# 3 Technical Inheritance as an Approach to Data-Driven Product Development

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**Abstract**

Hallmarks of modern technical products or systems are an accelerated time-to-market by clear modification cycles, the processing of large amounts of data, an increased flexibility as well as a quick reaction to changes in market situations. The monitoring of technical products is state of the art nowadays. Due to new communication possibilities that have emerged, a multitude of data exist that can be transferred into information and knowledge about products through their life cycle. The developing communication possibilities facilitate new innovative approaches for the application of product life cycle data. New methods of data management and data processing are required for cross-generational process analysis as are software and hardware tools. Furthermore, new methodologies for developing technical products are demanded. This chapter describes the Paradigm of Technical Inheritance, which is based on the idea of developing and modifying a new generation of products or services taking into account the information gathered from the life cycles of the previous generations. The basic principles of this approach are outlined, a process model including data collection, monitoring and analysis methods is presented, and application examples for both a generation-oriented development of a single component and for a complex technical system are given.

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## 3.1 Evolution in Technology and Generation Oriented Product Development

Throughout human history, the progressive development of society is ultimately conditioned by and inextricably linked to the development, improvement and advancement of engineering and technology. There are various concepts of the origin of technology, which see the development of technology from the expedient human activity and the need for rational use of the means of this activity (Kapp 1877). One of the concepts of the emergence of technology was proposed by O. Spengler (Kidd 2012). According to this concept, technology and technical systems are a way of organizing the joint activities of large masses of people. Therefore, a technology should not be seen as a set of tools, but as a way of handling them. A different concept of the origin of technology is offered by L. Mumford (Fortner 2014), who supposes that machine technology is a product of biotechnology, technology arises from the characteristics of human functioning and in its nature is closely related to the nature of peoples.

Analyzing the history of technological development, we can find the following tendency: non-creative aspects of human work functions are gradually transferred to technical devices, while the creative ones remain for men. Since the early 80s of the twentieth century, the theory of industrial society has been replaced by the concept of information society, where a special role is played by information and the ways of its collecting, processing, distribution and usage. Among the famous works of the authors of this concept we would like to mention the works of A. Toffler (1990), who distinguished three waves of the development of society and the works of D. Bell (Waters 2003), in which he describes three technological revolutions. Within the concept of the information society, the main and decisive factor in social development is the production and use of scientific, technical and other information, which contributes to the development of the service economy and the information sector, as well as radically changing production processes, as we see in Industry 4.0 (Anderl 2015).

### 3.1.1 Evolutionary Processes in Nature and Technology

Nature, objects of the material world, technologies and various fields of knowledge develop according to their specific laws. Technologies develop in close interaction with social developments and nature and are subject to the laws of dialectics. A brief review of the laws of evolution of technical systems is given in (Lachmayer et al. 2014). The laws of technical evolution describe a generalized idealized process of system development, taking into account the static, kinematic, and dynamic aspects of development (Eversheim 2009). The known laws of evolution of technical systems were formulated by G. Altshuller (1984) and his followers. Among the laws should be noted the law of completeness of the parts of the system, which provides the minimal functionality; the law of transition of working parts of a system from macro to micro level; the law of increasing the degree of ideality of the system; the law of transition of quantitative changes into qualitative or the S-curve law, etc. Within studying the development of technical systems, parallels can be drawn between the laws of development of nature and technology, the method of analogy is used. Thus, the S-curve of the development of technical systems or products, often considered, for example, in innovation management, was first studied and substantiated in the study of the evolution of yeast fungus colonies (Kemp et al. 1999; Hughes 1987).

The evolution in nature became a major direction in development of evolutionary theories. Among the most famous are the Lamarck's theory of biological evolution, (Honeywill 2008), Darwin's theory (Storch 2013), modern synthesis evolutionary theory (Fischer 1958) and Neo-Darwinism, created by A. Weismann. Lamarck's theory is based on the inheritance of acquired properties and the inherent commitment of all living creatures to perfection. C. Darvin has put forward the principle of natural selection as a basis of evolution. The modern synthesis evolutionary theory is a doctrine of the evolution of the organic world developed on the basis of modern genetics, ecology and classical Darwinism. R. Fischer was one of the first representatives of the theory. The theoretically described mechanisms of mutation, recombination and selection are the base for, e.g., evolutionary optimization algorithms (Bäck et al. 2000).

### 3.1.2 The Role of Data in the Development, Monitoring and Analysis of Modern Products

The current state and trends in the evolution of technology and development of technical products imply the rapid and effective creation of products or systems using the experience and accumulated knowledge. Within the framework of the above-mentioned concept of information society, product developers are working in a dynamic and digitized time, where information about technical products and components can be collected and deployed (Kaufmann 2015). In the context of Industry 4.0 technical systems are networked with each other. Due to the modern created communication possibilities, a multitude of data sets exists which, with the right knowledge, methods and tools, can be transferred to information about the products (Abramovici and Lindner 2011; Wuest et al. 2016). Methods for collecting data records during the product life cycle are the so-called monitoring methods and tools for observing specific problems (Haken 2012).

Usually, today's development of technical systems rarely includes completely new developments. According to Albers et al. (2015), the classification according to Pahl and Beitz (Feldhusen and Grote 2013) into new, the adaptation and a variant design is no longer sufficient and refers to the most common type of development projects as product generation development. Nowadays, technical products are mostly developed from known solution principles or their combination and the most common type of development projects can be classified as product generation development or generation oriented product development. In the course of this, it has to be examined which existing data should be collected in the life cycle of a product or technical system so that the information obtained from the

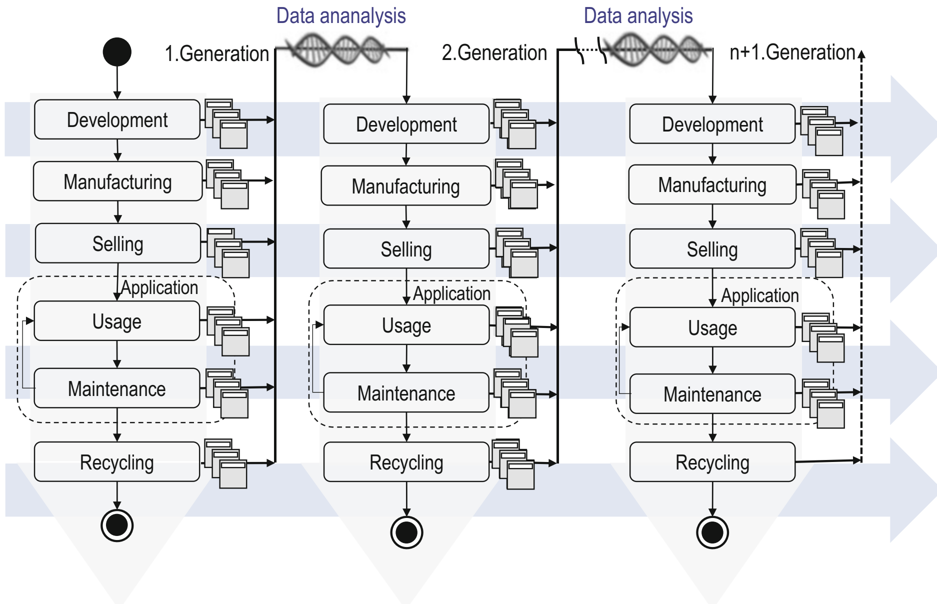



**Fig. 3.1** Transfer of life cycle data (Lachmayer and Gottwald 2014)

analysis of this data can be used to effectively develop and adapt a new generation of a product. Therefore, the integration of information as well as the increase of the flexibility of the development processes is necessary. Modern technologies for data collection and data analysis are used to capture relevant information and generate knowledge that can be passed on from one product generation to the next. In this approach, throughout all phases of the product lifecycle, the involved processes must not only be interconnected, but also data acquisition, storage and processing throughout the entire product life cycle should be available. An important aspect is the expansion of the range of services and data standardization. As shown in Fig. 3.1, the process of generation oriented product development is intended to enable the transfer of life cycle data from generation to generation.

Historically, during the life cycle of a product or system, the main sources of data are transactions and operations: order processing, interaction with suppliers and customers, customer service, etc. They can be supplemented with information from surveys and studies. By processing all of this data, manufacturers and suppliers gain mainly insight into consumers, demand and product costs (Ripperda and Krause 2017; Johannknecht et al. 2017), and less insight into how the system or product is used. Nowadays, that smart products and production systems deliver information, unprecedented in volume and variety and in real time, data, along with people (Graessler and Poehler 2019), technology and capital, has become one of the main assets of companies. This new data is valuable on its own, but its value is multiplied when it is combined with other data, such as development, manufacturing, selling, service history and usage patterns. Central importance in the presented process have the large amounts of data collected during the life cycle of the technical product, which form the history of the product, and which are relevant for the development of subsequent generations of this product. For a targeted extraction of information by means of data acquisition in each of the mentioned phases, the use of specially developed or adapted methods or algorithms is necessary (Eigner et al. 2014). In addition to extensive data analysis, the integration of data into the product development process is required.

## 3.2 Paradigm of Technical Inheritance

A process of technical evolution can be defined as a process that represents the controlled, gradual and continuous change of technical systems, products and processes as well as models with the aim of adapting to environment influences and requirements (Lachmayer et al. 2014). As a rule, a technical system consists of a set of system elements or subsystems and their relationships with each other. The system is delimited or demarcated from the environment by a system boundary. In the process of technical evolution, each system or system element has its own development dynamics (Fig. 3.2).

Each individual subsystem is not exclusively dependent on its parent system; it may be independent of the parent system, or acquired, developed, and operated alone or in conjunction with other systems. System elements or subsystems can be material objects such as components, assemblies, machines, devices, apparatuses, but also immaterial entities such as methods, algorithms, concepts or software.

The Paradigm of Technical Inheritance (TI), which was developed by the project partners in the Collaborative Research Centers 653 "Gentelligent Components in their Lifecycle" (Denkena and Mörke 2017), is based on an algorithmized feedback of information from the life cycle phases of a product into the next product generation. The main idea is the development or modification of a new generation of products or services taking into account the collected information from the life cycles of previous generations of the product. For this, materials, sensors, technologies and methods were developed in order to store knowledge and expand it depending on external loads. An outstanding feature is that the collected data is autonomously captured by intelligent products and stored and processed on them by a genetic code (Demminger et al. 2016; Mozgova et al. 2017).

### 3.2.1 Evolutionary Mechanisms in Technology

The known evolutionary mechanisms in biology can be tentatively taken as a basis for recognizing and describing the evolutionary processes in technical systems and subsystems. But evolution and hereditary information transfer processes in technology cannot occur exactly as in biological systems. The ideas for integrating evolutionary mechanisms into the product development process can be found in various process models,

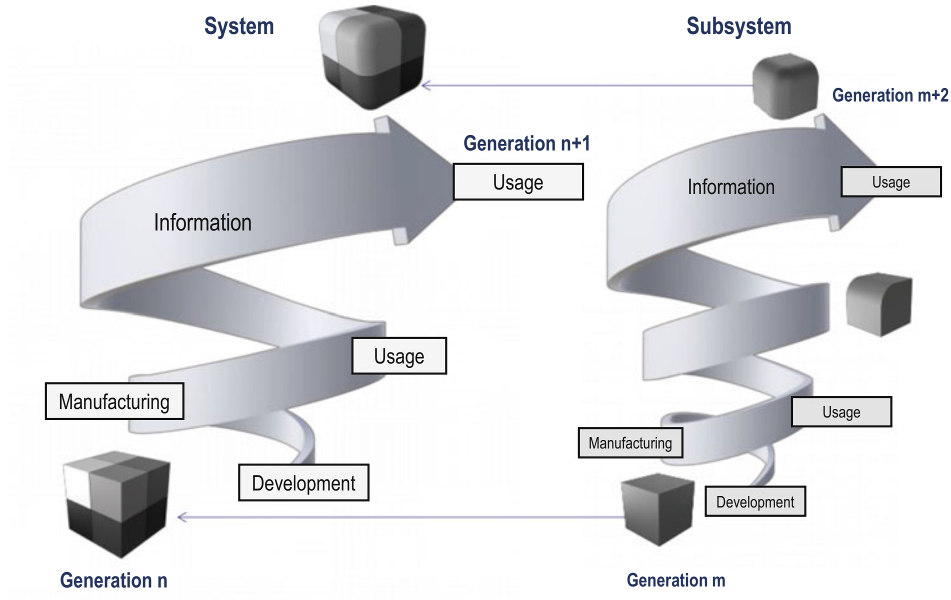



**Fig. 3.2** Evolutionary dynamics of systems and subsystems

such as the Munich process model (Lindemann 2009) or the autogenetic design theory (Vajna et al. 2005). The terminology and mechanisms used within the paradigm of TI are given in the Table 3.1.

Some of these terms can be explained at the example of the evolution of a wheel carrier for a race car developed by the Horse Power Team of the Leibniz University Hannover. The development of a first generation of a wheel carrier requires design experience, knowledge of basic design tools, understanding the laws of vehicle dynamics and general information about the expected loads on the component. This includes rough calculations of dimensions for the vehicle as well as multi-body simulations of the racing car to determine loads. As a result, a first generation of the component in the form of a parameterized CAD model is obtained. By testing different scenarios of race car motion, for example, using multi-body simulations, we gain information about the applied loads. By optimizing the resulting model of the component according to the load information computed during simulations of different driving scenarios, we achieve adapted variations of the original parametrized model. In analogy to the biological evolution processes, we name these adapted variations of the component genotypes (Fig. 3.3).

In producing each such variation of the original model, i.e. each genotype, we will obtain real physical components. Each of these produced wheel carriers, despite the common model, will be individual at the physical level. Thus, we are talking about individuals. These physical components must undergo quality control, i.e. selection. Furthermore, in the production process and depending on the parameters of the equipment and

**Table 3.1** Terminology of technical evolution

| Term | Definition |
|---|---|
| Technical Evolution | Process of control, stepwise and continuous change of technical systems, products and processes as well as models with the aim to adapt to influences and requirements |
| Technical Inheritance | Transfer of assembled and verified information from production and application to the next product generation |
| Individual | An individual is the smallest considered technical system, product, process or model in a population |
| Generation | A generation is a group of individuals with the same level of development |
| Population | A population consists of all generations of individuals of a technical system, product and process as well as a model at the current time |
| Selection | Selection process based on multiple criteria a requirement profile |
| Mutation | A process with targeted or non-targeted character to create variants with resulting modified properties |

Lachmayer et al. (2015)

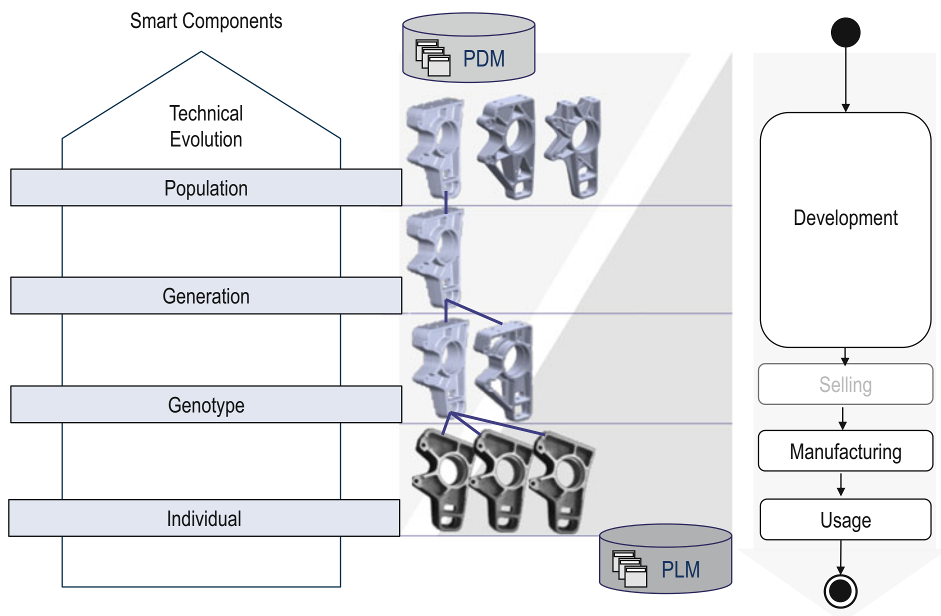



**Fig. 3.3** Assignment product life cycle phases and terms in the scope of TI

the production process itself, there can be deviations, for example, from the geometry of the genotype, i.e. there can be some mutations within the genotype. During the operation of the manufactured component, within the framework of the TI, data about the loads on the wheel carrier should be collected. The information obtained from the analysis of this data can be used in the development of the next generations of wheel carrier. All wheel carrier generations represent a population of these components.

Documentation corresponding to the development phase of a component, i.e. corresponding to the population, generation and genotype levels, is supposed to be organized and stored using Product Data Management (PDM) systems. The organization and storage of data and information obtained during the operation of components is achieved using Product Lifecycle Management (PLM) systems (Fig. 3.3).

### 3.2.2 Process of Information Transfer

For the development of the information transfer process, a goal-oriented algorithmic data feedback is to be realized, which includes statistical methods and operations as well as a design evolution for product adaptations in the development process. Since creating analytical or numerical models for interpreting heterogeneous data is a complicated task, it is useful to apply statistical data analysis that allows structuring and interpretation of data.

The first step is data preparation (Fig. 3.4). It is important to identify the relevant information contained in large amounts of data in order to reduce the size of the data set. Thus, it is useful to perform intelligent aggregation of data for modeling and optimization so that only the necessary information about dynamic changes is included in the data set. An additional effective strategy is to split data into segments and use models for each segment with further summary of results.

After the preparation, the preprocessing, a classification and a data analysis are performed. The analysis process is divided into two parts: the construction of the model and the application of the model to the new data. The developed method of analyzing results of the monitoring includes the methods of cluster analysis and pattern recognition.

For example, as shown below in Sect. 3.3, recognizing typical situations when using a racing car and using a combination of different statistical methods according to the different driving situations show representative patterns of signals and define a driver profile. The information obtained can be stored in the knowledge repository and is thus usable for the development of a new generation of a wheel carrier.

### 3.2.3 Framework of Technical Inheritance

As indicated in Fig. 3.2, TI takes place in cycles in which information from the life cycle phases of the product under consideration is collected and is available for the development of the next product generation. The central process of information feedback is divided into four phases (Gottwald 2016): identification of the life cycle information; implementation of the monitoring strategy; realization of the data analysis and algorithmized information feedback. The procedure model describes the activities and measures required to set up targeted component monitoring and the feedback of information over the entire life cycle.

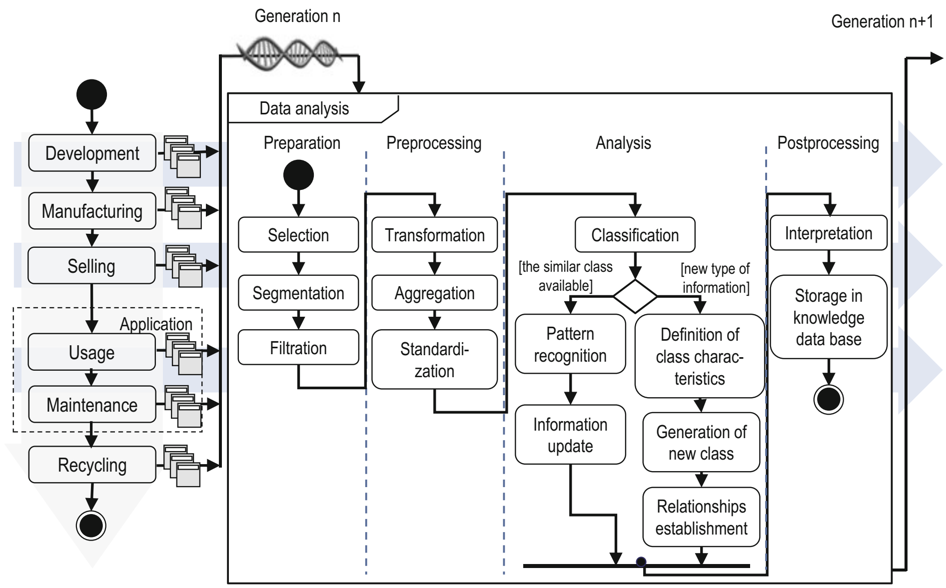



**Fig. 3.4** Data analysis (Mozgova 2017)

The approach includes identification of life cycle data and analysis of information flows in the process. For each life cycle stage, four aspects are to be considered: physical principles (stresses), human-related factors (safety), economic aspects and trends. In addition, life cycle information can be important not only for the next generation of a product or system, but can even influence the current development of rework, for example in the case of safety-relevant components or subsystems (Lachmayer et al. 2015).

The four phases of the process of information feedback are part of the methods workflow within the TI paradigm. As shown in Fig. 3.5, the paradigm rests on four pillars: the principle of technical evolution, evolutionary mechanisms, data analysis, and the genetic code of the product. The first three have been described above. A classification of information and Genetic Code (GC) of the component can be described as genetic information of a component and constitutes the basic information which is necessary to identify or reproduce components. This information can be stored as static, unchangeable data in the component and may have been inherited from an older generation of the component. Parts of a GC of a component are described in Mozgova et al. (2017). The implementation of information feedback requires a methodology, a set of methods and tools appropriate to the scope of the paradigm. Methodology in this context refers to a doctrine of scientific methods, totality of all methods applied within a given field. Methodology allows among all methods of data analysis to establish how to implement these through algorithms, how to determine the correct tools for realization of the algorithms and how to describe sequences of methods for an application area, i.e., methods workflow.

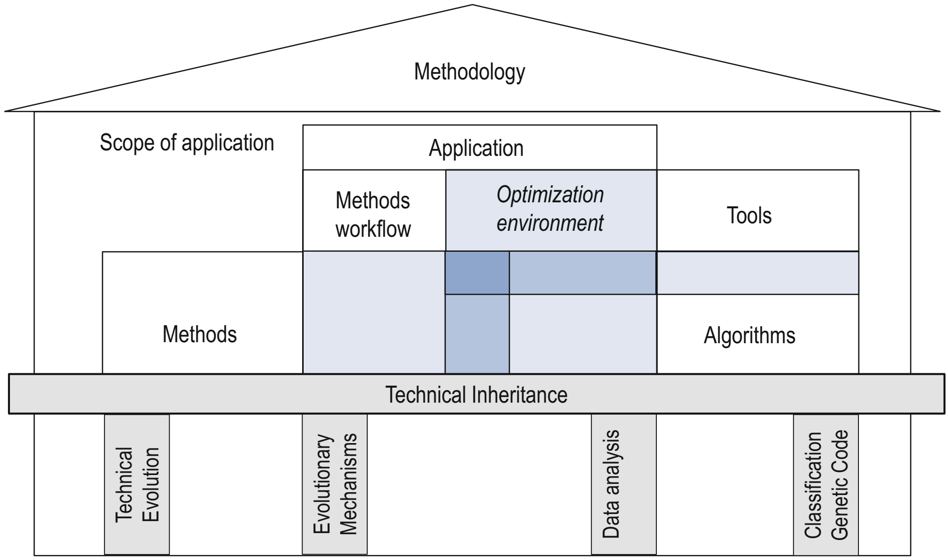



**Fig. 3.5** Framework of technical inheritance

The development and adaptation of a new product generation or product genotype is implemented using an automated design, modeling and data processing environment. For the example of a race car wheel carrier, this process is called design evolution (Lachmayer et al. 2013): the adaption of products by analyzing product life cycle while taking evolutionary mechanism into account.

## 3.3 Application Examples of Algorithmic Data Feedback for Technical Inheritance

For the demonstration of the TI approach, we can address the use of operation data for the development of subsequent generations. The application area includes technical systems with cyber-physical, smart or intelligent products, targeted data feedback and individualization & customization of products. The advantages are linking of life cycle data with the development process and targeted adaptation or configuration of the product based on real operational data. This chapter demonstrates a generation-oriented approach to product development, using the evolution of both the individual component and the system as a whole as an example.

### 3.3.1 Representation of the Process of Information Feedback for the Development of Structural Mechanical Components Under Dynamic Loading

The effectiveness of the presented approach can be illustrated at the example of an information feedback and the development of a new generation of a wheel carrier. During the development phase different generations of wheel carriers are designed and created, based on the received lifecycle information. The manufacturing uses the information from the development and based on this, individual production and process plans are created, which allows a rerouting of the component and an individual way through the manufacturing. During usage the amount of individual component information increases after the development phase and is saved in a PLM System, meanwhile the amount of generation information is determined after the development phase and stored in a PDM System (Fig. 3.6).

The development process itself is iterative and includes the phases of development and optimization of the component geometry, the selection of a suitable material and the choice of sensors (Mozgova et al. 2017). Each development phase has an iterative character. During developing and optimization of the geometry of the component, properties of the metallic alloy are considered. The selection of the type of sensors depends on the alloy and the geometry of a component. Conditional on the expected loads and simulation results obtained during the geometry development, it might be necessary to change e.g. the properties of the alloy from which the component is made of. That would entail the changes in the selection of sensors. Positions of sensors, for example, on the component surfaces, have to be planned not only taking into account critical or characteristic positions of loading, but also taking into account the availability of locations for reading and writing data and for preventive maintenance, repair or replacement (Mozgova et al. 2018). That can demand a change of the geometry of the component.

The general scheme of the approach to develop a new generation of a wheel carrier based on data collected during the usage of previous generations is depicted in Fig. 3.7. The approach involves manufacturing restrictions in the context of product and component development, analysing data of the component usage (Lachmayer et al. 2013; Lachmayer et al. 2018), monitoring and controlling the current state of the component and analysing the results of usage.

During the development process a selection of suited materials and the type and location of the sensors as well as choosing the data modeling and analysis algorithms is required. Figure 3.8 shows the results of the technical evolution of the wheel carrier.

The criteria of homogeneity of the stress-strain distribution of the component and of the reduction of the component weight were used as the target functions of multicriteria optimization of the component geometry. The simulation of the stress-strain state of the component was performed using the finite element method.

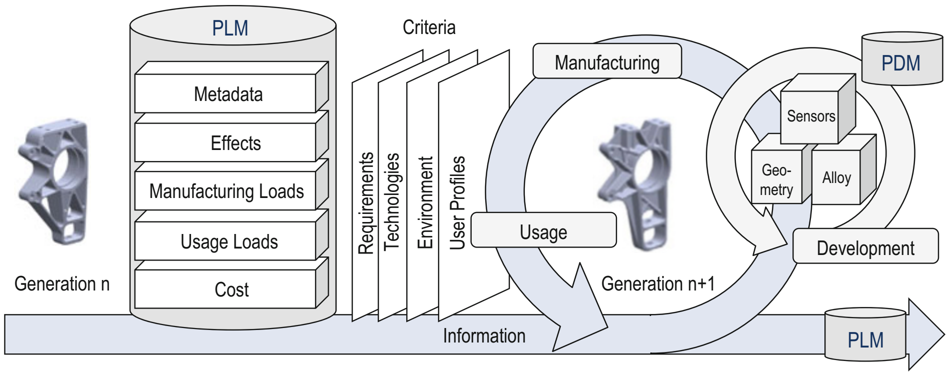



**Fig. 3.6** Evolutionary adaptation of the component

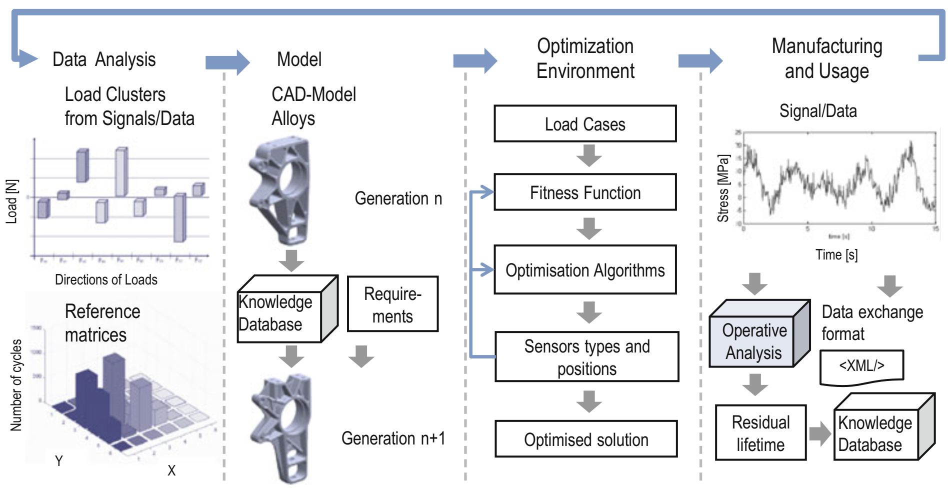



**Fig. 3.7** Algorithmized information feedback

### 3.3.2 Application of Technical Inheritance for the Design, Monitoring and Operation of a Technical System at the Example of an Electronic Sorting Device

The application of the paradigm of technical inheritance (TI) in the system development will be shown at the example of a sorting system. Within the scope of a collaboration with the Nordstadt Clinic Region Hanover, a technical solution for sorting object carriers was to be developed.

The object carriers to be sorted contain tissue sections, which are examined in the histology for diagnosis. After the examination, these are be archived for 20 years so that they can be used for follow-up examinations. In order to be able to guarantee later retrieval

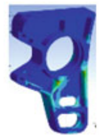
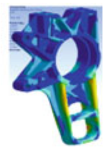
| | Development Goal | CAD-Model | Stress-Strain State (FEM) | Development Result |
|---|---|---|---|---|
| Generation 1 | Casting<br>FEM based stress-strain simulation |  |  | Weight = 740 g<br>Stress $\sigma_{max}$ = 132 MPa |
| Generation 2 | Casting<br>FEM optimization<br>Light weight |  |  | Weight = 607 g (↓ 18%)<br>Stress $\sigma_{max}$ = 79 MPa (↓ 40% ) |
| Generation n | 3D printing<br>Topology optimization<br>Geometry as an assembly |  |  | Weight = 585 g (↓ 21%)<br>Stress $\sigma_{max}$ = 75 MPa (↓ 43% ) |

**Fig. 3.8** Evolution of a wheel carrier

and error-free assignment of the object carriers, these need to be sorted and filed according to an identification number. The system consists of a table, on which 1000 sorting compartments and 40 compartments for rejects are located, and a gantry robot (Fig. 3.9). The object carriers are to be sorted into the sorting compartments by the gantry robot according to their case number. The object carriers are fed into the system using four magazines. Each of the four magazines has a mechanism for separation, which allows the object carriers to be removed individually from the magazines.

In order to be able to provide all data for a subsequent generation of the system, the CAD models, corresponding technical drawings and the source code of the PLC as well as the requirements list, all data sheets of the purchased parts and the maintenance plan were stored in the PDM system Autodesk Vault (Scheidel et al. 2017). In this way, the PDM system stores the documentation of the first generation of the electronic sorting unit. For all project documents, individual identification number were assigned to the CAD models and drawings according to the developed numbering system. The numbering system corresponds to the concept of the GC.

In developing this technical system within the TI paradigm, an analysis was conducted which data and information was required to monitor the functioning of the system during its operation. During the analysis the following data and information to be monitored was identified: number of slides per day, number of slides per case, waste area capacity, number of used trays, pattern in the sorting, interruptions during operation, system operation times.

It is then determined at which points these data and information are recorded. Preventive periodic maintenance has been defined for the electronic sorting unit, which is carried out at 6-monthly maintenance intervals. This strategy includes a check of all electronic,

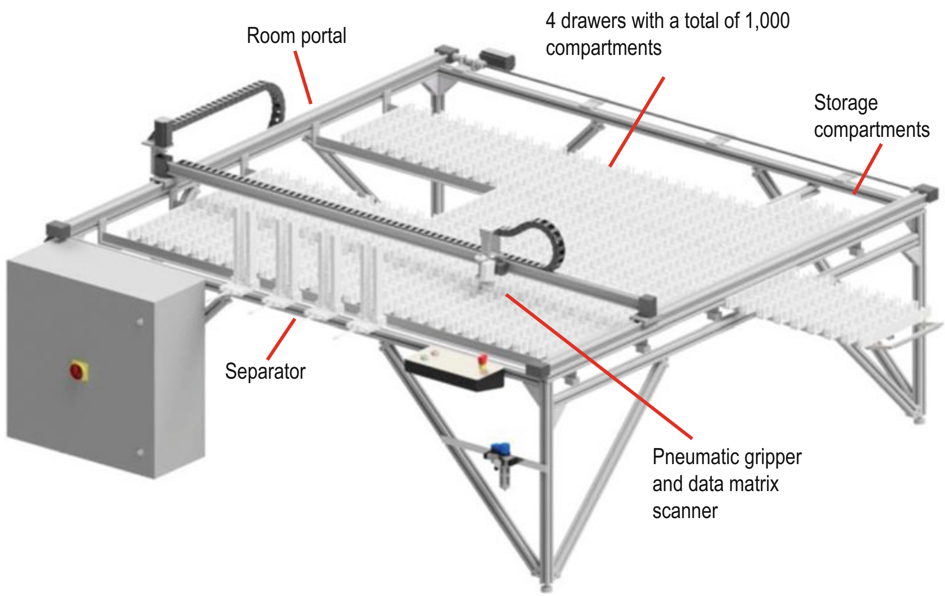



**Fig. 3.9** Electronic sorting unit

pneumatic and mechanical components as well as an update of the system code and test runs. All operational data were collected as part of this strategy.

The analysis of collected data and information obtained during the operation of the electronic sorting unit allowed to specify the requirements for the next generation of the system. As a result of monitoring of the system operation the following parameters were analyzed: number of scans, trips of a tray, departures of a tray, timestamp of trips. Based on the obtained information, the following adaptations for the second generation of the system were considered: dimensions and performance of the room portal and adaptation of its capacity, dimensions of the compartment intake, dimensions of the waste area, adjustment the sorting algorithm and adaptation of service activities.

When the waste area is approached, different types of errors can occur and are documented. For example, object carriers with an incorrect location code or an incorrect sorting year can be returned to the sorting process for a later sorting run. During usage was recorded that object carriers were found in the wrong slots and that the design of the carrier holder for the slots was too small. Analysis of the causes of this type of error showed the need to develop an adapted design of carrier holder (Fig. 3.10).

Thus, at the example of this system we can observe different dynamics of development of the whole system and its subsystems, as described in Sect. 3.2: for the first generation of the electronic sorting unit the second generation of the carrier holder is developed. Figure 3.10 also shows the GC obtained according to the numbering created for the electronic sorting unit. Thus, according to the technical inheritance approach, the information obtained during operation was transferred to adapt the second generation of carrier

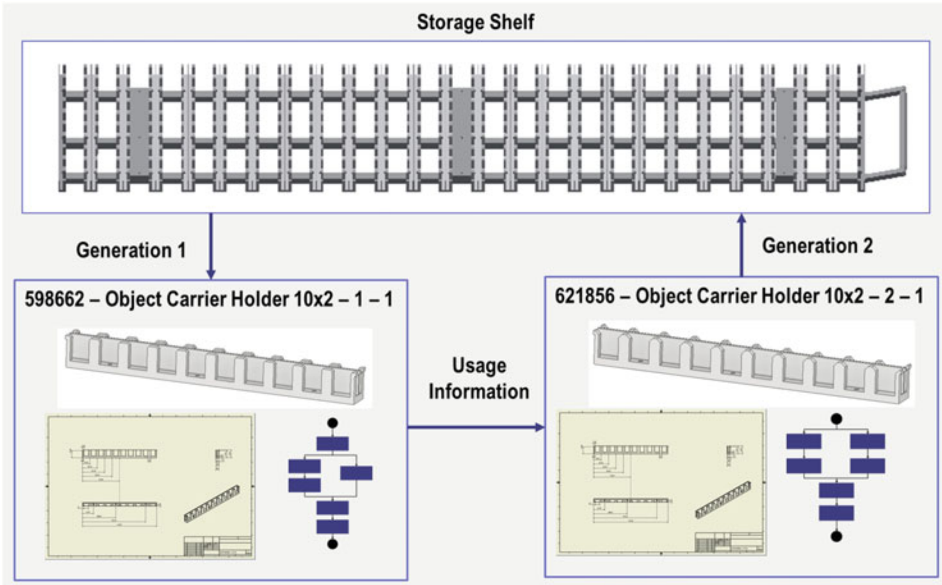



**Fig. 3.10** Two generations of the subsystem object carrier holder (Scheidel et al. 2017)

holder. Furthermore, the traversing speeds of the sorting arm determined for the first generation are adjusted based on the number of cycles, which enables the reduction of the size and the use of smaller stepper motors and shorter linear guides.

In general, data processing during device use included summarizing, sorting and formatting process data, filtering errors and duplicates. The data analysis revealed that the size and operating capacity of the second generation of the electronic sorting unit can be optimized. For example, the analysis showed that that only 33.5% object carriers of the original were used is the case and the waste area can therefore be reduced by about 50%. Thus, fewer compartments can be provided for the next generation of the electronic sorting unit, whereby a dynamic assignment of the compartment numbers makes sense here. It must be taken into account that the cases are not distributed randomly over the compartments, but follow a pattern. Thus, for the next generation of the electronic sorting unit, both an adjustment of the number of compartments and a possible adaptation of the sorting algorithm is planned. So, the dimensions of the frame and the height of the compartments are therefore adjusted in this concept. The gantry arm and the associated stepper motors must also be reduced in size. Compared to the gantry arm of the first generation of the electronic sorting unit the reduction in its size results in a saving of 25% of item cost.

## 3.4 Conclusions

The current state and trends in the evolution of technology and development of technical products imply the rapid and effective creation of new generations of products using the experience and accumulated knowledge throughout the life cycle of previous product generations. The information gathered during the product life cycle is then fed back into the development process of new product generations. This facilitates to reduce development times and costs. This leads to an increase in resource efficiency as well as higher dynamics and thus increased productivity.

The described Paradigm of Technical Inheritance (TI) is a generation-oriented approach for the development of technical systems and products. The paradigm is based on the application of the laws of technical evolution and evolutionary mechanisms. Integral part of the presented paradigm are methods, algorithms and means of data analysis, as well as methods of classification and identification of technical systems and subsystems, which are the basis of a product's genetic code and allow performing unambiguous authentication. The application of the paradigm includes an identification of the life cycle information, implementation of the monitoring strategy, realization of the data analysis, algorithmized information feedback and is carried out within the framework of the TI. Based on a methodology appropriate to the scope of the application, a selection of methods, algorithms and data analysis tools for a technical system or product is performed to adapt a new generation of the system or product.

A methodology for targeted data feedback was presented and it was shown how the operational data can be used for development as well as adaptation of the next generation of a product. At the example of wheel carrier was shown how the paradigm of TI can be used to optimize lightweight constructions with additionally improved stress distribution. The example of the electronic sorting unit demonstrates the application of the TI paradigm for the design of a whole system and individual subsystems.

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