INVESTIGATION AND SUPPORT OF EVOLUTIONARY DESIGN

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Abstract

Current research proposes a distinction between evolutionary and revolutionary approaches aimed at supporting design. Earlier investigations showed that in design of one-off products but also serial production products evolutionary processes can frequently be identified. However, one important insight of the presented research was also the identification of a lack of research into evolutionary design processes. This paper aims to address this discrepancy by means of an analysis of different sources of insight concerning evolutionary design. This sources range from a literature review of analyses of single designers and design teams over observations of design teams in design education to three kinds of design in industrial practice: design of one-off products and of serial products (hand-held construction tools and automotive components).

Keywords: Design methods, Design practice, Design management

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1 INTRODUCTION

In current research a distinction between evolutionary and revolutionary approaches aimed at supporting design was proposed (Stetter et al. 2011). The investigation showed that in design of one-off products but also serial production products evolutionary processes can frequently be identified. However, one important insight of the presented research was also the identification of a lack of research into evolutionary design processes. This paper aims to address this discrepancy by means of an analysis of different sources of insight concerning evolutionary design. This sources range from a literature review of analyses of single designers and design teams over observations of design teams in design education to three kinds of design in industrial practice: design of one-off products and of serial products (hand-held construction tools and automotive components).
The structure of this paper follows. Section 2 summarizes the research approaches applied. In section 3 the notions evolutionary and revolutionary approaches to support design are clarified and described. Additionally the lack of support for evolutionary approaches is shown. The following sections summarize insights concerning potential and approaches for supporting evolutionary design. The fourth section is focused on insights concerning single designers. The main emphasis of section five is design teams. Section six concentrates on evolutionary design in industrial practice.

2 RESEARCH APPROACH

The conclusions presented in this paper are based on a retrospective analysis of three design managers in design, who are actively participating individuals in certain roles. Additionally, an extensive literature review and logical deduction were employed.
Actively participating individuals can be understood as persons who are an integral part of the organization and who carry their own responsibilities for a part of the company core processes. In the case of qualitative, exploratory research, a retrospective analysis of participating individuals can help to investigate the underlying causes and complicated phenomena such as the effects of certain approaches to design (e. g. evolutionary or revolutionary approaches). In this aspect retrospective analyses are similar to "insider research" which is usually performed by observers with the main purpose to carry out the research. Brannick&Coghlan (2007) underline the value of "insider research" and see no inherent issue why being "native" is an issue. Current research analysing the role of Ph.D. students in industry led to the conclusion that such insiders have great possibilities to closely study their own organisations and reveal new insights about organisational life (Kihlander et al. 2011). The limitations of this investigation method are the limited capabilities of human beings to remember correctly, the possibility that memories are unconsciously adapted to concepts of current interest and the fact that each participant will only be able to explore a small fracture of industrial reality.

3 EVOLUTIONARY UND REVOLUTIONARY APPROACHES

The core of all design is the product. Generally, products can be distinguished into evolutionary and revolutionary products by analysing their genealogical tree. Revolutionary products have either no predecessor or a predecessor which is different form the new product with regard to decisive characteristics. Two typical examples could be the car as an example for an evolutionary product which is enhanced over product generations and the first Apple iPad as a revolutionary example with no real predecessor (it can be argued that the iPad is just a larger iPhone – but it still generated a new market segment). Frequently, it can even be observed that during evolutionary cycles products are growing. Especially in computer science it is easy and less dangerous to keep the existing functions and only to add new functions. The complexity of such products is also increasing.
However, as this paper is mainly concerned with supporting designers, the process is in the focus of interest. Obviously product and process dispose of a strong connection. Probably a revolutionary product is more likely to be the result of a revolutionary process (a revolutionary process in this sense is not characterized by the outcome – the product – but other characteristics which are described later in this paper). However, this is currently a field for speculation and the authors will concentrate in the following sections on approaches which influence directly the process and only indirectly the product.
Until now, the terms "evolutionary" and "revolutionary" were only sparsely used in connection with design. Bamberger (2005) reports: "Up until now, no distinguishing between different types of design has been made.... for both of the basic kinds of design that are practiced: evolutionary and

revolutionary design. Evolutionary design is the most often practiced form of product development, and is based on existing designs that are further developed to better achieve a set of existing or newly defined functional requirements.… Revolutionary design, on the other hand, has no legacy but starts with a clean sheet of paper" (Bamberger 2005). Similar concepts are reported by Robinson et al. (2005) in the scope of innovation: "Innovation is a complex competency, however, and it is widely acknowledged that two distinct types exist. The first, whereby existing products or processes are improved, is referred to as incremental or evolutionary innovation, and the second, whereby entirely new products or processes are generated, is referred to as radical or revolutionary innovation" (Robinson et al. 2005). Additionally Thomond&Lettice (2002) report that "innovations can be thought of as falling onto a continuum from evolutionary to revolutionary". In the field of innovation management, Ottosson (2006) is mentioning the two concepts in the framework of distinguishing technology push (revolutionary) and market pull (evolutionary). Evolutionary approaches in the field of engineering design are reported by Kittel&Vajna (2009).

Evolution can be defined as a gradual process of change and development (Cambridge Advanced Learners Dictionary 2011). Concerning the support of engineering design, the following characteristics could be identified, which designate a purely evolutionary approach (as one end of a continuum between evolutionary and revolutionary):

- the process starts with an existing product and its components;
- the main process depiction is a circle;
- changes are carried out altering the product or its components (at the absolute end of the continuum these changes would be arbitrary as opposite of a completely planned approach);
- appropriate tests are carried out in order to test the "fitness" of the generated solution alternatives;
- iterations are the essential element of the approach;
- flexibility is the central advantage of such approaches.

Similar approaches can be found in software engineering under the notion "continuous design" which is understood as the process of using refactoring to continuously improve a program's design (Shore 2004). Also the notion "incremental design" is in general describing similar approaches in programming (Larman 2003).

In general, revolution is understood as a sudden, complete or marked change in something. For the designation of a purely revolutionary approach, the following characteristics can be used:

- the process starts with necessities, needs or wishes of customers or society or with an independent vision;
- the main process depiction is a linear procedure scheme;
- the development of the product and its components proceeds from abstract to concrete in a well-ordered, systematic manner;
- tests are theoretically only necessary for verification purposes ("are the requirements fulfilled?") but not for validation purposes ("were the requirements showing the real needs of users and application?") as the product is perfect as the result of a perfect revolutionary process;
- iterations are not necessary;
- the chance to achieve something totally novel and/or optimum is the central advantage of such approaches.

For describing revolutionary processes also the notions "radical design" or "radical innovation" are used. Norman & Verganti (2014) employ an analogy to hill climbing and describe: "Incremental innovation attempts to reach the highest point on the current hill. Radical innovation seeks the highest hill".

Figure 1 summarizes the characteristics of evolutionary and revolutionary approaches.

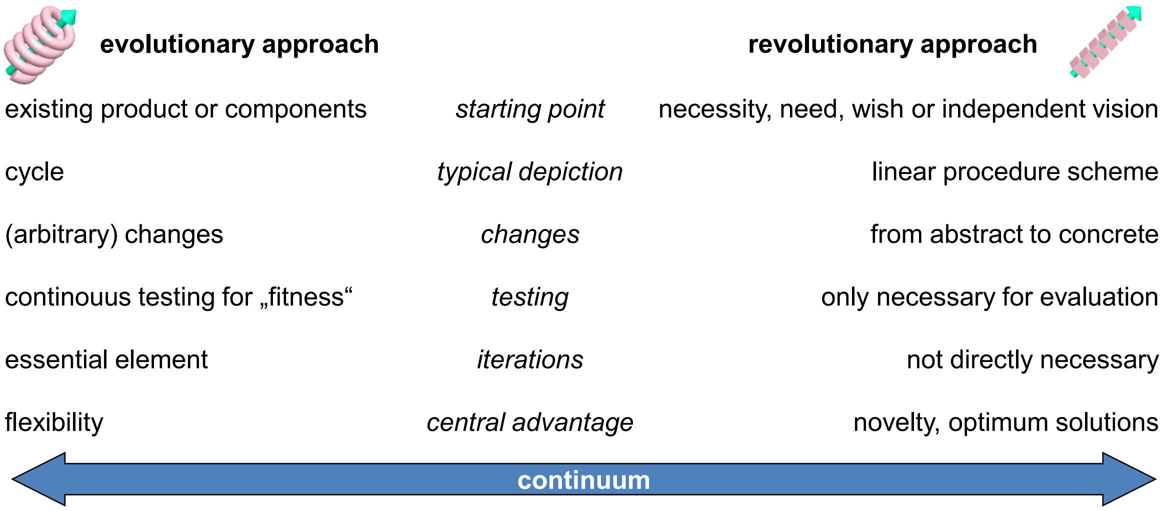

Figure 1. Characteristics of evolutionary and revolutionary approaches (Stetter et al. 2011)

4 ANALYSING EVOLUTIONARY DESIGN: SINGLE DESIGNERS

One prominent example of a single designer using an evolutionary approach was described in detail by Dylla (1990). One of his test persons is called Rolf; he is an experienced designer (engineering design) and is able to achieve a very good result in a very short time (the design problem is a wall mounting for an optical device). This designer Rolf creates alternative solutions often and seemingly without high effort. His proceeding style can therefore be labelled: "evolutionary". One interesting insight is that he replaces inferior solutions with better solutions without emotional involvement (Dylla 1990, p. 127). Another test person who only achieves a mediocre result appears to be annoyed, if he has to replace a prior solution (Dylla 1990, p. 115). This observation could lead to the hypothesis that an evolutionary process can be hindered by an emotional connection with certain solutions. Additionally, Rolf and the other test person with a very good result (Hans) exhibit the largest share of quantitative analysis (Dylla 1990, p. 98). Also Fricke (1993), who performed a similar investigation, concludes that timely executed evaluations are process characteristics which correlate with successful products. Accurate analyses seem to be a cornerstone for successful design, also valid for evolutionary design. This may lead to the second hypothesis: "evolutionary design can be successful if accurate analyses are used to determine better solutions". One main insight of Dylla (1990) is furthermore that good results can be achieved by test persons with a rather evolutionary approach (Rolf – "Typ 1") as well as persons with a rather revolutionary approach (Hans – "Typ 2"). A general dominance of one of the approaches can not be claimed. This distinction was investigated in detail by Günther&Ehrlenspiel (1999). They distinguish mainly between P-Designers and M-Designers. The M-Designers (educated in systematic design approaches) in general set up a list of requirements, divide the problem into several sub-functions and start to search for principal solutions for every sub-function.

In opposite to that approach, the P-Designers (designers from practise without methodical education) spend less time on clarifying the requirements, choose one sub-function and one concept and then detail this part of the problem up to final embodiment design as a core of their work. Often documentation of rough embodiment design and an analysis of this state are skipped. The solution for the next sub-function is then added to the existing ones and is then detailed again. Günther&Ehrlenspiel (1999) name these different approaches phase-oriented (M-Designers) and sub-problem-oriented (P-Designers) procedure (Figure 2).

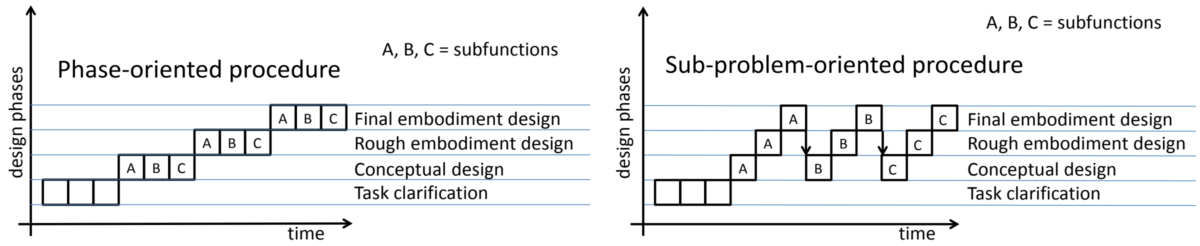

Figure 2. Phase-oriented and sub-problem-oriented procedure (Günther&Ehrlenspiel 1999)

An important finding is that the sub-problem-oriented approach works, if the first sub-function chosen is a main function. In case the first sub-function is a side function with low impact on the overall concept, elaborating this sub-function can lead into a dead end, when adding concepts of more important sub-functions.

5 ANALYSING EVOLUTIONARY DESIGN: DESIGN TEAMS

Blessing (1994) reports a detailed observation of a product development process of a medical device executed by a large design team. She reports that usually no alternatives were generated when a reasonably satisfying solution had been generated already, or could be obtained. This observation from industry could be interpreted that after a certain level of satisfaction is reached, neither an evolutionary nor a revolutionary process is used. The generation of new solution seems to be blocked by time pressure and other influencing characteristics of an industrial process. This can lead to the hypothesis (concerning specifically evolutionary design): In evolutionary design the creation of better solutions can be hindered by time pressure and by a satisfaction with existing solutions.

Also Frankenberger (1997), who investigated several product development processes carried out by design teams in industrial practice, is not directly focusing on the distinction between evolutionary and revolutionary design; however the episodes he is describing (e. g. on page 41 (Frankenberger 1997)) make clear that evolutionary processes were frequently observed. Again and again are the designers facing new problems and are changing there product without any conscious generation of alternatives. Frankenberger (1997) lists success factors for the activity "searching for solutions"; the central variable for unsuccessful searches for solutions is a lack of available information about solution possibilities and surrounding conditions. This observations leads to a central hypothesis concerning evolutionary design: A central success factor for evolutionary design is the availability of information concerning solution possibilities and surrounding conditions. In further parts of his thesis, Frankenberger (1997) lists many other success factors e. g. for crisis management; however the factors are independent from the proceeding style (evolutionary or revolutionary) and are therefore not discussed in here.

At the Hochschule Ravensburg-Weingarten (HRW) a number of products were developed in the last years under the supervision of one of the authors (Stetter et al. 2011). A part of the education at the HRW is concerned with the strategies, methods and tools of systematic design; additionally a special emphasis especially in the mechatronics courses is given to VDI 2206. In the design education the professors try to force students in the direction of a revolutionary approach (“clarify requirements first” or “plan your project in an early phase”). The daily work with students shows that such recommendations are reluctantly followed, but with little enthusiasm. Probably many design mistakes and detours are not reported to the supervisor or are even consciously hidden; still the observable process is highly iterative and evolutionary. Interestingly, the most successful projects were characterized by a rush towards the later stages of a design process and ongoing improvements at this stage. The students were working enthusiastically with hardware. They enjoyed testing and improving and even accepted large changes, if they agreed that these changes were necessary. This can lead to the third hypothesis in this section, that evolutionary design is more probable to be successful if the designers are able and allowed and have the necessary resources to investigate hardware in early stages of the design (first fast prototyping). It seems that the conscious analysis possibilities as well as the unconscious user experience with the product under development more than counterweight the negative effects from early concretisation steps (some kind of decision making) which are inevitable for the realisation of prototypes. However, the capability to deviate again from the direction shown in the prototypes seems to be a necessary prerequisite in such procedure.

6 ANALYSING EVOLUTIONARY DESIGN: DESIGN IN INDUSTRIAL PRACTICE

This section summarizes insights concerning evolutionary design in three different industrial environments.

6.1 Design of one-off products

One of the authors is responsible for the design and manufacturing of plants for the woodworking industry e. g. to produce 3-layer-parquet, solid wooden panels or window scantlings. These plants are highly individualized applications: often one-off products have to be designed in order to fulfil the customer requirements (Figure 3).

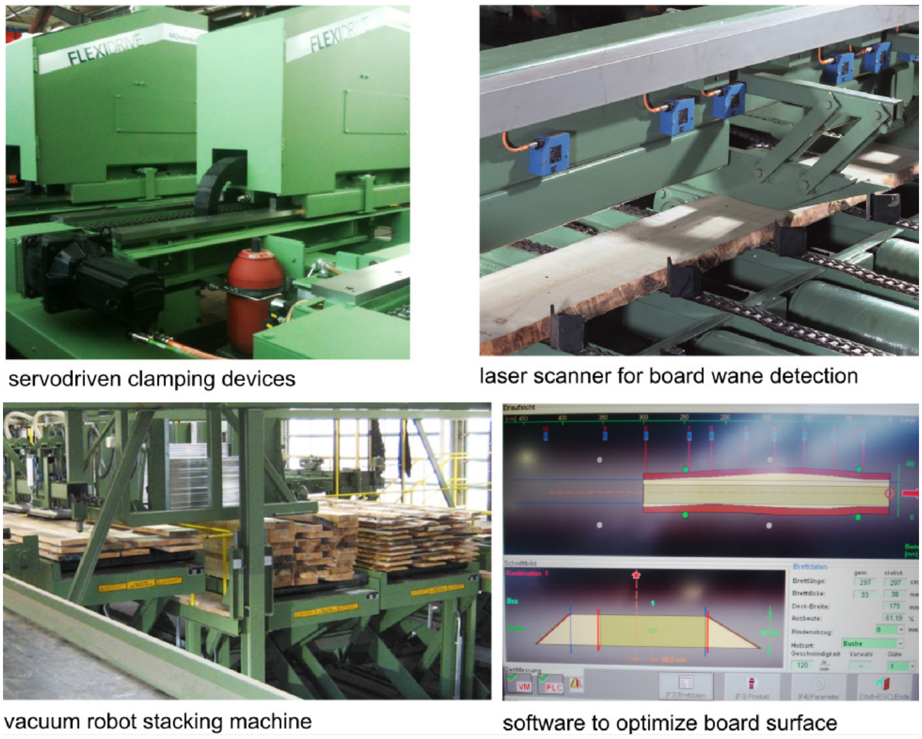

Figure 3. One-off mechatronic products for woodworking plants

Plant engineering usually combines known product components (standard modules, bought-in products), customer-specific designed one-off products and customer-specific adapted products. Evolutionary design is applied in two different ways:

1) Designing a new plant project

Following the particularity of plant engineering, every new plant project has unique product requirements. As a first step, these requirements have to be properly defined. The second step is to establish a rough overall plant design and to decide at which position which of the three above mentioned product types will apply: known product components, new one-off products or adapted products. Even if the result of the rough plant design phase shows that only known product components can be used, the design process is not finished yet. The product requirements have to be verified in detail, interfaces (spatial, functional, signal/energy), working conditions have to be clarified etc. The evolutionary design process is supported by team organisation and documentation tools. Project experience is a crucial factor for a robust design. Therefore a specific design team is established at the beginning of every new plant project consisting of the involved sales engineer, a project manager with experience in similar plant types and several design engineers responsible for technology families such as conveying equipment, sawing units, waste handling systems, electronic and control systems. The project manager has to coordinate the design activities and integrate additional involved departments (external suppliers, manufacturing, assembly, commissioning)

according to the different design phases. The design progress is driven by stage gates in order to verify quality, time and cost targets of the project. Standardized project documentation helps to ensure the design specification and the knowledge transfer from other plant projects.
2) Evolutionary improving of product families
Known product components are organized in product families. Design improvement is initiated in two ways: costumer requirements lead to new demands such as higher output, better production efficiency, higher degree of automation etc. Based on these demands, design projects are established to improve design features of a product component or a whole product family. Every design project is managed by one design engineer who is responsible to run this project and to fulfil the project goals. Depending on the size of the design task additional design resources or external support are addressed to the project. The second initiative comes from the computer-based error tracking system (Möhringer 2006). In this system errors which occur in running plant projects during all phases from design until after-sales phase are documented. According to an evaluation of priorities (error costs, frequency of occurrence, consequences of defects etc.) documented errors are chosen and design projects are organized to improve the product features to avoid errors in the future. The project can be very small or only a task of a supplier. It can be as well very important and fundamental. The tracking system is a very useful help to organize these numerous design projects beside the daily work, to keep an eye on priorities and time lines and to improve consequently product quality by evolutionary design.

6.2 Design of medium-complexity serial products

The source of experience for this section was the development department of a world-class manufacturer of products mainly aimed at construction industry (e. g. handheld power tools). In handheld power tools development most of the products in the market are today quite mature. The basic functions (e. g. drilling or cutting) and components of the tools (e. g. motor, gearbox, chuck) are already optimized and there is often a family of tools in different weight classes (e. g. drillhammers with 5 kg, 7 kg and 9 kg weight of the tool). This maturity leads to "next-generation-projects". The need to offer new products in short time periods without inventing the wheel newly, leads to projects which start with the core of the existing product, keep some of the assembly groups and change some others and add new features (e. g. additional gear, anti-vibration-handle, chuck with more lifetime), see figure 4.

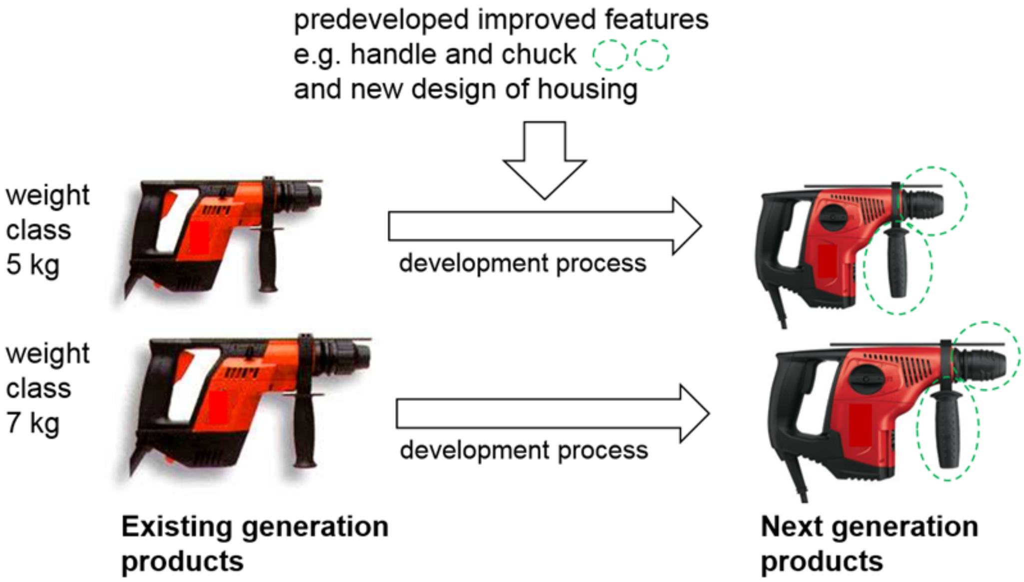

Figure 4. Principle of the next-generation-approach which includes different weight classes

Often a new design of the housing is also included in those projects. The authors name these projects "next-generation-projects" which follow a more evolutionary approach. For next-generation-projects a conscious analysis and interpretation of the predecessor product but also of the development process that led to this product are of paramount importance. The serious discussion with people who have been involved in the development of the existing product is a must.

It is obvious that this evolutionary approach is taking less time for development than developing a new drilling tool for the first time. One element to support those next-generation-projects is to have a professional documentation and understanding of the predecessor. Having at least one developer from the tool XYZ on the project team for XYZ-next-generation helps, too. If new features (e. g. a vibration reduction handle) are developed in a pre-development department, then these solutions can be used for different tool areas (e. g. cutting and drilling).

6.3 Design of high-complexity serial products

A modern automotive drivetrain is for itself as well as being part of the whole car a highly complex and highly mechatronic product. The engine control unit (ECU) can be regarded as the most complex part in what can be called "a driving computer". It comprises several thousand functions including the actual engine control, self-diagnostic systems, security layers, as well as interfaces to other control units such as the gearbox control, chassis control or navigation systems; some ten thousand parameters; and connections to around fifty or more sensors and actuators. Figure 5 shows a sample engine control unit a selection of its most important functions.

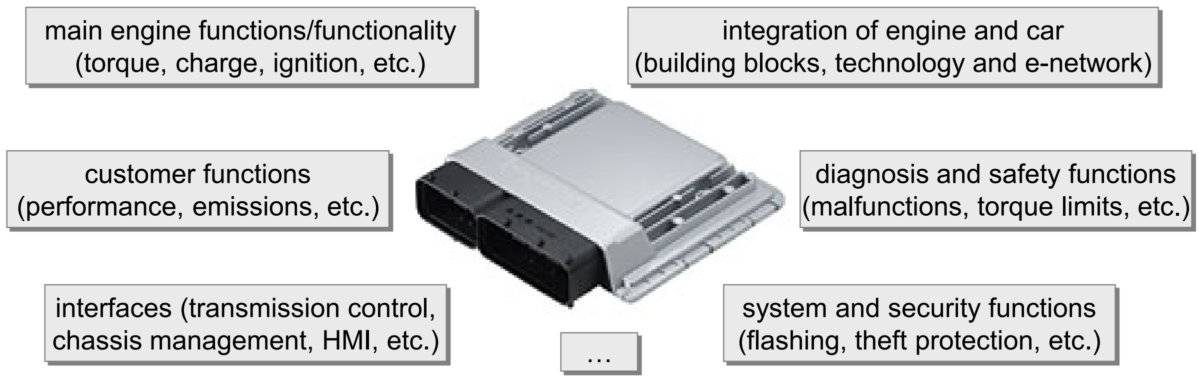

Figure 5. Engine control unit and a selection of the most important functions

The respective author worked in a department being responsible for the integration of the drivetrain into the vehicle and thus for its overall functionality. This is primarily done by adaptation of the parameters to the current project, which can lead to necessary software (functions) or hardware changes. The engine or drivetrain can be considered as a building block, which is integrated in different vehicle projects; the software of its control is separated into functions and data; while the functions are tried to be kept identical, the data is adapted to the continuously starting or running projects and defines the final characteristics of the car. Though this paper regards a wide range of products, the main focus of this section is on the software of the engine control unit.

Software enables a quite flexible respond to problems, new requirements, or new ideas – with some restraints: Though the software itself can be changed quite quickly (there is no need for changing tools e. g.), the process of changing software including testing etc. can be relatively long, since the whole software package has to be changed and approved; thus the main flexibility lies in its functional flexibility. The software has an extremely high complexity, which can hardly be overviewed in whole. It is partly being developed by the supplier of the ECU, partly by the OEM itself. This leads to a certain dependency on the supplier, to an extremely expensive development process regarding tools, manpower, organisation, time, cost, etc. and to the fact that only an evolutionary design approach is possible, where the considered department is responsible for the overall function of the drivetrain, i.e. for pushing and evaluating the evolutionary process.

The whole development process is evolutionarily arranged and based on changes. It is steered by a tool-based change management system for the functions as well as a configuration management system for both the functions and the data. These are the heart of the process. Even completely new projects, when a more revolutionary approach is – at least partly – attempted, are run within the change management system. Therefore, e. g. requirement specifications are both ways exchanged with the change proposals.

In order to manage the complexity of the different projects – one software has to fit into different projects – there are different levels for software releases. There is a meta track, which is identical for all drivetrains and regularly, but not too often changed. Beneath that, project specific release tracks

only comprise changes relevant for the respective project. Nevertheless, these changes can be integrated into the meta track if reasonably at a later stage. On the lowest level, there are software releases only for a certain new function or change, where they can be tested and developed, so that only a validated function/change is implemented in the actual software.
The evolutionary approach allows that a new software release can be evaluated on an existing system, i. e. the new software has to exactly fulfil the functions of a previous version, which can be tested automatically or manually; the adaptation and evaluation of the changes take place in a second step. Therefore, new functions generally can be switched off by certain parameters. This allows – to a certain degree – to also use new software releases on products, which are already in the market.
The evolutionary process is supported by different other tools, such as automated calibration, automated code generation and documentation, software or hardware in the loop testing, etc. Both a strict documentation and a clear versioning are fundamental for the functioning of this complex and extensive process, which can only work with highly motivated personnel and a modular approach to the product.
Side effects of the evolutionary approach such as the carrying along old functions, hardly being able to overview the whole system, and functional interferences leading to always new changes seem to be in line with natural evolutionary developments.

7 SUMMARY OF OBSERVATIONS

This section is aimed at summarizing the insights gathered in the different fields of experience. The structure is generally following the structure in section 6. The main observations and hypotheses resulting from the multi-view investigation concerning successful evolutionary design are:

- An emotional connection with certain solutions seems to be dangerous.
- Accurate analyses to determine better solutions seem to be a major success factor.
- For innovative, evolutionary design time pressure and early satisfaction seems to be a negative factor.
- If information concerning solution possibilities and surrounding conditions have be worked out by the development team readily, the chances for success seem to be higher.
- It seems to be necessary that designers are able and allowed to realize first fast prototyping.
- In evolutionary design it is especially important to clarify interfaces (spatial, functional, matter/energy signal) and operation conditions as well as to verify product requirements.
- The implementation of (computer-based) error-tracking systems seems to improve the knowledge about predecessors and thus support evolutionary design.
- It seems to be necessary to involve all domains, especially in later phases of the design process.
- Central questions seem to be: Which system is the predecessor? Who has in depth knowledge about the predecessor tool? Which are the functions, components to redesign, which are not touched? Which redesigned or added functions are recognized and appreciated by the customer? What is the time frame of the project (the time available can define the scope of new features – only facelift or really some features added)?
- Conscious versioning and a change management system for the functions as well as a configuration management system seem to be inevitable for complex systems.
- It seems to be necessary that for complex systems the evolutionary changes are organized on different levels.
- A modular product structure seems to be helpful and new product components should maintain the existing functionalities.

8 SUMMARY AND OUTLOOK

In a nutshell, evolutionary design is characterized by many optimization steps which from the outside may even be considered arbitrary. Evolutionary design can be observed at different levels of a design process and at different stages of design – it even seems to be the predominant form of design even in very successful industrial companies. Design research has over the last decades very often focused on a rather revolutionary procedure scheme highlighting for instance the importance of a detailed clarification of the task at the beginning and the necessity to look for alternatives on abstract levels. This paper does not intend to argue the merit of these insights and suggestions. However, if evolutionary design is very often adopted by engineering designers in industry should one not seek for possibilities to support this kind of design? This paper has summarized some characteristics of evolutionary design from different sources of insight. Obviously, this process is just started and more contributions are needed to come up with a solid body of supporting strategies, tools and hints for evolutionary design.

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