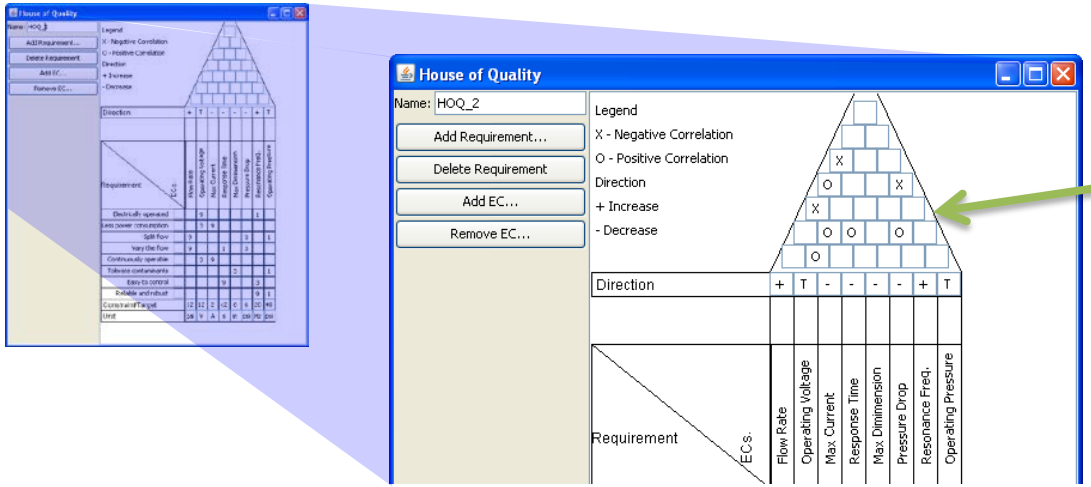


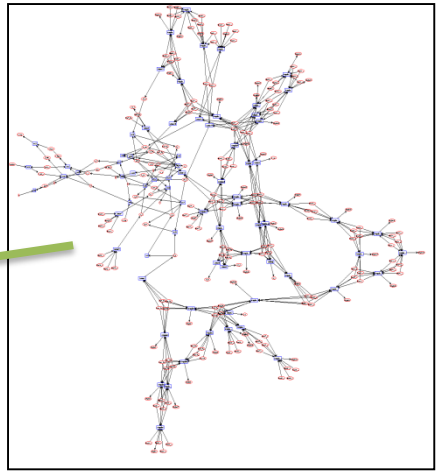
Morphological Matrix

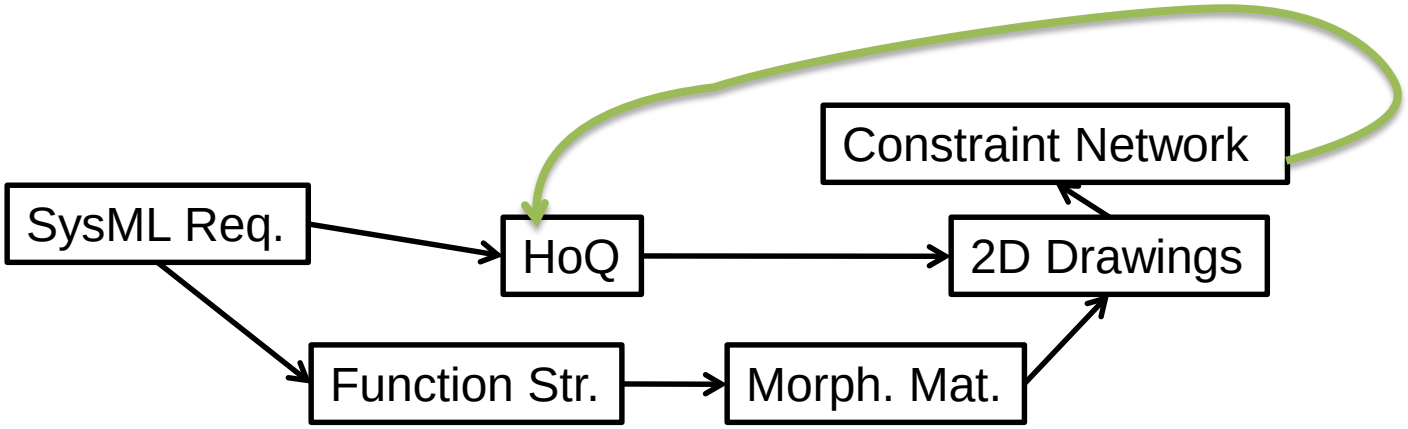
Coolant Valve Design



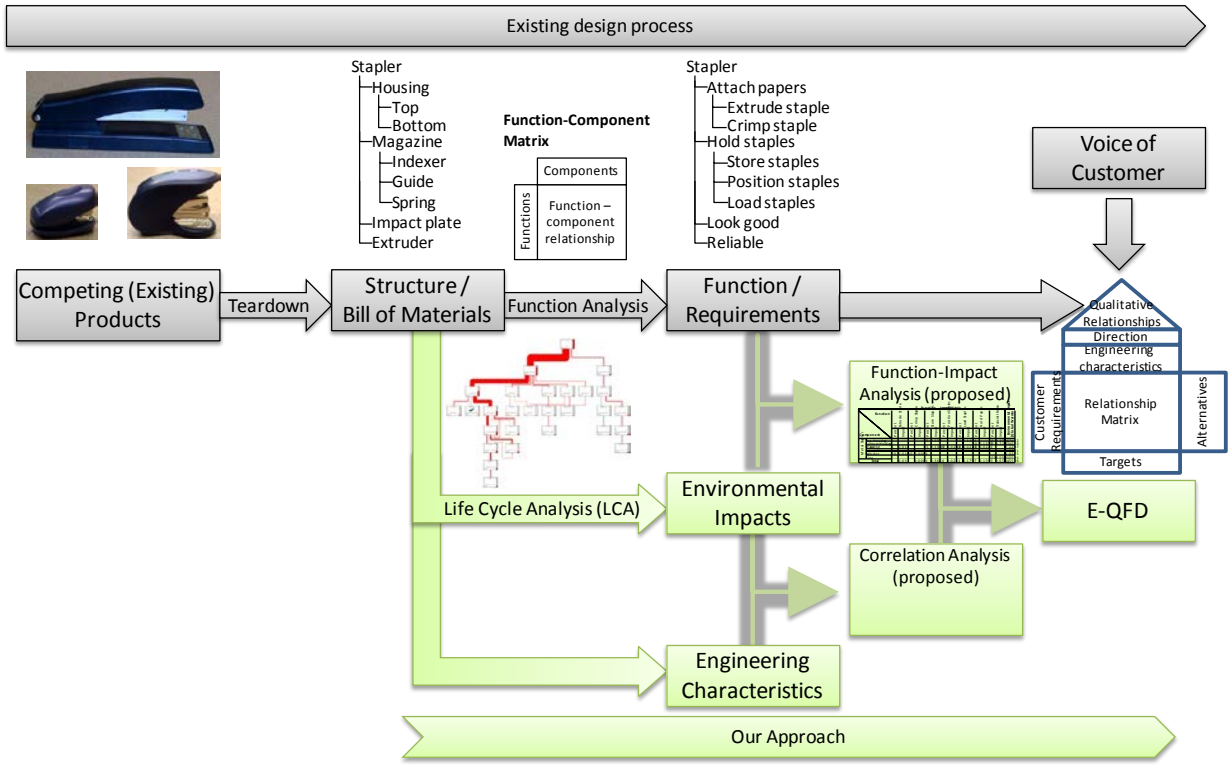
Coolant Valve Design

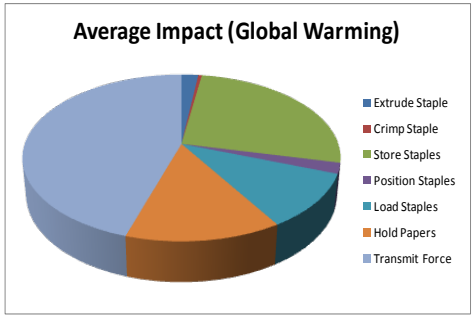






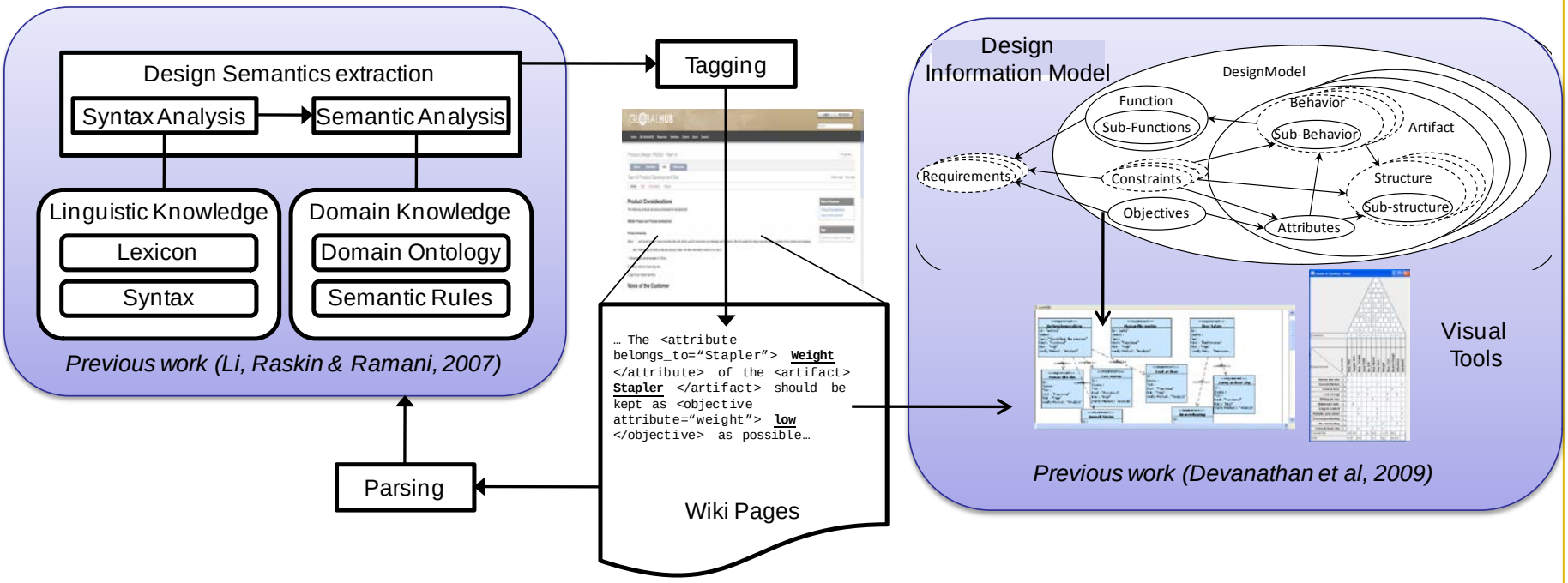
Application – Design for Sustainability



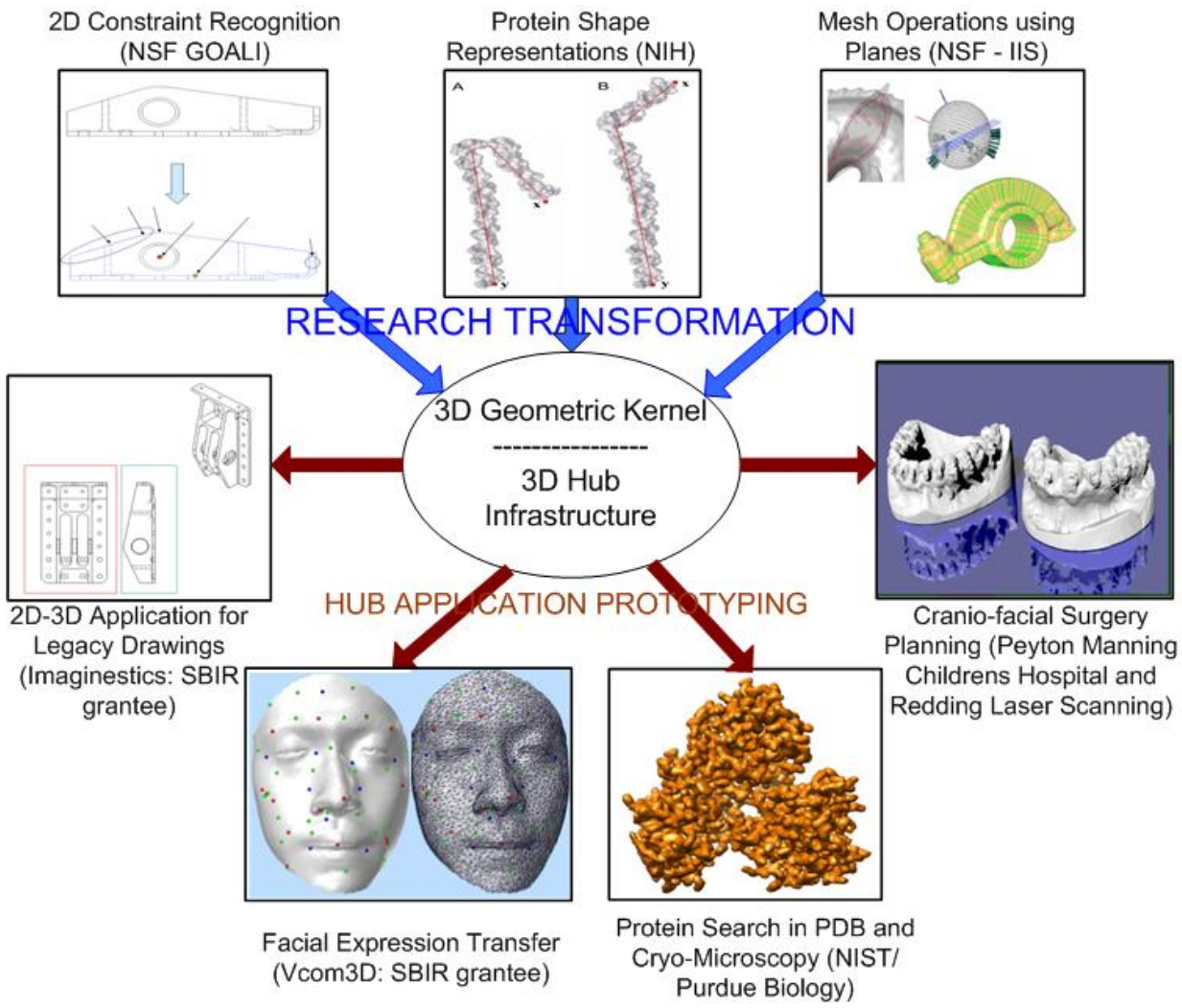


Contribution of each function to the overall impact of the stapler.

Future work – Wiki Integration



3D Hub


2D Constraint Recognition (NSF GOALI)
Protein Shape Representations (NIH)
Mesh Operations using Planes (NSF - IIS)
RESEARCH TRANSFORMATION
3D Geometric Kernel
3D Hub Infrastructure
HUB APPLICATION PROTOTYPING
2D-3D Application for Legacy Drawings (Imaginestics: SBIR grantee)
Cranio-facial Surgery Planning (Peyton Manning Childrens Hospital and Redding Laser Scanning)
Facial Expression Transfer (Vcom3D: SBIR grantee)
Protein Search in PDB and Cryo-Microscopy (NIST/ Purdue Biology)

Conclusions

- Working knowledge is much more than product data:
  - Contains all the alternatives that were considered, and the relationships between them to easily reason among them
  - Allows reasoning about the design in any level of detail and abstraction
- Important aspect of working knowledge
  - Allows setup of commonly used computational (simulation, optimization, configuration etc.) and manual (QFD, Morphological matrix, etc.) decision support tools
  - The decisions and the rationale (knowledge) taken using the support tools are added back into the working knowledge
  - Contains the information about what design tasks have been performed and what tasks have to be done… (This is future work)

Publications

1. S. Devanathan, C. Sauter, A. Albers, and K. Ramani. A working knowledge model for supporting early design through visual tools, in International conference on engineering design, ICED'09, Stanford, CA, 2009.
2. S. Devanathan and K. Ramani, "Creating Polytope Representation of Design Spaces for Visual Exploration Using Consistency Technique," IDETC/CIE 2009. 31 Aug - 2 Sept. 2009, San Diego, CA, USA
3. S. Devanathan, F. Zhao, and K. Ramani, “Integration of Sustainability into Early Design through Working Knowledge Model and Visual Tools” 2009 International Manufacturing Science and Engineering Conference MSEC, West Lafayette, IN, 2009
4. D. Min, J. Cho, and K. Ramani, A method for measuring part similarity using ontology and a multi-criteria decision making method, IDETC/CIE 2009. 31 Aug - 2 Sept. 2009, San Diego, CA, USA. (Paper# DETC2009-87711)
5. Walthall, C., S. Devanathan, L. Kisselburgh, K. Ramani, and E. Hirleman. A Framework for evaluating wikis as a medium for communication within engineering design teams,. IDETC/CIE 2009. 31 Aug - 2 Sept. 2009, San Diego, CA, USA
6. C.J. Walthall, C. Sauter, T. Deigendesch, S. Devanathan, A. Albers, and K. Ramani. Survey of Wikis as a Design Support Tool. ICED'09, 24-27 Aug. 2009, Stanford, CA, USA
7. S. Murugappan and K. Ramani, "FEAsy: A Sketch-based Interface Integrating Structural Analysis in Early Design", To appear in Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2009), SanDiego, CA
8. S. Murugappan and K. Ramani, "Towards beautification of Freehand Sketches using Suggestions", in review 'Sixth Eurographics Workshop on Sketch-Based Interfaces and Modeling, SIGGRAPH 2009
9. D. Cao, K. Ramani, M. W. Fu, and R. Zhang, "Port-based Ontology Semantic Similarities for Module Concept Creation,” IDETC/CIE 2009. 31 Aug - 2 Sept. 2009, San Diego, CA, USA