Interpreting SysMLv2 into the Category of Relations for Architecture, Analysis and Design

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Mathsig Presentation to SE DSIG

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Mathsig: OMG Mathematical Formalism Domain Special Interest Group (DSIG)

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Background

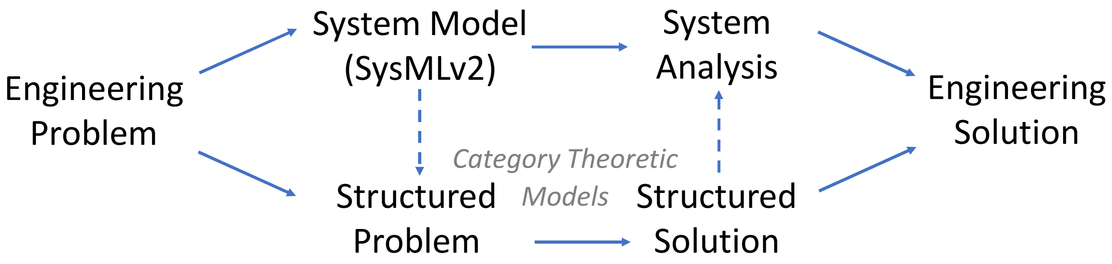
- Ongoing research with industry partners within and outside OMG
- Mathsig Presentations
  - September 2024: AI PTF, C4 DTF, Mathsig
    A Brief Introduction to Category Theory for Systems and Software Engineers [1]
  - June 2024: Mathsig
    ROSETTA Implementation in SysMLv2 Revisited [2]
  - March 2023: SE DSIG
    Implementation of ROSETTA in SysMLv2 and Underlying Maths Formalisms [3]
- This builds on and extends UPR 1.0 Constraint Driven Design [4]

Investigating practical methods for industrial applications supported by commercially available tools and founded in mathematics.

Context: Using SysMLv2 to Solve Engineering Problems

Category Theoretic Models Directly Reflect Solutions

Transformation of SysMLv2 models into mathematical abstractions



Purpose of presentation: inform nonspecialists in the SE DSIG how category theory might be used to enhance SysMLv2 tool expressiveness.

Topics of the Presentation

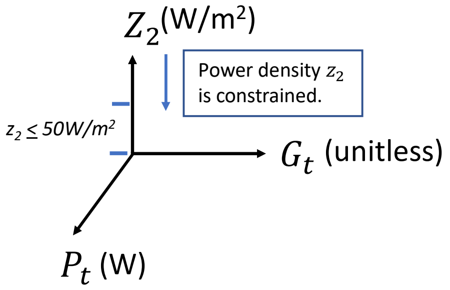
- ***Structuring Problems at a Higher Level of Abstraction***
- Definition, Usage, and Analysis in SysMLv2
- Category Theory as a Language for Architecture, Analysis and Design
- Conclusions: Complementing SysMLv2 with Category Theory

Category theory can be leveraged for structured modelling & analysis.

Reference Problem: Safety Constrained Radar System Design

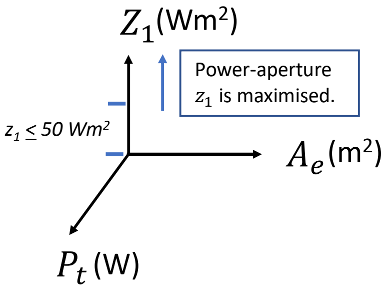
A safety requirement on power density (z_2) constrains the power-aperture product (z_1).

System design analysis is driven by the competing objectives z_1 and z_2.



Safety Design Space: $X_2 = (P_t, G_t)$

At the safety perimeter of d meters, power density z_2 must be $\leq 50W/m^2$.



Performance Design Space $X_1 = (P_t, A_e)$

Radar detection performance is improved by increasing power-aperture product.

Using the Category of Relations (*Rel*) for System Modelling

Correspondence with object orientation

Category theory reveals how different types of structures are related to one another [5, §1.3].

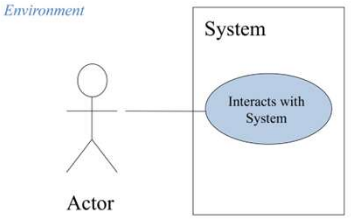
Key ideas:

- Models are central to systems and software
- Mathematical models are realised in mathematical
  - relational structures to include
  - graphical structures (e.g., in object orientation)
- Predicates can express *relationships between objects*.

This use case diagram states, 'Actor interacts with System.'

In category theory, a *relationship* between two objects is represented by an *arrow* called a *morphism*.

A category is concerned with its morphisms; *not details of its objects*.



(a) Predicate (verb-noun phrase) in Use Case diagram

$$A \xrightarrow{P} S$$

(b) Predicate as a morphism in the Category of Relations (*Rel*)

Rel : the category of relations. The objects of *Rel* are sets. Its morphisms are binary relations.

Using the Category of Relations (*Rel*)to Express Domain Knowledge

Example of knowledge representation using (relational) morphisms

Structures in category theory can be used to represent knowledge (e.g., ontologies, models).

Key ideas:

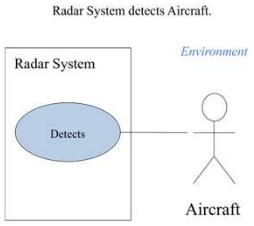
Relations can be used to express properties of objects.
Expression of properties as morphisms in the category *Rel,*

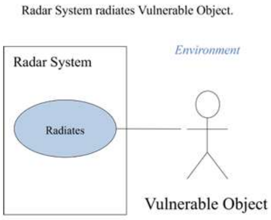
$F: X_1 \rightarrow Z_1$ (e.g., performance: power-aperture product)

$H: X_2 \rightarrow Z_2$ (e.g., safety: power density)

These two *morphisms are abstract structural elements* that reveal how the radar transmitter and antenna relate to system design.

Radar system domain knowledge can be expressed using the morphisms to define system properties.





**In [6], Architecture is investigated as a mathematical class and properties of structures.*

Analysis Case 1: Radar System Performance

Radar power-aperture product (Wm²) drives detection

F: $X_1 \rightarrow Z_1$; $R(z_1) \subseteq Z_1$ (performance requirement: maximise detection)

X_1 is a *design space*[1] with two attributes power (W), aperture (m^2)

Z_1 is an *objective space*[1]*:* attribute power-aperture product (Wm^2)

Design problem: maximise z_1 = power-aperture product (Wm^2)

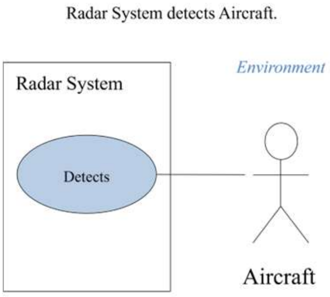
OMG UPR 1.0 Constraint Driven Design[1]

Requirement (as a constraint) →

Knowledge Map

$$\begin{tikzcd}
R \arrow[d, dashed] \arrow[r, phantom, "\subseteq"] & Z_1 \\
V \arrow[r, phantom, "\subseteq"] & X_1 \arrow[u, "F"']
\end{tikzcd}$$

Solution Set →



The association line in the use case can be expressed as a binary relation F between the objective and design spaces.

[1] *For further details refer to [4]* https://www.omg.org/spec/UPR/1.0/About-UPR/

Analysis Case 1: Radar System Performance

Radar power-aperture product (Wm^2) system analysis

$F: X_1 \rightarrow Z_1$; $R(z_1) \subseteq Z_1$ (performance requirement: maximise detection)

X_1 is a *design space* with two attributes power (W), aperture (m^2)

Z_1 is an *objective space:* attribute power-aperture product (Wm^2)

Design problem: maximise z_1 = power-aperture product (Wm^2)

At this stage of analysis, the requirement set R is unconstrained.

OMG UPR 1.0 Constraint Driven Design

$$\begin{tikzcd} R \arrow[d, dashed, "F^{-1}"'] \arrow[r, phantom, "\subseteq"] & Z_1 \\ V \arrow[r, phantom, "\subseteq"] & X_1 \arrow[u, "F"'] \end{tikzcd}$$

Requirements Transformation

Knowledge Map

Solution Set

Mathematical Analysis[1]

If $R \cap F(X_1) \neq \phi$, then $F: X_1 \rightarrow Z_1$ implies an inverse relation,

$$F^{-1}: R \rightarrow V$$

The inverse relation F^{-1} is not necessarily defined on the whole of R. It is only defined on $R \cap F(X_1)$.

Therefore, the structured solution set is,

$$V = F^{-1}(R \cap F(X_1))$$

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[1] *For further details refer to [7]* Architecture, Analysis, and Design of Systems Using Extensions of Category Theory

Analysis Case 2: Radar System Safety

Radar power density (W/m^2) drives the safety constraint

$H: X_2 \rightarrow Z_2$; $S(z_2) \subseteq Z_2$ (safety requirement: constrain radiation)

X_2 is a *design space*[1] with two attributes power (W), gain (unitless)

Z_2 is an *objective space*[1]*:* attribute power density at range *d* (W/m^2)

Design problem: constrain z_2 = power density (W/m^2) at range *d*.

OMG UPR 1.0 Constraint Driven Design[1]

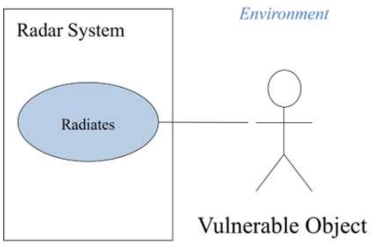
$$\begin{tikzcd} S \arrow[d, dashed] \arrow[r, phantom, "\subseteq"] & Z_2 \\ W \arrow[r, phantom, "\subseteq"] & X_2 \arrow[u, "H"'] \end{tikzcd}$$

Requirement (as a constraint)

Knowledge Map

Solution Set

Radar System radiates Vulnerable Object.



The association line in the use case can be expressed as a binary relation H between the objective and design spaces.

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[1] *For further details refer to [4]* https://www.omg.org/spec/UPR/1.0/About-UPR/

Analysis Case 2: Radar System Safety

Radar power density (W/m^2) safety analysis

$H: X_2 \rightarrow Z_2$; $S(z_2) \subseteq Z_2$ (safety requirement: constrain radiation)

X_2 is a *design space* with two attributes power (W), gain (unitless)

Z_2 is an *objective space:* attribute power density at range *d* (W/m^2)

Design problem: constrain z_2 = power density (W/m^2) at range *d*.

At this stage of analysis, the requirement set S is constrained at the range d by $z_2 \leq 50\ \mathrm{W/m^2}$.

OMG UPR 1.0 Constraint Driven Design

Requirements Transformation

Knowledge Map

$$\begin{tikzcd} S \arrow[r, phantom, "\subseteq"] \arrow[d, dashed, "H^{-1}"'] & Z_2 \\ W \arrow[r, phantom, "\subseteq"] & X_2 \arrow[u, "H"'] \end{tikzcd}$$

Solution Set →

Mathematical Analysis[1]

If $S \cap H(X_2) \neq \phi$, then $H: X_2 \rightarrow Z_2$ implies an inverse relation,

$$W^{-1}: S \rightarrow W$$

The inverse relation H^{-1} is not necessarily defined on the whole of S. It is only defined on $S \cap H(X_2)$.

Therefore, the structured solution set is,

$$W = H^{-1}(S \cap H(X_2))$$

[1] *For further details refer to [7]* Architecture, Analysis, and Design of Systems Using Extensions of Category Theory

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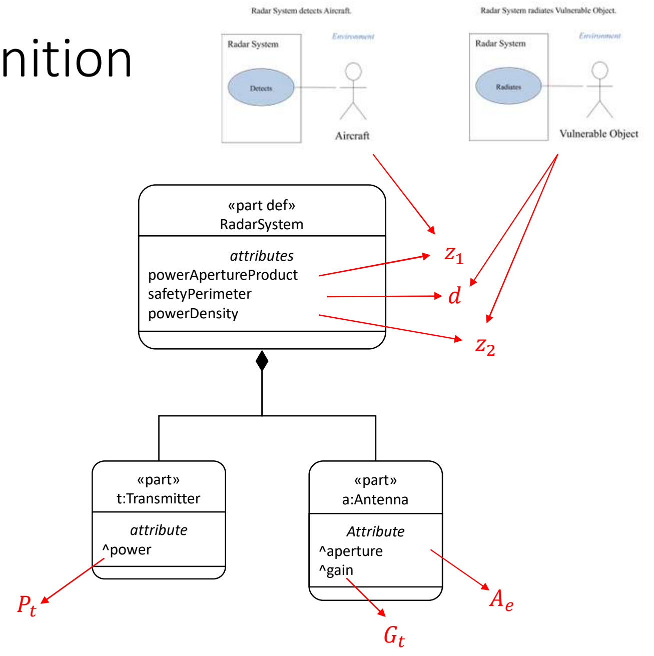
Topics of the Presentation

- Structuring Problems at a Higher Level of Abstraction
- ***Definition, Usage, and Analysis in SysMLv2***
- Category Theory as a Language for Architecture, Analysis and Design
- Conclusions: Complementing SysMLv2 with Category Theory

This section proposes preliminary concepts for a future SysMLv2.1.

Symbolic Variable Definition

- *Requirement:* A user shall be able to define a **symbolic variable** within a system element that is characterised by such a variable.
- For example, a transmitter component of a Radar system is characterised by the power of the transmitter. This characteristic could be modelled by a variable, named P_t.
- This could be supported by SysMLv2 Part Definition, Part Usage, Attribute Definition and Attribute Usage, but needs be more constrained.
- Requires analysis tool to read the attributes as **symbolic variables**



Radar System detects Aircraft.

Radar System radiates Vulnerable Object.

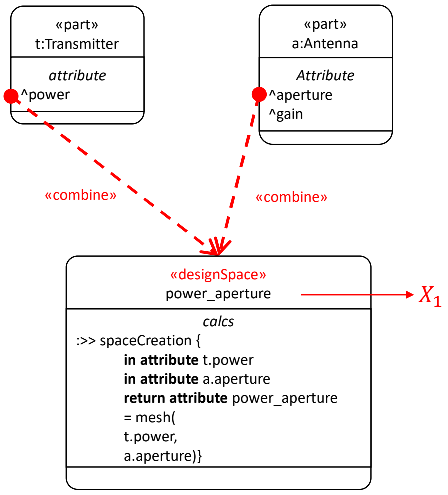
«part def»
RadarSystem
attributes
powerApertureProduct
safetyPerimeter
powerDensity

«part»
t:Transmitter
attribute
^power

«part»
a:Antenna
Attribute
^aperture
^gain

Space* Definition

- *Requirement*:
  - A user shall be able to specify a **Design Space** by selecting and combing a set of specified variables, represented by a symbolic variable. E.g., Design Space $X_1 = (P_t, A_e)$
  - A user shall be able to specify an **Objective Space** by selecting and combining a set of specified variables, represented by a symbolic variable. E.g., Object Space Z_1
  - The specification of the spaces shall optionally allow the user to specify the boundary for each of the variables applicable to the space definition so that the space is constrained
- *Proposal*:
  - «designSpace def» & «objectiveSpace def» extends Definition with a calcs compartment that utilises «cal def»;
  - «combine» that extends Dependency for visualisable traceability.
- «combine» can be realised by *Cartesian Product.* Ideally, this should be a machine-readable operation which will combine one-dimensional **variables** into a multi-dimensional **space**. *function* mesh() is a type of Cartesian Product.



«part»
t:Transmitter
attribute
^power

«part»
a:Antenna
Attribute
^aperture
^gain

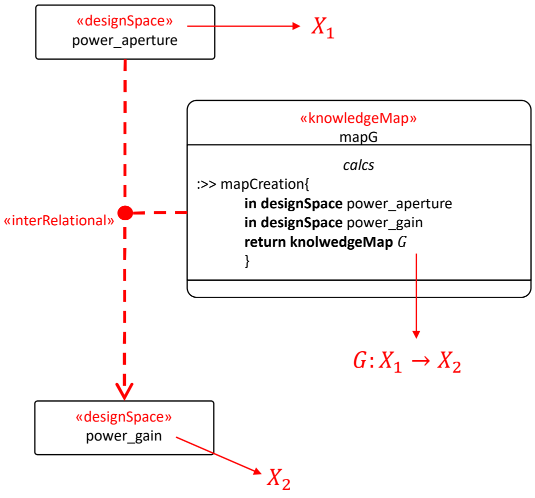
«designSpace»
power_aperture
calcs

```
:>> spaceCreation {
        in attribute t.power
        in attribute a.aperture
        return attribute power_aperture
        = mesh(
        t.power,
        a.aperture)}
```

* *For further details refer to [4],* https://www.omg.org/spec/UPR/1.0/About-UPR/

Relations Definition

- *Requirement*:
  - A user shall be able to specify **Binary Relations** between **symbolic variables**. E.g., a mathematical function, $f(P_t, A_e) = P_t A_e$, in which the inverse may **NOT** be a function.
  - A user shall be able to specify a **Relation** (of relations) that connects two specified **Spaces**. These could be a relation between two Design Spaces, a relation between two Objective Spaces, or a relation between a Design Space and an Objective Space. E.g., $F: X_1 \rightarrow Z_1$
- The first requirement is already addressed by SysMLv2
- Whilst there is a –nary Dependency graphical/textual notation, but it is rather abstract for analysis.
- *Proposal*:
  - «knowledgeMap def» extends Definition with a calcs compartment that utilises «cal def»;
  - «interRelational» that extends –nary Dependency for visualisable inter-relational structure and traceability.



Analysis Cases Issues

«analysis»
radarPerformance

subject
radarAlternatives [*] :>Radar

objective
doc maximize the detection range with varying power and aperture

calcs
:>> evaluationFunction {
in attribute radar.t.power
in attribute radar.a.aperture
return attribute radarPerformance = f(
radar.t.power,
radar.a.aperture)}

«analysis»
radarSafety

subject
radarAlternatives [*] :>Radar

Objective
doc minimise power density with varying power and aperture

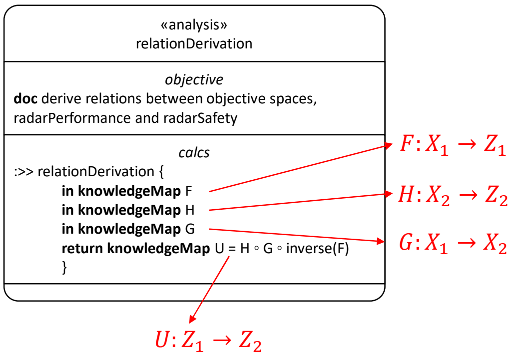
calcs
:>> evaluationFunction {
in attribute radar.t.power
in attribute radar.a.aperture
In attribute radar.safetyPerimter
return attribute radarSafety = h(
radar.t.power,
radar.a.gain, radar.safetyPerimeter)}

- Complex multi-objectives design involves **multiple** trade-off analysis cases
- What is the relation between the cases, when they have **shared variables**?
- Need a way to model and analyse the coupling.
- Machine-readable modelling of shared variables in a physical process or in software is a challenge.

Relations Usage

It is useful to integrate the multiple model elements into a single matrix representation (such as ROSETTA)

- With various relations defined, one could start to use these relations a specific analysis case to derive further relations for understanding the complexity



«analysis»
relationDerivation

objective
doc derive relations between objective spaces, radarPerformance and radarSafety

calcs

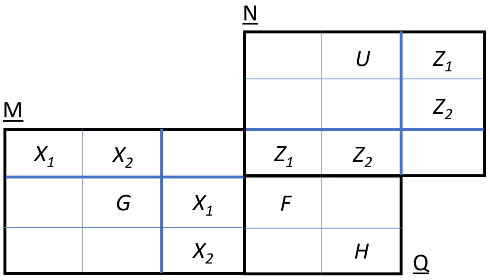
```
:>> relationDerivation {
        in knowledgeMap F
        in knowledgeMap H
        in knowledgeMap G
        return knowledgeMap U = H ◦ G ◦ inverse(F)
}
```

$F: X_1 \rightarrow Z_1$

$H: X_2 \rightarrow Z_2$

$G: X_1 \rightarrow X_2$

$U: Z_1 \rightarrow Z_2$



Relational transformation (of the relation G):

(X_1, X_2) with (X_1, Z_1) and (X_2, Z_2) → $\exists U$, $(Z_1, Z_2) = U$

The new relation *identified* is denoted as *U*, which is *defined* by the chain of relations (Z_1, X_1), (X_1, X_2), and (X_2, Z_2). Thus, *U* is defined by the composition,

$$U = H \circ G \circ F^{-1}.$$

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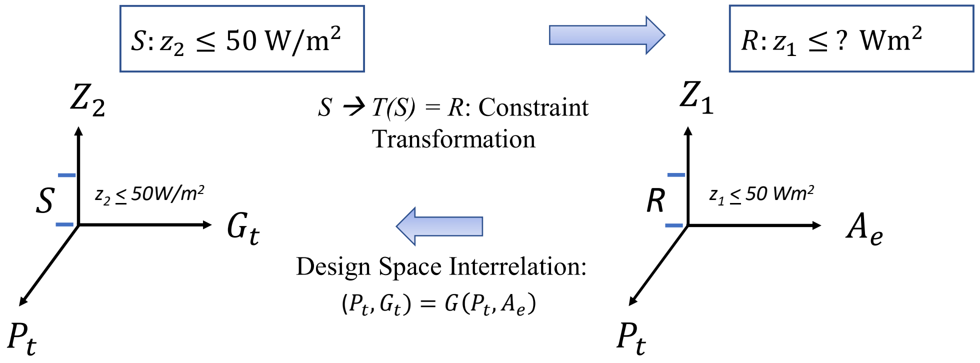
- Structuring Problems at a Higher Level of Abstraction
- Definition, Usage, and Analysis in SysMLv2
- ***Category Theory as a Language for Architecture, Analysis and Design***
- Conclusions: Complementing SysMLv2 with Category Theory

Models can be structured using the language of category theory.

Engineering Representation of a Constraint Transformation T

***One 'value'** of the transformation of the safety requirement S constrains power-aperture product R to:* $z_1 \leq 50 Wm^2$.



$S: z_2 \leq 50\ \mathrm{W/m^2}$

$R: z_1 \leq ?\ \mathrm{Wm^2}$

$S \rightarrow T(S) = R$: Constraint Transformation

Design Space Interrelation:
$(P_t, G_t) = G(P_t, A_e)$

Safety Design Space: $X_2 = (P_t, G_t)$

Performance Design Space $X_1 = (P_t, A_e)$

At the safety perimeter of d meters,
power density z_2 *must be* $\leq 50W/m^2$.

*What is **the general form** of the*
constraint transformation T: $Z_2 \rightarrow Z_1$ *?*

Matrix View of a Relational Structure for Safety Analysis:
ROSETTA Framework when the objectives are *dependent* variables

There are three *defined relations*,

$F: X_1 \rightarrow Z_1$
$H: X_2 \rightarrow Z_2$
$G: X_1 \rightarrow X_2$

There is one ***implied relation***,

$U(G): Z_1 \rightarrow Z_2$,

which is identified using *relational transformation*.

The matrices of a ROSETTA framework use standard row-column notation, e.g., (Z_1, X_1) is the relation F, but they have a different algebra than ordinary matrices.

ROSETTA: Relational Oriented Systems Engineering Technology Trade-off and Analysis

N (Target)

M (Source)

				$U(G)$	Z_1
					Z_2
X_1	X_2		Z_1	Z_2	
	G	X_1	F		
		X_2		H	

Q (Transformation)

Algebra of the relational transformation (of the relation G):

(X_1, X_2) with (X_1, Z_1) and $(X_2, Z_2) \rightarrow \exists U$, $(Z_1, Z_2) = U(G)$

The new relation *identified* is denoted as U and is *defined* by the chain of relations (Z_1, X_1), (X_1, X_2), and (X_2, Z_2). Thus, the relation $(Z_1, Z_2) = U(G)$ is defined by the composition,

$$U = H \circ G \circ F^{-1}.$$

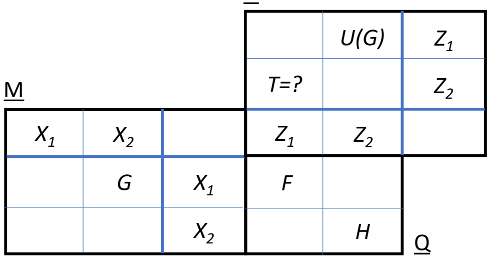
Comparison of Relational Transformation of *G* using ROSETTA with Relational Composition in *Rel*

There are four *defined or implied* relations,

$F: X_1 \rightarrow Z_1$	(X_1, Z_1)
$H: X_2 \rightarrow Z_2$	(X_2, Z_2)
$G: X_1 \rightarrow X_2$	(X_1, X_2)
$U: Z_1 \rightarrow Z_2$	(Z_1, Z_2)

Relational Transformation: Graphical View

$$\begin{tikzcd}
 & Z_1 \arrow[dl, "F^{-1}"'] \arrow[d, dashed, "G \circ F^{-1}"] & {} \arrow[dd, "U"] \\
X_1 \arrow[r, "G"] \arrow[dr, dashed, "H \circ G"'] & X_2 \arrow[d, "H"] & \\
 & Z_2 & {}
\end{tikzcd}$$



			N		
				U(G)	Z_1
M			T=?		Z_2
X_1	X_2		Z_1	Z_2	
	G	X_1	F		
		X_2		H	Q

The relational structure of the framework is complete.

The relational transformation of (X_1, X_2) with (X_1, Z_1) and (X_2, Z_2) implies *a chain of relations* (Z_1, X_1), (X_1, X_2), and (X_2, Z_2). Thus,

$$\boxed{U = U(G) = H \circ G \circ F^{-1}}$$

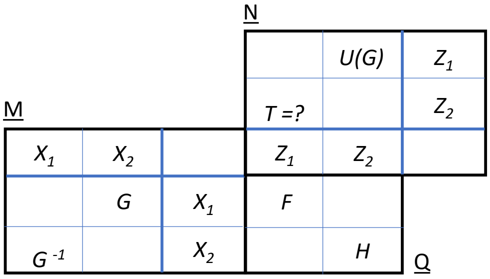
The *problem is structured* by joining up the arrows, but the transformation *T* does not yet belong to the framework.

Matrix View of a Relational Structure for Safety Analysis:

Structured Solution for *T* using the ROSETTA Framework

There are six *defined or implied* relations,

$F: X_1 \rightarrow Z_1$	(X_1, Z_1)
$H: X_2 \rightarrow Z_2$	(X_2, Z_2)
$G: X_1 \rightarrow X_2$	(X_1, X_2)
$G^{-1}: X_1 \rightarrow X_2$	(X_2, X_1)
$U: Z_1 \rightarrow Z_2$	(Z_1, Z_2)
$T: Z_2 \rightarrow Z_1$	(Z_2, Z_1)



			N		
				U(G)	Z_1
M			T =?		Z_2
X_1	X_2		Z_1	Z_2	
	G	X_1	F		
G^{-1}		X_2		H	Q

Formulae can be expressed in SysMLv2.

$$\boxed{\begin{aligned} &F\,(P_t, A_e) = z_1 = P_t\,A_e \\ &H\,(P_t, G_t) = z_2 = P_t\,G_t/4\pi d^2 \\ &G\,(P_t, A_e) = (P_t, 4\pi A_e/\lambda^2) \end{aligned}}$$

Relational transformation (of the relation G^{-1}):

(X_2, X_1) with (X_2, Z_2) and $(X_1, Z_1) \rightarrow \exists T, (Z_2, Z_1) = T(G^{-1})$

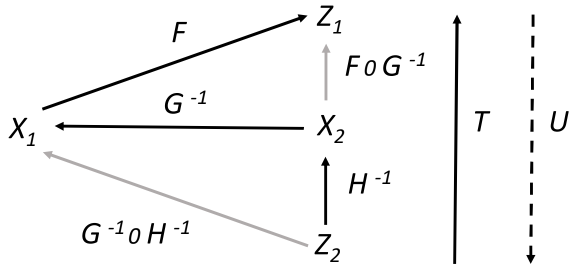
The new relation *identified* is denoted as *T* and is *defined* by the chain of relations (Z_2, X_2), (X_2, X_1), and (X_1, Z_1). Thus, *T* is defined by the composition,

$$\boxed{T = H^{-1} \circ G^{-1} \circ F}$$

Comparison of Relational Transformation *T* of G^{-1} using ROSETTA with Relational Composition in *Rel*

$F\,(P_t\,,A_e) = z_1 = P_t\,A_e$
$H\,(P_t\,,G_t) = z_2 = P_t\,G_t/4\pi d^2$
$G\,(P_t\,,A_e) = (P_t\,,4\pi A_e\,/\lambda^2)$

Relational Transformation: Graphical View



Derivation of T from U(G)

N

M

				U(G)	Z_1
			U^{-1}		Z_2
X_1	X_2		Z_1	Z_2	
	G	X_1	*F*		
		X_2		*H*	

Q

The structured solution for T can also be derived from U(g):

$U = H_0\,G_0\,F^{-1} \rightarrow T = U^{-1} = (H_0\,G_0\,F^{-1})^{-1} = F_0\,G^{-1}{}_0\,H^{-1}.$

Either way, as seen in the algebraic calculations in the annex, when the formulae for *F*, *G*, and *H* are used, a formula for *T* then follows,

$$\boxed{z_1 = T\,(z_2) = d^2\lambda^2 z_2.}$$

For a perimeter with $d\lambda = 1$, $z_2 \leq 50W/m^2 \rightarrow z_1 \leq 50Wm^2$.

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*Engineering solution and optimisation using constraint driven design**

Requirements Transformation (ISO/IEC/IEEE 15288) using ROSETTA

OMG UPR 1.0

ISO/IEC/IEEE 15288 Requirements Transformation

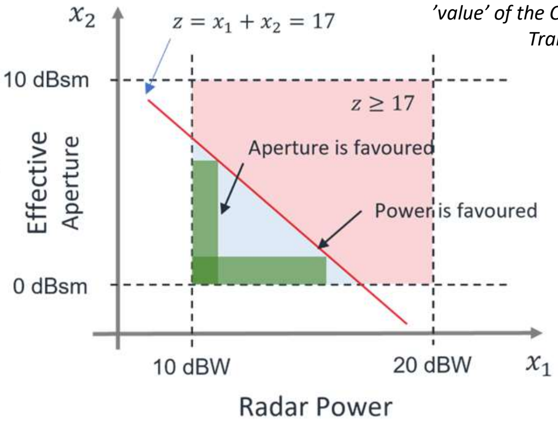
Knowledge Map (Physics)

$$\begin{tikzcd} R \arrow[r, phantom, "\subseteq"] \arrow[d, dashed, "f^{-1}"'] & Z \\ V \arrow[r, phantom, "\subseteq"] & X \arrow[u, "f"'] \end{tikzcd}$$

$V = f^{-1}\,(R \cap f\,(X))$

Representation in the design space X = $(x_1\,, x_2)$ = [10 dBW, 20, dBW] x [0 dBsm, 10 dBsm]
Transformation of requirements (in decibels) defines the solution set V (x_1, x_2), *(blue triangle)*:
Power aperture product = z = f $(x_1, x_2) = x_1 + x_2$
$f^{-1}\,(R \cap f\,(X)) = f^{-1}\,([0, 17] \cap [10, 30])$
$= f^{-1}\,([10, 17]$
$z \in R = [10, 17] \rightarrow x_1 + x_2$ is a solution
Maximising *z* (dBWsm) *(green rectangles)* is constrained by the *safety* requirement.

Constraint Driven Design for Radar Safety Analysis



$x_1 + x_2 \leq 17$ is just one 'value' of the Constraint Transformation

*Adapted from the Loughborough University WS66 System Design MSc module.

Conclusions (1 of 2): Problem Solving in Category Theory

Modeling, Analysis and Design using Structures

Transform a Use Case predicate into a morphism P in *Rel*.

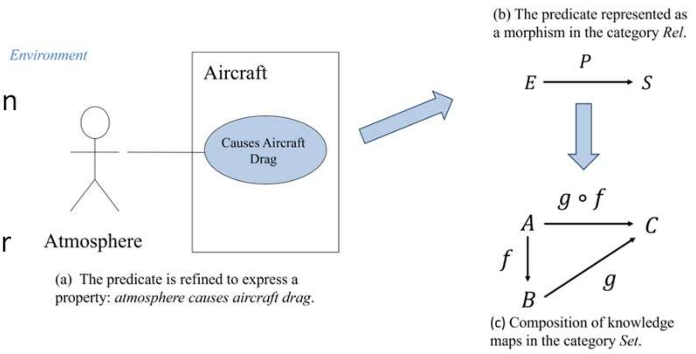
Express domain knowledge models in *Set* to quantify P as a property.

Mathematical models are needed, e.g. to compose relations to solve for drag, *c*, as a function of altitude, *a*,

$$f: A \rightarrow B$$
$$g: B \rightarrow C$$

$c = g \circ f(a) = (1 - a/10)c_0$

These support *analysis and design*.[1]



(a) The predicate is refined to express a property: *atmosphere causes aircraft drag*.

(b) The predicate represented as a morphism in the category *Rel*.

(c) Composition of knowledge maps in the category *Set*.

Model specification and transformation in Rel.

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[1] *For further details refer to [1], A Brief Introduction to Category Theory for Systems and Software Engineers.*

Conclusions (2 of 2)

Applications of Category Theory and Why Should OMG Care?

The Category of Relations (Rel)

Offers a language for direct transformation of models into structured solutions.

Can be a *useful language of architecture* for system modeling and analysis.

Categoric theoretic diagrams have promising associations with SysMLv2.

But must be integrated with domain knowledge for *engineering practice*.

Promises intuitive rigorous structured methods for integrating SysMLv2 analysis cases.

Way ahead:

Continue discussions with SE DSIG about future SysML v2.1 opportunities

Investigate further applications to engineering problems and practice and …

Category theoretic foundation of object orientation and software applications

Questions?

Annexes

A-1 Algebraic Solution for the Constrain Transformation

A-2 References

A-1 Algebra of the Constraint Transformation Relational Structure (in dB)

(1) $z_1 = x_1 + x_2$ *Power Aperture Product*

(2) $z_2 = x_1 + x_3 - r$ *Power Density at safety perimeter (d)*

(3) $0 = x_2 - x_3 + k$ (this derives from $x_3 = x_2 + k$)

$r = 4\pi d^2$ $x_1 = P_t$ in dB ($x_1 = x_{11} = x_{21} = P_t$)

$k = 4\pi/\lambda^2$ $x_2 = \mathrm{A_e}$ in dB ($x_2 = x_{12} = \mathrm{A_e}$)

$x_3 = \mathrm{G_t}$ in dB ($x_3 = x_{22} = \mathrm{G_t}$)

$(x_{11}, x_{12}) \in X_1$ and $(x_{21}, x_{22}) \in X_2$ $P_t = x_1 = x_{11} = x_{21}$ is a shared attribute

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A-1 (continued) Solution for the Transformation by Algebraic Methods

Add equations (2) and (3) to obtain,

(2) + (3): $z_2 = x_1 + x_2 - r + k$

Substitute (1), $x_1 + x_2 = z_1$, into this to obtain,

$z_2 = z_1 - r + k \rightarrow z_1 = z_2 + r - k$ in dB

In SI units we then have,

$z_1 = (z_2)\,(4\pi d^2)/(4\pi/\lambda^2\,) = z_2\, d^2\lambda^2$

This defines the constraint transformation as,

$$\boxed{z_1 = T(z_2) = d^2\lambda^2\, z_2 = 50Wm^2 = 17dBWsm \text{ for } \lambda d = 1.}$$

This agrees with both OMG results [2] and a forthcoming paper.

References

[1] *A Brief Introduction to Category Theory for Systems and Software Engineers, September 2024,* on the Mathsig homepage https://www.omg.org/maths/ , or the AI PTF. A recording of the presentation can be found at, https://www.omg.org/cgi-bin/doc.cgi?ai/2024-09-06

[2] *ROSETTA Implementation in SysMLv2 Revisited, June 2024,* on the Mathsig homepage https://www.omg.org/maths/

[3] *Implementation of ROSETTA in SysMLv2 and Underlying Mathematical Formalisms, March 2023, in the Mathsig archives https://www.omg.org/maths/*

[4] https://www.omg.org/spec/UPR/1.0/About-UPR/

[5] Stanford Encyclopedia of Philosophy, "Category Theory", 29 August 2019. Available online at

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[7] Dickerson, C.E. and Wilkinson, M.K., "Architecture, Analysis and Design of Systems Using Extensions of Category Theory", *IEEE Open Journal of Systems Engineering*, 23 July 2024. Digital Object Identifier 10.1109/OJSE.2024.3432570. Available open source online at,

Architecture, Analysis, and Design of Systems Using Extensions of Category Theory