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REDUCING DATA ACQUISITION EFFORT BY HIERARCHICAL SYSTEM MODELLING

Wieland Biedermann[1], Ben Strelkow[1], Florian Karl[2], Udo Lindemann[1] and Michael F. Zaeh[2]

[1]Institute of Product Development, Technische Universität München
[2]Institute for Machine Tools and Industrial Management, Technische Universität München

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1 INTRODUCTION

The design structure matrix (DSM) is a powerful tool for system analysis and modelling. It has been successfully applied in process management, product design and many other areas (Browning, 2001). The methodologies based on DSMs have led to more extensive matrix models such as the domain mapping matrix (DMM) and the multiple-domain matrix (MDM) – see Lindemann et al. (2009) for an overview. Methods based on matrices depend on high-quality system models. Data acquisition is crucial for the quality of the results of a later analysis. There are different approaches for data acquisition e. g. based on interviews, discussed e.g. in (Dong, 2002) with a focus on avoiding interviews if feasible, on workshops, discussed e.g. in Lindemann et al. (2009), or existing system models such as bills of materials or computer aided design models, proposed e.g. in Kusiak (2008). A general framework for the transformation of existing models was introduced in Helms et al. (2009). Interviews and workshops are rather time consuming. Biedermann et al. (2009) proposed a system of metrics to support workshops by highlighting the consequences of a decision during data acquisition. However, this method requires a pre-filling of a DSM and does not reduce the effort but focuses discussions.

In this paper a possibility to reduce the data acquisition effort is presented. It uses several levels of hierarchical system models. Starting at an abstract level the network is then mapped to a more detailed level using matrix multiplications as shown in Lindemann et al. (2009). Moreover, a case study modelling an assembly cell consisting of 103 components is presented. Thereby, it is shown that the proposed method can reduce the data acquisition effort by up to 65%. Finally, possible reasons for the acceleration are given and an outlook to future research is displayed.

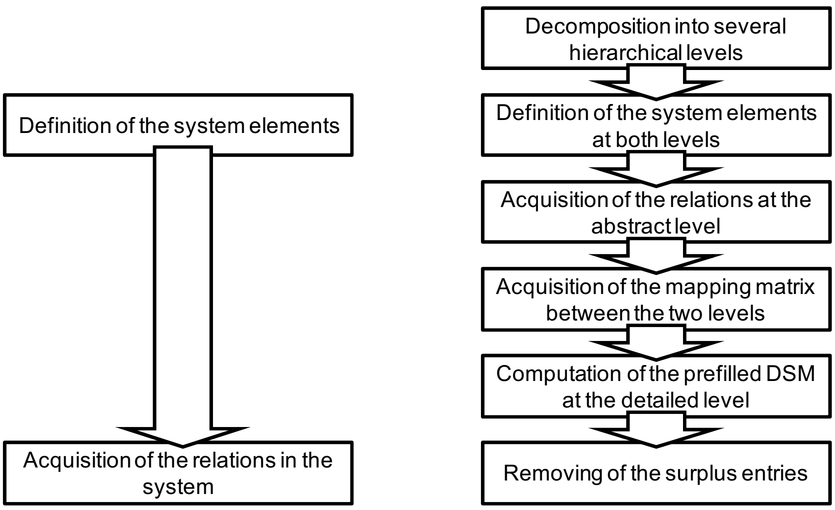

Figure 1. Comparison of the standard process (left) and the incremental process (right)

2 METHODS

The standard method for defining DSMs is to acquire the system elements first and then to identify the relations among the elements as shown on the left side of figure 1. The new approach relies on the idea that it is more efficient to create an abstract system model first and then to add more detail incrementally. This approach requires several additional activities as shown on the right side of figure 1. First, the two levels of abstraction have to be fixed. Then the elements of the systems at both levels are defined. Next, the mapping matrix is derived from the links between the abstract-level and the detailed-level elements. This mapping matrix is used to compute a pre-filling of the detailed-level DSM. Finally, the detailed-level DSM is acquired by removing the entries of the pre-filled matrix, which are not present in the system. The new method increases the number of acquired matrices, as it introduces the abstract-level DSM, the mapping DMM and the pre-filled DSM. Figure 2 shows the transformation concepts for the DSMs.

Tilstra et al. (2009) proposed a method for distributed data acquisition. Similar to the approach presented here the matrix is split into sub-matrices. Each sub-matrix is filled and the final matrix is formed by fitting the sub-matrices together. They claim that the overall process is accelerated. This is true. However, only the duration not the effort is reduced as all matrix fields still have to be discussed when fitting the sub-matrices together. Moreover, Tilstra et al. (2009) show by simulation that the chosen hierarchical structure strongly influences the reduction of time. They propose to use the structure given in bill of materials (see also the work by Kusiak, 2008) and show that this structure is about 10% better in terms of reduction of time than a randomly chosen one.

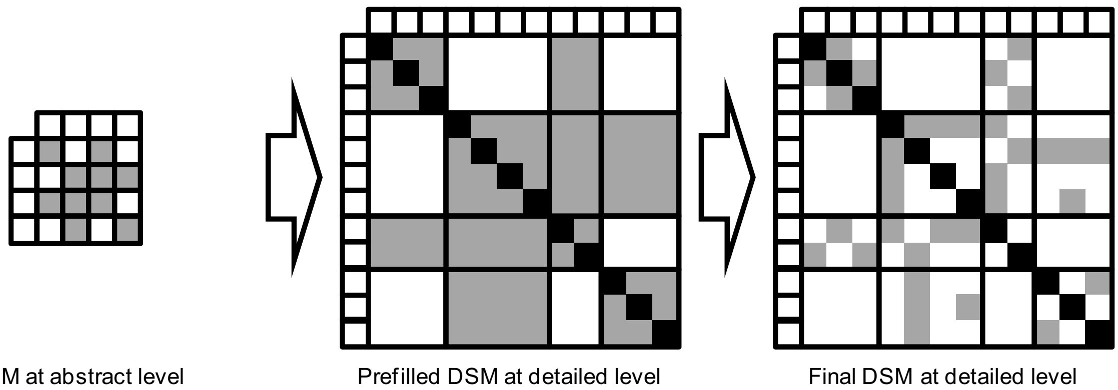

Figure 2. Matrix evolution in incremental data acquisition

Two facts have to be kept in mind when applying the new method. First, the abstract-level DSM has to have entries on the diagonal. Otherwise, the detailed elements, which are connected to the same abstract element, are not connected in the pre-filled matrix as these relations are not computed during the mapping to the detailed level. Second, each detailed element is only connected to one abstract element. Thus, the mapping matrix has only one entry in the row/ column of each detailed element.

The effort reduction of the new method mainly relies on the reduction of the number of discussed matrix fields. However, this effect largely depends on the structure of the abstract DSM. If it is rather sparse, the acceleration is high, as the number of matrix fields in the detailed matrix is reduced. The additional creation of the mapping matrix hardly increases the acquisition effort, as DMMs are generally easier to fill (Lindemann et al., 2009). Particularly, in case they are as simply structured as is shown above. Another acceleration effect is the reduction of options when filling a matrix, as the pre-filled matrix already contains all possible relations. The only decision to be made is whether an entry has to be deleted or not.

3 CASE STUDY

The case study system is an assembly cell of a research platform for cognitive automation systems, which is described in Zaeh et al. (2008). The overall research project aims at assessing the flexibility and changeability of production systems. One approach for the assessment is to use structural metrics to evaluate the production system’s structure. The same approach has already been applied to engineering design processes (Kreimeyer, 2010). To gain a holistic understanding of the system, several views onto the system, e. g. geometry or pneumatics, are modelled in the MDM, which is shown in figure 3. In this paper the focus is on the acquisition of the component DSM, which models the physical contacts among the components.

	component	cable/hose	sensors	actuator	controller	manual control	displays	signals
component	contacts	contacts	is a	is a	is a			
cable/hose								
sensors								creates
actuator								responds to
controller								creates
manual control								creates
displays								responds to
signals					processes			

Figure 3. Multiple-domain matrix of the assembly cell

The determination of the levels of abstraction is based on the hierarchical classification model for production resources as shown in figure 4 and introduced in Zaeh et al. (2006). The abstract level in the case study is the function group level. The detailed level is the component level.

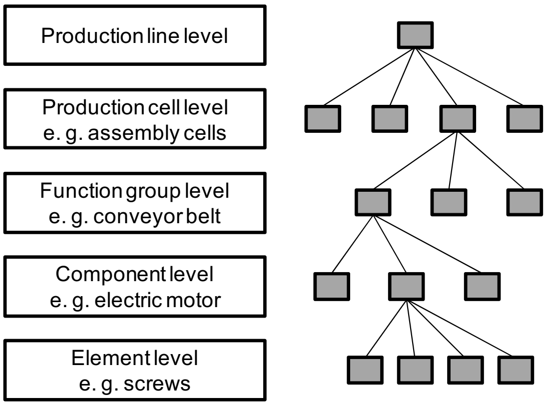

Figure 4. The hierarchical classification model for production resources, based on (Zaeh et al., 2006)

Table 1 shows the size and duration of the acquisition of the three matrices. The matrices were acquired by a three-man team. Several reviews and improvements of the matrices were done during the acquisition. The values in table 1 are the overall values including all reviews and changes. The values refer to the net working time and do not include pauses. The duration of the acquisition of the DMM also includes the pre-filling of the component DSM. All DSMs are symmetric, as the contact relations have no direction. Thus, only half the matrix has to be filled.

The function group DSM is rather sparse with a relational density of about 15 %. Thus, the pre-filled fields for the component DSM are only 25 % of all matrix fields. The average time for dealing with a matrix field of the function group DSM is twice the time in the component DSM. The average time for the DMM fields is much less than both.

Due to the lack of empirical results to compare the new and the standard method, the improvement through the new method has to be estimated. The major parameter of interest is the overall duration in both cases. The duration of the new method has been observed in the case study. To estimate the duration of the standard method the average time for one matrix field (as observed in the case study) is multiplied by the number of all matrix fields. The estimated duration of the standard method is 5253*0.6 minutes ≈ 53 hours. The new method reduces the acquisition time by more than 65% (≈1-18/53).

Table 1. Acquired matrices and acquisition duration

	DSM of the function groups	DMM between the function groups and the components	DSM of the components
Number of system elements	18	--	103
Number of matrix fields	153	2060	5253
Number of relevant fields	153	2060	1306
Number of filled fields	24 (+18 diagonal entries)	103	134
Overall duration	3 h	1 h	14 h
Duration per relevant field	1.2 min	0.03 min	0.6 min

4 DISCUSSION

The duration of the acquisition is reduced by about 65%. This can mainly be explained by the reduction of the number of discussed matrix fields. 1459 DSM fields and 2060 DMM fields have to be discussed instead of 5253 DSM fields in the standard case. The DMM fields are very easy to discuss as the DMM is very simply structured. Moreover, several additional activities such as the pre-filling of the detailed DSM can be automated.

On average the matrix fields of the detailed DSM are faster discussed than the fields of the abstract DSM. Possible reasons are training effects, as the detailed matrix is discussed after the abstract one, and reduced decision options as discussed above. Another reason is that the abstract matrix has to be discussed more carefully to avoid error with huge consequences on the detailed level.

The mapping matrix is created much faster than the DSMs. One reason is that DMMs are easier to acquire in general (Lindemann et al., 2009). In this case the simple and a priori known structure of the DMM is more important. Only one entry in each row/column of the detailed components is existing. Thus, the discussion of a component can be abandoned once the entry is found. Often, no discussion is necessary at all as the DMM can be determined by a simple model transformation.

However, the method may decelerate the acquisition if the system structure is not appropriate for the method. The system structure must be sparse particularly at the abstract level. Otherwise, the number of discussed fields may not be reduced and the additional effort to determine the additional matrices increases the overall effort. Moreover, the acceleration depends to a certain degree on the mapping between abstract and detailed level. If the mapping is chosen disadvantageously, the abstract matrix might be dense even if the detailed matrix is sparse.

Another risk when applying the new method is to make high-consequence errors. The abstract structure predetermines the structural properties of the detailed structure. Thus, small errors at the abstract level may lead to huge errors at the detailed level. So, the abstract matrix must be acquired much more carefully. Through the acceleration additional reviews and changes become possible and should be included into the acquisition process.

5 CONCLUSION

In this paper a method for accelerating the acquisition of large-scale DSMs in workshops was introduced. The main acceleration effect is the reduction of the number of discussed matrix fields. The acceleration is created at the expense of three additional matrices – the abstract-level DSM, the mapping DMM and the pre-filled DSM. However, the mapping DMM and the pre-filled DSM are very easy to acquire, as they can be deduced from existing models and can be computed respectively.

The case study describes the acquisition of the components DSM, which represents an assembly cell of a production system. The reduction of the duration through the new method was estimated to be above 65% compared to the standard method. Thus, the new method bares the potential for considerable effort reduction when acquiring DSM models in workshops. Yet, the new method requires more careful acquisition particularly at the beginning. Errors in the abstract level DSM can hardly be detected and corrected later. Therefore, the abstract DSM has to be subject to several reviews. One method to support critical decisions is described in (Biedermann et al., 2009). The additional effort due to more careful acquisition is compensated by the overall effort reduction. The new method is not suitable for all DSMs. The modelled system has to have a sparse structure and has to consist of several dozen of elements, otherwise the additional effort is not compensated. On balance, the new method offers possibilities for much more efficient data acquisition for large-scale DSMs.

ACKNOWLEDGEMENTS

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Contact: W. Biedermann
Technische Universität München
Institute of Product Development
Boltzmannstr. 15
85748 Garching
Germany
Phone +49.89.289.15136
biedermann@pe.mw.tum.de
http://www.pe.mw.tum.de

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Wieland Biedermann[1], Ben Strelkow[1], Florian Karl[2],
Udo Lindemann[1] and Michael F. Zaeh[2]
[1]Institute of Product Development
[2]Institute for Machine Tools and Industrial Management
Technische Universität München

Technische Universität München
UNIVERSITY OF CAMBRIDGE

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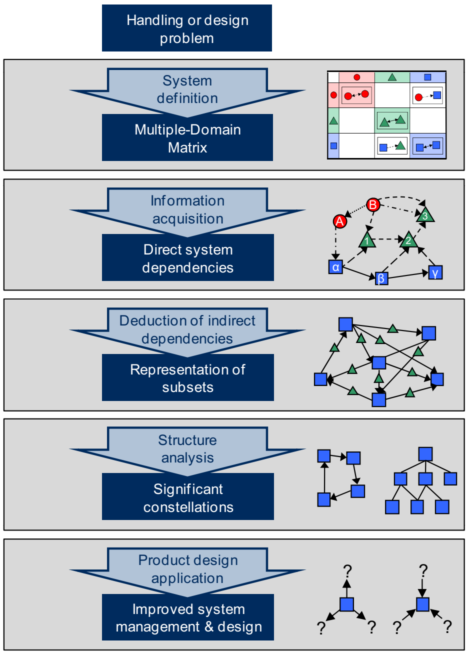
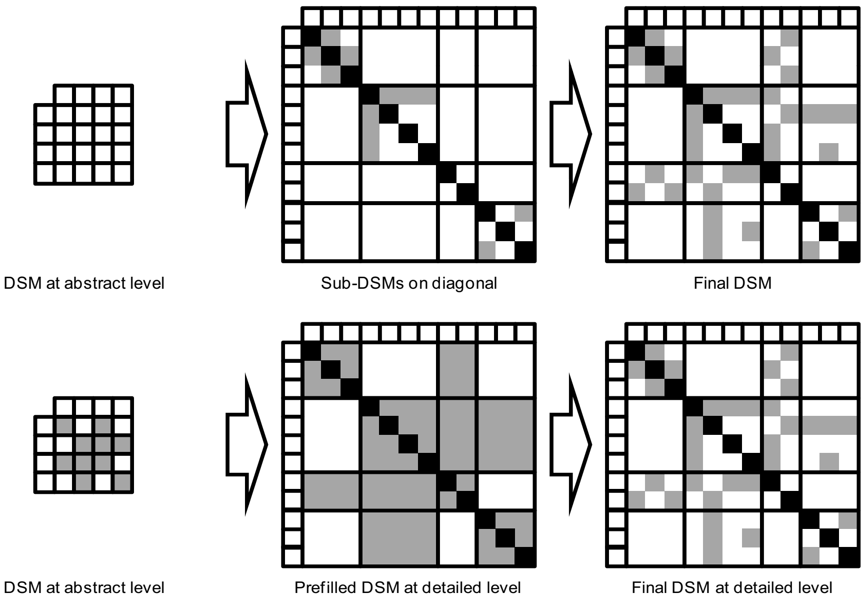
Data acquisition in DSM modelling



- Fundamental methods
  - Do-it-yourself
  - Interviews/Workshops
  - Surveys
  - Model transformation
  - Data mining/farming
- Acceleration methods
  - Divide and conquer
  - Substructures
  - Hierarchical system modelling

Hierarchical system modelling for effort reduction



Effort reduction by incremental modelling

Accelerative effects

- Reduction of the number matrix fields → only pre-filled fields discussed
- Decision options changed → removal of entries instead of setting
- Additional effort rather small → DMMs easier to acquire in general

Keep in mind

- Diagonal of abstract matrix must be filled → all relevant fields pre-filled
- Abstract matrix should be sparse → hardly any reduction otherwise
- Suitable hierarchical structure possible → hardly any reduction otherwise

Modelling a production system

	component	cable/hose	sensors	actuator	controller	manual control	displays	signals
component	contacts	contacts	is a	is a	is a			
cable/hose								
sensors								creates
actuator								responds to
controller								creates
manual control								creates
displays								responds to
signals					processes			

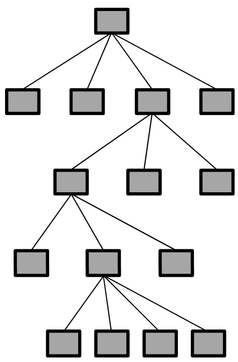
Production line level

Production cell level
e. g. assembly cells

Function group level
e. g. conveyor belt

Component level
e. g. electric motor

Element level
e. g. screws



How long it took

	DSM of the function groups	DMM between function groups and the components	DSM of the components
Number of system elements	18	--	103
Number of matrix fields	153	2060	5253
Number of relevant fields	153	2060	1306
Number of filled fields	24 (+ 18) (diagonal entries)	103	134
Overall duration	3 hours	1 hour	14 hours
Duration per relevant field	1.2 minutes	0.03 minutes	0.6 minutes

Observations and possible explanation

Estimation of effort reduction

- Effort without hierarchical modelling: 5243 * 0.6 min ≈ 53 hours
- Effort reduction by up to 65% (≈ 1 - 18/53)

Detailed matrix fields on average faster

- Training effects
- Abstract matrix more carefully discussed
- Decision options changed

DMM & matrix pre-filling very fast

- DSM structure simple and a priori known
- Pre-filling automatable

Conclusion and future work

Conclusion

- Method for hierarchical system modelling
- Validation shows up to 65% effort reduction
- Major effects: reduction of number of matrix fields
- Abstract matrix more carefully to discuss
- More checks possible and reasonable

Future work

- Additional validation in further projects
- Integration of quality controls into the method
- Integration in software tool for data acquisition