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LARGE-SCALE ENGINEERING PROTOTYPING - APPROACHING COMPLEX ENGINEERING PROBLEMS CERN-STYLE

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Abstract

During the early concept creation phase of complex engineering problems with high degrees of uncertainty the design requirements are mostly unknown. Therefore, modules, usually used in manufacturing, and their boundaries cannot be predefined. During the fuzzy front end, requirements need to evolve according to discoveries. We suggest a wayfaring approach consisting of designing, building and testing of ideas where the learning of a test outcome leads to the next design. Instead of rigid boundaries, we suggest flexible envelopes, self-assigned areas of expertise and responsibility, which adapt to changing requirements and project needs. Unproblematic design changes within the envelope are directly implemented but changes that influence neighboring envelopes are negotiated by the developers through a justification and sense-making process. This bottom-up approach, inspired by an organizational structure at CERN, supports interlaced knowledge that enables developers to understand the various design ideas and to debate conflicting design choices already during the ideation phase. Furthermore, the project organization architecture can emerge evolutionary according to the actual needs.

Keywords: Complexity, Large-scale engineering systems, Uncertainty, Requirements, Fuzzy-Front-End

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1 INTRODUCTION

Creating new products and systems that are not incremental improvements of existing concepts but are instead disruptive often needs large-scale and multidisciplinary projects. They are too complex and uncertain to foresee all upcoming problems and some of these problems may not have a known solution and are thus called unknown unknowns (Sutcliffe and Sawyer, 2013). They therefore require a more agile and longer-term dynamic adaption of requirements as various approaches must be designed, built and tested. This is a way to avoid design fixation (Purcell and Gero, 1996; Linsey et al., 2010). The large-scale and the multiple disciplines involved demands close collaboration between developers with different areas of speciality as well as different disciplines and a mutual understanding of designs.

Many of today's engineering projects have agreed upon requirements at the beginning of the process (Sanchez and Mahoney, 1996; Baldwin and Clark, 2000; Garud and Kumaraswamy, 1995; Simon, 1991; Ulrich, 1995). Defining requirements at the beginning can lead to a stable project architecture that is enforced by a top-down hierarchy (Clark, 1985) often organizing the project using pre-defined modules with responsibilities and distinct interfaces. Possible solutions are confounded to build upon the concept that was chosen as the basis for defining these modules and interfaces in the first place. This leads to design fixation (Purcell and Gero, 1996; Linsey et al., 2010). Any questioning and changing of the concept requires a holistic dispute across modules and a concept change necessitates a redefinition of modules and interfaces. Therefore, we argue that such segregation into pre-defined modules and interfaces inhibits the challenging of assumptions and the emergence of product architectures that can efficiently adapt to the project needs.

We suggest an agile, bottom-up network and vision guided approach on the basis of design, build, test cycle iterations and justification of emerging ideas inspired by the ATLAS detector development at CERN (Türtscher, 2008; Türtscher et al., 2014)

In this paper we define the scope and what kind of engineering projects we aim to use this approach for. We then give an example that highlights the existing problems of a conventional top-down modularity approach and introduce how the wayfaring model can be combined with this CERN inspired bottom-up network approach to overcome these problems.

We elaborate with examples from CERN how our approach applies there and what we can conclude for the applicability and limitations.

2 DEFINITION OF A COMPLEX ENGINEERING PROJECT

What have CERN, DARPA challenges, the Apollo program and fusion reactors in common? They are all initiated by a **vision** that requires "to boldly go where no man has gone before" (Goldstone, 1966). This vision is defined in a way that it is clear what the goal is and when it can be considered achieved. The vision is the common ground (Srikanth and Puranam, 2011) for the entire project and does not or rarely change. It shall be known to everyone involved in the project and is relevant for everyone's contribution. These vision or challenge based projects often have a **high degree of uncertainty** and many **unknown unknowns** (Sutcliffe and Sawyer, 2013). That implies that the path towards fulfilling the vision is unclear and requires **radically new approaches** as there is no existing technology that can be harnessed to solve the problem. Not only the solution to a specific problem is unknown but also the problems themselves are unknown at the beginning and they only emerge and evolve as the project progresses.

With such radical projects with many unknown unknowns, one cannot foresee which problems need to be overcome and the creation of knowledge is essential to the success of the project. Imagine you were the first human to fly to space. You would not know how to build what we now know as a rocket or how humans behave in weightlessness and indeed previous space missions relied on testing and redesigning (Harland and Lorenz, 2007). Those projects require constantly overcoming challenges that were never faced before and testing new ideas is eminently important as a source for learning and creating knowledge. The further path is then influenced by the learning outcome and experiences from testing.

Some of these visions can be fulfilled with a small team (cliché of the garage start-up) but many require far more resources. Besides the above-mentioned attributes, we are interested in **large-scale, multidisciplinary** projects that cannot be overseen in detail by a single individual. In a classical hierarchy these projects would have multiple hierarchical levels and are divided into multiple subprojects. The projects we are interested in require contributors with diverse backgrounds in terms of education, profession and experiences in life because they require diverse and specialized knowledge from different communities. No single systems integrator can have a sufficient **holistic understanding** or what Postrel (2002) referred to as “trans-specialist” understanding of all subprojects and their **interdependencies**. Two or more subprojects are interdependent when changes in one subproject lead to requirement adaptation in at least one other subproject.

3 MODULARITY AND THE PROBLEM OF PRE-DEFINED INTERFACES

Modularity intentionally creates high degrees of independency between component designs by standardizing component interface specifications that allow for autonomous and concurrent development of those loosely coupled components (Sanchez and Mahoney, 1996).

Standardizing component interfaces and outputs makes the development process more efficient because it reduces the need for continuous exercise of managerial authority (Sanchez and Mahoney, 1996) as long as the standardized component interfaces do not change. Sanchez and Mahoney (1996) argue that

> "a modular product design process creates a complete information structure […] that defines required outputs of component development processes before beginning development of components."

Radically new approaches, as described in the previous chapter, are by their nature untested and usually contain several unknown unknowns that developers need to discover by designing, building and testing ideas repeatedly throughout the project. Developers may also encounter serendipity findings. Those unforeseen instances make a project planning infeasible and lead to frequent and sometimes drastic design changes that in turn causes design changes in many other interdependent areas of the project.

In a conventional top-down modular approach this would mean that the management needs to incorporate the learnings from testing and re-specify component interfaces before starting the next design cycle. This increases managerial workload and the project is halted until the new interfaces are specified. This is unfeasible and in contrast to the aim of modularity to make the development process more efficient by decreasing the need of managerial influence. Thus, modular approaches rely on planning at the beginning of the development process to pre-define modules and interfaces and then change those as seldom and little as possible. Consequently, this locks the concept of the solution to the initial concept used to set up the modules and interfaces and leads to design fixation.

As an example for illustrating how pre-defined planning can lead to design fixation, we present a radically new approach for a planetary exploration robot that could never have been explored in a modular development process with pre-defined modules based on conventional assumptions. The novel approach is a tensegrity structure as shown in figure 1 left. For comparison figure 1 right shows three of the existing NASA mars rover that were deployed on mars. They differ in size but follow similar and proven design principles consisting of a platform mounted to six independently movable wheels. The tensegrity robot consists of tension and compression structures and has a suspended payload in the centre. This structure can endure considerable impacts because externally applied forces distribute through the structure and it can move itself by varying the tension in the cables between the rods (Sunspiral et al., 2013). This makes it very suitable for entry, descent, landing and surface mobility as it can be crash-landed on planets and the same structure can then move around the surface of the planet. It has about one quarter of the landing mass of the Pathfinder mars rover and at the same time provides about 12 times more useful scientific payload at lower costs (Nilsen, 2012; Sunspiral et al., 2013).

The main take away from this example is that using the existing knowledge to pre-define modules and interfaces based on current mars rover knowledge cannot lead to radically different approaches like the tensegrity-style planetary exploration robots. Within the design of the tensegrity robot there are several uncertainties that have interdependencies between major components. For example it was unclear what the optimal cable elasticity or rod length and configuration for locomotion would be (Kim et al., 2014). The cable elasticity has an influence on the required motor strength which in turn influences the power electronics and weight distribution and thus causes changes in the control loop.

These uncertainties and interdependencies make a modular development approach unfeasible because changing a parameter in one module needs readjustment in other modules.

In this early phase, sometimes called the Fuzzy Front End, where project requirements and concept are still unknown design changes are frequent and a more agile approach is needed. The question is how to incorporate this agile approach into large-scale projects?

Figure 1. Left: Prototype of a tensegrity robot consisting of incompressible rods, tensile cables and a payload in the centre. Right: Replica models of three NASA rovers that landed on Mars. From left to right: Spirit/Opportunity (2004), Sojourner (Pathfinder mission, 1997) and Curiosity (2012)

4 COMBINING WAYFARING WITH A CERN INSPIRED BOTTOM-UP NETWORK APPROACH

The wayfaring approach has so far only be proven suitable for small-scale engineering project with a high degree of uncertainty (Reime et al., 2015; Gerstenberg et al., 2015). It can be described as an exploration journey guided by a vision and shaped by the test outcomes of previous probing cycles. A probing cycle starts with a divergent idea creation phase influenced by the abductive learning outcomes (Burks, 1946; Eris, 2004; Leifer and Steinert, 2011) from previous experiences. In the convergent phase the design is then prototyped (physical prototype, simulation, user behaviour observation, …) and tested. The test results are then the input for the divergent idea creation for the next design. This leads to a development journey that is usually not streamlined, has dead-ends with ideas that were discarded and often does not lead to the final design that was anticipated at the beginning of the project. Such a journey is depicted in Figure 2. The wayfaring approach allows probing several different and possibly contradicting ideas simultaneously and compare outcomes. The key is that those probing cycles are repeated as often as possible to maximize learning. Such a probing cycle is shown in Figure 3. Each probing cycle needs to be financially and timely efficient. This is achieved by focussing only on the critical functions and building low-resolution prototypes (quick and dirty mind-set) that are just sufficient as a proof or disproof of the tested idea. In our tensegrity robot example this means that the rods were built out of balsa wood as this was easier and therefore faster to machine and an off-the-shelf LEGO Mindstorms controller block was used instead of a designated control system.

The wayfaring journey either stops if no reasonable new idea is found and the project is abandoned or with the definition of requirements that can then be fulfilled with conventional sequential approaches like the waterfall model (Boehm, 1988), Pahl and Beitz (2013) or other agile and lean approaches.

The previous application of this approach was in small-scale projects consisting of only a few contributors. That meant that everyone was automatically involved and informed about all aspects of the project (Reime, 2015). This is obviously not feasible in large-scale projects because there is neither enough time nor sufficient mental capacity for all developers to develop an in-depth understanding of every detail in the entire project. Applying the wayfaring approach to large-scale engineering projects means that despite its size the project architecture needs to allow for those frequent changes in design requirements.

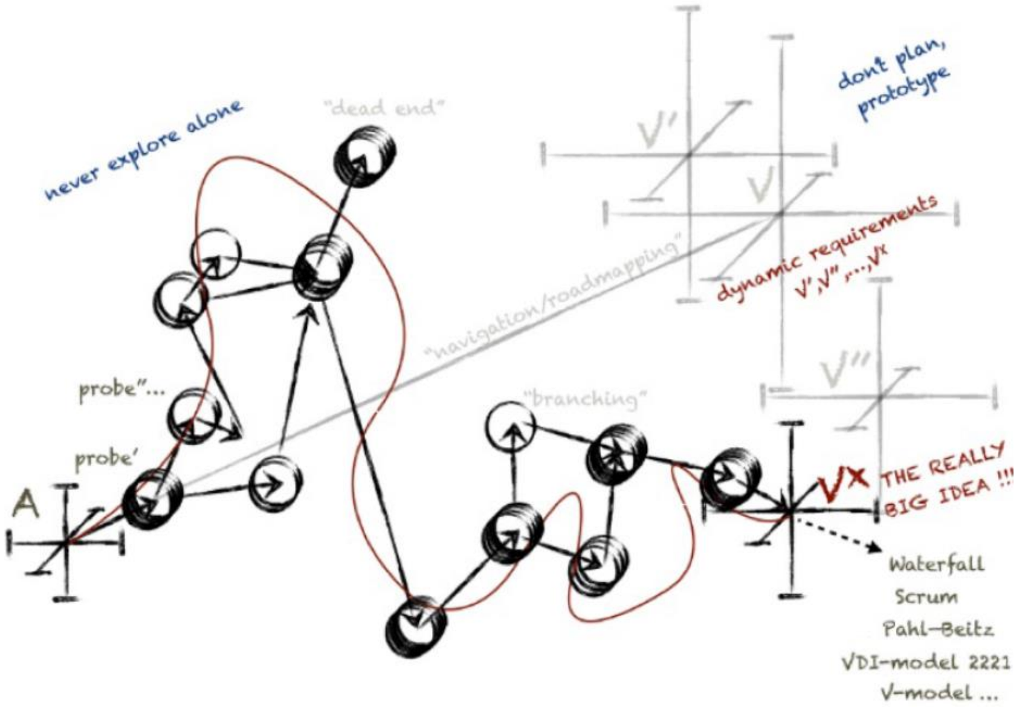

Figure 2. Depiction of a design journey following the wayfaring approach from the beginning at point A to the definition of requirements at the end. Each circle corresponds to a probing cycle and the new development directions is decided after each probing cycle. The design journey can split up in multiple design ideas or lead to a dead end

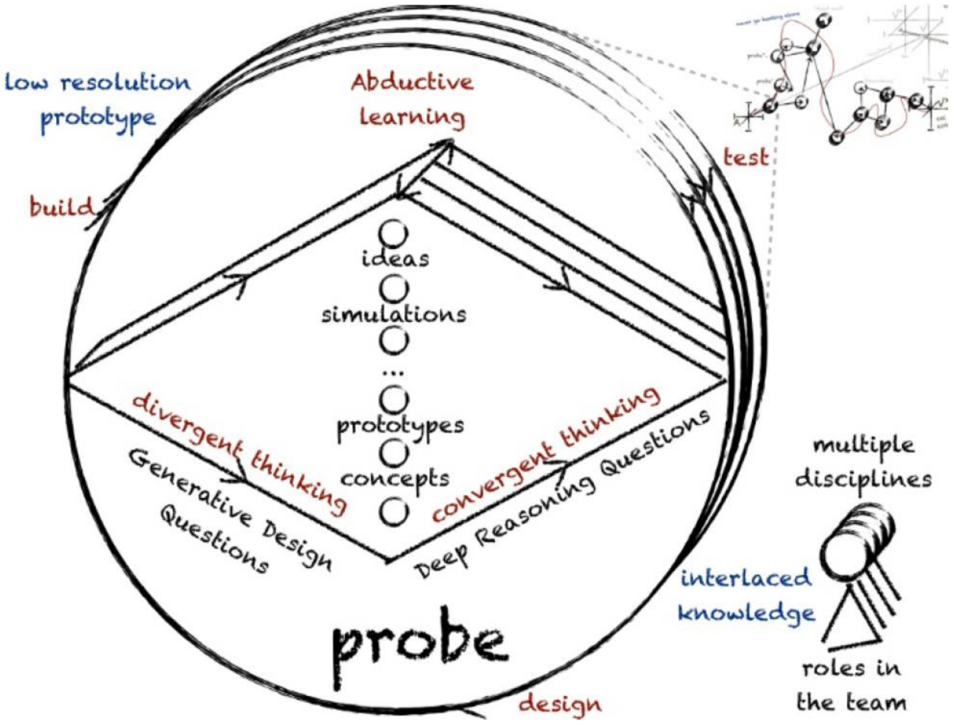

Figure 3. Depiction of a single probing cycle that consists of idea creation that is influenced by previous experiences, building a prototype and testing it

We suggest to combine the wayfaring method with an organizational approach that is not top-down but has a lateral hierarchy with participators "organized" in a network. In this bottom-up, network-like structure everyone has access to the work done in the entire project and is encouraged to also engage in areas away from the contributor's main area of work. This network is comparable to a loosely defined group of software developers working on an open source project with a common goal.

Each contributor has an own **envelope**, an area of expertise and self-assigned responsibility, within the project. These envelopes characterize the contributors influence onto the project without defining clear interfaces or allocating resources and ownership. Contributors are not bound to rigid assigned tasks and can choose for themselves how they can contribute most purposefully. This means that envelopes can overlap and the contributors need to negotiate design proposals and requirements. A design choice in one envelope can be interdependent with design choices from other envelopes. Then the contributors from the interdependent envelopes can engage in a sense-making process and together find a solution that can be in better harmony with the project aim because it is not limited by complying to rigid module boundaries. Envelopes can extend by reaching out to other contributors, for example, when seeking help from developers in different envelopes or shrink when a solution is more certain, requirements change less frequently, i.e. less collaboration is needed and contributors disengage to focus more onto their specific contribution. This allows the network to evolutionarily adapt and keep up with the current design requirements as needed.

For the project not to end in organizational chaos of individual interests, contributors need to agree to a common overarching vision. This vision can be understood as a compass ensuring a collective interest that unites efforts towards a common aim. This vision needs to be defined openly enough to allow for diverse ideas to emerge yet concrete enough to make clear what falls inside the common aim and what does not. In projects with a high degree of uncertainty these ideas cannot be deemed right or wrong as there is no obvious best option. Several coexisting and sometimes conflicting ideas are designed, built and tested. The test results allow for comparisons between ideas and build up a knowledge about which ideas work and especially why others fail. Ideas are brought to a network consisting of a wider range of participators in order to engage in a sense-making and justification process. There, the idea is explained in terms of what and how but especially why it is the way it is. This gives the community the possibility to question the current idea and add more ideas or raise objections about how it fits into the entire project. For that to happen constructively it is vital that the community understands the reasons behind the design decisions. This justification process leads to interlaced knowledge between different areas. This is helpful, even necessary, in a bottom-up architecture without a systems integrator (Brusoni et al., 2001) when developing ideas that have interdependencies to other areas of the project. Having this more holistic, interlaced knowledge enables the community to shared decision making in the interest of the entire project and foreseeing interdependencies when creating new ideas. Changing to a new idea in one area may cause trouble and the need for design adjustments in other areas. A highly interlaced knowledge makes it possible to make informed decisions that touch and sometimes sacrifice already made developments in other areas for a substantial gain in one area and thereby for the benefit of the whole project. Over time, this generated interlaced knowledge about other areas can be used to foresee interdependencies and already prevent the development of ideas that are harmful to fulfilling the overall vision in the first place. The justification process also creates a knowledge of knowledge meaning that the contributors over time learn where to find a certain knowledge and whom to ask for help when a special expertise is needed. This leads to an informal problem solving process that does not require the justification to a larger part of the community, less managerial influence and thereby already speeds up the learning process at the earlier idea generation and testing phase.

In the following we will define and describe the influence of justification and interlaced knowledge in further detail.

Justification is a factual engagement of contributors with different ideas and from different areas of the project. It teaches the other participators what, how and especially why the presented idea was developed. It aims to give an understanding that enables to give suggestions and to point out flaws and positive or problematic interdependencies with other designs. It also allows questioning the proposed design or if existing designs shall be adapted to fit the new proposal. Furthermore, the preparation for the justification process enforces a self-reflection and self-questioning. This can also be achieved through test result gained by rapid iterations of the design-build-test cycle. The test results can be used to justify design decisions to the designers as well as critics. By continuously getting feedback, iteratively improving the current design and justifying the newest designs the most promising proposal becomes obvious to everyone involved in the justification process. The baseline design emerges instead of being deliberately chosen by an authority. When the “decision” is made it is rather a formal selection of the already obvious design proposal then an actual decision (Türtscher et al., 2014). The justification process thereby also makes the decision comprehensible for the initiators of the not selected proposals and serves a motivational role and appreciates the work done (Türtscher et al., 2014). The justification is most needed during the design and development phase and when road blocks appear. It decreases during the implementation phase.

Interlaced knowledge is shared and cross-linked knowledge within an area and between different areas of a project creating a knowledge network. It is a result of the learning outcome made possible by the justification process. In some cases, it can be beneficial to include developers and critics from other areas of the project into the testing procedure. This gives the opportunity to target the test procedure for finding interdependencies to those other areas and increases interlaced knowledge. This interlaced knowledge is overlapping of several areas and therefore redundant. This redundancy is suboptimal from an information processing and acquiring point of view but this extra effort is expected to be regained by replacing managerial interventions because it allows participants to coordinate themselves effectively within the project's architecture. A holistic understanding of several areas of the projects enables the participants to classify their own efforts and to see how the influence they have within the overall project. The interlaced knowledge allows to know and therefore consider interdependencies already in the idea generation. It makes a renegotiation of requirements possible in real time as all parties share a common understanding about what they are discussing.

This becomes important when the test results of a design-build-test cycle push for design changes that have consequences for other areas of the project. In a top-down modular approach with pre-defined module interfaces developers either are restrained to the module boundaries or need to engage with management and apply for module boundary changes. That implies that management either decides insufficiently informed or needs to learn about the details of the involved modules. In the network based bottom-up approach the envelopes can adapt to the requirement needs and developers can negotiate those envelope changes directly and informally with the involved developers from other envelopes. When problematic interdependencies exist, the developers of the involved envelopes engage, negotiate and try to find a solution that is optimized taking considerations from both (or more) envelopes into account. This allows to design within a wider solution space and with the vision in mind instead of focusing onto how to find a solution within the more restricted solution space of one's own envelope or module.

The justification process furthermore creates a knowledge of knowledge meaning that contributors know to whom and where to reach out if they do not possess the knowledge themselves. The seeking for interdependencies and sense-making processes tends to increase with higher uncertainty (March et al., 1991). This is in alignment with our claim that the creation of interlaced knowledge is especially important in projects with a high degree of uncertainty.

5 EXAMPLES FROM CERN

In the following we will further illustrate the bottom-up approach by giving real examples from the study by Philipp Türtscher about the ATLAS detector at CERN (Türtscher, 2008; Türtscher et al., 2014). The vision of CERN is motivated by research about the standard model for particle physics. It predicts particles such as the Higgs boson after the collision of hadrons at sufficiently high energies. For reaching these energies the Large Hadron Collider (LHC) was constructed and for measuring the originating particles several detectors were built. One of those is the ATLAS detector, which we will focus on in this paper.

Based on the vision many contributors that were already working on relevant technologies began developing ideas and project architecture emerged from the different areas of interest (Türtscher, 2008) The overall project was too complex for every single participator to be accomplished individually. Therefore, it was necessary for everyone to reach out to others and coordinate. This was done in a justification process in panel meetings. In those meetings, different designs are explained, justified and questioned by participants developing opposing ideas as well as from other areas.

As a concrete example, this proved meaningfully in a review of the cooling system (Türtscher, 2008). The inner detector community chose the use of binary ice cooling as the solution with the best cooling performance. The risk of water leakage was not perceived eminent by the inner detector community but rather by the argon calorimeter community. Even though it was not their main focus to ensure a suitable cooling system for the inner detector it was still in their interest to design an overall well-functioning detector and therefore it made sense to point out this problem. This critical questioning resulted in a redesign to an evaporation based cooling system that does not have the danger of leaking water and enhances the calorimeter measurements because it uses less absorbing material shielding the calorimeter from the collision point. The redesign was the result of both communities justifying their designs and interests to each other and therefore making it plausible to the other community why they need the requirements to be changed. This interlaced knowledge led to adaptive coordination as the concerns of other areas could be kept in mind when designing new ideas. Furthermore, the redesign of the cooling system meant a delay for the inner detector design that also hindered the progress of other areas. Consequently, a new architecture of components surrounding the inner detector was proposed to decouple the delayed components from the rest. This change implied joint efforts of the surrounding components as they also had to adapt to the new design.

This shows the importance of the justification process to generate an interlaced knowledge of competing and other involved areas to allow for judgements that are most beneficial for the success of the entire project and towards fulfilling the vision. Furthermore, it enhances the awareness of interdependencies across areas of focus and makes more informed decisions during the design process possible. In the earlier phases of the ATLAS detector design, the muon spectrometer community engaged far less in the justification process (Türtscher, 2008). A formal complaint from within the muon spectrometer community remarked that the “way of justifying – or rather not justifying – is unacceptable” (Türtscher et al., 2014). This continuing attitude resulted in a revolt of the participants whose proposals were denied and finally lead to a justification process and a reassessment and denial of the initial design choice. The paper also mentions the significance of justification for the motivation and appreciation of work. One person of the muon spectrometer community remarked that “I firmly believe that after many man-years of hard and dedicated work the proponents of all technologies, but especially the losing ones, are entitled to at least one line of comment as to what are, in the eyes of the panel members, their flaws or weaknesses in comparison to the competitors.” (Türtscher et al., 2014).

Furthermore, the study (Türtscher, 2008) evaluated the amount of justification of different areas of the ATLAS project by latent semantic analysis and compares the results to the density of the knowledge network. An inverse correlation between the amount of justification and delay of the project was found. Although a case study, this result can be seen as an indicator for increased justification leading to higher performance.

Only the thoughtful combination of all considerations makes the project a success. In a large-scale multidisciplinary project like this, it is impossible for participators from one area with their limited background to overlook the entire project and foresee all upcoming interdependencies. Therefore, the network of interlaced knowledge between different areas helps to connect all areas of the project as long as everyone shares a common vision and reaches out to other areas.

6 APPLICABILITY AND LIMITATIONS

We aim to bring this approach that combines wayfaring with methods from scientists at CERN to the early phase of engineering projects that require so frequent design changes that a pre-planned sequential approach with modules would be difficult to implement.

In this early concept creation phase the solution space is intentionally kept open to allow for a wide variety of concepts and it is initially unclear which expertise is needed in the project. Therefore, the project is guided by a vision that "invites" contributors to take part with the expertise that they can offer. The contributors chose for themselves how they can best contribute to the project. This is very similar to contributions in Open Source software projects. When the scale of the project exceeds the expertise of a single contributor they need to reach out to other contributors to seek the knowledge that they are lacking to be able to integrate their contribution into the greater picture of the project. The outreach is self-motivated and driven by the common goal of fulfilling the vision. Thereby, a network of collaborator with overlapping areas of expertise emerges based on the current development needs. When the project needs change an adapted network architecture can arise. The restructuring of the network will become faster as the project progresses because the contributors are already know whom to contact for the newly needed information. Knowledge from other contributors is found and accessed through personal reference by the "I know a friend of a friend who can help you" principle.

This opens the question about how much the network structure is determined by the actual need for help and information within the development or by other influences (social, political, location). This can be researched by capturing interactions between contributors (Sjöman et al., 2015; Sjöman and Steinert, 2016; Olguín et al., 2009) and comparing this to the actual component interdependencies of the technical solution at that point in time.

Obviously, the downside of this network-based approach can be that too much resources are spent on creating the network and the interlaced knowledge structure for projects where this is not needed. It becomes a trade-off between the capability to be more innovative through exploring many radically different design approaches and the efficiency loss due to spending resources on creating an interlaced knowledge. We, however, argue that if design requirement changes are frequent the network-based approach can be more efficient because managerial interaction is greatly reduced.

So far, it remains unclear how the optimal desired network structure is determined and how it can be influenced. Network characteristics to look at can be network density (ratio of connections in a network to the number of connections that are theoretically possible (Mitchell, 1969)) and average geodesic distance (average number of connections in the shortest paths that connect each pair of nodes (Freeman, 1978)).

We recommend to try the wayfaring bottom-up network approach in the concept creation phase of highly uncertain projects before design requirements are fixed.

Once the exploration is finished and the requirements are fully determined a traditional, sequential and milestone based approach is more effective and should be deployed.

7 SUMMARY

In the early phase of large-scale engineering projects, the final concepts are often unclear and need to be discovered. We argue that a pre-planned modular approach is not suitable for the creating of radical concepts and we present an example where we illustrate the difficulties of such a modular approach for finding radically new design solutions. Instead, we advocate a more agile wayfaring approach based on rapid iterations of designing, building and testing new ideas and explain how it can be combined with a bottom-up, large-scale approach used at CERN. This bottom-up approach relies on justification of design choices and creating interlaced knowledge between different contributors of the project. We explain how especially the testing and designing phase of the wayfaring approach is important for justification and interlaced knowledge.

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