IMPLEMENTING INNOVATION IN A COMPLEX CONTEXT- THE AEROSPACE APPLICATION

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Abstract[1]

Aerospace and defense systems face increased complexity due to increasing system of systems integration and globalization. The systems typically have a long life cycle, often with inherited solutions from earlier products. Together this leads to systems that are at risk of being very constrained in terms of possible innovation.

At the same time, the dynamic context and globalisation generates a need for intense innovation in the system, and a possibility to adapt to new requirements. The challenge then is to build the system such that it is open to change in needed areas throughout its life, and to be able to stimulate and implement innovations in desired areas.

The architectural principles that open up for innovation are briefly summarized to support the discussion on innovation possibilities.

Selected project examples are given from several types of innovative situations, The implementation of innovation is subject to different conditions depending on the type of situations. Some experiences on how to reach implementation are shared. In particular, the use of demonstrators shows particular favorable properties to bridge between a research focus and an application focus. This is discussed with the support of design spaces.

1 Introduction

Aerospace systems are among the systems that have the longest life cycles in our society despite that they have existed just for roughly one hundred years. A number of products have managed to be relevant for about half of this time, e.g. among many others the DC 9 series aircraft and the B 52. These products have survived many generations of technology for its subsystems and in its context.

Aerospace and defence development today includes important considerations on the context in which the system is operating. E.g. are communication and navigation systems using more and more external resources even in flight critical domains, passengers demand possibilities to communicate with internet, terrorism threats may come from the use of false external information and the system is becoming increasingly autonomous. Many of these aspects are further emphasized when looking at the application of unmanned vehicles, where the human backup is no longer available.

Even without this tighter integration to the context, aerospace systems have been known to be very constrained in their innovation abilities due to e.g. safety aspects where airworthiness requirements are increasing the effort heavily when introducing a new feature or functionality. Further, most designs in the system are subject to a multitude of requirements and design rules that requires a comprehensive understanding of the design and its requirements in order to understand what is possible.

Together, the above implies a situation where the system complexity is growing, partly due to

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the evolution within the system, but also due to its stronger relation with its context, leading to risks of being even more constrained in its design. At the same time, the system needs to develop and be subject to more intense innovation adapting to new requirements over its life than before.

The challenge then is to build the system such that it is open to change in needed areas through- out its life, and to be able to stimulate and implement innovations in desired areas.

So, how could different types of situations be handled? What management practices and contextual influence could contribute to a successful innovation in the complex aerospace system?

In this paper we focus on aerospace systems with the following general properties:

- requirements are changing through- out the life of the system and are not fully known à priori.
- need for adaptability through flexibility
- growing complexity and systems of systems integration
- long life with a wide range of life in the different subsystems it is composed of
- strong need to maintain system integrity over time

These properties are considered as general properties of this class of complex systems, referred to as “complex systems with long life cycles”, [7]. Hence, we could study different types of innovative situations that provide results that has relevance for systems within this class. E.g. by defining the long life cycle for a system as a life cycle where several subsystems have to be replaced during the life due to obsolescence, it is possible to study systems that have an essentially shorter time span for its life cycle, [2].

In this paper we present studies of three innovative situations. These are discussed from two major aspects. First, how can the innovations be stimulated and oriented in a desired direction. Second, how can one stimulate the implementation of these results into follow on activities and products.

2 System characteristics

The complex system with long life cycle could be studied in the perspective of its time dependencies. In [5], it is described how the management of such a system should be decomposed based on its stability over time using the *time balance cross*, see Figure 1.

The context of the system is normally complex and partly stable, or static, where changes are small and the conditions for the system are well known throughout its life. On the other side a subset of the context may be very unstable, or dynamic, where it is difficult to predict what conditions will be necessary to meet for the system. An example of such decomposition is the electronic flight control system with high demands on reliability and real time performance. This is optimized in its functionality at early stages and remains stable over time, while mission related functionality is subject to frequent updates throughout the life of the system and is less safety critical.

A similar pattern applies for the complex system in general. In certain domains the product is rigid, it requires a substantial effort to implement changes, e.g. due to a high level of optimality and strong interaction between design solutions fulfilling different requirements. In other domains the system is easy to change, it has a strong flexibility.

By combining these aspects in four fields, as in Figure 1 from [5], it can be seen that the system and its context could be analyzed in four quadrants, Q1 to Q4. These quadrants are referred to throughout the paper as Q1 to Q4.

In *Q1* conditions are changing rapidly and the system is able to respond. This part of the system has to be supported by a dynamic and innovative environment where the change frequency is expected to be high. Innovation is not particular constrained in these domains.

In *Q3* the conditions are stable and the system is developed once, with few later changes expected. It is often motivated to optimize to a high degree, as it is likely to maintain about the same optimum throughout its life. In this part of the system innovation is highly constrained as soon as the initial design solution is selected.

Parts of the system belonging to *Q2* are a threat to the system as they are not able to respond to changes in the requirements to a sufficient degree. Normally these solutions have to be decomposed into solutions in Q1 and Q3 in order to maintain sound properties of the total system.

In *Q4*, the flexibility of the system supersedes the need for change. This might lead to changes that have limited connection to the customer needs of the system. It further includes difficulties such as obsolescence when solutions are based on external sub-systems. Hence, these parts of the system might well lead to a non-motivated cost burden for the sustainment of the system.

When the complex system is subject to changes, these have to be performed such that the desired properties of the system are maintained, e.g. a change should not introduce a locking that is transforming the properties of a domain from Q1 to Q2 type.

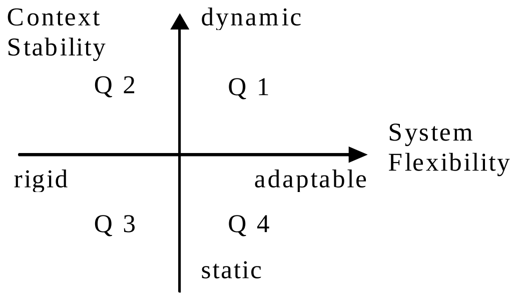

Figure 1 System flexibility and context dynamics in the time balance cross

With the level of complexity that an aircraft has, it is neither desirable nor possible to use a single set of objectives to define the good properties of the system, or to orient the whole system characteristics to one quadrant in Figure 1. The objectives include aspects that at first sight might appear contradictory for the system. E.g. the system has to be highly optimised, but it also has to be flexible. Further, functional integrity is needed e.g. due to airworthiness needs, while innovation is needed in order to keep the system behaviour attractive. In [7] it is showed that the system has to be decomposed into domains where subsets of the overall objectives are dominant, and the way to develop and handle these domains has to be differentiated. Considerations of the time properties, or clockspeeds, of the system context and the system are important criteria to define how to decompose the system into these domains. The use of these criteria to define how to decompose and differentiate the integration of a complex system could be referred to as *time balanced integration*.

If the decomposition of the system is done in a successful way, such that the system can respond to changes in needed areas quickly, the whole system could be perceived as flexible.

3 Innovation

This chapter outlines the perspectives on design and innovation that are used for the cases and the analysis.

3.1 C-K theory and Design Spaces

Hatchuel proposed a unified design theory, the C-K theory that is reported in e.g. [4]. The C-K theory has a strong theoretical foundation, but is here only referred to on application level together with the application of design spaces as described in [6].

The C-K theory includes innovation and creativity into the design model in an explicit way by using the notion of a knowledge space (K) to denote existing knowledge of possible solutions. These solutions are possible to judge for a designer whether they are feasible solutions or not in a particular design situation (also fuzzy judgments may apply). The concept space (C) on the other hand includes new ideas and concepts that could not be judged by the designer without a design effort. As design is performed for the new concepts it is phasing over to the knowledge space, or rather, the knowledge space is expanding. If a design situation does not include concept content, then it is only based on existing knowledge.

The C-K theory defines four design operators to cover the ideal design situations, these are

K⇨C	opens up new concepts based on the existing knowledge (alternatives and possibilities)
C⇨ K	links knowledge to concepts and validates candidate designs
C⇨C	develops concepts based on combination, inclusion or partition of concepts
K⇨K	handles systematic expansion of the knowledge space

These operators could be represented in the so called design square, where the arrows represent the different operators as in Figure 2.

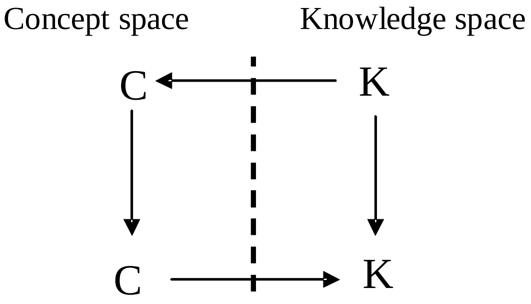

Figure 2 The design square

This design square could be exemplified by a general perception of the Saab aerospace product development conditions:

The K⇨C operator covers the ability to generate new concepts. The existing (K) base is built on experts, training, information availability and networks internal and external to the company. The ability to generate (C) relates to a large extent to the company culture. New ideas are often well received and people coming with new ideas are respected. New ideas are followed up and discussed, refined, changed or debated in a way that leads to new concepts. This forms a key part in the C⇨C operator. Development processes and enabling aids supports the C⇨ K operator. Finally labs (e.g. generating data for a new material) and analysis departments (e.g. do internal loads analysis for a new load set) are playing a key role in the systematic generation of knowledge supporting the K⇨ K operator. Both the latter examples also contribute to the C⇨ K operator in their role in the development process as enabling aids.

When a K⇨C operator has generated a new concept, there is a need “to learn what has to be learnt” in order to judge whether the concept is a valid design and hence being a part of the new knowledge space. A design space is defined as the space “to learn what has to be learnt”. Design spaces could be of several types, in this paper two dimensions of design spaces are used, phenomenological and functional, see [6] for further definitions.

One can consequently give the following (symbolic) representation of the different archetypal design spaces, [6]: a design space is represented by an arrow that symbolizes the progress on two dimensions, exploration of functions and exploration of phenomena. The origin of the arrow symbolizes the set of functions and phenomena that are initially “active”.

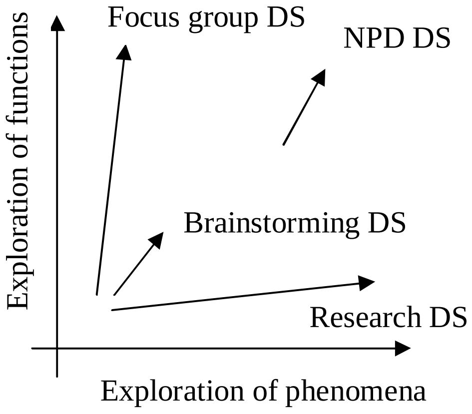

Figure 3 Design space archetypes

3.2 Innovation in complex systems

For systems where at least one domain is subject to conditions as in Q1, this could be seen as the system is subject to an innovation intense environment.

To continuously drive innovation at a sufficient rate in such an environment is a challenge that e.g. has been addressed for software systems with emergence methods by Highsmith, [3]. The possibilities to innovate is then assured by setting sufficiently challenging missions, and always continue to find new challenges that pushes further ahead in this adaptive software development. Development projects are striving to be at the borderline of chaos. Highsmith states that rapid developments are not difficult, but rapid changes are. He further emphasizes the importance to adapt over the importance to optimize ([7] advocates that it has to de selected where to optimize, and where to be adaptable). This is attractive as long as the total system is not at risk when looking for challenges in e.g. particular sub- systems. The architectural decomposition described in chapter 2 is an approach that opens up more areas, of the Q1 type, to innovation in line with this. The key to innovation in emergence methods as of Highsmith is the perceived challenges. Other aspects that influence the innovation situation include contextual aspects such as attitudes towards innovations in the organization, time influence, attention and needs and knowledge of the design situation.

For the three studied cases we have attempted to highlight these aspects with relation to how they influence innovation in the actual case.

4 Innovative situations- case studies

The selected cases include different characteristics: one situation with critical demand, one concept demonstrator and one research demonstrator.

4.1 The Escape system[2]

When the JAS 39B Gripen aircraft was developed as the two seater version following the initial one seater version, this was largely handled by an introduction of a new section behind the initial cockpit. This required a number of aspects to be addressed. One of these was the escape system for the rear seat.

Figure 4 The JAS 39 Gripen one and two seater versions

In the handling of this aspect it was detected at a late stage that there was difficulties when blasting away the canopy before the ejection of the pilot as there was a risk of canopy fragments hitting the rear seat crewmember. At the time this was detected, the program was well under way and the issue was close to the critical line of the program without having an obvious solution in sight.

The design considerations in the cockpit included many design aspects, such as heavily utilised space, man machine integration, air condition, structural integrity including bird impact, the pilot escape system and others. Hence, the design situation is constrained by its many aspects of design at the same time as an innovative solution is needed in order to avoid difficulties for the program.

Due to the criticality of solving the issue, significant attention was paid by senior management in the program.

Within the team that was dealing with the issue, there was a wide representation of expertise as well as a project leader with strong entrepreneurial talents.

Summarizing the situation, the project faced the need of a new design solution, was subject to strong time pressure with important consequences if the plan could not be met, and they

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[2] This is based on the study by Björkvik [1]

had a strong management attention. This situation is to a large extent an emergence situation as described by Highsmith [3] where the team should be challenged to the borderline of chaos.

In an earlier program there had been discussions on the use of airbags in the escape system. This possibility was again proposed by one of the senior team members that had been on the earlier program. After discussions concluding that it should be tried as a solution, the Swedish airbag provider Autoliv AB was contacted. With just one days notice, an initial meeting was set up and possible solutions were discussed. Formal negotiation was very limited, Autoliv saw possibilities in learning and also in being associated with air safety. Autoliv provided personnel that work together with the Saab team to understand the design problem and to identify a solution. The team worked together in a very open spirit. Several iterations of testing and refinement took place including e.g. adjustments of cutting patterns of the airbags in order to achieve the proper effect in situations, such as at different altitudes.

As Autoliv was normally working with automotive industry, there was a need for a substantial effort not only to introduce the new supplier, but also to ensure the right quality level for an airworthy solution. This included that Saab took the responsibility for the solution, requirements and documentation were analysed extensively, as well as help was provided to support Autoliv with the possibility to identify component suppliers meeting the requirement level.

The project achieved its goal with an innovative solution that was developed in a rapidly formed supply relation. Key to its success was insight to design constraints and knowledge in the team, the attitudes of involved people and the attention paid to the issue.

The dynamics of this situation could be mapped as below. The development process was open to handle design solutions that were not necessarily feasible in the beginning and adapted to a new situation (Q1). This combined with a non formal introduction of a new supplier (Q1). The supplier relation later was matured to meet the airworthiness requirements (Q3). At initial design stages, it was a clear risk that the design context would be constraining (Q2), but the selected design solution did not put any additional requirements on the design context hence placing it in Q3. The resources needed and allocated to achieve the solution was much less than the value of completion, hence the budget was not constraining the project (Q1).

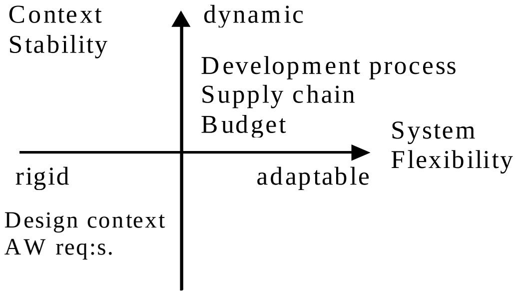

Figure 5 The time balance cross for the escape system

From an implementation point of view this project shows some ideal properties. The strong demand for the solution defines clearly the direction of innovation and the design goals, as well as it ensures the application of a successful innovation. All this orients the innovation in the desired direction and increases the likelihood of successful implementation. However, having these beneficial properties of a straight forward implementation situation comes at the price of exposing the project to a substantial risk that could hardly be accepted if not necessary as in the actual case.

Several approaches could candidate for creating innovative situations that share at least some of the above properties without having the same level of risk exposure. The following two cases studies two types of demonstrators that have some of these properties.

4.2 ND-Sysim[3]

At the turn of the century, Revolution in Military Affaires was heavily discussed in the defence community. A net centric defence trans-

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[3] This study is performed together with ENSMP [6]

formation was decided by the Swedish government at this stage including the use of existing defence assets in a networked environment that enables much more flexible use of resources as well as information fusion capabilities improving the ability to make use of the vast information available throughout such a system.

A Net Defence system simulator, ND- Sysim, was developed at this stage to support the convergence of the conceptual discussions at the time, as well as providing a demonstration opportunity for potential customers and a future lab. It should support studies of technologies and possible products in a net centric environment. A key aspect at the time was to refine the understanding of the concept of Net Defence.

Figure 6 ND- SySim

The studied project was running for six months was subject to a multitude of goals and expectations. The project had requirements from several domains, it should be a good and clarifying customer demonstrator, it should be a good lab for future simulations, further it should contribute to more scalable simulation architectures with increasing network simulation capabilities. Goals were adapting over the project time. The project had a high level of attention and a fix deadline relating to the possibility of being a part of an exhibition of that year.

The project had developments in areas comprising operational analysis and scenario developments, simulation architecture, devices, software and standards application, as well as data fusion, man- man –machine interaction (M^3I) and other areas. All these provide design spaces composed of different levels of functional and phenomenon components. Examples are given in Figure 7 where requirements on distributed simulation were at a fairly mature level and the functional expansion was mainly attributed to what types of scalabilities that was searched. The main principles for NCW were further defined. A major knowledge expansion in both functional and phenomenon dimensions was in the interaction between scenario and simulation combining OA and simulation such that relevant simulations could be performed to mature the NCW concept. For example, operational analysis people had one view of the level of scenario to simulate while the possible simulation capability was substantially more limited in that aspect. The discussions that followed between these groups allowed the operational analysis people to better understand what the realistic level of phenomenon to simulate was, and the simulation engineers learnt more about what are the needs of the users for simulation capabilities in a net defence simulator.

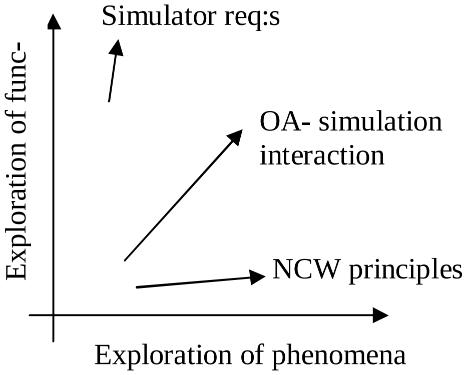

Figure 7 Some of the design spaces for ND SySim

During the initial phase of this project, exploratory activities dominated. The involved team spent much time on discussing the key principles of Net defence and its implications on what to achieve. Later when the “Net defence thinking” had matured it was time for the project focus on delivering the demonstration. There were actually some difficulties to re- focus the project between these two different phases. The first project leader resigned and a new was taken on board. The focused phase of the project went smoothly, even though intense.

During the project learning was partly related to the different domains, but most important was probably the cross learning between knowledge domains.

The projects initial phase with conceptual discussions provided a certain level of innovation. Equally, later phases included some innovative solutions with respect to simulation technology. But the main innovation possibilities follow the project. The quality of the dialogue with potential customers improved, as well further developments of different technologies. Non defence applications have been demonstrated, such as coordination of emergency resources for a city.

The study of this project indicates that there was a potential to be more innovative during the project. In its exploratory phase the project seems to have been too vague to sufficiently orient innovation in a meaningful direction. When it came to the convergence phase time was pressing to a degree where innovation was difficult to consider.

To perform this project in six months was an achievement, it included challenges in software, in supplier interactions for equipment as well as in the definition of what to demonstrate and achieve. The demonstration goal and deadline were achieved. The demonstrator have also served its purpose to contribute to the understanding of Net defence and served as a lab for future work.

In Figure 8 the demonstrator decomposition is mapped. The IT architecture was defined with stable conditions that provide a flexible mechanism to achieve new and changed simulation models. Further, models in areas intended to study in the simulator, e.g. M^3I and fusion, are easily modelled. Achieving sufficient real time performance simulation is a constraining factor, i.e. there was a wish to build more complex scenarios.

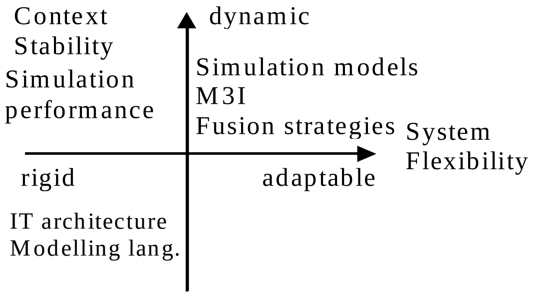

Figure 8 The time balance cross for ND- SySim

The implementation of these results has several dimensions as a consequence of the projects multiple goals. We have mentioned the customer dialogue and other demonstrations that contribute to further refinement and understanding of the importance of different aspects of net defence.

A challenge in this multiple goal situation is to bridge knowledge or gained values into new projects that continue to benefit from the achievements in the single project, progressing towards sufficient maturity for being a product. This bridging of value between projects is highly dependent on a continuous value management process that supports the redefinition of goals and promotes reuse of knowledge between projects.

4.3 WITAS[4]

WITAS was a long term research project at Linköping University aiming at fully autonomous flight. The first phases of the program were set to seven years ending with the intention to demonstrate fully autonomous flight before the end of 2003. The goal was selected as a very challenging goal in order to create a "moon- lander project" that would stimulate research. It was using the Yamaha RMAX RPV as platform and focus on the autonomy developments for this platform. As research project it had the interesting property of combining a large scale demonstration with ambitious research contributions in the involved domains. This was formulated as "each project member should contribute both to a successful demon-

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[4] This study is performed together with ENSMP [6]

stration and to the research in his or her domain".

Figure 9 WITAS rotorcraft UAV

The project board have been composed of academics, Industrialists and people from government agencies. As the initial demonstration goal was found insufficient in its definition, it has been important with a good dialogue between the board and the project such that the goals could be refined and redefined as the insights grow during the project.

The demonstration goal has contributed to many discussions on relevant research questions. It was felt by the researchers that the demonstration goal has helped to formulate relevant research questions. It has further been important to stick to the fundamental aspect of actually flying autonomously and not only simulate the flights as this would have opened up to e.g. make simplification assumptions on the need for real time behaviour of the system.

The demonstration was achieved in time, and research have been achieved to a level where e.g. real time planning needs have led to new planning methods that has a performance that makes earlier benchmarks in this research area irrelevant.

The architectural work in WITAS has been based on a decomposition of the system into an events based architecture for the autonomy system. The architectural decomposition of the project and demonstrator has led to the ability to link a challenging demonstration goal to challenging research goals within the different domains through divided but related design spaces. The balancing of these decompositions and design spaces is an important part of achieving good levels of innovation in the project. If the task is not challenging enough, then it does neither stimulate nor orient innovation. If it is too challenging then it is ignored as something non achievable. The project leader played a key role in both identifying this balance and to adjust it throughout the project as goals were adapting etcetera.

The results of the WITAS project are to a certain extent the demonstration, but this as such is not the main deliverable. Those include research results in different domains, experiences that have industrial application, the demonstrator architecture and the people that have worked within the project. In addition, proposals for new research domains also appear as a consequence of the demonstration focus. E.g. for an autonomous system, there is a linking between control theory and artificial intelligence that should be addressed.

The combined focus of demonstration and research leads to a bifurcation situation at a certain stage, where the tension between the focuses motivates a division into a research focused continuation in parallel with a industrially oriented product focus.

5 Conclusions

As illustrated in Figure 10, a development project has a desired starting point where functional requirements and needed solutions are well defined. Convergence properties of a product development does not allow for extensive learning without creating a high risk exposure (compare the escape system example). In order to arrive at a feasible starting point for the development project several strategies could be applied.

The innovative situations presented in this paper include an initial K⇨C operation, or set of operations, that defines a need to achieve a design effort before it is possible to implement the solutions in a product. The C⇨ K and other operations (C⇨ C and K⇨ K) that follows has led to an architectural decomposition of each project where several design spaces and new K⇨C operations have appeared. This has led to design spaces of functional (requirements), phenomenological (solutions) and of combined character.

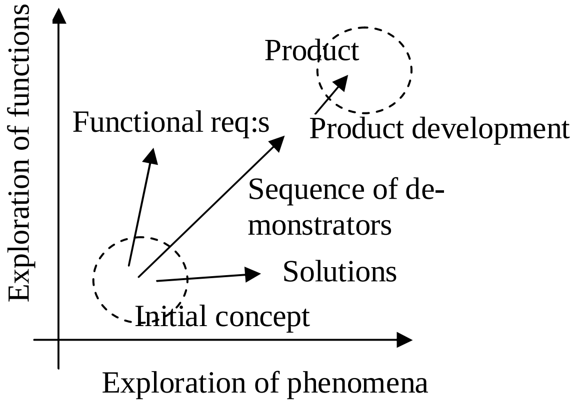

Figure 10 Bridging from a concept to a product

The time balance cross helps analyzing what concept propositions could be feasible for a complex system. If the proposition implies a change in the system domain distributions between Q1 to Q4 that increases the deviation from ideal distribution it is then likely providing negative long term aspects and is to face implementation difficulties. If it leaves the distribution unchanged or improves it, the success likelihood is strengthened.

In particular, the two demonstrator projects studied have shown favorable properties both in orienting and stimulating the innovation, and in providing the ability to balance between the functional and phenomenological dimensions. An important part of this capability lies in the handling of the architectural decomposition of the demonstrator and its project. Further, the cross learning between different domains was important in both projects.

It is rarely the case that a single demonstrator definition and project closes the gap between the initial concept and the starting point of a development project. It is rather a sequence of demonstrations, or other project types that through a continuous value mapping allows closing the gap in an efficient manner [6]. The implementation of innovation relates to this value management, where implementation either aims at contributing to products, existing or new ones, or to continue into further innovative design spaces. This leads to implementation needs of different characters and the value management process could seldom be seen as a linear process of maturing towards a single goal.

The studied cases show an acceleration of innovation in the desired direction. Still, there exists a need for balancing the number of demonstration steps and the overall risk level in the value mapping such that the innovative product arrives in the market in the best way.

The mechanisms for stimulating innovation in [3], i.e. creating challenges and attentions are noted in the studied cases. Demonstrators appear as a possibility to achieve efficient orientation without generating unacceptable risk. The use of realistic conditions for the demonstrator (such as performing real flight in WITAS) appears as an important factor in ensuring the relevance of the results for later product implementation.

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