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SUSTAINABILITY IN MODERN PROJECT MANAGEMENT

Proceedings of the 18th International DSM Conference

São Paulo, August 29th and 30th, 2016

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Table of Contents

Part I – Managing Design and Innovation

Part II – Analyzing and Managing Organizations

Part III – DSM Application and Case Studies

Part IV – Project Management

Foreword

Welcome you to the 18th annual International Dependency and Structure Modeling (DSM) Conference. The 2016 conference is hosted by the Polytechnic School at University of São Paulo (USP) in São Paulo, SP, Brazil, August 29-30. It is organized in collaboration with Technische Universität München (TUM).

This year's theme is "Sustainability in Modern Project Management". The link between project management and sustainability is still fragile. However, in complex systems, the potential impact on sustainability are huge on economic, environment and social issues. In this context, a bridge between these research areas must be built and DSM can help on modeling and structure sustainable variables in the project life cycle. The design structure matrix has proved useful for modeling, analyzing, visualizing, and understanding complex systems. Over the last 25 years in particular, DSM researchers, practitioners, and software developers have designed and enhanced many varieties of DSM methods, tools, and applications. That work continues at this conference and in these proceedings.

The International DSM Conference provides an annual forum for practitioners, researchers, and developers to exchange ideas and experiences and showcase results and tools. This year's conference begins with two open sessions the morning of August 29th, mixing the vision of practitioners "DSM Case BOSCH Brazil - Project to Improve the Product Development Process" and the scholars perspective "Interesting opportunities for DSM research and applications". In the afternoon, an introductory tutorial for those new to design structure matrix methods and models is presented. In the second day, August 30th the main sessions will discuss the "Sustainability in Modern Project Management" and "DSM to help understand the challenges of integrating new technologies into systems under development".

Each of the papers submitted for this year's conference was peer-reviewed by at least two members of the Scientific Committee, who made acceptance/rejection recommendations and provided helpful guidance for revisions. The accepted papers appearing in these Proceedings have each been improved based on that feedback. This volume contains 12 peer-reviewed papers that describe the recent advances and emerging challenges in DSM research and applications. They advance the DSM concepts and practice in seven areas:

1. Managing Design and Innovation
2. Analyzing and Managing Organizations
3. DSM Application and Case Studies
4. Project Management

These Proceedings represent a broad overview of the state-of-the-art on the development and application of DSM. There are a significant number of papers with industry authors or co-authors, reflecting this balance and synergy between conceptual development and real-life industrial application, which are in the genes of the DSM Conference series.

The Program Chairs

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The review process of all submissions is directly supported by our scientific committee. All contributions are reviewed towards their content, significance, originality, relevance, and presentation.

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The International DSM Conference is an endorsed event of the Design Society.

Part I

Managing Design and Innovation

18th INTERNATIONAL DEPENDENCY AND STRUCTURE MODELING CONFERENCE, DSM 2016
SÃO PAULO, BRAZIL, AUGUST 29 - 30, 2016

Performance measurement in interdisciplinary innovation processes – Transparency through structural complexity management

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Abstract: Performance measurement and controlling of innovation processes are essential for the successful development and implementation of new products and services. Firms need to understand drivers of success or failure within their innovative performance. Despite the recognized value of innovation controlling, adequate performance measurement in innovation processes is hard to accomplish, particularly in complex interdisciplinary settings and / or for complex product-service systems (instead of pure product offerings). In this paper, we develop and apply matrix-based approaches from structural complexity management to the field of innovation controlling. We use DMMs and a MDM to match economic impacts of interdisciplinary models and methods in the innovation process with strategic business goals and firm performance indicators represented in a Balanced Scorecard. Our approach facilitates the selection of relevant performance indicators, research methods and models for companies trying to achieve their business goals.

Keywords: Innovation controlling, balanced scorecard, process management, structural complexity management

1 Introduction

The development of high-quality products was for a long time the main goal of European and US companies. However, through the challenges of a globalized economic system, such as enhanced price and competitive pressure, these companies nowadays have to offer their customers additional value, as they can hardly compete with the price level of emerging economies (Neely 2007). Companies therefore require a sophisticated management of their innovation processes in order to develop, produce, and provide innovations effectively and efficiently without faults. One particular challenge is adequate performance measurement of innovation processes. Drivers of success or failure in innovation processes are often intangible and hard to measure. This challenge is particularly persistent in interdisciplinary and highly complex settings aiming to provide complex product-service systems (PSS), instead of mere product offerings.

Within this paper, we develop and introduce an approach for the performance measurement of interdisciplinary innovation processes within the context of the Collaborative Research Centre "Managing cycles in innovation processes" (SFB 768)[1]. The SFB 768 aims at facing the described challenges by providing models and methods

[1] http://www.sfb768.de/

to manage and shape innovation processes under consideration of affecting cyclic influences. The variety of models and methods within the SFB 768 include e.g. applications of system dynamics, SysML, structural models and many others. Cycles are defined as recurring patterns of internal and external influencing factors under which companies have to act and react successfully along the innovation process. Besides technical aspects, innovation processes include psychological, sociological and economic aspects. Thus, the different developed models and methods support the management of innovation processes from different viewpoints, e.g., facilitating the development process, analyzing changes, or improving the performance of teams. Each model thereby influences certain aspects of the company, e.g. financial performance, innovative performance, team performance or knowledge. A big challenge, which arises for companies, is the measurement of the overall impact of the different models and methods on the innovation process. Therefore, this paper describes an approach, which is based on the established concept of the Balanced Scorecard (BSC), to measure the 'enhanced' economic influences on the innovation processes ('enhanced' refers to the fact that not all influences can be measured by mere financial value, e.g., knowledge creation or learning processes). By using matrix based approaches the influences of the different models on the identified performance indicators can be analyzed and presented effectively to the different stakeholders.

This paper is structured as follows: In Section 2 the state of the art regarding balanced score card approaches as well as methods for structural complexity management are presented. Section 3 describes the used research methodology in detail and based thereon, the outcomes and findings are described in Section 4. A short discussion of the proposed approach is given in Section 5. Finally, the paper shows the limitations of this research and gives a conclusion as well as suggestions for future research in Section 6.

2 State of the art

2.1 The difficulty of performance measurement for innovation processes

Despite the recognized value of innovation for firm strategy, organizations still struggle with measuring the outcome of innovation processes (Gama et al., 2007; Zizlavsky, 2014). Performance measurement of innovation processes is difficult for various reasons. Outcomes of innovation processes are often intangible (Gama et al., 2007), information is fuzzy and ambiguous (Wang et al., 2010; Zizlavsky, 2014), hard to measure (Eilat et al., 2008). Furthermore, it often needs a long-term business perspective that often conflicts with short-term performance evaluations within firms (Banwet and Deshmukh, 2006; Zizlavsky, 2014). To date, there is no one-size-fits-all approach for performance measurement in innovation processes. Innovation processes are unique – controlling instruments need to account for this uniqueness (Vuolle et al., 2014). Firms need to choose suitable measures according to an organization`s strategy and environment (Ojanen and Vuola, 2003).

2.2 A balanced scorecard approach

A Balanced Scorecard approach has recently been referred to as a promising approach for measuring the returns of R&D processes (Neufeld et al., 2001), by overcoming many of the above mentioned issues (Banwet and Deshmukh, 2006). The Balanced Scorecard (BSC) is an established tool for performance measurement and controlling in the strategic management literature (Kaplan and Norton, 1996, 2007). To date, there are several papers using adapted BSCs to measure innovation processes and R&D outcomes (e.g., Eilat et al., 2008; Garcia-Valderrama et al., 2009).

A BSC offers an established framework for performance measurement closely linked to the strategy of an organization (Kaplan and Norton, 1996). It includes both, financial and non-financial measures (Kaplan and Norton, 1992). These measures are grouped into four perspectives that are hierarchically related to each other. The highest level consists of the financial perspective, consisting of the most important financial indicators for the particular organization. The second layer, the customer perspective aims at analyzing how customers see the organization, including measures such as customer satisfaction or retention. The third layer takes an internal processes perspective, capturing measures on the effectiveness and efficiency of business processes. The lowest layer of the BSC is comprised by measures within the perspective of learning and growth. This perspective is intended to analyze firm capabilities and assets for improving, learning and adapting towards environmental changes (Kaplan and Norton, 1992; Kaplan and Norton, 2007). The four perspectives are assumed to mutually influence each other. By including financial and non-financial measures, the BSC offers a holistic approach to analyze and control drivers for firm performance. The approach is adaptable for various purposes (such as innovation management) and contexts. Within the four perspective framework, organizations chose and weight measures according to their own strategic perspective and environment (Kaplan and Norton, 2007).

Within this paper, we develop an adapted BSC for performance measurement of interdisciplinary innovation processes.

2.3 Multiple-Domain-Matrices for structural complexity management

Performance measurement requires company and case specific indicators to assess innovation processes. Furthermore, an interdisciplinary perspective on innovation is important to respect the different facets and requirements linked to innovation processes. Even though the BSC helps to reduce the complexity by grouping the indicators into four categories, there is still a need for methodical support to describe and analyze the complexity. Therefore, we decided to use structural complexity management because multiple interrelations among the different indicators need to be documented and analyzed. One main advantage of structural complexity management is that it allows linking different objects like components, documents or people (Lindemann 2009). Especially in the context of innovation processes a more holistic or socio-technical perspective is useful.

Structural complexity management is a matrix based approach that comprises three different matrix types: Dependency Structure Matrix (DSM), Domain Mapping Matrix (DMM) and Multiple-Domain Matrix (MDM) (Lindemann 2009). A DSM is an intra-domain matrix, which is squared and maps elements within one domain. The MDM is an intra-domain matrix, which links elements from two different domains and therefore the number of rows and columns is not always the same. The MDM is based on DSMs and DMMs. The creation of a MDM is often the starting point for complexity management because a MDM helps to identify and describe the system in focus and the dependencies between the different domains.

3 Research methodology

In order to measure and document the economic impact of the models and methods developed within the SFB 768, we chose an integrated bottom-up and top-down approach.

The bottom-up approach represents the perspective of the SFB 768 comprising different discipline-specific approaches and viewpoints. As part of the bottom-up approach, we conducted 13 semi-structured interviews with all disciplines in order to identify all existing methods and models of the research groups. Within these interviews, specific performance indicators – so called SFB performance indicators (see Figure 1, abbreviation sI) - enabling the different disciplines to indicate the economic impact of their methods and models, were elaborated.

The top-down approach on the other side represents the firm perspective (in our case specifically the perspective of a PSS provider). We used the BSC framework to adequately cover relevant business goals. Using the four BSC perspectives as a framework, we derived performance indicators of strategic relevance for PSS providers from company goals (see Figure 1, abbreviated as bI). The BSC offered a support tool for exploring the economic impacts of the models and methods developed within the various perspectives of the SFB: Financial perspective, customer perspective (e.g., customer satisfaction), process perspective (e.g., rate of changes), or learning and growth (e.g., knowledge and information management).

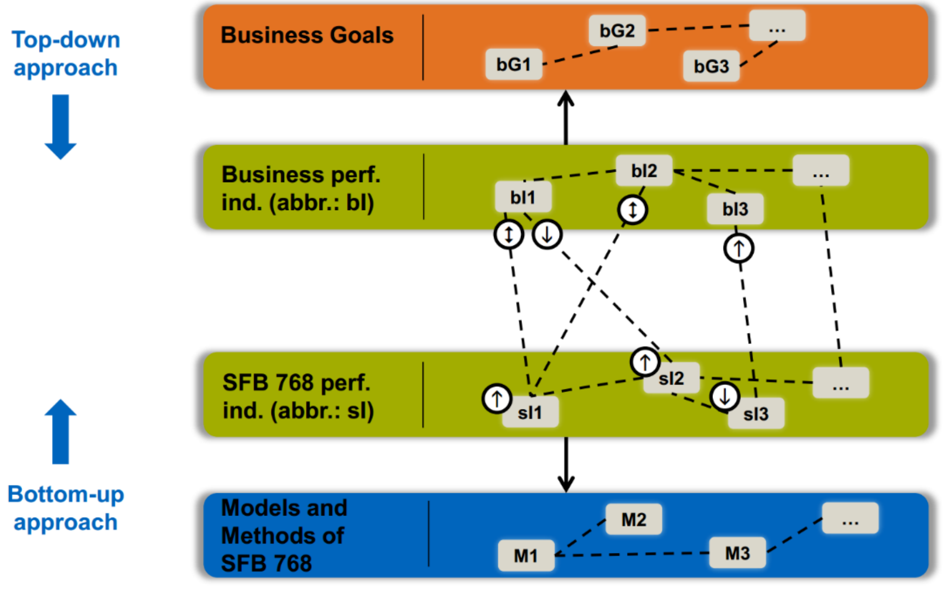

Figure 1. Top-down and bottom-up approach to collect the data

In an interdisciplinary workshop with all disciplines, the bottom-up and the top-down approach were brought together by linking SFB performance indicators (sI) and business performance indicators (bI). Through the integration of the top-down and bottom-up approaches, we merged the perspective of the SFB with the firm perspective.

In order to analyze and visualize the interconnections of the SFB performance indicators and the business goals, the bottom-up and top-down approach were extended by a MDM. The bottom-up and top-down approach as well as their integration are important to make our research findings accessible and useful for practitioners. A comprehensive and user-friendly presentation is an important prerequisite for the applicability in companies. For this purpose, a digital visualization tool was created to facilitate access to the results of the top-down / bottom-up approach.

4 Analysis and results

This paper aims at developing an interdisciplinary approach to capture the relationships among diverse methods designed to manage the innovation process. We focus on the model's influence on performance indicators and their relationships through influencing the same indicators. Therefore, the objective is to contribute to the understanding of the complexity within innovation processes by analyzing dependencies in order to derive implications for research and practice.

The interdisciplinary interviews conducted within the SFB 768 provide a comprehensive description concerning the dependencies between methods/ models and performance indicators, as well as between performance indicators and indicator blocks. The indicator blocks were extracted from literature on performance indicators. The advantage of this data set is that it comprises inputs with respect to innovation management from different disciplines (e.g., psychology, mechanical engineering, computer science, and management). Thus, it takes into account the importance and need of an interdisciplinary perspective on innovation processes. In order to manage the complexity resulting from the interdisciplinary approach of the SFB 768, we decided to analyze the collected data using structural complexity management.

Reading direction	**Model**	**Indicator**	**Indicator Block**
Model	***influences*** (calculated)	***affects*** (interview based)	
Indicator		***influences*** (calculated)	***is assigned to*** (interview based)
Indicator Block			

Figure 2. MDM describing the analyzed domains and relations among the domains

In more detail, we created a MDM with three domains: model (including methods), indicator (performance indicator) and indicator block. The dependencies between the three domains were assessed in the interviews. The MDM is visualized in Figure 2. Our final MDM (dimension: 71 rows and columns) compromises the following information:

34 models, 28 indicators and 9 indicator blocks. To further analyze the data, we split the overall MDM in two DMMs: one DMM capturing the dependencies between models and indicators, and another DMM capturing the dependencies between indicators and indicator blocks. The two DMMs form the basis for following analysis.

4.1 Analysis of the interview data

First, we analyzed the DMM that described the dependencies between the models and the indicators. In total, the DMM included 34 models and 28 indicators as well as 134 dependencies. The analysis showed that

- 16 models / methods influence indicators assigned to the process perspective,
- 15 models / methods affect indicators of the learning and growth perspective,
- 3 methods / models influence the customer perspective.

Further, we found the strongest interconnection of SFB indicators and business goals in the process perspective. On average each model was related to mean = 3.9 (standard deviation = 2.2) indicators and on average each indicator was related to mean = 4.8 (standard deviation = 4.1) models. Models had a maximum and minimum of max = 11 and min = 2 relationships to indicators; and indicators a maximum and minimum of max = 17 and min = 1 relationships to models. Second, we analyzed the DMM by showing the relationships between the indicators and the indicator blocks, which had a total number of 28 indicators and 9 indicator blocks. The descriptive data for the indicators are: mean = 4.8, standard deviation = 4.1, min = 1, max = 17. The models / indicators and indicator blocks with the highest and lowest number of relationships for both DMMs are shown in Figure 3 and Figure 4. The DMMs already provide extensive information on the number of relationships (i.e., degree of interconnectedness) between models, indicators and indicator blocks. We conducted further analyses to investigate the indirect relationships between models and indicators.

	Highest number of relations	***Lowest number of relations***
Model	▪ PSS integration framework ▪ SysML4Mechatronics & engineering change effects ▪ Conceptual traceability reference model for PSS	▪ Generic PSS structure model ▪ Structure based System Dynamics model ▪ Model to assess the risk of a technology ▪ Context model for production change management
Indicator	▪ Planning accuracy ▪ Reaction time ▪ Knowledge concerning engineering change effects	▪ Number of customer inputs ▪ Number of changes within the collaboration ▪ Employee satisfaction

Figure 3. Results of the connectivity analysis of the DMM - Model affects indicator

	Highest number of relations	Lowest number of relations
Indicator	▪ Planning accuracy ▪ Reaction time ▪ Knowledge concerning engineering change effects	▪ Number of customer inputs ▪ Number of chances within the collaboration ▪ Employee satisfaction
Indicator Block	▪ Development process ▪ Production of products and services process	▪ Customer perception ▪ Sales and service process

Figure 4. Results of the connectivity analysis of the DMM - Indicator is assigned to indicator block

4.2 Calculation and analysis of indirect dependencies within the domains

The conducted interviews provide data concerning the relations among different domains. However, it is also of great importance for the performance assessment of innovation processes to understand how indicators and models are indirectly related within their domain. This analysis provides information for researchers and practitioner about indirect dependencies of models and thus, the necessity of (interdisciplinary) collaborations and coordination. For the calculation of the indirect dependencies, Equation (1) was used (Lindemann 2009).

$$DSM = DMM \cdot DMM^T \quad (1)$$

The two DMMs derived from the interviews were transferred into binary DMMs to prepare for the calculation of the indirect dependencies. The outcome of the calculation is a symmetric undirected DSM, which describes how many indirect dependencies exist between the different elements. Overall, the results show that the indicators and the models are highly linked through indirect dependencies. The density of a matrix reveals what percentage of the possible links exists. The results in our case are that the DSM_{Models} has a density of 43.2 % and $DSM_{Indicator}$ has a density of 35.7%. The models and indicators with the highest indirect connections (within domain) are shown in Figure 5.

	Highest number of indirect dependencies	Lowest number of indirect dependencies
DSM – Model influences model	▪ PSS integration framework ▪ Process model for production structure adaption ▪ Process model for reconfiguration planning	▪ Context model for production change management ▪ Structure based System Dynamics model ▪ Customer input ontology
DSM – Indicator influences indicator	▪ Planning accuracy ▪ Knowledge concerning engineering change effects ▪ Duration engineering change	▪ Number of chances within the collaboration ▪ Employee satisfaction ▪ Number of variants ▪ Number of customer inputs ▪ Planning accuracy concerning user integration

Figure 5. Results of the analysis of indirect dependencies within the model and indicator domain

5 Discussion and implications

5.1 Discussion of the analysis results

The results that show the direct connectedness between different domains (models and indicators or rather indicator blocks) as well as indirect relationships with domains (models via indicators as well as indicators via models) suggest several implications for managing the innovation process.

When aiming at improving the innovation process by trying to enhance a specific performance indicator (e.g., the planning accuracy) or performance indicator block (e.g., the development process), it is necessary to take into account multiple models that all influence the respective indicator or indicator block. Furthermore, when changing or implementing a model in the innovation process, indirect dependencies to other models have to be considered. The dependent models need to be aligned, in order not to undermine or weaken the other models' effect on an indicator or indicator block. Similarly, when focusing on improving a performance indicator, indirect effects on other indicators need to be considered. Our study provides an approach how the dependencies can be explored, measured and modeled. Ultimately, the approach provides guidance for interdisciplinary collaborations and cooperation within the innovation process, as it is likely that the dependent models and indices are addressed by people of different disciplines and in different phases along the entire innovation process.

5.2 Implications for research

This paper has two important implications for research in the area of performance measurement of interdisciplinary innovation processes.

First, with regard to structural complexity management – We show that matrix-based approaches mainly used in the field of product development, can also be used for other purposes and in other contexts. We apply a matrix based approach in the context of performance measurement of innovation processes. We use a MDM and DMMs to match and integrate performance measurements of interdisciplinary methods and models with a company / practitioner perspective – represented by the adapted BSC.

Second, we contribute to prior literature using the BSC for measuring R&D performance. We add on to this literature by building an adapted BSC to measure performance for innovation processes that are characterized by high complexity within the outcome (integrated PSS instead of mere technical products) and high interdisciplinarity (technical as well as socio-technical perspectives involved). We find that the BSC offers a comprehensive and suitable approach to both merge those different perspectives and to build a framework for exploring different drivers of success or failure of innovation management for PSS.

5.3 Implications for the management of innovation processes

Companies need to identify and measure relevant and evidence-based performance indicators for their innovation controlling in order to be able to initiate changes of business processes, customer-interfaces, people- and culture management activities properly. For this practical purpose, the value of this research is twofold. On the one hand, the integrated

BSC proposes a holistic, interdisciplinary framework for the controlling of innovation processes, mapping well-established and research-based performance indicators with theoretical models and methods that influence these performance indicators. Practitioners could map these results with their own process- and innovation management. They can use this framework to select theoretically and empirically founded performance indicators. Our approach also helps to understand and influence the underlying cycles that occur along the organizational innovation processes of PSS-companies. On the other hand, companies can derive strategic and operational implications for the management of innovation processes by analyzing and understanding relationships between specific performance indicators (e.g., employee satisfaction) or indicator blocks and the related methods and models (e.g., model of management of cycles of teams and complex networks). The information on direct and indirect dependencies between performance indicators, models and methods helps companies to identify and influence hidden mechanisms that might affect the performance within their innovation process. For example, the analysis of the DMM shows that planning accuracies within the PSS innovation process can be influenced by many methods (e.g., PSS integration framework).

6 Conclusion and outlook

In this paper, we developed and applied matrix-based approaches from structural complexity management to the field of innovation controlling. By using DMMs and a MDM to match economic impacts of interdisciplinary models and methods in the innovation process with strategic business goals and firm performance indicators, we provide a first integrative framework for an evidence-based innovation controlling. The approach allows the analysis of direct and indirect linkages and the detection of strongly interconnected methods, models and performance indicators. By applying a Balanced Scorecard (BSC) perspective, we make this research more accessible for the strategic and operational management. It facilitates the selection of relevant performance indicators, research methods and models for companies trying to achieve their business goals. It should be noted that, to date, the linkages are elaborated only in a descriptive manner, while the strength and direction of the individual relationships between all models, methods and performance indicators are not reflected yet. Thus, it is part of future research to close this gap and extend the approach by incorporating these properties comprehensively - in a qualitative and quantitative manner. Future research should also focus on further effects as well as the interdependencies and interactions between the interdisciplinary models, methods and performance indicators. Further possible enhancements include prioritizing and selection of significant performance indicators on both sides (research and industry) to reduce complexity. Future research should also strongly focus on the validation of the framework and its components by field research and collaborations with PSS providers in order to maximize its practical utility.

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References

Banwet, D., Deshmukh, S., 2006. Balanced scorecard for performance evaluation of R&D organization: A conceptual model. Journal of Scientific and Industrial Research 65, 879.

Eilat, H., Golany, B., Shtub, A., 2008. R&D project evaluation: An integrated DEA and balanced scorecard approach. Omega 36, 895-912.

Gama, N., da Silva, M.M., Ataíde, J., 2007. Innovation scorecard: A balanced scorecard for measuring the value added by innovation, Digital Enterprise Technology. Springer, pp. 417-424.

Garcia-Valderrama, T., Mulero-Mendigorri, E., Revuelta-Bordoy, D., 2009. Relating the perspectives of the balanced scorecard for R&D by means of DEA. European Journal of Operational Research 196, 1177-1189.

Kaplan, R.S., Norton, D.P., 1992. The balanced scorecard - measures that drive performance. Harvard Business Review 70, 71–79.

Kaplan, R.S., Norton, D.P., 1996. Using the Balanced Scorecard as a Strategic Management System. Harvard Business Review 74, 150–161.

Kaplan, R.S., Norton, D.P., 2007. Using the Balanced Scorecard as a Strategic Management System. Harvard Business Review 85, 150–161.

Lindemann, U., Maurer, M., Braun, T., 2008. Structural complexity management: an approach for the field of product design. Springer Science & Business Media.

Neely, A., 2007: The servitization of manufacturing: An analysis of global trends. 14th European Operations Management Association Conference.

Neufeld, G.A., Simeoni, P.A., Taylor, M.A., 2001. High-performance research organization. Research Technology Management 44, 42.

Ojanen, V., Vuola, O., 2003. Categorizing the Measures and Evaluation Methods of R&D Performance-A State-of-the-art Review on R&D Performance Analysis. Telecom Business Research Centre Lappeenranta. Working papers-16, Lappeenranta University of Technology, 1-22.

Vuolle, M., Lönnqvist, A., Schiuma, G., 2014. Development of key performance indicators and impact assessment for SHOKs. Publications of the Ministry of Employment and the Economy. Innovation 27, 2014.

Wang, J., Lin, W., Huang, Y.-H., 2010. A performance-oriented risk management framework for innovative R&D projects. TECHNOVATION 30, 601-611.

Zizlavsky, O., 2014. The Balanced Scorecard: Innovative Performance Measurement and Management Control System. Journal of technology management & innovation 9, 210-222.

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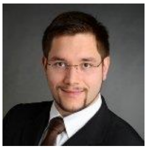

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Applying DMM and DSM to Support the Quantitative Investigation of Process-Oriented Fundamental Elements of Design Thinking

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Abstract: New theories and approaches need to be progressively characterized to achieve maturity and proper handling. The characterization of their fundamental elements is typically approached with qualitative methods. Those procedures may be arduous to perform when the target element to be characterized is numerically expressive. This work is part of a wider project that aims to compare elements of an emerging theory (design thinking) with the elements of a well-established theory (development process). This paper proposes a method for characterizing the fundamental elements of a given process-oriented element category of a theory or approach, mainly when fundamental elements are voluminous. The method proposed in this work is based on content analysis, which was combined with the application of design structure matrices (DSM) and domain-mapping matrices (DMM) in order to process information. The method was tested through experts' analysis attempting to characterize the fundamental tasks of the design thinking approach.

Keywords: DSM, DMM, characterization, method, design thinking

1 Introduction

The design thinking (DT) approach as an organizational resource[1] can be considered a new emerging theory. DT is a trend in human-centered design that "blends an end-user focus with multidisciplinary collaboration and iterative improvement to innovative products, systems, and services" (Meinel and Leifer, 2011), being popularized after Brown's (2008) introductory publication. This approach is relatively new and has been oversimplified in literature due to great focus on practitioners (Dorst, 2011).

In order to perform research about DT theory and handle it properly, it is important to enhance the scientific community knowledge and evolve the DT theory. Characterizing DT by identifying its fundamental elements can provide a better understanding and definition of this theory. This work classifies fundamental as the adjective of a construct or a given theory that forms its base, "from which everything else develops" (Cambridge, 1999). Thus, if an element is fundamental to a theory, it is expected that most propositions of that theory shall contain this element. Investigating the fundamental elements of DT may support the incorporation of this approach into more traditional

[1] The term "design thinking" (DT) has been used to designate two other research lines that approach different topics of DT as referred in this work. The first one approaches DT as the cognitive process embedded in the design process (Kimbell, 2011). The second one is related to the general theory of design, where the cognition process may lead to the solution of so called "wicked problems" (Kimbell, 2011).

theories, such as product development. This kind of investigation, though, offers some challenges to overcome.

First of all, in order to assure the quality of a qualitative analysis, some requirements must be fulfilled, such as the application of trustful techniques and methods, the credibility of the researcher, and the "philosophical belief" (Patton, 1999). In order to fulfill the first requirement, a proper method for investigating specific elements in literature is essential. Additionally, a way to deal with voluminous data is needed, since those elements may be numerous.

The characterization of new theories is progressively done in literature by means of several methods. Recent approaches, such as agile development, agile manufacturing and DT, have been characterized by means of qualitative analyses derived from literature review (Dybå and Dingsøyr, 2008; Liedtka, 2014; Reimann and Schilke, 2011), single and multiple case studies (Dybå and Dingsøyr, 2008; Thienen et al., 2011; Zhang, 2011), surveys (Dybå and Dingsøyr, 2008; Hinds and Lyon, 2011), among others.

One method that allows researchers to perform a deeper qualitative analysis is known as content analysis. It consists of a set of techniques used to analyze communications, such as written texts and verbal speeches, through systematic procedures in order to decode the content of a message (Bardin, 2013). It requires mathematical operations to be performed in order to quantitatively process the analysis. Those operations depend on the characteristics of the target elements that are being analyzed.

One tool that allows the systematization of large amount of information is the design structure matrix (DSM), "a network modeling tool used to represent a system and their interactions", relating one domain with itself (Eppinger and Browning, 2012). Although it is usually applied for product architecture representation, Eppinger and Browning (2012) propose the use of this tool for several distinct applications, such as organization architecture, process architecture and even the reorganization of the US senate. Another tool that may be useful for dealing with large amount of data is the domain mapping matrix (DMM), which establishes the relationship of two distinct domains.

Other authors in literature have already combined content analysis and matrix-based methods, i.e. DSM and DMM, for other purposes. Hepperle et al. (2011), for example, combine those methods to increase systems understanding in early planning phases by establishing the interrelation of Design-for-X guidelines based on the product characteristics. However, those methods were not previously combined in literature with the purpose of characterizing a new theory or approach. Additionally, the amounts of elements they deal with are not so numerically expressive.

This work is inserted in the context of a wider research project, which intends to integrate DT in the product development process models. As part of this research project, this particular work aims to combine the content analysis method with the use of DSM and DMMs to structure results of analyses composed by numerous elements in order to identify the fundamental ones.

2 Methodology

The hypothetico-deductive approach was applied in order to develop the proposed characterization method. The first proposal of this method was based in the hypothesis that a theory or approach may be characterized by its elements and that some elements may be complex or too numerous for a simple qualitative analysis. Another assumption is the hypothesis that the content analysis method can support a systematic qualitative analysis and that applying DMMs and DSMs may allow the qualitative analysis to be quantitatively processed for numerically expressive elements.

A first iteration, which resulted in a proposal of fundamental elements, was performed. Several tests were executed in attempts to falsify the results. More than twenty iterations were repeatedly performed, improving the method whenever a failed aspect was identified. The method was developed through continuous improvement based on the findings derived from the iterations, which were performed in a single context.

This method was tested and evolved during attempts to characterize the DT approach. This characterization aims to identify what are the fundamental tasks (process oriented elements) of DT, with the goal of further comparing those fundamental tasks to the development process tasks in order to identify where they superpose and where they diverge (Rosa and Rozenfeld, 2016).

The method proposed in this work evolved until tasks that were identified as fundamental by means of this method effectively represented the main intersection of most DT methodologies, covering the most recurrent tasks. This achievement was analyzed by means of experts with large experience in the DT practice.

3 Content analysis

The content analysis is a set of techniques that are combined to extract the core meaning of a textual composition by means of deep understanding its content, what may include inference of implicit information (Bardin, 2013).

Bardin (2013) proposes that the content analysis is composed by three main stages:

- Pre-analysis: In this stage, the researcher analyzes as many sources of information as possible. This pre-analysis aims to clarify what the goals and hypotheses of the content analysis are. It shall aid the researcher on outlining what is the information to be sought. This is where the corpus of analysis is defined and the rules of cutting, categorization and codification are established.
- Material exploration: This second stage covers the effective textual analysis, where the rules of cutting, categorization and codification are in fact applied. During this stage, the thesaurus may be developed based on the thorough analysis of the material that composes the corpus.
- Statistical operations: This stage covers the statistical operations that are performed based on the textual analysis, which are followed by the results' synthesis, selection and interpretation.

The main frame of the method presented in this work is based on the proposal of Bardin (2013) for content analysis. The procedure, already adapted with the DSM and DMM application, is illustrated and explained in section 4.

4 Procedure

The characterization method procedure proposed in this work is represented in Figure 1.

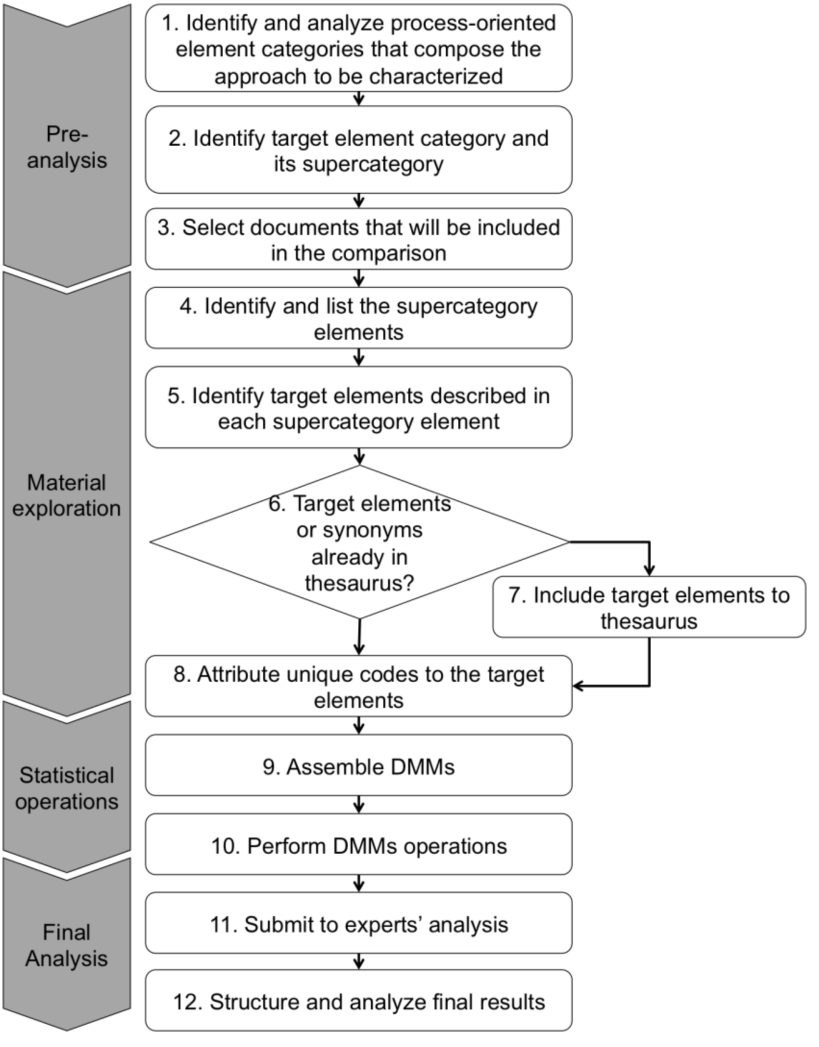

Figure 1. Characterization method procedure

A brief explanation of how each step should be performed is presented in the following topics.

1. Identify and analyze process-oriented element categories that compose the approach to be characterized: Each design approach or theory, such as DT, may be structured by means of element categories, which may be seen as the metadata of that given approach. In this method, it is suggested to structure it in process-oriented element categories. In this step, each element category must be identified, proposing a structure similar to a typology. Those element categories must be structured hierarchically, identifying how they relate to each other. The product development process, for example, could be structured by means of the following element

categories: phase, activities, methods and tools, tasks, good-practices, inputs, deliverables, people and resources (Rosa and Rozenfeld, 2016; Rozenfeld, 2007). DT methodologies, on the other hand, could be structured by means of the following element categories: methodology, stages, methods and tools, guidelines, tasks, resources, people, inputs, deliverables and actions (Rosa and Rozenfeld, 2016).

2. Identify target element category and its supercategory: Depending on the goals of each researcher, one of the element categories must be chosen as a target for comparison. The element category that was chosen as a target is herein after called target element category. The element category that is hierarchically superior to the target element category is hereinafter referred to as supercategory and must also be identified. For example, in this case, it was noticed that DT methodologies are usually presented in the shape of sets of methods, which are described by means of tasks. It was identified that one way to connect DT and the product development process is by means of the tasks (Rosa and Rozenfeld, 2016). In order to characterize what the fundamental tasks of DT are, the element category "task" is to be chosen as target element category, whose supercategory is the element category "method". If the element category is composed by complex elements, it is important to frame the chosen element category properly. For example, a task may be seen as a set of a subject, an event (verb) and an object (deliverable or input). In this particular application, 942 tasks were identified in 184 methods that were presented by 7 methodologies.
3. Select documents that will be included in the comparison: Based on the target element category, prescriptive documents related to the approach to be characterized must be selected. Those documents must contain, at least, the supercategory elements and the target element to be compared. For product, service, or PSS development process, the documents might be process models. For the DT approach, they would be the DT methodologies that are available in literature.
4. Identify and list the supercategory elements: In this step, the analysis is already pre-structured. Then, a thesaurus must be developed in order to guarantee that only unique meanings will be used, avoiding including synonyms that may compromise the analysis. First of all, every supercategory element must be identified in the corpus, extracted and sequenced into a list. For the DT approach case, where "methods" is the supercategory, each method should be listed.
5. Identify target elements described in each supercategory element: Whenever a new supercategory element is identified in the corpus, it is probably accompanied by its description. The proper extracts of the supercategory elements' description must be selected by identifying those that contain elements belonging to the target element category. The elements of those extracts must be identified and selected.
6. Target elements or synonyms already in thesaurus?: This step is part of the analysis explained in the following two steps.
7. Include target elements to thesaurus: If a target element is identified for the first time in the analysis, it must be included in the thesaurus. A similar approach must be performed if a frame of sub-elements composes the target element. In this case, each sub-element that had no synonym identified is included in the thesaurus. This extraction is illustrated in Figure 2.

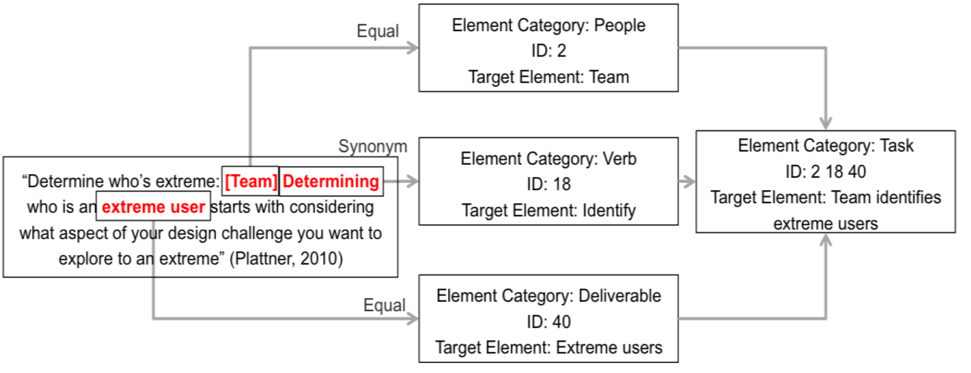

Figure 2. Identification and Codification of the elements of an extract of the method "Extreme Users" proposed by Plattner (2010)

8. Attribute unique codes to the target elements: All target elements that are synonyms in the thesaurus are established under a unique code. If a target element is not composed by a single word, this process is not performed with the target element, but the sub-elements that frame it, i.e., if a target element is composed by given sub-elements, such as a subject, an event and an object, each sub-element is associated to a code in the thesaurus. The final target element is the combination of all sub-element codes. One example of codification is illustrated in Figure 2. This procedure is performed in order to check the recurrence of each target element, avoiding synonyms to be separated. In this particular case, 942 tasks could be allocated in 193 unique identification codes, composing 193 unique tasks.
9. Assemble DMMs: The target elements listed in the thesaurus and the supercategory elements are associated by means of DMMs. For each document in the corpus, a DMM is assembled. Each column of the DMM is associated to a target element code. All target element codes must be included in the DMM and they must appear only in one column. Each row of the DMM is associated to a supercategory element. Only the supercategory elements that appear on the document related to that DMM should be included. For each matrix element (i,j) of each DMM, it must be identified whether the target element (j) and the supercategory element (i) are related between themselves, i.e., if that given document cites that target element (j) on the supercategory element's (i) description. If they are related, the matrix element (i,j) value is set as 1. If not, it becomes 0. Each DMM would be similar to Figure 3. In our case, the supercategory elements are the methods found in the DT methodologies and the target elements are the tasks that compose those methods. All DMMs must be combined into a complex joint DMM, as shown in Figure 4.

Document X	Target Element 1	Target Element 2	Target Element 3	Target Element 4	Target Element 5	Target Element 6	Target Element 7	…	Target Element N
Supercategory Element 1	1	1	1	0	0	0	0	…	0
Supercategory Element 2	0	0	1	1	1	0	0	…	0
Supercategory Element 3	0	0	0	0	0	1	1	…	0
Supercategory Element 4	0	0	0	0	0	0	0	…	0
Supercategory Element 5	1	0	1	0	0	0	0	…	0
Supercategory Element 6	0	0	0	0	0	0	0	…	0
Supercategory Element 7	0	0	0	0	1	1	1	…	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Supercategory Element M	0	0	0	0	0	0	0	…	0

Figure 3. DMM example

		Target Element 1	Target Element 2	Target Element 3	Target Element 4	Target Element 5	Target Element 6	Target Element 7	Target Element 8	Target Element 9	Target Element 10	Target Element 11	Target Element 12	Target Element 13	…	Target Element M
Document 1	Supercategory Element 1	1	1	1	0	0	0	1	0	0	0	0	0	0	…	0
	Supercategory Element 2	0	0	1	1	1	0	1	1	1	0	0	0	0	…	0
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Supercategory Element N_1	1	0	0	0	0	0	1	1	1	0	0	0	0	…	0
Document 2	Supercategory Element 1	1	1	1	0	0	0	1	1	1	0	0	0	0	…	0
	Supercategory Element 2	0	0	1	1	1	0	1	1	1	0	0	0	0	…	0
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Supercategory Element N_2	1	0	0	0	0	0	1	1	1	0	0	0	0	…	0
.	.	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
.	.	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
.	.	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Document K	Supercategory Element 1	1	1	1	0	0	0	1	1	1	0	0	0	0	…	0
	Supercategory Element 2	0	0	0	0	0	0	0	0	0	0	0	0	0	…	0
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Supercategory Element N_3	0	0	0	0	0	0	1	1	1	0	0	0	0	…	0

Figure 4. Complex joint DMM

10. Perform DMMs operations: To achieve the final results, one mathematical operation must be performed with the complex joint DMM. The DMM must be transposed and multiplied by itself ($[DMM]^T$ x [DMM]). This operation provides a final DSM that

relates each element with the other elements, excluding the supercategory elements of this analysis. The final DSM is similar to Figure 5.

	Target Element 1	Target Element 2	Target Element 3	Target Element 4	Target Element 5	...	Target Element M
Target Element 1	5	3	2	0	1	...	1
Target Element 2	3	7	1	1	1	...	0
Target Element 3	2	1	2	1	0	...	0
Target Element 4	0	1	1	8	4	...	0
Target Element 5	1	1	0	4	5	...	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Target Element M	1	0	0	0	0	...	1

Figure 5. Final DSM illustration

In the main diagonal (green), each element of index (*i*,*i*) represents how many times the target element of code "*i*" appears in all documents that were analyzed, counting each target element just once for each supercategory element. Out of the main diagonal (orange), each matrix element of index (*i*,*j*) illustrates on how many supercategory elements the element of index "*i*" appears related to the target element of index "*j*". In order to identify the fundamental elements, a proper statistical method must be selected based on the characteristics of the performed analysis. For the DT analysis, the fundamental elements were considered those that appear on more than half of the methodologies that were included in the analysis. Techniques such as Bollinger Bands may also be used (Bollinger, 1992). The most recurrent elements according to the statistical analysis are to be considered as the fundamental ones. In this case, the objects to be compared were tasks from different

11. Submit to experts' analysis: It is recommended to submit the final results of this analysis to experts in order to validate the final results. The goal of the experts' analysis is to verify whether target elements that should be considered fundamental were excluded from the analysis or non-fundamental elements were inadvertently included and to validate the content analysis per se, verifying the linguistic validity of the analysis. In this context, people were considered experts when they had a concrete background either on the DT approach, including wide practical application of its techniques, and linguists to assure the linguistic validity of the content analysis. The reasons for why each target element was or was not included must be thoroughly analyzed in order to avoid errors. This analysis shall be done after the researchers analyzed the whole corpora.
12. Structure and analyze final results: Finally, the final results must be structured and analyzed in order to properly communicate the final findings. In the case of this work, 59 fundamental tasks were identified from 193 unique tasks that composed the analysis. One possibility is to structure the results in the shape of a table or to

keep them in the shape of a DSM, what may allow the identification of "chunks" of fundamental elements, i.e. what fundamental elements are usually associated in their supercategory elements. Due to space limitations and since the purpose of this work is to present the method per se, the results of this analysis are not presented in this work.

5 Final discussion

This work showed that matrix-based methods, such as DSM and DMM, are compatible to structuring results of content analyses of corpora composed by numerous elements in order to identify the fundamental ones. This work may be an inspiration on how to perform analyses when large amounts of data need to be handled.

It is important to highlight that the methodology used on the development of this work was the hypothetico-deductive approach, which depends on repetitive attempts to falsify the proposal. Thus, one failed attempt may falsify the method proposed, but hundreds of successful attempts cannot prove its validity for every context. Thus, the experts' analysis was included in the method in order to improve the quality of the results as one qualitative attempt to falsify the proposal on each application. Thus, it restricts this limitation generated by the methodology that was applied.

We believe that the necessity of including experts' analysis to the method may insert a certain bias to the process, since experts may be biased on their perspective about the approach or theory in analysis, which in this case was DT. The authors of this work intend to improve the replicability of this method by better structuring the content analysis with frame analysis and linguistic techniques in order to reduce the need of experts to validate the analysis. This technique shall also be used in the context of analyzing PSS development process models in order to develop it even further.

The method proposed in this work proved to be useful on supporting the characterization of the fundamental tasks of the DT approach based on seven DT methodologies that were previously selected on the corpus definition. However, further tests shall be performed to verify and validate the application of this method in different contexts.

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References

Bardin, L., 2013. L'Analyse de Contenu, 2nd ed. Presses Universitaires de France, Paris.

Bollinger, J., 1992. Using Bollinger Bands. Stock. Commod. 10, 47–51.

Brown, T., 2008. Design thinking. Harv. Bus. Rev. 86.

Cambridge, 1999. Cambridge Dictionaries Online [WWW Document]. URL http://dictionary.cambridge.org/dictionary/english/ (accessed 4.3.16).

Dorst, K., 2011. The core of "design thinking" and its application. Des. Stud. 32, 521–532. doi:10.1016/j.destud.2011.07.006

Dybå, T., Dingsøyr, T., 2008. Empirical studies of agile software development: A systematic review. Inf. Softw. Technol. 50, 833–859. doi:10.1016/j.infsof.2008.01.006

Eppinger, S.D., Browning, T.R., 2012. Design Structure Matrix Methods and Applications. MIT Press, USA.

Hepperle, C., Biedermann, W., Böcker, A., Lindemann, U., 2011. Design for X-guidelines and lifecycle phases with relevance for product planning - an MDM-based approach, in: Proceedings of the 13th International DSM Conference. Cambridge, MA, pp. 215–220.

Hinds, P., Lyon, J., 2011. Innovation and Culture: Exploring the Work of Designers Across the Globe, in: Design Thinking: Understand, Improve, Apply. Springer-Verlag Berlin Heidelberg, Berlin, pp. 101–110.

Kimbell, L., 2011. Rethinking Design Thinking: Part I. Des. Cult. 3, 285–306. doi:10.2752/175470811X13071166525216

Liedtka, J., 2014. Perspective: Linking design thinking with innovation outcomes through cognitive bias reduction. J. Prod. Innov. Manag. 32, 925–938. doi:10.1111/jpim.12163

Meinel, C., Leifer, L., 2011. Design Thinking Research, in: Design Thinking: Understand, Improve, Apply. Springer-Verlag Berlin Heidelberg, Berlin, pp. xiii–xxi. doi:10.1016/B978-0-12-387667-6.00013-0

Patton, M.Q., 1999. Enhancing the quality and credibility of qualitative analysis. Health Serv. Res. 34, 1189–1208. doi:http://dx.doi.org/10.4135/9781412985727

Plattner, H., 2010. Bootcamp Bootleg. Design School Stanford, Stanford.

Reimann, M., Schilke, O., 2011. Product Differentiation by Aesthetic and Creative Design: A Psychological and Neural Framework of Design Thinking, in: Design Thinking: Understand, Improve, Apply. Springer-Verlag Berlin Heidelberg, Berlin, pp. 45–57.

Rosa, M., Rozenfeld, H., 2016. Looking for Fundamental Elements of Design Thinking, in: International Design Conference 2016. Cavtat - Croatia.

Rozenfeld, H., 2007. Reference model for managing product development, in: Sustainability in Manufacturing. Springer-Verlag Berlin Heidelberg, Berlin, pp. 193–206.

Thienen, J. von, Noweski, C., Meinel, C., Rauth, I., 2011. The Co-evolution of Theory and Practice in Design Thinking - or - "Mind the Oddness Trap!," in: Design Thinking: Understand, Improve, Apply. Springer-Verlag Berlin Heidelberg, Berlin, pp. 81–99.

Zhang, D.Z., 2011. Towards theory building in agile manufacturing strategies - Case studies of an agility taxonomy. Int. J. Prod. Econ. 131, 303–312. doi:10.1016/j.ijpe.2010.08.010

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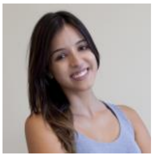

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Enhancing Collaboration between Design and Simulation Departments by Methods of Complexity Management

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Abstract: The significance of CAD-CAE coupling has grown with the increasing use of simulations in development processes. With the focus on technical aspects like simulation data management in literature, however, there is a lack of research on the implications on collaboration. This paper uses methods of structural complexity management to improve communication and collaboration between simulation and design departments. Design structure matrices and multiple domain matrices are derived from system graphs that come from interviews. A case study uses these methods to handle data to enhance collaboration between departments. The results are techniques to deal with lacking information and low degrees of connectivity in the matrices. After an overlay of different matrices, standard procedures like triangulation and clustering can be applied that would otherwise not have been sensible. This leads to knowledge clusters and sequences of documents and task that help to integrate simulations more smoothly into the product development process.

Keywords: CAD-CAE, structural complexity management, DSM, DMM, MDM, system graph, collaboration and collaboration, human behaviour in design

1 Introduction

Compared to the past, simulation is taking an increasing role in product development today (Maier et al., 2009). The iterative procedures in product development create a huge demand for the integration of simulation in the product development process as simulation and design departments collaborate with each other frequently. Deubzer et al. (2005) considered a holistic approach for the problem by defining the four dimensions of the integration problem in terms of product, people, data, and tool. Kreimeyer et al. (2005) added the process dimension and completed the five dimensions of the integration problem. Thus far, despite the increasing role of simulation in product development that demands for a holistic approach (Maier et al., 2009), the tool, data, and process dimensions have been the focus of researchers (Kreimeyer et al., 2005). Kreimeyer et al. (2006) were then the first to apply methods of complexity management in research on CAD-CAE integration. This is also the topic of this paper, which presents a methodology to deal with very low degrees of connectivity, unreliable data, and unnecessary input.

2 State of the Art

Since the beginning of the application of simulation tools in product development, numerous attempts have been made to integrate simulation in the product development process. However, these attempts always focus on specific, often technical aspects. For example, direct CAD-CAE data exchange first started in the 1990s and was follewed later by parametric modeling (Hirz et al., 2013, p. 31).

For publications on further technical aspects of CAD-CAE integration like data interoperability see for instance Forsen & Hoffmann (2002), Schumacher et al. (2002), Assouroko et al. (2010), Park & Dang (2010), and Gujarathi & Ma (2011), among others.

Browning first defined the design structure matrix to deal with integration problems by decomposing systems into its subsytems (Browning, 2001). Ulrich and Eppinger (2004) highlighted the significance of the design structure matrix for the management of engineering projects and Engel et al. (2012) applied it for the optimization of systems architecture for adaptability, to name just a few examples. Kreimeyer et al. (2006), on the other hand, came up with the idea that the design of hierarchical product structures with matrices alone is not enough for efficient product development, since customers mostly focus on the functionalities rather than components. This conflict can especially be observed when it comes to the interaction between CAD and CAE departments as designers manly have a component-oriented view on the product while simulation experts rather take a function-oriented perspective. Therefore, they utilized the design structure and domain mapping matrices to integrate components (CAD) and functionalities (CAE). This paper takes a similar approach as it links people, knowledge, and documents in this context.

3 Methodology

The structural complexity management as presented by Lindemann et al. (2008) aims to reveal the underlying system properties by the use of matrices. A design structure matrix (DSM) provides a clear information about the system by decomposing it into its subsystems, noting the relations between the subsystems, and finally anaylsing the matrix (Browning, 2001). While the design structure matrix is restricted to one domain, a domain mapping matrix (DMM) can be used to note the relations between different domains. However, both DSM and DMM are not capable of dealing with complex systems if they stand alone. As presented by Lindemann et al. (2008), a multiple domain matrix (MDM) is the combination of all DSMs and DMMs in a system.

Application of structural complexity management includes four main steps:

1. Information acquisition for direct dependencies
2. Construction of the MDM
3. Deduction of indirect dependencies
4. Application of optimization techniques

For this paper, a case study was conducted with a German automotive supplier with the aim to enhance collaboration between design and simulation departments. Structured interviews were conducted at the mentioned German automotive supplier and the results of the interviews were transferred into a graph with the software Soley Modeler. This paper, however, focuses on the evaluation of the derived data, not on data acquisition. It may have been better to directly transfer the data from the interviews into a MDM. However, this was not possible in this case due to the nature of the research project. Therefore, based on the information in the graph, a MDM was constructed. However, this MDM had a very low degree of connectivity. The degree of connectivity is obtained by dividing the number of the filled cells by the number of all possible cells. As there exists no dependency on the diagonal, the number of possible cells in an n-by-n MDM is n(n-1). As the degree of the connectivity was too low for sensible calculations in this example, indirect dependencies had to be deducted as well.

According to Maurer (2007) there are six ways of extracting data from available data sets in an MDM. It is the conventional way to apply only one of these methods ("The Conventional Method" in section 4). However, in case of the lack of direct dependencies, those methods may be applied separately and overlapped, too ("The Six Deduction Logics" presented by Maurer). Figure 1 represents all of the six ways for deriving indirect dependencies for a DSM.

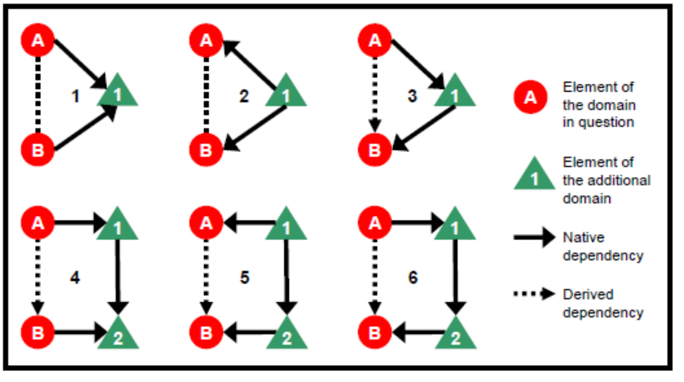

Figure 1. The Deduction Logic for a DSM (Maurer, 2007, p. 85)

This logic is also valid on DMM level. Hence, it can be taken as a reference for MDM applications. As observed according to Maurer, the dependencies between the elements of the additional domains have to be in the same direction, while the dependencies between the elements of the domain in question and the element of the additional domain may vary.

A third method may be to define all indirect dependencies as bidirectional by only defining the native dependencies in the same direction as unidirectional, e.g. case 3 and 6 in Figure 1 if the information in the system graph is not very reliable. The indirect dependencies in this case study are deducted not only to the second distance but also to higher distances to obtain a reasonable degree of connectivity and apply standard procedures from structural complexity management like sequencing and clustering.

The methods described above in are applied on the case study's data with two main goals:

- to apply techniques of structural complexity management to enhance the collaboration and communication at the industry partner and
- to further elaborate these methods and gain insights on the influence of the degree of connectivity on the applicability of these methods from an academic point of view.

4 Results

The MDM that resulted from the system graph of the case study includes 135 elements and has a degree of connectivity of 0.01 (Figure 2). Due to the confidentiality agreement with the industry partner, only exemplary values are displayed and elements are grouped together without displaying the different items.

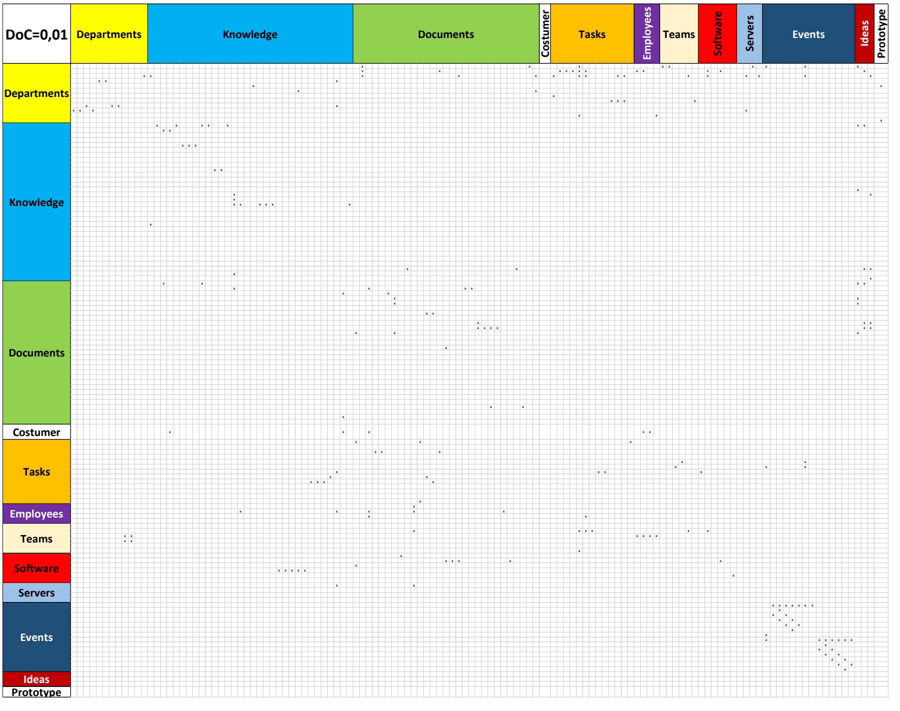

Figure 2. Original MDM with a degree of connectivity of 0.01

As expected, an increase in the degree of connectivity can be obtained by applying the deduction methods. Through the application of the conventional method, a maximum degree of connectivity of 0.12 is obtained (Figure 3). Due to the low degree of connectivity and the distribution of it on the matrix, this method cannot be utilized further.

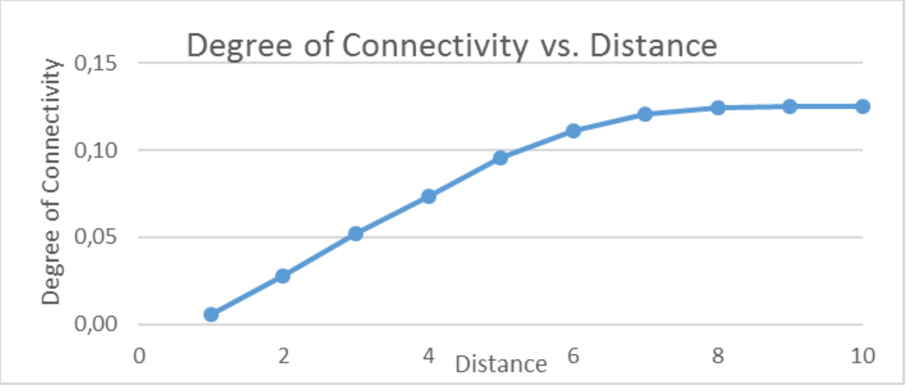

Figure 3: Degree of Connectivity vs. Distance - The Conventional Method

The application of the second method gives reasonable degrees of connectivity. The calculations have shown that it might be useful to create a MDM with a degree of connectivity around 0.3 - 0.4. Therefore, a matrix with distances up to 4 was used for the second method (Figure 4). This MDM can be used for sequencing and clustering purposes.

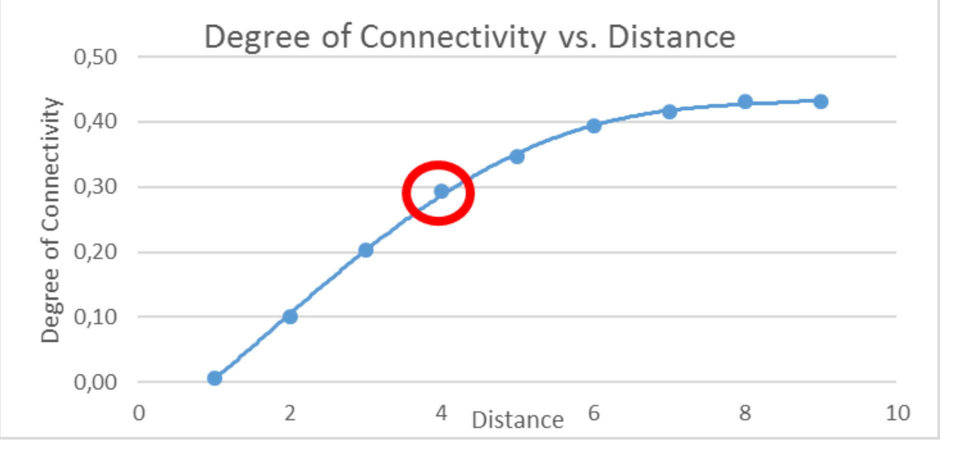

Figure 4: Degree of connectivity vs. distance when applying the six deduction logics

Due to the same reason, in the third case a MDM up to the distance 3 is created (Figure 5). Since this MDM is highly symmetrical, it cannot be used for sequencing purposes.

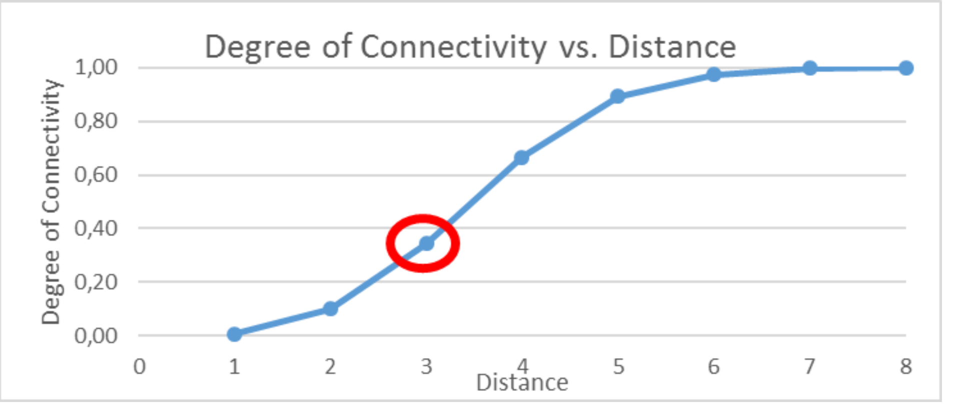

Figure 5: Degree of connectivity vs. distance when using all dependencies

This leads to the MDM displayed in Figure 6, which has a degree of connectivity of 0.34.

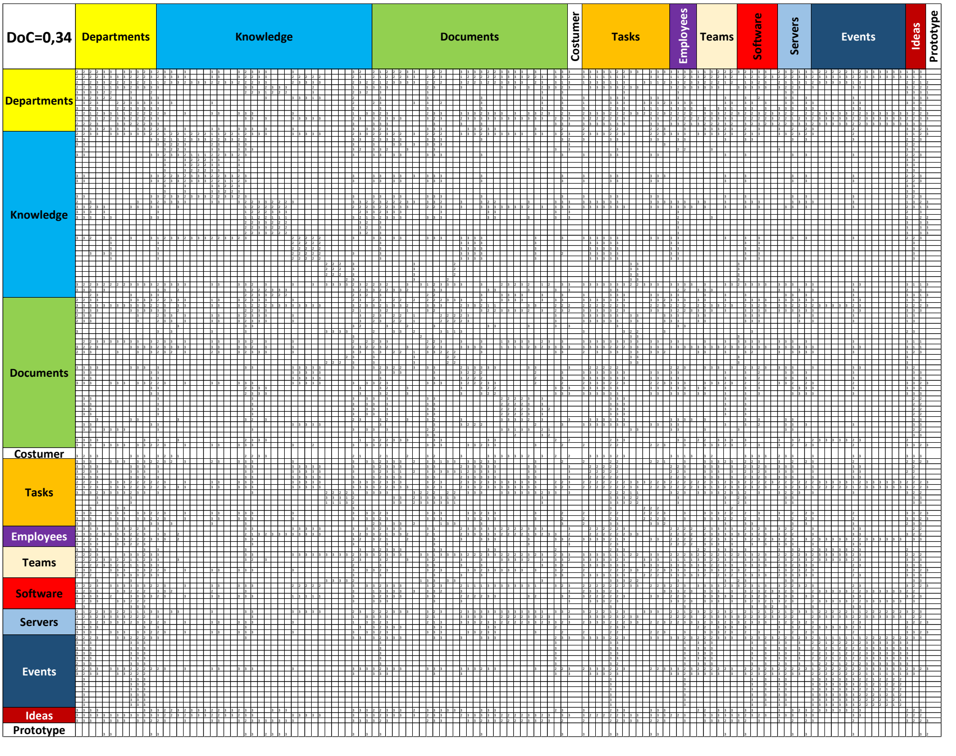

Figure 6. Example for the application of bidirectional and unidirectional dependencies up to distance 3

After that, we come back to the original question, since the interviews and the MDM were originally not conducted and created for the purpose of integrating simulation in the product development process, all elements in the MDM that are not involved in the integration of simulation in the product development, have to be deleted. As the directions in the graph are not very reliable, the MDM constructed through the third method was considered in this case. For this purpose, the minimum distance at which each element either affects the simulation and design departments or is affected by them, was determined for each element. As seen in Figure 7, every element is somehow related with the design and simulation departments at a distance of 4. Twelve elements were deleted from the MDM, as they do not fully serve for the integration purpose.

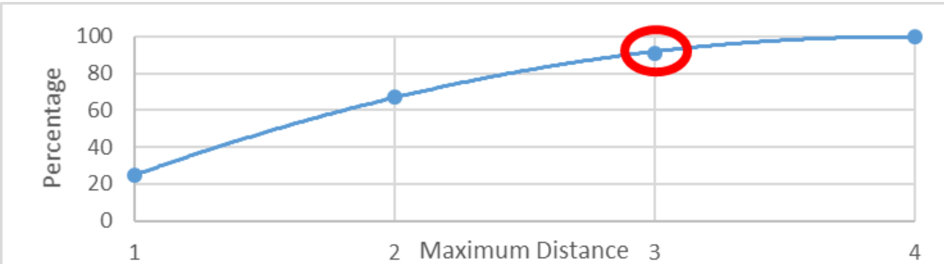

Figure 7. Percentage of elements with a dependency to design or simulation departments vs. maximum distance

Figure 8 is a clustering example in the domain of knowledge through the application of the third method. The increase in the degree of connectivity compared to the beginning (0.01 to 0.34) has enabled the creation of the clusters.

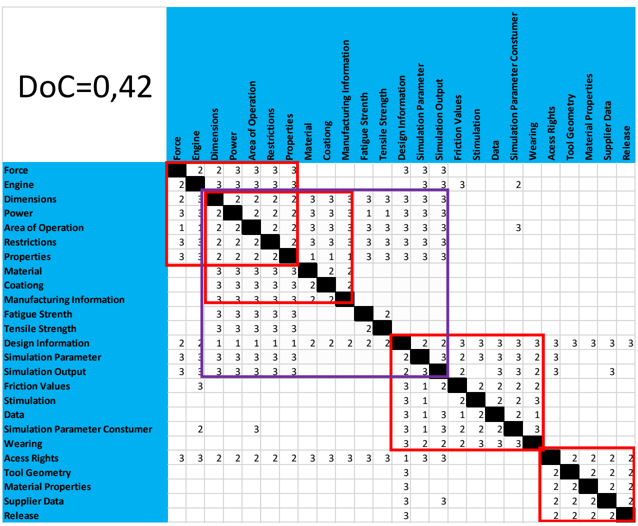

Figure 8. Clustering after the application of the third method for the domain of knowledge

Figure 9 shows a sequencing example after the application of the second method. The symmetrical relations are colored with red to indicate why no further sequencing is possible.

DoC=0,34	Simulation Assignment	Design Guideline (2 Versions)	Finite Element Report	Test Report	Excel Lessons Learned	Data Sheets of Gearing	Costumer Assignment	FE Assignment	MBS Assignment	CAD model chain	CAD model of control assembly	CAD model of parts	Simulation Report	Dimensioning Rules	Responsibilities	Simulation Results	Simulation Models	Drawing Chain	Specifications	.dxf and .stp files	Manufacturing Data	Tables	Diagrams	Visualizations	Teaching Material
Simulation Assignment		2	2	2	3	2	1	1	1	3	3	3	3	3	3	4	4	3	2	4	4	4	4	4	3
Design Guideline (2 Versions)	2				3	3	3	3	3		2	2	3	1	3	4	4		4	3	4	4	4	4	3
Finite Element Report	2					4	2	3	3	4	4	4	3	4	4			4	4		4	4	4	4	4
Test Report	2					2	3	3	3	3			3	3	3	4	4	3	4	4	4	4	4	4	3
Excel Lessons Learned							2						2			3	3		3		3	3	3	3	
Data Sheets of Gearing	2			2			3	3	3	3			3	2	2	4	4	3	4	4	4	4	4	4	2
Costumer Assignment	3		2		2			2	2	4	4	4	2			3	3	4	1		3	3	3	3	
FE Assignment							2		2										3						
MBS Assignment							2	2											3						
CAD model chain											2	2	3				3	1		1					
CAD model of control assembly		2								2		2		3				2		1					
CAD model of parts		2								2	2			3				2		1					
Simulation Report					2	3	2							3	3	2	2	2	3		1	1	1	1	3
Dimensioning Rules						2									2										2
Responsibilities						2								2											2
Simulation Results													2				2				3		1		
Simulation Models													2			2		2			1		3		
Drawing Chain										2	2	2	2				2			2					
Specifications																									
.dxf and .stp files																		2							
Manufacturing Data																						2	2	2	
Tables																					2		2	2	
Diagrams																					2	2		2	
Visualizations																					2	2	2		
Teaching Material						2								2	2										

Figure 9. Sequencing example of documents with highlighted bidirectional relations

5 Discussion

The MDM in the case study consists of 135 elements and 11 domains, which means that 18,090 decisions had been made when creating the grapgh in the Soley Modeler. However, one can quickly realize that some direct connections may be missing in the MDM. For example, the design department and CAD data should have been directly connected. However, there is no direct dependency between them in the MDM. This is probably due to the fact that the interview results were first modelled in the Soley Modeler and some first degree connections were modelled as 2nd and maybe 3rd degree connections because it is difficult to model so many direct connections in Soley. Then this data was converted into the matrix form. This situation once again stresses the importance of the verification of the acquired data through interviews since the quality of the final results highly depends on the quality of the original data. Although the optimal degree of connectivity is unknown, this research has shown that a degree of connectivity around 0.3 and 0.4 is suitable for the application of the specific methods of sequencing and clustering. Very low degrees of connectivity can be increased by the use of distance matrices. On the other hand, the already existing know-how can easily verify the application of this methodology. For example, one cluster includes CAD-related data like *CAD model of control assembly*, *CAD model of parts*, *.dxf and .stp files*, and *CAD model chain*. Another cluster example includes *data sheets of gearing*, *design guideline (2 versions)*, *finite element report*, *simulations assignment*, *drawing chain*, *simulation models*, *simulation report* and *excel lessons learned*. These clusters are sensible and fit to the actual working situation at the industry partner. The same situation is also valid for the sequencing example. *Simulation order, simulation order for FEA and MBS, CAD models, simulation results,* and *technical drawings* follow each other, as they should.

When regarding these results, it seems questionable whether the approach really results in new clusters or workflows, which could not have been derived without matrix techniques. What it can proof, however, is the importance of certain elements like the Simulation Assignment in Figure 9. This provides a starting point for improvement, which can be very helpful as the many relations between the different elements make it hard to decide, which elements can be a fruitful point for improvement.

6 Conclusion and Outlook

Overall, in this research a new methodology to deal with very low degrees of connectivity, unreliable data, and unnecessary input has been presented. Indirect dependencies are deducted both through the use of the six deduction logics presented by Maurer and considering all directions. The first one was used for sequencing purposes while the later one is used for removing the unnecessary data and clustering purposes.

What the case study cannot provide are general rules for the relationships between the distance and the degree of connectivity for instance. Therefore, the methodology should be applied on further and more complex case studies in order to check its validity and to further elaborate the used metrics.

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References

Assouroko, I., Ducellier, G., Belkadim, F., Eynard, B., & Boutinaud, P. (2010). Improvement of engineering design and numerical simulation data exchange based on requirements deployment: a conceptual framework. Proceedings of the 7th International Product Lifecycle Management Conference, Bremen.

Browning, T. R. (2001). Applying the design structure matrix to system decomposition and integration problems: a review and new directions. Engineering Management, IEEE Transactions on, 48(3), 292-306.

Deubzer, F., Herfeld, U., Kreimeyer, M., & Lindemann, U. (2005). A structured holistic approach for the integration of CAD and CAE environments. Paper presented at the ProSTEP iViP Science Days 2005-Cross Domain Engineering.

Engel, A., Reich, Y., Browning, T.R., Schmidt, D.M., 2012. Optimizing system architecture for adaptability. Proceedings of INTERNATIONAL DESIGN CONFERENCE - DESIGN 2012 May 21 - 24, 2012.

Forsen, J., & Hoffmann, R. (2002). Assoziative FE-Netze in der Karosserieentwicklung. Düsseldorf: VDI-Verlag.

Gujarathi, G., & Ma, Y.-S. (2011). Parametric CAD/CAE integration using a common data model. Journal of Manufacturing Systems, 30(3), 118-132.

Hirz, M., Dietrich, W., Gfrerrer, A., & Lang, J. (2013). Integrated computer-aided design in automotive development. Book). http://books. google. com/books.

Kreimeyer, M., Deubzer, F., Herfeld, U., & Lindemann, U. (2005). Holistic Integration of CAD and CAE: Analysis and Combination of Diverse Current Approaches In: Ekinoviæ: S.

Kreimeyer, M., Herfeld, U., Deubzer, F., Dequidt, C., & Lindemann, U. (2006). Function-driven product design in virtual teams through methodical structuring of requirements and components. Paper presented at the ASME 8th Biennial Conference on Engineering Systems Design and Analysis.

Lindemann, U., Maurer, M., & Braun, T. (2008). Structural complexity management: an approach for the field of product design: Springer Science & Business Media.

Maier, A. M., Kreimeyer, M., Lindemann, U., & Clarkson, P. J. (2009). Reflecting communication: a key factor for successful collaboration between embodiment design and simulation. Journal of Engineering Design, 20(3), 265-287.

Maurer, M. S. (2007). Structural awareness in complex product design. Universität München.

Park, H.-S., & Dang, X.-P. (2010). Structural optimization based on CAD–CAE integration and metamodeling techniques. Computer-Aided Design, 42(10), 889-902. doi: http://dx.doi.org/10.1016/j.cad.2010.06.003

Schumacher, A., Merkel, M., & Hierold, R. (2002). Parametrisierte CAD-Modelle als Basis für eine CAE-gesteuerte Komponentenentwicklung.

Ulrich, S.D., Eppinger, K.T., 2004. Product Design and Development, 3rd ed. McGraw-Hill, New York, pp 331-335.

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Part II

Analyzing and Managing Organizations

18th INTERNATIONAL DEPENDENCY AND STRUCTURE MODELING CONFERENCE, DSM 2016
SÃO PAULO, BRAZIL, AUGUST 29 - 30, 2016

An Empirical Investigation of Enterprise Architecture Analysis Based on Network Measures and Expert Knowledge: A Case from the Automotive Industry

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Abstract: Enterprise architecture (EA) may be considered an organizational blueprint that helps experts manage organizational complexity. In this regard, EA analysis is an emerging field gaining greater attention, and considering EA as an intertwined system of components and relationships and performing EA analysis from a structural perspective are promising areas of research. This paper analyzes EA data from a German commercial vehicle manufacturer, modeling a subset of its EA with the help of design structural and domain mapping matrices. Thus, we propose an analysis approach based on network measures that uses structural knowledge generated by the network analysis to validate or refine experts' tacit knowledge about EA key components from different layers. We refer to this approach as the diagnosis analysis method. Based on our results, we successfully combine the structural knowledge with expert knowledge and provide useful validations for experts.

Keywords: Enterprise architecture, network analysis, DSM modeling

1 Introduction

Enterprise architecture (EA) can be considered a blueprint that describes a general organization in terms of its components to help experts manage organization complexity. Management of all these components (e.g., goals, business process, applications, and IT infrastructure), their interdependencies, and their evolution allows organizational changes to be coordinated and aligned with mid- to long-term company objectives (Ahlemann, 2012). In companies that deal with a vast set of applications supporting several business processes, the task of gleaning additional value from current EA models (EA analysis) is made even more complex by the lack of suitable analysis tools (Santana et al., 2016).

EA analysis has attracted researcher attention in the last decade (Santana et al., 2016). The literature includes several different paradigms for EA analysis, such as probabilistic relation models (Buschle et al., 2010), EA intelligence (Veneberg et al.,, 2014), complexity management (Schneider et al., 2014), ontology-based analysis (Antunes et al., 2013) and network-based analysis (Dreyfus and Wyner, 2011).

Considering EA as an intertwined system of layers, components, and relationships and performing EA analysis from a structural perspective holds promise. However, the application of network measures in EA analysis still has considerable room to grow, according to Santana et al. (2016) and Simon and Fischbach (2013). A similar challenge of analyzing interdependent components has also been faced in other fields such as system engineering and product engineering. In these areas, the literature has emphasized the importance of the design structure matrix (DSM). The principles on which DSM and other similar methods are based have proven to be valuable and viable in numerous applications (Kreimeyer et al., 2009). Related research also reports the application of the DSM through the use of strength-based graphs and algorithms from network theory (Kreimeyer et al., 2009).

In this paper, we take a similar approach to analyze EA data from a large commercial vehicle manufacturer located in Germany, modeling a subset of its EA with the help of DSMs and applying network measures. In the end, we offer two contributions: First, we frame an empirical subset of EA data as DSMs and apply matrix transformations to this subset, deriving a co-affiliation network. We then apply network measures to identify key components in the primary and derived networks. With that, we expect to foster the discussion for applying DSM to EA analysis with primary and derived data. Second, we propose an analysis approach based on network measures to be applied to our data, modeled as primary and derived DSMs. We take the expert knowledge and compare it with the structural information generated by the network measures in order to validate and/or refine experts' perceptions about key EA components. We refer to this approach as the *diagnosis analysis method*. We demonstrate the use of this approach, aiming to answer the following research question: *How can expert and structural knowledge about EA components be combined to help an expert perform EA analysis?*

This paper is organized as follows: Section 2 presents key concepts discussed. Our research design is described in Section 3. Section 4 presents results and our analysis. Section 5 presents our conclusions.

2 Key concepts

This section is a short introduction to the topics covered in the paper: enterprise architecture, EA analysis, the DSM and multiple-domain matrix (MDM), and EA network analysis. Related works are also detailed in this section.

2.1 Enterprise architecture

EA is defined in a variety of ways. We adopt the definition proposed in the literature review of Schütz et al. (2013), which is also supported by Open Group (2011). According to that definition, EA is a system formed by four subsystems: business (or business layer), data (or information layer), application (or application layer), and infrastructure (or technology layer). In this paper, we model these EA subsystems (which might also be called EA layers or architectures) as networks/graphs.

2.2 Enterprise architecture analysis

EA can be considered an organizational blueprint composed of the four layers above. Creating such a blueprint is worthwhile only if resultant models can add value to the architectural decision-making process, help in managing organizational complexity, and lower risks (Naranjo et al., 2014). As part of the broader EA management lifecycle, EA analysis initiatives might target different concerns such as EA domain redesign, application support to business processes support, identification of misalignment of resources, EA decision making, and so on. These analysis initiatives may have different degrees of abstraction and coverage, ranging from a full-edged impact analysis over the entire model to an in-depth analysis of a specific domain (Naranjo et al., 2014).

2.3 Modeling EA as a complex network

In the context of network theory, according to Scott (1992), a graph or network is a set of components (nodes or vertices) and links (edges or relations). The use of graph theory and network measures to analyze single software systems extends back to the 1980s (Hall and Preiser, 1984). Clustering algorithms, a common approach found in software modularity studies (group or cluster analysis), was introduced in the EA context by Aier and Winter (2009) to identify EA virtual domains and thus aid in EA redesign. However, analysis measures at the individual level—such as eigenvector and degree centrality—appear more frequently in EA research than does clustering, as shown in Santana et al. (2016).

When modeling EA as a set of networks or layers, nodes may represent different components. In the application layer, for instance, nodes might represent applications that support business functions that integrate the business layer (Simon and Fischbach, 2013). Nodes in the technology layer can represent IT infrastructure components such as application servers. Edges represent relationships and interdependencies between applications. In general, these relationships can take different forms (Simon and Fischbach, 2013). For example, links between application components in the application layer may indicate the same vendor or a data flow. These modeling choices for nodes and relationships are closely related to the EA concerns one may wish to analyze (Wasserman and Faust, 1994).

2.4 DSM, MDM

If the goal of architecture is to provide flexibility, robustness, and adaptability, then any change to the architecture must be managed to minimize its complexity (Schmidt, 2013). Schütz et al. (2015) define EA complexity as having two dimensions: structural (interdependence of the elements) and heterogeneity. In this paper, we focus on the first of these two.

The DSM-based methods have been well established for many years, and are typically applied to systems engineering, product architecture, and so on, to analyze aspects such as dependency and modularity (Kreimeyer et al., 2009). We find, however, only a few applications of DSM in the context of enterprise architecture (Lagerström et al., 2013).

According to the literature review of Santana et al. (2016), research that considers DSM modeling in EA analysis is scarce; the exceptions are the works of Lagerström et al. (2013) and Lagerström et al. (2014). In the view of Lagerström et al. (2013), "interestingly, many of the problems encountered by software architects dealing with a single software system are similar to those that occur for enterprise architects on a system-of-systems level." The authors took the DSM expertise from the analysis of single software architectures in Baldwin et al. (2013) and applied it to EA. In the end, Lagerström et al. (2013) proposed the "hidden structure method" to classify EA components into four categories according to their position in the network. Later, Lagerström et al. (2014) used their previous method and adding a correlation analysis between the position occupied by the component in the network and the cost of change propagation and architecture flow.

The multiple-domain matrix (MDM) is an extension of the DSM to model entire systems consisting of multiple domains, each having multiple elements and connected by various relationship types. Bartolomei et al. (2012) present an MDM representing several domains of systems engineering for modeling large-scale, complex systems projects. They consider six component classes belonging to five domains. Hollauer et al. (2015) also propose an MDM that supports dynamic modeling of sociotechnical systems consisting of seven domains.

In this paper, we advocate and reinforce the use of EA as an organizational blueprint, together with DSM and MDM modeling and constructs taken from network theory, to build a toolbox to perform EA structural analysis. One possible application that arises immediately is to use an MDM to model EA and derive single DSMs to explore new analysis perspectives.

3 Methodological aspects

This work can be classified as exploratory and applied research. We have adopted a design science research approach (Hevner et al., 2004).

In practice, EA analysis depends critically on human cognitive abilities (e.g., expertise) (Hevner et al., 2004) to produce effective results (Simon and Fischbach, 2013). We believe that, particularly in organizations with dozens or even hundreds of business processes supported by a similar number of applications, one might want to use additional knowledge sources to add confidence to the analysis. As our design artifact, we develop a method to combine expert knowledge (subjective by nature) about EA components (critical business units (BUs), business process (BPs), and business objects (BOs)) with network measures outputs (structural criteria). Figure 1 depicts this approach.

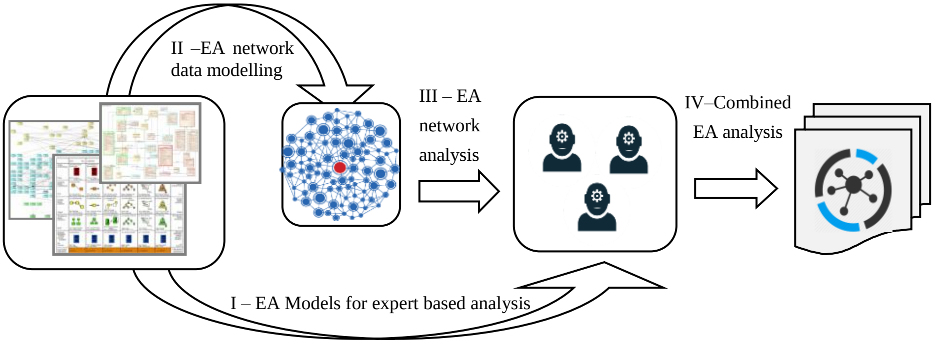

Figure 1: Combined EA analysis. Cycle I: EA models are analyzed with expert-based techniques; Cycle II: EA models are converted into EA network data; Cycle III: EA network analysis is performed using network measures; Cycle IV: Combined EA analysis

We believe this approach allows for designing a more robust method for EA analysis. We validated the artifact with a real-world example, using data from a business unit of a German automotive company with global operations. The company (henceforth referred to as “Autocompany”) has multibillion-dollar revenues and more than 40,000 employees around the world.

To model our networks, we preprocessed documents made available by Autocompany that were complemented with a round of two meetings to model the data properly. Table 1 describes the subset of EA layers analyzed. Components such as application (from application layer) and technology (from technology layer) are not discussed in this paper due to space limitations.

We used these data to build the primary or original networks (i.e., BOxBO, BPxBP). The primary network was created based on the data provided by Autocompany. We also worked with a second category of data, so-called derived network data. For instance, the BUxBU is a network (or DSM) derived from the BUxBP network (or a MDM) by the co-affiliation mechanism described in Borgatti and Halgin(2016).

Table 1. Dataset description of our case

EA component	EA layer	Amount of components in dataset	Network model
Business unit	Business	15	BUxBU
Business process step	Business	101	BPxBP
Business object	Information	70	BOxBO

According to Scott (1992), different network measures can be used as proxies for various structural concepts. We use the set of measures described in Table 2.

Table 2. Network measures used, and their contextualization

Network measures	Meaning in the context of BPxBP network
Betweenness centrality	BPs that are important intermediary channels of information
In-Closeness centrality	BPs can be reached easily from other nodes (in our case, BPs that are common destinations of information flow)
Eigenvector	BPs connected with other significant (well-connected) BPs; these are structural nodes in the network of BPs
In-degree centrality	BPs that receive several inputs from other BPs
Out-degree	BPs that provide several inputs for other BPs
Total degree	BPs with high total degree centrality represent BPs that interact directly with several other BPs

To capture this diversity of concepts, we define a majority voting strategy to select the “Y” most recurrent outliers from our voting committee based on the “X” outliers identified by each network measure. With this voting strategy, we consider the TOP 15 (X=15) outliers of each of the six measures in Table 2. We then compute the most “cited” outliers among them to build a ranking containing the ”Y” most recurrent components, as depicted in Figure 2. The “Y” and “X” parameters are adjusted *ad hoc* by the experts (one might want to analyze the 10, 20, or 30 most recurrent outliers among the TOP X outliers of each measure). This ranking represents a synthesis of the most significant outlier components in terms of structure.

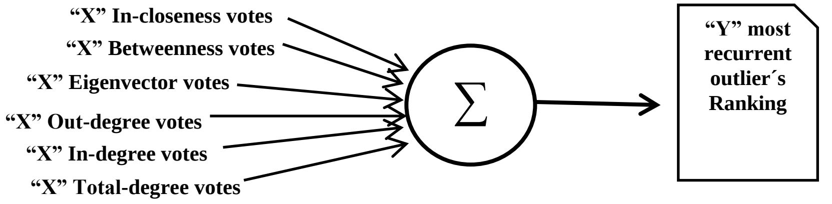

Figure 2. Voting strategy to build the outliers´ ranking

We can use this information in different ways. The most obvious one is a context-independent analysis to identify the components that play important roles in terms of structure. We propose, thus, a second possibility, which is to combine this structural knowledge with expert's tacit knowledge (*a priori* knowledge). We call this *diagnosis analysis*. We are interested in validating the expert knowledge with the components that are true positives (i.e., components identified as critical both by network measures and the experts) and potentially providing new information for the experts with the false positives (i.e., components identified as critical only by the network measures).

We performed this analysis for the BUxBU, BPxBP, and BOxBO networks, aiming to answer the following research question: *How can expert and structural knowledge about EA components be combined to help an expert perform EA analysis?* Section 4 presents our results.

4 Results and discussion

In this section, present the three aspects of our network analysis: BPxBP, BOxBO, and BUxBU.

4.1 BPxBP network analysis

With this analysis, we aimed to answer the following question: *Can the business process outliers (central points of the network BPxBP) also be identified as elements of the critical path defined by experts?* Our EA analysis concern, then, was to identify key structural components of an EA layer (in this instance, the business process layer). We used as input for this analysis the BPxBP network (primary data) extracted from Autocompany's documents.

Our hypothesis H1 is that network measures will be able to identify the main components belonging to the critical path already defined by Autocompany's experts. Additional components will also be identified and may have their importance validated.

The experts identified seven BP components in the critical path (the data had to be anonymized). Following the algorithm of the diagnosis analysis method defined in Section 3, we selected the TOP 15 outliers generated for each of six network measures. We then took the most recurrent components among all measures, using the voting strategy. This resulted in the selection of 21 distinct components (BPs), among which it was possible to identify successfully, from a universe of 102 BPs, the seven BPs that constitute the critical path defined in Autocompany's documents. This selection also included components considered for further analysis by Autocompany's experts, who classified all of them as important BPs. As one expert remarked about these complementary BPs, for example, "BP64 confirms the overall tech concept. BP68 formalizes this concept and turns it into a planned bill of material, and BP73 makes a document that contains these three aspects. Thus, this cluster makes total sense." In short, the experts found the results consistent with their expectations and very helpful. Thus, we found support for H1.

4.2 BOxBO network analysis

The research question here is: *Can network measures identify the most important BOs (according to the experts' opinions*)? Thus, our concern with the analysis concern was about key components of business object components, entities produced by business processes that might be handled by other business process components. The BOxBO network is a primary network that aims to represent how a BO is related to other BOs.

The experts classified 12 BOs as critical. Applying the diagnosis analysis method, we first selected the TOP 15 (X=15) components voted by each network measure from a universe of 70. From among all voted components, we chose the 19 most voted (Y=19), seeking to verify whether the 12 critical BOs were among the BOs in the ranking (H2 hypothesis). As a result, nine (9 of 12) critical BOs were identified among the 19 ranked components.

The experts indicated that identifying this set was a good result. As one said, "This is a very nice result. We recreated a discussion that we had when we designed the critical path for the BOs. At the time, and until now, we were unsure what the critical path indeed included." We still had 10 additional BOs identified as critical by the network measures (10/19) that had not been mentioned *a priori* by the experts (see yellow circles in Figure 3). One expert stated that "these 10 components might take part in the main information flow in case of a broader selection." Therefore, we decided to build the Ishikawa diagram in Figure 3 to check this information visually:

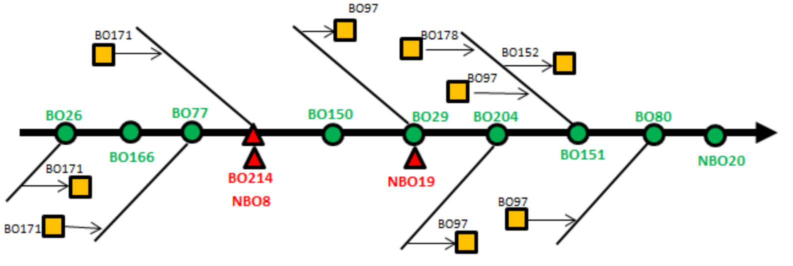

Figure 3. Ishikawa diagram for true positive, false positive, and false negative BOs

The red BOs (triangles) in Figure 3 were not identified by our method. We can divide the yellow BOs(squares) into two subsets. The first is components with high values for global centrality measures. This is the case for BO152 (high betweenness), BO171, BO97 (high eigenvector), BO178 (high betweenness), and BO97 (high eigenvector). These BOs appear in the surrounding areas of the significant BOs (green circles). The second subset comprises components with high values for local centralities, such as BO57 (high in-degree centrality value) and BO91, BO99, and NB05 (total degree centrality). This second group is not connected with the important BOs identified by the experts but is identified as important due to local importance of the components (high number of in-connections or out-connections to other local BOs) and may be worth of the experts' attention. We claim that these results support H2.

4.3 BUxBU network analysis

We consider organization business units (BUs) as stakeholders that execute different workloads depending on each process phase. We consider two phases for analysis purposes: PROD (phase I) and KONZ (phase II), and we pose this question: *Can we identify key stakeholders in different process phases?* Thus, our analysis concern here is stakeholder management, which might be important when it comes to involving the right people (BUs) in the EA decision-making process. As input, we took the BUxBP and applied a matrix transformation to generate a derived BUxBU network. With this derivation method, if two processes BP1 and BP2 are connected an artificial connection is created between their respective BUs in the BUxBU network (a co-affiliation network). The hypothesis H3 formulated by the experts is then broken down as follows. H3.1: *In Phase I, the focus of the project management unit (BU1) should be fairly continuous as they manage all activities.* H3.2: *In Phase II, the focus will be more on the technology people, with a ramp up to production and logistics and possibly to purchasing.* H3.3: *Overall, in Phase II, design engineers will be fairly central, as they function as a sort of information hub around which all technical concept design focus.*

We combined two types of network analysis outputs: the network measures rankings described in Figure 2 and the heat maps depicted in Figure 4. With the heat map, it was possible to check the high intensity of the information flow from B1, BU5, and BU7, which is spread out in Phase I. There was intense activity inside BU1, as can be seen in the dark blue cell, confirming the importance of BU1 for Phase I (thus supporting H3.1). Figure 4 also suggests a strong interaction from BU5 to BU1. This might confirm that both BUs together are the most active BUs in Phase I in terms of process interactions. From Table 3, we notice that BU1, BU5, BU2, and BU7 also appear in different rankings of network measures, reinforcing our visual analysis results from Figure 3.

Table 3. Network analysis at the component level for BUxBU Prod (Phase I)

TOP Out-degree BUs		TOP Eigenvector BUs		Most recurrent BUs	
BU5	product management	BU1	project management	BU1	Project management
BU1	project management	BU5	product management	BU13	Prod. Preparation
BU7	total vehicle integration	BU2	controlling	BU2	Controlling
BU3	quality	BU7	total vehicle integration	BU5	Prod. management
BU2	control	BU13	production preparation	BU7	Total vehicle integration

For H3.2, we obtained the following results: BU13, responsible for production aspects, became imperative in Phase II (detected by high in-degree centrality components and eigenvector centrality); Purchasing (B15) had importance detected by high in-degree centrality and also was among the most recurrent outliers; Validation and integration (BU7, BU10, BU3) aspects received focus in Phase II, detected by eigenvector centrality, most recurrent outliers, and out and in-degree centralities. Although identified by the experts *a priori*, logistics did not appear as a focus in Phase II. In conclusion, we found H2.3 to be partially supported.

For hypothesis H3.3, integration, validation, and preparation for production activities were the main ones in Phase II. So, we can conclude that H3.3 was also supported.

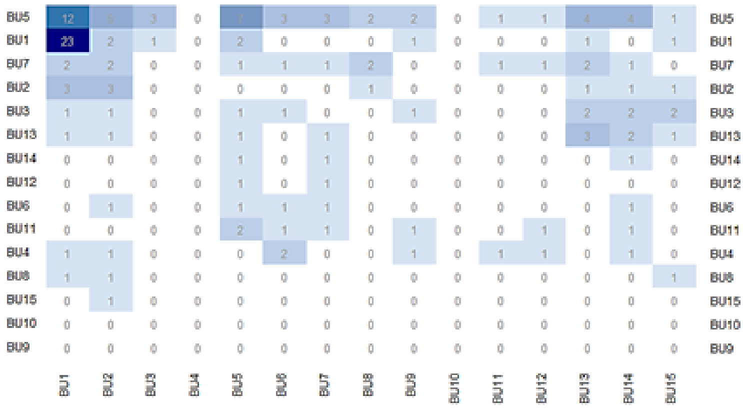

Figure 4. Heat map for BUxBU Prod phase

5 Conclusions

In this research, we propose an analysis approach we call *diagnosis analysis* that we believe provides two key information gains: 1) confirmation of components' importance, including from the structural perspective (confirming what experts identify prior to analysis as the critical BPs and BOs), and 2) suggesting for further analysis other components with similar network values and labeled as important by network measures, at first neglected by experts (based only on their own opinions), and ultimately validated as important by the experts. We also detected the expected shift of BUs' focus along the two process phases. In the end, we showed that combining expert and structural knowledge (the latter provided by primary and derived data) is a useful tool to assist experts in EA analysis.

There are some limitations to our research. First, the data collection and modeling processes were manual; future research might benefit considerably from use of a software plugin that can convert data from architecture models to network representations. Second, we analyzed only two EA layers. Other EA MDMs and DSMs (primary and derived) must be explored. Finally, we need to apply the proposed approach in other organizations and to other EA concerns to test whether it can be generalized.

We agree with Lagerström et al. (2013; 2014) that DSM and network analysis-based methods should be explored further in the context of enterprise architecture. Thus, we are working on the development of a matrix-based framework to support EA modeling with DSMs, including their possible co-affiliation networks.

References

Ahlemann, F. Strategic Enterprise Architecture Management: Challenges, Best Practices, and Future Developments. DOI: 10.1007/978-3-642-24223-6.

Aier,S. and Winter, R. "Virtual Decoupling for IT/Business Alignment – Conceptual Foundations, Architecture Design and Implementation Example", Business & Information Systems Engineering, vol. 1, no. 2, pp. 150-163, 2009.

Antunes, G., Bakhshandeh, M., Mayer, R., Borbinha, J. and Caetano, A. Using ontologies for enterprise architecture analysis, in Proc. EDOCW, 2013, pp. 361–368.

Bartolomei, J. E., Hastings, D. E., de Neufville, R. / Rhodes, D. H. in Systems engineering -new York-; 15, 1; 41-61; systems engineering -New York-by John Wiley & Sons, Ltd; 2012

Borgatti, S. and Halgin, S. Analyzing Affiliation Networks.Available:http://www.bebr.ufl.edu/sites/default/files/Analyzing%20affiliation%20networks.pdf

Buschle, M., Ullberg, J., Franke, U., Lagerström, R. and Sommestad, T., A tool for enterprise architecture analysis using the PRM formalism. LNBIP, v. 72 pp. 108–121.

Dreyfus, D. and Wyner, G.M. “Digital Cement: Software Portfolio Architecture, Complexity, and Flexibility”. Proc. 17th AMCIS, Detroit, Michigan, USA, 2011

Hall, N. R. and Preiser, S. Combined Network Complexity Measures. Ibm Journal of Research and Development (Impact Factor: 0.69). 02/1984; 28(1):15 - 27. DOI: 10.1147/rd.281.0015

Hevner, A., March, S., Park, J., Ram, S.: Design Science in Information Systems Research. MIS Quarterly, v. 28, p. 75–105, 2004

Hollauer, C., Wilberg, J., Mayada, O. A matrix-based framework to support dynamic Modeling of sociotechnical systems. In: Proc. of the 17 DSM Conference 2015.

Kreimeyer. M, Maier. J, Fadel, G. and Lindemann, U, editor, Proceedings of the 11th International DSM Conference, Greenville, SC, 12 - 13 October 2009, page 369-381.

Lagerström, R, Baldwin, C.Y. , MacCormack, A. and Aier, S, Visualizing and Measuring Enterprise Application Architecture: An Exploratory Telecom Case”. Harvard Business School Working Paper, no. 13-103, 2013.

Lagerström, R., Baldwin, C., MacCormack, A., and Aier, S. 2014. Visualizing and Measuring Enterprise Application Architecture: An Exploratory Telecom Case. In Proc. of the HICSS

Naranjo, D., Sánchez, M.E and Villalobos, J: PRIMROSe: A Graph-Based Approach for Enterprise Architecture Analysis. ICEIS (Revised Selected Papers) 2014, p. 434-452

Santana, A, Fischbach,K and De Moura, H, “Enterprise Architecture Analysis and Network Thinking : a Literature Review.” In Proc. HICSS 2016.

Schmidt, C “Measuring and Managing Enterprise Architecture Complexity”.(online).Available: http://scape-consulting.de/tl_files/scape/publications/CALM3_Scape.pdf

Schneider, A. W. , Zec, M. and Matthes, F. “Adopting Notions of Complexity for Enterprise Architecture Management”. Proc. AMCIS, 2014.

Schütz, A., Widjaja, T. and Kaiser, J., Complexity in enterprise architectures: conceptualization and introduction of a measure from a system theoretic perspective, In Proc. of 21st ECIS

Scott, J. Social Network Analysis. Newbury Park, CA: Sage, 1992.

Simon, D. and Fischbach, K. “IT Landscape Management Using Network Analysis.” In G. Poels (ed.), LNBIP (Vol. 139), Springer Berlin Heidelberg, pp. 18–34, 2013

The Open Group (2011). TOGAF Version 9.1. Van Haren Publishing.

Veneberg, R. K. M., Iacob M., van Sinderen, M. J. and Bodenstaff, L. “Enterprise Architecture Intelligence: Combining Enterprise Architecture and Operational Data”. Proc. EDOC, pp. 22–31.

Wasserman, S. and Faust, K.. Social Network Analysis. Cambridge: Cambridge University Press.1994.

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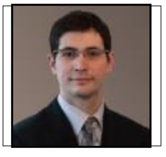

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Systematic Partitioning in Mechatronic Product Development by Modeling Structural Dependencies

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Abstract: Mechatronic product development is an interdisciplinary approach that has to deal with the immanent complexity of mechatronic products. While different approaches can be found in literature which aim to support interdisciplinary development, many companies still struggle with a lack of transparency regarding interfaces on product level as well as on an organizational level or process level. This conceptual paper presents an approach towards systematic partitioning that investigates interfaces on all three levels. The approach extends and combines existing approaches by integrating domain allocation and discipline allocation based on structural dependencies. The resulting structural models are used to computationally derive coordination needs. These allow project managers to explicitly plan coordination measures and give an overview for all developers. The paper also discusses further potentials of the analysis and use of the generated structural models.

Keywords: Mechatronic Product Development, Partitioning, Coordination

1 Introduction

Mechatronic product development is an interdisciplinary approach, which combines mechanics, electronics and information technologies (Isermann, 2000). Mechatronic systems feature a high degree of complexity due to a high number of elements from different technical domains and various interdependencies/interrelationships between them (Gausemeier and Moehringer, 2003; Tomiyama et al., 2007). One resulting major challenge regards interdisciplinary collaboration and communication (Isermann, 2000; Hehenberger and Bradley, 2016). This highlights the necessity of analyzing the interfaces between different domains or disciplines in order to plan sufficient coordination.

1.1 Research setting and motivation

This research is embedded in a research project in collaboration with an association of Bavarian companies from the metal and electronical industry which aims at developing support for mechatronic product development. One of the main challenges identified in a qualitative exploratory study with four partner companies (and also often described in literature, e. g. Alvarez Cabrera et al. (2011)) is the fact, that mechatronic product development is strongly dominated by the mechanics domain. The investigated companies further complain about historically grown organizational structures and development processes, and a resulting lack of transparency about cross-domain interfaces for new products. This leads to a lack of necessary coordination throughout the design process, to rework, and thus to increased development effort.

1.2 Research Need

There is a close interplay between the product architecture, the organizational structure of the development team and the design activities (process structure) (Browning et al., 2006; MacCormack et al., 2012). A general underlying question is which of these three systems is dominant for the whole development project system structure. In theory, when changing the product architecture, the organizational system and the process system have to adapt by generating new cross-team interactions and processes (Sinha et al., 2012). However, in practice, it often seems to be the other way around. The products are developed in the context of existing organizational structures and process structures. Still, additional intra- and inter-team coordination is necessary due to the novelty of the system under development (Sinha et al., 2012). New product extents lead to a lack of transparency about who is doing what and who needs to interact with whom (necessary coordination), especially when considering interdisciplinary coordination (Figure 1).

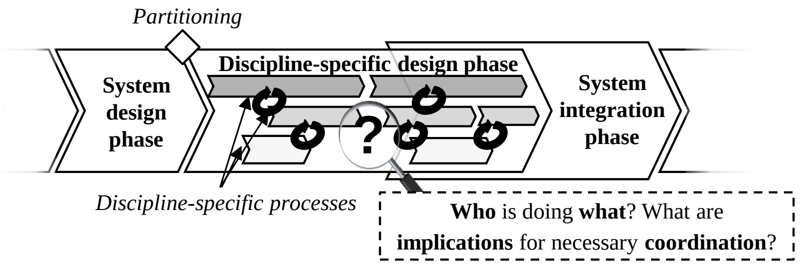

Figure 1. Observable process structure in practice with ambiguity of necessary coordination.

Explicit partitioning (i. e. allocating different technical domains to product elements) is a means that aims to manage the complexity and heterogeneity in a mechatronic product by systematically allocating product elements to different domains (Gausemeier and Moehringer, 2003). According to Jansen (2007) partitioning takes place in the system design phase. We observed in our partner companies that this allocation is often happening only implicitly based on historical structures. Additionally, an explicit domain allocation on a product level does not automatically uncover coordination needs on organization and process level. We found no practical approach addressing this issue in literature and therefor state two guiding research questions for this paper:

- How can discipline-specific design activities (process perspective) and responsibilities (organizational perspective) be systematically allocated based on a product concept at the end of the system design phase?
- How can resulting coordination needs within the discipline-specific design phase be derived systematically?

2 Theoretical Background

2.1 Product perspective

On the one hand, mechatronic products can be described as a combination of a physical basic system (e. g. mechanical, electro-mechanical, hydraulic or pneumatic systems), sensors, actors and an information processing system (VDI, 2004). These elements are interrelated through the kinetic flows *energy flow*, *material flow* and *information/signal flow* (VDI, 2004; Pahl et al., 2007).

On the other hand, standard frameworks describe technical products on three levels of abstraction: functional interrelationships (functions); working interrelationships (working principles); and constructional interrelationships (components) (e. g. Pahl et al., 2007). This step-by-step detailing of a product concept is also the basis for systems engineering approaches (c. f. Walden et al., 2015). In systems engineering, the consideration of interfaces plays an important role. Direct interfaces occur on a functional or geometric level and are summarized in Table 1. Moreover, the product architecture can be defined as the one-to-one, one-to-many or many-to-one mapping of components fulfilling functions (Ulrich, 1995).

Table 1. Overview of functional and geometric interfaces based on Stone and Wood (2000) and Pahl et al. (2007).

Contact	adhesive bond	**Energy**	human	hydraulic	**Material**	human
	form connection		acoustical	magnetic		gas
	friction force connection		biological	mechanical		liquid
	force field connection		chemical	pneumatic		solid
	elastic force connection		electrical	radioactive	**Signal**	status
			electromagnetic	thermal		control

The assignment of abstract product model elements on a functional or component level to the constituting elements of a mechatronic system (cf. Figure 2) is called partitioning or domain allocation (Welp and Jansen, 2004). A detailed approach that supports to model the different levels of abstraction and the allocation of technical domains to functions, components or solution principles is presented by Jansen (2007).

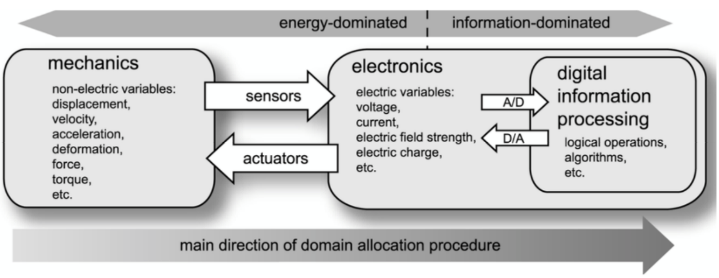

Figure 2. Overview of domains and their interfaces (Welp and Jansen, 2004).

2.2 Process perspective

The general design of a mechatronic system is described in the VDI-guideline 2206 (VDI, 2004) using the V-model and is divided into the phases *system design phase*, *discipline-specific design phase* and *system integration phase*. The discipline-specific process steps are not detailed any further in the guideline, but references to literature from the respective disciplines are given. Interestingly, it is mentioned in the guideline that functional incompatibilities, which could arise from the separation in discipline-specific development activities, are to be resolved in the system integration phase. We think that this kind of rework should be reduced by effective coordination.

Literature suggests to take advantage of synergies by coordinating interdisciplinary interactions with simultaneous engineering approaches (e. g. Isermann, 2000). Then, the adjustment of processes regarding content and timing depend on a high level of interdisciplinary communication and synchronization (Stetter and Pulm, 2009). This requires knowledge about all coordination needs. Hellenbrand and Lindemann (2011) present methodical support towards synchronization planning. Their approach links process steps with product elements (functions or components) via process results (information, documents) on a generic level. Yet, correlations that arise from the novelty of a product under development are not considered. Hence, this approach cannot be used in order to increase the transparency for project-specific coordination needs.

2.3 Organizational perspective

Companies that develop mechatronic products often group their engineering departments in the three disciplines *mechanics*, *electrics/electronics*, and *information technologies*. However, we also found other types of disciplines in our partner companies that can be distinguished:

- Company-wide, functional disciplines such as: management; (research &) development; testing; sales; marketing; purchasing; production; service; etc.
- Project-specific, functional disciplines such as: team leading, project management, testing, engineering; etc.
- Divisional disciplines such as: motor, gear box, body, tool holder, etc.

Regarding the organizational structure, individuals are affiliated with different departments or project-specific teams. Responsibility assignment matrices (PMI, 2013) are often used in order to define who is responsible for what.

3 Approach towards Systematic Partitioning

The approach towards systematic partitioning at the end of the system design phase aims at identifying coordination needs in the subsequent discipline-specific design phase. It extends and combines existing approaches (Jansen, 2007; Hellenbrand and Lindemann, 2011; Chucholowski and Lindemann, 2015) and especially supports to link the (conceptual) product structure to the organization and process structure via allocating domains and disciplines, respectively. For this we make use of dependency structure modeling techniques such as multiple domain mapping (Lindemann et al., 2009) and graph transformation (Heckel, 2006). In summary, the approach contributes to answering the question: Who has to talk to whom about what in discipline-specific design?

Note: We want to use the term *domain* from a product perspective and *discipline* from an organizational or process perspective. Other authors often use the terms interchangeable.

The approach consists of five parts: preparation; discipline allocation (organizational perspective and process perspective); domain allocation (product perspective); integration, and structural analysis and coordination planning.

3.1 Preparation

Existing information about the product system, organizational system and process system is collected as a preparation. Known elements from different types and their interrelations within these three systems are modeled. On the one hand, not a lot of details about the product under development are known in the system design phase. On the other hand, we assume that the products are seldom developed from scratch but are based on existing developments from the past. Consequently, the planned product architecture is already known (product functions and – as far as already defined – components mapped to the functions). Companies have an organizational structure (individuals being part of departments) and have models of their development processes. A predominant part of the necessary data is stored in different IT systems in our partner companies, such as PDM systems, ERP systems, process/project management tools, or even spreadsheets and presentation programs. Missing data has to be modeled manually.

The following steps summarize the preparation phase as illustrated in Figure 3.

- Model the product system with all known functions, components, functional interfaces, geometric interfaces and the product architecture. Within this step, also new potential working principles as solution variants can be identified.
- Model the process system with all predefined process steps and their logical dependencies (sequence).
- Model the organization system with relevant departments or teams, available individuals and their affiliation.

3.2 Discipline allocation

Discipline allocation concerns the organizational system and the process system. In our simplified example we distinguish the three disciplines *mechanics*, *electronics* and *information technologies*. The disciplines have to be allocated to the elements of the organization system and the process system. The discipline allocation for an academic example is shown in Figure 4 (Step 1). It is acknowledged that the discipline allocation always takes place at least implicitly. We allocate the disciplines explicitly in order to facilitate systematic partitioning and to be able to structurally derive resulting coordination needs.

3.3 Domain allocation

Based on the models generated as preparation, the allocation of domains on product level is done by mapping the elements from the product system to domains (cf. Jansen, 2007). Again, the three domains *mechanics*, *electronics* and *information technologies* are differentiated. Step 2 in Figure 4 shows the mapping in an academic example.

3.4 Integration: Connecting product perspective with organizational and process perspective

This step responds to the following question: Who is doing what and when? It aims to support the clarification of which department or team develops which extents of the mechatronic product and what discipline-specific processes are necessary. To do so, elements from the product system that are allocated to more than one domain should be decomposed first.

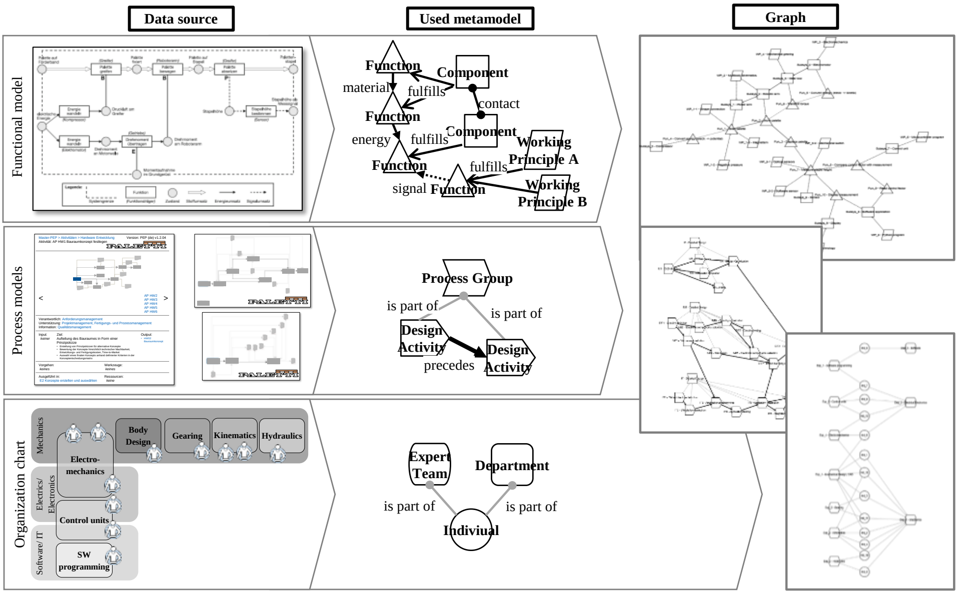

Figure 3. Illustration of the transfer of existing data into a graph using an academic example.

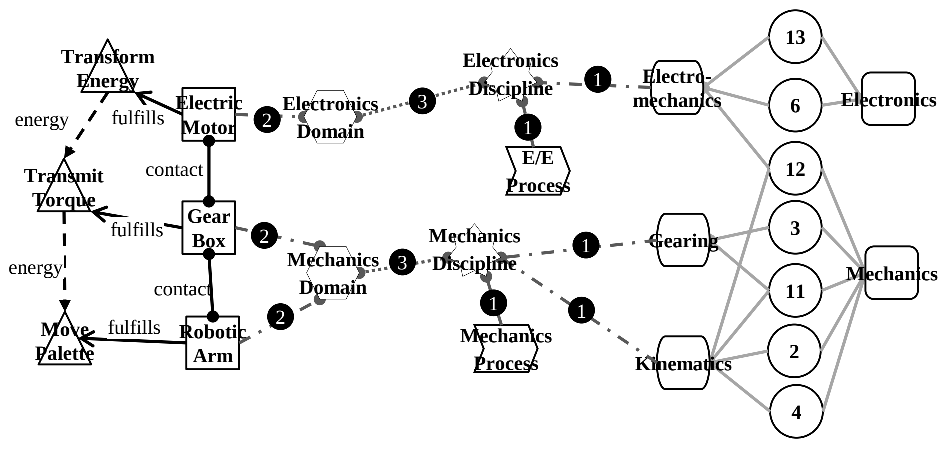

Figure 4. Exemplary discipline allocation for the organization and process system (1), and domain allocation (2). The mapping of domains and disciplines brings all perspectives together (3).

After detailing the modeling basis, the organization and process systems can be correlated indirectly with the product system by matching domains and disciplines (Step 3 in Figure 4). This step is trivial in our example, but is not necessarily trivial in practice (refer to section 2.3) and is therefore made explicit in our approach. Furthermore, discipline-specific processes for each product system element can be instantiated based on the respective generic discipline-specific processes (see different detailed processes in Figure 5).

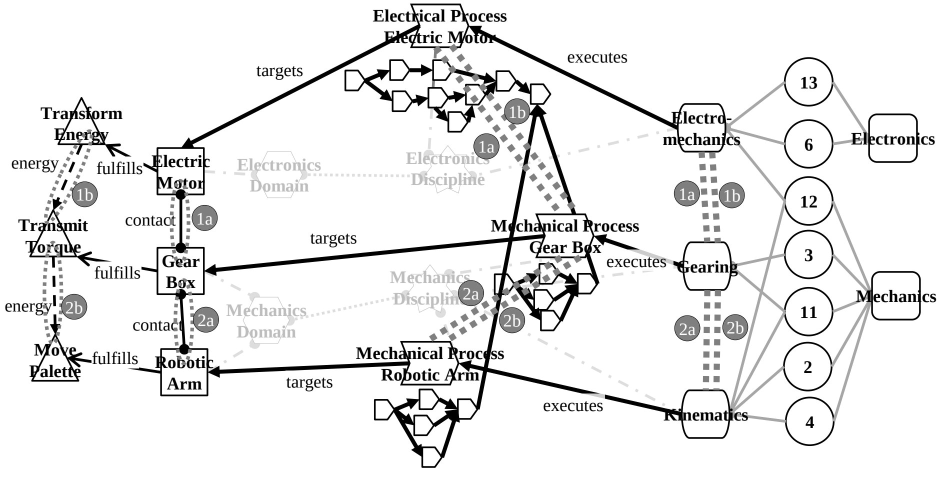

Figure 5. Exemplary instantiation of the discipline-specific processes and structural analysis. Coordination needs between the correlated processes and organizational units are derived for each interface within the product system (1a, 1b, 2a, 2b).

3.5 Structural analysis and coordination planning

Coordination needs between organizational units (departments, individuals) and between processes (instantiated process steps) can now be derived from the modeled structures by looking at interfaces on product level. Since the design process steps have been instantiated for different product system elements (one process stream each), interfaces can be projected on a process level as need for coordination. The coordination has to take place to some extent somewhere in between the two process streams and indicates about what and when interaction is needed. In addition, the interfaces between product system elements can be projected to interfaces between organizational units and give indications who has to interact with whom. The projections can be derived computationally by either using graph transformation with predefined rules or by multiplying the underlying adjacency matrices (=DSMs and MDMs). We considered all direct and first-order indirect relationships in our example. Additional information about each coordination need can be provided by characterizing the product interfaces with the help of Figure 2. For example, issues regarding a geometric interface between two components could be: statics, dynamics, force transmission, etc. If the components share an indirect functional relationship and are allocated to different domains (mechanics, electronics), the indirect relationship implies that a converter could be needed.

The computationally derived coordination needs serve as a basis to systematically plan coordination measures. For this, however, expert judgement about the relevance and about adequate coordination measures is necessary.

4 Discussion and Outlook

This research contributes to the state of the art by presenting an actionable approach towards systematic partitioning that integrates the product perspective, organizational perspective and process perspective. The integration of the three projects systems is done by matching the technical domains allocated to the product with disciplines allocated to discipline-specific processes and the organization. A structural analysis of the product system in terms of interfaces then enables the derivation of needs for coordination on a process and organizational level. The derivation is done computationally by the use of dependency structure modeling techniques such as multiple domain matrices and graph transformation. The generated list of coordination needs not only enables project managers to explicitly plan coordination, but also gives developers an overview of who should talk to whom about what (product interface) and when (related processes).

The presented approach bears potentials when applied consequently. First, the models generated during the application of the approach in previous, similar development projects can be used as input for the preparation phase. This minimizes the modeling effort in this phase. Second, companies can define their own domains and disciplines (and a specific mapping of the two) that are relevant for them. This would also enrich the interpretation of the respective cross-domain and cross-disciplinary interfaces. As an example, considering information technologies it is reasonable to differentiate programming languages such as Python, C++ or Java since they require different software architectures and programming skills. This is why skills/expertise on a certain level of abstraction could also be considered as disciplines for the discussed approach. Third, it is proposed to use the approach to consider coordination needs in the discipline-specific design phase based on data available at the end of the system design phase. But also new upcoming coordination needs, which arise due to a more detailed or changed product structure during discipline-specific design, could be identified. Thus, it could be valuable to keep the structural models updated and repeat the analysis continuously.

So far, the approach is kept as detailed as necessary in order to create new implications but as simple as possible. Still, extensions of the approach could enhance its value:

- Functional and non-functional requirements could be included in the product system model. This would enable the consideration of further relevant indirect relationships via relationships with and in between requirements. Also the modeling of the tool system could be worthwhile. The different tools are strong indicators for relevant domains, disciplines or even required skills/expertise.
- Predefined tailoring criteria that enable to differentiate prescriptive process variants for process instantiation could be used.
- Further analysis could also consider second-level indirect relationships derived from first-level indirect relationships.
- When considering complex systems, a very large number of derived coordination needs is expected. Structural criteria such as the criticality of components (refer to Lindemann et al., 2009) could be helpful indicators for the relevance of a coordination need. This enables computational prioritization.

The approach was developed based on explorative studies on the situations and needs of our industry partners regarding systematic mechatronic product development. As a next step, the approach will be evaluated with our industry partners. For this, we are working on a software prototype, which eases modeling and enables automatic computational analysis and visualization of the results.

References

Alvarez Cabrera, A.A., Woestenenk, K., Tomiyama, T., 2011. An architecture model to support cooperative design for mechatronic products: A control design case. Mechatronics 21 (3), 534–547.

Browning, T.R., Fricke, E., Negele, H., 2006. Key concepts in modeling product development processes. Systems Engineering 9 (2), 104–128.

Chucholowski, N., Lindemann, U., 2015. An Initial Metamodel to Evaluate Potentials for Graphbased Analyses of Product Development Projects, In: Proceedings of the 17th International DSM Conference, Fort Worth, Texas, USA. November 4-6, 2015, pp. 75–88.

Gausemeier, J., Moehringer, S., 2003. New Guidline VDI 2206: A Flexible Procedure Model for the Design of Mechatronic Systems, In: Proceedings of the 14th International Conference on Engineering Design, ICED'03, Stockholm.

Heckel, R., 2006. Graph Transformation in a Nutshell. Electronic Notes in Theoretical Computer Science 148 (1), 187–198.

Hehenberger, P., Bradley, D. (Eds.), 2016. Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and their Designers. Springer International Publishing, Cham.

Hellenbrand, D., Lindemann, U., 2011. A Framework for integrated Process Modeling and Planning, In: Proceedings of the 18th International Conference on Engineering Design, ICED11, Copenhagen, Denmark.

Isermann, R., 2000. Mechatronic systems: concepts and applications. Transactions of the Institute of Measurement and Control 22 (1), 29–55.

Jansen, S., 2007. Eine Methodik zur modellbasierten Partitionierung mechatronischer Systeme. Shaker, Aachen.

Lindemann, U., Maurer, M., Braun, T., 2009. Structural Complexity Management: An Approach for the Field of Product Design. Springer, Berlin.

MacCormack, A., Baldwin, C., Rusnak, J., 2012. Exploring the duality between product and organizational architectures: A test of the “mirroring” hypothesis. Research Policy 41 (8), 1309–1324.

Pahl, G., Beitz, W., Wallace, K., Blessing, L. (Eds.), 2007. Engineering design: A systematic approach, 3rd ed. Springer, London.

PMI, 2013. A guide to the Project Management Body of Knowledge (PMBOK guide), 5th ed. Project Management Institute, Newtown Square, Pa.

Sinha, K., James, D., Weck, O. de, 2012. Interplay Between Product Architecture and Organizational Structure, In: Proceedings of the 14th International Dependency and Structure Modelling Conference - DSM'12, Kyoto, Japan. September 13-14, 2012, pp. 275–288.

Stetter, R., Pulm, U., 2009. Problems and Chances in Industrial Mechatronic Product Development, In: Proceedings of the 17th International Conference on Engineering Design ICED09, Stanford, CA, USA. 24 - 27 August 2009, pp. 5-97 - 5-108.

Stone, R.P., Wood, K.L., 2000. Development of a functional basis for design. Journal of Mechanical Design 4 (122), 359–370.

Tomiyama, T., D’Amelio, V., Urbanic, J., ElMaraghy, W., 2007. Complexity of Multi-Disciplinary Design. CIRP Annals - Manufacturing Technology 56 (1), 185–188.

Ulrich, K., 1995. The role of product architecture in the manufacturing firm. Research Policy 24 (3), 419–440.

VDI, 2004. Entwicklungsmethodik für mechatronische Systeme - VDI 2206. Accessed 12 October 2015, 118 pp.

Walden, D.D., Roedler, G.J., Forsberg, K., Hamelin, R.D., Shortell, T.M. (Eds.), 2015. Systems engineering handbook: A guide for system life cycle processes and activities, 4th ed. Wiley, Hoboken, New Jersey.

Welp, E., Jansen, S., 2004. Domain allocation in mechatronic products, In: Proceedings of the 8th International Design Conference, DESIGN 2004, Dubrovnik, Croatia.

Systematic Partitioning in Mechatronic Product Development by Modeling Structural Dependencies

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Analyzing Organizational Capabilities as Systems: A Conceptual Framework

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Abstract: Operational capabilities are used in resource based view in strategic management literature to explain how the difference in performing similar activities results in heterogeneity between firms. In order to advance our understanding of this concept, using a system metaphor, we try to shape a framework for micro-level analysis of operational capabilities. Following two stages of holism and focus for identifying system boundaries through looking related literatures, we propose knowledge, skills and tools as general micro elements of operational capabilities in form domain. Using Dependency Structure Matrix (DSM), we finally synthesize our conceptual framework to capture interactions of aforementioned micro elements and to show how this system works toward sub activities in function domain which their integration to a whole provides the firm with an operational capability. This paper is the first step in using a system metaphor to investigate organizational capabilities and paves the way for future researches of its kind.

Keywords: Organizational capabilities, Operational capabilities, Micro-level analysis, system metaphor, system analysis, form domain, function domain, interactions, Dependency Structure Matrix (DSM), literature review

1 Introduction

A firm’s success depends on the congruence between its portfolio of activities and its external opportunities as well as the quality of performing such set of activities (Saloner et al., 2001). Resource based view (RBV) in strategic management literature has acknowledged the important role of organizational capabilities in explaining how good firms can perform their activities (Grant, 1991; Amit and Schoemaker, 1993). A distinction is generally made between operational capabilities (OCs) and dynamic capabilities, so that the former enables firms to perform their ongoing tasks of making a living (Helfat, Finkelstein et al., 2007), while the latter concerns building, integrating or reconfiguring operational capabilities (Kiamehr, 2012). This paper only deals with OCs. In recent decades, a large body of literature (for example: Penrose, 1959; Rumelt, 1984; Wernerfelt, 1989 and Barney, 1991) has been produced on the nature and importance of firms’ capabilities within RBV strand (Kiamehr, 2012). Despite years of development and many theoretical contributions, the conceptualization, operationalization, and application of RBV has remained problematic (Noori et al., 2012). One aspect of the literature that still seems to be unsettled is the confusion over the definition of this concept (Kiamehr, 2012). Capabilities refer to the organization's potential for carrying out a specific activity or set of activities (Grant, 1991; Amit and Schoemaker, 1993; Teece and Pisano, 1994; Fernandez et al., 2000; Helfat and Peteraf, 2003; Galbreath, 2005) but there is no consensus on OCs definition in the literature (Kiamehr, 2016). For the purpose of this paper, we define an organizational capability (OC) as an actual synthesis of organizational assets which allows for performing some specific activities.

Most sciences or subfields, in their early stages of development, begin at some aggregate level of analysis and thus implicitly assume that micro-level phenomena has relatively uniform effects on aggregate level phenomena, and/or that variation at the micro-level does not inform variation of aggregate level phenomena (Felin et al., 2012). As fields progress, evidence suggests that assumptions about micro-level uniformity prove unsustainable and inaccurate (id.). Indeed, micro-level phenomena are often more idiosyncratic in nature than not (McKelvey, 1998). Advancing the understanding of particular phenomena and, in turn, a field, thus may require expanding theoretical and empirical work to encompass multi-level effects, including micro-level effects (e.g. Hitt et al., 2007). Elster (1989, p. 74) indeed argues that 'reduction is at the heart of progress in science'. Scientific reduction is a call for explaining collective phenomena and structures in terms of what are seen as more fundamental, nested components (Kincaid, 1997) and the search for, and explication of, the constituent components that underlie aggregate and collective phenomena (Felin et al., 2012).

To shape a micro level understanding of organizational capabilities, it seems fruitful to use a system metaphor. This idea rose from the similarity between definitions of organizational capabilities and systems. Systems are defined as a set of entities and their relationships, whose functionality is greater than the sum of the individual entities (Crawley et al., 2015). In our aforementioned definition of OCs, a synthesis of organizational assets is a set of entities which their relationships makes performing some activities possible for the firm which are not possible in such a way otherwise. So, it seems that considering organizational capabilities as systems and doing system analysis at micro level bears fruit.

This paper aims to present a conceptual framework as a basis for analyzing OCs as systems. The above discussion shows that such framework may help to have a better understanding of OCs and to decrease current conceptual ambiguities in related literatures.

The next section of this paper analyzes OCs using system science literature. The third section, synthesizes our conceptual framework. The final section presents some limitations of this work and also spreads an agenda for future researches.

2 Organizational capabilities as systems

Systems simultaneously have the characteristics of form and function (Crawley et al., 2015). Form is what the system is and function is what the system does (id.). System science considers both domains for system analysis. Discrete parts of related literatures have also analyzed OCs in both form and function domains. In this section, we first try to identify micro elements of OCs in the function domain as well as their interactions. Thereafter in the second subsection, OCs are decomposed in the form domain while their interactions are also considered. Finally we will link those two domains to show how the system integrates to a whole which enables the firm for doing specific activities.

2.1 Analysis in function domain

Function domain deals with what a capability can perform, i.e. activities. For analyzing an OC in the functional domain, it should get decomposed into its underlying sub activities first. Each sub activity may again be decomposed to its lower layer sub activities. This decomposition process could be continued until we reach to simplest tasks in the lowest layer. Some of related literatures has analyzed OCs in the function domain. For example, when CoPS (Complex Product Systems) literature breaks systems integration mega capability into functional, project and strategic management sub capabilities (Davies and Hobday, 2005), analysis has been done in function domain. Again, when innovation studies consider idea generation, design and development, implementation and commercialization as major sub capabilities of innovation capability (Tidd et al., 2005, Cagliano et al, 2000), they are speaking in function domain. For many of today's products with a systemic nature, the design and development sub activity itself, could be braked into system level and component level design sub activities (Crawley et al., 2015). Figure one proposes such decomposition for innovation capability and also for its design & development sub activity into its second layer.

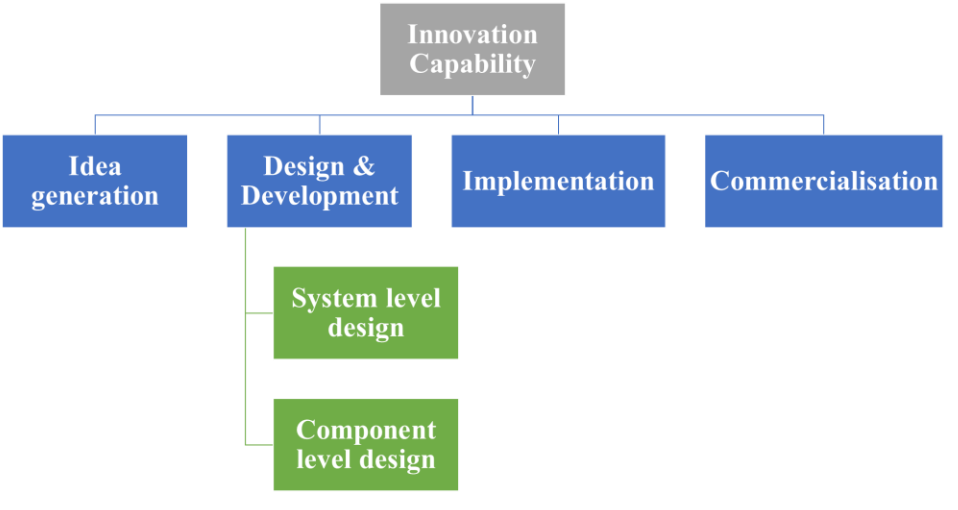

Figure 1. Analysis of innovation capability in function domain

Afterward, the interactions of micro level sub activities could be considered. These interactions which occur through a process or routine, then integrate into a whole capability which allows the firm for doing a specific set of activities. Table one illustrates those interactions for a typical OC at its first level of decomposition in function domain using Design Structure Matrix (DSM) which is widely accepted in system science for presenting interactions in a system. The red (Bold) lines in this figure, show the system (OC) boundary. The system receives inputs from its environment and acts upon the operand to change the operand while there would be some other outputs (byproduct) too.

Table 1. First level interactions of a typical OC in function domain

OC	Inputs	Operand	A1	A2	…	An	Changed operand	Other Outputs
Inputs			•					
Operand			•					
A1				•	•			
A2					•			
…						•		
An							•	•
Changed operand								
Other outputs								

To provide an example, table two decomposes innovation capability in the function domain to its first level sub activities.

Table 2. Analyzing innovation capability in function domain at the first level of decomposition

Innovation capability	1	2	3	4	5	6	7	8
1: Budget, …			•	•	•	•		
2: Previous product			•	•	•	•		
3: Idea generation				•				•
4: Design & Development					•			•
5: Implementation						•		•
6: Commercialization							•	•
7: Innovated product								
8: Job satisfaction								

2.2 Analysis in form domain

The form domain deals with what the system is. In regard of micro elements of OCs in the form domain, related literature has provided a wide list. Leonard-Barton (1992) suggests that skills and knowledge bases (embodied in people or disembodied in the form of technical systems) are at the core of capabilities, but certain organizational dimensions affect this core. These dimensions include managerial systems (such as formal and informal ways of creating knowledge), organizational norms and values assigned to various types of knowledge (such as engineering versus marketing expertise) and processes of knowledge creation and control (such as formal degrees versus experience) (Kiamehr, 2012). Prahalad and Hamel (1990) as well as Lall (1992) specify capabilities as mere skills or knowledge sets. The range of micro elements in the literature is in fact broader than merely organizational and technical elements (Henderson and Cockburn 1994; Levinthal and Myatt 1994; Bell and Pavitt 1995), and for example includes important personal characteristics of individuals, especially managers (Augier and Teece, 2006; Teece 2007). Christensen and Caufman (2006) have emphasized on resources, processes and priorities in this regard. Felin et al. (2012) has pointed to individuals, processes and structures as three main categories of micro elements. Porter (1995) and Drejer (1996) imply to knowledge, hardware and skills while talking about technological capabilities. Such a long list may be beneficial as all elements that might be important to the system should be initially identified through a holistic thinking (Crawley et al., 2015). The next issue that the system thinker faces is focus—that is, to identify what is important to the question at hand (id.). Expanding outward from the system, the first level of context we encounter includes the other objects that are not part of the system but are essential for the system to deliver its functionality (id.). These are called the accompanying systems (id.). The sum of the system and the accompanying systems is called the whole system (id.). The system is separated from the accompanying systems by the system boundary (id.). Expanding one more step outward, we find the next level of context, the use context (id.). The whole system fits within this use context, which includes the other objects that are normally present when the whole system operates but are not necessary for it to deliver its function (id.). The use context is important because it informs the function of the system (id.). It gives place to the whole system, and it gives us information on the environment in which the system operates and informs system design.

The aforementioned discussion clears that from the wide list of micro elements from the literature, some should be considered inside the systems boundary as the main micro elements of OCs while some others should be considered as accompanying systems and some others would be better to place in use context. This classification depends on the question at hand but some general guidelines seem recommendable.

This paper limits itself with managerial implications and tries to provide a better understanding of OCs as a basis for their improvement plans. So it may be a good idea to separate those elements under managerial control within the firm from those which are placed in external environment such as national infrastructures. Those external elements could be dealt with as external opportunities in use context. Although some other elements such as organizational culture are internal to the firm, they are very hard to control at least in short term and they also are not attributable to any specific capability. So, they could be considered as accompanying systems in the whole system. Strategy literature has also acknowledged that OCs perform within an organizational context (Leonard-Barton, 1992; Porter, 1985 and Drejer, 1999). So, we adopt knowledge, skills and tools from strategy literature (Leonard-Barton, 1992; Porter, 1995 and Drejer, 1996) as general micro elements of capabilities in form domain. Fig. two shows OCs' boundary within organizational boundary, accompanying systems and the use context in the form domain.

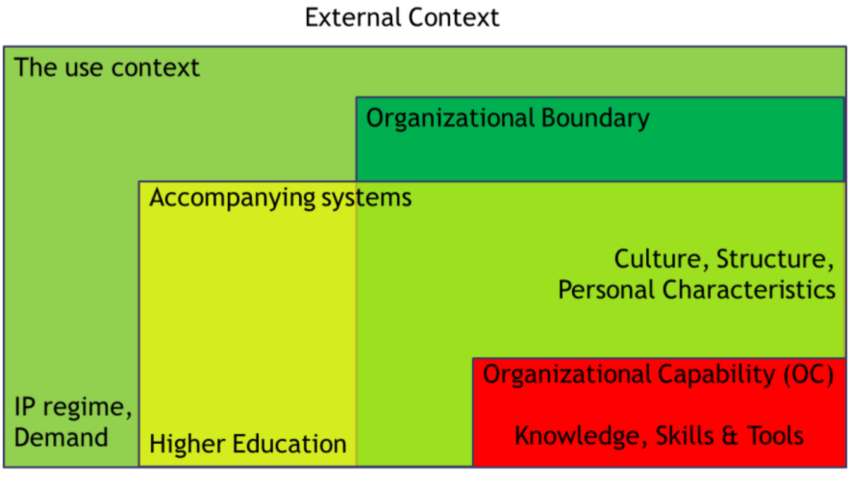

Fig 2. Operational Capabilities boundary within its environment in the form domain

These micro elements interact to perform an activity, sub activity or just a simple task. Using DSM, table three illustrates those interactions for a simple task (Ti) at the lowest level of decomposition. As the figure shows, skills are the main synthesizing mechanism of OCs which utilize other organizational assets (Knowledge and tools) to perform a task. It worth to note that tools have embodied some sorts of knowledge and skills themselves which are not completely captured in this figure.

Table 3. Interactions of microelements of operational capabilities in the form domain

Ti	Inputs	Operand	Know-How	Tools	Skills	Changed operand	Other outputs
Inputs				•	•		
Operand				•	•		
Know-How				•	•		
Tools					•		
Skills						•	•
Changed operand							
Other outputs							

In order to provide an example, table four represents the analysis of component level design sub activity (which we had mentioned in the previous sub section) in the from domain. In this table, budget is one of the system inputs which is necessary for the system to operate. Designers with optimization skills deploy their component knowledge and also design softwares to change the component specifications which are delivered from the system level design sub activity of the figure one (System's operand) into component design documents. Verification documents may be considered as other outputs of this sub activity.

Table 4. Analysis of component level design sub activity in the form domain

Component level design	1	2	3	4	5	6	7
1: Budget,…				•	•		
2: Component specifications				•	•		
3: Component knowledge				•	•		
4: Design software					•		
5: Optimization skills						•	•
6: Component design docs							
7: Verification docs							

3 Conceptual framework

To synthesize our conceptual framework, we need to link the two aforementioned domains to show how OCs perform their function as a whole system. For this purpose, we adopt IDEF0 (a widely accepted modeling standard in system science) as the basis for our conceptual framework. Figure three represents our conceptual framework which links OC's micro elements in both form and function domains as well as their interactions.

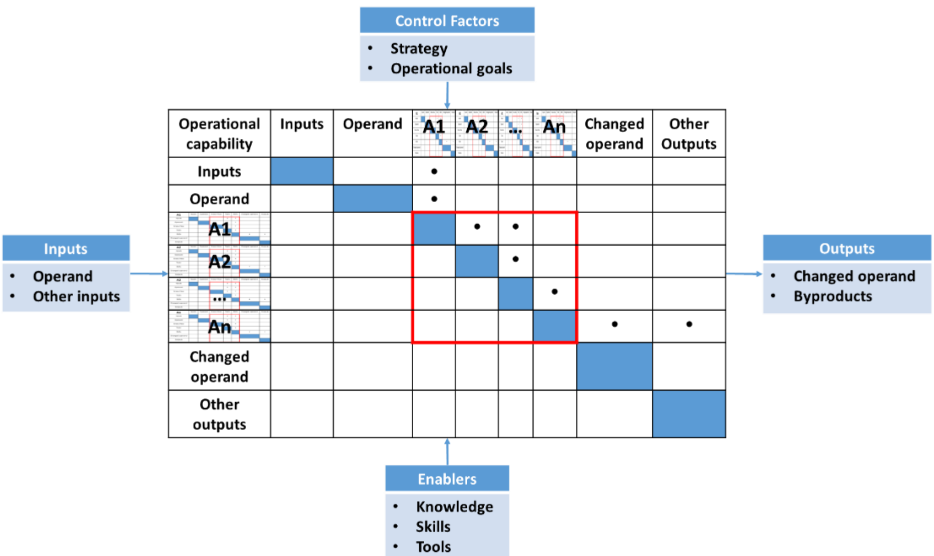

Fig 3. Conceptual framework for analyzing operational capabilities as systems

As this figure shows, operand and other inputs enter the OC from the external environment. Knowledge, skills and tools as general micro elements of OCs are enablers of OC which interact to perform each of sub activities A1, A2…An. Their interactions (which has been presented in table three has been zoomed out and captured into cells labeled A1, A2…An. Interactions in function domain (between sub activities) has been reflected in the bigger table and results in changed operand and probably other byproduct. This transformation are controlled and constrained with strategic and operational goals of the firm which reflect all affecting factors in the OCs context.

4 Closing remarks

This paper tried to contribute to strategy literature through providing a better understanding of the operational capabilities. For this purpose, we proposed a new lens to look to OCs as systems. Using system science concepts and tools, we decomposed OCs to their micro elements in both form and function domains and captured their interactions as well. Our final conceptual framework linked the two domains to show how the interaction in two domains integrates to perform specific activities as a whole system. Such an approach to organizational capabilities is new. Although a few of researches has implicitly (Morgan, 2005) or explicitly (O'Connor, 2008) mentioned OCs as systems, there are no try to operationalize such a metaphor. Thus, this work has set the agenda for a new strain which understands OCs and probably dynamic capabilities as systems.

Our conceptual framework may have considerable managerial implications. It can be used as a framework for gap analysis in OCs and as a basis for improvement plans. With considering other micro elements, it can be used as a guide for policy making as well.

Systems lifecycle includes different stages. In the highest level, a firm is able to conceive, design, implement, operationalize and dispose an OC. This paper have focused on operationalization phase only. Future work may investigate other micro elements of OCs and their interactions during other phases of lifecycle. For example, know-why is mostly utilized to inform process design knowledge in design phase. It is also worth to note that process design knowledge is different from utilization know-how which reflects a kind of user's manual. Using this framework in empirical settings seems also fruitful in the future works.

References

Amit, R., Schoemaker, P., 1993. Strategic Assets and Organizational Rent. Strategic Management Journal 14(1).

Augier, M., Teece, D., 2006. Understanding complex organization: the role of know-how, internal structure, and human behavior in the evolution of capabilities. Industrial and Corporate Change 15(2).

Barney, J.B., 1991. Firm Resources and Sustained Competitive Advantage. Journal of Management 17, 99-120.

Bell, M., Pavitt, K., 1995. The Development of Technological Capabilities, In: Haque, I.U., Bell, M., Pavitt, K. Trade, Technology, and International Competitiveness. World Bank, Washington.

Cagliano, R., Chiesa, V., Manzini, R., 2000. Differences and similarities in managing technological collaborations in research, development and manufacturing: a case study. Journal of engineering and technological management 17, 193-224.

Christensen, C.K., Kaufman, S.P., 2006. Assessing Your Organization's Capabilities: Resources, Processes and Priorities. Harvard Business School Module Note 607-014.

Crawley, E., Cameron, B., Selva, D., 2015. System Architecture: Strategy and Product Development for Complex Systems (1st Edition). Pearson.

Davies, A., Hobday, M., 2005. The business of projects; managing innovation in complex products and systems. Cambridge university press, New York.

Drejer, A., Riis, J.O., 1999. Competence Development and Technology: How Learning and Technology can be Meaningfully Integrated. Technovation 19(10), 631-644.

Elster, J., 1989. Nuts and Bolts for the Social Sciences. Cambridge University Press, Cambridge and New York.

Felin, T., Foss, N.J., Hiemeriks, K.H., Madsen, T.L., 2012. MICROFOUNDATIONS OF ROUTINES AND CAPABILITIES: INDIVIDUALS, PROCESSES, AND STRUCTURE. Journal of Management Studies 49(8), 1351-1374.

Grant, R., 1991. The Resource-Based Theory of Competitive Advantage: Implications for Strategy Formulation. California Management Review.

Helfat, C., Finkelstein, S., 2007. Dynamic Capabilities: Foundations. Dynamic Capabilities. Blackwell Publishing.

Henderson, R., Cockburn, I., 1994. Measuring Competence? Exploring Firm Effects in Pharmaceutical Research.

Hitt, M.A., Beamish, P.W., Jackson, S.E., Mathieu, J.E., 2007. Building theoretical and empirical bridges across levels: Multilevel research in management. The Academy of Management Journal 50, 1385-1399.

Kiamehr, M., Hobday, M., Kermanshah, A., 2014. Latecomer systems integration capability in complex capital goods: the case of Iran's electricity generation systems. Industrial and Corporaate Change 23(3), 689-716.

Lall, S., 1992. Technological Capabilities and Industrialization. World Development 20(2).

Leonard-Barton, D., 1992. Core Capabilities and Core Rigidities: A Paradox in Managing New Product Development. Strategic Management Journal 13(Special Issue: Strategy Process: Mapping Corporate Self-Renewal).

Levinthal, D.A., Myatt, J., 1994. Co-Evolution of Capabilities and Industry: The Evolution of Mutual Fund Processing. Strategic Management Journal 15(Winter), 45-62.

McKelvey, M. 1998. Evolutionary innovations: learning, entrepreneurship and the dynamics of the firm. Journal of Evolutionary Economics 8, 157-175.

Morgan, p., 2005. THE IDEA AND PRACTICE OF SYSTEMS THINKING AND THEIR RELEVANCE FOR CAPACITY DEVELOPMENT. European Centre for Development Policy Management.

Noori, J., Tidd, J., Arasti, M.R., 2012. Dynamic Capability and Diversificatio, in: Tidd, J. From knowledge management to strategic competence: Assessing technological, market and organizational innovation (3rd edition). Imperial College Press. Sussex, Series on Technology management 19, 3-20.

O'Connor, G.C., 2008. Major Innovation as a Dynamic Capability: A Systems Approach. The Journal of Product Innovation Management 25, 313-330.

Penrose, E., 1959. The Theory of the Growth of the Firm. John Wiley, New York.

Porter, M., 1985. Competitive Advantage.

Prahalad, C.K., Hamel, G., 1990. The Core Competencies of the Corporation. Harvard Business Review 68(3), 79-91.

Rumelt, R. 1984. Towards a strategic theory of the firm, In: Lamb, R. Competitive Strategic Management. Prentice-Hall, Englewood Cliffs.

Saloner, G., Shepard, A., Podolny, J., 2001. Strategic Management (1st Edition). Wiely.

Tidd, J., Bessant, J., Pavitt, K., 2009. Managing innovation: Integrating technological, market and arganizational change.Wiley.

Wernerfelt, B., 1989. From critical resources to corporate strategy. Journal of General Management 14, 4-12.

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Supporting the Design of Competitive Organizations by a Domain-Specific Application Framework for the Viable System Model

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Abstract: Industrial companies face the challenge of a rapidly changing environment and struggle to keep up with the pace needed to be competitive. Organizational deficiencies are often reasons for failure. The Viable System Model (VSM) supports organizational diagnosis and design to ensure viability and avoid deficiencies. The objective of this paper is to further support the application of the VSM in industry. Therefore, we conducted a literature review and analyzed twenty-five VSM case studies in order to derive a common application pattern. The results showed that the main assessment criterion was the existence of all VSM subsystems. However, interrelations within the VSM subsystems are often ignored. This paper presents an extended framework for applying the VSM, emphasizing subsystem relations when diagnosing as well as designing organizational systems. The extension is provided in the form of four Domain-Structure-Matrices, which reveal necessary interrelations and connections for a should-be organizational design.

Keywords: Systems thinking, Viable System Model, Management Cybernetics, Organizational Cybernetics

1 Problem Setting and Motivation

Companies are increasingly challenged by the disruptive character of the digital world and further external trends. Kodak for example was not able to respond to the trend of digital photography, which led to a disaster: it suffered an 80% reduction in labor force, over 100,000 employees (Lucas and Goh, 2009). To prevent such disasters, organizations strive for fast responsiveness to external events and fast internal handling of actions stemming from their response.

Cybernetics, especially Management Cybernetics (MC) targets the organizational responsiveness issue by providing structural as well as procedural approaches and models to support organizational communication and coordination (Wiener, 1948). Concerning the challenge of coping with increasingly dynamic environments, within MC we put the spotlight on the Viable System Model (VSM) (Beer, 1972). The VSM is a generic model of any viable system at a functional level. Viability means the ability to maintain the outcomes of a situation within a target set of desirable states and to balance out disturbances that could lead the system out of this desired state. The VSM helps to diagnose and design organizational structures and processes (Espejo, 2003). Unfortunately, the VSM is not a “plug-and-play” model due to its abstract and holistic perspective on systems. Therefore, translating the VSM into a target domain is still a challenge for practitioners (Hildbrand and Bodhanya, 2015). Hildbrand and Bodhanya (2015) target this issue by providing a guideline for novice VSM users. Nevertheless, there is no support for the translation of the holistic VSM to a domain-specific application.

The paper aims to improve the applicability of the VSM by providing a procedural model for the domain-specific application of the VSM and further extends the model by including four Design Structure Matrices (DSMs). The DSMs enable a quantified analysis of VSM subsystem relations and dependencies to assist with organizational diagnosis and design.

2 Theoretical Background

2.1 Management Cybernetics and the Viable System Model

Cybernetics, the science of communication and control of living and technical systems, forms the theoretical backbone of Management Cybernetics (MC) and further for the VSM (Wiener, 1948). MC applies the concept of feedback loops in control theory to empower organizational management with self-organization and self-control (Schwaninger, 2008). Based on MC, Stafford Beer developed the VSM by applying the concepts of self-regulation, learning, adaptation, and evolution of the human nervous system to organizational design (Beer, 1972; Ríos, 2010). The model respects both the structure and the processes of an organization (Pfiffner, 2010). The VSM is used to design a viable organization or to diagnose an existing one concerning deficiencies (Jackson, 2009).

The VSM consists of five subsystems and relation channels linking the subsystems with each other as well as with the surrounding environment. Jackson (1988) characterized these channels to be either for communication (pure information flow), coordination (of actions of one or more subsystems), control (forced actions), or interaction (acting by changing the state of a subsystem). Figure 1 depicts the entire VSM and its subsystems. Important to note is the recursive character of the VSM: each subsystem contains and consists of viable systems. Viable systems need to consist of all five VSM subsystems and every subsystem needs to consist of viable systems in a recursive manner (Ríos, 2010). The five subsystems of the VSM are:

- System 1 (S1): Operational unit, producing outcome, e.g., goods or services of the organization. It therefore iteratively interacts with the environment and shares information and knowledge with other subsystems.
- System 2 (S2): Regulatory center for S1 units. It provides rules and guidelines for smooth operations and damps oscillations between the S1 units.
- System 3 (S3): Control unit, engaging in resource negotiations with S1 units and executing strategic instructions by controlling operations. In this manner, S3 acts rather supportive than autocratic (Leonard, 2007).
- System 3* (S3*): Auditing unit, supporting S3's control function with periodic audits and additional information on the state of the operational units.
- System 4 (S4): Strategic unit, focusing on strategic planning for the organization by constantly monitoring the potential future environment to anticipate changes. It discusses need for action with S3.

- System 5 (S5): Policy and normative management, defining mission, goals, objectives, values and culture of an organization (Jackson, 2009). It further decides what S3 and S4 cannot agree on.

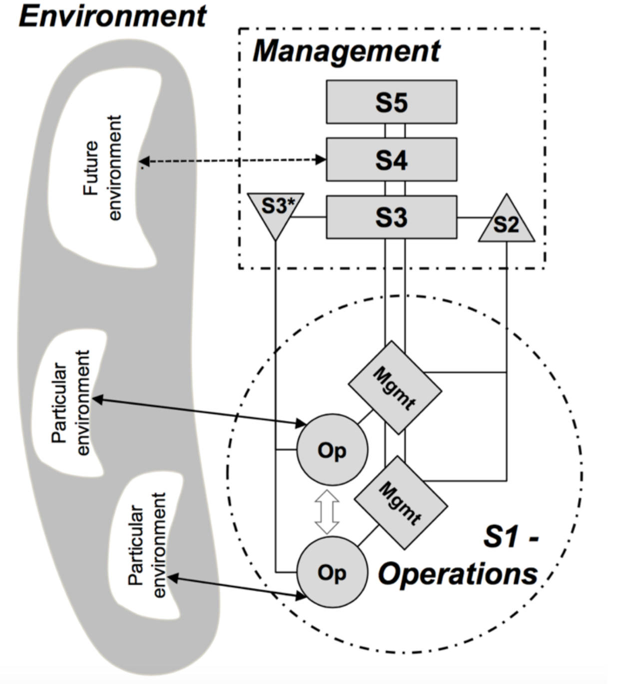

Figure 1. Viable System Model (VSM) adapted from Beer (1972) and Rios (2012)

2.2 Functional Decomposition of the Viable System Model

Practitioners mainly benefit from model descriptions on a functional level, because this is the abstraction level they work on (La Rosa et al., 2011). In order to provide assistance in this regard, Schmidt et al. (2014) propose a function list for all five VSM subsystems, consisting of forty-four functions. Each subsystem includes a set of functions, which are necessary for viability of the entire system. Practitioners can apply this function list to cross-check to find missing functions or in a design setting to implement functions.

2.3 Structural Complexity Management and the Viable System Model

Structural Complexity Management (StCM) uses a matrix-based methodology that captures dependencies in complex systems to make them more transparent and manageable (Lindemann et al., 2008). The methodology consists of matrices that can either link elements of the same domain in a Design Structure Matrix (DSM) or of different domains in a Domain Mapping Matrix (DMM).

Elezi et al. (2013) already tackled the issue of using StCM in combination with the VSM to enhance and support organizational diagnosis and design. The advantage of StCM is that it can help to visualize subsystem relations in structural and procedural problem settings and it allows to deduct insights from it, e.g., related clusters, missing or deficient communications. The matrix approach also supports quantifications of relations, e.g., calculation of passive, active, and critical characteristics (Elezi et al., 2013).

3 Analysis of Case Studies

The purpose of the VSM is to design viable systems or to assess an existing system for structural as well as procedural deficiencies. In order to gain an understanding on how previous literature applied this model to solve various types of problems on an organizational level, we reviewed the literature presenting VSM case studies. The goal was to reveal similarities or implicit patterns in the application of this model, especially concerning the translation of this rather abstract model to an organizational level.

The literature research comprised of a journal, mainly *Kybernetes*, and paper search on ScienceDirect, IEEE Xplore, and Google Scholar online platforms using search terms “Viable system model (VSM) case study, VSM use cases”. The result were twenty-five case studies described the time period of 1993 until 2015. Looking at the number and timing of published research, a constant average of two publications per year concerning VSM case studies appeared from 1993 until 2013. Then the number of publications increased significantly up to four in 2014 and five in 2015. This underlines the statement that the VSM still offers support when it comes to solve organizational issues. Table 1 lists these case studies sorted by purpose of application (diagnosis and/or design) and type of system (structural or procedural).

Table 1. VSM use cases assigned to their problem setting and solution approach

	Problem		**Approach**	
Source	Struct	Proce	Diag	Desig
(Britton and Parker, 1993)	x			x
(Herring, 2002)	x		x	x
(Schwaninger, 2006) Case	x		x	x
(Schwaninger, 2006) Case	x		x	x
(Schwaninger, 2006) Case	x		x	
(Schwaninger, 2006) Case		x	x	x
(Leonard, 2007)	x			x
(Laumann et al., 2007)		x	x	x
(Yang and Yen, 2007)		x		x
(Rakers and Rosenkranz,		x		x
(Wee and Wu, 2009)		x	x	x
(Jun-Feng and Wo-Ye, 2011)		x		x
(Rosenkranz and Holten,	x		x	x
(Khosrowjerdi, 2013)		x		x
(Tanaka, 2013)		x		x
(Brecher et al., 2013)	x			x
(Elezi et al., 2014a)		x		x
(Elezi et al., 2014b)		x	x	x
(Mugurusi and de Boer, 2014)		x		x
(Rahayu and Zulhamdani,	x		x	x
(Wilberg et al., 2015b)		x	x	x

(Groten and Schuh, 2014)	x			x
(Preece et al., 2015)	x		x	
(Mayangsari et al., 2015)	x		x	x
(Wilberg et al., 2015a)		x	x	x

It is important to mention that many structural case studies also had a procedural aspect and vice versa. The focus here is on the primary goal which turned out to be either procedural or structural.

Table 1 shows that most case studies followed a design approach while only a few covered standalone diagnosis of an organizational system. The main purpose of VSM application in real case studies seems targeted towards a new design from scratch or a redesign based on a deficient system. The latter appeared to be the most common case.

4 Model for domain-specific application of the VSM

4.1 Research gap and methodology

All case studies had in common that they did not follow a single guideline in how to translate their domain-specific problem into the VSM domain in order to solve it. All authors interpreted the structure and characteristics of the VSM on their own or proposed a guideline suited to their specific problem or domain. Interestingly, their approaches revealed a common pattern. In addition, many case studies searched for missing subsystems. System diagnosis and design mostly concerned the subsystems and not their interrelations. Inspired by the approaches presented in the case studies, we extracted similarities in the process and formalized them in a framework which is described in the following section. Furthermore, we extended the framework to address the research gap.

4.2 Formalized application pattern from use case analysis

In this section, we first present a common pattern for VSM application: The formulation and further specification of a problem, the framing by the VSM to make the problem accessible to analysis, the development of a domain-specific solution model, and finally the translation of the theoretic solution approach to a real case study. Figure 2 visualizes step 1 to 7 of this pattern on two layers of abstraction as well as a *tool box layer,* which includes additional methodological support.

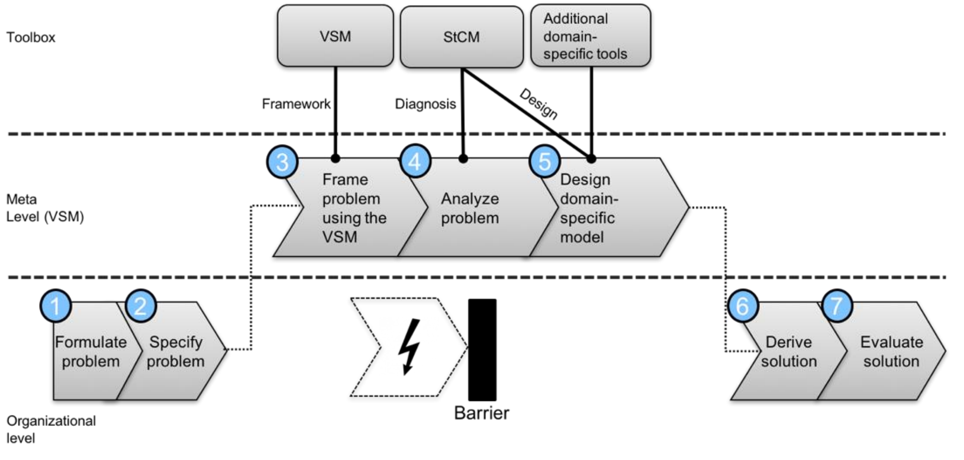

Figure 2. VSM application framework for system diagnosis and design, adapted from Elezi et al. (2014b)

Figure 2 depicts that a problem on an organizational level cannot be solved on the same abstraction level, as was described in detail by Elezi et al. (2014b). Therefore, the goal is to solve it on the meta-model level, because on this level the VSM can provide assistance in solving the problem. Methodological input from the tool box is displayed by dotted arrows. On this level, the VSM, StCM and additional domain-specific tools offer support. The following explains the developed framework step by step:

1. Formulate a problem on organizational level.
2. Specify the problem though a first interpretation of the problem causes.
3. Use the VSM framework to model the problem setting into its structure. Formulate the problem within the VSM meta-model domain.
4. Analyze the problem on a structural and procedural level by checking for incomplete or missing VSM subsystems and relation channels. To check for completeness, use the function list by Schmidt et al. (2014).
5. Create a domain-specific model to solve the problem. Use familiar tools of your domain as input. Here, StCM can guide channel design, as is described later.
6. Formulate a theoretical solution in form of a model or approach.
7. Apply of the model on an organizational level by conducting a case study.

This framework provides step-by-step guidance on how to overcome the challenge of fitting the VSM to a problem on an organizational level. The *Toolbox Layer* provides additional methods and tools to be applied to support various steps of the process. This framework presents a formalized process for VSM application derived from a literature review. Because the analyzed use cases revealed a lack of focus on subsystem relations (most of their analysis concerned the systems themselves) in the following we focus on relations and dependencies of VSM subsystems and augment the presented model by an additional tool to diagnose and design them as well.

4.3 Extending the framework enable diagnosis and design of interlinking channels

StCM enables the reduction of complexity by providing approaches to map structural and procedural relations; doing so proves to be highly compatible to the VSM. In this case, the relations are derived from the function list by Schmidt et al. (2014), because they implicitly formulate the role of each subsystem and its relations to other subsystems. Within the function list, five types of functional relations appear: (1) non-linked channel functions (fulfilled by only one subsystem with no connections to other subsystems), (2) input channel functions, (3) output channel function, (4) bidirectional channel functions, and (5) connecting system functions (connecting the inputs and outputs of two subsystems). Figure 3 depicts these five function types and how they interlink VSM subsystems.

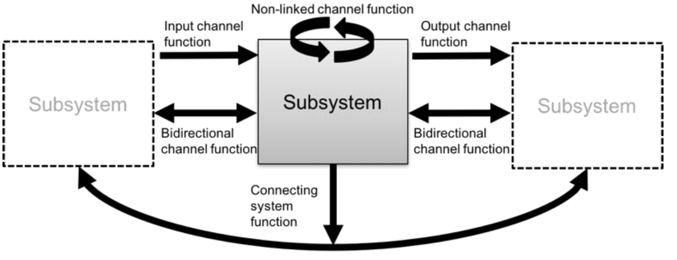

Figure 3. Characterization of different function types within the VSM

An abstract description of subsystem functions is still not very useful for practitioners' intent on analyzing problems on an organizational level. Jackson (1988) revealed the four channel types, which we further interpreted: (1) communication (pure information exchange), (2) coordination (managing the relations of other subsystems), (3) interaction (exchanging more than information and leading to state changes of subsystems), and (4) control (directed forced actions). Having characterized all functions, we mapped them into a DSM, using their assigned number instead of their name. Non-linked channel functions do not appear in the matrix, as they do not form a relation channel.

Communication matrix

	S5	S4	S3	S3*	S2	S1	Env	Active Sum
S5			16					1
S4	4, 10							2
S3	4, 19							2
S3*			14					1
S2			13					1
S1	41		12, 40	26				4
Env		6, 8						2
Passive Sum	5	2	5	1				

Coordination matrix

	S5	S4	S3	S3*	S2	S1	Env	Active Sum
S5			21					1
S4			11, 18					2
S3		11, 18				21,23, 27,43		6
S3*						27		1
S2			33, 34					2
S1			23, 43		33, 34			4
Env								
Passive Sum		2	7		2	5		

Control matrix

	S5	S4	S3	S3*	S2	S1	Env	Active Sum
S5		5	5			42		3
S4			15					1
S3						20, 22, 24, 44		4
S3*								
S2								
S1								
Env								
Passive Sum		1	2			5		

Interaction matrix

	S5	S4	S3	S3*	S2	S1	Env	Active Sum
S5								
S4								
S3								
S3*	28	28	28					3
S2								
S1							35, 36	2
Env						36		1
Passive Sum	1	1	1			1	2	

Figure 4. DSMs mapping function types to channel characteristic

The DSMs show the functional relations and dependencies between all VSM subsystems concerning the four domains (communication, coordination, interaction, and control). The column on the left influences the upper row of the matrix, e.g., function 16 in the *Communication matrix* ("receive goals, values, instructions from S5 and higher recursion levels") indicates how S5 is active in communicating goals, values, and instructions to a passive (receiving) S3. This relation consists only of pure and directed information flow; this is why function 16 was inserted into the *Communication matrix.* After this description of how these four DSMs have been created, the following section details the quantified analysis which is one major feature of a DSM.

<u>Quantified analysis of the DSMs:</u> The sum of functions (inserted by their listing number in the function list, (see VSM function list in Schmidt et al. 2014) in columns is calculated and displayed as *passive sum*, meaning how other functions influence this particular function. In rows, the sum of functions is accordingly calculated in the right column as *active sum*, meaning the influence this function has on other functions. Highlighted are active and passive sums showing a value over 3 (with 7 as the maximum value, this is considered to be a significant high score). For example, within the *Coordination matrix* S3 is highly involved in coordinating activities among higher and lower order subsystems. S1 units are involved in coordination activities. The *Communication matrix* clearly shows S5 passive in receiving and S1 highly active in providing information. Coming back to the framework in Figure 2, these DSMs and their implicit insights aim to assist in diagnosing existing relations between identified VSM subsystems during Step 4, the analysis. In Step 5, the domain-specific model design, the matrices aim to support the detailed understanding of necessary channel relations between specific subsystems in order to create a viable system. This now allows for a quantified analysis of subsystem relations using active and passive sum calculation. This matrix visualization further

enhances a general overview over the VSM and its implicit functional relations. Practitioners can use these matrices to gain an understanding of critical relations between VSM subsystems.

5 Summary and Outlook

The Viable System Model (VSM) is a tool to reveal deficiencies in organizations by providing a description a should-be state for viability. Although useful, there is still no structured approach guiding the general translation of the model to solve a problem on an organizational level. Existing literature shows how the VSM can be used to solve domain-specific problems. The analysis of twenty-five VSM cases studies from literature revealed a common application pattern. All these case studies implicitly used a similar approach from which we derived a model for the domain-specific application of the VSM. Looking deeper into the case studies revealed not only a common application pattern but also a missing consideration of the relations between VSM subsystems. Therefore, we extended the derived framework to target this issue. This extension is derived from an analysis of the VSM function list by Schmidt et al. (2014). We derived four DSMs (communication, coordination, interaction, and control) that enabled a quantified analysis of VSM relation channels. These DSMs can also be used to design an organizational model by offering a should-be perspective for relations in viable systems.

Further research could concern System 3 and its role in the VSM in terms of relations with other subsystems. It is visible in the DSMs how System 3 is highly involved (active and passive) in all four channel types. of its tight interrelation with other subsystems makes it vulnerable for deficiencies. Further work could concern case studies on implementing strategic changes derived from monitoring the external environment based on technology road mapping. Such research may lead to an increased understanding of how to achieve requisite variety in a dynamic environment.

6 References

Beer, S., 1972. Brain of the firm: The Managerial Cybernetics of Organization, Allen Lane the Penguin Press, London.

Brecher, C., Müller, S., Breitbach, T., Lohse, W., 2013. Viable System Model for Manufacturing Execution Systems. Procedia CIRP 7,

Britton, G.A., Parker, J., 1993. An Explication of the Viable System Model for Project Management. Syst. Pract. 6, 21–51.

Elezi, F., Resch, D., Tommelein, I., Bauer, W., Maurer, M., Lindemann, U., 2014a. A Viable System Model Perspective on Variant Management based on a Structural Complexity Management Approach, in: 16th International Dependency and Structure Modelling Conference, DSM 2014.

Elezi, F., Resch, D., Tommelein, I.D., Lindemann, U., 2013. Improving Organizational Design and Diagnosis by Supporting Viable System Model Applications with Structural Complexity Management, in: DSM 2013 - 15th International DSM Conference, Melbourne, Australia.

Elezi, F., Schmidt, M.T., Tommelein, I.D., Lindemann, U., 2014b. Analyzing Implementation of Lean Production Control with the Viable System Model 1–5, 2014 IEEE International Conference on Industrial Engineering and Engineering Management, 443-447.

Espejo, R., 2003. The Viable System Model: A briefing about organizational structure. Syst. Pract. 3, 219–221.

Groten, M., Schuh, G., 2014. Design and simulation of a logistics distribution network applying the viable system model (VSM), 16th International Congress on Systems and Cybernetics.

Herring, C.E., 2002. Viable software: The Intelligent control paradigm for adaptable and adaptive architecture. Electr. Eng. 343.
Hildbrand, S., Bodhanya, S., 2015. Guidance on applying the viable system model, Kybernetes vol. 44, Iss. 2, pp. 186-201.
Jackson, M., 2009. Systems Approaches to Management. Springer.
Jackson, M., 1988. An Appreciation of Stafford Beer's "Viable System" Viewpoint on managerial practice. J. Manag. Stud. 25.
Jun-Feng, S., Wo-Ye, L., 2011. Design of Equipment Procurement Project Organization Based on Viable Systems Model. Procedia Eng. 24, 809–815. doi:10.1016/j.proeng.2011.11.2742
Khosrowjerdi, M., 2013. Designing a viable scientific communication model: VSM approach. Libr. Hi Tech, vol. 29, iss. 2, pp. 359-372.
La Rosa, M., Wohed, P., Mendling, J., ter Hofstede, A.H.M., Reijers, H.A., van der Aalst, W.M.P., 2011. Managing Process Model Complexity Via Abstract Syntax Modifications. IEEE Trans. Ind. Informatics 7, 614–629. doi:10.1109/TII.2011.2166795
Laumann, M., Rosenkranz, C., Kolbe, H., 2007. Diagnosing and Redesigning a Health(y) Organization - An Avarto (Bertelsmann) Action Research Study. Proc. Fifteenth Eur. Conf. Inf. Syst. 1990–2001.
Leonard, A., 2007. Symbiosis and the viable system model, Kybernetes, vol. 36, iss. 5/6, pp. 571-582.
Lindemann, U., Maurer, M., Braun, T., 2008. Structural Complexity Management: An Approach for the Field of Product Design (Google eBook). Springer.
Lucas, H.C., Goh, J.M., 2009. Disruptive technology: How Kodak missed the digital photography revolution. J. Strateg. Inf. Syst. 18, 46–55. doi:10.1016/j.jsis.2009.01.002
Mayangsari, L., Novani, S., Hermawan, P., 2015. Batik Solo Industrial Cluster Analysis as Entrepreneurial System: A Viable Co-creation Model Perspective. Procedia - Soc. Behav. Sci. 169, 281–288. doi:10.1016/j.sbspro.2015.01.311
Mugurusi, G., de Boer, L., 2014. Conceptualising the production offshoring organisation using the viable systems model (VSM). Strateg. Outsourcing An Int. J. 7, 275–298. doi:10.1108/SO-10-2014-0026
Pfiffner, M., 2010. Five experiences with the viable system model. Kybernetes 39, 1615–1626. doi:10.1108/03684921011081196
Preece, G., Shaw, D., Hayashi, H., 2015. Application of the Viable System Model to analyse communications structures: A case study of disaster response in Japan. Eur. J. Oper. Res. 243, 312–322. doi:10.1016/j.ejor.2014.11.026
Rahayu, S., Zulhamdani, M., 2014. Understanding Local Innovation System as an Intelligent Organism Using the Viable System Model Case Study of Palm Oil Industry in North Sumatra Province. Procedia - Soc. Behav. Sci. 115, 68–78. doi:10.1016/j.sbspro.2014.02.416
Rakers, M., Rosenkranz, C., 2008. Organizational impact on project management in financial data warehousing: a case study, European Conference on Information Systems (ECIS), 1-13.
Rios, J.P., 2012. Design and Diagnosis for Sustainable Organizations. Springer.
Ríos, J.P., 2010. Models of organizational cybernetics for diagnosis and design. Kybernetes 39, 1529–1550.
Rosenkranz, C., Holten, R., 2011. The variety engineering method: analyzing and designing information flows in organizations. Inf. Syst. E-bus. Manag. 9, 11–49.
Schmidt, M.T., Elezi, F., Tommelein, I.D., Berghede, K., Lindemann, U., 2014. Supporting Organizational Design Towards Lean with the Viable System Model. Proc. 22nd Annu. Conf. Int. Gr. Lean Constr. 1, 73–83.
Schwaninger, M., 2008. Intelligent Organizations Powerful Models for Systematic Management. Springer.
Schwaninger, M., 2006. Design for viable organizations. Kybernetes, 35, 955–966.

Tanaka, H., 2013. A Viable System Model Reinforced by Meta Program Management. Procedia - Soc. Behav. Sci. 74, 377–387.

Wee, H.M., Wu, S., 2009. Lean supply chain and its effect on product cost and quality: a case study on Ford Motor Company. Supply Chain Manag. An Int. J. 14, 335–341.

Wiener, N., 1948. Cybernetics: Control and communication in the animal and the machine. MIT Press.

Wilberg, J., Elezi, F., Tommelein, I., Lindemann, U., 2015a. Supporting the Implementation of Engineering Change Management with the Viable System Model, IEEE International Conference on Systems, Man, and Cybernetics (SMC 2015), 731-736.

Wilberg, J., Elezi, F., Tommelein, I.D., Lindemann, U., 2015b. Using a Systemic Perspective to Support Engineering Change Management. Procedia Comput. Sci. 61, 287–292. doi:10.1016/j.procs.2015.09.217

Yang, C., Yen, H., 2007. A viable systems perspective to knowledge management. Kybernetes, vol. 36, iss. 5/6, pp. 636-651.

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Part III

DSM Application and Case Studies

18th INTERNATIONAL DEPENDENCY AND STRUCTURE MODELING CONFERENCE, DSM 2016

SÃO PAULO, BRAZIL, AUGUST 29 - 30, 2016

A Case Study in the Application of Design Structure Matrix for Improvement of Policy Formulation in Complex Industrial Wastewater Treatment

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Abstract: Designing effective and acceptable policy is a non-trivial task for decision makers and stakeholders. Especially, policy formulation related to environmental management is still a serious challenge. It requires development of new tools to support better understanding of the complexities involved in addressing problems and finding the best solutions. We believe that using a systematic approach to design public policies helps to model the structure of complex policies, which can drive the whole system structure of organization management towards sustainability. A case study in policy formulation and analysis related to a large industrial wastewater treatment plant in Brazil is presented. The results obtained from the morphological analysis are used in the formulation of policy alternatives through the application of design structure matrix. The results have the potential to further promote the use of modeling tools in the formulation of policies for improvement of policy performance and effectiveness for different areas.

Keywords: policy design, public formulation, design structure matrix, complex systems, sustainability

1 Introduction

The increased complexity of our socio-technical systems confronts us with increasingly difficult policy design problems that are not easily solved (Flüeler, 2006). In modern organizations and enterprises, people must work together and face the need to solve problems and upgrade environmental public policy design (Steward, 2003; Birkland, 2005). These types of problems are rather complex, involving a large amount of tasks and multidisciplinary fields (Eppinger and Browning, 2012), e.g. engineering, architecture, planning and operation management, with internal communications and numerous possible measures (Steward, 2015). One of the major challenges in organizational problem complexes is considered to be sustainable policy design and upgrading policy measures, (Birkland, 2005) which includes for example knowledge designers, planners and policy makers who work with complex tasks (Browning, 2001). It requires development of new tools and modeling to support better understanding of the complexities involved in addressing problems and to find the best solution. Modeling has always been an essential part of organizational design as well as information systems development. Models enable decision makers to filter out the complexity of the real world, so that efforts can be directed towards the analysis of the most important parts of the system. Moreover, in recent years there has been a growing interest in designing environmental public policy, which demonstrates a framework for linking policy design with sustainable development within an organization. This motivates this study to develop a systematic approach that helps to improve the entire system structure of a complex organization.

Within the specific context of this study, the problem is to propose and establish a systematic approach enabling the formulation, design and improvement of wastewater treatment (WWT) public policies for modern enterprises. As both complex systems and environmental policy problems are emerging research areas, still a need exists for research on development of a new integrative approach for designing sustainable environmental public policies for modern enterprises.

The design and development of complex engineering processes, methods and tools requires the expertise of many participants from different backgrounds, leading to the efforts and cooperation of the complex relationship between people and tasks (Yassine, 2004). We believe that by introducing a systematic approach for exploring, designing and improving the alternative policies using a computational methodology that integrates diverse modeling techniques such as: morphological analysis (MA), design structure matrix (DSM), network analysis (NA) and business process modeling and notation (BPMN), we can: (1) Better understand the problem structuring and decomposing into sub problems, (2) Improve analysis and optimization of the process of environmental policy formulation, (3) Decrease the required time for problem analysis.

A case study devoted to policy formulation and analysis related to a large industrial wastewater treatment plant (WWTP) in Brazil is presented. The case study considers the design, procurement, construction and operation of an industrial WWTP. The approach is based on the previously proposed integrative modeling methods, in a way that the integrated approach supports complex problem solving of public policies in WWTP (Buzuku at al., 2015). The research is focused in the application on industrial WWT systems as they are classified as complex systems (Buzuku at al., 2015). An analysis of policy measures for development of policies is carried out based on their internal connection and interconnections as well as their relations/interactions with other policy measures. The optimal combination of policy measures derived from MA is fed into DSM that formulates policy alternatives (clusters) for analyzing the process flow of the dependencies/variables. Thus, a set of policy measures, or cluster, is modeled in BPMN to formalize the description of the integration processes (still under development). The final decision on which policy to implement will remain a crucial task for the decision makers and analysts. From an implementation point of view, the decision makers will decide whether if they may include additional policies or remove some of the recommended ones. We expect the results will further promote the use of modeling methods for policy formulation in different sectors (energy, environment, healthcare, food, water, etc.) that can be systematically employed for decision support systems (DSS). This facilitates modeling procedures in problem solving of complex systems such as those found in environmental policy management.

The document is organized as follows: The background information on policy design is briefly discussed in Section 2. Methodology is explained in section 3. In Section 4 we introduce the proposed approach. The results achieved in the development of the system with an illustrative example are described in Section 5 followed by the conclusions and future work in Section 6.

2 Background on Policy Design

Firstly, it is useful to define the terms policy formulation, policy design and policy tools. A policy is a principle or guideline for action in a specific context (Pohl, 2008), and policy design is the task in which the components of a policy are selected and the overall policy is formulated. The term policy formulation is the development of effective and acceptable courses of action to address items on the policy agenda (Birkland, T., 2005). Within environmental management studies, environmental policies have traditionally been defined as policies, which support the successful introduction of sustainability. Several authors have discussed system engineering approaches and tools connected to policy design and proposed them to solve environmental problems in the early stage of conceptual design. Many of traditional approaches such as Cost-benefit analysis (CBA) techniques and Multi-criteria decision analysis (MCDA) techniques are commonly used in the policy domain (Taeihagh et al., 2014). For example, some aspects of a policy are modeled mathematically. However, decisions about the desirable future also involve social values and political influence (Robinson et al., 2006). We believe that traditional approaches to policy-making is not well suited for solving the 21st century's complex problems. Therefore, further research and development is required. A methodology that supports the identification, design, modeling and evaluation of public policies to tackle complex problems is still missing. This is because existing methodologies and frameworks are not fully developed to deal with the complexity of policy formulation in organizations. A review of existing traditional methodologies shows drawbacks when applied for public policy design of sustainable development in organizations. Therefore, different approaches and tools will have to be used in order to take into account these differences and limitations while introducing avenues for their integration based on the concept of designing public policies (see Buzuku et al., 2015 for further motivations). This paper proposes to systematically apply and combine MA, DSM and BPMN to better facilitate modeling processes in problem solving of complex systems and DSS.

3 Methodology

The methodology consists of proposing an integrative framework for designing a public policy that helps to improve the policy effectiveness, as well as the whole system structure for sustainable management in organizations. The method is based on the organization of policy design in engineering companies exploring and observing legal, technical, financial, social and environmental dimensions from a life cycle perspective.

In this paper a new methodology is proposed by incorporating two or more existing modeling methods in order to encompass all properties and impacts of complex systems. This combines analytical models (i.e. MA, DSM and BPMN) to understand how complex systems operate, model a complex system, how well systems meet overall goals and objectives and how they can be improved (William & Nicoleta, 2014) in order to find the best solution. Therefore, the adapted methodology is depicted in Figure 1, which consists of: Step 1. Policy formulation, Step 2. Design modeling methods and tools, and Step 3. Process of evaluation and validation. This systematic approach enables modeling complex systems that involve a large number of stakeholders and many possible measures connected by multiple domains. Using advanced computer techniques, it is possible to solve very complex computational problems in a large-scale hierarchical model for DSS.

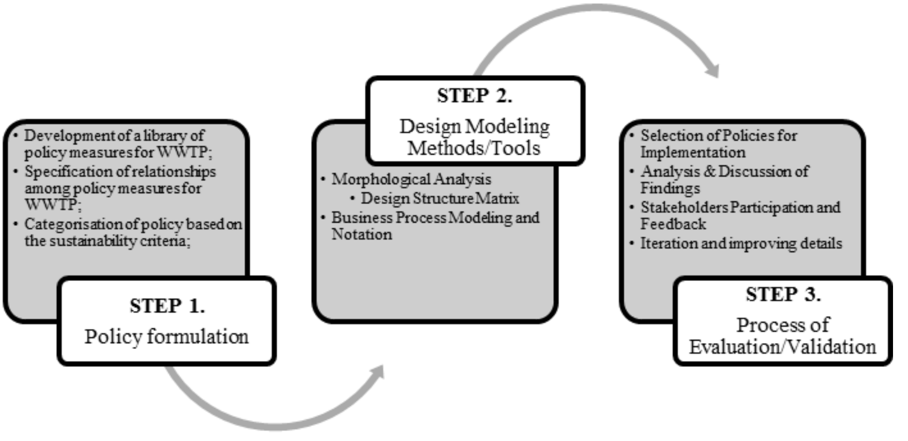

Figure 1. Steps for development a systematic approach for design and improvement of public policy

STEP 1: Many policy measures have been developed to address the multiple environmental externalities of WWT management. The first step of the methodology is to define the scope of the project. The development of policy measures is created in several steps and it is based on sustainability criteria. These steps are: (1) Development of a library of policy measures for WWTP; (2) Definition and specification of relationships among policy measures for WWTP; and (3) Categorization and analysis of the policy-measures based on the sustainability criteria.

STEP 2: A framework to facilitate the policy formulation leading to the effective achievement of its objectives has been proposed and a software system is being implemented using this framework with the purpose of usability for different policy design areas.

1. Morphological Analysis – has been widely used as a general method for formulating, structuring and studying complex problems (Zwicky, 1969). The MA technique is a decomposition method that breaks down a system into subsystems with several attributes and selects the most valuable alternative (Yoon and Park, 2007). MA has been used in many fields: jet and rocket propulsion systems (Zwicky, 1969), computer-aided design modeling (Belaziz et al., 2000), language modeling (Huckvale and Fang, 2002), mathematical modeling (Arciszewski, 1987), technology forecasting (Wills, 1971) and policy formulation (Buzuku and Kraslawski, 2015). In all these domains MA has been a powerful tool for linking and evaluating possible combinations of the variables in the given problem and for establishing an internal structure, based on iterative cycles of analysis and synthesis in a systematic manner.

2. Design Structure Matrix – DSM has been widely used in several contexts, especially in product/project decomposition, and it is considered a consolidated approach to

manage complexity (Browning, 2001). The DSM representation was originally developed by Steward (1981a, 1981b) for the analysis of parametric description of designs (Ulrich and Eppinger, 1995). According to Eppinger and Browning (2012) the diagonal cells represent system elements and off-diagonal cells are used to record relationships among them. The basic procedure of system design using the DSM approach was developed by Eppinger and Browning (2012). Moreover, DSM has been a powerful tool that aids business analysis through visualizing, analyzing, innovating and improving systems including product architectures, organizational structures and process flow (Eppinger and Browning, 2012).

STEP 3: Process of Evaluation and Validation. Selection of policies for implementation, analysis and discussion of findings, stakeholder participation, feedback, iteration and improving details.

4 Proposed approach

This section examines the overall process, giving a brief explanation of each stage at the same time. The proposed approach for managing complexity of environmental policy formulation for industrial wastewater management is shown in Figure 2. It consists of three stages: (i) Policy measure derivation with MA, and (ii) Reorganizing and improving the policy measures in DSM and (iii) application of UML language of policy implementation process.

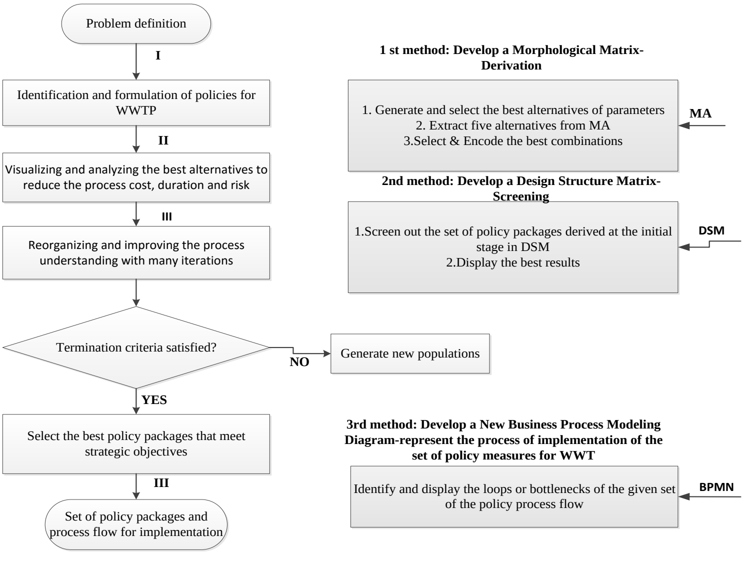

Figure 2. Overall process of using design modeling methods for policy formulation

5 An illustrative example

This section shows the effectiveness of our proposed approach by an illustrative example. Here, a case study related of a large industrial pulp and paper mill for building, construction and operation of a WWTP is presented to show the proposed approach.

5.1 Policy measures derivation with MA

The first stage of MA was conducted with the participation of a panel of domain experts in a two-day workshop that resulted in a policy measure reduction model, which allowed modelers to compare different policy options in terms of sustainability planning and implementation. Figure 3 shows the development of the morphological field with five parameters and their range of values. The problem field includes legal, financial, technical, social and environmental variables. Referring to the above classification, it follows that the morphological field potentially contains a total of 2250 (6x5x5x3x5) distinguishable configurations, which are designated by the matrices [P1V1…6; P2V1…5; P3V1…5; P4V1…3; and P5V1...6;], where all V(s) may be assumed as taking the specific values 1, 2, 3, 4, 5 and 6. In this case, there are clearly too many combinations to enable a reasonable choice. We select P1V1 as independent variable because it shows high potential priority for WWTP according environmental experts judgments. For instance, if P1V1 Environmental Law Conama 20 is selected as an independent variable marked with red, we gain the two sets of results marked in blue as are: P1V1 = P2V1, P3V1, P4V1, P5V1 and P1V1 = P2V1, P3V1, P4V1, P5V3, which is considered to be the best solution of policy measures to create a policy package.

Parameters / Values	P1 Implement Legislation	P2 Water/Effluent Quality	P3 Effluent treatment plant	P4 Capacity building	P5 Monitoring
V1	Conama 20 Requirements – Brazilian Environmental Law	Temperature = 40°C, Settleable solids = 1 ml/1 L	Cooling towers	Training for safety measures in the working place (for all)	River water (Authorities)
V2	EU- BAT Bref (2001)	COD = 8 – 23 kg/ADt, AOX< 0.25 kg/ADt	Oxygen delignification, ECF bleaching	Training for general environmental aspects (for workers at various departments)	Untreated effluent quality
V3	World Bank/IFC EHS Guidelines	Temperature increase no more than 3°C at mixing zone	Extended aeration	Training for operators of the Effluent treatment plant	Treated effluent quality
V4	Parana River Water Quality Requirements (Class II)	DO = 5 mg/l, minimum Turbidity 100 NTU, Maximum	Collecting, control, recycling used clean waters		Groundwater (especially in the surroundings of big tanks)
V5	Water footprint	Separation of uncontaminated and contaminated storm waters	Storage lagoons		Groundwater (especially in the surroundings of big tanks)
V6	Storm water control				Outlet of storm water lagoons

Figure 3. Development of the morphological field with five parameters and their ranges of values

5.2 Input Data

The 25 policy measures identified in the case study of the WWTP project are used to build the DSM matrix. Firstly, the policies are represented and mapped on a 25 x 25 square DSM model (Figure 4), where these policies are listed on the left side of the DSM. Secondly, input and information dependencies between each of the identified policy measures were defined. Three dependency levels between policy measures were identified: low, medium and high according to Yassine et al. (1999). Based on the policy measure dependencies, a DSM graph structure was build and analyzed. Next step, an analysis of the created DSM and optimization of the policy sequence through partitioning and tearing of dependencies within iteration blocks was performed. The screening mechanism was constructed and implemented using ProjectDSM v2.0 project planning software (www.projectdsm.com).

5.3 Analysis and visualization of the policy measures using DSM

Once the appropriate policy measures that comprise a project have been identified based on expert's interviews, they are listed in the DSM as row and column symmetrically. The policy measures relationships within DSM are identified by asking the appropriate group of experts and planners for input, information and dependencies between each of the identified policy measures. The results from the DSM are the formulated policy partitioning and tearing, which in turn are used for the future work on development of business process diagrams. The second stage consists on visualization and analysis of the best alternatives in order to estimate and reduce the process costs, duration time, risk (high, medium, low) and effort (days). The information on cost estimation analysis is still underway and the final results of this step cannot be published yet. Below, each block is visualized separately and independently from the others, which places the most connected elements in the matrix. Figure 4 visualizes the potential partitioning policy process in the matrix. It provides the graphic information on combinations of measures that should be avoided, or at least be considered carefully before implementation.

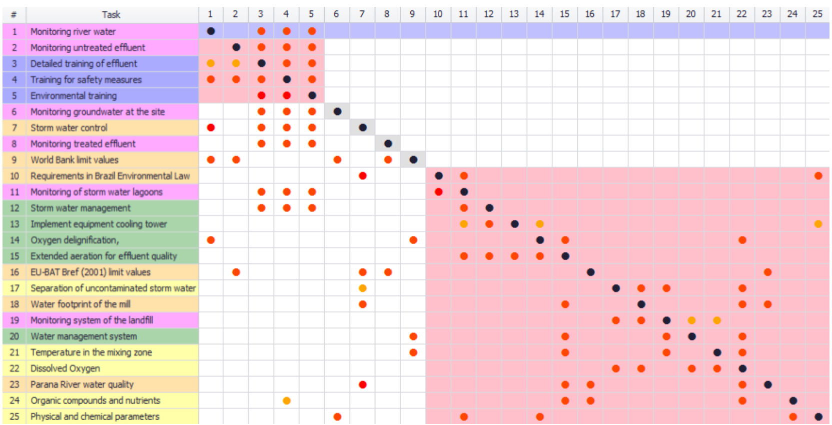

Figure 4. WWTP policy formulation process DSM after partitioning

5.4 Reorganizing, screening and improving of the policy measures in DSM

The last stage consists of the reorganizing, screening and improving of policy process understanding via diverse iterations. A two-day workshop is organized with the participation of panel experts of diverse background and specialization from the project to rate the sets of policy measures with respect to the screening and derive suggestions for improvements of the policy measures for environmental policy formulation. Although numerous criteria have been proposed to screen out or evaluate the policy measures and packages (Givoni, 2014; Taeihagh et al., 2014; Justen et al., 2014), details for a policy package have rarely been revealed with DSM. For this reason, the most critical factors to be considered were identified and analyzed for further improvements in the presence of domain specialists and expert managers involved in the project, who found the defining the process and its sequence of policy was valuable. Figure 5 visualizes the potential simplification of the largest coupled block into two smaller blocks achieved by tearing, which is much more complex. The results were validated in the presence of the panel of environmental experts, engineers and managers that were interviewed. As an example, the 'Requirements in Brazilian Environmental Law' row (10) in the first row of the biggest coupled block is in potential contradiction with four other policy measures in columns (20, 21 and 24, 25) in the inventory, taking the top position from both methods in MA as well as in DSM. This shows the highest priority among the other policies in MA and it is found to be unplanned iterations in the DSM model. In the discussion with experts and managers, the focus was directed to policy row (10) for reorganizing and improving the process flow of policies. However, this process highlighted some unexpected planned and unplanned iterations, and we embarked on addressing each of the unplanned iterations revealed in the DSM model.

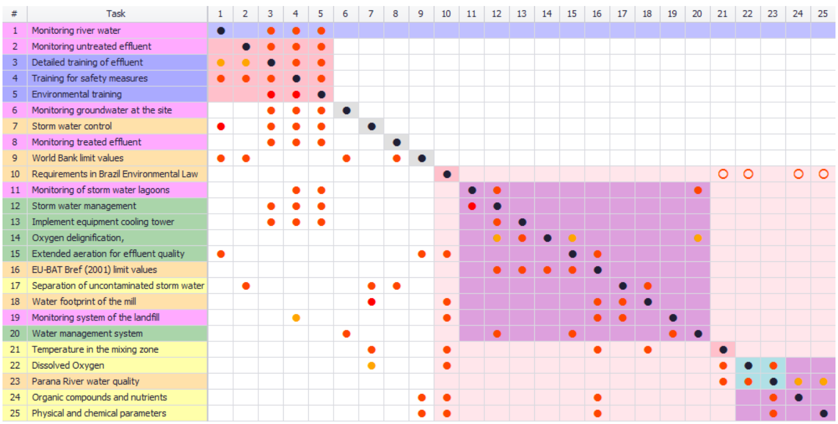

Figure 5. Simplification of the second largest coupled block was achieved by tearing two dependencies

6 Conclusions and Future Work

We proposed a new systematic approach for generation and improvement of policy formulation process in WWTP, which consisted of two stages: the possible combinations of policy measure derivation with MA and policy measure screening and improving in DSM. The MA has been used to structure and assess possible policy alternatives. Next, the obtained results have been applied in formulation of policy alternatives using DSM. The proposed approach can be effectively and efficiently used for managing complexity of environmental policy formulation for industrial WWT management. The results proved the usefulness of the approach in a real case study. A set of policy measures were derived at the first stage by exploring all possible combinations of the morphology matrix, and the second stage dealt with reorganizing, screening and improving the policy process understanding with many iterations. The effectiveness of this systematic approach was demonstrated by an illustrative example. The obtained results show the possibility of use of MA and DSM in formulation of policies applicable to management of complex systems. The result shows the potential of applying DSM to significantly improve the development of policy alternatives, accelerate the design of policies and improve the entire system's policy structure for sustainable management in organizations. As a future work we plan to enhance the generation and evaluation procedures and further improve the process implementation using BPM via BPMN (as well as input data to the MA and DSM).

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References

Arciszewski, T. T., 1987. Mathematical modeling of morphological analysis. Mathematical Modeling 8, 52-56

Birkland, T., 2005. An Introduction to the Policy Process: Theories, Concepts and Models of Public Policy Making, 2nd edn (London: M. E. Sharpe).

Browning, Tyson R., 2001. Applying the design structure matrix to system decomposition and integration problems: A review and new directions. IEEE Transactions on Engineering Management 48 (3), 292-306.

Buzuku, Sh., Kraslawski, A., 2015. Application of morphological analysis to policy formulation for wastewater treatment. Proceedings of the Mining Institute, 214: 102-108.

Buzuku, Sh., Kraslawski, A., Harmaa, K., 2015. Supplementing morphological analysis with a design structure matrix for policy formulation in a wastewater treatment plant in: Modeling and Managing Complex Systems. Proceedings of the 17th International DSM Conference Fort Worth, Texas, USA, 4-6 November.

Eppinger, S. D., Browning, T. R., 2012. Design Structure Matrix Methods and Applications. The MIT Press, Cambridge, MA.

Flüeler, Thomas. 2006. Decision Making for Complex Socio-Technical Systems: Robustness from Lessons Learned in Long-Term Radioactive Waste Governance, Springer.

Givoni, M., 2014. Addressing transport policy challenges through policy packaging. Transportation Research Part A 60, 1-8.

Huckvale, M., Fang, A. C., 2002. Using philologically constrained morphological analysis in continuous speech recognition. Computer Speech and Language, 16 (2), 165-181.

Justen, A., Fearnley, N., Givoni, M., Macmillen, J., 2014. A process for designing policy packaging: Ideals and realities. Transportation Research Part A 60, 9-18.

Pohl, C., 2008. From science to policy through transdisciplinary research. Environmental Science and Policy, 11 (1), p.46-53.

Robinson, J., Bradley, M., Busby, P., Connor, D., Murray, A., Sampson, B., Soper, W., 2006. Climate change and sustainable development: Realizing the opportunity. Ambio, 35(1), p. 2-8.

Steward, Donald V. (1981a) "The Design Structure System: A Method for Managing the Design of Complex Systems" in IEEE transactions on Engineering Management Vol. EM-28, Number 3, August 1981.

Steward, Donald V. (1981b) Systems Analysis and Management: Structure, Strategy and Design, (Petrocelli Books, Inc., now McGraw-Hill).

Steward, Donald V. 2003. It's all about problem solving. In: Proceedings of the 5th International Design Structure Matrix (DSM) Workshop, Cambridge, UK, October 22-23.

Steward, D.V., 2015. DSM foundations and applications, and an update on the explainer. Proceedings of the 17th International DSM Conference Fort Worth, Texas, USA, 4-6 November.

Taeihagh, A., Bañares-Alcántara, R., Givoni, M., 2014. A virtual environment for the formulation of policy packages. Transportation Research Part A 60, 53-68.

Ulrich, K.T., & Eppinger, S.D. 1995. Product Design and Development, Second Ed. New York: McGraw-Hill,

Yassine, A., D. Falkenburg, and K. Chelst. 1999, September. Engineering Design Management: An Information Structure Approach. International Journal of Production 37 (13): 2957-2975.

Yassine, A., 2004. An introduction to modeling and analyzing complex product development processes using the design structure matrix (DSM) method. Urbana 51. 9: 1-17.

Yoon, B., Park, Y., 2007. Development of a new technology-forecasting algorithm: Hybrid approach for morphology analysis and conjoint analysis of patent information. IEEE Transaction on Engineering Management 54 (3), p. 588-599.

William B. R., Nicoleta, S., 2014. Understanding and Managing the Complexity of Healthcare (Engineering Systems) 1st Edition. The MIT Press, Cambridge, Massachusetts, London, England.

Wills, G. 1971. Technological Forecasting. Pelican Books, U.K.

Zwicky, F., 1969. Discovery, Invention, Research – Through the Morphological Approach. The Macmillan Company: Toronto.

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Application of DSM for Integrating Modern Technology into Operational Architecture of Aerial Firefighting

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Abstract: Aerial firefighting plays an integral role in containing wildfires, which have been growing rapidly in frequency and intensity over the past decades. However, the current aerial-resource management models were developed decades ago, based on the technology available then. This research aims to investigate how and what modern technologies can be integrated into aerial firefighting operation to help it keep up with the worsening situation. DSM has been used as an engineering tool to decompose the complex problem space into separate manageable segments. Using a task-based DSM, the interdependencies which give rise to unnecessary complexities are visualized, and the potential to integrate new technologies in resolving these complexities is discussed. Finally, unmanning the airtanker and "co-placing" the airtanker-pilot and the Incident-Commander is proposed as a new operational concept. The new arrangement will provide the Incident-Commander with time critical situational awareness, speed up the operation, and eliminate the risk of pilot fatality.

Keywords: Aerial firefighting, airtanker, operational architecture, modern technology, DSM

1 Introduction

Wildland fire burns millions of acres of United States forests annually (USFS, 2012), and costs above a billion dollars to suppress (USFS, 2015). In comparison to 1970s, fire seasons are 78 days longer, burn more than twice the area, and cost considerably more (USFS, 2012).

According to the National Interagency Aviation Council (NIAC, 2009), a 1% decrease in the success rate of "initial attack" (the first response to a fire incident), leads to a 200 million dollar increase in the overall cost of fire suppression. The primary assets in the initial attack are airtankers (aircrafts carrying water or chemical retardants), since they enable a fast response with large payload capacity. Studies have shown that the success rate of the operation of airtankers in initial attack depends primarily on the speed of the operation (Calkin et al., 2014).

On the other hand, a field survey on 135 firefighting experts (USDA, 1998) demonstrated that 108 out of 135 experts believe that the most important problem of aerial firefighting lies in the category of "Operations and Management", and 94 experts added "Communications" to the list. Also, the National Interagency Aviation Council (NIAC, 2009) stated that the current fire operation management models were developed decades ago, based on the technology available at that time, and "in a much different and more benign atmosphere" than what is faced today. The council called for an investigation on the possibility of enhancing the aerial resource management model by integrating modern technology and new methods (NIAC, 2009).

An unpleasant symptom of the current aerial firefighting system is its high fatality rate. The complicated maneuvers in the often turbulent, smoky and congested fire environment (NIAC, 2009), accompanied with excessively high stress levels experienced by airtanker pilots (Melton et al., 1968), have made aerial firefighting a dangerous career. According to the National Transportation Safety Board (NTSB), in the 1955 to 1999 period, 250 airborne firefighting personnel have lost their lives (NTSB, 2016). Accident investigation data in a 20 year period shows that in 74.5% of the aviation related accidents, “human error” was the primary cause (USDA, 1998). To the contrary of what one might expect, the increased aviation safety of the 21st century did not decrease the trend of aerial firefighting casualties; and 82 more airborne personnel passed away in the 2000-2015 period (Butler, 2015) (NTSB, 2016).

This paper aims to investigate the operational architecture of aerial firefighting; and propose how and what new technologies can be introduced in the mission to improve its speed, effectiveness, and safety. Dependency Structure Matrix (DSM) is an effective tool in visualizing the complexities and interdependencies of a process architecture (Eppinger and Browning, 2012). A binary task-based DSM will be used in this research to provide a system view on the aerial firefighting operational architecture. The focus of the DSM model will be on detecting the unnecessary interdependencies among tasks that can increase the operation time, reduce its effectiveness, and increase the risk of human error; and to investigate how modern technology can aid in resolving the detected complexities.

2 DSM Modeling

The data used to develop the DSM model is extracted from “Interagency Aerial Supervision Guide” (NIAC, 2008), and the “National study of tactical aerial resource management to support initial attack and large fire suppression” (USDA, 1998). In these Studies, the activities and the flow of information among parties present at a typical wildfire fighting mission is described. Additional information regarding the tasks of airtanker pilots were obtained from direct contact with firefighting experts and pilots.

A task-based binary DSM has been used in this research to model a typical initial attack operation. The inputs are put in rows and feedbacks above diagonals (Eppinger and Browning, 2012). Figure 1 shows the task-based DSM model of the operational architecture. The roles involved in this mission are introduced in Table 1 along with the abbreviations used in naming their tasks. Each task includes the sender and receiver of the information, respectively at the beginning and end of its name.

Table 1. Roles and Abbreviations

Role	Abbreviation
Air Tactical Group Supervisor	ATGS
Incident Commander	IC
Leadplane Pilot	LP

Airtanker Pilot	Pilot
Ground Firefighting Crew	GC
Dispatch staff	Disp

The "Project DSM" software version 2.0.1 was used to sequence the original task-based DSM. As it can be seen in Figure 1, the process can be divided into four segments: 1) Developing Tactics and making decisions, 2) Relaying the decisions to the airtanker pilot, 3) Performing the cooperative drop maneuver, and 4) Evaluation and adjustments. The DSM model shows that the first three segments are the major contributors of complexity in the operation. The colored blocks represent the interrelated tasks.

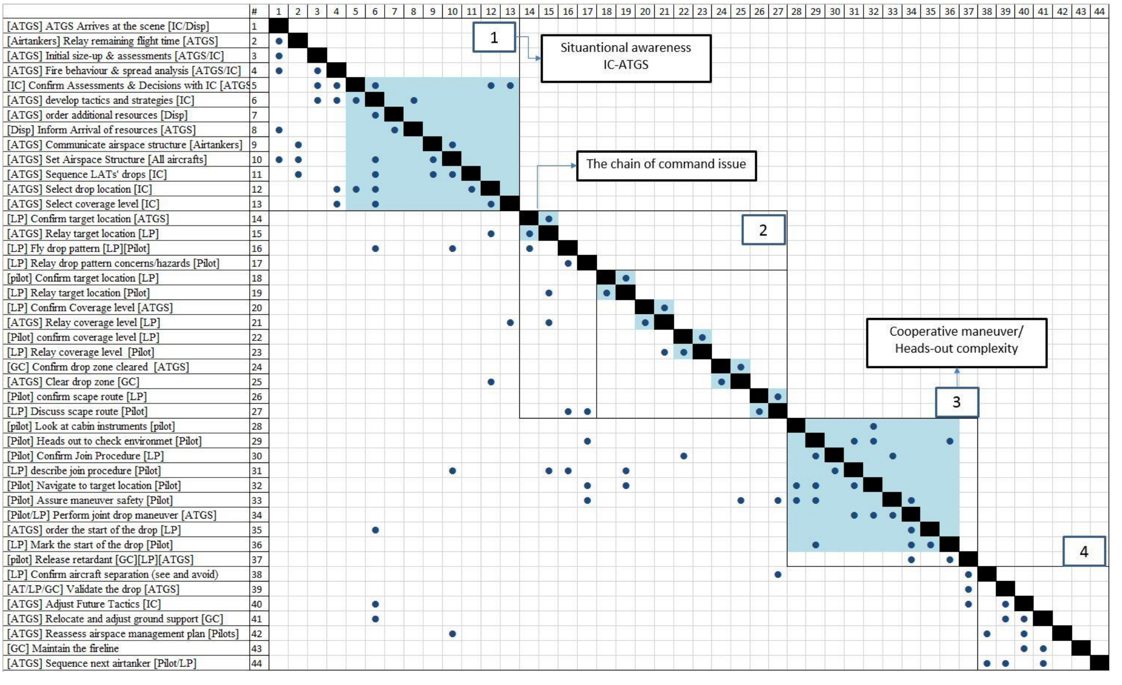

Figure 1. Task-based DSM of a typical firefighting operation

However, not every interrelation and complexity is undesirable in a process (Eppinger et al., 2013). Sometimes interrelations are necessary to achieve higher accuracy or effectiveness (Browning, 1998). Nonetheless, in the case of an outdated management model, equipped with outdated technology, it may happen that the existing complexities are unnecessary; Which means they can be resolved via integration of modern technology, while keeping at least the same level of accuracy and effectiveness. These supposedly “unnecessary complexities” are investigated in each segment of the operation, with more detail, to see how modern technology can be helpful in resolving them.

2.1 Developing tactics and making decisions

After the Aerial Supervisor (ATGS) arrives at the scene, he establishes contact with the ground crew and aerial resources, performs size-up, assesses the environment and risks, analyses fire behavior and spread pattern, and receives updates of incoming resources from the dispatch center. Then he should relay all the “situational awareness” information to the Incident Commander through voice communication. Verbal description of the quickly-changing and hostile environment of the fire incident, not only takes precious minutes, but also interferes with the ATGS’s other roles, as he has to constantly keep track of ground resources and set and manage the air-traffic. As it can be seen in Figure 2, this phase of the operation exhibits task-complexity, mainly because IC needs situational awareness to confirm tactics and strategies, but he is not present at the scene; and the ATGS has to describe every required information via voice communication.

Figure 2. Inter-dependencies in developing tactics and making decisions

		1	2	3	4	5	6	7	8	9	10	11	12	13
[ATGS] ATGS Arrives at the scene [IC/Disp]	1	■											1	
[Airtankers] Relay remaining flight time [ATGS]	2	●	■											
[ATGS] Initial size-up & assessments [ATGS/IC]	3	●		■										
[ATGS] Fire behaviour & spread analysis [ATGS/IC]	4	●		●	■									
[IC] Confirm Assessments & Decisions with IC [ATGS]	5			●	●	■	●						●	●
[ATGS] develop tactics and strategies [IC]	6			●	●	●	■		●					
[ATGS] order additional resources [Disp]	7						●	■						
[Disp] Inform Arrival of resources [ATGS]	8	●						●	■					
[ATGS] Communicate airspace structure [Airtankers]	9		●							■	●			
[ATGS] Set Airspace Structure [All aircrafts]	10	●	●				●			●	■			
[ATGS] Sequence LATs' drops [IC]	11		●				●			●	●	■		
[ATGS] Select drop location [IC]	12				●	●	●					●	■	
[ATGS] Select coverage level [IC]	13				●		●						●	■

2.2 Relaying the decided tactics to the pilot

When the ATGS and IC come to a mutual decision about the location of the drop, and the coverage level, their decision must be clarified for the airtanker pilot. So the ATGS relays the desired drop location to the leadplane pilot via voice communication. After the leadplane pilot understands and confirms the drop location, the same process should be repeated between the leadplane pilot and the airtanker pilot. The coverage level of the drop is another important parameter that travels the same route. The back and forth voice communications take time and increase the risk of human error. Presumably, modern technology can be used to shortcut the information flow route, while ensuring the accuracy of the transferred information.

		14	15	16	17	18	19	20	21	22	23	24	25	26	27
[LP] Confirm target location [ATGS]	14	■	●												
[ATGS] Relay target location [LP]	15	●	■												
[LP] Fly drop pattern [LP][Pilot]	16	●		■											
[LP] Relay drop pattern concerns/hazards [Pilot]	17			●	■										
[pilot] Confirm target location [LP]	18					■	●								
[LP] Relay target location [Pilot]	19		●			●	■								
[LP] Confirm Coverage level [ATGS]	20							■	●						
[ATGS] Relay coverage level [LP]	21		●					●	■						
[Pilot] confirm coverage level [LP]	22									■	●				
[LP] Relay coverage level [Pilot]	23								●	●	■				
[GC] Confirm drop zone cleared [ATGS]	24											■	●		
[ATGS] Clear drop zone [GC]	25											●	■		
[Pilot] confirm scape route [LP]	26													■	●
[LP] Discuss scape route [Pilot]	27			●	●									●	■

2

Figure 3. Inter-dependencies in the chain of command

2.3 Performing the cooperative drop maneuver

After the target location is made clear for both pilots, the airtanker and leadplane must join together to form a chase maneuver, flying over the drop zone. During this maneuver, which requires elaborate synchronization, the pilots have to watch the outside environment (heads-out function) to clear terrain and obstacles, as they are too close to the ground; and simultaneously pay attention to the flight instruments inside the cabin. Since the altitude of the aircrafts in the drop maneuver is usually below 300 ft (above ground level) and they are flying at the speed of 200 to 250 ft/sec in a smoky, congested airspace, the margin for error is extremely small. Furthermore, the current way that the payload release is triggered makes the situation more complex. The ATGS must follow the cooperative maneuver, and order the start of the drop to leadplane pilot by voice. The leadplane then should mark the start of the drop for the airtanker pilot. This is usually done by leaving a smoke trail behind its path, or shaking a control surface or by voice command (NIAC, 2008). The latter two methods will result in a dislocated drop-line due to parallax view problem (USDA, 1998), and the first method requires the airtanker pilot to keep looking at the leadplane, and therefore the cabin instruments get overlooked (NIAC, 2009).

		29	30	31	32	33	34	35	36	37	38
[pilot] Look at cabin instruments [pilot]	29	■				●					
[Pilot] Heads out to check environmet [Pilot]	30		■		●	●				●	
[Pilot] Confirm Join Procedure [LP]	31		●	■			●				
[LP] describe join procedure [Pilot]	32			●	■						
[Pilot] Navigate to target location [Pilot]	33	●	●		●	■					
[Pilot] Assure maneuver safety [Pilot]	34	●	●				■	●			
[Pilot/LP] Perform joint drop maneuver [ATGS]	35				●	●	●	■			
[ATGS] order the start of the drop [LP]	36							●	■		
[LP] Mark the start of the drop [Pilot]	37		●					●	●	■	
[pilot] Release retardant [GC][LP][ATGS]	38							●		●	■

3

Figure 4. Interdependencies in the cooperative drop maneuver

The very existence of the leadplane, which was meant to facilitate the operation, is increasing the complexity of the drop maneuver, as it requires continuous, elaborate coordination and synchronization with the airtanker pilot, in a highly stressful atmosphere. Figure 4 depicts the coupling of tasks in the cooperative drop maneuver.

Although the functions performed by a lead role are necessary, the physic to support those functions do not necessarily need to be an aircraft; And while the airtanker needs to be piloted, it does not necessarily mean that its pilot should sit in the airtanker cabin. The latter two sentences would have looked bizarre decades ago, but are common practices for modern technology today.

3 Modern Technology Solutions

The DSM model demonstrated that the current operational architecture has three issues:

1. The information exchange between Incident Commander (IC) and the Supervisor (ATGS) about the situational awareness, tactics and strategies.
2. The chain of command, from the Supervisor, to the lead role, to the airtanker pilot.
3. The complexity of the cooperative drop maneuver, which requires the pilot to look outside and inside the cabin at the same time.

The authors propose that the pilot be removed from the cabin of the airtanker, and be placed in the ground-station, near the IC. The authors prefer to call the new role "In-Station Pilot" or "ISP", in order to distinguish it with the pilot who sits inside the airtanker. Unmanned flight and remote piloting has already been practiced in UCAVs (Unmanned Combat Air Vehicles). The "co-placement' of the ISP (In-Station Pilot) and the IC is a new concept in aerial-resource management of firefighting operation, enabled by modern technology. The ISP will be seated in a ground-station, flying the airtanker remotely anywhere in the U.S. In this case, the ISP would need a live video feed from the airspace he is flying into. This can be provided via a "wide-angle" camera attached to the airtanker, and SATCOM technology (Satellite Communication) to send and receive data.

The primary outcome of this arrangement is that the *IC will be able to see the same video feed as the ISP*. This will provide the IC with invaluable situational awareness over the fire incident, and save considerable amount of time; which had to be squandered while ATGS described the scene "verbally" to the IC. Therefore, the workload of the ATGS will be reduced, as he can use the extra time to focus on his other tasks; and instead of supporting the IC, he is now being supported by the IC. It is also proposed that the camera attached to the airtanker be augmented by Forward Looking Infra-Red (FLIR) to enhance the fire spread awareness of the IC, and help him make better informed-decisions.

Another benefit of this "co-placement" is that the IC can directly relay drop location information to the ISP, which solves the second problem, regarding the chain of command. After the IC decides the target location and coverage level with the help of the ATGS, the data can be sent "visually" to the ISP; instead of the undesirable, time-consuming verbal contact and involvement of the leadplane pilot, The IC can simply draw a line on his "touch screen monitor", and the pattern becomes visible in ISP's monitor. Pilots are well used to this way of navigation. The landing process in low light conditions in airports with the help of runway lights is a similar practice. Moreover, setting the coverage level, and triggering the payload release, can both be carried out by the IC, and the ISP can be left focused on controlling his/her aircraft.

The third complexity will also be resolved as a direct result of the new arrangement. Since the ISP is looking at a digital monitor instead of the cabin window, all the required flight instrument data can be shown digitally (like a glass cockpit) in the monitor. In other words, ISP's monitor will be providing a composite view of a live video from the scene, the flight instruments, and the drop pattern.

Also, if the pilot is stationed on the ground, instead of the airtanker cabin, he will experience lower stress levels. Lower stress leads to lower fatigue and lower human error, and therefore, a safer, and more effective mission.

The last but not least benefit of the proposed concept is that no airtanker pilot will lose his life on the line of duty anymore. In case of any mishaps, the airtanker may be damaged or lost, but the pilot is always saved.

4 Conclusion

The main reason behind application of DSM in any work is usually to visualize the complexities of the operation at hand; as current aerial firefighting operations are. At its least outcome, DSM helps clarify blocks of interrelated tasks, inefficient interfaces and outdated tasks that have traditionally been used without logical evaluations. In this work, we have been able to systematically identify the main contributors to the success of the firefighting activities and the sources of complexities involved. In fact, DSM model has helped us to better understand the numerous fatal accidents relevant to the long history of aerial firefighting. A new look at the selected accidents, in one side, and emerging new technologies on the other side, has also led us to propose a new concepts named as "Remote Aerial Fire Fighting Station (RAFFS)". In this concept, the pilot is remotely placed in a station next to the IC. The video-link provides proper views to the fire from air-tanker. Such information provides the necessary, time-critical awareness and decision-making ingredients for both IC and the pilot. The camera attached to the airtanker can be equipped with FLIR technology to enhance IC's situational awareness. The ISP's monitor could help resolve any need to simultaneously observe both inside and outside the aircraft cabin. A composite digital view involving surrounding environment and flight instruments could also enhance mission effectiveness. Any tactical decisions made by IC is then transferred visually to the ISP; and therefore, any air-tanker and lead-plane cooperative maneuver would not be necessary. Obviously, this helps reduce the existing risk of fatal accidents.

The RAFFS concept is also expected to reduce the mission associated cost and help increase the drop accuracy through decreasing human error. Although, the risk associated with air-tanker maneuvers still very much depends on the nature of the fire at hand, nonetheless, ISP is no-longer at risk. Moreover, a new air-tanker design, similar to that of large UAV's, could definitely change the whole approach to the firefighting throughout the world.

In this work, task-based DSM has been effectively used to model the operation of an air-tanker role in a general aerial firefighting mission and the associated fatal accidents. The work, however, could definitely be enhanced by adding other types of DSM to create a complete model, involving (1) firefighting parameters and (2) firefighting team to reach an overall cost-estimate for firefighting budgeting. This approach could help one of the main stumbling blocks for most needed passive defense to prevent wild-forest fires. In fact, authors propose to have a comprehensive cost-estimator model for aerial firefighting based on DSM. In this approach, then governments have two clear choices; (1) they could use that budget to prevent wild-forest fires or (2) to actually use that budget to put-out wild-forest fires they encounter every year. Obviously, the next logical step is to integrate the three matrices to form a Multi-Domain Matrix (MDM), which is beyond the scope of the current work.

References

Eppinger, S.D., Browning, T.R., 2012. Design Structure Matrix Methods and Applications. MIT Press, Cambridge, Massachusetts.

Browning, T.R, 1998. Use of Dependency Structure Matrices for Product Development Cycle Time Reduction. Fifth ISPE International Conference on Concurrent Engineering: Research and Application. Tokyo, Japan.

Eppinger, S.D., Bonelli, S., Gonzalez, A.M., 2013. Managing Iterations in the Modular Real Estate Development Process. 15th International Dependency and Structure Modelling Conference, Melbourne, Australia

Calkin, D.E, Stonesifer, C.S, Thompson, M.P, McHugh, C.W, 2014. Large airtanker use and outcomes in suppressing wildland fires in the United States. International Journal of Wildland Fire 23,259-271

Melton, C.E., Wicks, M., Saldivar, J.T., Morgan, J., Vance, F.P., 1968. Physiological Studies On Air Tanker Pilots Flying Forest Fire Retardant Missions. Department of Transportation, Federal Aviation Administration (FAA).

Butler, C., 2015. Aviation-Related Wildland Firefighter Fatalities United States 2000–2013. Centers for Disease Control and Prevention, 1600 Clifton Road Atlanta, GA 30329-4027, USA

USFS (United States Department of Agriculture, Forest Service), 2015. The Rising Cost of Fire Operations: Effects on the Forest Service's Non-Fire Work. available at http://www.fs.fed.us/sites/default/files/2015-Fire-Budget-Report.pdf

USFS (United States Department of Agriculture, Forest Service), 2012. Large Airtanker Modernization Strategy. available at http://www.fs.fed.us/fire/aviation/airtanker_modernization_strategy.pdf

NIAC (National Interagency Aviation Council), 2009. Interagency Aviation Strategy (Phase I, Phase II and Phase III). available at http://www.fs.fed.us/aboutus/budget/requests/6244655_FSNIAC_Strategy_Final.pdf

NIAC (National Interagency Aviation Council), 2008. Interagency Aerial Supervision Guide. available at http://www.fs.fed.us/aboutus/budget/requests/6244655_FSNIAC_Strategy_Final.pdf

USDA (U.S Department of Agriculture), Department of Interior, Bureu of Land Management, 1998. National Study of Tactical Aerial Resource Management to Support Initial Attack and Large Fire Suppression, Final Committee Report. available at http://www.fs.fed.us/fire/publications/aviation/tarms.pdf

NIFC (National Interagency Fire Center), 2016. Historical Wildland Firefighter Fatality Report. available at https://www.nifc.gov/safety/safety_documents/Fatalities-Type-of-Accident.pdf

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DSMDE: A Data Exchange Format for Design Structure Models

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Abstract: We propose **D**esign **S**tructure **M**odel **D**ata **E**xchange file format as a common file format to promote reliable and efficient exchange of Design Structure Model (DSM) data. The DSMDE is an extension of the Matrix Market (MM) file format, a widely used file format for the exchange of dense and sparse matrix data arising in numerous scientific applications. At present there does not exist a common standard for sharing DSM data. We believe that a standardized exchange format will greatly facilitate research and development of DSM modelling techniques by making data widely available than currently possible. The DSMDE is expected to be a standard way to share DSM data among researchers, practitioners, and on different programming environments.

Keywords: Sparse Matrix, Complex Network, EBNF Grammar, Portable Exchange, DSM, MDM

1 Introduction

The DSM is a modelling tool to capture, display, and analyze interactions between constituent elements of a complex system. As elucidated in (Eppinger and Browning, 2012), a DSM *M* is an $n \times n$ matrix where element i of the system is associated with column and row i such that the entry $M(i,j), i \neq j, i, j \in \{1,2,\dots n\}$ represents the interaction between the elements i and j. Depending on the underlying system a pair of elements may interact in multiple ways. In general, interactions between elements i and j can be represented by a small set of attributes some of which may be symbolic. However, in almost all cases attributes can be easily mapped to numerical values. Hence, for all practical purposes, we can view a DSM *M* as a $n \times n$ matrix where each interaction is encoded by a vector of dimension $d \geq 1$ (i.e. in $\Re^d$), where d is the number of attributes associated with an interaction. For a comprehensive review of the DSM methods we refer to (Browning, 2016).

2 Rationale and Design Philosophy

Many real world examples of DSM matrices remain scattered in the literature and most of these examples are not in an easily retrievable digital form. Recently, the book by Eppinger and Browning (Eppinger and Browning, 2012) has compiled 44 DSM examples from diverse areas. As DSM techniques continue to find its applications in new and emerging areas (e.g., complex networks), it is conceivable that exchange of data will play a crucial role in future development of techniques and algorithms for DSM data analytics challenges. The purpose of this work is to suggest a common framework for exchange of model data. Fundamental to our proposal is the exploitation of duality between sparse matrices and graphs (as complex networks). For recent overviews on graph and matrix file formats we refer to (Roughan and Tuke, 2015) and (Bodlaj, 2014). The following basic features (in no particular order) are considered desirable in a file format.

1. **Portability**. The data in the file should be easily transferable between hardware and operating systems efficiently.
2. **Simplicity**. By simplicity we mean ease of reading and writing data. We require that the file can be viewed with general purpose text editor programs such as vi(m), emacs, TextEdit, NotePad, etc. The stored data should be structured such that it facilitates easy input and parsing.
3. **Extensibility**. The format should be flexible enough to allow adaptation and extension of the base format without requiring too much effort. For example, it is reasonable to envision applications in which interactions involve more than two elements. One way to represent such information is by extending the 2-dimensional matrix framework to higher-dimensional tensors.

The simplicity and portability requirements allowed us to rule out binary (non text) files from consideration. Our design emphasizes simplicity of representation such that the proposed format is to be independent of specific software toolkit for display and manipulation of data. Consequently, we only consider ASCII (and UNICODE where applicable) text files.

The Harwell-Boeing (HB) sparse matrix collection (Duff et al., 1989) is one of the earliest efforts to compile and maintain a standard set of sparse matrix test problems arising in a wide variety of scientific and engineering disciplines. Unfortunately, HB format is not easily extensible. Further, because of HB format's heavy reliance on FORTRAN specific input/output constructs, it is somewhat complex to comprehend the data. Graph and Matrix Format (GAMFF) (Zien et al., 1995) is a closely related (to HB) format which is more flexible in that it permits additional information specific to graphs and hypergraphs. One difficulty with using compressed column (or compressed row) is the potential for overflow of indices.

The Matrix Market (MM) exchange format (Boisvert et al., 1996) is a simple but extensible file format for storing and exchanging sparse and dense matrix data stored in an ASCII text file. The MM format enables extensibility by allowing format specialization in the form of qualifier attributes and structured documentation. The information about the matrix is organized in three syntactic sections: Header, Comment, and Data, in that order. The header section encodes metadata such as numerical field, structure, data format etc. The comment section consists of free-format lines of text and can be used to provide specific information about the data. The last section, the data section, contains the numerical values. Recently, Yzelman and Bisseling (Yzelman and Bisseling, 2010) proposed Extended-Matrix-Market-Format (EMM) suitable for storing sparse matrices and vectors. The new features of EMM enable sparse matrices and vectors to be used in a distributed computing environment for performing sparse matrix

operations. Our proposal, the DSMDE, exploits MM format's extensibility while maintaining its generality and is independent of specific computing environments.
The remainder of the paper is structured in the following way. Section 3 contains elaborate description of the proposed DSMDE exchange format. The section concludes with an Extended Backus-Naur Form (EBNF) specification of the grammar for DSMDE format. We note that the original MM exchange format specification does not include an EBNF description. In Section 4 we provide an example DSM taken from (Eppinger and Browning, 2012) and show its representation in DSMDE exchange format. Finally, the paper is concluded in Section 5 with a discussion on directions for future development.

3 The Extended File Format for DSM and MDM Data

It is nearly impossible to come up with "the best" format since some of the required properties may be conflicting. In this section we provide the general specification of our proposed format DSMDE as an extension of MM exchange format. As in MM format the contents of a DSMDE file are organized into three main sections: Header, Comments, and Data, in that order.

1. **Header**. Our choice of MM exchange format to form the basis for DSMDE has largely been influenced by MM format's simplicity and extensibility. The header of MM format has the following structure:

   Banner ObjectType FormatType Qualifiers

   Banner is the literal string %%MatrixMarket of 15 ASCII characters. The DSMDE exchange format views design structure models as matrices (and in general, higher-order tensors). Extensibility of the base MM format can be realized in a number of ways. It is not necessary to change the banner string of the base MM format since the additional features needed to represent DSM, MDM, and DMM objects can be incorporated in the remaining fields of the header section. The header is extended to include the objects DSM, MDM, and DMM under *ObjectType* field. That is, in addition to Matrix we allow DSM, MDM, and DMM as type of mathematical objects that can be represented. The existing data layout schemes Coordinate and Array of MM are adequate for the new object types. A matrix can be full (in which case each matrix entry is explicitly stored with Array specification) or sparse (only the nonzero entries are stored with Coordinate specification). The third component of MM header enables us to specify a list of qualifiers. DSMDE takes advantage of this field to provide properties that are specific to DSM, MDM, and DMM data. The two MM qualifiers *Numeric-Field* and *Structure* are retained. We introduce the following additional qualifiers.

   a. *Orientation*. This qualifier (*Orientn*) encodes information about the DSM orientation convention for off-diagonal marks. The two variants are: Input in Row and output in column (IR) and Input in Column and output in row (IC). With IR, in a process DSM, "feedback" is indicated by a mark above the main diagonal (FAD) while with IC a mark below the main diagonal (FBD) indicates "feedback". Accordingly, we use the codes IR and IC to represent orientation.
   b. *Interaction Attributes*. While for "simpler" system models, a scalar value would suffice to represent system interaction, many real-life models have a more elaborate interaction structure. Eppinger and Pimler (See Example 3.1 in (Eppinger and Browning, 2012)) studied the climate control systems of cars and trucks produced by Ford Motor Company. They have identified four types of interaction among the system components: spatial, energy, information, and materials. Interactions may also differ with respect to the source they originate from. The product architecture example "Building Schools for the Future" (Example 3.8 in (Eppinger and Browning, 2012)), uses three interaction

sources: explicit, inferred, and perceived. In the DSM model of software library CSparse (Hossain et al., 2015), dependencies (between code files) can be due to function calls or object references, for example. There are DSM models that use colors to depict specific interactions. In the Helicopter Change Propagation DSM model (Example 3.6 in (Eppinger and Browning, 2012)), red, amber, and green shadings represent "significant-", "lower-", and "small-risk" of change propagation, respectively. For simplicity, DSMDE treats interaction varieties as attributes. The number of interaction attributes is recorded in the header with the qualifier *NIattribute*. A mapping between the attributes and the integers $1, 2, \ldots, n_a$, where n_a denotes the number of interaction attributes, can be provided in the comments section. The same qualifier can also be used to represent a composite DSM (composition of different instances of the same model). In the product architecture model "Johnson & Johnson Clinical Chemistry Analyzer", the Expert DSM (See Example 3.7, Figure 3.7.2 in (Eppinger and Browning, 2012)) model displays interactions recorded at two different dates.

As noted earlier, an attribute may assume a numerical value (integer, real, complex) or a symbolic name (e.g., color red, color green, etc.). For symbolic names, the DSMDE requires a mapping between the names and the integers $1, 2, \ldots, n_s$ to be specified; n_s denotes the number of symbolic names that can be attribute values. The mapping can be documented under the Comments section of the DSMDE file. For a pattern DSM (*Structure* = pattern) $n_a = 0$ since the type of interaction is binary.

The qualifier *NumericField* for a DSM or a DMM object has *NIattribute* (n_a) components. This is due to the fact that for each attribute its *NumericField* has to be specified. An MDM is treated as a collection of DSMs and DMMs such that the header field for an MDM has a simpler structure.

c. *Domain*. To incorporate MDM models in DSMDE, we record the number of domains $n_d \geq 1$. For DSMs and DMMs we have $n_d = 1$, for MDMs, $n_d > 1$. An MDM model can be viewed as a block triangular matrix as shown below.

$$A = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n_d} \\ 0 & A_{22} & \cdots & A_{2n_d} \\ \vdots & \ddots & \cdots & \vdots \\ 0 & 0 & \cdots & A_{n_d n_d} \end{bmatrix}$$

The diagonal blocks A_{ii}, $i = 1, \ldots, n_d$ correspond to the DSMs. The off diagonal blocks A_{ij}, $i < j \text{ and } i, j = 1, \ldots, n_d$ represent interactions between elements in domains $i \neq j$ and are known as domain mapping matrix (DMM). In an n_d-domain MDM, there are n_d DSMs and $\sum_{i=1}^{n_d-1} i = \frac{n_d(n_d-1)}{2} \equiv n_{dmm}$ DMMs. The header section is modified accordingly. There are $1 + n_d + \frac{n_d(n_d-1)}{2}$ header lines where the first line consists of the banner string, MDM as object type and the number of domains; each of the next n_d lines must have a value for each of *FormatType*, *Numerical Field*, *Structure*, *Orientn*, *NIattribute* for the DSMs contained in the MDM. Each of the $\frac{n_d(n_d-1)}{2}$ lines must have a value for each of *FormatType*, *NumericField*, *Structure*, *NIattribute*, for the DMMs. For a DMM object, orientation information is not needed. The relevant data for DMMs are stored according to "block row-major" order. The block row- major order is to consider the off-diagonal blocks in the order $A_{12}, \ldots, A_{1n_d}, A_{23}, \ldots, A_{2n_d}, \ldots, A_{n_{d-1}n_d}$.

The overall DSMDE header section is depicted in Table 1. Note that when *ObjectType* is DSM or DMM the header section consists of only one line. As in the MM format it is to be emphasized that not all header filed combinations are meaningful. In general, context-free grammars are not powerful enough to express context-sensitive requirements. Consequently, header field combinations are validated informally.

2. **Comments**. As we have already observed, the header section of the DSMDE format provides a high-level specification of the DSM, MDM, and DMM data contained in the file. Information such as name of design elements, source and type of interactions etc. are essential components of the underlying models. The comments section provides a convenient

Table 1. Header section components and their values in DSMDE

Fields	*Banner*	*Object Type*	Qualifier (*Ndomain*)	Qualifier (*Format Type*)	*Qualifier (Structure)*	Qualifier (*NIattribute*)	*Qualifier (Numeric Field)*	Qualifier (*Orient n*)

Values	`%%MarixMarket`	`Matrix,`
		`DSM,`
		`MDM,`
		`DMM`
			n_d	`Coordinate,`
				`Array`
					`General,`
					`Symmetric,`
					`Skew-symmetric,`
					`Hermitian`
						n_{a_1}
						n_{a_2}
						n_{a_3}
						.
						.
						.
						$n_{a_{n_d}}$
						$n_{a_{n_d+1}}$
						.
						.
						.
						$n_{a_{n_d+n_{mdm}}}$
							`Integer,`
							`Real,`
							`Complex,`
							`Pattern`
							.
							.
							.
								`IC,IR`
								`IC,IR`
								`IC,IR`
								`IC,IR`
								
								`IC,IR`

way to record such information about the data. To enable automatic (machine) parsing of the information, the DSMDE comments section enforces specific syntactic rules on the text that appear here. The comments section consists of two parts: a required section and an optional section. The optional section is similar to the comments in MM format - no specific syntactic structure is enforced. The required section consists of three ordered subsections as described below.

a. **Domain**. For a DSM $(n_d = 1)$, this is a one-line description of the model. Each such string can be used to provide a brief description of the corresponding DSM model. The subsection is enclosed in the pair of literal strings beginDomain endDomain.

b. **Model Element**. For a DSM $(n_d = 1)$ model, the element names are provided in the file as a list of n character strings, one per line. The subsection is enclosed in the pair of literal strings beginModElement endModElement.

c. **Interaction Attributes**. For a DSM $(n_d = 1)$, this is a list of n_a character strings describing the interaction attributes. A mapping between the n_a names (of attributes) and the set $\{1, 2, \dots, n_a\}$ must be provided. The subsection is enclosed in the pair of literal strings beginAttribute endAttribute. For a MDM $(n_d > 1)$, the above documentation is repeated for each DSM (the diagonal blocks of the block upper triangular representation of MDM). This is followed by the documentation for each DMM in block row major order (the off-diagonal blocks of the block upper triangular representation of MDM). An optional subsection of the comments section can be used to provide additional information about the model.

3. **Data**. As in the base MM exchange format, the data section records the numerical data. Intuitively, each matrix/DSM/MDM/DMM data point (i.e., interaction) represents an instance

of a relation defined on interaction attributes. An element (or a data point) of a matrix is uniquely identified by its location. For a two-dimensional matrix object the location information is provided as an ordered pair (i, j), where i denotes the row index and j denotes the column index. Each element of the matrix possesses certain attributes depending on the type of the object. Consider the product architecture DSM example 3.8 "Building Schools for the Future" (Eppinger and Browning, 2012). There are three sources of interactions: Explicit (1), Inferred (2), Perceived (3), and three types of interactions: Structural (1), Spatial (2), and Service (3). For the purpose of data exchange, we just need to identify each interaction attribute with a unique integer from the set $\{1,2,3\}$ as discussed in the preceding section. With *FormatType* = Coordinate and *NumericField* an ordered pair (Integer, Integer) where the first component is associated with the attribute "interaction source" and the second associated with the attribute "interaction type", a dependency mark can now be specified with an ordered 4-tuple (i, j, s_{ij}, t_{ij}) where $i, j \in \{1, \dots, n\}$, indicates the row index and the column index, respectively; $s_{ij} \in \{1,2,3\}$ indicates interaction source, and $t_{ij} \in \{1,2,3\}$ indicates interaction type associated with the mark at location (*i*,*j*). This information is recorded in DSMDE exchange format as:

$$i \quad j \quad s_{ij} \quad t_{ij}$$

in a line in the file. Formally, a tuple of the form (i, j, s_{ij}, t_{ij}) is an element of the set produced by the Cartesian product $\mathfrak{J} \times \mathfrak{J} \times \mathfrak{S} \times \mathfrak{T}$ where,

$$\mathfrak{J} = \mathfrak{J} = \{1,2, \dots, n\},\ \mathfrak{S} = \mathfrak{T} = \{1,2,3\}$$

for this particular example. Note also that the location of an interaction in a DSM or DMM object (in Coordinate format) is a k-tuple; $k = 2$ implies a matrix and $k > 2$ implies a higher-dimensional tensor. For a MDM object, ordering of the data is as below.

a. **DSM** data. $A_{11}, A_{12}, \dots, A_{n_d n_d}$
b. **DMM** data. $A_{12}, \dots, A_{1n_d}, A_{23}, \dots, A_{2n_d}, \dots, A_{n_{d-1} n_d}$

3.1 DSMDE Grammar

In this section we provide the syntax specification of DSMDE exchange format using EBNF (Extended Backus-Naur Form) notation. Unfortunately, notation to describe grammar rules in BNF/EBNF has not been standardized (Zaytsev, 2012). Hence, we describe the meaning of symbols used and the syntactic conventions adopted.

1. **Start nonterminal**. The start nonterminal of the EBNF grammar for DSMDE format is denoted by the string DSMDEFORMAT.
2. **Reserved Words**. Text strings written in `teletype` font have special meaning in DSDME format. They appear as string literals in DSDME formatted files. They are: `%%MatrixMarket,Matrix,DSM,MDM,DMM,Coordinate,Array,Integer,Real,Complex,Pattern,General,Symmetric,SkewSymmetric,Hermitian,IC,IR,%beginDomain,%endDomain,%beginModElement,%endModElement,%beginAttribute,%endAttribute,`
3. **Nonterminal**. Words with first character in uppercase denote nonterminal symbols.
4. **Terminal**. Words with first character in lowercase denote terminal symbols. A terminal symbol or token describes a lexical pattern of strings defined over the set of ASCII printable characters (ASCII code 33,…,126). For example, the token named "Integer" matches strings defined over ASCII characters $\{0,1,2,3,4,5,6,7,8,9\}$. Thus, the string 311 is an "Integer" while the string 102a is not. The literal string `%%MatrixMarket` matches the token named "banner" and this is the only such string. In the EBNF syntax description, the name "charSymbol" denotes a printable ASCII symbol. Additionally, we use the following ASCII symbols.

a. newline (ASCII LF (in some computing environment); value 10) to start a new line in the file
b. space (ASCII value 32), to separate adjacent tokens appearing in the file
c. tab (ASCII HT; value 9), to separate adjacent tokens or to format text strings.

We remark that adjacent tokens in a DSMDE file must be separated by at least one separator symbol.

5. **EBNF Meta Symbols**
   a. **Repetition**. S* implies zero or more occurrences of grammar symbol S; S+ implies one or more occurrences of grammar symbol S; [S] implies zero or one occurrence of grammar symbol S.
   b. **Option**. Options are indicated as R|S, meaning either R or S but not both.
   c. **Scope**. Parentheses are used to group together grammar symbols to indicate scope.

Table 2. EBNF Grammar for DSMDE Exchange Format

DSMDEFORMAT	::=	Header+ Comments Data
Header	::=	banner [objectType] [Qualifiers]
banner	::=	`%%MatrixMarket`
objectType	::=	`Matrix | DSM | MDM | DMM`
Qualifiers	::=	[NDomain] QualList
QualList	::=	(formatType [structure] [NIAttribute] [numericType] [orientn] newline)+
formatType	::=	`Coordinate | Array`
numericType	::=	`(Integer | Real | Complex | Pattern)+`
structure	::=	`General | Symmetric | Skew-Symmetric | Hermitian`
NDomain	::=	Integer
NIAttribute	::=	Integer
orientn	::=	`IC | IR`
Comments	::=	TextLine* Documentation+ TextLine*
TextLine	::=	%charSymbol* newline
Documentation	::=	[DomainNames][ModElementNames] [InteractAttributeNames]
DomainNames	::=	beginD newline TextLine+ endD newline
ModElementNames	::=	beginME newline TextLine+ endME newline
InteractAttributeNames	::=	beginIA newline TextLine+ endIA newline
beginD	::=	`%beginDomain`
endD	::=	`%endDomain`
beginME	::=	`%beginModElement`
endME	::=	`%endModElement`
beginIA	::=	`%beginAttribute`
endIA	::=	`%endAttribute`
Data	::=	CoordData | ArrayData
CoordData	::=	NRows NCols Nnz newline CoordDataLine+
ArrayData	::=	NRows NCols newline ArrayDataLine+
CoordDataLine	::=	RowIndex ColIndex Values newline
NRows	::=	Integer
NCols	::=	Integer
Nnz	::=	Integer
RowIndex	::=	Integer
ColIndex	::=	Integer

ArrayDataLine	::=	Values newline
Values	::=	IAttribute*
IAttribute	::=	Integer | Real | Complex
Integer	::=	[sign] digit+
Real	::=	[sign] digit* . digit* [Mantissa]
Sign	::=	+ | -
Mantissa	::=	`E` [sign] digit+
Complex	::=	Real Real
digit	::=	`0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9`
Separator	::=	space | tab

4 Example

In this section we illustrate the DSMDE exchange format with a real-life design structure model.

```
%%MatrixMarket DSM 1 Array General 4 Real Real Real Integer IC
%
% Product Architecture DSM Model of AW101 Change Propagation
% Example Fig. 3.6.3;[Steven D Eppinger and Tyson R Browning;
% Design structure matrix methods and applications; MIT press, 2012].
% Number of domains:  1
% Number of attributes : 4
% Input convention: : Input in column (IC)
%
%beginDomain
% Product Architecture DSM
%endDomain
%beginModElement
% 1 = air conditioning, 2 = auxillary electronics, 3 = avionics,
% 4 = bare fuselage, 5 = cabling and piping , 6 = engines,
% 7 = engine auxillaries, 8 = equipment and furnishings,
% 9 = fire protection, 10 = flight control systems, 11 = fuel,
% 12 = fuselage additional items, 13 = hydraulics,
% 14 = ice and rain protection, 15 = main rotor blades, 16 = main rotor
head,
% 17 = tail rotor, 18 = transmission, 19 = weapons and defensive systems
%endModElement
%
%beginAttribute
% 1 = Impact(height), Real; 2 = Likelihood(width), Real; 3 = Risk(height*
% width), Real; 4 = Change Propagation(shade), Integer (Red = 3, Amber =
% 2, Green = 1)
%endAttribute
19 19
0 0 0 0
0.4 0.8 0.32 2
0.7 0.8 0.56 3
```

Figure 1. Product Architecture DSM Model AW101 (Eppinger and Browning, 2012) in DSMDE Format.

4.1 Product Architecture DSM Example (Fig. 3.6.3 of (Eppinger and Browning, 2012))

Figure 1 displays a product architecture DSM model in DSMDE exchange format. The header line

```
%%MatrixMarket DSM 1 Array General 4 Real Real Real Integer IC
```

indicates that the file contains a DSM object (*ObjectType* = `DSM`, *NDomain* $n_d = 1$) stored in array format (*FormatType* = `Array`), contains no special structure (*Structure* = `general`), uses 4-attribute interactions (*NIattribute* $n_a = 4$) of type real, real, real, integer, and that it uses input-in-column (*Orientn* = `IC`) convention. Recall that array format stores all n^2 entries of the DSM in column-major order. The next 8 lines after the header line provide information on the DSM model. This part is optional. The three-part structured documentation section provides the name of the domain (DSM), enumerates the model elements and their integer mapping, followed by the attribute names and their integer mapping information. These three subsections are enclosed in their respective "begin" and "end" format tags. For brevity, the mapping of model elements and attributes are not shown in the required syntactical format (they must occur one per line). The first line of the data section,

```
        19      19
```

indicates that the DSM model consist of 19 rows and 19 columns. The next $19 \times 19 = 261$ lines contain interaction data, one interaction per line. The second line of the data section,

```
        0       0       0       0
```

corresponds to the interaction object located at row 1 and column 1. The four zeroes indicate that the diagonal element does not have any useful information. The next line (line 3),

```
        0.4     0.8     0.32    2
```

corresponds to DSM cell at row 2, column 1. The four numerical values represent Impact (height) $= 0.4$, Likelihood (width) $= 0.8$, Risk (height*width) $= 0.4 \times 0.8 = 0.32$, and Change Propagation (shade) encoding value Amber $= 2$. Figure 1 displays only the first 2 interaction values of the DSM.

5 Concluding Remarks

A DSM is much more than an adjacency matrix representation of a complex network. As has been articulated in (Browning, 2009) the characteristics of a complex system may not be fully comprehensible from a single viewpoint. A DSM provides an important "view" of such a system. The design and analysis of complex engineered systems (Eppinger and Browning, 2012) can be greatly aided by techniques and tools that can capture, organize, and represent nontrivial interactions among systems' elements. The new exchange format is an extension of the widely used Matrix Market data exchange format. As such, it retains the simplicity and flexibility of the base MM format and now facilitates the exchange of DSM, MDM, and DMM model data. The structured comments section can be used to record important system information about the models stored in the file. For the purpose of data exchange an interaction is viewed as a k-tuple (conceptually) consisting of two parts: the address or location and the value. Although the DSMDE exchange format does not require any special software to read or write model data, in practice, some software support is typically expected to perform input and output. We have implemented a syntax-directed interpreter in JAVA programming language for input and output. We are currently developing a software tool that will have support for task/activity sequencing and data visualization in a user-friendly manner.

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References

Bodlaj, J., 2014. Network Data File Formats, in: Encyclopedia of Social Network Analysis and Mining. Springer New York, NY, pp. 1076–1091.

Boisvert, R.F., Pozo, R., Remington, K.A., 1996. The Matrix Market Exchange Format: Initial Design. NISTIR, 1996. math.nist.gov/MatrixMarket/reports/MMformat.ps.gz (accessed May05, 2016)

Browning, Tyson R., 2009. The many views of a process: Toward a process architecture framework for product development processes. Systems Engineering, 12(1), pp. 69-90.

Browning Tyson R., 2016. Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities. IEEE Transaction on Engineering Management, 63(1), pp. 27-52.

Duff, I.S., Grimes, R.G., Lewis, J.G., 1989. Sparse matrix test problems. ACM Trans. Math. Softw. 15, 1–14.

Eppinger Steven D., Browning Tyson R., 2012. Design Structure Matrix Methods and Applications, MIT Press.

Hossain, S., Khan, S.F., Quashem, R., 2015. On Ranking Components in Scientific Software. in the Proceedings of 17th International DSM Conference, pp. 245-254.

Roughan, M., Tuke, J., 2015. The Hitchhikers Guide to Sharing Graph Data. 3rd International Conference on Future Internet of Things and Cloud (FiCloud), pp. 435-442.

Yzelman, A.N., Bisseling, R.H., 2010. Extended matrix-market file format – an extension to the standard schme http://www.staff.science.uu.nl/~bisse101/Mondriaan/Docs/(accessed May05, 2016)

Zaytsev, V., 2012. BNF was here: what have we done about the unnecessary diversity of notation for syntactic definitions. Proceedings of the 27th Annual ACM Symposium on Applied Computing - SAC '12. ACM Press, New York, USA, pp. 1910-1915.

Zien, J.Y., Simon, H.D., Woo, A.C., 1995. GAMFF - A Graph and Matrix File Format. http://www.nas.nasa.gov/Software/GAMFF/ (accessed May 05, 2016)

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Part IV

Project Management

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Estimating the effects of Engineering Changes in early stage product development

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Abstract: Constantly changing requirements pose a major challenge for industry, especially in the early phases of product development where there is little information available. One of the main reasons for that are the effects of change propagation. Several tools and methods address how Engineering Changes affect further product components, however how these changes affect the project cost and time has not been sufficiently addressed so far. We propose a method that aims to estimate the additional effort and impact on project time of implementing a change, providing an additional decision support whether or at what cost to implement a requirement or an engineering change.

Keywords: Engineering Change Management, Change Prediction, Project Modelling

1 Introduction

Mechatronic products are constantly affected by change to improve functionality, adapt to customer needs and regulatory standards and remove mistakes. The importance of Engineering Changes (ECs) has even increased over the last years due to the need for product individualization, shorter development cycles and carry-over parts (Hamraz, 2013).

Often these ECs may have negative consequences such as higher costs and deadline overruns (Hamraz, 2013). In order to retain market competitiveness, the importance of a company's ability to handle ECs properly increased even further (Nichols, 1990).

Although literature covers a wide field of different research on ECs including case studies and methods supporting the Engineering Change Management (ECM) process, it still poses a major challenge for industry. One of the main reasons for that are the effects of change propagation. A change initiated to one element of a system can result in changes of other elements of the system by propagating through connections between them. These knock-on effects are often difficult to estimate and even the whole system can be affected (Hamraz, 2013).

In fast paced environments, such as our industry partner situation, the decision whether to implement a change has to be made quickly. How well informed these decisions are can be a decisive factor for the project.

There are a number of tools and methods, such as the ones proposed by Clarkson et al. (2004) or Grantham-Lough et al. (2006), to support decisions in the EC process. Promising methods in the area of change prediction help to understand how initial changes spread through a system affecting other parts and systems. However, how these changes affect the project has not been sufficiently addressed so far.

In highly dynamic contexts, the classical approaches of process modelling and analysis often reach their limits, since the depicted elements and relations are usually assumed to be static (Kasperek et al. 2014). Thus, the impact of changes is hard to predict (Kasperek et al. 2014). System Dynamics is a method to model and simulate the dynamics of systems that enables to analyze the dynamic behavior of a system – in this case the development project.

In this paper we enhance existing methods for change management decision support with elements of modelling the dynamics of projects. The approach proposed supports the estimation of the effect of changes on the project in early stage product development. The aim is to provide support for decisions under high time pressure and few information and expertise in regard of the assessment of engineering changes, especially changes triggered by stakeholders, e.g. the customers.

2 Background

In this section, two main topics are addressed. Firstly, an introduction to the possible impacts of engineering changes on projects is provided, as well as an overview on current tools and methods for assessing these effects. Then, an existing approach on simulating projects is introduced, which is discussed later in section 5.

2.1 Engineering Change Management

A broad variety of definitions of "Engineering Change" exist, however in this paper we use the definition proposed by Hamraz et al. (2013, p. 475), where Engineering Changes *"are changes and/or modifications to released structure (fits, forms and dimensions, surfaces, materials etc.), behavior (stability, strength, corrosion etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behavior (design principles), or behavior and structure (physical laws) of a technical artefact."* In this definition an artefact is a representative term, which may refer to a component, a system or a whole product. Engineering Change Management (ECM) is the organizing, controlling and execution of the process of Engineering Changes (Jarratt et al., 2010).

While several ECM processes have been proposed by different authors, the process by Jarratt et al. (2004) is shown in Figure 1.

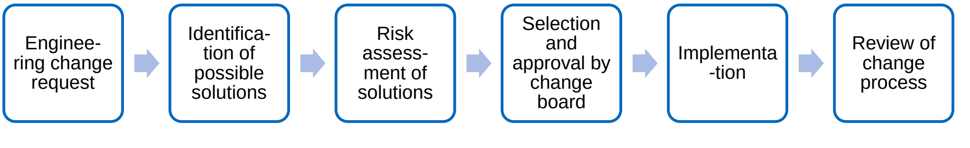

Figure 1: Engineering Change Management process, adapted from Jarrat et al. (2004)

The effects of implementing a change have been covered broadly in literature by several authors. According to Nichols (1990), ECs impact all determinants of competitive advantage of products, namely cost, quality and time-to-market. Costs and be further split down. Hamraz (2013) divides the costs resulting from ECs into direct costs and indirect costs. Direct costs include for example costs for (1) design, (2) changes in prototype tools and (3) changes in production tools (Terwiesch and Loch, 1999). Indirect costs include fines, loss of profit due to delays and costs related to damage to a company's reputation. Additionally, change propagation influences all processes throughout the value chain of a product, the number of changes and their outcomes highly influence the magnitude of time delays and project overruns (Hamraz, 2013).

Furthermore, in most cases, a change does not only affect the initial component or part, but propagates through the system. It is similar to a chain reaction, when one change causes another change, which then causes further changes. Therefore a change can spread to other parts or components of the product and even to other products (due to common platforms, processes and businesses). Terwiesch and Loch (1999) identified three key couplings that may lead to propagation: (1) Between components and manufacturing, (2) Between the components within the same subsystem and (3) Between components in different subsystems.

In order to cope with ECs, many supporting tools and methods have been developed. Jarratt et al. (2010) divide these models into two groups: those that help manage the process (documentation or work flow) and those that support engineers in making decisions during the engineering change process. The focus of this paper relays on the second group of tools and methods, which is introduced in this subsection.

According to Ahmad et al. (2011) models that support decision making through estimating the effects of changes can be differentiated between single-domain methods and cross-domain methods. Single-domain methods focus on mainly on a single product domain (e.g. components) while cross-domain methods aim on multiple domains (e.g. functions and components) and also include change propagation between domains. The method presented in this paper belongs to the cross-domain ones.

Moreover, following two methods are the base of the method described in section 4.

The Change Prediction Method by Clarkson et al. (2004), which is a single-domain method, illustrates the overall risk of changes propagating through a system, if one component is changed. The main structure of the model is the DSM, where products are modelled as linked components. These linked components are associated with a risk term, which is the product of the likelihood of the change occurring and the impact of the change. This matrix is then used to analyze new product requirements to decide on redesign plans.

Using the Information Structure Framework (ISF), Ahmad et al. (2010) add to the component layer of the CPM the further domains requirements, functions and the detailed design process. A change in requirements leads to certain changes in functions, which leads to changes of those components that are supposed to implement the respective functions. Within the components layer, a change of one component can propagate to other components, which is considered by using the CPM approach. Changes in components finally lead to changes of the detailed design process and their respective design parameters. Main downside of this model is the applicability only for stable product architectures and design processes.

2.2 Simulating project dynamics

System Dynamics is a mathematical modeling technique for framing and understanding complex issues and problems (Kasperek and Maurer 2013). Over the last 20 years, these models have been used on management of projects, including planning the determining measurement and reward systems, evaluating risks, and learning from past projects (Lyneis and Cooper 2001). One of the main elements of modelling projects is the rework cycle. A rework cycle can represent a project, a phase or a task that can be divided in further activities. Many variants of this structure exist, the one used in this paper is described below.

Here, all activities are stored in the “Work to be done” stock at the beginning of the project. Depending on the people available and their productivity, these activities flow into the “Work really done” stock. However, errors occur depending on the quality of the work. These activities do not flow into the work done but instead into the stock “Undiscovered rework”. When these errors are discovered – which can be hours, days or even years later – the work becomes “Known rework”. This “rework” gets eventually done. (Lyneis and Cooper 2001)

3 Methodology

The research approach of this work follows the Design Research Methodology (DRM) introduced by Blessing and Chakrabarti (2009), which comprises following four main stages: Research clarification, Descriptive study I (DS I), Prescriptive study (PS), Descriptive study II (DS II).

First, an overview of the current situation was obtained by a literature survey and the observation of development projects at the industry partner (DSI). Then requirements of early stage development were acquired and both from industry partner and literature sources. These requirements (not in this paper) were used to assess current ECM methods and choose the most promising method. In the Prescriptive Study, the most promising methods – the CPM by Clarkson et al. (2004) and the Information Structure Framework (ISF) by Ahmad et al. (2010) – were then extended and enhanced by the dynamic simulation approach based on Kasperek et al. (2014) and implemented as a software prototype. An initial evaluation of the proposed method was then carried out within the DS II stage (c.f. section 4.4).

4 Method for estimating the impact of engineering changes

As illustrated in Figure 1, the ECM process comprises six steps: The method for estimating the impact of engineering changes supports mainly step three, which consists of assessing each solution to the Engineering Change Request in regard of the risk of implementing it, including factors such as impact on design and production schedules.

As shown in section 2.1 several tools and methods exist that support the decision-making within engineering change management. However, existing methods are not well suitable to early stage product development. Most ECM methods are designed for changes on already existing products. These changes for example cover improvements, error removal and individualization of existing products. Nevertheless, in the early stages of the development process, when a product is developed from scratch, new challenges occur. Thus, a suitable decision making support has to fulfil requirements that address following challenges:

- **No complete product model:** Projects in early stage developments mostly start with no or little knowledge about the product to be implemented. Therefore, only a basic product model exists at the beginning. Consequently, it is important that the underlying product model is easy to extend during the project.

- **High amount of changes:** The uncertain environment of early stage development results in many changes.
- **Changes often arise from stakeholders**: To steer the product development in the right direction, stakeholders are closely integrated in the development process.
- **Customers with no technical background**: A suitable method needs to deliver easy understandable output and serve as a communication platform

Additionally, further challenges derive from the situation of the industry partner, which was founded only few years ago and where the majority of the workforce consists in students, PhD candidates and young engineers. Thus, easy usage of a suitable method is important. Moreover, no or only little existing information can be reused for building the product model.

In order address these challenges, new domains are added to the existing domain "components" of the CPM building on the Information Structure Framework (ISF) (Ahmad et al. 2010). These new domains include people for stakeholder centricity, tasks to establish an interface with project management, and requirements and functions to improve product understanding and communication. The domains and their relationships among the domains described are illustrated in the MDM in Figure 2.

	People	Requirements	Functions	Components	Tasks
People		Initiate changes to	Initiate changes to	Initiate changes to	
Requirements			Fulfilled by		
Functions			Deliver signal, energy, or material to (Flow)	Implemented by	
Components				Connected to	Realized by
Tasks					Affect

Figure 2: MDM as an overview of the supported domains and their relationships

The methodology proposed in this paper comprises four stages as shown in Figure 3. In the first stage the necessary information about the system to develop and the planed tasks is acquired. The second stage uses existing CPM algorithms to compute the risk of change propagation within the system. Then, the dynamic model is built based on the information acquired and generated in stages 1 and 2. Finally, the system dynamics model is simulated and the results are used in the decision making regarding the analyzed change or changes.

Figure 3: Four stages of the estimation of changes' effects during the early phases

The following sections (4.1 – 4.4) provide a detailed description and an exemplary application of each of the stages, as well as their application with the corresponding software tools.

4.1 Information acquisition

The first step is to acquire the information about the system to develop and the project plan that is necessary to build the models in stages 2 and 3. For this purpose a MDM containing the relationships among the system's elements (requirements, functions, components and tasks) and its corresponding graph is developed. Figure 4 illustrate an example of a subsystem that fulfills exactly one requirement. This subsystem was chosen as an example due to its low complexity in order to exemplify the methodology.

Firstly, the relationships among the system elements are documented with information from product models and drawings. Figure 4 depicts the sub-systems' architecture and the corresponding tasks in form of a graph.

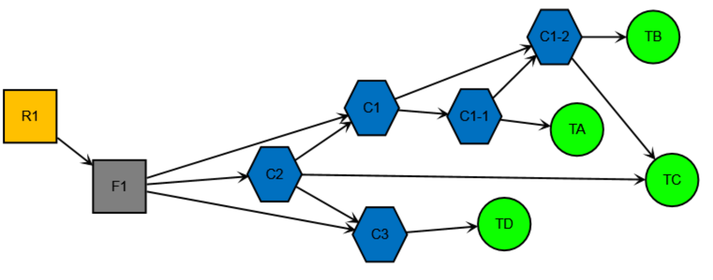

Figure 4: Relationships among requirement (R), function (F), components (C), and tasks (T)

Afterwards, the likelihood and impact values of changes are quantified trough deeper information search and expert interviews, similarly as in Clarkson et al. (2004). Moreover, for easy and quick model building, only the values 0, 0.3, 0.5, 0.7 and 1 are used for evaluating the likelihood and the impact of a change propagation. Although that limits the level of detail, it is sufficient for the purpose of this method. As described in section 2.1, risk is defined as "likelihood x impact". Here, the project structure (i.e. the Tasks DSM) is not included since this information flows directly into the project modelling (Stage 3).

4.2 Change propagation computing

When an engineering change is triggered by a stakeholder at a requirement, function or component level the risk of propagation is calculated up to the risk of changes on tasks.

Two cases are distinguished, Engineering Changes can trigger a new task or cause rework in an existing task. In this paper we focus on the second case, where Engineering Changes cause rework within an existing task. In order to calculate the combined risk, the CPM algorithms (c.f. Clarkson et al. 2004) are applied to the Risk-MDM (Figure 5). For an easier application, these algorithms were implemented in the graph processing software *Soley*.

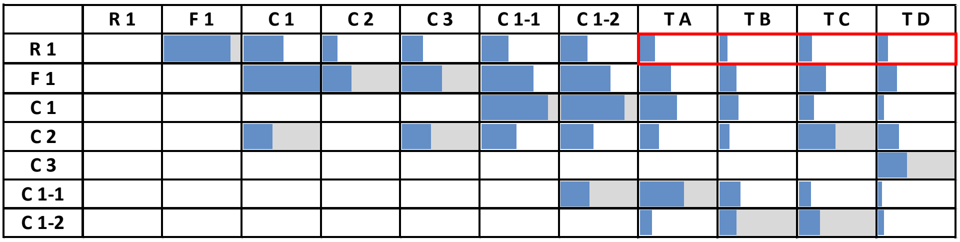

Figure 5: Computed risks of change propagation, with especial interest on propagation of requirement changes into the tasks (framed red)

In this case, the computed risks of change propagation from the requirement R1 into the tasks A through D (red in Figure 5) are especially interesting, since they represent the total risk for a change in the requirement affecting these tasks. Thus, based on these values we can estimate how much more effort (in average) would it be required to fulfill a change in R1. These calculated risk values are then transferred to the systems dynamics model. This approach is described in detail in the next sections (4.3 and 4.4).

4.3 Model building

The system dynamics model represents the project's dynamics as a series of interconnected tasks. Each task is modelled as a rework cycle, which is the basis of many dynamic models of projects (Lyneis and Cooper 2001). The tasks' dependencies that are derived from the project plan define how the "Work done" in one task influence the "progress rate" in the downstream task. Similarly as in (Kasperek 2014), the system dynamics model is developed based on the project structure documented in a DSM. The rework cycle for Task A and Task B are depicted in Figure 6.

In the next step, the changes that are caused by changes in other tasks are modelled (orange in Figure 6). For this purpose, we suggest an additional flow of activities parallel to the "normal" work, so the additional effort due to the change can be traced. The modelled risk is also estimated based on the formula "likelihood x impact".

Moreover, the changes caused by the propagation of the requirements change through the system structure are modelled separately (Green in Figure 6). The risks computed in the second stage directly affect the "change rate" together with the variable "requirements change", which is the user input of the model, in this case a step function.

The change rate of a task is then calculated through the combination of changes that propagate through the systems' architecture and the changes triggered by changes in an upstream task. Following formula provides a detailed example:

$$\textit{Change rate B} = \textit{Changes A} * \textit{Risk BA} + \textit{Changes R1} * \textit{Risk R1A}$$

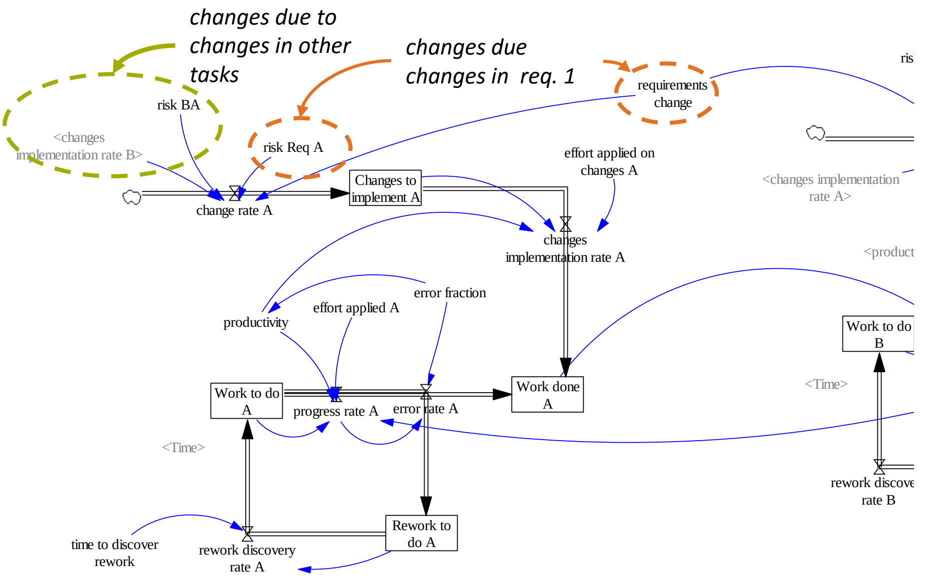

Figure 6: simplified System Dynamics Model (Task A)

4.4 Dynamic simulation

The last stage comprises the dynamic simulation of the model build in stage 3. Figure 8 shows the progress and the effort curves for all four tasks with (red/grey) and without changes (blue/green). With help of these curves, the additional effort to implement the requested requirement change can be visualized and estimated.

4.5 Evaluation

The approach developed is only beneficial as a supporting tool if it provides reliable data and information. A user should be able to identify critical elements and the effects of a change. Moreover, the accuracy of change prediction is difficult to assess and there is no right and wrong, as illustrated by Ahmad et al. (2012). Thus, the first two stages[1] of the approach were evaluated in regard of:

- The identification of critical elements: Users can identify critical elements with a high likelihood of change and is supposed to be used in the overall project planning and sprint planning.
- Identification of the effects of a change: Users can identify the elements with a high effort of implementing a certain change. This information is enhanced by the results in stage four.

[1] The evaluation of stages three and four will take place in future research.

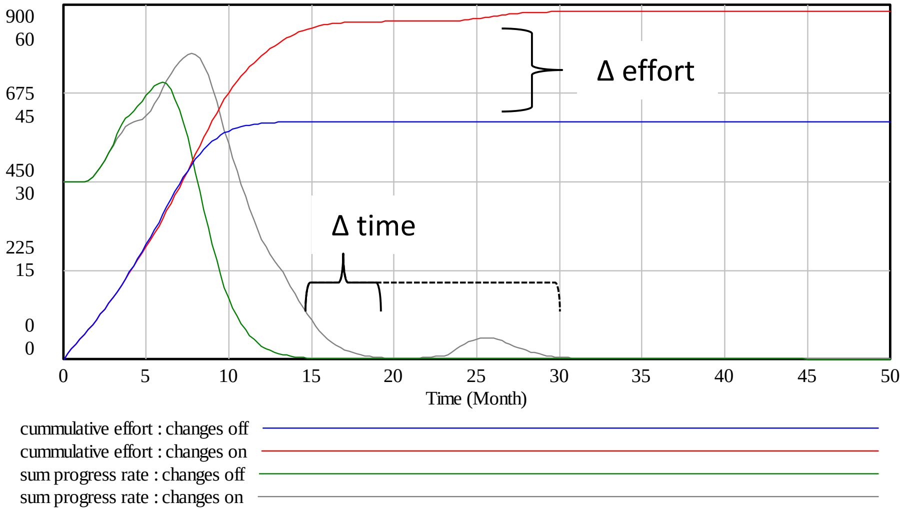

Figure 7: Simulated progress rate and cumulative effort

Two participants took part in the evaluation. Both of them had a technical background however no previous knowledge of the product nor the method. First, the participants had to identify critical elements that have a high change likelihood. Secondly, three different initiating change elements were given and the participants had to identify elements with high risk and assign them valued for the expected effort the effort. These valued were between 1 (little effort) and 6 (high effort). The time the participants needed for each task – alternating between with and without the support presented in this paper – was measured and the outcome of each task was documented.

The evaluation shows that the participant with the support was able to conduct both tasks quicker for each change and mostly performs better. Nevertheless, it has to be considered that both participants had problems with estimating the effort of implementing a change. Future evaluations should test if the system dynamics model provide a richer support for this task.

5 Conclusion and outlook

This paper presents a decision making support method for assessing the effects of engineering changes on the project’s costs and time. Overall research goal namely an improved CP for early stage development was achieved. However some limitations emerged, firstly the quality of the estimation depends highly on the quality of the product model. Another important limitation is that the results depend on the initial estimations of impact and likelihood. Further research could provide additional support to form a base for these estimations.

On the other hand, thanks to the implementation of the CPM in *Soley*, the underlying DSM is not static anymore. Thus this system model organically together with the information generation process during the early phases of development; fulfilling the one of the main requirements.

Moreover, the method proposed enables an interactive assessment with the stakeholders in the ECM process. The results from stages 2 and 4 deliver visual communication documents to engage with the costumers. Finally, the dynamic simulation gives a valuable support to estimate the efforts that derivate from changing requirements.

Future work would include a comprehensive evaluation in more industrial case studies and the development of an interface between the *Soley* model and the system dynamics simulation.

References

Ahmad, N., Wynn, D. C., & Clarkson, P. J. (2010). Development and evaluation of a tool to estimate the impact of design change. Paper presented at the International Design Conference (Design 2010), Dubrovnik, Croatia.

Ahmad, N., Wynn, D. C., & Clarkson, P. J. (2012). Change impact on a product and its redesign process: a tool for knowledge capture and reuse. Research in Engineering Design.

Blessing, L. T. M., & Chakrabarti, A. (2009). DRM, a Design Research Methodology. London: Springer.

Clarkson, P. J., Simons, C., & Eckert, C. (2004). Predicting Change Propagation in Complex Design. Journal of Mechanical Design, 126(5), 788-797.

Grantham-Lough, K., Stone, M., & Tumer, I. (2006). Prescribing and Implementing the Risk in Early Design (RED) Method. ASME 2006 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia, USA.

Hamraz, B. (2013). Engineering Change Modelling Using a Function-Behaviour-Structure Scheme. (PhD), University of Cambridge, Cambridge, UK.

Jarratt, T. A. W., Eckert, C. M., Caldwell, N. H. M., & Clarkson, P. J. (2010). Engineering change: an overview and perspective on the literature. Research in Engineering Design, 22(2), 103-124.

Jarratt, T. A. W., Eckert, C. M., & Clarkson, P. J. (2004). Engineering change. In P. J. Clarkson & C. M. Eckert (Eds.), Design process improvement (pp. 262-285). New York, USA: Springer.

Kasperek, D., & Maurer, M. (2013). Coupling Structural Complexity Management and System Dynamics to represent the dynamic behavior of product development processes. In Systems Conference (SysCon), 2013 IEEE International (pp. 414-419). IEEE.

Kasperek, D.; Chucholowski, N.; Maisenbacher, S.; Lindemann, U.; Maurer, M. (2014): A Method for Impact Analysis of Cyclic Changes within Innovation Processes of PSS. In: Procedia CIRP 16, S. 205–210.

Lyneis, James M., Kenneth G. Cooper, and Sharon A. Els. "Strategic management of complex projects: a case study using system dynamics." System Dynamics Review 17.3 (2001): 237-260.

Nichols, K. (1990). Getting engineering changes under control. Journal of Engineering Design, 1(1), 5-15.

Terwiesch, C., & Loch, C. H. (1999). Managing the process of engineering change orders: The case of the climate control system in automobile development. Journal of Product Innovation Management, 16, 160-

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Predicting Technical Communication in Global Product Development Projects Related Change Propagation

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Abstract: Technical communication is a key feature in Global Product Development (GPD) project to coordinate geographically distributed change management process due to a new functionality requirement or technology. Design Structure Matrix (DSM) and Multi-Domain Matrix (MDM) models are effective approaches for predicting technical communication and change propagation, optimizing GPD organization, and reducing change complexity. This paper presents the involvement degree matrix with the notion of gain factors among distributed teams to explore the factors influencing communication frequency in GPD. Further, this paper proposes a method to measure the combined change likelihood matrix based on numerical change propagation paths order, which extends previous change propagation algorithms. Finally, an industrial example is provided to illustrate the proposed models of predicting technical communication related to product's change. Results provide an integrated managerial insight to reflect how change propagation can impact the technical communication among team's organization.

Keywords: global product development (GPD), project management, technical communication, change propagation, design structure matrix (DSM), multi-domain matrix (MDM)

1 Introduction

Global products continually evolve through frequent complex process changes (i.e. redesign). Managing this process across global PD team's coordination barriers become more complex because of the technical communication exchange challenges to reduce the development cost effort within a GPD team organization (Yang et al., 2015). This may lead the project managers and the engineering managers to identify the GPD team organization associated with redesign process (Sosa, 2008). The Design Structure Matrix (DSM) and Multi-Domain Matrix (MDM) (Eppinger and Browning, 2012) are a powerful structural method to model the numerical effects of potential change propagation between components in a complex product, and predict the amount of redesign effort for future changes. Global PD organization is likely to be symmetric (i.e., an actor requires information while the other one provides information) and is typically determined by the directionality of components dependencies. In this paper, we extend previous models proposed by Hamraz et al. (2013) to measure the numerical change propagation in process redesign, and models proposed by Bonjour et al. (2010) and Sosa et al. (2008) to predict technical communication derived from change propagation in GPD project organization. We contribute a systematic method for predicting technical communication in GPD organization using MDM (Section 2). The paper presents a new involvement degree of PD teams in process design related to the factors influencing technical communication. The paper illustrates new numerical DSMs to evaluate the combined change likelihood for multiple potential change propagation order (Section 3). In Section 4, an industrial example is used to verify the proposed model. We conclude the paper in Section 5.

2 Technical communication of GPD teams related to product change using DSM/MDM

Change propagation analysis has been based on the view that the design change of one component can propagate through the interdependence relationships, requiring redesigns of many other components until all components can work together to perform the intended function (Clarkson et al. 2004; Hamraz et al. 2013; Maier et al. 2014).

The likelihood of change (i.e., the probability) can help designers adjust components and interfaces to manage product modularity and evolution. Still other analyses have used DSMs as the basis for calculating various metrics, especially pertaining to modularity (e.g., Chiriac et al., 2011; Sarkar et al., 2013). Researchers also built DSM models of project risks to show the relationships among components and determine the second-order risks emerging from risk interactions (e.g., Fang and Marle, 2012; Marle et al., 2013). Because the implications of design or engineering changes reach across the product, process, and organizational domains, several have used MDM models to investigate change propagation in various industries (e.g., Koh et al., 2012; Mikaelian et al., 2012; Pasqual and De Weck, 2012). Rich MDM models have provided a basis for capturing and storing system-level knowledge about products, design tasks, design organizations, etc. (Tang et al., 2010) and for identifying organizational core competencies (Bonjour and Micaëlli, 2010).

The predicted technical communication in the reorganized GPD organization determines the pair of teams that could potentially handle indirect changes if one component is redesign in the product (Sosa et al., 2008； Bonjour et al., 2010).

Fig. 1 shows the steps of predicting technical communication in GPD organization related to the possibility of change propagation between components in the product DSM (*P_DSM*) (i.e., the estimation of the combined likelihood of change in *P_DSM*) and the involvement degree of a team in the redesign of one component (i.e. $ID(I,i)$).The predicted organization DSM (*O_DSM*) estimates the potential technical communication interactions that would need to coordinate changes in component (i.e., how to reorganize GPD teams if component C_i is redesigned?).Thus, the technical communication of GPD teams related to product change can be calculated by equation 1.

$$O_{DSM\,(I,J)} = \sum_{i=1}^{n} ID(I,i) \times \sum_{j=1,j\neq i}^{n} (ID(J,j) \times (CL(i,j) + CL(j,i))) \quad (1)$$

For the GPD projects, not only the time zone difference but also the dependency relationship between activities will impact the communication efficiency between globally distributed teams. The typical dependency relationship between activities can usually be divided into sequential activities and coupled activities (Eppinger and Browning, 2012). Therefore, the overlapping process can lead to increased synchronous communication. We assume that the synchronous communication between the teams can be negligible if no overlapping exists. In GPD, overlapped coupled activities involve strong communication frequency with more synchronous communication, which is a major driver of project cost and schedule overruns. So, there is a two-way communication between teams performing coupled activities. We present the concept of the team's *Gain Factor* (in the synchronous situation (i.e., GF_S) and the asynchronous situation (i.e., GF_A)) which is defined as the potential gain degree of the team involved in the PD process to emphasize communication in the environment of GPD project. The *communication dependency strength* (*CDS*) between teams related to the redesign process is as follows:

$$CDS(I,J) = PSC(I,J) \times GF_S(I,J) + PAC(I,J) \times GF_A(I,J) \quad (2)$$

$$GF_S(I,J) = \lambda_1 \cdot \lambda_2 \cdot \frac{\ln(\alpha \times T_{OV}(i,j) \times DSWR(i,j) + 1)}{N_I(I) + N_I(J)} \quad (3)$$

$$GF_A(I,J) = \gamma \cdot \frac{\ln(\beta \times DAWR(i,j) + 1)}{N_I(I) + N_I(J)} \quad (4)$$

The *proportion of synchronous communication* (*PSC*) and the *proportion of asynchronous communication* (*PAC*) are the ratio of synchronous and asynchronous communication frequency to the total required communication frequency respectively, and $PAC(I,J)=1-PSC(I,J)$. $N_I(I)$ (or $N_I(J)$) represents the number of individuals in the team *I* (or team *J*) performing activity *i* (or activity *j*). Since larger sizes of the team have fewer opportunities to participate in discussions than team members from smaller teams (Bardhan et al. 2012), so $N_I(I)$ and $N_I(J)$ is the inverse function of GF_S and GF_A (Equations (3) and (4)).

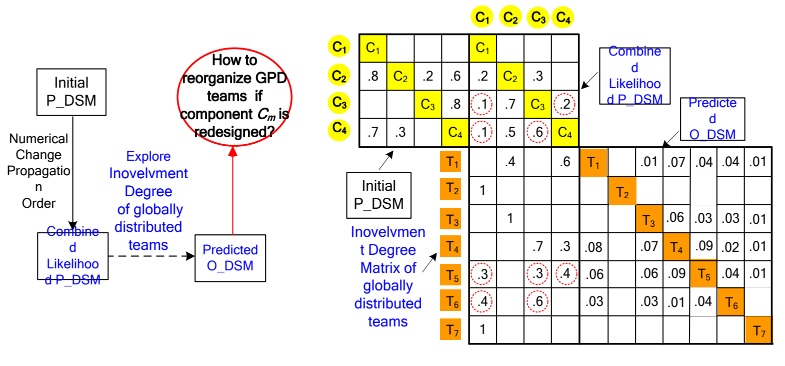


Figure 1. Steps of predicting technical communication of GPD teams related to product change

λ_1 represents the value of different overlapped situation (λ_1=0.5 for the overlapped sequential activities and λ_1=1 for the overlapped coupled activities). λ_2 represents the organization's IT facility for increasing communication of overlapped work in geographically distributed environments. α represents the capability for reducing misunderstanding and communication uncertainty related to spatial distance. *Β* indicates the level of importance and emergency of information exchange between teams during shifting working hours. γ represents the IT that can be used by a team's individuals during shifting hours to facilitate asynchronous information exchange. *DSWR* is the *Daily Synchronous Working Ratio* between team's activities as the ratio of *DSWH* to the total working hour of a location's activities (i.e., *WH*(*I*) and *WH*(*J*)).

$$DSWR(i,j) = \frac{DSWH(i,j)}{WH(I) + WH(J) - DSWH(i,j)} \quad (5)$$

DSWH refers to the time of synchronous communication during the workday between teams responsible for overlapped activities.

Because the redesign process of component *m* may involve more than one team, the original *relative communication dependency strength* ($RCDS_O$) of teams *I* compared to the *CDS* of all the involved teams in *m* can be obtained as follows:

$$RCDS_O(I,m) = \sum_{J=1}^{N_T} CDS(I,J)_m \quad (6)$$

where N_T is the size of teams. In order to obtain a normalized $RCDS(I,m)$, the value of $RCDS_O(I,m)$ is divided by the maximum. The involvement degree ($ID(I,m)$) is defined as the ratio of $RCDS(I,m)$ to its entire *RCDS* in the redesign process of all involved components.

3 Combined change likelihood of different change propagation path

Managing change propagation effectively is necessary not only to understand the state of the design and the connectivity between the product's parts but also how design changes could propagate into the organizational structure and the impact of technical communication among the teams involved.

First-Order (Direct) Change Propagation

The initial product DSM indicates the direct effect of change design between components *n* and *m* is the *single likelihood* of first-order change propagation ($SL^{(1)}$).

$$SL^{(1)}(m,n) = DSM(m,n) \quad (7)$$

Second-Order (Indirect) Change Propagation

The $SL^{(2)}$ resulted from the indirect impact of a design change of component *n* on component *m* through an intermediate component *p* (i.e.,$C_n \rightarrow C_p \rightarrow C_m$) (see Fig. 2(a)is:

$$SL^{(2)}(m,n) = \sum_{p=1}^{N_C} SL^{(2)}(m,n) = \sum_{p=1}^{N_C} DSM(p,n) \times DSM(m,p) \quad (8)$$

where $p \in \{1,2,\ldots,N_C\}$, $m \neq n$, $n \neq p$, $m \neq p$.

Third-Order (Indirect) Change Propagation

The $SL^{(3)}$ resulted from the indirect impact of design change of component *n* on *m* through two intermediate components *p* and *q* (i.e.,$C_n \rightarrow C_p \rightarrow C_q \rightarrow C_m$) be calculated without cyclic path (see Fig.2(b)):

$$SL_{p,q}^{(3)}(m,n) = DSM(p,n) \times DSM(p,q) \times DSM(m,q) \quad (9)$$

where $q \in \{1,2,\ldots,N_C\}$.For the situation of the change propagation with cyclic path (see Fig. 2(c)), the $SL^{(3)}$ would also allow a loop for the second component which involves higher coordination costs between redesign teams (Sosa et al., 2013):

$$SL_p^{(3)}(m,n) = DSM(m,n) \times DSM(p,m) \times DSM(m,p) \quad (10)$$

The $SL^{(3)}$ from *n* to*m* through all possible intermediate components is:

$$SL^{(3)}(m,n) = \sum_{p=1}^{N_C} \sum_{q=1}^{N_C} SL_{p,q}^{(3)}(m,n) + \sum_{p=1}^{N_C} SL_p^{(3)}(m,n) \quad (11)$$

Combined Change Likelihood

The combined change likelihood (i.e., $CL(m,n)$) (see Fig.2(d))refers to the integrated change probability in the design of component *n* leading to a design change in component *m* through all potential change propagation path *z*.

$$CL(m,n) = SL^{(1)}(m,n) \cup SL^{(2)}(m,n) = 1 - \prod_{z=1}^{3}(1 - SL^{(z)}(m,n) \quad (12)$$

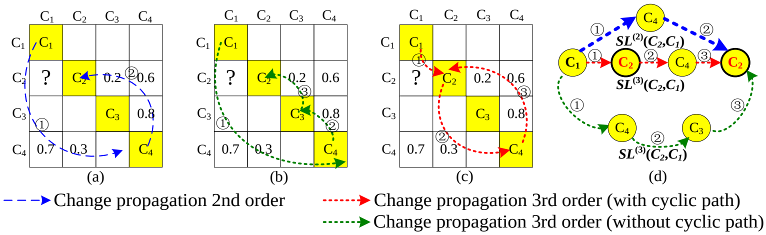


Figure 2. An example of the first, second and third order change propagation

4 Illustrative Example

An industrial example, Wrapper Revamping redesign project or Paradise Food Industry managed by the Italian Cavanna Packaging Group is used. The Wrapper Revamping redesign project is a globally distributed to meet customers’ requirements. The technical teams executing the process of the redesign are distributed in four locations across Southern Europe and Northern America: two Italian plants located at Prato Sesia and Turino, two American plants located in Allendale and Duluth. The Involvement Degree Matrix is shown in Fig. 4. We developed the program using Matlab 15 software. The parameters in equations (3) and (4) are evaluated according to the project manager’s knowledge and experience.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
A		.42						.58										
B				.52					.40				.04		.04			
C	.54								.46									
D						.82		.09			.05		.04					
E		.26	.31									.42						
F			.26				.44									.18	.12	
G				.24						.53				.23				
H					.68								.32					
I	.15									.12								.73
J																		
K						.25								.75				
L		.04						.27	.68				.01					
M				.66	.17							.10			.07			
N																1		
O			.51								.49							
P	.63																.37	
Q							.37						.32			.31		
R				1														
S																	1	
T			.78										.22					
U						.20				.51								.29
V					.40							.60						
W						.55				.18						.27		

Prato Sesia Allendale Duluth Turino

(b)

Figure 4.Involvement Degree Matrix

The original likelihood DSM is elicited from the chief designers, sales managers, and project managers. The combined likelihood is the resulted change propagation after three paths order. $SL^{(1)}(m,n)$ and $CL(m,n)$ are shown in Fig. 5(a) and (b) respectively.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Sealing Wheel	1	1	.3		.6											.4			
Zero5 Wrapper	2	.5	2									.7	.7			.3			
Differential Box	3		.8	3			.8	.5									.5		
Servo Motor	4	.5	.8		4					.8									
Dwell Gear Box	5			.8		5												.5	.3
Conveyor	6			.3			6												
Lane Reducer	7		.8	.1				7		.5								.9	
Electrical Panel	8								8										
Screen HMI	9	.4		.3	.1					9									
Row Preparation	10							.6			10			.6					
Buffer Fifo	11	.1										11							
Stream In Feed	12												12						
SBF Loader	13								.8					13					
Crimper Jaws	14			.5						.4			.2		14	.3			.6
Loading System	15	.7														15			
Stacking Device	16			.8								.1					16		
Pull-Nose Device	17					.7												17	
Transfert Unit	18										.4								18

(a) $SL^{(1)}(m,n)$

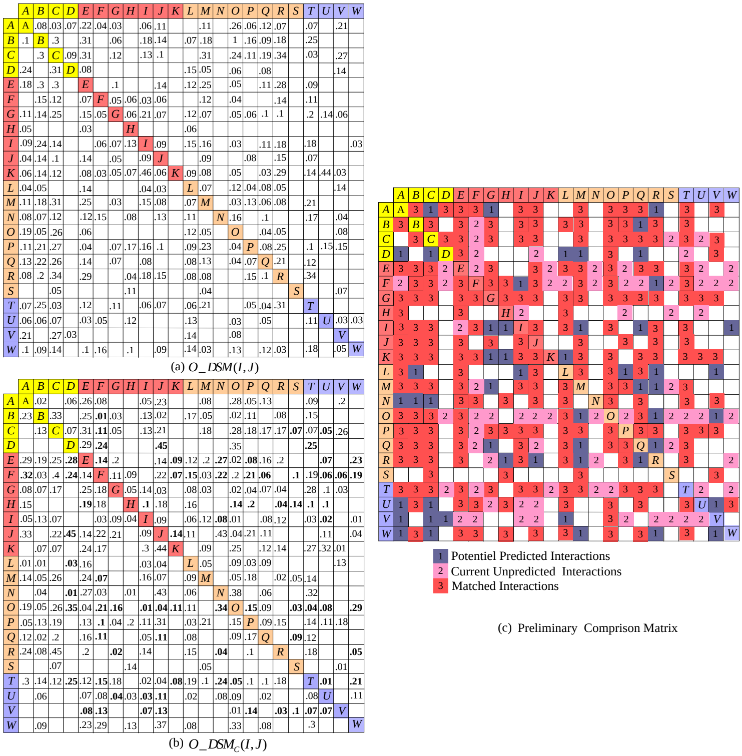
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1	.55		.63					.48		.55	.07			.93			
2	.63	2		.72					.69		.48	.60			.98			
3			3															
4	.76	.98		4					.87		.78	.85			.85			
5					5													
6	.62	.46		.54		6					.93	.26			.45			
7	.25	.32		.29			7		.65						.87			
8								8										
9	.85	.83		.91					9		.93	.89			.88			
10	.76			.91			.65	.93	.80	10			.76					
11	.62	.46		.15							11	.69			.25			
12	.42	.93		.31							.39	12			.49			
13								.33					13					
14	.76	.89	.93	.77			.74	.88	.78	.89			.86	14	.87			.84
15	.93	.49		.39					.93		.39	.37			15			
16	.31	.31	.56								.93	.62				16		
17					.83												17	
18							.43	.43	.02	.93			.21					18

(b) $CL(m,n)$

Prato Sesia Duluth Turino

Figure 5. Single and combined change likelihood DSMs

The development organization structure obtained by simulating change propagation is presented in Fig.6(a). We overlap the current organization DSM (i.e., $O\_DSM_C(I,J)$ (calculated by replacing $CL(m,n)$ with $SL^{(1)}(m,n)$ in Eq. (1)) with the predicted $O\_DSM(I,J)$(calculated by Eq. (1)), which is obtained by subtracting $O\_DSM(I,J)$ from $O\_DSM_C(I,J)$(i.e., Δ $O\_DSM(I,J)$). We can present a comparison matrix M whose element $M(I,J)$ can be defined as follows: $M(I,J) = 1\ If\ \Delta O\_DSM(I,J) = O\_DSM(I,J)$; $M(I,J) = 2\ If\ \Delta O\_DSM(I,J) = O\_DSM_O(I,J$; $M(I,J) = 3\ If\ \Delta O\_DSM(I,J) = \alpha_{\in \Re}$. We define the co-affiliation matrix which refers to a couple of teams commonly involve in the redesign of certain components (Field et al., 2006). By overlapping the co-affiliation matrix with the preliminary comparison matrix we can identify truly predicted (unattended) interactions between teams. We introduce the notion of *Team Performance Index* (*TPI*), which refers to a team's performance to align their pattern of technical communication with their pattern of change in design components. *TPI* ranks the teams involved to reorganize the overall organization DSM (see Fig. 7(b) and (c)).

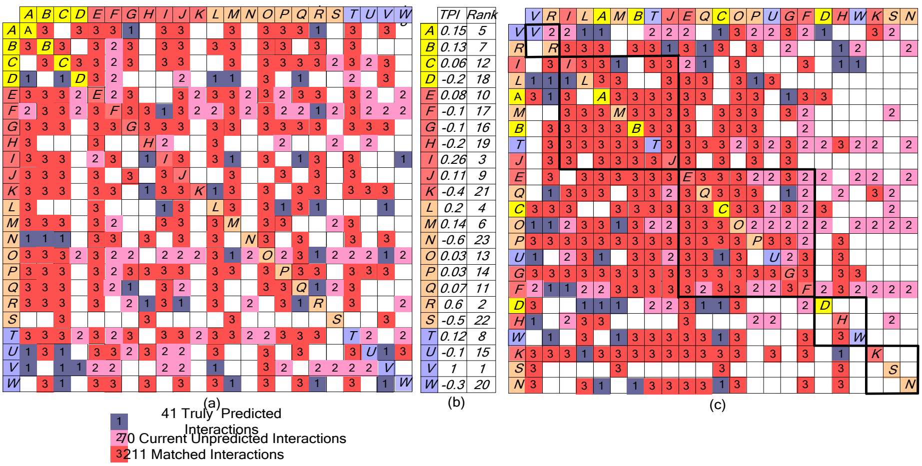


(a) $O\_DSM(I,J)$

(b) $O\_DSM_C(I,J)$

(c) Preliminary Comprison Matrix

Figure 6. Preliminary comparison analysis



(a) (b) (c)

Figure 7. Optimized organization DSM

5 Conclusion

A systematic method for predicting technical communication between geographically dispersed teams related product change in GPD projects has been presented in this paper.

We argue that not only the time zone difference (i.e. downstream activities located at eastern or western time zone compared to upstream activities) but also the dependency relationship between activities (i.e. *overlapped sequential activities* and *overlapped coupled activities*) impacts the communication efficiency between globally distributed teams. In practice, the project manager can utilize our models to predict the potential team organization distributed across geographical boundaries if changes occur in the product architecture.

References

Bardhan, I., Krishnan, V. V., Lin, S., 2012. Team dispersion, information technology, and project performance. Production and Operations Management 1-16.

Bonjour, E., Harmel, G., Micaelli, J. P. and Dulmet,M., 2010. Simulating change propagation between product architecture and development organization. International Journal of Mass Customisation3(3), 288-310.

Bonjour, E., Micaëlli, J.-P., 2010. Design Core Competence Diagnosis: A Case From the Automotive Industry. IEEE Transactions on Engineering Management 57, 323-337.

Chiriac, Hölttä-Otto, N. K., Lysy, D., Suh, E.S., 2011. Level of Modularity and Different Levels of System Granularity. Journal of Mechanical Design 133.

Clarkson, P. J., Simons, C., Eckert, C., 2004. Predicting change propagation in complex design," Transactions of the ASME 126, 788-797.

Eppinger, S. D., Browning, T. R., 2012. Design structure matrix methods and applications. MIT Press, Cambridge, MA.

Fang, C., Marle, F., 2012. A Simulation-based Risk Network Model for Decision Support in Project Risk Management. Decision Support Systems 52, 635-644.

Field,S., Frank, K., Schiller, K., Riegle-Crumb, C., Muller, C., 2006. Identifying social positions from affiliation networks: preserving the duality of people and events.Social Networks 28 (2), 97-186.

Hamraz, B., N. H., Caldwell. M., Clarkson, P. J., 2013. A Matrix Calculation Based Algorithm for Numerical Change Propagation Analysis. IEEE Transactions on Engineering Management 60 (1), 186-198.

Koh, E.C.Y., Caldwell, N.H.M., Clarkson, P.J., 2012. A Method to Assess the Effects of Engineering Change Propagation. Research in Engineering Design 23, 329-351.

Maier, J. F., Wynn, D. C., Biedermann, W., Lindemann, U., Biedermann, W., 2014. Simulating progressive iteration, rework and change propagation to prioritize design tasks. Research Engineering Design 25, 283-307.

Marle, F., Vidal, L.-A., Bocquet, J.-C., 2013. Interactions-based Risk Clustering Methodologies and Algorithms for Complex Project Management. International Journal of Production Economics142, 225-234.

Mikaelian, T., Rhodes, D.H., Nightingale, D.J., Hastings, D.E., 2012. A Logical Approach to Real Options Identification with Application to UAV Systems. IEEE Transactions on Systems, Man, and Cybernetics--Part A: Systems and Humans 42, 32-47.

Sarkar, S., Dong, A., Henderson, J.A., Robinson, P.A., 2013. Spectral Characterization of Hierarchical Modularity in Product Architectures. Journal of Mechanical Design 136, 011006.

Sosa, M. E., 2008. A structured approach to predicting and managing technical interactions in software development. Research Engineering Design 19 (1), 47-70.

Sosa, M. E., Mihm, J., Browning, T. R., 2013. Linking cyclicality and product quality. Manufacturing & Service Operations Management 15 (3), 473–491.

Tang, D., Zhu, R., Tang, J., Xu, R., He, R., 2010. Product Design Knowledge Management based on Design Structure Matrix. Advanced Engineering Informatics 24, 159-166.

Yang, Q., Kherbachi, S. Hong, Y. S., Shan, C., 2015. Identifying and managing coordination complexity in global product development project. International Journal of Project Management 33 (7), 1464-1475.

Yang, Q., Yao, T., Lu, T., Zhang, B., 2013. An overlapping-based design structure matrix for measuring interaction strength and clustering analysis in product development project. IEEE Transactions on Engineering Management 61 (1), 159-170.

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	Chucholowski, Nepomuk; Kriegler, Johannes; Hollauer, Christoph; Kattner, Niklas; Becerril, Lucia; Weidmann, Dominik; Lindemann, Udo	Technical University of Munich, Germany	Systematic Partitioning in Mechatronic Product Development by Modeling Structural Dependencies
	Arasti, Mohammadreza (1,3); Khaleghi, Mahdi (2,3)	1: Graduate School of Management and Economics, Sharif University of Technology, Tehran, Iran, Islamic Republic of; 2: Faculty of Management, University of Tehran, Tehran, Iran, Islamic Republic of; 3: CRiTIMiX (Center for Research in Technology and Innovation Management in compleX industrial systems), Sharif University of Technology, Tehran, Iran, Islamic Republic of	Analyzing Organizational Capabilities as Systems: A Conceptual Framework
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	Malaek, S. M.; Mahrooz, M. H.	Sharif University of Technology, Iran, Islamic Republic of	Application of DSM in Integrating Modern Technology into Operational Architecture of Aerial Firefighting
	Ansari, Lazima; Hossain, Shahadat; Khan, Ahamad Imtiaz	University of Lethbridge, Alberta, Canada	DSMDE: A Data Exchange Format for Design Structure Models
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