APPLICATION OF MULTI-DOMAIN MATRIX WASTE REDUCTION METHODOLOGY IN MECHATRONIC PRODUCT DEVELOPMENT

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As part of an industrial cooperation project with a German Car Manufacturer, the authors of this paper applied a matrix-based waste reduction methodology to the case study Multi-Domain Matrix (MDM) model of a sliding sunroof Product Development (PD). The application of the methodology resulted in a reduction of iteration marks by 96.5% in the process model, and the consequences for different waste types are described. In addition, the application of the methodology made possible the identification of meta-teams, which can potentially support better coordination and information flow between the teams involved in the development effort. The study concludes that MDM methodology is potentially a powerful tool for waste elimination in incremental mechatronic product development processes.

Keywords: Lean, Waste, Mechatronic product development, Complexity, Multi-domain matrix, Design structure matrix, Value stream mapping.

1. INTRODUCTION

A Multi-Domain Matrix (MDM) methodology that supports waste elimination and facilitates information flow in Product Development (PD) was recently introduced [Elezi *et al.*, 2010]. This methodology addresses waste in PD from a systemic perspective by reducing the so called Excessive Complexity (EC). EC is defined as the complexity that emerges mainly due to presence of waste in the system, and does not add any value in respect to customer requirements. Namely, while traditional Value Stream Mapping (VSM) methodologies directly attack what is defined as "waste" in Lean Thinking, a methodology that is based in MDM model can be employed to eliminate EC, thus achieving similar improvement effects to the PD processes. In other words, a typical structural complexity management tool is used to reduce systems' complexity [Lindemann *et al.*, 2009], and the effects of such action upon waste are observed. As part of an industrial cooperation project with TU München, the authors applied the abovementioned methodology to the MDM model of the development of sliding sunroof in a German Auto-manufacturer. The objective of this research is to apply the MDM methodology in a real mechatronic PD project, observe the reduction of complexity and analyze the impact on waste.

The initial input is the MDM model of the sun roof PD project containing 4 domains: functions, system elements (product elements), deliverables, and work packages (process domain). The 6 step MDM methodology (see Figure 1) is then applied to obtain the improvements in PD process.

In the first step, the identification of already developed elements or modules of the product is performed. The second step incorporates applying a clustering algorithm to obtain meaningful structural constellation of the remaining product DSM, with the aim of identifying the interfaces of product modules. This information is used in later stages for restructuring the process DSM. Step 3 and 4 involve process restructuring (by using a partitioning algorithm) and elimination of unplanned

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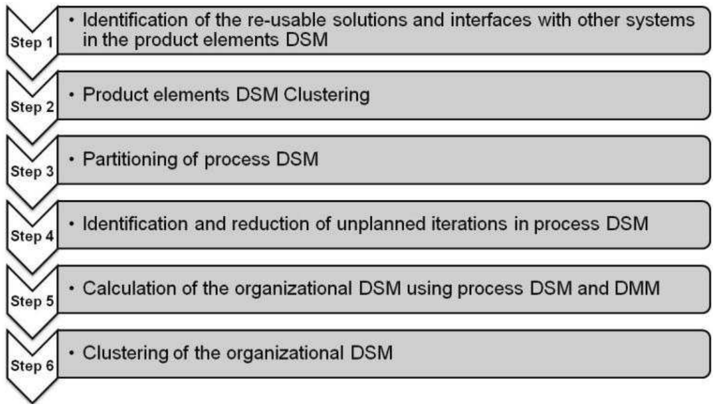

Figure 1. Steps of the MDM waste reduction methodology [Elezi *et al*., 2010].

iterations. Step 5 and 6 involve calculation of organizational DSM and application of a clustering algorithm to obtain meta-teams. In part 2 of this paper the step-by-step application of this methodology will be described.

1.1. Introduction of the sliding sunroof MDM

Researchers at TUM have mapped the sliding sunroof PD in an MDM as part of cooperation project with the car manufacturer.

The MDM contains 4 relevant domains that are described below:

1. Functions domain — the elements of this domain are the functions that the new product should contain. The elements and interdependencies of this domain were obtained from extensive analysis of function structure and interviews with project stakeholders.
2. Product elements domain — comprises the product parts. In our case, the product parts are divided into three main groups: electric, electronic and mechanical parts. There are total of 32 listed elements in this domain. The elements and interdependencies were obtained from parts list, exploded view drawings and were validated by means of interview with project team members.
3. Deliveries domain — the elements of this domain are deliveries that comprise outputs of one to several work packages, depending on the requirements of the process. There are total of 72 elements identified in this domain. Deliveries were obtained from a document called synchronisation plan and Gantt charts from the subcontractors. A synchronisation plan represents a map showing milestones and highlights the deliveries produced in different phases of the project.
4. Work Packages domain — is one of the most important domains for describing the process model. This domain comprises of 166 tasks. The tasks and interdependencies were obtained from process documents and interviews with project members.

The DSMs and DMMs provided are highlighted in Figure 2 in darker and lighter grey respectively.

2. APPLICATION OF THE METHODOLOGY

Following is the step-by-step application of the methodology mentioned in the introductory part into the sliding sunroof MDM model.

2.1. Identification of reusable parts and interfaces in Product DSM

The idea behind this step is to identify the parts of the product that will not be developed in this particular project. In this way, the number of elements in Product DSM is reduced, and the focus of

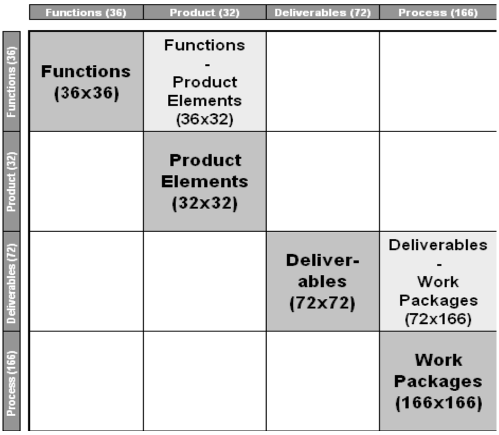

Figure 2. Sliding Sunroof MDM model.

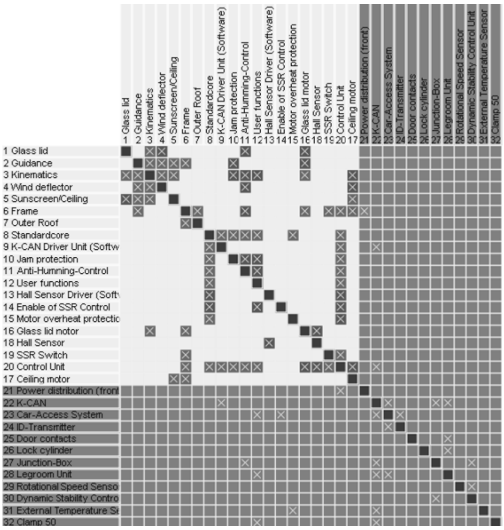

Figure 3. Product DSM with the highlighted parts (dark grey) that are not to be developed.

analysis is vested in the parts to be developed. The project team revealed total of 12 elements (parts) that will be not be developed but rather used as ready-made solutions. In Figure 3, the product DSM is shown. The elements (product parts) identified as reusable by the project team are marked in dark grey.

Most of the marked elements belong to electronic/electric area, while most of software and mechanic belong to parts that are to be developed.

2.2. Product DSM clustering

This step involves applying the clustering algorithm to the reduced product DSM (Figure 3 — the unmarked part of matrix). The aim is to find structural patterns that can potentially help in identifying interfaces between product modules, and interfaces with other car systems.

The software tool used for applying this algorithm was Loomeo v.2.1. The best clustering result was obtained by setting the number of cluster to 2. As seen in Figure 4, the upper cluster represents the

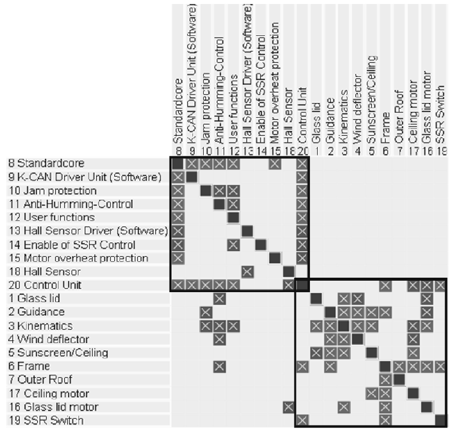

Figure 4. Product DSM after clustering.

software modules, while the lower cluster contains mainly mechanical parts. The control unit is clearly an interface between these two clusters, which brings together software, mechanical parts, sensors and actuators.

2.3. Partitioning of Process DSM

Before starting this step certain adjustments to the process DSM have to be performed. Sliding sunroof PD process has 4 main **non-overlapping** phases. However, the process DSM is provided as a single matrix containing all 166 tasks. Therefore, the process DSM has to be divided into 4 smaller DSMs and the partitioning algorithm should be run in each of them. In fact there are some benefits of dividing the process DSM in this way:

a. The visibility of the process is increased as fewer elements and dependencies are present, thus following the map is facilitated for the users.
b. Analyzing the partitioned DSMs and subsequent correction is also facilitated.

2.3.1. Partitioning of Phase 1 DSM

The first phase process DSM has 40 elements. This phase of the development process is the stage where all the initial concepts are drawn and in particular the electrical and electronics parts are conceptualized. This phase initially has 7 feedback loops and 1 pair of coupled tasks.

After the partitioning algorithm was applied to this matrix (again using Loomeo v.2.1), the following DSM is obtained:

It can be seen that all the iterations are eliminated except the iteration between coupled tasks (task 6 and 7). Partitioning is context-free algorithm, in other words, it tries to sequence the process without taking into account some limitations that might be present in the process. The project team revised the partitioned DSMs and consequently validated the sequences as technically feasible.

2.4. Identification and reduction of unplanned iterations in process DSM

Control unit was identified in Sec. 2.2 as the central part that interfaces with most of the other parts in the sunroof mechatronic system. Unplanned iterations can be eliminated if control unit (as highly networked part) and its interfaces are defined early in the PD process [Ulrich, Eppinger, 2008]. However, in this particular case study, there was no need to implement these measures as apparently the very first phase of the process defines the control unit and its electronic/electric interfaces. Apparently, process

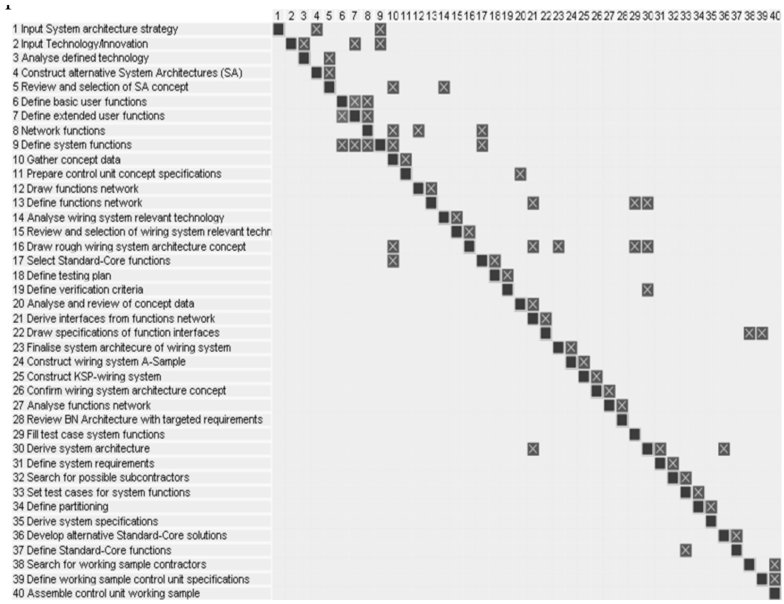

Figure 5. Un-partitioned Phase 1 process DSM.

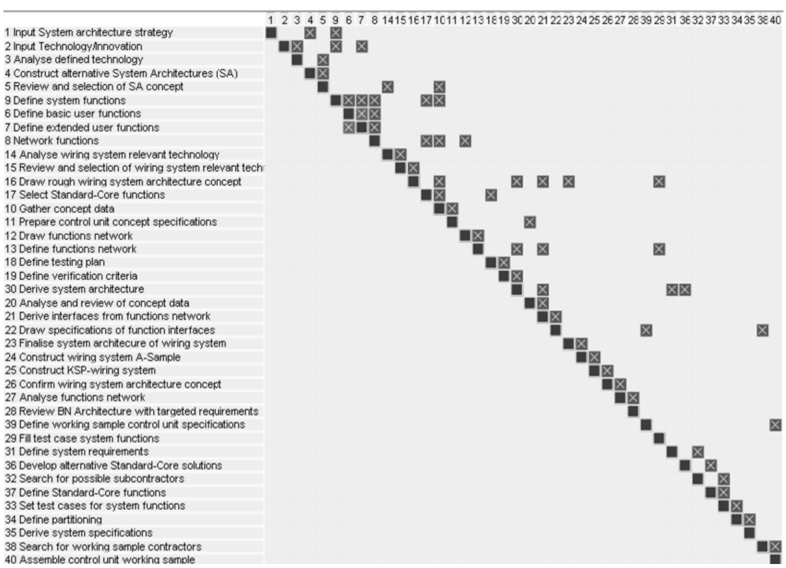

Figure 6. Partitioned Phase 1 process DSM.

engineers at the car manufacturer realized the importance of defining this central part at the beginning of the development process. By doing so, the unplanned iterations that would occur particularly when integrating the mechanical parts with the electric/electronic components are avoided (phase 3 of sunroof PD process).

It has to be kept in mind also, that the sunroof PD is an incremental innovation project and the unplanned iterations in these projects can be relatively easily avoided by re-sequencing the tasks in the process. This would however not be the case in radical innovation PD projects, where lots of unplanned

	EI-613 1	EK-323 2	PTG 3	EK-414 4	EK-321 5	EG-32 6	EG-2 7	EK-302 8	EK-402 9	SUB-1 10	SUB-2 11	SUB-3 12
41 Input loft												
42 Define SW-Development process	X											
43 Plan SW-Quality specifications	X											
44 Define control unit SW-Architecture	X											
45 Update System specifications to I-stage	X											
46 Integrate user functions in control unit	X									X		
47 Create list of functions for EBG	X											
48 Determine EBG-relevant system functions	X											
49 provide update of test cases (EBG)	X											
50 Construct test area for EBG subsystem		X										
51 Define control unit functions architecture	X											
52 Interpret the test results KSP	X											
53 Revise functions interfaces specifications	X											
54 Select subcontractor	X		X									
55 Develop 0-Series sample of control unit										X		
56 Develop B Sample wiring system				X							X	
57 Design inner lid					X							X
58 Design glass lid					X			X	X			X
59 Design foam-tool					X							X
60 Design guidance					X				X			X
61 Design kinematics					X				X			X
62 Design wind deflector					X				X			X
63 Design flat spring of wind deflector					X							X
64 Design bellows					X							X
65 Design ceiling					X							X
66 Design frame-front					X	X	X	X				X
67 Design cover panel					X							X
68 Design frame-rear					X	X	X					X
69 Design frame floor					X							X
70 Design frame seal					X			X	X			X
71 Design water drain					X							X

Figure 7. Phase 2 process-responsibilities DMM.

iterations will be present throughout the process as parts and modules would have to be tested and retested at each phase, and it would be a major challenge to reduce the iterations without sacrificing the quality of the product and/or the emergence of innovative solutions.

2.5. Calculation of the Organisational DSM

The calculation (deduction of dependencies) of the organizational DSM is performed by using the process DSM and the process-responsibilities Domain Mapping Matrix (DMM). As the sunroof PD process is comprised of 4 phases, it is logical to deduct the organizational DSMs for each phase. Again, because of the space constrains, only the calculation of the second phase organizational DSM will be shown.

2.5.1. Organisational DSM for Phase 2 of the process

To calculate the organizational DSM for phase 2, two input matrices are required: phase 2 process DSM and the corresponding process-responsibilities DMM (Figure 7).

The DMM in Figure 7 was provided later by the project team for the implementation of this step. The process-responsibilities DMM can be easily integrated in the MDM by adding the responsibility domain to the MDM. The DMM shown above relates the tasks of phase 2 with certain functional departments in the car manufacturer (renamed because of confidentiality reasons) and 3 outside subcontractors (SUB1 to SUB3). For example task 42 is performed by functional Dept. 1, while task 57 is performed by Dept. 5 and subcontractor SUB-3.

The calculation is performed using Loomeo v.2.1 and the following result is obtained:

The organizational DSM above shows how functional departments interact between each other during the 2nd phase of the PD process. For example, Dept. 3 and Dept. 1 interact in selecting the subcontractor (task 54) and this relation is shown in Figure 8. Similarly, it can be seen that EK-321 interacts with several other departments and subcontractors (Dept. 6, Dept. 7, Dept. 8, Dept. 9 and SUB-3).

2.6. Clustering of the Organisational DSM

By applying clustering algorithm to phase 2 organizational DSM, the following structure is obtained:

The DSM in Figure 9 shows 4 clusters and one independent department which does not belong to any cluster (functional Dept. 2). The two clusters at the top left corner overlap, which means that

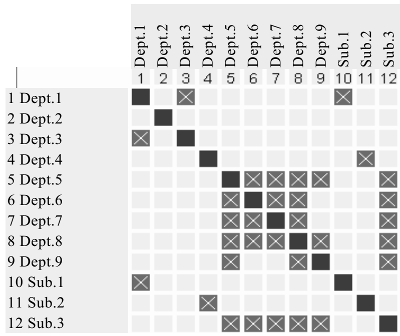

Figure 8. Phase 2 organizational DSM.

functional Dept. 1 belongs to both clusters. In order to facilitate the flow of information, 4 teams are proposed to be formed during phase 2 of the PD process. This would enhance the communication between the functional departments thus promote the flow of information significantly, by enhancing the interaction of these departments (e.g. by co-locating, setting up a joint database or sharing standard software applications) during this phase of the process. The independent department in this phase, Dept. 2, should not belong to any team. Thus, the anticipated team formation in phase 2 of the sliding sunroof PD process would consist of:

- Team 1: Dept. 1 and SUB-1;
- Team 2: Dept. 3 and Dept. 1;
- Team 3: SUB-2 and Dept. 4;
- Team 4: Dept. 5, Dept. 6, Dept. 7, Dept. 8, Dept. 9 and SUB-3

2.6.1. Observations on Organizational Matrixes

The organizational DSM is an effective tool for representing the interaction of different departments within the organization and subcontractors. It provides a base for discussion about alternative organizational structures. Therefore, its use can improve organizational understanding and support information exchange. Simply by calculating the organizational DSM encourages different people and department to increase mutual awareness and understanding. By clustering the organizational DSM possible meta-team structure is identified [Browning, 2001]. Moreover, clustering also reveals the inter-team interaction as in the case of the department Dept. 1 (see Figure 9) that belongs to both team 1 and 2. Even more importantly, these interactions can be seen for each phase of the process, which allows for dynamic team management. The car manufacturer as a functional organization, after

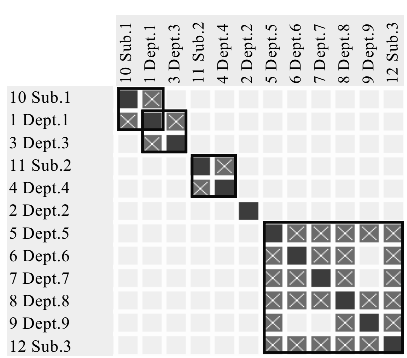

Figure 9. Clustered phase 2 organizational DSM.

Table 1. The impact of the methodology in the case study MDM.

	No. of iteration marks before	No. of iteration marks after	No. of coupled tasks before	No. of coupled tasks after
Phase 1	7	0	1	1
Phase 2	2	0	1	1
Phase 3	19	1	0	0
Phase 4	1	0	0	0

identifying and agreeing on team formations for each phase, can decide whether there is a need for co-location, special software tools or common databases to support this dynamic inter and intra-team communication.

3. CONCLUSION

The first two steps involved analysis of the product architecture (structure) and as expected, the role of the control unit was identified as central. This knowledge was planned to be implemented into the process, by defining the control unit and its interfaces in the early stages of the process. This would be achieved by agreeing on the control unit interfaces at the beginning of the process. However, this action was already implemented by the engineers at the auto manufacturer as they define the control unit and its interfaces early in phase 1 of the process.

Another important observation is that partitioning of process DSMs yielded better than expected results (step 3). Namely, in this step, most of the iteration loops were eliminated (see Table 1).

Before the methodology was applied, the entire sliding sunroof MDM process model had included 29 feedback (iteration) marks. After the methodology had been applied, the number of feedback marks was reduced to 1 (one). This represents a reduction of 96.5% of iterations. As rework (as defined in Lean thinking) is directly related to number of iterations [Kato, 2005; Bauch, 2004], it is expected that rework is reduced by the same amount. This result is quite surprising, as many authors argue that simple re-sequencing of the task does not lead to radical improvements in the process [eg. Yassine, 1999; Yassine *et al*., 2000]. So why in this case it was possible to improve the process model to such an extent only using partitioning? There are some arguments that can potentially give a reasonable explanation to this question:

1. First of all, the case study represents an incremental innovation PD process. This means that basically nothing significant is being invented, but rather improved and new functions supplemented to fulfill additional customer requirements. Mechatronic systems have the advantage of allowing functional extensions with small hardware and software changes.
2. Phase 3 of the sliding sunroof PD project, where most of the iterations should have occurred, involves system integration and testing. At the car manufacturer this phase is divided in 2 stages. In the first stage, the first prototype is built and tested and after recording and updating the information, the second stage begins where the changes are implemented and the second prototype is built. This means that stages 1 and 2 employ similar tasks and same teams and as such it represents in fact an iteration on its own.
3. The car manufacturer models mechatronic PD processes using milestones and deliveries, rather than tasks. Therefore the MDM model did not capture the “living process” but rather the planned one.
4. As with any other model, the MDM might contain errors, where not all the relationships are properly recorded. This would cause the model to look simpler and less iterative.

The methodology also reduces re-invention and transport/movement waste. The very first step in the proposed methodology involved an effort to identify which parts and modules of the product would be developed and which ones would not be developed. This knowledge is crucial for the process, so the parts/modules that the organization has already developed are re-used in the current project. However, quantitative measuring of the reduction of this waste is almost impossible, unless the model is applied in the process and the measurements are done from the process itself, not from the model.

On the other hand, transport and movement waste are expectedly reduced, as they are heavily influenced by the number of iterations [Kato, 2005]. More iterations mean more transport and movement of information. Similar to the re-invention waste, it is difficult to quantify the reduction of this waste from the model itself. The methodology also enables the visualization of meta-teams which ultimately might be used as information for facilitation of information flow within the developing functions of the company.

Finally, it can be concluded that the MDM methodology is potentially a powerful tool for waste elimination in incremental mechatronic product development processes.

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