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Managing Evolution from Mechatronics to Intelligent Technical Systems

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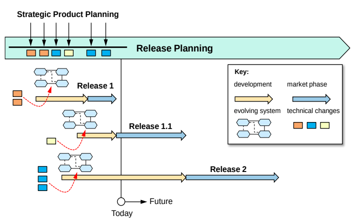
Graphical abstract



Abstract

Technological change from mechanics to intelligent technical systems leads to a fast evolution of products. This evolution is characterized by manifold product generations and product versions, each of them comprising a bunch of new product features and technical changes. To cope with these changes, companies need to systematically manage product evolution in terms of concerted innovation and adaptation steps. Based on this need, this paper outlines a framework for managing evolution of intelligent technical systems. The need for evolving technical systems is detailed and the main fields of action in managing evolution of intelligent technical systems are introduced. The paper concludes by deriving release planning as a suitable approach and an important discipline for future development of intelligent technical systems.

Keywords: Product evolution, intelligent technical systems, release planning

1.0 INTRODUCTION

Todays' technical systems are shifting from classic mechanic-centered products to mechatronics. These systems are based on the close interaction of mechanics, electronics, control engineering and software engineering. The technical systems of tomorrow will go beyond current mechatronics by incorporating additional information processing leading to so called intelligent technical systems (ITS) or cyber-physical systems (CPS) [1].

Advances in information and communication technology offer fascinating possibilities for the integration of a continuously increasing number of new product features based on the combination of mechanics, electronics and software. The interdisciplinary character of these features and their degree of interdependence results in an increasing complexity of the technical system and its development process. At the same time, technological advances, volatile markets and a continuously changing system-environment cause high dynamics in system development [2], [3]. The integration of new product features leads to frequent technical changes and therefore to a fast evolution of products within their economic life-cycle.

An evolution of a product is characterized by an incremental transition from a simpler to a more advanced stage [4]. Therefore, manifold product versions, facelifts and product generations are offered at the market, each comprising a bunch of new product features and technical changes. This incremental development based on existing systems is in stark contrast to the development of products from scratch, which typically happens in so called megaprojects with tremendous development budgets and long time-horizons. Incremental development is done in small product releases under considerable time- and cost-pressure in a changing environment. Due to fast technological advances especially in software and electronics, the time between these releases is shrinking. The results are short product release-cycles challenging many companies and leading to the need to manage product evolution by means of concerted innovation and adaptation steps.

Within this paper, we outline a framework for managing evolution of intelligent technical sys-tems. Therefore, the basic characteristics of intelligent technical systems are described in chapter 2. In chapter 3, the need for evolving technical systems is detailed. Prerequisites for managing evolution of intelligent technical systems are introduced in chapter 4. Based on these fundamentals, chapter 5 outlines Release Planning as a suitable approach for managing product evolution. In chapter 6, we sum up the major points and give a short outlook on our future work.

2.0 CHARACTERISTICS OF INTELLIGENT TECHNICAL SYSTEMS

The term "intelligent technical systems" is representative for a technology concept which is based on two fundamental assumptions: First, future mechatronic systems have an inherent partial intelligence that goes beyond today's information processing. Second, driven by advances in communication technology, the interconnection of these systems will increase. Therefore, only the interaction and cooperation of the individual systems opens up the functionality of the whole system. The change from mechatronics to intelligent technical systems is driven by three general trends in technology [5]:

1) Miniaturization of electronics provides numerous advantages by combining the parallelization of information processing, an increase of storage capacity and a reduction of energy demands. This, in turn, enables the development of suitable hardware for intelligent technical systems.

2) Software technology more and more penetrates modern engineering products, enabling new functions. However, at the same time, the complexity of such systems is increasing rapidly, es-pecially in systems with embedded software. Modern, model-based methods, notations and tools of software technology enable to cope with complexity and help to create software of high quality.

3) Networking of information systems: The "Internet of Things", "Ubiquitous Computing", "Per-vasive Computing" or "Ambient Intelligence" are current research areas that deal with electronic networking, mostly wireless, of information processing systems. This technological trend is the basis for intelligent networking systems.

Based on these trends, technical but also non-technical disciplines such as cognitive science, neurobiology and linguistics are developing a variety of methods, technologies and procedures that integrate additional sensory, actuatory and cognitive functions into technical systems. These functions aim at four key properties that characterize intelligent technical systems [1]:

1) Adaptive: They interact with the environment and adapt their operation modes autonomously. In this manner, they can evolve during the runtime within the framework set by the designer and ensure their existence in the long term.

2) Robust: They are able to flexibly and autonomously operate in a dynamic environment, even in situations that are unexpected or were not foreseen by the developer. Uncertainties or the lack of information can be handled, at least to a certain degree.

3) Anticipative: Using empirical knowledge as a base, these systems anticipate future impacts and possible states. In this manner, dangers can be identified earlier and appropriate strategies to resolve the problems can be selected and executed. Objectives can be achieved more efficiently.

4) User-friendly: They adapt to user-specific behavior and interact sensibly with the user. Its behavior is comprehensible for the user at all times.

Porter and Heppelmann choose another characterization of intelligent technical systems and structure their capabilities into the four stages "monitoring", "control", "optimization" and "autonomy". They emphasize the fact that each of these capabilities already provides customer benefits, but at the same time is also a precondition for the next stage. For example, the integration of sensors and external data sources enables comprehensive monitoring functionalities, which at the same time is the foundation for product control and optimization. Autonomy at the highest stage combines monitoring, control and optimization capabilities to enable functionalities such as self-diagnosis and autonomous product operation [6]. Therefore, when implementing such capabilities, technical dependencies between these functions always have to be checked and considered. At the same time, the structuring into stages already indicates the evolutionary character of intelligent technical systems, as one function builds up on the other. Fast technological advances are a major driver of change and lead to a stream of new product features that cannot be realized at once. This results in frequent changes of system requirements that force companies to evolve their products. This evolution is characterized by manifold product generations and product versions, each of them comprising a bunch of new product features and technical changes.

3.0 NEED FOR MANAGING EVOLUTION OF INTELLIGENT TECHNICAL SYSTEMS

The concept of evolution has its starting point in Darwin's theory on heritable variation and natural selection [7]. Although biological and social theories are not directly transferable to com-plex technical systems [8], the following conclusion applies: systems have to adapt continuously to changes to stay competitive and to survive. In order to compete in the market, products must be maintained systematically by implementing new product features. However, typical development projects are planned to meet stated requirements at a point in time. Often, those plans do not ac-count for the fact that requirements change and systems must undergo major upgrades due to shifts in market demand, legal revisions or technological improvements [2], [9].

Especially in the context of intelligent technical systems, fast technological improvements force companies to adapt their products in even shorter cycles than ever before. The shortened innovation cycles go back to the rising share of software and electronics, which are upgraded much more frequent than mechanics due to higher innovation dynamics. While, for example, electronic components in an automobile rarely last longer than 18 month, mechanically embossed power trains remain unchanged for several years [10]. This leads to the so called "innovation cycle dilemma" that refers to the difficulty of integrating the innovation cycles of the different domains [11].

The "innovation cycle dilemma" is representative for the high dynamics in system development and the associated difficulties. In the past, products have been subject to minor changes only, and stayed in the market unchanged for several years. Today, they are refreshed frequently including also bigger revisions. Therefore, companies are challenged by shrinking product release-cycles and continuous changes. These changes result from both, the integration of an increasing number of product features and minor technical modifications. To cope with these changes, companies need to speed up the adaption of their products. This adaption cannot be done by a complete replacement and new development of the technical system since this is becoming increasingly time-consuming, expensive and risky due to an ever increasing complexity of the systems. As a consequence, changing requirements are often met by evolutionary development based on existing systems [3], [12], [13]. Certain functional units are redesigned based on new solution approaches to integrate innovative product features, while other sub-systems are reused unchanged from previous product versions. This way, sub-systems are subject to manifold changes during the lifespan of the system, while the main product structure and architecture typically remains from the original system. However, the effort to implement certain changes can be significant. Even the redesign of secondary sub-systems can result in unexpected efforts as the change can ripple through the system due to known or unknown technical dependencies [8]. Due to the interdisciplinary character of intelligent technical systems, these dependencies increase, making change efforts even more difficult to predict. To avoid additional efforts and unwanted side effects, the implementation of changes and the evolution of technical systems have to be supported and controlled by concerted innovation and adaptation steps. This results in the need for a systematic management of product evolution.

4.0 PREREQUISITES FOR MANAGING EVOLUTION OF INTELLIGENT TECHNICAL SYSTEMS

Evolution of technical systems means the incremental implementation of new product features and technical changes. These development activities are characterized by releases, each com-prising a coherent set of improvements that is developed, tested and released for production together. However, the management of evolution by means of releases requires two preceding activities: First, anticipating future product features and preparing them for system integration. Second, designing for changeability in a way that the ripple effects caused by the resulting technical changes are kept small [8]. To master these activities, companies have to meet certain prerequisites, which are illustrated in Figure 1.

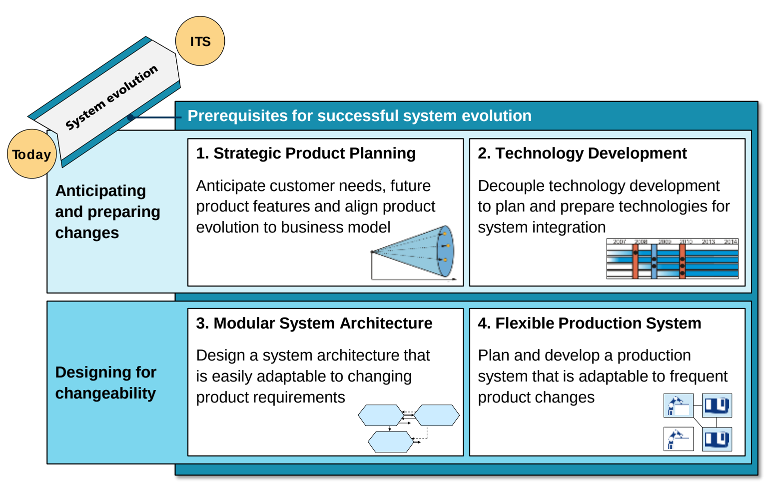


Figure 1 Four prerequisites for successful system evolution

4.1 Strategic Product Planning

Generally, strategic product planning precedes the actual product development activities. Its task is to concretize anticipated potentials for success to beneficial product features. That way companies make sure that there is a continuous stream of ideas and concepts for new and improved products. As illustrated above, especially the change from mechatronics to intelligent technical systems promises extensive potentials for improved products. Therefore, companies need methods to systematically identify and tap these potentials. An example for this kind of methods give Anacker *et al*. [14]. However, product features and associated changes do not only originate from technological advancements but also from anticipated customer needs, market developments, legal revisions or customer complaints. Thereby, strategic product planning defines which features and technical changes have to be implemented but also gives priority based on monitoring of customer needs and competitive conduct. Furthermore, it makes sure that product evolution goes along with an alignment of the business model as Peitz demonstrates in his work [15]. Thus, strategic product planning guides the way, technical systems have to evolve.

4.2 Technology Development

Implementation of new product features often comes along with the need to develop advanced and new technologies. Their complexity and degree of novelty result in risks that can alter or even compromise projects' success. One approach to reduce these risks is the decoupling of technology development and the actual development of the next product release. That way, the uncertainties associated with a technology are transferred to individual technology development projects, which have other general conditions and more freedom in terms of timing and budget. That point in time, a technology has reached a certain degree of maturity, it is ready for system integration and can be planned for one of the next product releases. Decoupling technology development requires companies to adopt certain technology management concepts: "technology-roadmapping" makes sure that the right technologies are available when needed; "technology-readiness-levels" (TRL) determine maturity to decide for system integration. A well-organized technology development prepares for evolving the technical system.

4.3 Modular System Architecture

The need for evolving the system emphasizes its ability to be changed time and cost efficient. The literature discusses this ability under the collective term "changeability" [2], [16]. The term summarizes various properties of a system that affect the ability to adapt to changes. According to Fricke and Schulz, these are flexibility, agility, robustness and adaptability of a system [2]. For influencing these properties, the design of the system architecture is of crucial importance. Following Ulrich, a system architecture describes the structure of a system in the form of its functions, its system elements and their relationships to each other as well as the relationships between functions and system elements [17]. By following certain design principles, the "changeability" of a system can be increased. One of the most common used design principles is the design of modular system architectures, which allow localizing a change to a certain module and thereby reduce potential ripple effects. The design of modular system architectures is a key competence for successful product evolution.

4.4 Flexible Production System

The growing number of product versions challenges product development but also product manufacturing. Frequent changes of drawings as well as new technologies require the production system to adapt very fast. This is true, especially in situations, in which different product versions of one and the same product must be produced at the same time. In this context, Industrie 4.0 promises high potentials, as it aims at versatile production systems that are able to produce individualized products up to a lot size one [18]. These production systems are based on automation technology that incorporates approaches like plug-and-produce as well as integrated engineering models from product development to production. Like modular system architecture, these flexible production systems are another key enabler for successful product evolution.

5.0 MANAGING EVOLUTION OF INTELLIGENT TECHNICAL SYSTEMS

Meeting the described prerequisites is fundamental for successful product evolution. However, it does not answer the questions of how to predict and plan product evolution in terms of product versions, facelifts and product generations. This is the task of release planning, which emerged from software development in the late eighties as an instrument for planned and systematic implementation of technical changes [19]. The basic concept of release planning is illustrated in Figure 2.

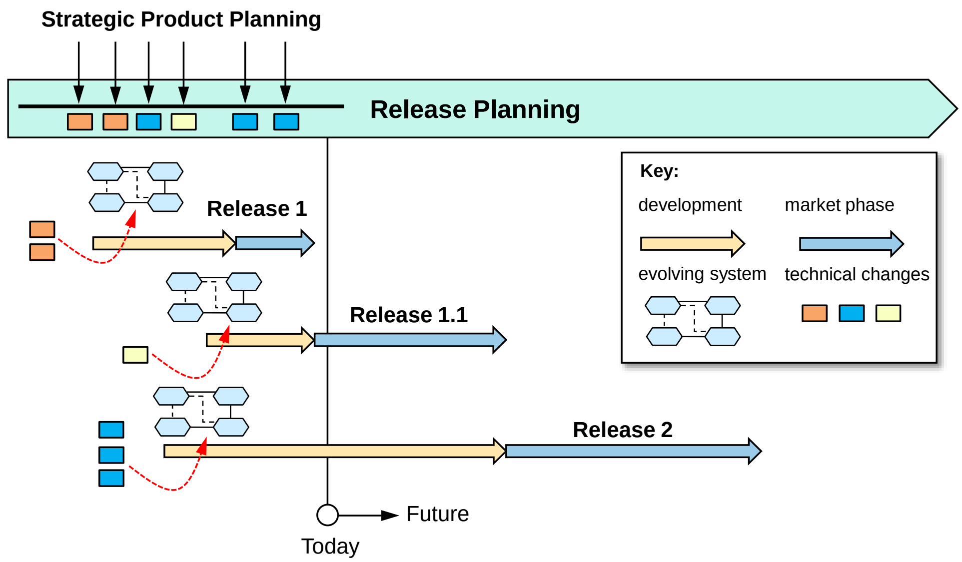


Figure 2 Basic concept of release planning

Strategic product planning delivers a rich stream of technical change requests resulting from different sources like new product features or new legal requirements. Instead of implementing these changes immediately after they occur, they are bundled to releases and implemented together. The simultaneous transfer of changes reduces the total efforts for necessary tests, documentations, follow-up changes and the coordination of the development process [19].

When bundling features and changes for releases, different aspects like urgency and im-portance of a change must be considered. However, next to priority it is also necessary to consider technical dependencies and restrictions. Certain features and technical changes may require each other and cannot be implemented solely; some may offer the potential for synergy effects when bundled; others are independent and flexible and thus can be delayed to a later release to save time and development costs. These technical dependencies are especially meaningful in complex technical system design. Due to its multidisciplinary character, dependencies and constraints from mechanics, hardware and software have to be analysed in an interdisciplinary way. Therefore, release planning requires a comprehensive and interdisciplinary understanding of the impacts of new features to the existing technical system as well as of the resulting dependencies. Therefore, a systematics for release planning is needed considering the distinct characteristics of intelligent technical systems. This opens up the need for further research.

6.0 SUMMARY

Technological advancements force companies to evolve their products in even shorter cycles than ever before. To cope with this challenge, companies need to speed up the adaption of their prod-ucts resulting in the need for a systematic management of product evolution. Based on this need, we outlined a framework for managing evolution from mechatronics to intelligent technical systems. This framework includes two main fields of action: 1) Inducing the prerequisites for successful product evolution and 2) Managing product evolution in terms of release planning. The prerequisites for a systematic management of product evolution are strategic product planning, decoupled technology development, modular system architectures and a flexible production system. Based on these fundamentals, companies are able to evolve their products in releases, each comprising a coherent set of product improvements. However, bundling changes to releases and prioritizing the implementation of change is a challenge, especially in the context of intelligent technical systems. New design methodologies are needed, opening up the need for further research.

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