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AXIOMATIC DESIGN AS A MEANS TO FIND CONTRADICTION IN AN INTEGRATED APPROACH FOR PRODUCT DESIGN

Sergio Rizzuti.
rizzuti@unical.it
Dept. of Mechanical Engineering
University of Calabria
Via P. Bucci, 44/c 87030 Rende (CS) Italy

Luigi De Napoli.
ldenapoli@unical.it
Dept. of Mechanical Engineering
University of Calabria
Via P. Bucci, 44/c 87030 Rende (CS) Italy

Francescantonio Giampà.
giampa@unical.it
Dept. of Mechanical Engineering
University of Calabria
Via P. Bucci, 44/c 87030 Rende (CS) Italy

Francesco Lofranco.
francesco.lofranco@unical.it
Dept. of Mechanical Engineering
University of Calabria
Via P. Bucci, 44/c 87030 Rende (CS) Italy

ABSTRACT

The present paper aims to underline the strict connection among a series of valuable methods for product design: Functional Analysis, Axiomatic Design and Quality Function Deployment, that must be employed jointly in order to allow a designer to reach a good solution for an industrial product. These methods, that share the matrix format common basis, must mutually exchange the elements at the basis of each method: Customer Needs, Functional Requirements, Design Parameters, in a sort of virtuous circle.

After a brief introduction to the matrix formulation of each method, the circular exchange of parameters among the methods will be discussed.

A case of study will clarify how the methods can interact and how the parameters can be used in each single method allowing the designer to have a better control of the whole design process.

Keywords: Interaction among design methods, Functional Analysis by means of Graph, Axiomatic Design, Quality Function Deployment.

1 INTRODUCTION

Since the seventies of last century, many work has been proposed about the engineering approach to design, starting from the pioneer studies of Hubka and Eder [1988] and Palh and Beitz [1996]. In the copious literature on this subject, a shared viewpoint considers the design process as based on a continuous assessment activity towards the "right" solution to the problem. In this process the designers must organize and order the elements that characterize the solution and verify if they merge with the original starting point related to the customer needs.

Several methods have been suggested to aid the design process, and many of them can be profitably used for single phases depending on domain-specific views. Further the personal attitudes of designer and the stakeholders involvement degree can suggest the most suitable road map to be followed. In this paper the integration among Functional Analysis (FA) Axiomatic Design (AD) and Quality Function Deployment (QFD) will be outlined and a central role assigned to the Design Matrix of AD will be highlighted.

Axiomatic Design methodology has gained in the years a certain attention by designers and academics in that it gives a formal and analytical data structure that can allow checking the validity of the solution under investigation [Suh, 2001].

The Design Matrix, core of the method, can validly support the designer only when a solution has been reached and a correlation between functional requirements (FRs) and design parameters can be established. Axiomatic Design offers so a methodology able to solve conflicts that can emerge when some rows of the Design Matrix are in linear combination and many design parameters influence conjointly several functional requirements. This is the moment in which the designer has to solve the conflict, redesigning the solution or searching for modified version, for the Functional Requirements. In any case, the whole matrix must be reviewed and a new design architecture must be analyzed.

This process can't be thought independently from the design thinking and the customer needs. So designers should have continuously under control how the solution has reaching a valid design and how this adheres to the requirements extrapolated from the customer needs. Only an active circulation of these three aspects can be guarantee, with a sufficient degree, that the solution begins to converge towards a valid solution.

Functional Analysis of an industrial product [Stone and Wood, 2000], [Bruno *et al.*, 2003] is a valuable method that can support the conceptual design. Any industrial product can be represented by a graph structure [Kusiak and Huang, 1996], [Rizzuti *et al.*, 2006]. Really it can be represented as a series of four overlapping graphs in which each level reports the connectivity among the functional blocks subject to a particular kind of link (energy, material, signal, force). While the first three graphs describe what happens inside the solution in term of flow of energy, material and signal respectively, and they are directed graphs, the forth represents the so called liaison graph and is a non-directed graph. This latter can guide the physical architecture of the solution when the functional requirements are replaced with real parts and the links assume the meaning of the physical connection among them. This kind of representation is self consistent till a level of Functional Requirements decomposition in which, each Functional Requirement, can be associated to a real component.

QFD has been confirming, since its appearance in the early seventies in Japanese area, as a valid methodology to globally evaluate the designed solution in a strict contact with the customer needs from which it has taken form [Hauser and Clausing, 1988]. During this time the House of Quality (HoQ), the structured data collection related to the design process, has been used for different tasks, in that several researchers have employed it by putting in evidence many aspects of the way by which a firm can reach a solution [Lee and Kusiak, 2001], [Kreng and Lee, 2004].

In the context of product development putting in relation how to solution works, collecting the main characteristic of the product and its main parameters, and the customer needs can only be done when at least one product architecture has been performed. So HoQ can properly start at a certain stage of development for a new product, or in the design review process.

An intriguing context for product development consist in striving for innovative characters of the solution and a certain attention has been given to the inventive problem solving. Triz (or TIPS) methodology [Altshuller, 1998] seems to support this aspect. Its main contribution consists in a certain strategy to find contradictions embedded in the solution "invented" to solve a problem. This paper would aim to demonstrate that an alternative way to find contradiction in a design solution is possible and that it can be mainly based on the Axiomatic Design method.

2 DATA STRUCTURES FOR THE DESIGN PROCESS

A real advantage in using the design methodologies, briefly outlined, consists in the possibility for them to be supported by software tools that can really aid the stakeholders involved in the process. The design process is typically dynamic and so also dynamic should be the data structures required, even the final target of a unique software ambient, in which the whole design process can be represented, is not forthcoming.

A first problem to be solved in this direction is related to the data structure that can be used. The matrix format that contain information between pair of parameters is the most suitable. This is confirmed also by other methods currently used in project management, as the Design Structure Matrix that provides a simple, compact and visual representation of a complex system that supports innovative solution to decomposition and integration problems [Browning, 2001]. Further, the matrix format allows to operate the multiple domain mapping [Deubzer *et al.* , 2008], even mapping is not a novelty, being extensively employed either in AD or in QFD.

The information contained in each cell of a matrix can indicate: the presence of a relation or a formal equation or a value that characterizes the degree of the relation. Further the matrix format can be easily updated in dimension adding/removing elements from its row or column.

The most evident peculiarities of a such data structure are:
- it is able to support an integrated development tool;
- it is able to manage the evolution towards a solution
- it is able to manage the problem decomposition.

Each of the three methods Functional Analysis, Axiomatic Design and QFD, are supported by matrix formulations and their integration can be pursued.

2.1 DATA STRUCTURE FOR FUNCTIONAL ANALYSIS

In order to describe the interrelation among the methods the Functional Analysis is limited to the only liaison aspect among components/functions. It can be described by a square matrix with identical row and column labels (see Table 1.). The rows and columns contain all the Functions that the solution should perform. Further the first row and column represents the outer of the "system", with which the whole "system" interacts. The Function name is of type FRijh and follows the way in which a Functional Requirement is represented in Axiomatic Design. So the indexes i-j-h are related to the h-th sub-sub-function of the j-th sub-function of the i-th function. The "outer" is represented by the symbol Ω in the Liaison Matrix.

Every time a function FRk is decomposed in m sub-functions the existing row and column change meaning, assuming the FRk1 label, and m-1 rows and columns are added right way and down way from the pointer p(k) to the FRk row and column.

Each diagonal term contains a Data Structure (DS), related to the Functional Requirement, that collects a set of information about the function (Name and Action) and a device that performs the function (Material Characteristics and Environmental Impact Factor). The DS has the following standard fields:

- Functional Block Name
- Action Developed
- Material Involved
- Material Property
- Environmental Impact Factor

and it has been designed to support a life cycle assessment of the designed solution since the early stage of product development. A tool able to manage the DS has been implemented in Matlab®.

The off-diagonal terms of the matrix, or cells, contain information about the liaisons among the FRs. This part of the matrix is really an unvalued adjacence matrix of a graph by which can be visualized the functions structure related to the solution or to a product architecture, designed when the functions are replaced by devices. Each cell i-j (when i≠j) of the matrix represents an edge of the graph and can assume the values 1 or 0 if a connection is present or not. Figure 1 represents the graph associated to the Liaison Matrix of Table 1., visualized by the Matlab application.

These information can be processed in several ways. Off-diagonal part of the Liaison Matrix is checked in order to verify if each function (components) is related (connected) to others. The Liaison Matrix is mainly important for this study and the FRs, developed at each stage of design process, can be directly transferred to the Design Matrix of Axiomatic Design.

Table 1. Liaison Matrix.

	Ω	FR1	FR21	FR22	FR23	FR3	FR41	FR42	…
Ω	_	1					1		
FR1	1	**DS1**	1	1			1		
FR21		1	**DS21**		1	1			
FR22		1		**DS22**				1	
FR23			1		**DS23**	1			
FR3			1		1	**DS3**			
FR41	1	1					**DS41**	1	
FR42				1			1	**DS42**	
…									…

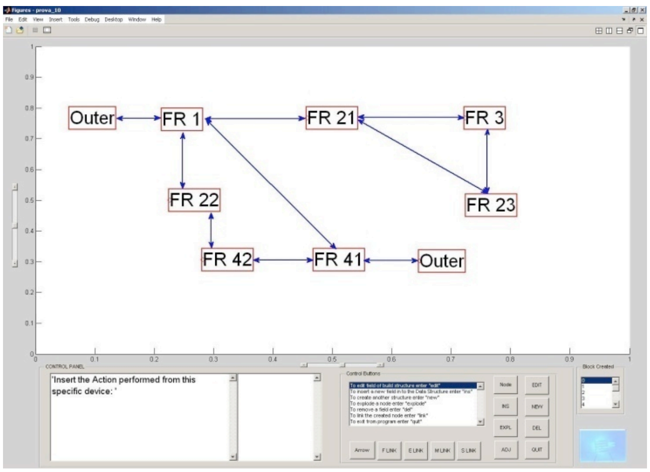

Figure 1. Graph associated to the Liaison Matrix of Table 1.

2.2 DATA STRUCTURE FOR AXIOMATIC DESIGN

Axiomatic Design method can give a valid support at the early stage of product design, by the application of the first Axiom. In this phase the designer is urged to individuate the right Design Parameters (DPs) that must be associated to the FRs that have been identified in the previous step. Also for this analysis the designer should arrive to a square matrix as a necessary condition in order that a problem can be formally analysed. The study of the Design Matrix can guide the designer to discover hidden contradiction in the solution, or better, in the way how the FRs are performed by real components and are controlled by suitable DPs. The sufficient condition by which a problem can be validly controlled requires a lower triangular matrix. For the designer is important to reach this state and the Design Matrix form gives most useful information how to modify the solution. In fact, this crucial phase can require or a better search for new parameters or a radical revision of the product architecture and/or the search for new formulation of the FRs, that, being expressed in the classical form of "active verb + noun", can require major stress in the expression used. Until that a lower triangular matrix (or ideally a diagonal matrix) is reached the designer must return in the previous domain (Functional Domain) and re-elaborate the solution. Table 2. reports a classical "coupled" matrix that requires a revision. A detailed exam must be done to FR21 and FR23 and the nature of their associated parameters DP21 and DP23 should be verified.

Table 2. Design Matrix.

	DP1	DP21	DP22	DP23	DP3	DP41	DP42	…
FR1	X							
FR21		X		X				
FR22		X	X					
FR23		X		X				
FR3					X			
FR41					X	X		
FR42		X				X	X	
…								

A further phase can be taken into account when most of the problems are solved and the robust design phase should start. The emphasis is so centered on the way how the solution performs in respect to the target defined at the beginning. In this phase the second Axiom can suggest where investigate for better solution.

2.3 DATA STRUCTURE FOR QFD

The relation matrix of QFD has a rectangular form since the number of rows, in which the Customer Needs (CNs) are reported, can be different from the number of columns, in which the main characteristics of the solution found are reported. The main characteristics, so generally named in literature, in this approach coincide with the Design Parameters, that emerge after the conjoint work in the Functional Domain and the Axiomatic Domain.

In the cells of the relation matrix a certain number of figures or symbols that express a strong positive, medium positive, medium negative, strong negative relation between CNj and DPi, are reported (see Table 3.). The designer, and all the stakeholders, are invited to discuss on the solution found and on its strength or weakness, in comparison to other solution by competitors.

The discussion in this phase can also introduce elements to be taken into account in the process, even these are more addressed to management problems than to technical problems.

Table 3. Relation Matrix.

	DP1	DP21	DP22	DP23	DP3	DP41	DP42	…
CN1	9		3		1		9	
CN2		9		3				
CN3	3	9	3		9	3		
CN4			9	9				
CN5	1			1	9			
CN6			1			9	3	
…								

3 DATA STRUCTURE INTERRELATION

Figure 2. shows the ambient in which the methods described in the previous paragraphs interrelate. The data exchange gives coherence to the whole process, and the matrix format avoids the loss of information during the design steps. This starts typically from the input represented by the Customer Needs, explicitly or implicitly expressed, that are collected and interpreted employing the techniques currently used in marketing practice.

The CNs are transformed in a certain number of Functional Requirements that characterize the solution to be searched. After the definition of the main function, the functional analysis can proceed till a certain degree of detail applying the decomposition of functions. This must be seen in strict contact to the customer needs. The application of graph theory in the functional area offers the possibility to store the elaborations or "inventions", in a matrix format.

The FRs so defined, becomes the rows of the Design Matrix. The search of Design Parameters associated to the FRs can be considered the core of the design process. The so called zigzagging for decomposition and hierarchy is conjointly operated between the FA and AD data matrices. The first method allows to check the consistency of the solution in term of connectivity, the second check how the solution can be controlled by the most suitable parameters.

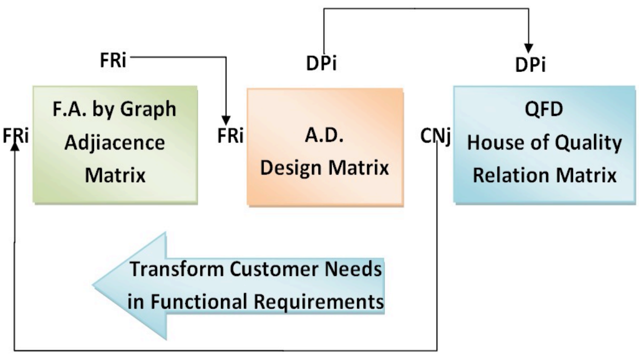

Figure 2. Interrelation between matrix structures.

The DPs able to control the solution can be transferred at the roof of HoQ, and starting form this moment it is possible to close the circle and verify how the solution that can be considered sufficiently adequate, in engineering terms, remains valid also in the wider context of customer satisfaction. The interaction between AD and QFD can suggest the best values or ranges for Design Parameters, not only oriented to robust design but also to the most attractive solution for the customer.

4 CASE OF STUDY

The example chosen to illustrate how to operate according to the approach concerns the redesign of an indicator for a modern motorbike.
Figure 3 shows a sample of this product typology.

Figure 3. The indicator under consideration

The Customer Needs take into account not only functional aspects but also psychological factors that can influence motorcyclist. A list of this needs is as in the following:

- CN1: Racing aspect
- CN2: Dimension reduced
- CN3: Weight reduced
- CN4: Good aerodynamic penetration
- CN5: Good luminous efficiency
- CN6: Affordable costs
- CN7: Conform to Traffic Rules

After the Customer Needs definition has been completed it is necessary to transform the CNs in a certain number of Functional Requirements (FRs).

The first functional block, namely FR0 in Figure 4, represents the overall function of the product, that can be expressed as: "to indicate the direction of turning". This can be represented by a functional block that interact with the outside, by means of three kind of links: a) a link of energy (depicted by the red line) related to the electricity used to turn the lamp and to the light emitted; b) a link of signal (depicted by the green line), related to the actuator an to the intermittent light; c) a link of force (depicted by the blue line) by which is represented that the device is fixed to the motorbike.

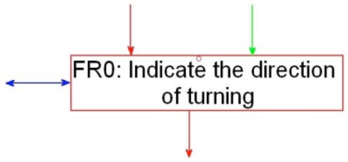

Figure 4. The main Functional Requirement.

The procedure continues with the decomposition in many more blocks to further detail all the possible functions involved. The designer must continuously analyze the functional structure of the product in order to build a valid product architecture that satisfy the Functional Requirements. Considering that the energy and signal links remain unchanged, the following analysis will focus on the logic connection among blocks associated to the physical liaison among the parts that can perform each task. The first block FR0 could be decomposed into the following blocks (see Figure 5a):

FR1: Emit light in a specific direction
FR2: Fit to the motorbike

and still decomposing, we can achieve the following block structure (see Figure 5b):

FR11: Emit the light
FR12: Direct the light
FR21: Fit to the motorbike
FR22: Support the parts
FR23: Improve the aerodynamic penetration

The function FR22, according to Customer Needs, has to be performed in such a way to respect an important constraint for the sector to which the product is aimed, that is to reduce the total weight of the motorcycle. Even the weight of the device is imperceptible with respect to the total motorcycle weight, it is recognized as highly relevant by motorcyclists.

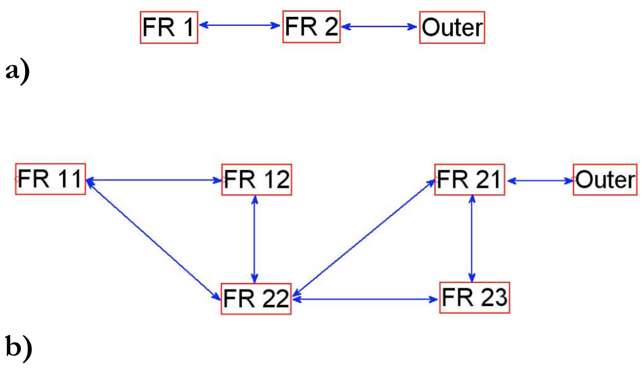

Figure 5. Decomposition of Functions. a) first level of decomposition; b) second level of decomposition.

Supposing that it is not required any further decomposition of block in sub-blocks, the Liaison Matrix has the structure reported in Table 4.

Table 4. Liaison Matrix for the case study.

	Ω	FR11	FR12	FR21	FR22	FR23
Ω	–			**1**		
FR11		**DS11**	**1**		**1**	
FR12		**1**	**DS12**		**1**	
FR21	**1**			**DS21**	**1**	**1**
FR22		**1**	**1**	**1**	**DS22**	**1**
FR23				**1**	**1**	**DS23**

In order to complete the Data Structure related to each Functional Requirement it is necessary to identify the parts that perform the function represented by the functional block of this level of decomposition. It is intuitive, at this point, to recognize as the functions can be performed by various components such as: light-bulb, the lens hood with the plastic transparent glass, the coupling, the shell that support the indicator, the shape of the indicator.

Once known the Functional Requirements and also the potential solutions for each of them, it is possible to find the Design Parameters able to control the FRs. For this product, the Design Parameters, could be:

- DP11 - The light intensity, measured in candles or better in Watts
- DP12 - The opening angle of the light beam in radians
- DP21 - The diameter of the stem to be joint to the motorbike in mm
- DP22 - The product weight in grams
- DP23 - The coefficient CX of aerodynamic penetration or simply the frontal section in mm²

The Design Matrix becomes as in Table 5:

Table 5. Design Matrix for the case study.

	DP11 (W)	DP12 (rad)	DP21 (mm)	DP22 (gr)	DP23 (mm²)
FR11	**X**				
FR12		**X**			**X**
FR21			**X**		**X**
FR22				**X**	**X**
FR23		**X**	**X**	**X**	**X**

It is possible to recognize a conflict between FR12 and FR23 because both parameters DP12 and DP23 conjointly influence them, in that the angle of the light beam and the aerodynamic penetration could affect mutually. Further, the aerodynamic penetration (DP23), expressed by the frontal section, is in relation with the indicator stem by which are explained the functions FR21 and FR22. On the other hand there is a relationship between the functional requirement of improving the aerodynamic penetration with the limited weight of the whole apparatus. The relation is not direct and it is present because, in practice, reducing the size of the product, its weight tends partially to decrease.

Now, at this level, it is possible to put in relation the Customer Needs (the "What") with the Design Parameters (the "How") through the Relation Matrix of the Quality Function Deployment.

Table 5. Relation matrix of HoQ for the case of study.

HOW (DPs) / WHAT (CNs)	**Relative importance**	The light intensity	The opening angle of the light beam	The diameter of the stem of the joint	The product weight	The coefficient of aerodynamic penetration or the frontal section	**Influence of DPs on CNs**
Racing aspect	5					9	9
Dimension reduced	4	1	3		9	9	22
Weight reduced	5		3		9		12
Good aerodynamic penetration	3	1	3		9	9	22
Good luminous efficiency	3	9					9
Affordable costs	1	3		3	3	3	12
Respect of traffic rules	2	9	9	3		1	22
Technical importance		55	54	6	111	113	

From this analysis it appears that the limited size, the good aerodynamic penetration and the respect of traffic rules are the market demands most affected by the design choices.

The functions to improve the aerodynamics, and subordinately, to have a weight reduced, have the higher technical importance. This is exactly what it is expected from those who buy a product to replace the original on his motorbike, ignoring other aspects probably more important, but certainly less trendy.

These considerations emerged from QFD and revised by stakeholders should lead to a review of the product design, where conflicts are recognized, by iterating through a Functional Analysis, Axiomatic approach and QFD until the solution is acceptable.

5 REVIEW PROCESS

The case of study is a typical example of a motorcycle part that can be replaced by a so called aftermarket product. Really a wide range of alternative solutions are already available on the market for this part. In the following two of them will be analyzed on the basis of the approach discussed.

5.1 SOLUTION A

Solution A, shown in Figure 6, presents only a reduced global dimension with respect the original one. So for this solution all the discussion made about FRs, DPs and their influence on CNs remain unchanged. In the design matrix the contradiction related to the influence of the coefficient DP23 (aerodynamic penetration) on many FRs remains. The part has only a reduced frontal section that, in any case, influences positively the aerodynamic aspect. The reduced dimension implies in any case a lower weight.

Figure 6. Solution A

5.2 SOLUTION B

Solution B, shown in Figure 7, presents a radically different product, in which the parameters related to weight reduction and aerodynamic penetration are stressed.

Figure 7. Solution B

To fulfill this task the part that badly influenced the aerodynamic performance was eliminated, by coupling the indicator in direct contact with the vehicle hull. This allowed to remove the stem.

The only Functional Requirements that remain active are the following:

FR11: Emit the light
FR12: Direct the light
FR2: Fit to the motorbike

with a simplification of the functional schema, reported in Figure 8.

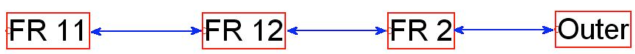

Figure 8. Decomposition of Function for the Solution B

Table 6 reports the Liaison Matrix associated to this solution. As can be seen, the relationship among FRs is very balanced.

Table 6. Liaison Matrix for the Solution B

	Ω	FR11	FR12	FR2
Ω	_			**1**
FR11		**DS11**	**1**	
FR12		**1**	**DS12**	**1**
FR2	**1**		**1**	**DS2**

Table 7 reports the Design Matrix which presents a really minimal structure and reflects the reduced number of components.

Table 7. Design Matrix for the Solution B

	DP11 (W)	DP12 (rad)	DP2 (mm)
FR11	**X**		
FR12		**X**	
FR2			**X**

The result of this change has also a direct influence on the total weight reduction, while the possibility for the indicator to form one body so close to the hull improves its aerodynamic. The new product design also break down the cost, very high for the original one. The result of this new product is accordance with respect of the main Customer Needs. The only problem is related to the respect of EC rules, since the possibility to use the new component on the vehicle must be authorized by testing at Bodies.

6 CONCLUSION

The flow of information among the Relation Matrix of House of Quality, the Liaison Matrix of Functional Analysis and the Design Matrix of Axiomatic Design has been investigated in the paper. The interrelation among these methods has been possible mainly because all methods use the matrix format to store the data and the data exchange has been pursued because the dimension are correlated.

The relationship between Customer Needs and Functional Requirements is the starting point for product design and is regularly verified in order to guarantee that the FRs agree to the needs emerged in the market. The reasoning about FRs allows the designer to develop a functional structure, supported by a Liaison Matrix, and then to design a physical architecture for a solution. At this point the Design Matrix can start to check if the solution is valid. In this phase the First Axiom of Axiomatic Design can aid the designer to verify if the solution is really valid or hides any contradiction between Functional Requirements an Design Parameters. A further step requires to check the relation between Design Parameters and Customer Needs in the House of Quality. This latter closes the "design circle" and gives to the designer further information about the "quality" of the solution.

The paper has demonstrated that a virtuous circle can be activated among these methods, but a real improve can be reached only if a software tool can support it. In the near future major efforts will be dedicated to this aspect, mainly for supporting the Functional Analysis by a tool able to visualize the functional structure and to build the Liaison Matrix simultaneously.

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