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APPLICATION OF DSM TO MECHANICAL CALCULATIONS OF VERTICAL HYDRO GENERATOR

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1. Introduction

Design involves characterisation of many variables which togeather define a product, its behaviour and how it is made [Steward 1981]. For the one of the kind products, engineered by order although the function and structure elements are well known all the product's variables have to be revisited during the development process, precontract design and detiled design afterwards. This is a time consuming process with the highest impact on the quality of the future product. Structure analysis is the basis for the identification of structural potentials [Lindemann 2009], and it can point out relevant elements for which modification could lead to the improvement of structure. During design of vertical hydro generators, mechanical calculations are the most resource consuming operations necessary to define a number of variants of the future product. Mechanical calculations ensure mechanical stability and integrity of hydro generator in working conditions through its exploitation. They also have large impact to its's efficiency of design and optimization due to a fact that they define key materials and shapes of generator components. Usually there are more than twenty different mechanical calculations for most common types of large generator. Mechanical calculations for one project can be a time consuming process due to the fact that most of the calculations are dependent on each other, which leads to a conclusion that it is an iterative process.

One of the methods for structure analysis is design structure matrix (DSM). Design structure matrix, or dependency structure matrix, is a square matrix with simple, compact, and visual representation of complex system [Browning 2001] or project or any kind of interlinked data or events. It can be used to evaluate dependency between elements and to indentify interactions between them. DSM can depict component relationships, product components, performance attributes, process tasks or engineering requirements.

In these work is used DSM for system analysis which will give many informations. DSM is used because it is a method with visual representation of results in matrix format and the results are intuitively readable. DSM increases architectural understanding, identifies modules, predicts system interaction, reduces process duration, reduces rework, improves organization etc. Process of existing stream of calculations should be optimized. This is particulary important for the sequence of mechanical calculations to achieve that entire sequence is performed with minimum rework to improve organization and to indentify calculations with feedback loops. Feedback loops are also investigated with analysis called "Powers of the adjacency matrix".

2. DSM overview

With professor Don Steward as a founder of DSM, DSM has been introduced in industry application at NASA, Boeing, General Motors, and Intel in 1990s [Eppinger 2012]. Today there are numerous applications of DSM in wide range of industries and there are hundreds of research papers. Almost all DSM models can be classified into four types within three main categories as shown in Figure 1 [Eppinger 2012]. First category is static architecture which elements exist simultaneously (products which componets physically interact one with another/or organizations which elements communicate one with another). The second category is temporal flow which models are time-dependent, representing models which elements could be actuated over time. Third category is multidomain matrix models (MDM), they represent more than one DSM like product architecture, organization architecture or/and process architecture matrix all in one matrix. In these paper is used process architecture DSM, other DSM groups are not suitable for these case beacause elements or tasks are mechanical calculations which are time-dependent.

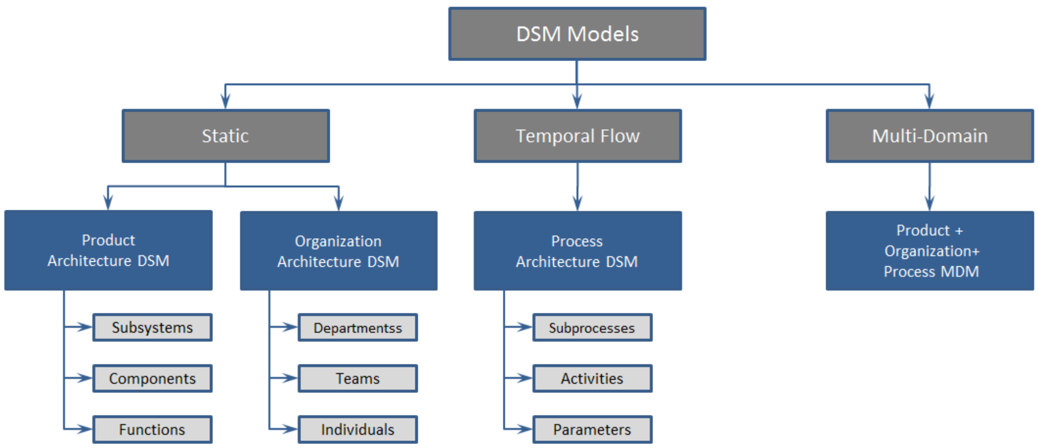

Figure 1. Types of DSM [Eppinger 2012]

Each DSM follows next five steps [Eppinger 2012]:

1. Decompose - break complex system into constituents
   - Create square DSM rows and columns labeled with tasks
2. Identify - document the relationships between elements
   - Identify all known interactions between tasks
3. Analyze [Oloufa et al. 2007]
   - Partitioning (process of manipulating with rows and columns in order to rearange DSM in such a way it does not contain any feedback loops, all dependencies are as close as possible to the diagonal (optimal solution is without any feedback loops - lower triangular form)
   - Clustering (finding elements that are mutually connected to form modules or clusters)
   - Tearing (process of choosing feedback marks which removal will result with lower triangular matrix)
   - Aggregation (agregating of two or more elements in one new)
   - Decomposition (manage rework by moving marks X as close as possible to or below diagonal)
4. Display
   - creating visual representation of matrix, with highlighted features of importance
5. Improve
   - making changes in order to optimize the system sequence

In temporal flow/time-based systems (sequences), partitioning try to move all dependencies below and far away from diagonal. Distance between backward dependencies and diagonal indicates the number of process tasks, this mean that dependencies farther from diagonal produce longer iteration time.
Clustering analysis is applicable on static models (Product architecture and Organization Architecture), while temporal flow (time-based) models need to be analysed with sequencing. After partitioning of DSM matrix, matrix looks like matrix in Figure 2. It could consist dependent, independent, interdependent and contingent links.

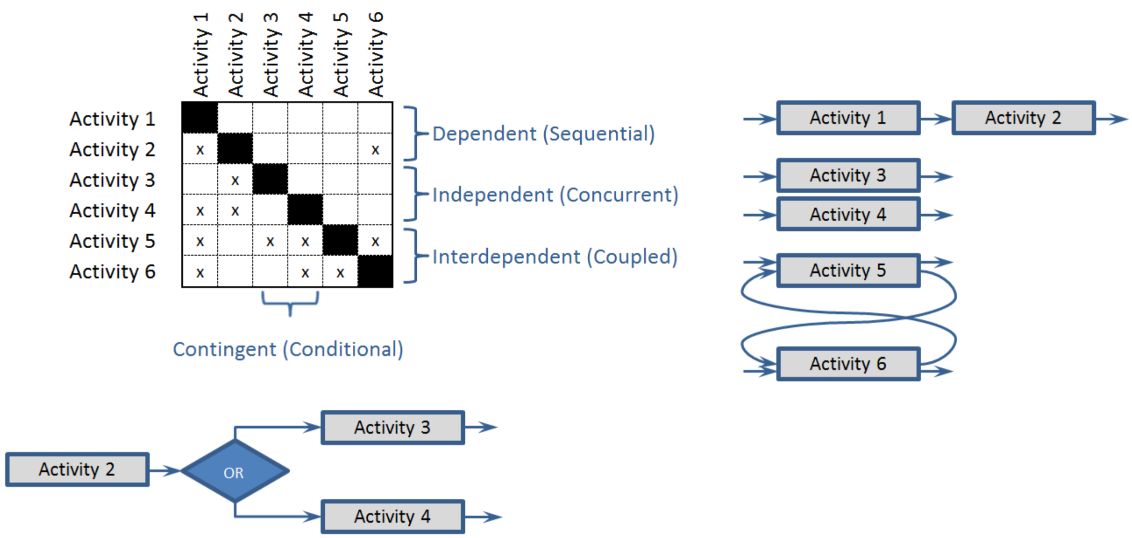

Figure 2. Activity relationships in an activity-based DSM

Partitioning could be done with few approaches which are similar [Talić 2013], with difference in cycle identification [DSMweb.org].
Circuits or feedback loops could be determined with:

- Path searching
- Powers of the Adjacency Matrix Method
- The Reachability Matrix Method
- Triangularization Algorithm

In this paper it will be investigated loops on whole unpartitioned matrix by "Powers of the adjacency matrix" [Lindemann 2009]. Binary square matrix (DSM) raised to the n-th power shows feedback loops on the diagonal cells shown in Figure 3. If we square DSM matrix, it shows that element A and B form a feedback loop, cubing the matrix shows that elements A,B and C form a feedback loop. Fourth power shows that all elements include feedback loop, elements A and B contain value 2, and that is because they form their own loop. Feedback loops for larger structures can not be analyzed by these approach, because feedback loops containing the same elements cannot be distinctively traced back to their implied elements [DSMweb.org]. This method is used only for determination of the existence of feedback loops.

	A	B	C	D
A	0	1	0	0
B	1	0	1	0
C	1	0	0	1
D	1	0	0	0

DSM

	A	B	C	D
A	1	0	1	0
B	1	1	0	1
C	1	1	0	0
D	0	1	0	0

Square

	A	B	C	D
A	1	1	0	1
B	2	1	1	0
C	1	1	1	0
D	1	0	1	0

Cube

	A	B	C	D
A	2	1	1	0
B	2	2	1	1
C	2	1	1	1
D	1	1	0	1

Power 4

Figure 3. DSM [Lindemann 2009]

3. DSM in mechanical calculations

Starting point of analysis was to indentify mechanical calculations which are common for the most variants of the vertical generators. The initial unpartitioned DSM is ilustrated on Figure 5 and includes relevant mechanical calculation procedures and product requirements, initial matrix is done for around two weeks. First part was to indentify which calculations will be included in the analysis (this means that generator has many more calculations, and many of them are nonformaly internally check without document), after that all selected calculations are examined in detials in order to indentify input data and output data from every calculation and to see which calculation is connected with which calculation. Some of calculations have very low influence on other calculations and that interactions are neglected. After indentification of all interactions, other experts for mechanical calculations additionaly checked the matrix and in agreement some of low influence interactions are neglected. Figure of some of relevant parts for easier understanding is shown below.

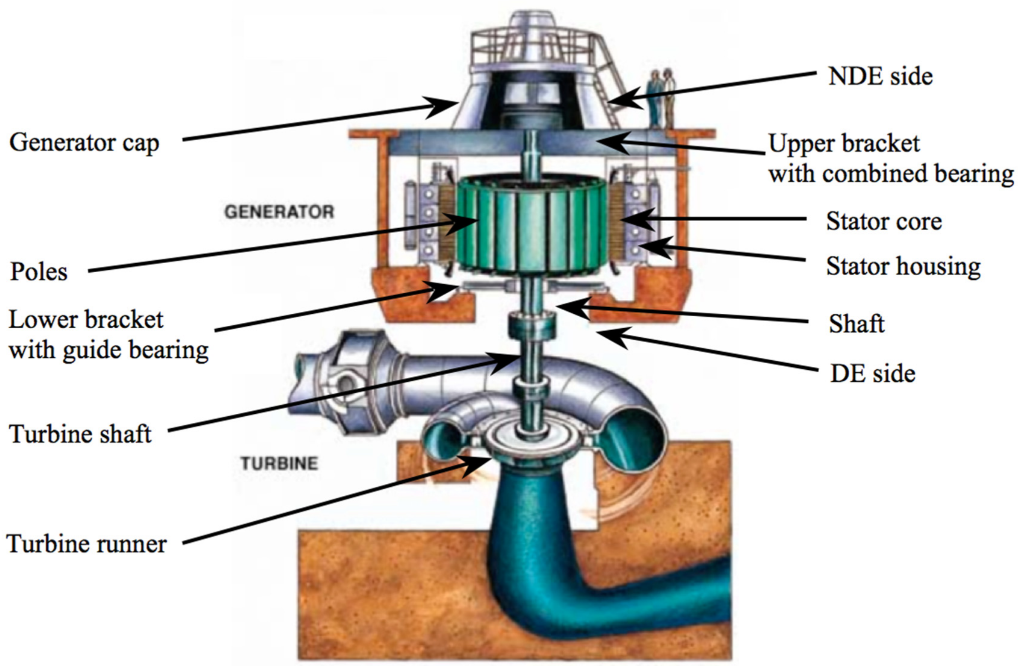

Figure 4. Vertical hydrogenerator [www.snowyhydro.com.au]

DSM analysis is done with free program for partirioning DSM_Program-v2.1 from DSMweb.org. Mechanical calculations cover the main functional subassemblies and parts of the product: rotor, stator, brackets (frame), guide bearing, thrust bearing, brakes, etc. Rotor and stator are the main generator parts which transforms energy [www.snowyhydro.com.au]. Rotor could be further divided into shaft, pole wheel, poles, interpole connections, pole leads, fans, braking ring etc. Stator could be divided into stator housing (frame), stator core, windings, etc. It is important to note that some of these calculations are done with finite element program, while others were done only analytically, in accordance with that most of the calculations done with FEM usually require much more time for preparation.

All dependencies between calculations are visible below. From dependencies it is evident that calculation p1 (Foundation loads), depend on many other calculations and requirement as p2, p3, p4, p5, p6, p9, p10, p11, p12, p18, p19, p20, p21 and p22. Calculation p9 (upper bracket) depends on calculations p3, p4, p5, p6, p10, p17, p18, p19, p20, p21 and p22. Calculation p10 (stator housing) depends on p3, p4, p5, p6, p9, p11, p17, p18, p19, p20, p21 and p22. Calculations p12, p17 (lower bracket and critical speed calculation) also depends on many other calculations and requirements.

Unpartitioned		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Foundation loads	1	1	1	1	1	1	1			1	1	1	1						1	1	1	1	1
Braking and jacking	2		2	1	1	1	1															1	1
Shaft flange and wedge	3			3	1	1	1															1	1
Turbine data	4				4																	1	1
Pole wheel	5		1	1	1	5	1															1	1
Pole	6						6															1	1
Interpole connections	7						1	7														1	1
Pole leads	8					1	1		8													1	1
Upper bracket	9			1	1	1	1			9	1							1	1	1	1	1	1
Stator housing	10			1	1	1	1			1	10	1						1	1	1	1	1	1
Stator core	11											11										1	1
Lower bracket	12		1	1	1	1	1						12					1	1	1		1	1
Rotor lifting device	13			1		1	1							13					1	1			
Rotor transport device	14			1		1	1								14				1	1			
Stator lifting device	15										1	1				15							
Stator transport device	16										1	1					16						
Critical speed	17			1	1	1	1			1	1		1					17	1	1		1	1
NDE fan	18																		18	1		1	1
DE fan	19		1	1	1	1	1												1	19		1	1
Generator cap	20				1																20		
Tender requirement	21																					21	
Generator data	22																					1	22

Figure 5. Unpartitioned DSM

The most time consuming calculations are usually finite element calculations which are in this case:

- p5 - Pole wheel,
- p6 - Pole,
- p9 - Upper bracket,
- p10 - Stator housing,
- p12 - Lower bracket,
- p13 - Rotor lifting device,
- p14 - Rotor transport device,
- p15 - Stator lifting device,
- p16 - Stator transport device,
- p17 - Critical speed,
- p18 - NDE (non-driving end) fan and
- p19 - DE (driving end) fan.

A goal of these analysis is to minimize rework time and it is especially desirable to minimize rework of calculations which are the most time consuming to minimize overall rework time.

4. Results

After partitioning of DSM matrix, matrix is close to lower-triangular form, with few reverse loops.
First come tender and tender requirements, next come generator project data which include ventilation data and turbine data, this is natural order of essential data for following mechanical calculations. Calculations p2, p3 and p5 are coupled and it is desirable to calculate them at the same time to reduce rework, calculation p5 should be done the last because it is the most time consuming calculation between them. Calculations p9, p10, p17 and p12 are also coupled, usual order is to calculate p9 (upper bracket), p10 (stator housing) than p12 (lower bracket) to get radial stiffnesses for critical speed calculation, with this order when lower bracket comes the last, critical speed should be done minimum twice because calculation of critical speed is done with assumption of lower bracket radial stiffness, than calculate true radial stiffness of lower bearing and than we must go back and again calculate critical speed. Usual procedure is to calculate upper bracket, stator housing then follows lower bracket and the last one is critical speed calculation (because if critical speed calculation satisfy tender requirements which is

usually satisfied, there is no need to return to calculation of upper bracket, stator housing and lower bracket).

Partitioned		21	22	4	6	7	11	20	2	3	5	8	18	19	9	10	17	12	13	14	15	16	1
Tender requirement	21	21																					
Generator data	22	1	22																				
Turbine data	4	1	1	4																			
Pole	6	1	1		6																		
Interpole connections	7	1	1		1	7																	
Stator core	11	1	1				11																
Generator cap	20			1				20															
Braking and jacking	2	1	1	1	1				2	1	1												
Shaft flange and wedge	3	1	1	1	1					3	1												
Pole wheel	5	1	1	1	1				1	1	5												
Pole leads	8	1	1		1						1	8											
NDE fan	18	1	1										18	1									
DE fan	19	1	1	1	1				1	1	1		1	19									
Upper bracket	9	1	1	1	1			1		1	1		1	1	9	1	1						
Stator housing	10	1	1	1	1		1	1		1	1		1	1	1	10	1						
Critical speed	17	1	1	1	1					1	1		1	1	1	1	17	1					
Lower bracket	12	1	1	1	1				1	1	1		1	1			1	12					
Rotor lifting device	13				1					1	1		1	1					13				
Rotor transport device	14				1					1	1		1	1						14			
Stator lifting device	15						1									1					15		
Stator transport device	16						1									1						16	
Foundation loads	1	1	1	1	1		1	1	1	1	1		1	1	1	1		1					1

Figure 6. Partitioned DSM

Sometimes a problem could arise if turbine data changes significantly from the begining of the project to the end of the project. If the change is significant that means to repeat all the mechanical calculations (from row 3).

Foundation loads are the last because they depend on many calculations and since it is one of the calculations demanded at the begining of the project, it is desirable to make one preliminary edition before final edition. Preliminary edition should be done with many assumptions like stator mass, rotor mass, axial force from turbine, generator moments etc. On this calculation later depends foundation calculation which is done by civil engineers and these assumptions should be as accurate as possible.

Feedback loops are also investigated by analysis "Powers of the adjacency matrix". Squared unpartitioned matrix is shown on the next picture, all calculations which are coupled can be indentified. Squared partitioned DSM shown in Figure 6. defines loops between:

- p2 - Braking and jacking,
- p3 - Shaft flange and wedge,
- p5 - Pole wheel,

- p18 - NDE fan,
- p19 - DE fan,

- p9 - Upper bracket,
- p10 - Stator housing,
- p17 - Critical speed,

- p17 - Critical speed,
- p12 - Lower bracket,

From squared DSM could be determined that p2, p3, p5, p9, p10, p12, p17, p18, p19 form loop, but it is not possible to see which calculations are in loop.

Cubed unpartitioned DSM shows two feedback loops comprised from three calculations and they are:

- p2 - Braking and jacking,

- p3 - Shaft flange and wedge,
- p5 - Pole wheel,

and

- p9 - Upper bracket,
- p10 - Stator housing,
- p17 - Critical speed,

Forth power of DSM shows that p18, p19 are coupled, but it is still unrevealed couple of p12 and p17. It is hard to connect calculations Lower bracket and Critical speed calculation which couple is visible from partitioned matrix.

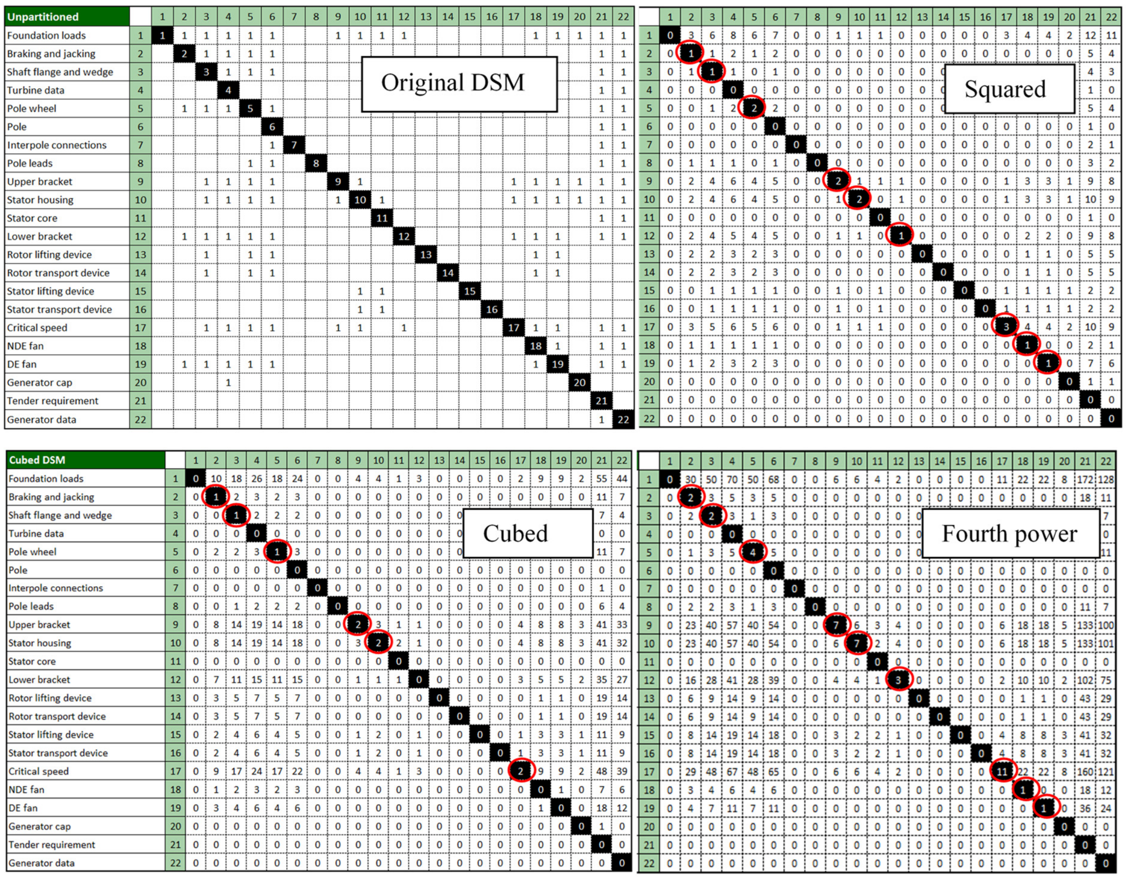

Figure 7. DSM

It is hard to conclude that p18, p19 and p17, p12 are also coupled. The deficiency of this method is much more complex indentifying of coupled calculations (elements), but it seems that these "Powers of the adjacency matrix" method is usable for indentifying elements with feedback loops on original matrix, because squared matrix showed all calculations with feedback loops as can be also seen from partitioned matrix. After all it could be concluded that partitioned matrix is much easier to read loops and except that, it reveals ideal sequence.

5. Conclusion

DSM is a wide spread visual method and it is applicable to a large number of industries, one of which is power production and production of electric generators.

It can be seen that DSM matrix after analysis give optimal sequence of mechanical calculations and required input data with one exception that lower bracket need to be calculated before critical speed

calculation (partitioning recognize critical speed calculation and lower bracket as coupled, but it put critical speed calculation first because it is also coupled with upper bracket and stator housing).
Partitioned DSM matrix gives insight that foundation loads need to be done last and it is necesarry to improve the sequence by adding preliminary edition of foundation loads calculation.
It is not possible to mark accurate differences between new sequence and sequence before analysis, because during the time of the project calculations are done with random order as soon as drawings are completed, and some of calculations have few revisons. Some other project will have different sequence and every project is unique. On one new project real sequence will be recorded and later compared with ideal sequence.
Overall DSM matrix seems to be very useful even in process like mechanical calculations.
Squared DSM matrix also shows all feedback loops but it is hard to identify which elements are coupled.
Further work and research will be oriented on creating own template for partitioning and banding and to expand model to a parametric level.

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