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The Concept of Technical Inheritance in Operation: Analysis of the Information Flow in the Life Cycle of Smart Products

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Abstract

Industry 4.0 opens great potentials in productions technologies by establishing communication between machines and equipment as well as processes along the life cycle of products. Within the Collaborative Research Center (CRC) 653 several aspects of the design and application of communicative and intelligent systems and components are demonstrated. The CRC aims to enable smart products, so-called gentelligent components, to give feedback to the product and production processes based on inherently stored information.

This work continues a series of publications regarding the development of the concept of Technical Inheritance. Here, the process of Technical Inheritance is applied to improve gentelligent components. This was realized according to the biological principle to transfer hereditary information on the basis of evolutionary mechanisms and variations of the information transfer.

To provide an efficient information management throughout the life cycle of components and to transfer relevant information from the current generation of the component to the next generation a unified closed data exchange format GIML was developed. At the example of a load-sensitive magnesium wheel carrier of the racing car RP09 this approach is demonstrated: the information flows over the life cycle are analyzed, the concept of Technical Inheritance applied and its advantages discussed.

Keywords: Technical Inheritance; Intelligent Process Planning; Condition-based Maintenance; Design Evolution; Genetic Code

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Introduction

The fourth industrial revolution is associated with changing production and design principles of machine components. Improving the development of components involves the application of specialized tools for different problems. The purpose of this study is the development, elaboration and practical testing of an approach proposed within the scope of the CRC 653 as previously discussed [1, 2]. This approach is based on the adapted principles of evolution in nature and has been named Technical Inheritance.

The within the CRC developed gentelligent components feature genetic and intelligent, smart properties. The general idea of such components is based on biological principles [3]. As genetic information of a component the basic information is defined, which is necessary to identify or reproduce the component as well as geometric descriptions or material information. This information is stored as a static, unchangeable data in the component and may have been inherited from previous generations of the component. The intelligence of the gentelligent component is the ability to analyze data and attain information about manufacturing and operation, for example, acting forces and temperatures, which can automatically be detected and saved inherently. Thus, the efficient development of the next generation of smart products is based on the analysis of the life cycle data of previous generations of the product and relevant information about their operation conditions.

1.1. Information in the Product Life Cycle

The important information characterizing the component is obtained during the life cycle as well as the manufacturing process and is used to adapt both the product and the production process to requirements and efficiency. The monitoring of technical equipment and appliances is state of the art nowadays.

By new ways of communicating a multiplicity of data sets are available to obtain valuable information about our products if proper knowledge for an analysis is available. Methods for the acquisition of data sets during the life cycle are based on monitoring certain problems.

Due to the developing communication possibilities new innovative approaches for the application of product life cycle data are facilitated [4]. New methods of data processing, data management and data handling are required as well as software and hardware tools and a holistic process analysis which is cross-generational.

1.2. Industry 4.0 and more

An adaptation process is achieved by a feedback of the information obtained and verified during the life cycle to engineering and manufacturing departments. Therefore, information and communication technologies were developed, which allow acquisition, product inherent storage and exchange of information along the various phases of the product life cycle. We call this approach „industry 4.0 and more“, since the production process is not only interconnected but data acquisition, storage and processing along the whole product life cycle are available. This includes the development and utilization phase of products, whereas new product generations are being developed based on production and utilization data from previous product generations [5].

2. The Concept of Technical Inheritance

Technical Inheritance is defined as a transfer of assembled and verified information from production and application to the next product generation. Here, this approach was realized by design evolution of a gentelligent components based on collected data to adapt and optimize the next component generation. Moreover, the abilities of gentelligent components were applied to detect current loads such as forces or temperatures and to store data inherently as well as to exchange this information. Data is obtained during the component’s production as well as during usage and can be applied to efficiently improve the process requirements concerning product development as well as manufacturing and maintenance.

One of the research and application goals of the CRC and an important part of the Technical Inheritance is the algorithmic feedback of information collected by or stored in gentelligent components to the production process and the product development process. For this purpose, the technologies developed in the CRC are integrated in a closed loop of the phases of manufacturing and usage, which include gentelligent production, monitoring, operation, maintenance and return of information for the design of a new generation of the product (s. Fig. 1).

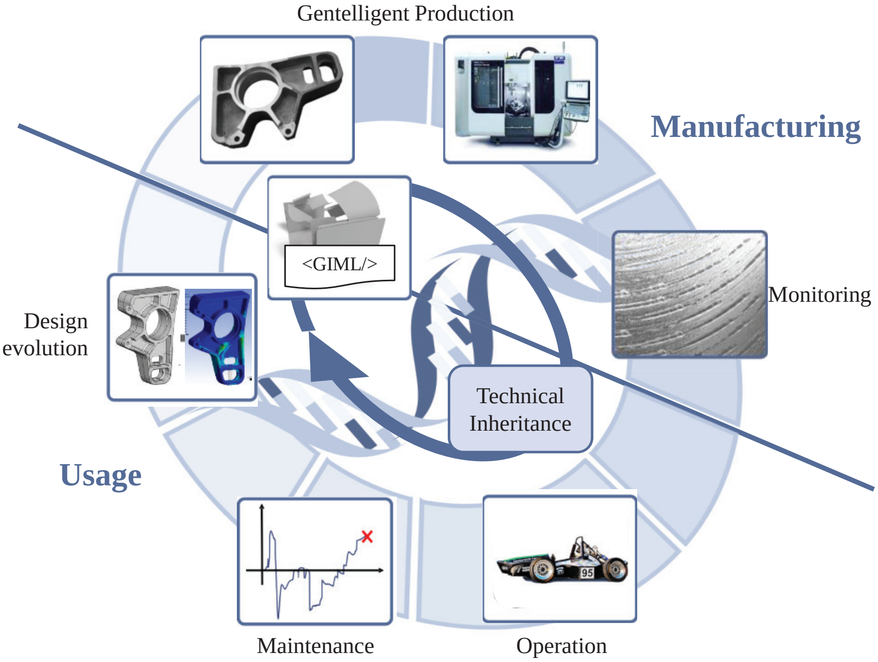


Fig. 1. Life cycle of gentelligent component.

Two aspects are within the focus of the given closed loop : Technical Inheritance and the associated standardized data exchange. In developing the paradigm of Technical Inheritance, that is drawing parallels to the evolution in nature, important issues are studies of the mechanisms of evolution and construction of the genetic code of components. Results of the analysis of the evolutionary mechanisms are given in previous publications [1, 2]. For example, among the existing evolutionary mechanisms in nature, for the evolution of technical products adapted mechanisms of selection and mutation were determined.

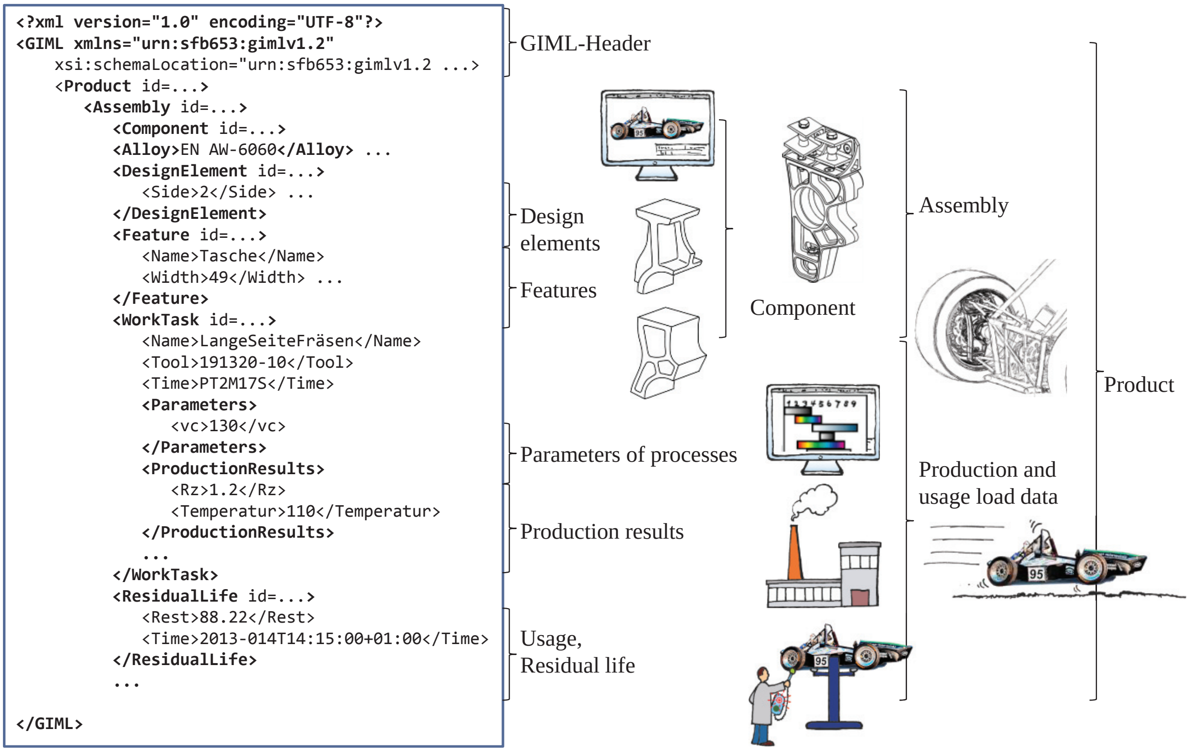
An adaptation process is performed by analyzing the information flow and giving a feedback to the development and manufacturing processes based on the accumulated life cycle data and the received verified information. So, for example, detected by an operation of a wheel carrier of a racing car driving load data can be used for an analysis of its condition and for an optimization of its geometry and thus for its design evolution. For these the capabilities of gentelligent components to detect, for example, forces and temperatures, are used.

In the study and construction of the genetic code of gentelligent components an important step is an universalization of communication at different stages of the life cycle of an intelligent products.

2.1. Standardization of Data Exchange Processes and a Genetic Code of Gentelligent Components

A major challenge in linking and reuse of information lies in the definition of a flexible data format, which can be used und adapted for storage and transformation of the information during the life cycle of the product whereas some kind of hierarchy is necessary. Another important aspect consists in the assignment of information, which includes characteristics of the product, to information, that describes the parameters of the product, which can be defined by the product developer. Often the information about descriptive characteristics, such as operation or production information, are inherently based on the design of the product. If the latter changes, the information will not be valid. This aspect relates to the different phases of a product life cycle as well as to the next generations of products, in which certain characteristics can be changed by adjustment and development of product's parameters.

Hence, for a standardization of data exchange the hierarchical Gentelligent Markup Language (GIML) had been developed; it is feature-based and regards a life cycle oriented hierarchy. The file format is open and allows the flexible storage of extended data such as, for example, product information, process forces, quality assessment, etc. As a basis for the text representation of gentelligent information the Extensible Markup Language (XML) had been used. Schematically, the hierarchical structure of the format is depicted on the Fig. 2.



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<?xml version="1.0" encoding="UTF-8"?>
<GIML xmlns="urn:sfb653:gimlv1.2"
    xsi:schemaLocation="urn:sfb653:gimlv1.2 ...>
    <Product id=...>
       <Assembly id=...>
          <Component id=...>
          <Alloy>EN AW-6060</Alloy> ...
          <DesignElement id=...>
             <Side>2</Side> ...
          </DesignElement>
          <Feature id=...>
             <Name>Tasche</Name>
             <Width>49</Width> ...
          </Feature>
          <WorkTask id=...>
             <Name>LangeSeiteFräsen</Name>
             <Tool>191320-10</Tool>
             <Time>PT2M17S</Time>
             <Parameters>
                <vc>130</vc>
             </Parameters>
             <ProductionResults>
                <Rz>1.2</Rz>
                <Temperatur>110</Temperatur>
             </ProductionResults>
             ...
          </WorkTask>
          <ResidualLife id=...>
             <Rest>88.22</Rest>
             <Time>2013-014T14:15:00+01:00</Time>
          </ResidualLife>
          ...

</GIML>
```

Fig. 2. The hierarchical structure of the data exchange format.

Identified during the analysis of information flows of a component's lifecycle, informative parameters, which are characterizing material properties, features of the component production process, component status and lifetime as well as geometry parameters for the development of a new generation of components, can be used to develop genetic code for an intelligent component. These parameters are discussed in the following two sections of this paper.

3. Analysis of information flows in the Manufacturing Process

A component's life cycle starts with the collection and evaluation of information and demands. This information is based on the positive and negative qualities of the preceding component generations and is inherited to the next generations. Therefore, every process step during the production and utilization phase of the component is influenced in this way.

3.1. Components with sensory properties for mechanical load detection

Relating to the wheel carrier geometry (Fig. 3, Simulation) the technical requirements and restrictions must be observed to optimize both, the casting process and the following production planning and production process. Within construction process performed metalcasting simulations are used to optimize the pouring, solidification and cooling phase, iteratively. During the real metalcasting process, the temperatures of melt and mold are recorded to a data logger for quality assurance.

Casting specific information such as production date, batch of material, component ID, alloy, casting speed, casting temperature, molding material and mold temperature are collected and further processed to the production planning using the GIML-format. In addition to that, the alloy specific properties like mechanical strength, hardness or grain size are determined in laboratory experiments and stored in the database, too [6, 7]. The production planning uses database information and is able to optimize the used tools and available machine tools. Moreover, the information stored in the database has to be unambiguous assigned to the individual component, which requires a unique labeling during the components manufacturing process. For this purpose several possibilities are suitable. However, e.g. the usage of radio-frequency identification (RFID) -labels has some disadvantages, on the one hand, the label itself is an additional part, that has to be applied during manufacturing and on the other hand, the label could be damaged, polluted or lost. Alternatively, if the material has ferromagnetic properties, a magnetic label directly on the components surface could replace a RFID-label.

Light metals are usually paramagnetic and common ferromagnetic materials are ferritic steels, cobalt and nickel alloys. By alloying pure magnesium or magnesium alloys, with ferromagnetic elements, particularly cobalt, several magnesium alloys were produced which exhibited measurable magnetic properties. The development of magnetic magnesium alloys offer alternative techniques for both, magnetic labeling and load detecting applications [8, 9]. With the possibility of magnetic labeling a unique component ID is stored directly on the material's surface. If it is assumed that a scheduled maintenance is realized, the read ID relegates to the database and additional information, established during service, are added. In this way at the end of the components life cycle, the pros and cons influenced by construction and manufacturing process serve the development of future generations. The materials sensory properties are used to monitor acting forces during operation (s. Fig. 3, Identification of deformation).

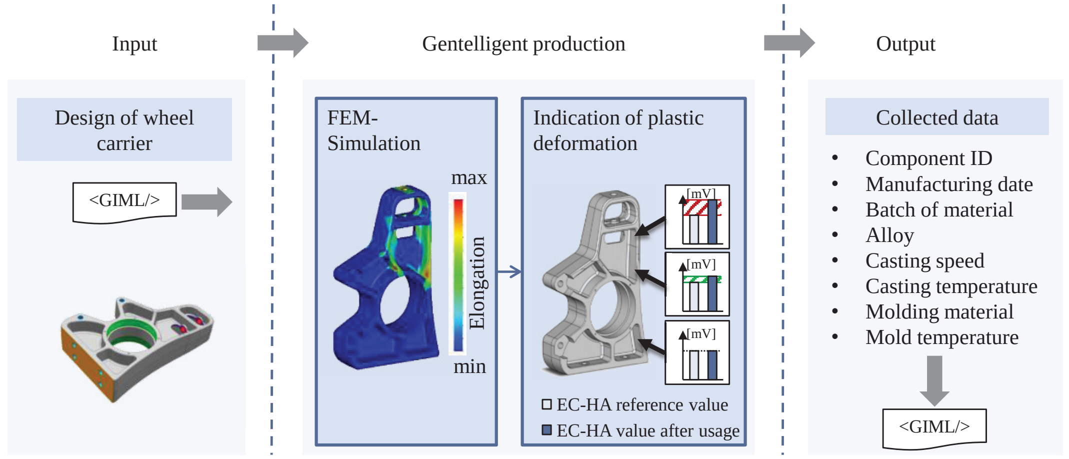

Fig. 3. Data Flow in the first step of Manufacturing Phase.

Essential for this is the magnetoelastic effect that occurs in ferromagnetic solid materials. This effect, also known as Villari effect, is thermodynamically inverse to magnetostriction and leads to a macroscopic change of the magnetic properties, which can be monitored by methods of non-destructive component testing, such as the harmonic analysis of eddy-current signals (EC-HA) [10]. That way, mechanical overloads during usage phase are detectable and inheritable to the next generation of gentelligent components.

3.2. Learning Process Planning, Simulation & Monitoring

In the context of machining, technical inheritance can be interpreted as the deployment of all data that has arised during the manufacturing of previous work pieces with the goal to produce consequent work pieces more efficiently. Combined with methods for operations planning, that consider status information of the sensing machine tools and work pieces, the gentelligent enabled production takes shape. The following sections analyses the data flows to, from and within the components of such gentelligent production.

Just as a conventional production planning, the gentelligent planning of the production of a work piece consists of several tasks [11]. At first, the resources and processes that will be deployed have to be identified and allocated. Afterwards, appropriate process parameters have to be chosen. Both stages require a geometric representation of the component that allows to derivate necessary production processes. In contrast to conventional planning, the gentelligent production planning considers the process results of all former processes as well as the status information from machines. In addition, not only a single work schedule will be identified, instead all possible combinations are explored and evaluated. This allows for rerouting the work piece, whenever a boundary conditions changes, for instance when a machine malfunction occurs or the priority of a commission changes [12].

The process planning stage applies a learning process simulation to predict process results and optimize production process. For that purpose, it uses signals of sensing machine components [13, 14], as well of signals from sensing work pieces [15] to parameterize models of the machine tool and the machining process. The composed process models also allow for estimating the process signals that are to be expected during the conduction of a process. They are transferred as process limits and target values to the process monitoring and allow the parametrization of the process monitoring.

Besides the machined work piece, the production phase also results in a GIML file, that documents all steps of the production process extensively. It contains the used machines, tools, process parameters, inspections results, a summary of measured signals and the total process time. Each single component has a production phase document that is dedicated to the component. As GIML is an XML-based format, the documents can be stored in an available XML compatible database. All data flows are shown in Fig. 4.

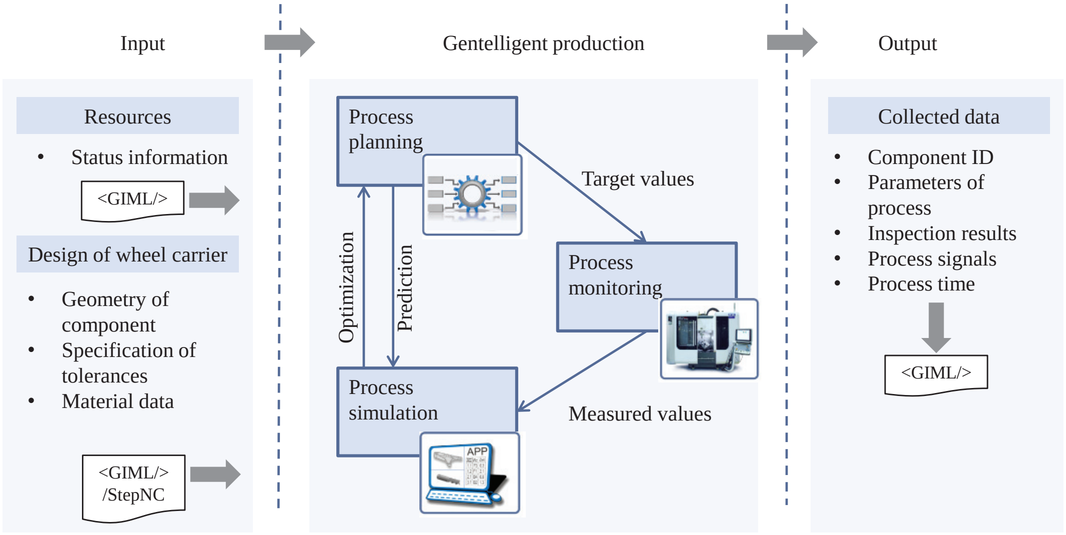

Fig. 4. Manufacturing Phase.

The process phase documents contain information that affect the cost of the production, which is particularly defined by the production time. Be feeding back this information to the development of the component, the production cost turns into a directly quantifiable optimization variable. In addition, the application of a gentelligent production offers further advantages. It enables a more flexible scheduling that reacts to changes of boundary conditions by considering current states of all necessary and available resources and machines. The use of a learning process simulation provides the opportunity to reduce defective components and to shorten the ramp up time by predicting the production results. Problems in manufacturing can be recognized early with an appropriate parameterized process monitoring that uses sensor signals from sensitive machine tool components and sensitive work pieces

4. Analysis of information flows in the Usage Phase of Components Life Cycle

Generally, the development of new technical products does not mean a completely new development. Technical products being developed are usually based on known existing systems, solution principles or their combination [2, 16, 17]. Here, an important role play the methods and monitoring tools of data analysis by an operation of the product. The organized and purposeful collection of product lifecycle data as well as the obtainment of information give an advantage in the analysis of the current state of the product, the forecast of its lifetime and can be used in the development for a new product generation.

4.1. Evaluation of life cycle data for condition-based maintenance

Technologies developed in the scope of CRC 653 allow load data detection during manufacturing and usage. These data collected during the life cycle may be evaluated to determine the component status, whose knowledge enables a condition-based maintenance. This implies a more precise maintenance planning and offers high potential for avoiding spontaneous breakdown even in case of material fatigue [4, 18].

Already during manufacturing mechanical and thermal load data curves may be detected and saved. In this context, also manufacturing parameters, such as feed rate, cutting speed and infeed, are memorized in GIML data format. This is done by reason of their influence on surface roughness and surface tension which have a certain impact on a components service life. Later in extending the life cycle, during the components usage, multiaxial load data curves can be detected and saved as well [19].

For condition-based maintenance these data need to be evaluated for experience-based residual life prediction. Therefore, the strains need to be read out and converted into an individual damage curve of the component. This can be done based on the approach of linear damage accumulation, which has been enhanced to consider the influence of the damage sequence as well as the instant of time. In order to take empirical data into account, suitable comparative components with similar strains during their life cycle need to be selected from an experience database where history of all prior used components can be saved. For this, equidistant time intervals and classification criteria need to be determined. Further, those components are selected as comparative components which possess a minimum percentage match of maximum damage, average damage as well as standard deviation for each interval. Subsequently the failure performance of these selected comparative components is evaluated statistically to deduce an expected time profile of failure probability. By defining a critical value of failure probability a residual life prediction may be derived [20, 21]. Based on the predicted remaining service life and other parameters, such as operating hours and strain characteristics, suitable preventive maintenance measures may be chosen by case-based reasoning regarding the experience database [22]. These selected actions can be saved in the components history as well as manufacturing and usage load data to be later used as empirical data likewise. The concept of technical inheritance by means of data storage and availability thus enables and is moreover required for the experience-based approach of condition-based maintenance developed in CRC 653, see Fig. 5.

4.2. Design Evolution

The focus in the design evolution lies in the research, development and adaptation of methods, tools and processes to support the product development. In all phases of the product life cycle it is possible to obtain a variety of data which can be used by the processing to identify information for the development of the next product generation [23]. By a development of specification and modeling techniques the flow of life cycle information can be mapped for different technical systems. Furthermore, an additional analysis to identify development-relevant information is possible. The design evolution process includes the steps of data analysis, modeling of component geometry, geometry optimization and finally the design of a new component generation (s. Fig. 6).

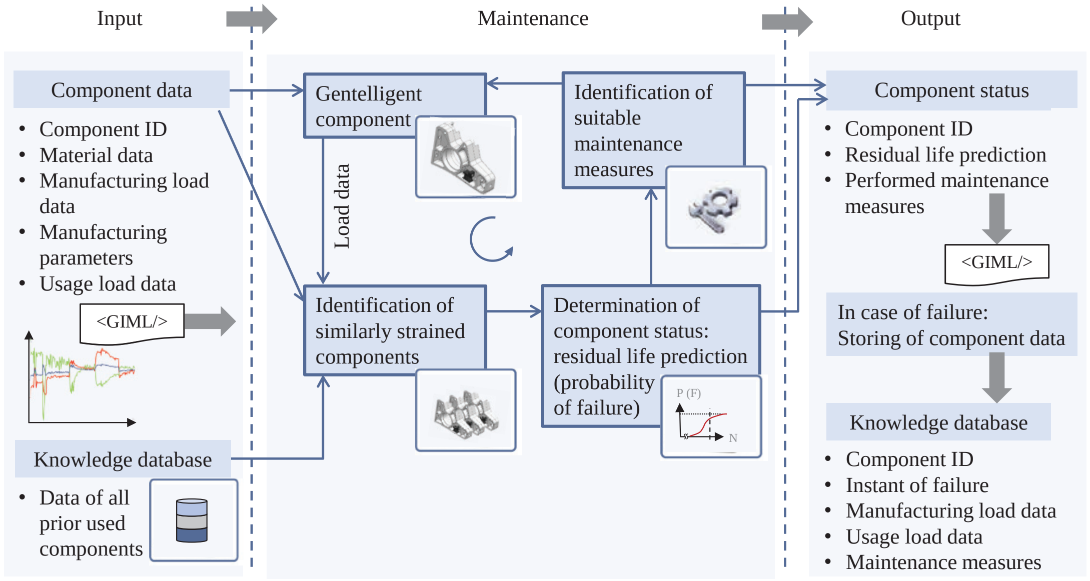

Fig. 5: Condition-based Maintenance enabled by Technical Inheritance and experience-based residual life prediction, based on [4, 20].

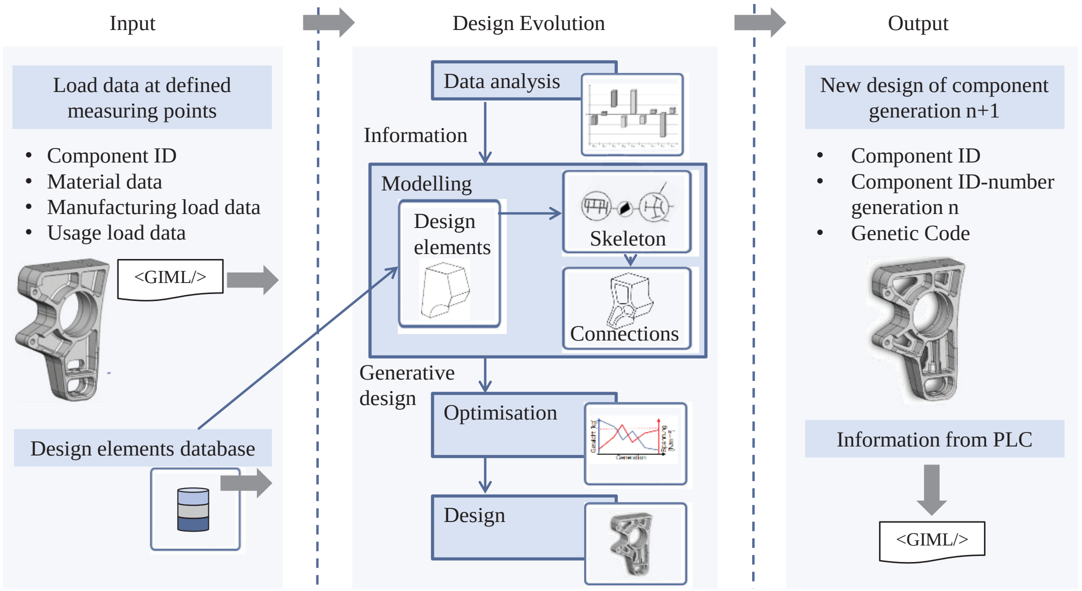

Fig. 6. Design Evolution Step.

According to the developed Generative Design Approach (GDA) [24] the first step of creating a new design of a component consists of choosing the so-called parameterized skeleton which provides the location of connecting surfaces. The skeleton‘s structure is given at the beginning of the component design and remains unchanged.

The next level is the appropriate standard basic design elements from a database. Each design element includes a set of parameters among which are manufacturing restrictions. Each component consists of a fixed number of design areas, a number which is determined in advance. Separate design areas can be defined as inherited objects to the next component generation in the case, when the requirements corresponding to these areas remain unchanged and e.g. are satisfied during the load operation. Part of a parameters’ set for each design element is a set of related area connection parameters, which are identical for neighboring design elements in the design of component. Operating loads of components from product life cycle (PLC) of the component can be stored in the GIML-format.

The genetic code (GC) of a component includes several parts and levels of parametrization. Thus, the first part includes information about the alloy of the component (s. Alloy GC, Fig. 7). The second part of the genetic code (Design GC) is represented by the skeleton structure, connecting surfaces and design elements. For a manufacturing of the component it is necessary to transform the Design GC into a Features GC.

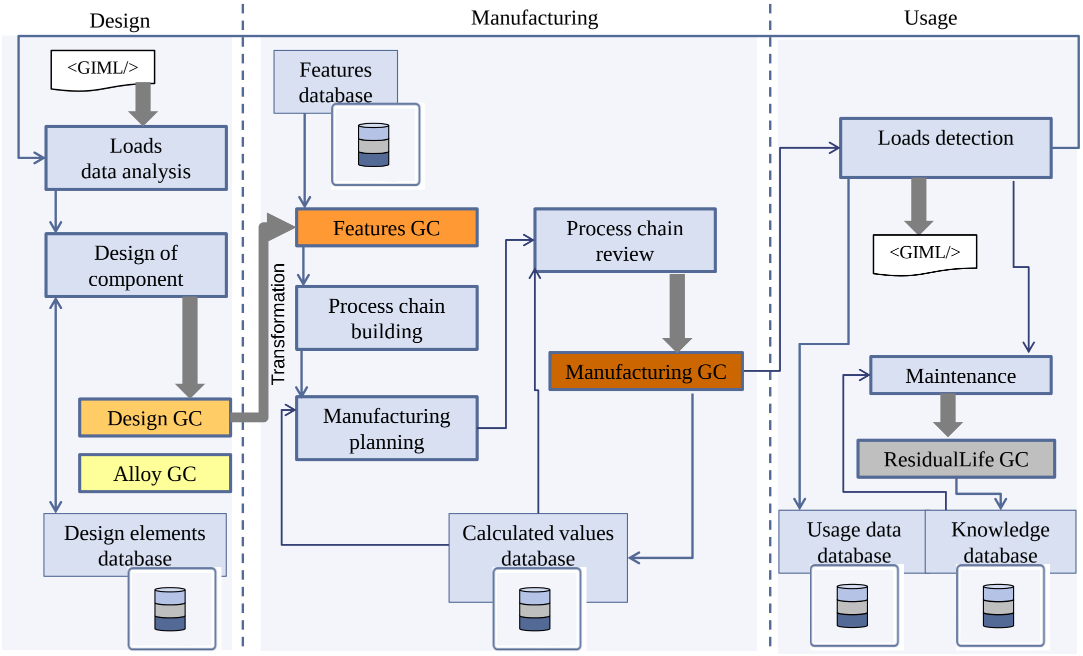

Fig. 7. Genetic Code of gentelligent Components.

The elements of the Features GC, for example, pockets or bores with corresponding processing tools, are stored in the appropriate features database. The optimal manufacturing chain is selected during planning and review processes and stored in the form of the Manufacturing GC. The result of a condition-based maintenance analysis can be stored in the form of a residual life GC. Thus, parts of the GC of gentelligent components are identified collected and relevant information for and from the development as well as the manufacturing and usage of a component. The GC of the component is currently under development and represents a convenient way to provide important and operational information about the component.

4. Conclusion

At the example of load-sensitive magnesium wheel carrier of the racing car RP09 results of the analysis of information flows during the life cycle of a demonstrator of the CRC 653 are presented. Storage and transfer of the assembled and verified information about the gentelligent components in their life cycle are the basis of the established in the CRC approach, called as the Technical Inheritance. In this approach, the mechanisms of inheritance and transfer of information in nature and the possibility of an adaptation of these mechanisms in relation to technical systems are studied. The advantage and one of the main purposes of Technical Inheritance is to create next generations of gentelligent components, which are significantly better adapted to the environmental requirements. The design of a new generation is performed on the basis of the goal-oriented collected information. The main influencing parameters which can be used as a basis for a genetic code of gentelligent components are presented. Furthermore, the standardized format for a data exchange beyond the different phases of the product lifecycle have been described, which are important to create a new generation of product information.

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