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# Concept for the Implementation of a Scaling Strategy into the Paradigm of Technical Inheritance

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## Abstract

A concept for the implementation of a scaling strategy into the paradigm of Technical Inheritance is proposed. The paradigm of Technical Inheritance allows monitoring the manufacturing and usage of a component, to analyse and employ the collected data into the development process of a subsequent generation of the component and to obtain an optimized structure. Regarding the development of the following generation a validation and hardware testing of the new structure becomes indispensable. For a time and cost efficient realisation of such a validation the usage of a scaled component structure is proposed to lower the manufacturing and testing expenditure. The basic scaling literature is reviewed and an overview of the implementation into the development phase of the Technical Inheritance is given. Possible distortions regarding the traditional scaling methods are considered.

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## 1. Introduction

In the development and operation of modern products progressively challenging market situations have to be taken into account. The developed products shall be individualized to an increasing degree to the customers' needs while offering high quality at an acceptable price. The temporal and especially economic claims are constantly growing, forcing the companies to develop a given product that matches the cost-side as well as the technical requirements in a short period of time [1].

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Regarding this aspect it becomes clear that especially in the development of a new product the product size has a significant influence on the lead time and the cost in following phases of a development process like e.g. prototype testing. Especially large scaled products have a high impact on the aforementioned aspects. Behrens and Nyhuis [2] show in their work on so called XXL-Products a first approach in the definition of such a product.

Particularly while handling large-scale products it is cost and time efficient to use a down-scaled model of the original component in the development. Not only the high manufacturing costs for a prototype but also for example long lead time because of capacity problems with suppliers have an impact. Further, the design and development process often includes several iterations before finding a suitable solution. Additionally, changes in a full-scaled product are also very time and cost consuming [2].

The concept of Technical Inheritance (TI) is devoted to the development of an approach of collecting and analysing data at different phases of the product life cycle with the aim of developing, producing and operating new generations of a product based on the life cycle data of previous generations which are more adapted to new requirements of the actual environment. The general scheme of the approach is described in [3]. Considering this approach and its benefits, an improvement regarding the before mentioned aspects in the development phase using an implemented and attuned scaling strategy is sought after and main topic in this article.

While the process of a geometrical scaling in all dimensions is a well-studied topic in literature, there are several aspects that may change the outcome of a scaled product test compared to an original sized product. The aim of this article is to address these aspects and classify them in the context of TI.

## 2. State of the Art

A geometrical example of the definition of similarity provides the consideration of two triangles that are regarded as similar if their side length ratios are constant. Such a ratio represents a simple form of a similarity term, which means that by maintaining this ratio the sizes are transferred geometrically similar [4]. Here, the ratio of two lengths represents an invariant about the length. More of these invariants are defined based on the SI system of units, out of which all similarities can be described from a dimensional point of view [5].

This consideration is taken up by the Buckingham Pi-theorem, which states that for every fully dimensional homogeneous relationship a dimensionless potency products relationship can be found [6]. The result of this so called “Dimensional Analysis” is a group of dimensionless products that are valid for the problem on hand. The dimensional analysis can be stated from a relevance list where all important variables are listed in. If all determined dimensionless potency products are respected, the considered problem is fully transferable from, for example, a model to a real-size description. The disadvantage with this procedure is the very intuitive approach and the necessary deep understanding of the overall physical problem that may lead to an underestimation and a false determination of the dimensionless potency products. In addition, there are no direct analytical connections between those products.

Kline [7] has shown extensions for the estimation of dimensionless similarity terms. He uses the “method of similitude” where an intuitive dimensionless force or energy condition is set up and through a balanced analytical equation dimensional groups can be determined. Other authors have taken up the approach of the dimensional analysis, as the method of determining similarity terms on the basis of the Pi-theorem, and expanded it [8] [9].

The formulation of the series development as stated by Pahl and Beitz [10] rather focuses on the product development. In this connection the previously mentioned dimensional invariants are used as a means of a complete similarity or a half-similarity. The definition of the changing increments is based on the decimal geometric series, and thus sets a standard for the development and production.

Rudolph [11], however, uses the similarity terms and applies his approaches on different problems. In this, he mainly uses the parameter reduction and associated simplification of equations and contexts that result from the dimensional analysis. For example, he presents a way to build neural networks by using similarity. Further, part of his work focuses on the development of a design language, as well as the distinction between a description and an evaluation of design solutions in a dimensionless mathematical space.

Another approach is presented by Franke [12] and Deimel [13] in their work on the integration of similarity terms into the development process. By using a so-called “task identification,” they are able to describe individual points of the design and use this description in a means of a comparison. As a result of a dimensionless consideration of the leading analytical equations, sensitivities can be found, which can then be used to perform an optimization.

Koschorrek [14] refers in his work more on the conceptual phase of the design process. In this, he also uses a dimensionless consideration for a description and functional evaluation of individual solutions.

A model-based modification and optimization of components is supported by a sizing-optimization. In this method a parametric CAD model is optimized by defining a solution space in regard to a target size and the modifiable parameters. An optimization algorithm then varies the parameters in a defined range regarding a given target function.

Based on the solution of a finite element software, the topology is modified and adapted regarding stresses for the investigated case of loading [15].

Another way of scaling is proposed by Dutson and Wood [16]. The main idea is a decoupling of the geometric change of a component and the material behaviour in the scaling process. Especially with large differences between the geometric size of the source and the target model, the scaling may cause fluctuations in relation to the properties because of, for example, material inhomogeneities. Transformation matrices are used to merge the empirically determined data of the geometrical and material changes that lead to an overall improvement of the estimation quality.

### 3. Scaling Distortions

Regarding the presented scaling methods in the state of the art, there is a variety of possible methods to use. Another important aspect to consider is the quality of the outcome and its possible deviations from the real problem and the affiliated reasons. In the work of Duston and Wood [16] a comprehensive overview of possible distortions from the scaling laws is given, as shown in Table 1. Here, the distortions are classified in four types. The geometric distortion results from a change in shape or the geometrical configuration. An ideal scaling is only possible if all geometric parameters are scaled uniformly, whereas the configuration may change the outcome according to a given load case.

Table 1. Types of distortions according to Dutson and Wood [16]

Distortion	Detailing	Example
Geometric	Shape	Square holes – round holes
	Geometric configuration	Horizontal beam – vertical beam
	Variable / nonlinear material behaviour	Nonlinear stress-strain state
Functional	Distinct material behaviour	Distinct material structures (isotropic / orthotropic)
	Functionally coupled parameters	Damping coefficient
	Improper boundary conditions	Unknown product boundary conditions
		Omit a dominant parameter
Parametric distortion	Incompatible system parameters	Similarity constraints not achieved
		Inaccurate material property data
	Distinct system configuration	Multiple-part system with parameters not achievable
Experimental distortion	Equipment limitation	Resolution of analysis equipment
		Sensor sensitivity

The functional distortion deals with the characteristics of the component. Accordingly, the material properties like a nonlinear stress-strain state or distinct material structures (isotropic vs. orthotropic) have an impact on the scaling outcome. However, changing boundary conditions or functionally coupled parameters like a damping coefficient are also classified as functional distortions. A parametric distortion is described by an unfulfilled similarity constraint, concluded e.g. from the similarity laws. The before mentioned dimensional analysis, which allows to extract the scaling laws from a relevance list is strictly linked with the provision of all relevant parameters. By omitting such a parameter it is possible to obtain a wrong outcome, although meeting all scaling constraints [6]. Regarding the beforehand mentioned material properties incorrect or inaccurate material data can falsify the expected results.

While monitoring an experimental analysis of a scaled structure the experimental equipment gains an increased influence on the empirical data. Exemplary limitations are the resolution of analysis equipment or sensor sensitivity and calibration.

Regarding the mechanical strength of a scaled structural component, several aspects have to be taken into account while using scaling laws. Table 2 gives an overview of static and dynamic cases regarding distortions. For a completely

static mechanical problem the scaled parameters are obtainable. Whether it is a similar stress state or similar forces and the resulting stresses that are of question.

The scaling factors for a structural component are derivable by taking into account the mechanical equations for a static load case. If the desired test situation is to obtain similar stress states as in the original, it is possible to use a stress ratio and obtain a scaling factor for further derivable characteristics.

Equation (1) implicates a scaling of the length applied in all geometrical directions by the factor  $\gamma$ , where the subscript 1 stands for the scaled length and 0 for the original component:

$$l_1 = l_0 \cdot \gamma. \tag{1}$$

For a similar stress-strain state equation (2) has to be fulfilled:

$$\frac{\sigma_1}{\sigma_0} = 1 = \frac{F_1 \cdot A_0}{F_0 \cdot A_1} \Rightarrow F_1 = F_0 \frac{A_1}{A_0}. \tag{2}$$

This leads to the following expression:

$$\frac{A_1}{A_0} = \gamma^2. \tag{3}$$

Finally the scaling factor for the forces to be applied on the scaled component are obtained:

$$F_1 = F_0 \cdot \gamma^2. \tag{4}$$

Using this scaling equation it is possible to obtain a completely identical stress-strain state using an original and a scaled component. This is valid only for the linear case. If nonlinearities occur, this equation is no longer valid. Additionally, these Equations are valid for the case where the Young's Modulus of the material of the original and scaled component are equal.

Table 2. Static and dynamic mechanical distortions

Static / Dynamic	Problem	Outcome
Static	Scaling of linear stress	Possible
Static	Scaling of linear stress (material inhomogeneities)	Error in elastic areas (statistically retrievable)
Static	Scaling of non-linear stress (global)	Analytically not obtainable
Static	Scaling of non-linear stress (local)	Error in elastic areas
Dynamic	Scaling of density	Not possible in real test
Dynamic	Scaling of gravitation	Not possible in real test
Dynamic	Scaling of linear stress (surface roughness)	Error due to possible crack propagation

However, in the static state several errors are possible which may change the expected outcome. Especially material inhomogeneities due to the manufacturing process can have a great impact. Small lunkers and air inclusions in the casing process, cracks due to a high feedrate in the turning process or the gradient heat distribution in a rapid prototyping process are examples for possible reasons of an inhomogeneity. These inhomogeneities change the structure of the component and can intensify a further crack propagation. This is not only a problem existing in the scaling domain but also in the original calculation of a component. Inhomogeneities of such nature are hardly to foresee and lower the lifetime and load resistance drastically.

The case of a local plastification regarding a scaled component can especially appear in the process of an upscaling. In case of a high scaling factor the forces are scaled quadratic, which can lead to local plastifications in the load application point. A possible consequence is a changed angular position of the load vector position and therefore an overall different load distribution.

While beforehand the considered case was static the presented problems are also valid for the dynamic case. The aforementioned equations show a major problem regarding time or mass dependant systems. Equation (5) shows the scaling of the displacement of a component which is obtainable analogous to equation (1):

$$y_1 = \gamma \cdot y_0. \tag{5}$$

With further regard to the time the scaled velocity is described by equation (6):

$$v_0 = \frac{dy_0}{dt} \Rightarrow v_1 = \frac{dy_0 \gamma}{dt} = \gamma \cdot v_0. \quad (6)$$

This leads to the scaled acceleration

$$a_1 = \gamma \cdot a_0 \Rightarrow g_1 = \gamma \cdot g_0. \quad (7)$$

For a dynamic time dependant load case the force is scaled in a similar way to equation (4):

$$F_{in1} = \gamma^2 \cdot F_{in0}. \quad (8)$$

The equation for a dynamic force leads to

$$F_{in0} = m_0 \cdot a_0 \Rightarrow F_{in1} = (\gamma \cdot m_0) \cdot (\gamma \cdot a_0) = \gamma^2 \cdot F_{in0}. \quad (9)$$

Therefore the equation for the mass is

$$m_0 = \rho_0 \cdot V_0. \quad (10)$$

Scaling of the mass according to (9) leads to:

$$m_1 = \gamma \cdot m_0; \quad (11)$$

$$m_1 = \gamma \cdot \rho_0 \cdot V_0 = \frac{\rho_0}{\gamma^2} \cdot \gamma^3 \cdot V_0. \quad (12)$$

Equation (12) shows that for scaling of a dynamic load the mass is scaled linear. This implies that the volume has to be scaled cubical and the density is scaled by the quadratic division. Because of the assumption of a remaining material in the scaled and original version, this is not possible to fulfil. While the Young's Modulus has to be constant for a consistent stress-strain state a changed density leads to a non-existing material.

A dynamic load case with regard to gravitational forces implicates a scaling of the gravity itself what leads to a not obtainable test situation.

#### 4. Implementation into the Technical Inheritance

As depicted in Figure 1, the proposed scaling approach is implemented into the development phase of the process of TI. After the concept of the component has been developed and the optimal geometry of the component is obtained taking into account the collected load information during operation of previous generations, an identification of similarities is carried out. The idea is to provide a similarity database with implemented scaling methods known from literature in a formalized and usable way.

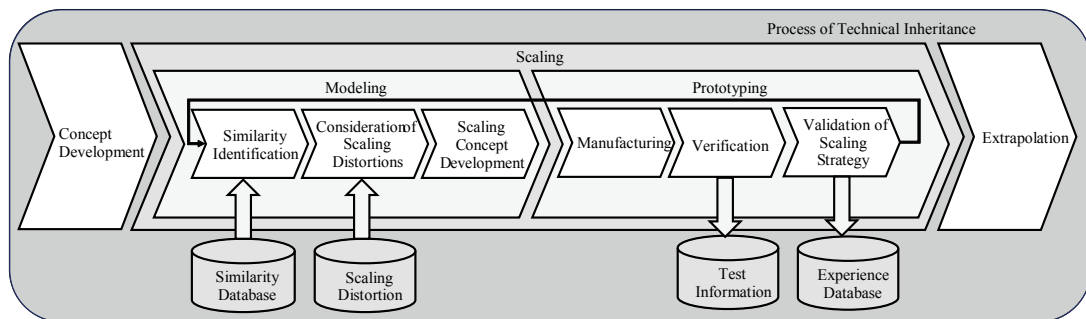


Fig. 1. Implementation of the scaling strategy into the development phase.

The user therefore can chose the scaling method most suitable for his purpose. In addition, a further database is implemented with possible distortions to the desired scaling method, as presented in Section 3. The user gets

information on possible distortions according to the scaling method as well as the physical domain, load case or the distinction between a static or dynamic case.

Furthermore, since not all of the components' features, such as the thickness of possible ribs, the transition radii or the technological holes, can be realized due to limitations of the manufacturing process, the scaling strategy includes the step of implementing model restrictions in the manufacturing process.

After obtaining the scaled component model, the subsequent steps include the manufacturing of two or more prototypes with different scaling factors, verification of the prototypes, for example, by carrying out static and dynamic loading experiments and validating the component's scaling strategy itself. Since the validation of the strategy is carried out on prototypes with different scaling factors, the obtained results allow judging the possibility of extrapolating the results to the original size of the component. The obtained results regarding the applied strategy are stored in the appropriate experience database and can be used to develop new generations of the component in the development phase of TI.

## 5. Conclusion

The article describes a concept for the implementation of a scaling strategy into the paradigm of Technical Inheritance for an increased efficiency regarding the time and cost effort within the development of a new generation of a component. Especially possible distortions to the expected outcome and the transfer to the original sized component are addressed and presented. Future work lays in the derivation of a suitable case study to further investigate the distortions as well as the actual benefit of the scaling strategy.

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