21st INTERNATIONAL DEPENDENCY AND STRUCTURE MODELING CONFERENCE, DSM 2019
MONTEREY, CA, USA, 23 – 25 September, 2019

Using the Design Structure Matrix for Space System Design

Jintin Tran[1,3], Mike Stowe[2], Markus Plattner[3], Markus Zimmermann[1]

[1]Laboratory of Product Development and Lightweight Design, Technical University of Munich, Germany
[2]The P5DC, Washington, USA
[3]Max-Planck-Institute for extraterrestrial Physics, Garching, Germany

Abstract: In the frame of space development projects, system design has to cope with large sets of requirements that are dependent from each other. The complexity becomes even higher since interdependencies often have a multidisciplinary character. The overall system complexity makes it difficult for design teams to intuitively understand the interactions of each physical domain not to mention the interdependencies of analyses and tasks. Dependency Structure Matrix (DSM) methods are used to represent the information flow of couplings as well as explore "what-if"-scenarios in the sense of trade-offs. Graphical representations of interdependencies allow the designers to deliberately vary couplings. In this paper we demonstrate a successful application of DSM methods for the design of the Wide Field Imager, a payload instrument on board ESA ATHENA.

Keywords: Space systems, Design Structure Matrices, Multidisciplinary Optimization, Change management, Complex system of systems

1 Complexity in Space System Design

Overall space systems design is a multidisciplinary process, which requires knowledge from different fields such as structures, environmental loads and system architecture. With increasing complexity and requirements regarding short development time and cost efficiency, it is necessary to develop a system understanding of the design processes and the effects of iterations. This is required not only on system level, but also within subsystems, on designer level. Proper decision management based on decomposition, concurrent engineering and parallel processing techniques, can then lead to effective product development. Unnecessary iteration loops within the design cycle can be avoided.

From the systems engineering point of view, understanding the flow of interdisciplinary design processes within a system of systems is important, especially within the conceptual project phase. The analysis of interdisciplinary design processes should be integrated as early as possible within the project coordination. Only in early project phases, is it possible to tailor the requirements according to design limits by design space exploration. As interdisciplinary collaboration is becoming increasingly important in international projects, it is further essential to incorporate as much knowledge as possible during the early design stages. This allows to mitigate risks and remain flexible on change management.

Space engineering is inherently iterative in the early stages of product development. Therefore, multidisciplinary approaches are most effective when applied in Phases A and B, much less so in Phase D. The project phases are depicted in Figure 1. With higher project phases, change requests become more costly and should be avoided. Exploring as many different combinations of design and performance measures, with a distributed design team, requires a more disciplined approach to understanding the implicit (binary) and explicit spatial and functional interfaces in the project development phases. Design Structure Matrices (DSM) methods (Steward, 1981; Eppinger, 2016), enable visualization of interdisciplinary correlations and provide systems design teams with a tool for getting the grip on system complexity.

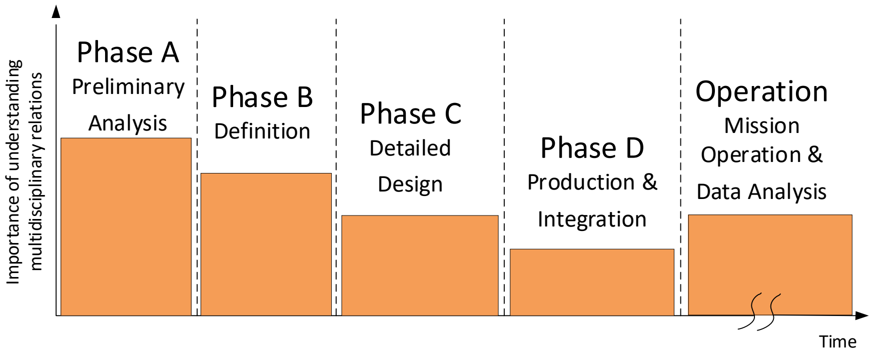

Figure 1. Degree of understanding during space project phasing

A multidisciplinary network of design processes is analyzed for the telescope instrument payload's Wide Field Imager (WFI), within the ESA space mission Athena. Based on the knowledge gained from the DSMs, the design processes are structured with the following outcomes:

- Project schedule and tasks are sequenced and forward/backward loops are identified
- Assistance in trade-off studies as a concurrent engineering tool to visualize various scenarios (Schaus, 2012)
- Communication between interdisciplinary teams is more transparent
- Subsystem modules can be clearly defined
- A multidisciplinary optimization (MDO) platform can be built based on identified interfaces between domains, i.e. interdisciplinary design variables are defined

By using DSM methods, a simultaneous view of various aspects on project management as well as on product design side are achieved. The analysis goals of each domain are measured by pre-defined key technical performance values. The additional benefit of using DSMs as a visualizing analysis method, is that in each design phase, changes and case scenarios can be analyzed and documented.

Subsystems can be classified by looking at the functionality and dependency of each component. With the DSM view, it can be decided if a subsystem can be a modular or an integrative system. When change requests occur, the design team will have to quickly assess the change effort against product benefit. Change decisions involve identifying which parts of the design are affected. The clustered DSM can show the overall benefit against the effort.

Concurrent engineering methods usually only consider the upper level requirements from mission design to spacecraft (Avnet, 2009; Yassine, 2003). However, a detailed design of components is barely taken into consideration but is very essential for designer teams. When using multidisciplinary optimization methods, the DSM analyses are essential to provide transparency between disciplines (Roloefsen, 2008; Xiong, 2015; Lambe, 2012). In Figure 2, the conventional engineering design process is shown. The optimization module represents a loop of a sequenced DSM. By using the DSM methods, possibilities within the design space can be analyzed before starting an analysis run. The goal is to visualize each domain and integrate them into an MDO design process. In this paper, a special focus on system design optimization of the satellite payload systems is chosen for DSM application.

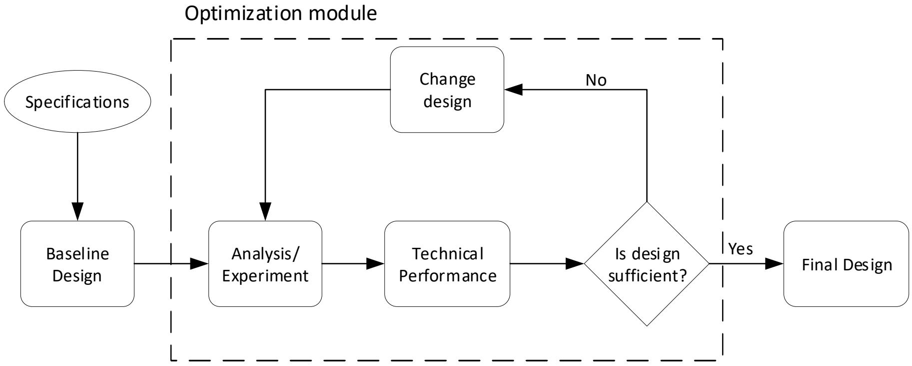

Figure 2. Optimization module integrated in conventional Design Process

2 ATHENA WFI

The deep space project by ESA, called Athena (Advanced Telescope for High-ENergy Astrophysics), is the next generation X-ray space telescope which will make a large-scale map of the warm-hot intergalactic medium. Athena entered the study phase in 2014. The mission launch is planned to be in the early 2030s and a lifetime of at least 5 years is foreseen. Currently the payload development is at the end of Phase A, which makes it a perfect use case for the application of DSMs for process understanding of complex space systems.

The concept of the Athena telescope is illustrated in Figure 3. A human character is illustrated in the figure as a scale reference. The telescope consists of a movable Mirror Module Assembly at one end of the telescope, which collects the light from the universe. The mirror focuses the light over a focal length of 12 m to the Scientific Instrument Module (SIM) where the payload platform is located. The instrument payload consists of two instruments: the X-IFU (X-ray Integral Field Unit) and WFI (Wide-Field Imager). The instruments will detect the X-rays by spectroscopy and imaging.

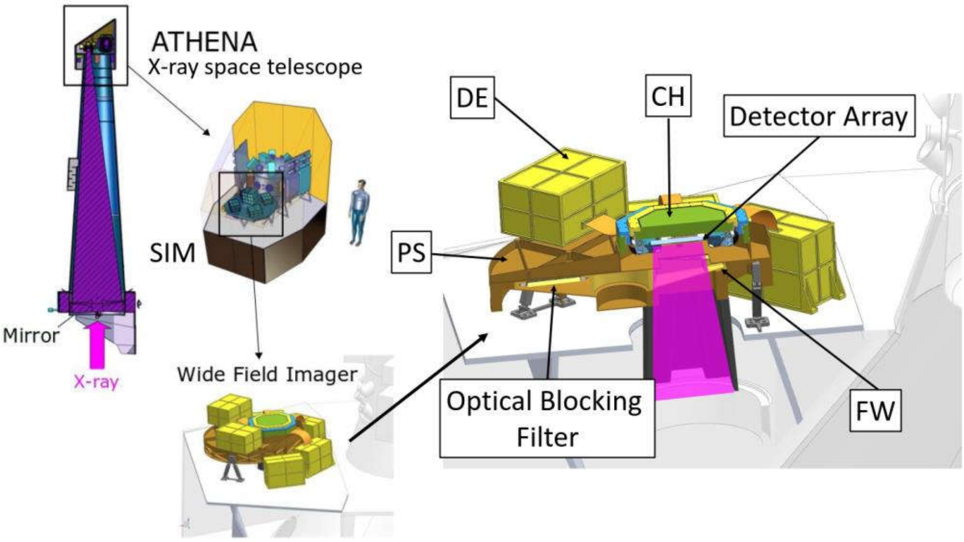

Figure 3. ATHENA space telescope including SIM platform and payload instruments on board (Source: ESA)

The WFI will be capable of performing spectrally and time resolved photon counting. A Filter Wheel, Camera Head, and Detector Electronics, are accommodated on the Primary Structure (PS), into one instrument unit. The PS is the Main Structure which has mechanical interfaces to the spacecraft platform (SIM). The Baffle is accommodated at the entrance of the instrument in order to avoid stray-light entering the instrument. The thermal interfaces link the thermal system of the spacecraft to the WFI instrument.

3 Application of DSM for WFI use case

As a main design challenge within the WFI, the Filter Wheel Assembly (FWA) has been identified. The FWA consists of the housing, which is integrated into the PS, the baffle, and the FW itself. The functional parts of the FWA are the FW and its actuator drive mechanism. The FW accommodates sensitive optical blocking filters as well as several calibration sources.

Due to single point failure risks of the FW drive, and environmental loads, such as vibrations and acoustic noise, this subsystem is rated critical. Without any protection mechanism, the baseline design indicates a high risk of filter damage during launch, which would not only cause loss of mission quality, but also particle contamination for other sensitive components, e.g. the detector.

As the WFI project is entering Phase B, it is important to clearly see the complexity of interacting domains in order to define the interfaces and requirements for each component. For that, the system complexity is analyzed by identifying related key parameters of each domain. The design drivers of a space system such as the FW are shown in Figure 4. The overall objective of the design is to achieve high performance (e.g. optical precision) and minimization of mass based on costs. The main challenge of the FW design, is to find a design that fulfills the goals and survives environmental loads.

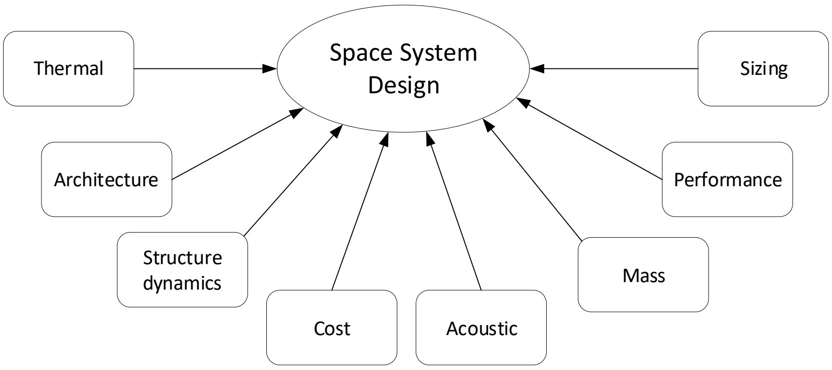

Figure 4. Design drivers for a typical space system

To abstract the problem, the parameter relations of the FW are shown in an attribute dependency graph displayed in Figure 5. These are the explicit relationships that can be used for coding of MDO systems. With the main goal of filter survival, the stresses have to stay below material yield strength σ_{yield}. The parameters differential pressure Δp, sound pressure level (SPL), acceleration a as well as coefficient of thermal expansion (CTE) mismatch have direct influence on the filter stress and are, therefore, called key performance parameters. Surrounding structures define the stiffness, mass, volume envelope etc. and have an indirect impact on the filter stress. The key performance parameters play a major role for the system design in all domains that are shown in Figure 4. With the help of DSM analysis, shared and independent parameters are identified in order to build the domain interfaces of multidisciplinary analysis. Based on the explicit relationships, a '5 Level DSM' may be created in order to show the relationship between implicit and explicit types of dependencies in the vertical integration across all hierarchical levels of the sequencing DSMs.

4 DSM for Multidisciplinary Optimization

MDO methods have taken the systems engineering design processes to another level by the need of considering couplings between each relevant module and discipline. DSMs have recently been used for structuring MDO algorithms (Lambe, 2012; Riccardi, 2012). Yao et al. (Yao, 2016) proposed a method to integrate the DSM into the MDO process (sequenced collaborative optimization) by introducing two parameters, bid values and coordination cost values, to extract the mutual coupling disciplines into groups with strong and weak ties on a simplified model. And English et al. (English, 2008) used a visual DSM to assist trade-offs with the aspects from MDO. In early 90s, DSM has been first applied in MDO for aerospace projects. Rogers (Rogers, 1997) introduced a DSM tool called 'DeMAID' for NASA projects. The aim was to reduce time and cost of a design cycle. The tool uses a genetic algorithm to optimize the processes. DeMAID is used specifically on functional oriented processes (Grose, 1994). Nonetheless, the implicit and explicit relationships of an MDO problem are not clearly separated in a DSM for MDO coding yet.

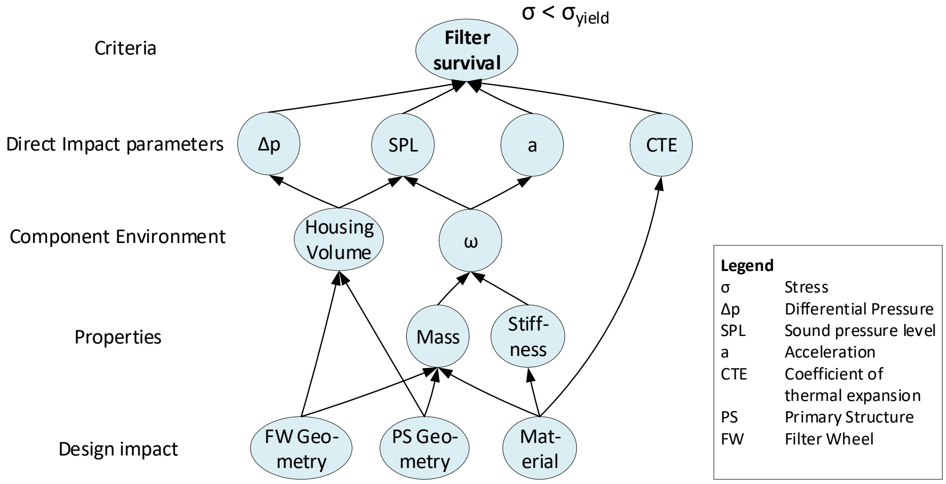

Figure 5. Attribute dependency graph for FW design problem

With the help of DSM methods, a solution in order to yield the best possible design is achieved. The aim of the DSM process is to better understand the dependencies of the interdisciplinary design variables. With this view, each subsystem can be obtained as a black box and only the exchanged parameters are considered. Therefore, the interaction of the disciplines such as acoustic noise, dynamic vibrations, shock, thermal expansion etc., for the FW system are aimed. With the help of the results, a sequence of design processes is defined and multidisciplinary optimization opportunities are identified. The complexity of the payload system is shown within the activities and output (aka component) DSMs.

The sequencing and clustering analyses of square matrices in a DSM, helps to guide the implicit (binary) mapping of the multidisciplinary interfaces, such that efficient time and resources can be spent on the 'happy' iterative sequences (HIS) (aka loops) in sequencing DSMs, and modular and integrative subsystem interfaces in clustering DSMs.

There are three types of possible couplings after sequencing a matrix. If tasks can be performed in sequence all existing dependencies are located at one side of the diagonal only. This means that no feedback loops exist in the structure and, therefore, no iteration steps are necessary. However, complex structures mostly have feedback loops that are kept at a minimum length during sequencing in order to achieve time-savings. In that case all edges are laid as close as possible to the diagonal (Lindemann, 2009). HIS are the ideal candidates for applying multidisciplinary optimization tools, so that you can proceed with the more straight forward serial and parallel processes. Early identification of 'unhappy' iterative sequences (UIS) (aka loops), is the enabler for avoiding unplanned time and costs. Tightly coupled blocks are indicated by overlapping loops. Items with no relation to each other indicate processes that can be processed in parallel and, therefore, decomposed for simplification.

An activity DSM for the WFI is shown in Figure 6. From the sequenced DSM it can be seen that most activities can be done in series. There is one loop identified which represents an MDO iteration. That loop contains structural, thermal, and acoustic analysis. Within each loop the overall design is updated. Based on the design and distributed requirements, the verification procedure and tests are planned. For WFI an MDO with structural, thermal and acoustic domains is, therefore, required.

	Start Project	Distribute Requirements	Perform Structure Design	Analyze Thermal Performance	Conduct Structure Analysis	Assess Acoustic Performance	Review Initial Multi Disciplinary Perform…	Establish Verification Procedure	Review Updated Multi Disciplinary Perfo…	Plan Tests	Assemble & Integrate WFI	Test Vibration Properties	Cycle Thermal Loads	Measure Acoustic Noise
Start Project	■													
Distribute Requirements	🟥	■												
Perform Structure Design		🟥	■	🟥	🟥	🟥								
Analyze Thermal Performance		🟥	🟥	■										
Conduct Structure Analysis		🟥	🟥		■									
Assess Acoustic Performance		🟥	🟥			■								
Review Initial Multi Disciplinary Perform…		🟥	🟥	🟥	🟥	🟥	■							
Establish Verification Procedure		🟥					🟥	■						
Review Updated Multi Disciplinary Perfo…		🟥	🟥	🟥	🟥	🟥	🟥		■					
Plan Tests		🟥	🟥						🟥	■				
Assemble & Integrate WFI			🟥					🟥		🟥	■			
Test Vibration Properties		🟥							🟥		🟥	■		
Cycle Thermal Loads		🟥							🟥		🟥		■	
Measure Acoustic Noise		🟥							🟥		🟥			■

Figure 6. Activities DSM: unsequenced (left) and sequenced (right)

The necessity of MDO application has been shown for the project Athena WFI. Based on the sequenced activity DSM, three kind of outcomes are identified: coupled loops, parallel and serial tasks. A design schedule is derived as shown in Figure 7. It clearly shows the required loops for each domain analysis which is marked by the blue rectangular. The schedule shows the work packages and is not a project timescale. With this view unnecessary and time-consuming UIS can be avoided.

Understanding the modular and integrative architecture of a product's subsystem/component interfaces (e.g. spatial, structural, thermal, noise) are the benefits of clustering. Clustering is used on the components-based DSM in order to group dependent components to subsystem modules. A change of one component of the cluster, causes subsystem internal change impact, whereas the replacement of the whole cluster only requires a few dependencies. Overlapping clusters indicate interacting systems. Therefore, the clustering criterion is used for subsystem architecture definition and change request decision management (Lindemann, 2009). The outputs that have a one-to-many relationship types, are indicators for application of MDO.

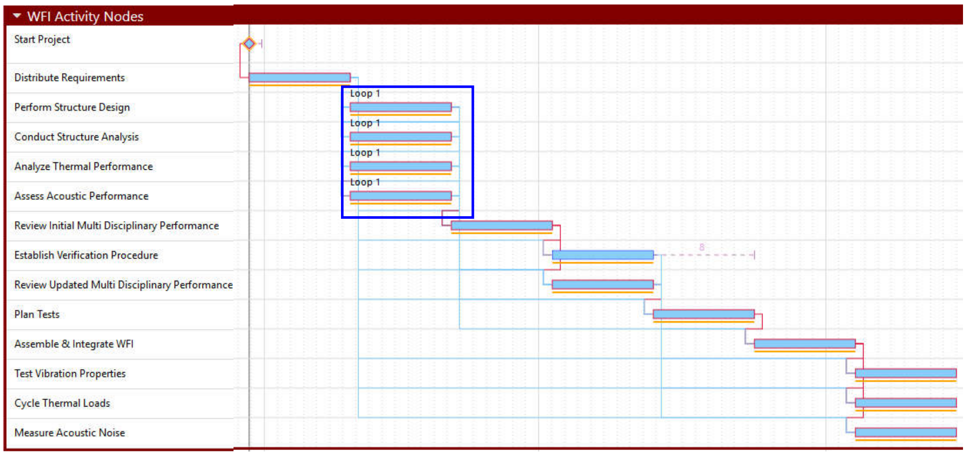

Figure 7. WFI activity schedule showing loops

For the project WFI the output DSMs are shown in Figure 8. As can be seen, two main clusters are identified. One smaller cluster contains mainly the detector assembly and its shielding (Camera Head). The remaining components show dependency in one big cluster, in which the calibration source, bearing and small filter assembly only affect the Filter Wheel Disc itself. Therefore, two major subsystems are identified: the Camera Head and the Main Structure that integrates the Filter Wheel Assembly with its functional components.

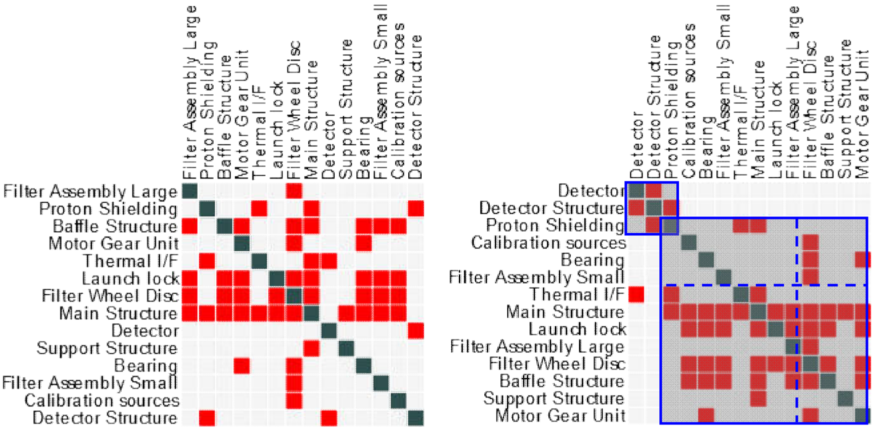

Figure 8. Output DSM: unclustered (left) and clustered (right)

Based on the outputs (aka components) analysis, the assembly and integration procedure of the instrument itself can be clearly identified as a modular Camera Head Structure, and a Main Instrument structure as shown in Figure 9. The thermal I/F are the connecting subsystem between Camera Head and Main Structure. The Main Structure with integrated Filter Wheel Assembly is identified as an MDO application due to multiple one-to-many relations.

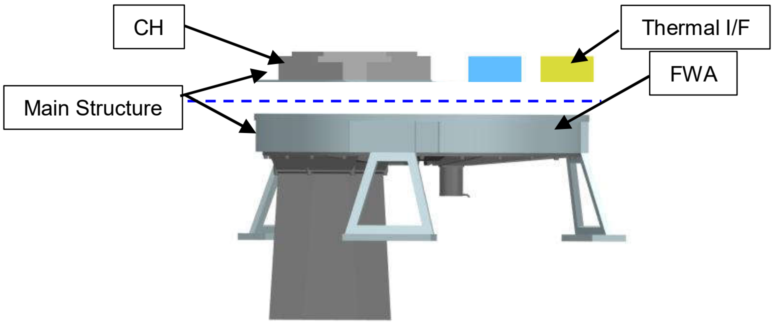

Figure 9. Substructured WFI based on clustered DSM

Though the sequencing and clustering DSMs are binary, they create the architecture of the explicit relationships (Figure 5) that need to be operated on to meet the technical performance measures and cost and schedule goals of the project. The DSM models will be used throughout Phases B and C, to help manage the decision process used by the development team, and to give 'indicators' on whether the project is converging or diverging from the stated goals. We can also use the output model to identity modular and integrative subsystems, to better manage change propagation.

5 Conclusion and Outlook

The DSM methodology has been used as a tool for the design process and identification of subsystem dependency for space payload systems based on the use case WFI. By sequencing the activity DSMs, identification and management of MDO opportunities is enabled. Technical key performance parameters can be derived as design variables, as explicit relationships for the actual MDO tools. With the clustered output model, modularity of subsystems is illustrated. From the optimized DSMs, it can be seen which subsystems clearly depend on each other. With that, the design development can be separated and, moreover, the assembly and integration plan can be defined. The clustered DSM also gives information on which subsystems require MDO analysis: With a one-to-many relation MDO analysis is necessary.

With the resulting DSMs, relations and components can be varied and various scenarios can be ‘quickly’ visualized for a better understanding. This is especially advantageous if change requests occur and design teams will have to review the options. The clustering method enables the design to visualize the dependencies of each component. For complex space systems, situational awareness as well as visibility is very important. This can be provided by optimized DSM views. For further model development and improved visibility, a multi-domain matrix (MDM) is aimed in order to have the ability to look at all domains simultaneously. The current DSM view would have to be classified to each domain. Moreover, for the relationship between implicit and explicit, further investigation on how to integrate the DSMs vertically and horizontally over all levels is required.

Acknowledgement

The authors thank Paul Waskett of the ADEPT Management Company for using their Flow DSM technology.

References

Avnet, Mark S., Weigel, Annalisa L., 2010. An application of the Design Structure Matrix to Integrated Concurrent Engineering. In: Acta Astronautica 66 (5-6), pp. 937–949. DOI: 10.1016/j.actaastro.2009.09.004.

Browning, Tyson R. , 2016. Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities. In: IEEE Trans. Eng. Manage. 63 (1), pp. 27–52. DOI: 10.1109/TEM.2015.2491283.

English, K.W., & Bloebaum, C.L., 2008. Visual Dependency Structure Matrix for Multidisciplinary Design Optimization Tradeoff Studies. JACIC, 5, 274-297.Lambe, Andrew B., Martins, Joaquim R. R. A., 2012. Extensions to the design structure matrix for the description of multidisciplinary design, analysis, and optimization processes. In: Struct Multidisc Optim 46 (2), S. 273–284. DOI: 10.1007/s00158-012-0763-y.

Eppinger, Steven D., Browning, Tyson R., 2012. Design structure matrix methods and applications. Cambridge, Massachusetts: The MIT Press (Engineering systems).

Grose, D., 1994. Reengineering the aircraft design process. *5th Symposium On Multidisciplinary Analysis And Optimization*. DOI: 10.2514/6.1994-4323

Lindemann, Udo, Maurer, Maik, Braun, Thomas, 2009. Structural complexity management. An approach for the field of product design. Berlin: Springer. pp. 136-139

Riccardi, Annalisa, 2012. Multidisciplinary Design Optimization for Space Applications. pp. 45-52

Roelofsen, J., Krehmer, H., Lindemann, U., Meerkamm, H., 2008. USING THE DESIGN-STRUCTURE-MATRIX FOR THE AVOIDANCE OF UNNECESSARY ITERATIONS. In: 10th international Design Structure Matrix Conference DSM08.

Rogers, James L., 1997. Reducing design cycle time and cost trhough process resequencing. In: International Conference on Engineering Dsign ICED 97.

Schaus, Volker, M. Fischer, Philipp, Quantius, Dominik, Gerndt, Andreas, 2012. Automated Sensitivity Analysis in Early Space Mission Design.

Steward, Donald, 1981. "The Design Structure System: A Method for Managing the Design of Complex Systems" IEEE Transactions on Engineering Management, vol. 28, pp. 71-74.

Xiong, Weitao, Liu, Can, Zhao, Qingsong, Yang, Kewei, 2015. DSM-based complex aerospace projects development process design and optimization. In: 2015 Annual IEEE Systems Conference (SysCon) Proceedings. Vancouver, BC, Canada, p. 409–415.

Yao, Xifan, Zhou, Jifeng, Li, Yongxiang, Liu, Erhui, 2016. An Enhanced Collaborative Optimization Approach with Design Structure Matrix Algorithms to Group and Decouple Multidisciplines. In Mathematical Problems in Engineering 2016 (9), pp. 1–8. DOI: 10.1155/2016/4340916.

Yassine, Ali & Braha, D., 2003. Complex Concurrent Engineering and the Design Structure Matrix Method. Concurrent Engineering: Research and Applications - Concurrent Engineering: R&A. 11.

Contact: J. Tran, Technical University of Munich, Laboratory of Product Development and Lightweight Design, Boltzmannstr. 15, 85748, Garching bei München, Germany, +49 89 289 15018, +49 89 289 15144, jintin.tran@tum.de