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A COMPARISON OF EVOLUTIONARY AND REVOLUTIONARY APPROACHES IN MECHATRONIC DESIGN

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ABSTRACT

From an extreme point of view, one could identify two antagonistic concepts for supporting mechatronic design. A purely revolutionary approach will start from nothing but necessities of users or society and will follow a rigid procedure in order to design something totally new. On the contrary, a purely evolutionary approach will start with an existing product and will proceed in numerous cycles in order to design something better. Obviously, no black-and-white distinction of the existing approaches is possible or sensible as nearly each published approach for mechatronic design places itself somewhere between those extremes. It is one important objective of the presented research to identify the position of the most prominent approaches for mechatronic design and design in general on this scale. In a second part, the suitability of evolutionary and revolutionary approaches for three important areas is discussed: for mechatronic design education, for one-off mechatronic products and for serial production products. The ultimate goal of the research is the formulation of guidelines how a combination of both directions could lead to more effective and robust mechatronic design processes.

Keywords: Mechatronic design, product development strategies, design strategies

1 INTRODUCTION

Since ICED 2007, the special interest group (SIG) "mechatronics" is discussing research on mechatronic design. At Design 2008 and ICED 2009, several topics and approaches were presented; at ICED 2009, a concentration around certain topics and approaches could be observed. At the Design 2010 the findings were summarized to a research framework in order to support and give structure to further activities [1]. During the numerous discussions, the insight appeared that one of the most important characteristics is the starting point and the general procedure style of the strategies, methods and tools for mechatronic design, for instance the necessary amount of chaos [2]. Two antagonistic concepts could be identified:

- One concept is a purely revolutionary approach, which will start from nothing but the necessities of users or society and will follow a rigid procedure (without any iterations in the most extreme form of a revolutionary approach concerning feedback from the market, i.e. "evaluation") in order to design something totally new.
- The second concept is based on Darwins paradigm "survival of the fittest". This purely evolutionary approach will start with an existing product and will proceed in numerous cycles (arbitrary cycles in the most extreme form of a evolutionary approach as an analogy to arbitrary changes of the gene pool for living entities) in order to design something better.

The presented research aims at identifying the position of the most prominent approaches for mechatronic design and design in general on this scale and to discuss the suitability of evolutionary and revolutionary approaches for mechatronic design education, for one-off mechatronic products and for serial production products. In each of these areas, the current situation is reflected and the potential of evolutionary and revolutionary approaches is investigated. On this basis, a SWOT analysis (strength, weaknesses, opportunities, threats) is carried out. The main objective is the formulation of guidelines for supporting mechatronic design processes. In order to build a basis for this purpose, this section presents firstly a definition of "Mechatronic Design" and secondly an explanation of the research procedure.

According to Möhringer&Stetter [1], "Mechatronic Design" describes the synergetic creation and integration of mechanical engineering, electrical engineering and information technology for the

specification and description of any kind of physical product and process. A detailed description of key research activities in mechatronic design was compiled and updated by Möhringer [3 resp. 4]. The main challenge of mechatronic design is the increased complexity as a consequence of the mutual interrelationships between the disciplines (compare e. g. [2]). The astonishing amount of chaos in real-life mechatronic design processes makes an investigation of appropriate modes of support desirable.
The vision guiding the described research is a sensible combination of revolutionary and evolutionary approaches for supporting mechatronic design. In order to allow a valid discourse, the rather novel terms evolutionary and revolutionary approach are clarified in section two. Prominent approaches for supporting mechatronic and conventional design are placed within this framework in section three. Sections four to six report the current situation in the fields "mechatronic design education", "design of one-off mechatronic products" and "design of serial production mechatronic products". On this basis, section seven presents the results of a SWOT analysis.
The conclusions presented in this paper are based on a retrospective analysis of three design managers in mechatronic design, who are actively participating individuals in certain roles. Additionally, an extensive literature review and logical deduction were employed.
Actively participating individuals are 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 mechatronic design (e. g. evolutionary or revolutionary approaches). 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. The results are meant to be used as a basis for further research and can be considered preliminary.

2 EVOLUTIONARY AND REVOLUTIONARY APPROACHES

The core of all design is the product. Generally, products can be distinguished into evolutionary and revolutionary products by analyzing their genealogical tree. Revolutionary products have either no predecessor or a predecessor which is different form the new product with regard to decisive characteristics. Figure 1 shows two examples: a car as an example for an evolutionary product which is enhanced over product generations and the 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).

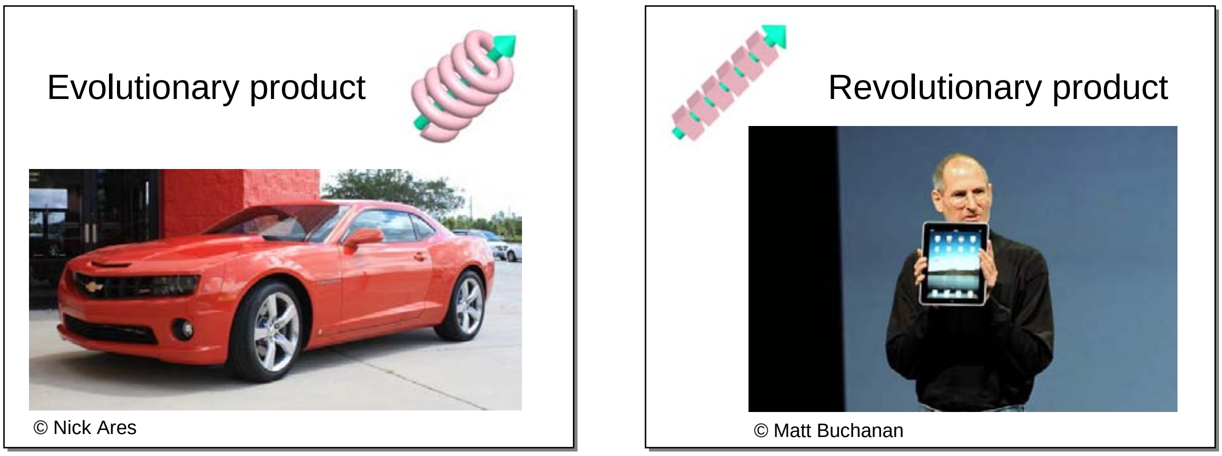

Figure 1. Evolutionary and revolutionary products

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 in general and with mechatronic design specifically. Bamberger 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” [5]. Similar concepts are reported by Robinson et al. 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” [6]. Additionally Thomond&Lettice report that "innovations can be thought of as falling onto a continuum from evolutionary to revolutionary”. In the field of innovation management, Ottosson is mentioning the two concepts in the framework of distinguishing technology push (revolutionary) and market pull (evolutionary) [7]. Evolutionary approaches in the field of engineering design are reported by Kittel&Vajna [8], [9].

Evolution can be defined as a gradual process of change and development [11]. Concerning the support of mechatronic 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.

In general, revolution is understood as a sudden, complete or marked change in something [12]. 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 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 process (this is marking the absolute end of the continuum);
- iterations are not necessary;
- the chance to achieve something totally novel and/or optimum is the central advantage of such approaches.

Figure 2 summarizes the characteristics of evolutionary and revolutionary approaches.

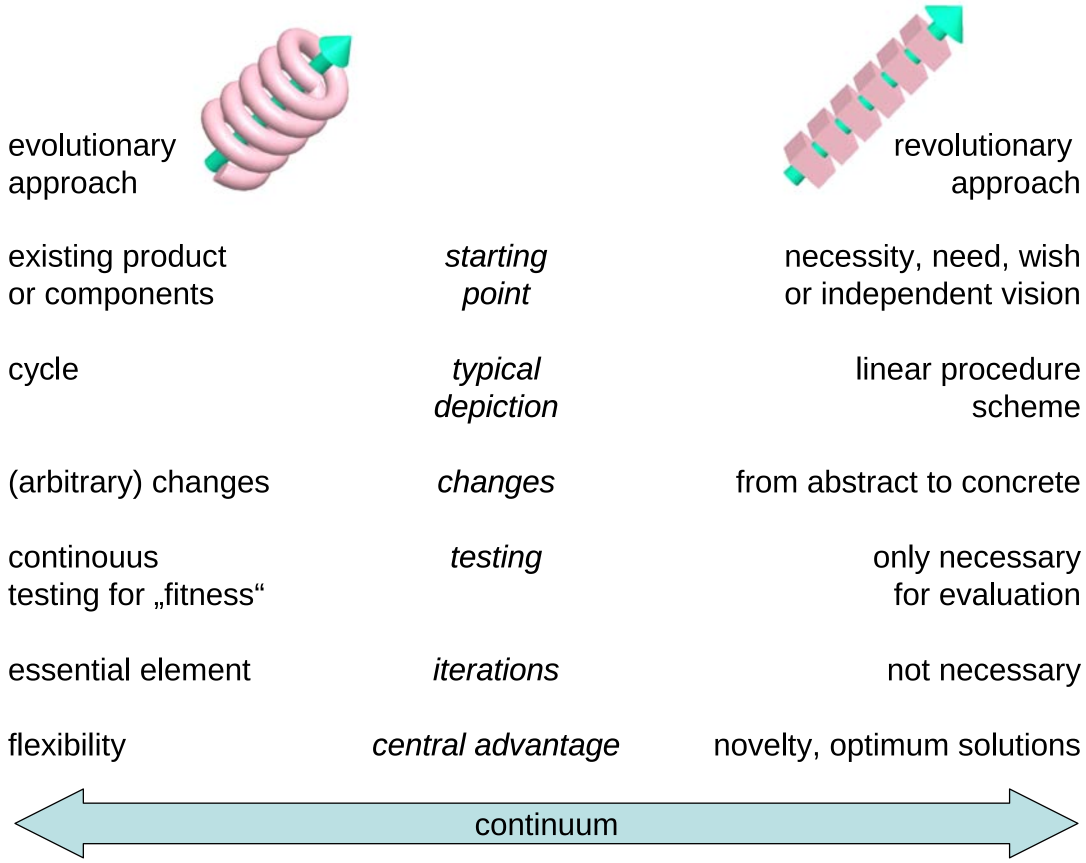

Figure 2. Characteristics of evolutionary and revolutionary approaches

It is important to note that design can have several dimensions including multiple layers of planning the process (reported e. g. by Giapoulis [13]). The character of a process (evolutionary or revolutionary) can be different on different levels. It may be possible that on the top-level planning a very strict revolutionary process is followed whereas on a lower day-to-day or hour-to-hour process a very iterative evolutionary approach can be observed. This phenomenon is sketched in Figure 3 and discussed in the later sections.

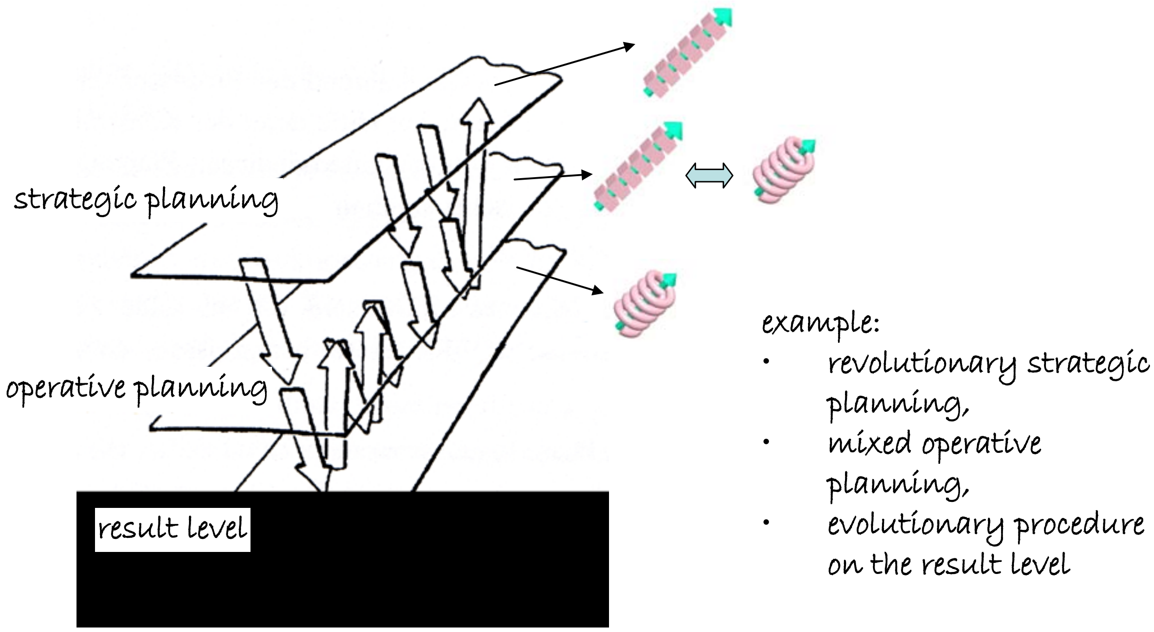

Figure 3. Evolutionary and revolutionary approaches on different process levels (compare [13])

3 PLACEMENT OF PROMINENT APPROACHES

In order to support the later sections, the authors have tried to place existing approaches on the continuum between evolutionary and revolutionary. As a second dimension, the continuum between academic and industrial was added in order to explore the origin and field of application of the methods. This second dimension was firstly just added experimentally but led to the identification of white areas and was therefore kept. The placement was done after an intensive negotiation process between the authors taking into account their individual knowledge and experience as well as available literature. Still, the placement is not yet the result of an in-depth investigation and other research groups may question the result and could arrive with different placements. A total of ten approaches (methodologies, schools, connected research groups) were placed in the two dimensions. Genetic algorithms in design have appeared in the last decades and describe essentially computer-based alterations of design (they emulate a "darwinian" evolution cycle) [14]. Up to now, no successful complete industrial physical mechatronic product could be created in this manner. The term "Prototyping" is intended to describe the current practice in industry where multiple prototypes in different stages are tested more or less systematically. The problem-solving-cycle is a very iterative approach proposed in many sources e. g. in the field of systems engineering (compare e. g. Daenzer&Huber [15]. The VDI 2206 is a well-known and generally accepted guideline for mechatronic design [16]. The term "systematic design" tries to combine the research work of predictive design science such as Pahl&Beitz [17], Ehrlenspiel [18], Lindemann [19], Cross [20], Pugh [21]. There is no clear distinction to "design science", but the main researchers such as Rodenacker [22], Hubka&Eder [23] focus to a stronger degree on the theory of design. The research groups based on the research of Altshuller are summarized under the notion "TRIZ/ARIS" (compare e. g. [24]). The notion "mechatronics" is intended to describe the elaborate procedures proposed in the field of mechatronics (not mechatronic design) e. g. by Isermann [25]. UDT is the abbreviation for universal design theory as proposed by a group around Lossack&Grabowski [26]. Axiomatic design was initially proposed by Suh [27] and has found several followers. The placement of these approaches is sketched in Figure 4.

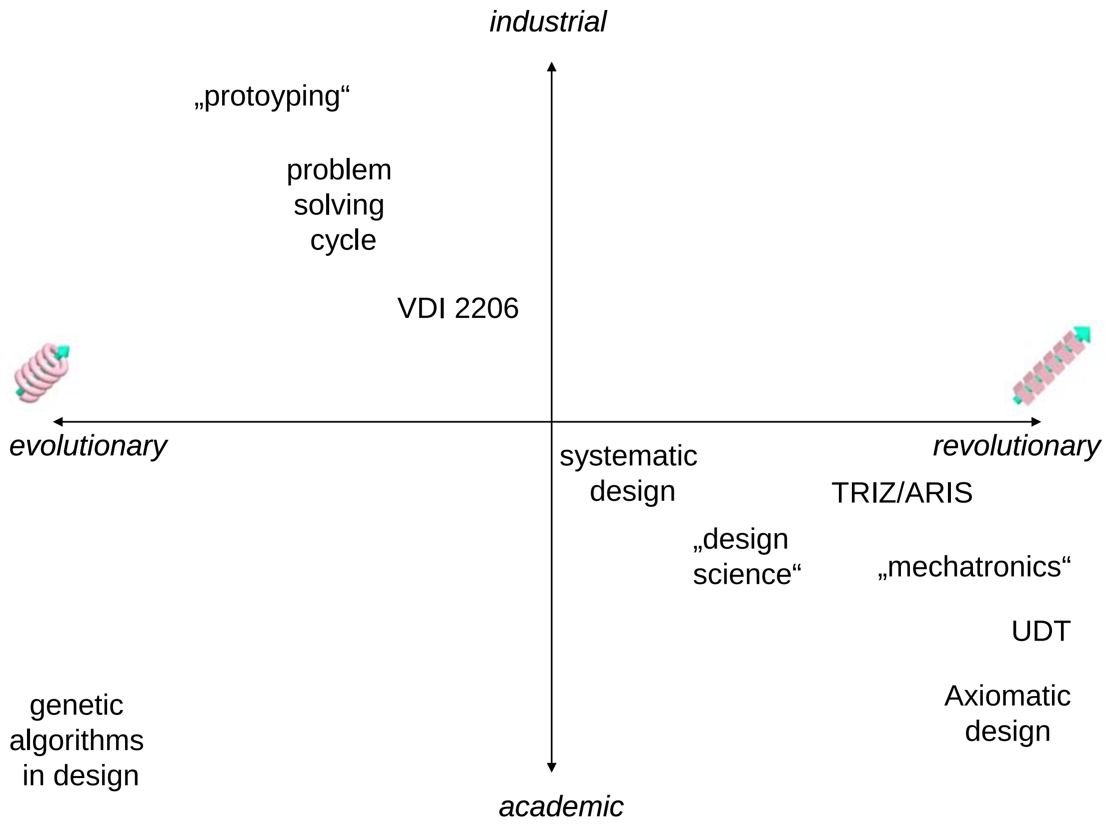

Figure 4. Placement of prominent approaches

It is important to note that some sections remain rather empty. On the academic side beyond genetic algorithms and related work [8] little attention is given on the exploration and improvement of evolutionary proceeding schemes. In industry, methods with a strong revolutionary bias have found little resonance – indicating that a purely revolutionary concept may not be suitable for real industrial processes.

4 MECHATRONIC DESIGN EDUCATION

At the Hochschule Ravensburg-Weingarten (HRW) a number of mechatronic products were developed in the last year under the supervision of one of the authors. The most important examples were a production vehicle with an innovative steering system requiring a dynamic control system, two formula student race cars, a "rescue-me" mobile robot chassis and a solid-state force feedback joystick (Figure 5).

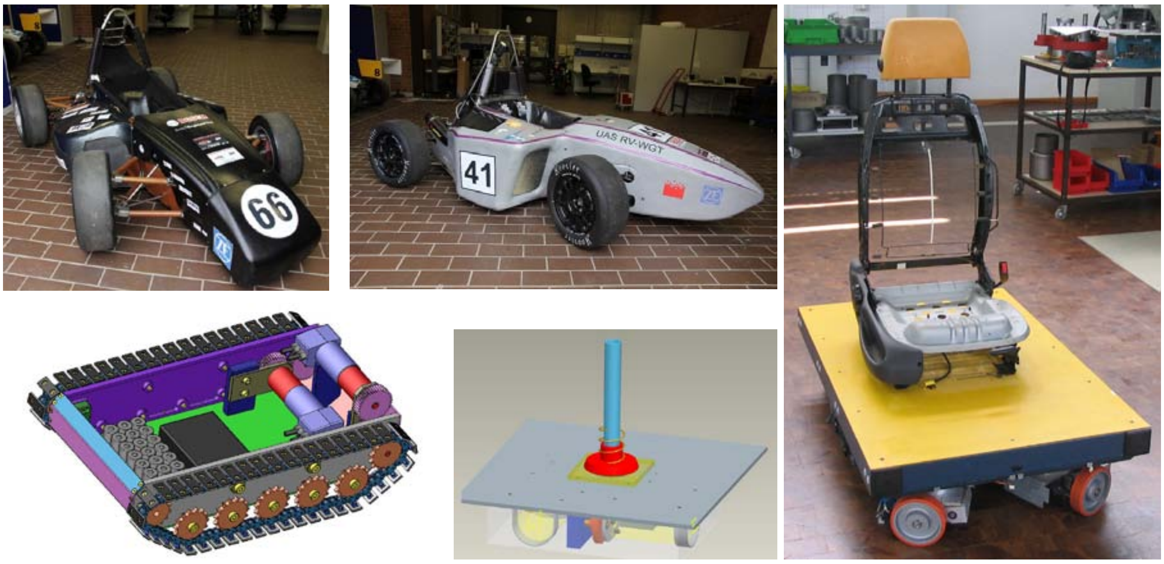

Figure 5. Products developed and realized at the Hochschule Ravensburg-Weingarten

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.

The VDI 2206 contains evolutionary aspects as V-models on the macro level can be repeated and as the problem-solving cycle at the micro-level describes an iterative procedure. However, these aspects were usually neglected by the students. They understood and valued the V-model and used it as a basis for project planning but did not allow multiple runs through the V-model and were not applying the problem-solving-cycle consciously.

It seems that engineering education is greatly improving the analytical capabilities of students and can provide some guidance for the application of revolutionary approaches but has little to offer to support students effectively during the evolutionary phases which seem to represent a large share of the design processes.

5 DESIGN OF ONE-OFF MECHATRONIC 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.

The products are typically mechatronic combining mechanics, pneumatics/hydraulics, electric/electronics and the software domain. Figure 6 shows product examples: a servo-driven clamping device clamps logs and turns the log into the optimal cutting position. 4 individually driven devices with hydraulic clamps need to be synchronized for parallel movement or turning of the log. High dynamics (400 mm/sec) and heavy log weight (up to 6 tons) need to be realized. The second example is a board scanner: several laser lights detect the board wane in order to identify the board shape and the usable board surface. Optimization algorithms calculate the best combination of cuts within the board surface. The third example shows a stacking robot for waney boards. Vacuum suction units lift the board and place it onto the appropriate board stack.

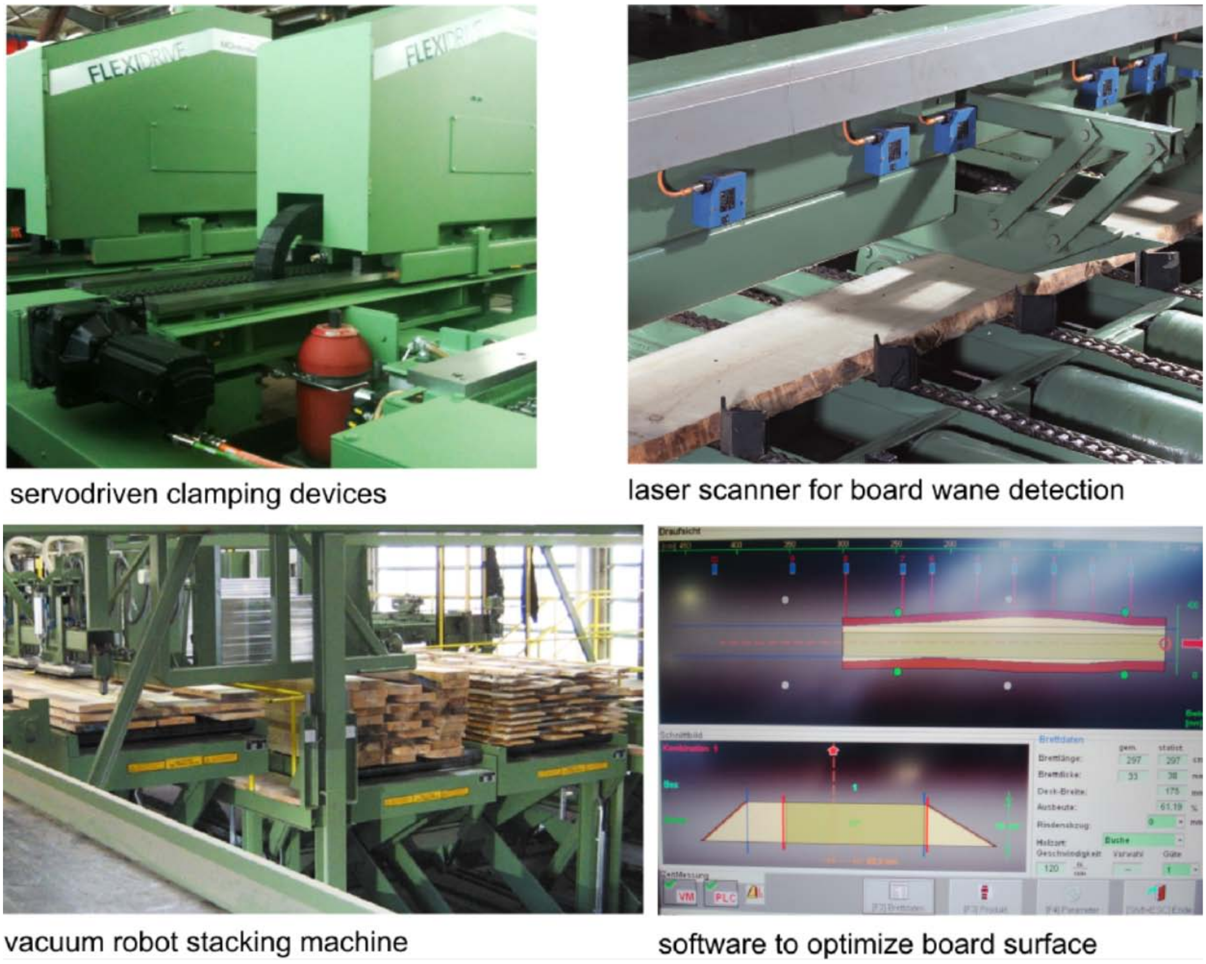

Figure 6. One-off mechatronic products for woodworking plants

Plant engineering usually combines known product components (standard modules, bought-in products), customer-specific designed one-off products and customer-specific adapted products. According to the characteristic of these product types, different design approaches are chosen.

The V-model of VDI 2206 guideline gives a common understanding for the design process: specification of product requirements, detailed domain-specific design and integration and testing of the design results. 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. Consequently the following design approaches are applied:

Evolutionary approach: this approach is used to implement known product components and to design adapted products. Even if the result of the rough plant design phase shows that a known product component can be used the design process is not finished yet. The product requirements have to be verified in detail, interfaces (spatial, functional, signal/energy) have to be clarified etc. Operation conditions e.g. a temperature of -30° Celsius in Russian Siberia can make a big difference for product reliability. The functions have to be thoroughly tested in interaction with the other surrounding components. The approach for adapted products is similar, mainly the detail design phase is longer. Design modifications (dimensions, workload, operation speed etc.) have to be done within the specific domains.

Revolutionary approach: new one-off products require a straighter and more-linear design approach like the revolutionary approach. However in plant engineering it cannot be applied in its pure form. Design iterations and testing – elements from evolutionary approach – cannot be avoided. There are mainly three reasons: The prototype and the final product are the same. It would be too costly to manufacture a serial product because it is maybe never used again. Therefore testing is an essential element to ensure the fitness of the prototype for the final product use. Secondly, virtual engineering and prototyping is limited due to economical reasons. The time and cost effort for modelling is high if the product is only manufactured one time. It is more effective to manufacture a pre-tested product concept and to verify the final design robustness with the real prototype even if certain design modifications may be necessary. Thirdly, a new one-off product as one part of many other products and components of a large engineering plant represents a considerable risk in terms of overall plant functionality and reliability. This risk has to be minimized because delays during plant start-up can lead to enormous costs for rectification of defects, contractual penalty etc. Therefore testing and design iterations are an inevitable design element to receive the best product quality possible for one-off products.

In order to define a standardized approach for each product type, which is applied in a mandatory and cross-department manner, the author implemented individual approach models according to VDI 2206 within the company (Figure 7). The experience shows that approach models with clearly defined milestones (results and time frames) help to coordinate parallel design tasks of different products.

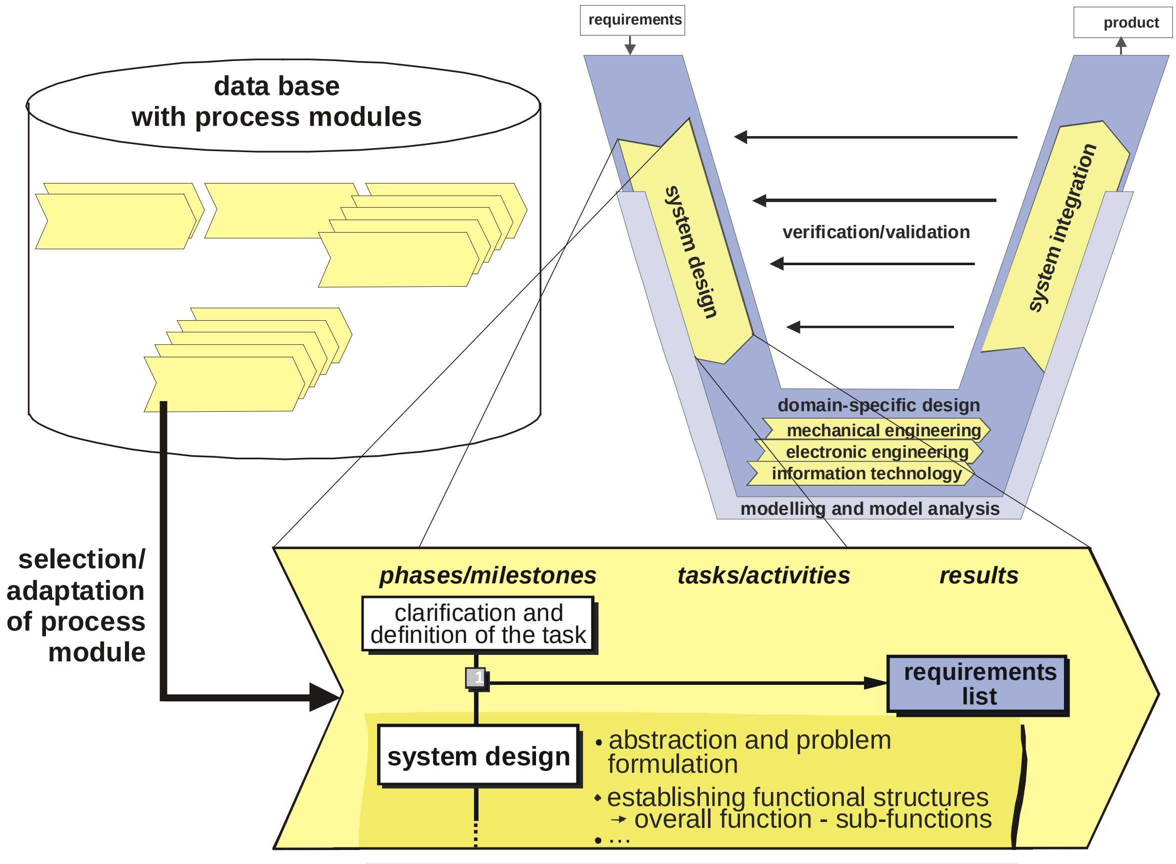

Figure 7. Individual configuration of approach models

6 DESIGN OF SERIAL PRODUCTION MECHATRONIC PRODUCTS

As a serial production mechatronic product, we regard automotives and especially their drive train and the engine management system, which provides numerous functions visible or invisible to the customer, which cannot be realized without software. The engine management system is one of the most complex elements in a modern car, which covers about 1,000 software functions and 20,000 parameters for adapting and integrating the engine into different models and for different markets. Furthermore, it is connected to various other electronic control units such as chassis management to realize driver assisting functions. The development of the product takes place in an equally complex organization with thousands of employees and within an equally complex process running over some years. Boundary conditions increasing that complexity and having a huge influence on the nature of the process cover a high amount of variants, high demands on quality, reliability and cost, as well as high time pressure and the continuous need for innovation.

The overall product is highly mechatronic. There are iterations between mechanics including thermodynamics, electrics and electronics, as well as software, which is not regarded here explicitly or – so to say – from a different viewpoint. The author works in the unit regarding the functionality and integration of the drive train. This business unit sets the parameters of the software itself, but – though or since it has the overall responsibility for the engine – only formulates demands for mechanics, electronics, and software functions. Nevertheless, since software parameters are set here, the focus of this contribution is on the software development or the functions development, regarding the mechanics as rather fixed, electronics as rather auxiliary, and software as the program code of the specified functionality – without minimizing the problems or efforts needed in those disciplines.

The operative design process, i.e. the daily business, can be placed quite far on the evolutionary side of the evolutionary-revolutionary scale. It is characterized by lots of iterations as well as some kind of trial-and-error in the meaning that an engine is integrated in a new car or new functions are added and then the behavior in the overall context is tested and improved as well as failures have to be identified and solved; such failures can be reported from different company units including service, giving notice of problems with products in the market; the continuous and iterative improvement of the behavior comes from e.g. stricter legislative regulations (such as emissions), a highest quality level adaptation to the final product as well as simultaneous working on different parts of the system without knowing each and every cross connection.

Due to the complexity, it is hardly possible to have a complete overview and understanding of the functionality and the system as a single person or unit. Thus, the functions are reused in new products and managed as building blocks in a construction kit, with the negative side effect that changes to one part of the software has to be considered by most projects. The development of the software is furthermore managed by a change management system as a central tool – even requirement or failure lists lead into this tool.

However, this outstanding evolutionary process is linked to or supervised by a revolutionary, i.e. structured process on a management level in order to accomplish projects and complete new models, which at some point have to be serial produced and brought to the market. This structured process gives milestones and integration points, where the results of the different evolutionary processes can be reviewed together.

There are also structured revolutionary processes for the development of completely new functions or technologies as well as to serve certain problems, but such a proceeding is up to the single developer responsible. And the outcomes of those processes always have to align with the existing solutions. This is also and especially the problem, when new technologies (such as hybrid or electric drive trains) have to be developed, which cannot base on an existing product, or when from time to time the existing structure of the evolutionary product is tried to be tidied up in a revolutionary approach. Due to constraints in resources as well as problems concerning the life time of the products and the building set approach, a link to existing solutions, the reuse of existing solutions, or a clear change strategy have to be used.

One might also find evolutionary aspects of product development on the company's level, e.g. when it comes to the evaluation of the product in the market, i.e. its success. There might also be revolutionary aspects on the individual level, e.g. in psychological terms, when someone tries new approaches to solve a certain problem. These aspects shall not be regarded in more depth here.

But there is a strong correspondence to the experiences described in the chapter on education. On the operative, actual working level one can observe a highly evolutionary proceeding; this is – often by a

higher instance – forced into a revolutionary approach, at best in order to align different strings of the process.
This contribution might suggest that there does not have to be a decision between evolutionary and revolutionary approaches, but that both academia and industry have to be aware of this distinction and – even more important – have to find ways to combine both kinds of approaches. In industry, there is often a fight between “process people” and “actual workers”, both not understanding the demands and viewpoint of the other, but it needs both to have an effectively working company of a certain size.
An evolutionary approach might be the only way to deal with an immense complexity, but there has to be a steering of that process with structured methods and revolutionary approaches. This is achieved by parallel processes and different business units.
One might question the degree of efficiency of such an organization, but – again – it is the only way to cope with such complex systems and maybe it *is* a high degree of efficiency. This might be discussed in further research.
In the duality of evolutionary and revolutionary approaches within one organization, it might be important not to force solutions of one approach on the other side of the product development. E.g. comprehensive requirements lists or strict testing procedures might not be appropriate in an evolutionary working environment. The only reuse of existing solutions also might not be right for a revolutionary product.
Though at the time there seems to be an organizational push towards revolutionary approaches, one should also consider support for the evolutionary work, such as documentation, aspects in order to simplify or cleanse existing solutions, configuration management etc.

7 RESULTS OF A SWOT ANALYSIS

On the basis of the retrospective analysis of the three areas, a SWOT analysis was carried out. The results are shown in Figure 8. Though the strengths and opportunities of the evolutionary approach will be close to the weaknesses and threats of the revolutionary approach and vice versa, both approaches have been regarded separately.

Figure 8. Results of the SWOT analysis

The main strengths of the evolutionary approach are its ability to deal with extremely high complexity and its proceeding via small steps, which allows to always have some kind of fall back solution and to continuously adapt to new requirements. This can finally lead to a new design paradigm and be supported by design automatism tools in order to provide higher functionality. Nevertheless, the main weaknesses and threats of the evolutionary approach are that there might be no complete overview and understanding of the system, which can lead to losing control of the process, which again can become ineffective and not leading to an end. This might be due to the fact that it is hard to align the

corresponding distributed development, that there might be no final target and lots of unnecessary changes. Finally, it is hard to develop completely new products with an evolutionary approach, though one might argue, that there is no completely new product without any predecessors.
The strengths and opportunities of the revolutionary approach are its structured, effective and directed proceeding, which is supported by much (academic and industrial) experience regarding the process and elaborate tools. The revolutionary approach allows to design to the requirements as well as from scratch. Its weaknesses and threats are the possibility to redesign existing products unconsciously (and thus not having an advantage against the evolutionary approach) and that validation might take a long time or that the design might even fail in the end. With revolutionary approaches it might be hard to deal with highly complex systems and it is partly inflexible when it comes to e.g. new requirements.
In can be interesting to regard the strengths, weaknesses, opportunities and threats of a combined revolutionary and evolutionary approach. The strengths and opportunities are to combine the just described advantages of both sides, i.e. to have a structured and directed process, which can still deal with high complexity and quickly react to new requirements or problems. Its main advantage is that it reflects industrial practice as well as the experience in student projects, i. e. that most of the operative work is done in an evolutionary manner, which is – at least partly – directed by a revolutionary process or in some parts supported by single revolutionary steps. The weaknesses and threats of this approach are that both sides of the scale or its respective agents do not understand the other side and, instead of combining the advantages, work against each other and try to convince the other side of their view; this can make the process quite ineffective – especially when things are done without any understanding of their reason and benefit – and destroy the last bit of overview, how the process is actually working.

8 SUMMARY AND OUTLOOK

This paper is aimed at starting a discourse of approaches supporting mechatronic design based on the continuum between revolutionary and evolutionary. A first important insight is that most design work has to be viewed as being conducted in a layer differentiated way, employing both evolutionary and revolutionary processes. Still, the two concepts can be observed in certain process levels and segments and may enhance the understanding of design. A first retrospective investigation in the three fields education, design of one-off products and design of serial products is pointing towards a promising white spot on the map with the two continua revolutionary-evolutionary and industrial-academic. It seems to be that despite of a dominance of evolutionary design in industry and astonishingly also in student projects the main point of emphasis of academic discourse and investigations is placed on revolutionary approaches. There seems to be a gap between the mostly iterative support of real industrial design – the problem-solving-cycle and purely theoretical evolutionary design approaches based on arbitrarily generated designs (genetic algorithms). The authors came to the conclusion that work in this area could also be attractive for industry as similarities with the daily work would be probable. Work in this area could result in methods, tools or only process recommendations which considerably improve product development processes.
Obviously, the nature of the presented results is purely explorative, qualitative and even a bit speculative, our main intention is to start a discussion on this topic and to state some topics to think about in both industrial and academic practive. Thus, additional research is necessary to support or contradict the presented hypotheses and insights.

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