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Graph-Based Analysis of Team Collaboration in an Agile Medical Engineering Project

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Abstract: Agile development approaches are gaining popularity in hardware product development and medical engineering. Consequently, techniques of structural complexity management can be applied on agile projects. This paper analyses the collaboration data of a twelve-month project to design a 3D-printed microtiter plate. Exchanged e-mails, created artifacts, and conducted tasks were analyzed to identify typical barriers of inter-disciplinary collaboration. Appropriate improvement measures to overcome these barriers were suggested and evaluated in a four-hour workshop with members of the core team of the project. As a result, out of the collaboration network with 851 nodes and 9001 edges, six main barriers were identified. The most hindering barriers according to the experts' opinion were matched with appropriate improvement measures. After an assessment of the cost/benefit ratio, two measures were chosen for implementation.

Keywords: modelling of socio-technical systems, complex development processes, graph analysis, MDM, DMM

1 Introduction

Three trends guide much of the current research on engineering design processes: growing complexity of products and processes; increasing digitization and associated generation and potential of data (Eckert et al., 2019); and a strong wish from industry to transfer agile development methods onto hardware design (Schmidt et al., 2018). In all of these three areas, inter-disciplinary development is key. With the benefits of interdisciplinarity like different points of view and access to knowledge from different sub-disciplines, additional barriers in the collaboration arise as well (Schweigert-Recksiek and Lindemann, 2018). The question of Sosa et al. (2007), whether engineers talk to each other when they should, is more relevant than ever. To answer this question – and others concerning efficient collaboration in agile engineering teams – this paper aims at identifying barriers in the collaboration of an agile medical engineering team and providing improvement measures to overcome these barriers by methods of structural network analysis.

2 State of the Art and Research

2.1 Structural Analysis of Collaboration Networks

For the structural analysis of engineering design collaboration networks and structural metrics for engineering design process, this research uses the approaches developed by

Kreimeyer and Lindemann (2011). According to the Goal-Question-Metric approach described by Basili and Weiss (2005), Kreimeyer defines a set of structural metrics for engineering design processes to build a measurement system as used in the framework of this paper. In a comparable approach, Mathieson and Summers (2017) describe a protocol using e-mail exchange and other data to build networks to analyse them via network metrics. This is used to identify member roles and work schedules. Piccolo et al. (2018) build multiple domain matrices of structural engineering project data to correlate properties of tasks and execution time. Maier et al. (2008) explore correlations between factors influencing communication in complex product development to make engineering communication more assessable (see also Maier et al., 2009). Jafari Songhori and Nasiry (2019) use the misalignment theory that compares organizational structures and product structures to conduct analyses of the decision making structure of engineering projects that can be applied to the collaboration of design and simulation departments as well.

2.2 Collaboration Analysis of Agile Projects

As agile approaches are increasingly applied also in the field of mechanical and mechatronic engineering (Schmidt et al., 2018), they find their way into engineering management literature. As Eppinger (2019) points out, the application of agile approaches can also benefit from the methods and tools developed for "traditional" complex engineering projects. Srinivasan et al. (2019) show how DSM techniques can identify enablers for the adoption of agile methods like DevOps. Also in frameworks like SAFE, which are already widely applies in industry, DSM techniques show characteristic patterns that can be used to optimize processes and organizational structures (Bajpai et al., 2019).

3 Methodology

3.1 Research Gap and Research Questions

As shown, structural collaboration analysis of agile projects in hardware development is evolving. This leaves the research gap of a structural collaboration analysis with special emphasis on inter-departmental collaboration using pattern recognition. To fill this gap, the following research questions have to be answered: **RQ1:** How can barriers of interdisciplinary product development be identified in complex collaboration networks? **RQ2:** Which improvement measures can be mapped to the identified barriers?

3.2 Research Methodology

3.2.1 Boundary Conditions of the Analyzed Development Project

The analyzed research project called IDAGMED (**I**nter-Disciplinary **AG**ile **MED**ical engineering) consisted of two phases of six months each. In each phase a core team of four to five students as well as research associates and employees from an industry partner developed a microtiter plate in an agile scrum-based development project (for more details on the developed product as well as the agile methods cf. Gerber et al. (2019)). The members of the core team hat the following roles: design engineer, simulation engineer, requirements engineer, scrum master, and product owner. The project finished successfully with a 3D-printed and biocompatible prototype of a new geometry for microtiter plates (cf. also (Goevert et al., 2019)).

3.2.2 Analysis Methodology/Preliminary Work

In order to analyze the collaboration of the core teams as well as their interfaces to other stakeholders of the project, collaboration data like e-mails, entries in a project management software and the produced files were tracked. This served as an input for the analysis according to the approach first described in (Schweigert et al., 2017). A set of structural network metrics build on Kreimeyer and Lindemann (2011) as described in (Knippenberg et al., 2018) was calculated from the data set in order to identify barriers in the collaboration. These barriers, which are not listed here but are described in (Schweigert-Recksiek and Lindemann, 2018), were matched to suitable improvement measures as elaborated in (Schweigert-Recksiek and Lindemann, 2020). The data was imported to Python, and the resulting graphs were exported to Neo4j to import them again into Gephi to create visualizations. These visualizations were presented to members of the core teams and discussed to decide on the applicability of the selected measures.

4 Results

4.1 Data Acquisition and Preparation

Meta data was collected according to the meta model depicted in Figure 1. The data set consisted of e-mails from the inboxes of eleven core team members, all files that were stored in exchange folders at the end of each sprint as well as documented user stories, sub-user stories, sub-sub user stories and tasks from each sprint. There were five sprints in phase one and six sprints in phase two.

		P	A	T
Person	P	communicates with [e-mail inboxes]	creates [files in drop folder]	performs [sprint backlog]
Artifact	A	-	-	-
Task	T	-	produces [files in drop folder]	is connected to [same (sub-)user story]

Figure 1. Meta model and data sources

The e-mails were exported after every phase from e-mail clients into spreadsheets to prepare them for the import into Python. This included some data cleaning like the unification of names and avoidance of special characters. As the e-mails came from different e-mail clients, they also had to be transferred into a consistent format. The user stories, sub-user stories, and sub-sub-user stories were collected in a spreadsheet throughout the projects. Tasks were documented in Trello. Unique IDs were given to every person, artifact or task to enable a consistent analysis. Between the so created nodes, the following relations were built. A person is connect to a person if it received an e-mail from this person. A person is connected to an artifact if it created it. A person is connected to a task if it was assigned to perform it. A task is connected to an artifact if this artifact resulted from it (e.g. reports, created CAD files). A task is connected to another task if they are contributing to the same (sub-)user story.

4.2 Key Facts

As shown in the graph of Figure 2, a total of 268 persons and organizations, 314 tasks, and 269 artifact formed the data set. They were connected by a total of 9001 relations with different weights (including 10915 e-mails, 438 task assignments, 323 assigned artifacts to persons, 2316 task-artifact relations, and 4881 task-task relations).

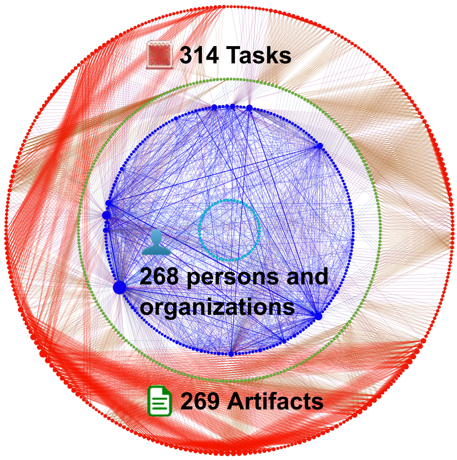


Figure 2. Overall graph with all nodes and relations

Figure 3 shows the overall data in the format of a multiple domain matrix (MDM). Due to space restrictions, it is not easily readable but is zoomable in the PDF, though.

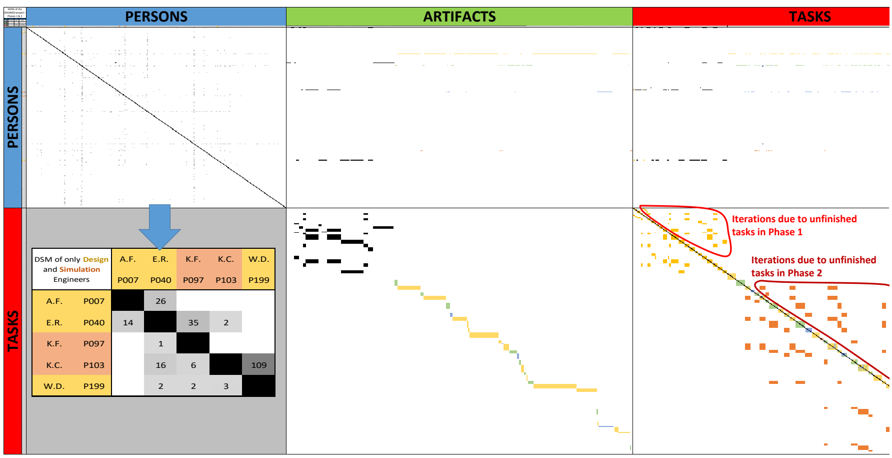
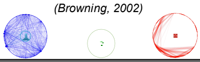
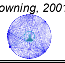
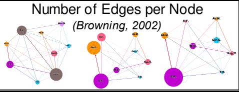
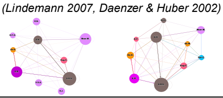
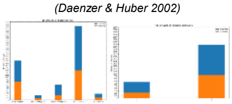
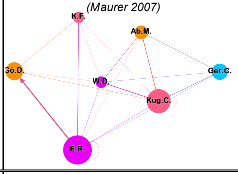


Figure 3. MDM of the overall data

4.3 Identification of Barriers

The collaboration network described above was searched for the 20 typical collaboration barriers listed in (Schweigert-Recksiek and Lindemann, 2018). There, they are formulated corresponding to the collaboration between design and simulation departments, while in IDAGMED, they were applied to inter-disciplinary collaboration in general. Table 1 lists the structural network metrics that were calculated from the graph in order to find hints on whether one or several of these barriers were also present in the collaboration of this project. The graphs were subsequently reduced according to the procedure described in Knippenberg et al. (2018) to produce one graph per metric as shown in the thumbnails of Table 1. Every network metric is linked to one or several barriers as described in (Schweigert-Recksiek and Lindemann, 2020).

Table 1. Applied Structural Network Metrics and associated Barriers

#	Structural Metric	Adapted Metrics for IDAGMED	(max) Value	Associated Barriers
2	Number of Nodes per Domain *(Browning, 2002)* 	M2.1 Number of Persons	268	B 3 (Challenging coordination of design and simulation processes)
		M2.2 Number of Tasks	314	
		M2.3 Number of Artifacts	269	B 19 (Unstructured information sharing) B5 (Conflict between explanation of complex issues vs. high documentation effort)
3	Number of Edges per Domain *(Browning, 2001)* 	M3.1 Number of edges between Persons * weight	8503 [e-mails]	B 4 (Inefficient frontloading and dependency of simulation on design and test departments) B15 (Physical distance that prevents face-to-face communication)
4	Number of Edges per Node *(Browning, 2002)* 	M4.1 Number of assigned tasks * weight per person	108	B 11 (Missing structures of collaboration (e.g. trigger points)
		M4.2 Number of assigned artifacts * weight per person	119	
		M4.3 Number of messages per person * weight	2887	
5	Activity/Passivity *(Lindemann 2007, Daenzer & Huber 2002)* 	M5.1 Number of messages received and sent [Person]	1898 / 1780	B 7 (Handling different human characters) B 8 (Lacking information sharing towards the simulation department) B 10 (Lacking acceptance and inadequate understanding of the capabilities of simulation experts) B 17 (Redundant time-consuming iterations (e.g. due to outdated geometries))
6	Degree correlation (nodes) *(Ahn et al. 2007, Nikoloski et al. 2005)* 	M6.1.1 Degree correlation of messages received and messages sent [Person]	1802:1912	B 8 (Lacking information sharing towards the simulation department) B 10 (Lacking acceptance and inadequate understanding of the capabilities of simulation experts) B 17 (Redundant time-consuming iterations (e.g. due to outdated geometries))
		M6.1.2 Degree correlation of messages received and messages sent between designers and simulation engineers [Person]	784:1185	
7	Fan criticality *(Daenzer & Huber 2002)* 	M7.1.1 Fan criticality (messages received/sent) per role/discipline (design engineer, simulation engineer, scrum master, product owner, requirements engineer)	1932:1284	B 8 (Lacking information sharing towards the simulation department) B 10 (Lacking acceptance and inadequate understanding of the capabilities of simulation experts) B 17 (Redundant time-consuming iterations (e.g. due to outdated geometries))
		M7.1.2 Fan criticality (messages received/sent) per team	1231:941	
8	Number of unconnected nodes *(Maurer 2007)* 	M8.1 Number of people that are indirectly connected via 2 tasks and have a communication relation with a weight below average	4	B 8 (Lacking information sharing towards the simulation department) B 10 (Lacking acceptance and inadequate understanding of the capabilities of simulation experts) B 17 (Redundant time-consuming iterations (e.g. due to outdated geometries))
		M8.2 Number of people (designer and simulation expert) that are indirectly connected via 2 tasks and have a communication relation with a weight below average	0	B 9 (Interdepartmental communication and feedback culture) B12 (Mistrust in simulation results)
9	Number of Connected Nodes *(Maurer 2007)* 	M9.1 Number of tasks + artifacts assigned to a person	227	B 3 (Challenging coordination of design and simulation processes)

The table shows a visualization of the reduced graph for each metric, which was also used in the discussion with the project team to select the most relevant barriers and come up with suitable improvement measures to overcome them. The numbering is according to Knippenberg et al. (2018). Key findings that can be drawn from the analysis are:

- **M4.1, M4.2 & M9.1:** While the distribution of work (measured by the number of assigned tasks and artifacts per person) was very equally distributed in team 1, it was far less so in team 2. This can be a hint for **B11** (missing structures of collaboration) and result in an even more challenging coordination of design and simulation processes (**B3**).
- **M4.3 & M5:** The product owners also had a very active role when it comes to project management, illustrated by their high amount of sent and received messages. This might also be the result of missing structures of collaboration (**B11**) or redundant time-consuming iterations (**B17**).
- **M6.1.2 & M7.1.1:** Simulation engineers (especially in phase 2) took a very passive role in the communication, e.g. illustrated by degree correlation of messages received and messages sent. This can be a result from **B10** (Lacking acceptance and inadequate understanding of the capabilities of simulation experts) or just different human characters (**B07**), often leading to redundant time-consuming iterations (**B17**).
- **M7.1.2:** Team 2 communicated much more via e-mail than team 1 (possibly resulting from more personal contact in phase 1). Lacking communication in general can be associated with redundant time-consuming iterations (**B17**).
- **M8.1:** While requirements engineers communicate actively, the communication between design and simulation is below the average of all inter-departmental communication, which is always challenging (**B09**).

4.4 Matching Barriers with Suitable Recommendations

Through an online survey and an interview study, barriers were matched with suitable recommendations for improvement measures in a domain mapping matrix (DMM). Figure 4 shows links just for the most relevant barriers according to the key findings (A DMM including all barriers and recommendations can be found in Schweigert-Recksiek and Lindemann, 2020). For many barriers, there is a link to one or several recommendations in both the survey data as well as in the opinions of the interviewed experts (black cells). For some, links could only be found in the interview findings (orange cells).

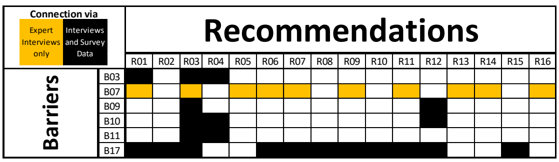


Figure 4. Matching of Barriers and Recommendations according to Schweigert-Recksiek and Lindemann (2020)

For B17 (Redundant time-consuming iterations (e.g. due to outdated geometries)) there is a broad range of possible recommendations for improvement measures. This is due to the variety of reasons that can cause these iterations. This requires a deeper analysis.

5. Application and Evaluation in an Expert Workshop

5.1 Workshop Setup

To validate the findings, a workshop was conducted with members from both phase 1 and 2. The participants (2 product owners [phase 1 & 2], 2 design engineers [phase 1 & 2], 1 simulation engineer [phase 1], 1 requirements engineer [phase 1], 1 data analyst [phase 1 & 2]) originated from all disciplines of the core team except a scrum master. The three-hour workshop consisted of introduction, presentation of the collaboration networks as well as key finds of the data analysis, discussion sessions on the barriers and proposed recommendations for improvement measures and a closing session with feedback.

5.2 Tools and Methods

Interactive element played a major role throughout the workshop. For each network metric, a visualization as well as the corresponding barriers were presented. A web-based interaction tool was then used to ask for the participants' opinion on each visualization of a metric via their smartphones. For each metric they were asked to rate the following aspects (cf. Figure 5): "This aspect surprises me/fulfils my expectations."/"The graph… [between "Not a bit" to "Totally!"]… helps me understand the collaboration./… helps me to identify barriers./… surprises me./... is sensibly linked to barriers."

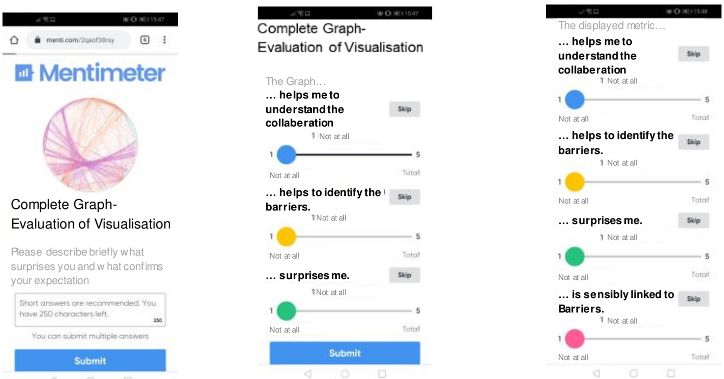


Figure 5. Mentimeter – User interface on smartphones of the participants

In order to create a deeper understanding of the barriers, the participants were also given a handout, listing all barriers and recommendations with short descriptions. Finally, they were asked to give the barriers a ranking to identify the most crucial ones.

5.3 Identified Barriers

As shown in section 4.3, the barriers B03, B07, B09, B10, B11, and B17 resulted as most relevant from the analysis. This overlaps mostly with the opinion of the participants as shown in Figure 6, while they also regarded B13 as very relevant instead of B10.

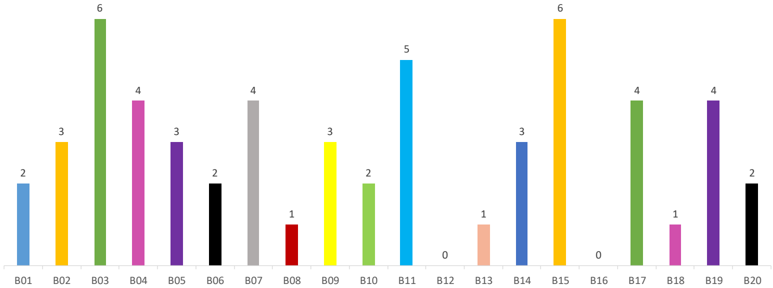


Figure 6. Relevant Barriers according to the participants' opinion

After this ranking, B03 (Challenging coordination of design and simulation processes), which is linked to M9.1 (Number of Connected Nodes) was put into focus.

5.4 Recommendations

To overcome this barrier B03 (Challenging coordination of design and simulation processes), three improvement measures are possible according to the DMM in Figure 4: R01, R03, and R04. Figure 7 shows the experts' opinion on the suitability of these measures to overcome B03.

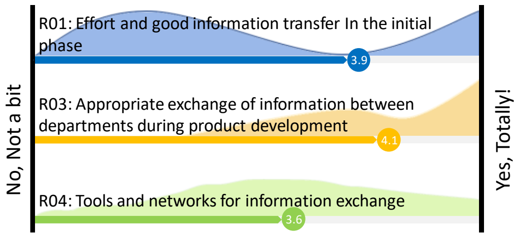


Figure 7. Assessment of measures

Both R01 and R03 also received high ratings concerning the cost/benefit ratio, while R04 was not rated as very beneficial (cf. Figure 8).

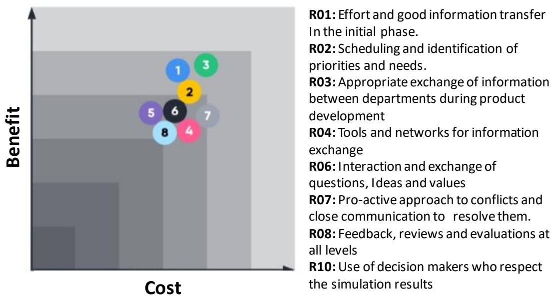


Figure 8. Cost/benefit diagram of possible improvement measures

6 Discussion and Outlook

Despite the high amount of data that was available for analysis, some limitations were present concerning data quality. Not all data was available, as only the e-mail inboxes of the core team could be analyzed, not the ones of all stakeholders. Only meta data was used for the analysis, no content of the communication, artifacts, or tasks. However, as shown by the workshop results, the analysis of this meta data makes collaboration more assessable and can contribute to determine the most relevant barriers in interdisciplinary agile product development as well as suitable measures to overcome them. The authors are currently conducting an interview study with experts from industry that were not part of IDAGMED to validate the experts' opinion concerning suitability of metrics, barriers, and measures as well as the cost/benefit ratio of the improvement measures. This shall include the analysis of further datasets from an industry background. The findings of this paper will not be used in future projects of the participants.

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