INTERNATIONAL DESIGN CONFERENCE - DESIGN 2012
Dubrovnik - Croatia, May 21 - 24, 2012.

DEVELOPMENT OF SYSTEMS THINKING IN MULTI-DISCIPLINARY TEAM INTERACTION: TWO CASES FROM SPACE INDUSTRY

H. A. Moser, G. D. S. Ziegler, L. T. M. Blessing and A. Braukhane

Keywords: space systems engineering, systems thinking, learning, boundary crossing

1. Introduction

Systems engineering is a multidisciplinary activity involving different professions, such as in space projects: mechanical specialists, software specialists, radio-frequency specialists, electronics specialists, and also financial specialists. Expertise in different disciplines is required, which can never be provided in time by a single individual. Teams are required. A team, as defined by Katzenbach and Smith [Katzenbach and Smith 2003], "is a small number of people with complementary skills who are committed to a common purpose, performance goals, and approach for which they hold themselves mutually accountable." The complementary skills mentioned in the team definition highlight one of two types of team heterogeneity, the disciplinary heterogeneity, i.e. teams are heterogeneous in the field of expertise. The other type is experiential heterogeneity, i.e. team members almost never have the same level of work experience. The disciplinary heterogeneity is mainly managed by project managers and system engineers who possess a broad knowledge of the system. If team members would consider other disciplinary perspectives in addition to their own, the required harmonization effort is expected to decrease. Considering other perspectives is regarded as a part of systems thinking. Davidz´s [David 2006] definition of systems thinking as considering "the componential, relational, contextual, and dynamic elements of the system of interest." underlines four basic elements of systems thinking: a) components of the system, e.g. subsystems; b) relationships inside the system, e.g. relationship between subsystem A and subsystem B, and with other systems; c) context of the system as being embedded in a larger system; e.g. influence of the operational environment on the system; and d) the dynamics of the system considering its time dependence. These elements can be also found in Lamb´s [Lamb 2009] definition which puts emphasis on the collaborative and emergent nature of systems thinking: "Collaborative systems thinking is an emergent behaviour of teams resulting from the interactions of team members and utilizing a variety of thinking styles, design processes, tools, and communication media to consider systems attributes, interrelationships, context and dynamics towards executing systems design." As Lamb mentions the emergent nature of systems thinking as being caused by interactions of team members, we expect that participating in a multi-disciplinary but goal oriented working activity is the major driver in the development of systems thinking. To facilitate its development, a better understanding of the activity and the connected development is necessary. The aforementioned authors, Davidz and Lamb, ground their theories on retrospections of participants in the form of questionnaires and interviews. They do not analyze interaction in the engineering process leaving the details of the identified emergence of systems thinking open. The research project aims on studying this emergence process in more detail. In the current paper we present a part of the research project focussing on the development of systems thinking within multi-disciplinary conversations. The temporal range of these verbal interactions in space systems engineering teams is minutes.

2. Background

2.1 Space systems engineering

Space systems engineering considers all lifecycle phases of a space mission. Depending on the organization, phases and labels of the space mission lifecycle deviate but all of them follow in principle the same sequence of phases [Wertz and Larson 1999]. Figure 1 gives an overview of the four main phases of the space mission lifecycle which starts with the conceptual design phase, followed by the detailed design phase, the production and deployment, and the operations and support phase. All four phases can be in the order of days to decades depending on the space system [Messerschmid and Bertrand 1999], [Bhopale and Finley 2009].

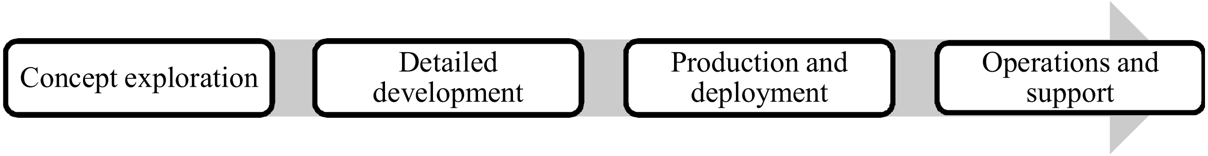

Figure 1. Space mission lifecycle according to [Wertz and Larson 1999]

Space missions consist of three main segments: the transfer segment, the ground segment, and the space segment. The transfer segment includes the transfer of the produced and integrated satellite (spacecraft) into the desired orbit. The ground segment consists of three elements: operation of the mission, the ground stations and the mission products, mainly data and services. The space segment consists of three elements, which are payload, orbit, and spacecraft. The main purpose of the spacecraft is to provide the required working conditions for the payload. The payload integrated in the spacecraft is often called space system. As the orbit is an important variable for the space mission it is defined as an extra element. The spacecraft itself can be divided into several subsystems: structures and mechanisms, thermal management, on-board data handling, power, communication, attitude and orbit control, propulsion, life support. Not all of them are always included, e.g. life support or propulsion [Wittmann and Hanowski 2009]. Space system engineering teams consist of people who are responsible for at least one subsystem of the system to be designed, developed, built and operated: in this case, the space segment and the ground segment. In small satellite industry space system integrator teams are often responsible for the entire space mission life cycle from concept to operations and support, i.e. cradle to grave. Typically these small satellite missions have short development durations until deployment [Fleeter 2000], [Sweeting and Underwood 2011].

2.2 Learning in multi-disciplinary interaction

The concept of situated learning, coined by Lave and Wenger [Lave and Wenger 2008] highlights the trend to regard activity, therefore interaction of humans in activity, as situated participation in a context. From a constructivist point of view the relation between the activity and the context is bidirectional, i.e. context and activity influence each other. Therefore, learning in the broadest sense can be conceptualized as change, e.g. change of knowledge, knowing, perspective, conception, thinking, expertise. More than two decades ago Persidis and Duffy [Persidis and Duffy 1991] described learning as an "important side effect" of interaction. Furthermore they identified a "cross-fertilization of knowledge" that is taking place in interactions between designers (of one engineering discipline). A better understanding of this important side effect of learning in interaction and the fertilization of knowledge across engineering disciplines is the central motivation of this article.

2.3 Assessment of multi-disciplinary knowledge

As we consider the four basic characteristics of systems thinking: components, relationships, context, and dynamics of the system a one dimensional model of knowledge is not sufficient for an assessment of knowledge states and its changes. An additional dimension has to be added to the single 'vertical' dimension describing the depth of knowledge in a certain field. The horizontal dimension of knowledge describes knowledge across these fields, i.e. the breadth of knowledge. These fields are entities in organizations (functional departments, project teams) and organizations (system integrator, subcontractor, manufacturer) themselves. Industries such as Aeronautics, Space, Architecture or Automotive also provide different fields. This horizontal dimension of knowledge is not (yet) represented in models of performance such as from Cross [Cross 2011] or in expertise classifications such as from Ahmed [Ahmed 2005]. The model of Anderson et al [Anderson et al. 2001] focuses on the vertical dimension of knowledge. It differentiates the assessment of knowledge into two sub-dimensions. Firstly, the cognitive process dimension with six stages: remember (1), understand (2), apply (3), analyze (4), evaluate (5), create (6). Secondly, the knowledge dimension which allows the classification into four types of knowledge: factual, conceptual, procedural, meta-cognitive).

To assess systems thinking change we modify Anderson´s model and combine it with the horizontal dimension representing different fields of expertise. Anderson´s meta-cognitive type of knowledge is replaced by relational knowledge. Relational knowledge highlights the relationship characteristic of systems thinking. Figure 2 shows an exemplary virtual profile displaying systems thinking characteristics within space systems engineering teams. The x axis represents different fields of expertise, i.e. the componential, contextual and dynamic characteristics of systems thinking. The three segments (ground, launcher, space) of a space mission are assigned to the fields. The space segment is split into payload, orbit and spacecraft. The spacecraft is split into seven spacecraft subsystems (Structures and mechanisms until Propulsion). The y axis describes the knowledge dimension of the adapted Anderson taxonomy (factual, conceptual, procedural, and relational). The z axis, describes the cognitive process dimension of Anderson's taxonomy where the six stages correspond to the height of the column (1: remember, 2: understand, 3: apply, 4: analyze, 5: evaluate, 6: create).

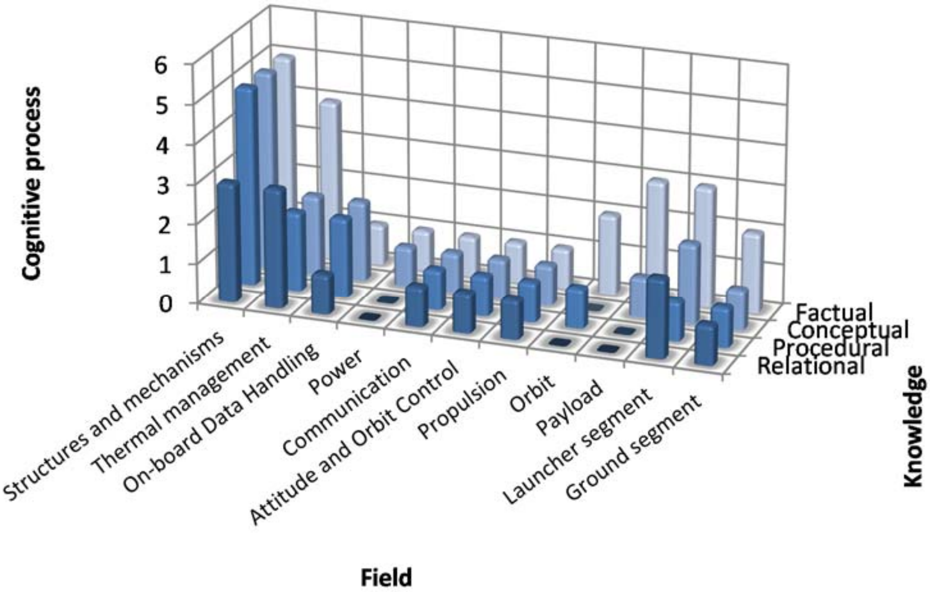

Figure 2. Alpine profile of knowledge

Having columns in the row of field 'power' means that knowledge has been applied by certain cognitive processes, i.e. something from the power field is known to a certain extent. In this field row two columns have the height '1'. The column in the factual knowledge row stands for remembering a fact in the power field, e.g. the word 'voltage'. The column in the conceptual knowledge row means that a conceptualization is remembered, e.g. voltage as the difference of electrical potential.

3. Methodology

3.1 Research methodology and design

The research project can be classified as research type 2 according to the Design Research Methodology (DRM) by [Blessing and Chakrabarti 2009]. This type comprises an initial research clarification stage, a comprehensive empirical study of the current situation and an initial prescriptive study to develop support for learning in practice. The current article describes parts of the descriptive study which comprises two empirical studies in two different organizations in space industry, empirical study 1 (ES-1) and empirical study 2 (ES-2).

ES-1 is a long-term study of a space system integrator team within a small space systems company covering two successive space mission lifecycles of five projects. The two major engineering programs of the company are firstly, design and development of subsystems for larger geo-stationary satellites within international consortia, and secondly, small satellite missions from concept exploration to operations and support, including the ground segment. The five projects EAGLE1, COLIBRI, EAGLE2, ORCA1, and ORCA2 are part of the second program. ES-1 data collection started with the projects EAGLE1 and COLIBRI in June 2008 when the main author joined the company. Data collection ends with the beginning of the operations phase of the successor project ORCA2 in November 2011. As a member of the system integrator team, the main author audio- and video-recorded office talk and formal meetings resulting in a data set of 470 h. 80% of the records′ content is indexed. Field notes of observations and complementary information are written in project journals immediately or shortly after the event. Emails, project documentation such as technical reports, and CAD data are used as secondary sources for complementing the data set.

ES-2 is a four day project performed by fifteen to twenty members of two public organizations in a facility dedicated for concurrent design of space mission concepts called Concurrent Engineering Facility (CEF) [Quantius et al. 2011]. The main room of the facility provides workplaces for the responsibles of the different subsystems of a space mission. The studies are scheduled into moderated sessions and so called postprocessing sessions. The moderated sessions are intended to facilitate exchange across the workplaces (subsystems) in order to accelerate design iterations. Postprocessing sessions are intended for longer calculations, analyses, and benchmarking. The objective of the project in ES-2 was to explore a concept of a solar science mission. To study the corona of the sun, a formation of two spacecraft was chosen, one (larger) instrument spacecraft and one occulter spacecraft [Quantius et al. 2011]. Activities of the study participants in the facility were recorded by four stationary video cameras with different view angles and foci, two handheld cameras as well as additional audio recorders. 36 h of recorded activity from different perspectives accumulated to 143 h of data. In addition three researchers with different backgrounds took fieldnotes while observing the activities. Reflective interviews with selected participants and collected documents such as hand sketches complement the data set. A detailed description of the CEF and the observation setup is provided in [Song et al. 2011].

3.2 Conceptual framework

To study interaction and development as learning in work activity on different levels of analysis a conceptual framework is developed. This is inspired by cultural historical activity theory, in particular on Engeström′s [Engeström 1987] triangular model of activity systems. Activity is always motivated by an *object(ive)* and *subjects* are trying to reach their *objective* by using tools and signs as *mediating artefacts*. Engeström added to Vygostsky′s [Vygostsky 1979] original model of mediated activity (subject - mediating artefact - object) three additional elements shown on the bottom of the large triangle in figure 3: a) *rules* of the activity which are explicit and implicit, self-defined and dictated; b) *community* to include the broader context of the activity such as adjacent activity systems and c) *division of labour* which is the major element for multidisciplinary work activities.

This triangular model simplifies activity and does not show its position and dynamics in time and context. The two activity system elements *community* and *division of labour* denote a hierarchy that is, as shown in Figure 4, a network of activity systems on different levels similar to the approach of [Boer et al. 2002] and [Korpela et al. 2001]. The upper level shows activity systems on the organizational level of project teams which themselves are split into activity subsystems on individual and domain level. The main driving force of activity, the motivating objective, defines these different levels of activity. The project team′s motivating objective is mainly to design, develop, and deploy a space mission. Motivating objectives of the lower level activity subsystems are e.g. design of the on-board computer or the structural configuration of the spacecraft. The horizontal arrows in Figure 4 highlight the connections between activity systems.

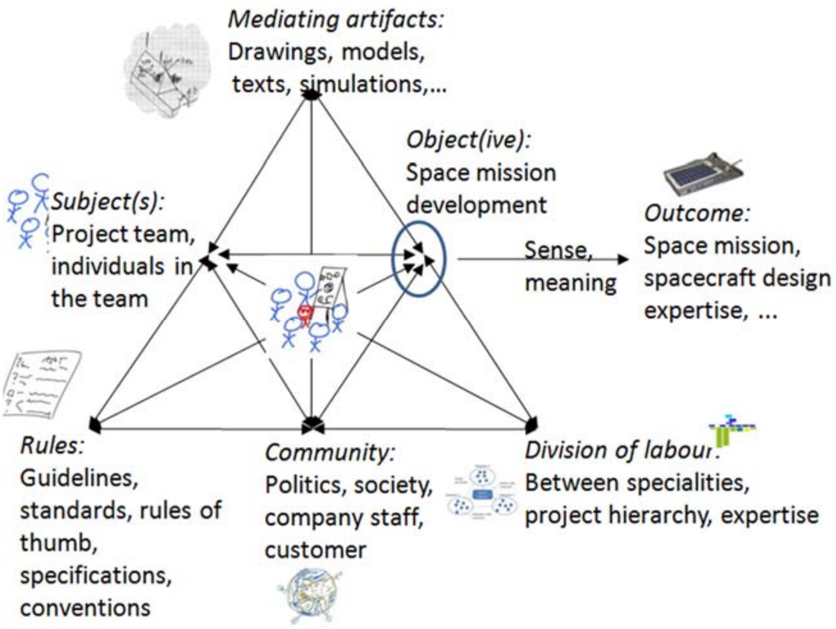

Figure 3. Activity system according to Engeström [Engeström 1987]

Engeström´s generation of activity theory requests the modelling and analysis of at least two activity systems. These connections are regarded as boundaries which are crossed in interaction with other activity systems. This boundary crossing involves boundary objects which are often tangible objects and tools that mediate between the subjects [Star 2010]. The boundary crossing leads to conflicts, such as different interpretations of numbers or lack of understanding. These conflicts are one of the three types of contradictions that are regarded as major source of learning.

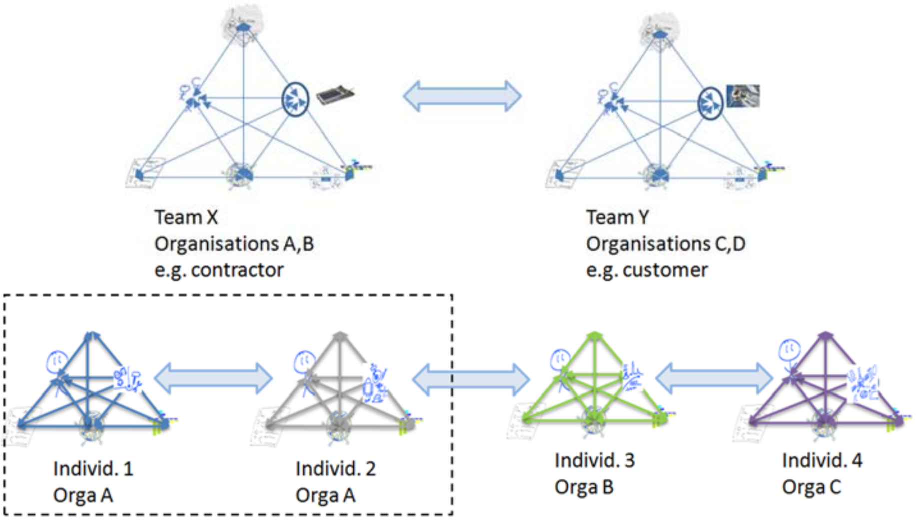

Figure 4. Two layers of an activity system network (the dashed square highlights the scope of the article)

The second type of conflict comprises contradictions between the elements of an activity system, e.g. rule-objective contradiction that is the contradiction between the objective ‘high-risk & lowest-cost space mission’ and the rules given by ‘lowest risk’ documentation standards. The third type of conflict entails contradictions amongst the elements of an activity system, e.g. unclear responsibilities as contradiction within the division of labour element. The analytical framework supports the analysis of work activity considering its history and its development in time by including different types of data sources and providing a classification for the different elements of human activity.

4. Analysis

4.1 Analysis approach and methods

The scope of this article is on the change of factual, conceptual, and relational knowledge of interactants in interaction. Therefore the level of analysis is the intra-viewpoint on group level, that is analysing interactions between members of a group [Korpela et al. 2001]. In Figure 4 this level of analysis is shown in left half of the lower layer. The different sources of ES-1 and ES-2 data are organized in two separate databases of the same chronological structure. Each database contains the content indices of the journals, emails, documents, and records. Both studies require the possibility of time series analyses but focus on different time ranges. This causes the major difference of the two databases, the time increment which is a day for ES-1 and a minute for ES-2. Although the data selection approach differs between ES-1 and ES-2 data, the analysis follows an analysis comprising an ethnographic description, theoretical sampling, transcriptions, and segmentation [Donnellon et al. 1986].

ES-1: Regular audio and video recordings of team meetings and office talk during a period of one year allow for downsizing the time increment to seconds. The content of these records, indexed in the database, allows for identifying interesting episodes.

ES-2: Firstly, interesting episodes were identified from the recorded material. These episodes were selected with an interactional analysis approach grounding on critical interaction instances [Song et al. 2011]. Secondly, the field notes (project journals) of three observers serve as ad-hoc indicators of interesting episodes. Intersecting identified episodes are analyzed first.

In sum then, out of more than ten currently identified episodes from the entire life cycle, two episodes (one from ES-1 and one from ES-2) will be presented in this paper.

4.2 The moment of inertia episode in ES-2

4.2.1 Data set

The total duration of the described episode is approximately five minutes. Video records from six perspectives build the data source. Observation field notes (project journals), available documentation and sketches complement the data set as secondary sources.

4.2.2 Description of the moment of inertia episode including recapitulations of main verbal elements

The motivating objective of the moderated session during the second day of the study is to minimize the mass of fuel (propellant) required for attitude and orbit control of the main spacecraft. The day before it had been suggested to move the centre of gravity from the area of the spacecraft´s geometric centre towards the outside corner around which the spacecraft has to be rotated regularly. A reduction of fuel consumption was expected by this modification. A moderator (MOD), the responsible for structures and mechanisms (STR), and the responsible for the attitude and orbit control subsystem (AOC) are standing at an overhead projector in front of a screen displaying the content of the overhead projector. Two solar scientists (SCI1, SCI2) being the customer and responsible for the scientific payload are sitting on their designated workplaces next to the overhead projector. The other participants in the facility are sitting on their designated workplaces.

The selected episode starts with a question from SCI1 who expresses doubts regarding the mass estimation of AOC. SCI1 asks AOC “if you artificially pull out the centre of gravity by adding more mass on the other side you increase the moment of inertia are you sure that it’s the maximum propellant.” This question causes MOD, STR, and AOC to orient towards the two scientists (SCI1, SCI2). AOC answers “I don’t care about the moment of inertia because just have to counteract the force coming in.” This statement displays his ’momentum conservation’ perspective of attitude control as counteracting incoming forces and torques no matter how the object loaded by these forces and torques looks like. As SCI1 does not accept this answer and precises the statement by highlighting that he thinks the increase of the moment of inertia is “a penalty” AOC explains his perspective. He agrees that the increase of the moment of inertia is a penalty but he does not agree that this has an impact on the fuel consumption for attitude control. He precises that if they want to rotate the spacecraft they would use reaction wheels which does not impact on the fuel consumption. MOD does not agree, which is displayed in his completion of AOC´s utterance: “unless we desaturate i mean if we need more momentum with the reaction wheels we need more desaturation this then adds fuel.” This statement does not comply with the ’momentum conservation’ perspective of AOC. Therefore he defends it for the third time: “yeah yeah but the momentum included in the reaction wheels is the integral of the total external momentum and this doesn’t change with the moment of inertia.” After a 7s pause AOC explains the ’momentum conservation’ argument for the fourth time: “yeah ok still the conservation of angular momentum is still valid so the reaction wheels spin only up if you have external momentum”. SCI2 interrupts AOC by starting to gesture with both hands ”putting mass towards outside” and thinking aloud that this would ”also stabilize”. For ten seconds there is no talk until AOC acknowledges that “it’s true we need bigger reaction wheels if we have a higher moment of inertia just for turning.” He continues with the fifth defence of the ’momentum conservation’ “but after the reaction wheels are in the same state as they have been before because [...] the angular momentum conservation is still valid.” MOD tries to wrap-up the discussion in reformulating the statement of AOC: “so you say we don’t have a problem if we extend the panel and which would increase the moment of inertia.” With this question MOD requests an affirmation for the first answer of AOC where he stated that he does not “care about the moment of inertia”. AOC does not affirm this answer but corrects it: “no we would need bigger reaction wheels with more power i don’t know if this is a problem but.” The power responsible shows no attention to this discussion and works on his workplace on the opposite side of the room. After a short “ok” from MOD, AOC elaborates on his answer: “in principle if we increase the mass of course we would need more fuel for reallocation that’s true but if we just increase the moment of inertia ehm its not a problem.” This answer shows that AOC still defends his ’momentum conservation’ perspective but he also acknowledges the fact that bigger reaction wheels will potentially increase the fuel consumption of the spacecraft. AOC continues in raising two other issues which seem more problematic from his point of view. He expresses doubts on the stiffness of the deployment arms which would lead to a change in moment of inertia when deployed, and he raises the issue of complexity, which would increase with these additional deployment mechanisms.

4.2.3 Findings

The discussed episode shows how the perspective of one disciplinary specialist, in this case the responsible for attitude and orbit control of the spacecraft (AOC), changes. The potential change of the others’ perspectives is not in focus in this paper. There are two underlying conceptions in the discussion on the relationship between the spacecraft´s mass and moment of inertia. The first conception is based on a mode where the spacecraft is counteracting disturbing forces. AOC considers this first mode with the ‘momentum conservation’ as the argument for not caring about the moment of inertia. The second conception is based on the mode where an attitude change of the spacecraft is intended. In this mode a higher moment of inertia means bigger reaction wheels under the same operational performance requirements. Throughout the episode the AOC´s perspective is dominated by the ’momentum conservation’ which he mentions and defends seven times in almost every instance he takes the floor. During the interaction he acknowledges that there is an impact of the moment of inertia on the size of the reaction wheels but he insists on the correctness of the ’momentum conservation’ law. After a longer pause AOC acknowledges that there is an influence because of the moment of inertia. He displays his awareness of the second mode in mentioning that bigger reaction wheels would require more power. Furthermore, he clarifies that higher spacecraft mass would require more fuel mass for reallocation but he does not explain the link that a higher power consumption of bigger reaction wheels will lead to higher power generation and storage needs. More power to be generated means for such missions more solar panel area which means more mass. The same increase applies for the storage capacity, i.e. capacity of batteries. Possibly, parts of the relationship could have been explained by the power responsible who was not part of this discussion group.

Transferred to the alpine knowledge display factual, conceptual and relational knowledge of four fields (attitude and orbit control, structures & mechanisms, power, and propulsion) has been displayed. Figure 5 shows the displayed knowledge at the end of the episode while the red dotted squares highlight the difference to the beginning. In the beginning AOC displays knowledge on a relationship across two subsystem fields (structures & mechanisms and attitude and orbit control). AOC defends the ‘momentum conservation’ perspective of the relationship which is regarded as ‘evaluating’ according to [Anderson et al. 2001]. Therefore the height of the column in the cell {‘attitude and orbit control / relational} is 5. The ‘momentum conservation’ perspective requires at least understanding (2) of conceptual knowledge in the related fields of knowledge. Although AOC as a specialist in the field is expected to have more knowledge only the parts displayed in the analyzed episode are considered. The revision of AOC´s perspective is indicated by the additional columns in factual and conceptual knowledge in the power and propulsion fields. The doubts in the stiffness and complexity of an additional mechanism displayed by AOC are regarded as ‘analyzing’ therefore a column height of 4 in the factual and conceptual knowledge of the field structures & mechanisms.

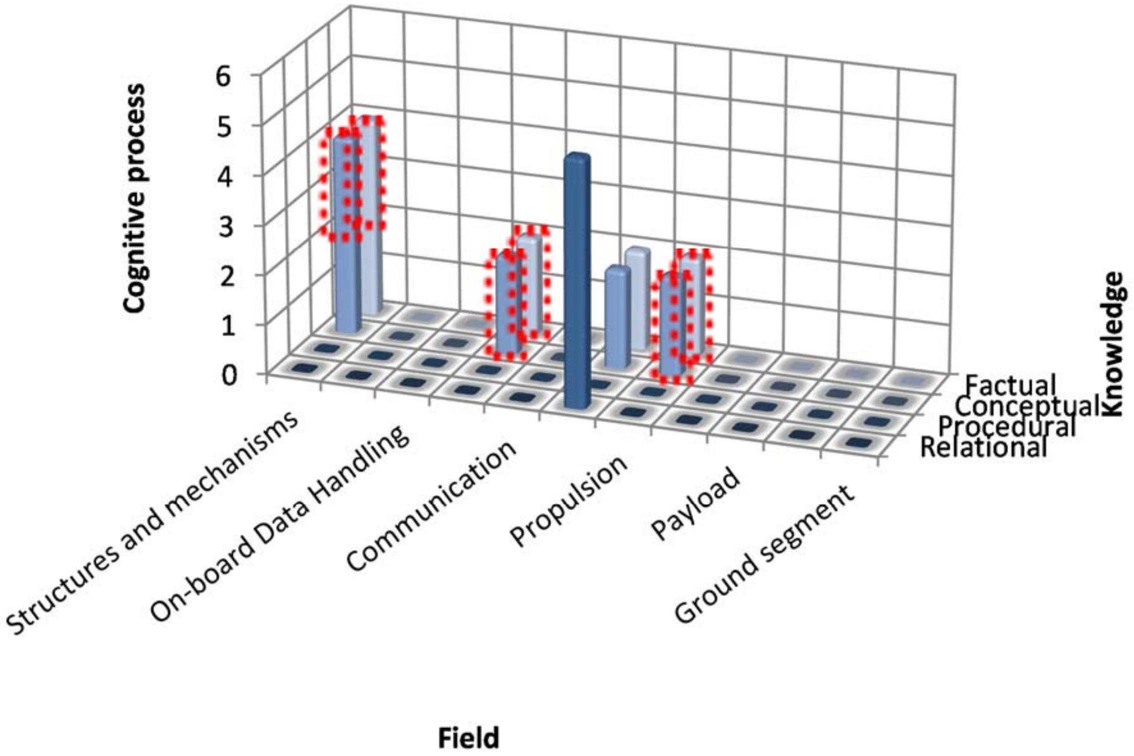

Figure 5. Identified knowledge display of AOC at the end of the episode (difference to the beginning highlighted by red dotted squares)

As the relationship has been uncovered in the interaction without the inclusion of the power responsible it is seen as an example of the benefits of collaborative systems thinking. Whether the interaction would have taken another path if the power responsible had joined the discussion cannot be affirmed as the statement from AOC concerning increasing power was acknowledged by the other participants as sufficient.

The initial critical question of the scientist and the following question by the moderator create awareness for the system view. SCI1 goes beyond the boundary of his subsystem, the payload. The moderator also asks a question which is not located in his direct responsibility. After AOC has recognized the need to think broader than the own perspective he mentions two additional extra-disciplinary issues, i.e. issues that are outside one`s discipline, responsibility, and in this case: outside of the pure attitude control perspective. Additional components and relationships of the system have been included into the decision making extending it to a multi-disciplinary decision making. Therefore one can regard the challenging questions from the other responsibles as triggers for raising awareness for other extra-disciplinary issues and changing perspectives.

4.3 The antenna placement episode in ES-1

4.3.1 Data set

The total duration of the described episode is approximately one minute. An audio record of the episode is the main data source which is complemented by field notes in the project journal, documentation, and the final product, i.e. the spacecraft.

4.3.2 Description of the antenna placement episode including recapitulations of main verbal elements

The episode starts seven minutes after the beginning of a regular progress meeting in the detailed design phase of the project ORCA2. These progress meetings are mainly intended to keep the team informed about the current states of the different subsystems and to discuss programmatic issues. Nevertheless, especially in the conceptual and detailed design phase, these meetings are also used to discuss technical issues with the whole team. Four participants are involved in the selected episode. Two participants share the responsibility for the structures & mechanisms subsystem of the spacecraft which includes the inner and outer configuration (accommodation) of components. One of these two participants (CON1) is also project manager, and the other (CON2) is the main author of the article. The third participant, a radiofrequency specialist is responsible for the communication subsystem (RF1). The fourth participant, also a radiofrequency specialist, is responsible for the payload and the system design of the mission (RF2). The selected episode starts with the clarification of the available volume envelope in the launch vehicle. The launch provider has not agreed with the previous concept of mounting four antennas in a turnstile configuration on the corners of the bottom of the rectangular satellite side faces. Therefore the antennas have to be moved to the top side of the side panels.
CON1 opens the discussion in showing the two options of placing the antennas on the top, namely at the corners or in the middle of the faces. He shows that he favours the ‘middle option’ and asks towards the radiofrequency specialists if this option is a problem for them. RF2 answers “just like that i cannot say” to mention that further calculations and simulations would be necessary to answer the question. He adds that he regards the impact of the antenna placement on the solar panels by shadowing as more important than the impact on the radiofrequency performance of the antennas. CON1 answers that “the physical mounting is also not trivial”. RF2 elaborates on the radiofrequency performance in referring to a simulation experience of another project (ORCA1) “from my experience what i did in ORCA1 if you place them in the centre the radiation pattern is less good then if you place them on the corners.” CON2 acknowledges this statement “ah ok” before RF2 completes his elaboration with “you lose a couple of dbs”. CON2 concludes “so just move from the bottom to the top” and RF2 specifies “the first guess would be that this is the best.” CON1 acknowledges this statement with “ok” and CON2 ads “and also from the shadowing point of view it should be better.” CON1 wraps up the discussion in highlighting the configuration perspective “we have to accommodate somehow the antennas in a location where are more hard points for mounting so we have to dig up something an extension strip from the current points of the panel and then we also have the cutouts in the panel from which we have to put the wires and one cannot be on top of the other.” After this wrap up they progress with another point on the meeting agenda.

4.3.3 Findings

The presented episode starts with CON1 displaying awareness of the extra-disciplinary radiofrequency perspective (communication) in asking explicitly for the opinion of the two radiofrequency specialists. The answer of RF1 inserts another perspective which RF1 regards as more important than the perspective asked for, namely the power perspective. Power perspective means in this case considering decreasing power generation performance due to shadowing of solar cells by the antennas. In addition to an answer concerning the radiofrequency issue CON1 and CON2 get another extra-disciplinary perspective to be taken into account, the power perspective. CON2´s completion after receiving the answer on the radiofrequency question is regarded as a wrap-up of the collaboratively identified issues to be taken into account for the placement of the antennas. Because of the two extra-disciplinary issues (from the configuration perspective) configuration option two, placing the antennas at the corners, was finally chosen although it was not the preferred option of the configuration responsibles CON1 and CON2.

Transferred to the alpine knowledge display factual, conceptual, and relational knowledge of three fields (structures & mechanisms, communication, power) has been displayed. Figure 6 shows the displayed knowledge at the end of the episode while the red dotted squares highlight the difference to the beginning. In the beginning of the episode the extra-disciplinary question of CON1 displays understanding of factual and conceptual knowledge in the fields of communication and structures & mechanisms (columns with height 2). In addition remembering relational knowledge between the structures & mechanisms field and the communication field is inferred from the act of posing an extra-disciplinary question (column with height 1). Using the relation between antenna position and power generation was displayed in CON2´s completion of CON1´s wrap up. According to [Anderson et al. 2001] using is categorized as the cognitive process 'applying' therefore column height '3'.

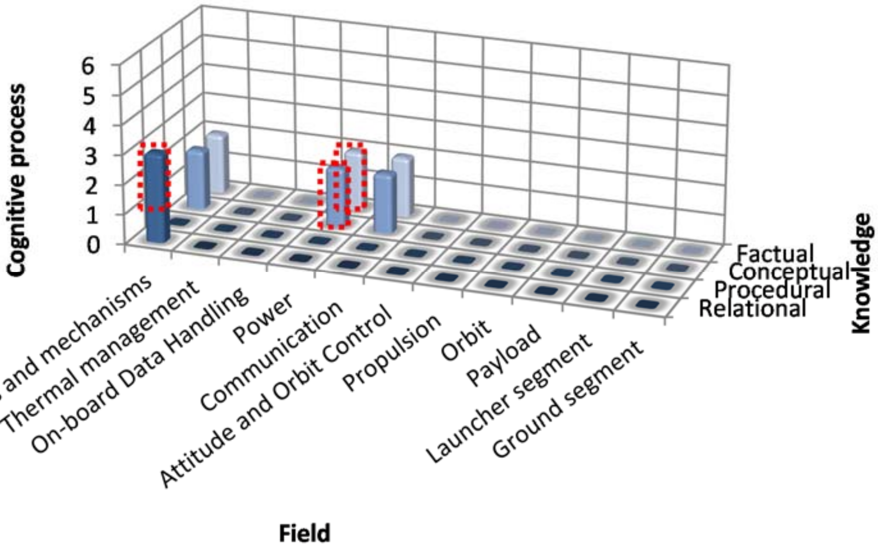

Figure 6. Identified knowledge display of CON1 at the end of the episode (difference to the beginning highlighted by red dotted squares)

5. Discussion of findings

To summarize and discuss the findings of the two presented episodes it is necessary to add more details on the contexts. The context of the two episodes differs in various ways. The first episode (moment of inertia) is situated in an early stage of concept exploration with public institutions as customer and a scientific mission goal. The second episode (antenna placement) is situated in the detailed design phase of a small satellite mission with a private organization as customer. The team of the first episode worked together for the first time and for one week in a dedicated facility. The lifetime of the team is very short compared to the team of the second episode whose team is working together in the same small company for more than a year partially in the third common project. Nonetheless, from an interactional point of view the discussions in both episodes can be looked at for analogies. The interaction of four participants can be traced; however, further subsystem responsibles are present in the room. These other participants might have been contributing to the issue at stake before and are likely to enter the interaction (again) after the episode we discuss here. The interaction as described in both episodes involves primarily hand sketches (on the overhead projector with screen or on the whiteboard) and gestures as mediating artefacts. In both episodes relational knowledge has changed. Both episodes are initiated by questions that are going beyond boundaries of disciplines, responsibilities, and subsystems. These questions display the questioner´s awareness of the extra-disciplinary issue. In the first episode the perspective of the questioned interactant is changing while in the second episode the perspective of the questioner is changing as an additional extra-disciplinary issue is judged by the answerer as more important. Both episodes underline the importance of the collaborative and emergent nature of systems thinking in line with Lamb´s work. In the first episode AOC revised his initial statement which was grounded in the field of attitude and orbit control subsystem of the space system. Finally he considered more components and a different relationship of the system than before. The same applies for CON1 (second episode) who considered after the interaction a changed relationship with more components of the system than the two components before. In addition CON1´s cognitive process improved from remembering (1) relational knowledge to using (3) relational knowledge. The complementary vision of the two team-processes where the episodes are taken from is expected to be limited to early design phases as size and distribution of the team of the scientific mission will increase significantly while the team of the small satellite mission remains constant.

6. Conclusion

Development of systems thinking as change of perspective has been identified in the presented article. A conceptual framework based on activity theory supported the analysis of collaborative cross-disciplinary communication and decision making in different work contexts. A model of multi-disciplinary expertise supported the identification and allowed for categorizing the different types of knowledge and cognitive processes. Systems thinking evolves when different subsystem responsibles interact. These discussions with durations in the range of minutes are often triggered by questions across disciplinary boundaries. Additional aspects of the system appear during the discussions in the analyzed episodes. The collaborative identification and discussion of these aspects compile a multi-disciplinary system perspective shared by several participants. This perspective creates a complement of expertise within a team and allows for partial expertise compensation of dedicated subsystem responsibles and additional monitoring as the interaction develops over time. The analyzed discussions have been identified in episodes from the early concept exploration phase and the detailed design phase. Similar discussions can be identified in episodes from later life cycle phases of small satellite missions. The discussions occur in small companies in front of a whiteboard in an office as well as in large organizations with dedicated facilities for concurrent engineering. In both episodes four participants out of more participants have been traced in these interactions.

To support the development of collaborative systems thinking, raising the interest and awareness for extra-disciplinary issues is seen as an important starting point. Identifying whom to ask and what to ask is seen as the beginning of systems thinking. For novice engineers a system map which provides an overview of the system with its subsystems, relationships, and corresponding responsible team members could be a possible support. Participation in a dedicated concurrent engineering facility could also serve as training that raises awareness for system aspects in a short timeframe.

Acknowledgement

The authors want to thank all the participants of the study, the organizations LuxSpace and the Institute of Space Systems of the German Aerospace Center (DLR) with the Concurrent Engineering Facility (CEF), Prof. Dr. Charles Max, the members of DICA-lab (Dynamics in Interaction, Communication and Activity) and the Engineering Design & Methodology research group at the University of Luxembourg, and all others who contributed to this article. In addition we want to thank the National Research Fund of Luxembourg (FNR) for financing the research project within the AFR-PPP programme.

References

Ahmed, S. (2005). Encouraging reuse of design knowledge: a method to index knowledge. Design Studies, 26(6), 565–592.

Anderson, L. W., Krathwohl, D. R., & Bloom, B. S. (2001). A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives: complete edition. New York: Longman.

Bhopale, A., & Finley, C. (2009). How ORS will answer the 7-day tier-2 challenge. In AIAA Responsive Space Conference RS7. Los Angeles, Calif.

Blessing, L. T. M., & Chakrabarti, A. (2009). DRM, a Design Research Methodology (1st ed.). Guildford, Surrey: Springer London.

Boer, N.-I., van Baalen, P. J., & Kumar, K. (2002). An activity theory approach for studying the situatedness of knowledge sharing. In IEEE (Ed.), Proceedings of the Annual Hawaii International Conference on System Sciences. Los Alamitos, Calif.: IEEE Computer Society.

Cross, N. (2011). Design thinking: Understanding how designers think and work. Oxford; New York: Berg.

Davidz, H. L. (2006). Enabling systems thinking to accelerate the development of senior systems engineers. Dissertation, Massachusetts Institute of Technology, Cambridge, Mass.

Donnellon, A., Gray, B., & Bougon, M. G. (1986). Communication, Meaning, and Organized Action. Administrative Science Quarterly, 31(1), 43–55.

Engeström, Y. (1987). Learning by expanding: An activity theoretical approach to developmental research. Helsinki: Orienta Konsultit Oy.

Fleeter, R. (2000). The logic of microspace: Technology and management of minimum-cost space missions. El Segundo, Calif.: Microcosm Press.

Katzenbach, J. R., & Smith, D. K. (2003). The wisdom of teams: Creating the high-performance organization. New York: Harper Business Essentials.

Korpela, M., Mursu, A., & Soriyan, A. (2001). Two Times Four Integrative Levels of Analysis: A Framework (and a bit of a case). In N. L. Russo, B. Fitzgerald, & J. I. DeGross (Eds.), IFIP TC8/WG8.2 Working Conference on Realigning Research and Practice in Information Systems Development: the social and organizational perspective, July 27-29, 2001, Boise, Idaho, USA. Boston: Kluwer Academic.

Lamb, C. M. T. (2009). Collaborative Systems Thinking: An exploration of the mechanisms enabling systems thinking. Dissertation, Massachusetts Institute of Technology, Cambridge, Mass.

Lave, J., & Wenger, E. (2008). Situated learning: Legitimate peripheral participation (19. print.). Cambridge: Cambridge Univ. Press.

Messerschmid, E., & Bertrand, R. (1999). Space stations: Systems and utilization. Berlin; New York: Springer.

Persidis, A., & Duffy, A. H. B. (1991). Learning in engineering design. In H. Yoshikawa, F. Arbab, & T. Tomiyama (Eds.), Intelligent CAD III (pp.251–272). Elsevier Science.

Quantius, D., Maiwald, V., Schubert, D., Romberg, O., Schlotterer, M., & Peter, H. (2011). The concurrent engineering approach applied on the solar magnetism explorer (SOLMEX) concept. 62nd International Astronautical Congress.

Song, J. Y., Kracheel, M., Ziegler, G. D. S., & Moser, H. A. (2011). Critical Interaction Instances in Collaborative Concurrent Engineering. In K.-D. Thoben, V. Stich, & A. Imtiaz (Eds.), 17th International Conference on Concurrent Enterprising (ICE 2011). Innovating products and services for collaborative networks .

Star, S. L. (2010). This is Not a Boundary Object: Reflections on the Origin of a Concept. Science, Technology & Human Values, 35(5), 601–617.

Sweeting, M. N., & Underwood, C. I. (2011). Small satellite engineering and applications. In P. W. Fortescue, G. Swinerd, & J. Stark (Eds.), Spacecraft systems engineering (4th ed., pp. 575–605). Chichester, West Sussex: Wiley.

Vygotsky, L. S., & Cole, M. (Eds.). (1979). Mind in society: The development of higher psychological processes (2. print.). Cambridge, Mass.: Harvard Univ. Press.

Wertz, J. R., & Larson, W. J. (1999). Space mission analysis and design: [SMAD III] (3. ed.). Space technology library: Vol. 8. Torrance, Calif.: Microcosm Press.

Wittmann, K., & Hanowski, N. (2009). Space missions. In W. Ley, K. Wittmann, & W. Hallmann (Eds.), Handbook of Space Technology (pp.16–30). John Wiley & Sons Canada, Limited.

Hubert A. Moser
LuxSpace S.a r.l.
Château de Betzdorf – Building B –
L-6815 Betzdorf, Luxembourg
Telephone: +352 267890 8049
Email: moser@luxspace.lu