INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016
Dubrovnik - Croatia, May 16 - 19, 2016.

UNCERTAINTY IN SIZE RANGE DEVELOPMENT - AN ANALYSIS OF POTENTIAL FOR A NEW SCALING APPROACH

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Keywords: size range, scaling, uncertainty, robust design

1. Introduction

This paper classifies different types of scaling uncertainty that occur in size range development. Scaling uncertainty can be divided into two groups: One that concerns variance in product or process properties, already described in literature; the other concerns effects that are neglected on purpose or due to ignorance. Uncertainty of this kind is related to product models and results in insufficient mathematic models for the scaling process. The consequence of this is that iterations are required to ensure a proper result in the scaling process. Examination of the different effects of scaling uncertainty shows how the size range development process is affected by uncertainty in a more detailed way. Depending on the effect, the size range development process can be improved by anticipation of size dependent effects during the early stages of the product design process. This is a way to implement a frontloading strategy in size range development. The potential for improvement is analysed qualitatively and linked to the occurring uncertainty.

2. Fundamentals

To assess the potential use of a modified size range development process, understanding of three basic components is required:

- Uncertainty classification
- Scaling of products, based on similarity laws
- Integration of the scaling procedure into the product development process and knowledge of which kind of uncertainty occurs at which point.

In addition, the existing literature on scaling uncertainty is essential to explain possible ways to handle scaling uncertainty. These approaches will be explained in the following sections.

2.1 Uncertainty

Uncertainty, according to [Engelhardt et al. 2010], is the lack of determinability of a system's process properties; uncertainty occurs in processes. The result of uncertainty is usually the deviation of product or process properties from planned values, which is a consequence of insufficient determination. In addition, uncertainty can be classified according to the level of information available to the designer [Engelhardt et al. 2010]:

- Unknown uncertainty occurs if the effect of uncertainty is not known (even the existence of the uncertainty itself might not be known to the designer): "unknown uncertainty".
- Estimated uncertainty occurs if the effect that the uncertainty will have on the process performed by the product is known, but the variance of the effect is only partly quantified.

- Stochastic uncertainty is similar to estimated uncertainty with a well known effect, but also with an acceptably quantified variance, usually probability density functions are known to the designer.

The transition between the three kinds of uncertainty is continuous.

In addition to these kinds of uncertainty, uncertainty can be either aleatoric or epistemic [Hoffman and Hammonds 1994], [Apostolakis 1999]: Aleatoric uncertainty is the uncertainty that cannot be reduced by gathering more information. This applies to validated ("true") probability density functions. Epistemic uncertainty has its roots in insufficient information and thus can be reduced by improving the amount or quality of information available to the designer. The purest form of epistemic uncertainty is unknown uncertainty, also called ignorance. Lack of information about the effect that uncertainty has (or by only assuming which effect it has), prevents the creation of a full model of the relevant effects.

Having a closer look at uncertainty related to product models, Oberkampf and Trucano found four kinds of uncertainty in mathematically describable models in the field of uncertainty quantification [Oberkampf and Trucano 2000] (it will be demonstrated that these are the models relevant to scaling):

- Product modelling uncertainty, which occurs if relevant influences might have been neglected during the modelling process. Würtenberger et al. [2015] further connect this kind of uncertainty with the attributes of pragmatism, representation and shortening, which were introduced by Stachowiak [1973]. This kind of uncertainty can be called epistemic uncertainty, according to [Hoffman and Hammonds 1994], [Apostolakis 1999].
- Mathematic modelling uncertainty, which occurs if it is not finally validated. The mathematical model represents the product model sufficiently; it also belongs to epistemic uncertainty.
- Parameter uncertainty, which occurs if parameter values are not considered or estimated correctly, which can be described with the terms of estimated or stochastic uncertainty from [Engelhardt et al. 2010] and is mostly aleatoric uncertainty in the terminology of [Hoffman and Hammonds 1994], [Apostolakis 1999].

The last type of uncertainty, according to [Oberkampf and Trucano 2000], is simulation uncertainty, which is not of interest in this paper since the computational methods for solving problems in size range development are considered identical to the methods used in general product development processes.

Finally, Würtenberger et al. give a definition of product model uncertainty [Würtenberger et al. 2015]: "Product Model uncertainty occurs when it is not clear that the created individualized product model sufficiently describes the reality represented by an ideal model."

It is important to understand that uncertainty in the quantification of parameters can be described as predominantly aleatoric uncertainty, while issues with model uncertainty are most often associated with insufficient information and therefore epistemic uncertainty. It can be useful to distinguish between the product model and the mathematical model when model uncertainty is examined.

2.2 Scaling based on similarity laws

Similarity laws are a common and powerful tool for scaling physical systems [Gibbings 2011]. When retaining similarity, at least one physical quantity is relatively constant throughout the scaling range, meaning that the proportion between the values of different physical parameters of the same kind is the same for every size the system is scaled to [Pahl et al. 2007]. The most widely known similarity is geometric similarity, which basically ensures that an equilateral triangle keeps being an equilateral triangle, regardless of its scaling factor. Besides geometric similarity, similarity can be stated for every SI basic unit [Pahl et al. 2007], depending on the objective of scaling.

The importance of retaining some kind of similarity is that similar systems show a similar behaviour. The laws of nature do not act according to the unit they are measured in, so every phenomenon can be described using relative quantities, i.e. invariants [Pahl et al. 2007]:

$$\varphi_L = L_1/L_0 \tag{1}$$

Equation 1 shows the invariant of size, with L_1being a length of the scaled design and L_0 being the corresponding length of the basic design. In the context of size range development, the scaled design is called sequential design, while the invariant φ_i is called the step factor. Physical relations described by

a monomial can be written using only step factors [Pahl et al. 2007]. Step factors that do not change with scaling (for example, the step factor of young's modulus) can be set to 1.
Similarity really gets useful when more than one similarity is retained: special similarities result [Pahl et al. 2007]. For example, having elastic force (represented by young's modulus E and the applied mechanical force F) and length L as invariants, a dimensionless number, the special similarity of Hooke, follows, ensuring that the relative elastic deformation (and therefore the strain) stays constant while scaling:

$$Ho = \frac{F}{E \cdot L^2} \tag{2}$$

Taking model theory into account, the system behaves similarly if the dimensionless number stays constant over scaling. So Eq. 2 can also be written using step factors:

$$\frac{Ho_1}{Ho_0} = 1 = \frac{\varphi_F}{\varphi_E \cdot \varphi_L^2} \tag{3}$$

Preferred numbers are often chosen for step factors. They are standardised and exhibit exponential growth [Pahl et al. 2007].
Retaining complete similarity is actually rare in size range development. Technological limitations, fits and tolerances (e.g. the tolerance unit i only growths by $\sim\varphi_L^{1/3}$ while proportional growth would be necessary for similar product behaviour), overriding similarity laws, other requirements (for example, man-machine interfaces that cannot be scaled at all or only within a certain, relatively small range) and overriding standards often force the designer to create semi-similar products [Pahl et al. 2007], which bring more complexity and development costs into size range development. This usually requires the assembly of more product-specific laws of growth.

2.3 Uncertainty scaling

There are several papers that deal with the mathematical formulation and application of uncertainty scaling. The common scaling methods based on similarity are used: dimensional analysis is used by Vergé et al. to scale uncertainty in systems retaining full similarity [Vergé et al. 2015], while the scaling of product properties using laws of growth/similarity laws for static and time dependent variation in parameters has been demonstrated [Lotz et al. 2014a,b].
All of the existing methods are applied to the aleatoric parameter uncertainty, according to the uncertainty classifications given in Section 2.1. They also allow model refinement by integrating a description of the effect parameter uncertainty has into the scaled physical effect [Lotz et al. 2014a,b]. What they cannot generally provide is the integration of effects of disturbances, interactions or internal quantities into the main effect. The influence of disturbances, interactions and internal quantities on the scaled target parameter may be incorporated into the similarity law or law of growth, but only if their size dependency is proportional to the size dependencies in the main effects and if they also follow the same physical principle. In all other cases, they do not permit reduction of epistemic uncertainty if they are not combined with additional methods.

2.4 Size ranges

The first description of a product development process for size ranges, which are scaled products, is the one described by [Pahl and Beitz 1974], which is described in more detail in [Pahl et al. 2007]. They define a size range as technical artefacts that have the same function, fulfilled with the same solution principle, that are made in various sizes using the same technology and material (if possible), and have the same level of material utilisation [Pahl et al. 2007].

3. Analysis of the scaling process

For the development of size ranges, there are basically only two holistic procedural models: the methodology of Pahl and Beitz [1974], [Pahl et al. 2007] and the Product Platform Exploration Method (PPCEM) of Simpson et al. [2001]. Additionally, there are a few publications that present approaches that try to give advice on how to optimize the step factors within a size range from an economic point of view, e.g. [Malakov et al. 2015]. Since the PPCEM has a strong focus on modular systems and computer-aided optimisation mostly at an embodiment level, it is difficult to explain the various facets of scaling uncertainty in this methodology. The basic idea of PPCEM is, accordingly to Pahl and Beitz, the utilisation of abstract modelling of physical principles of a basic design, which then is used to generate the sequential designs. The literature on the determination of step sizes interferes in a minor way with the uncertainty in size range development. The basis of further explanations will therefore be Pahl and Beitz's six-step development process for size ranges [Pahl et al. 2007]:

1. A basic design has to be created; this could be an existing product or a newly developed one.
2. Physical relationships have to be determined to get the similarity laws/exponents of growth.
3. Step sizes and scaling range have to be determined.
4. The scaling range has to be checked for compliance with overriding standards and technological requirements (e.g. minimum wall thickness for casting, etc.); deviations have to be recorded and added to the data sheet.
5. Scale layouts of the assemblies have to be checked for proper functioning, producability, etc., paying attention especially to critical areas in extreme dimensions of the size range.
6. The documentation has to be improved and completed; production documents have to be prepared.

3.1 Physical issues and the size range development process

This process can be explained and shown within Ehrlenspiel's model of product model concretisation, which was modified by Sauer [2006] and adapted for this paper (Figure 1).
The initial reason for creating a size range is that different customers need the same process realized, but require different process parameter values (for example, the different diameters of a hydraulic cylinder in different sized forklifts are needed to provide different forces for the process of lifting heavier or lighter goods). Realising variants of processes results in corresponding requirements. The corresponding requirements are linked to the determination of step sizes and scaling range (the third step of the Pahl and Beitz size range development process).
To solve this issue, the methodology requires a completed basic design to start off with. The basic design gets analysed at the effect level, where the similarity laws for the following scaling process are chosen and represent a mathematical model (just like laws of growth). Having determined the similarity laws of the system, the working principle level is skipped, as well as most of the tasks that are located at the embodiment level; only checking for proper function and completing and improving the documentation takes place there, as long as similarity can be retained. For semi-similar products or if overriding standards, overriding requirements, fits and tolerances require more changes to the scaled design, iterations are carried out at the embodiment level and the production solutions level.

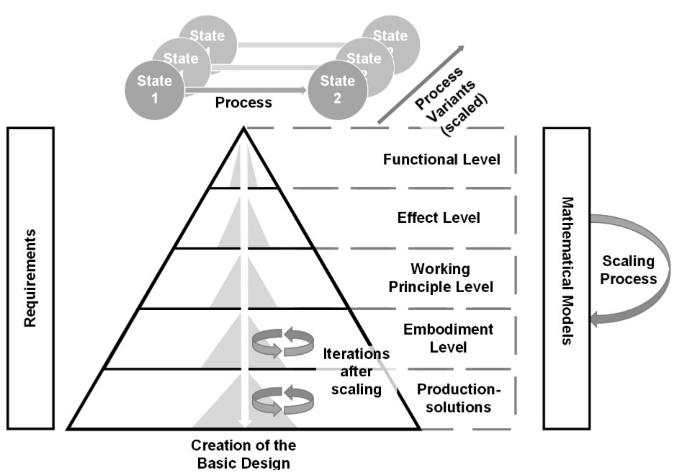

Figure 1. Size range development process, according to Pahl and Beitz, displayed in a product concretisation pyramid (extended and partly adapted from [Sauer 2006])

Pahl and Beitz claim that size ranges are advantageous in design and production rationalisation [Pahl et al. 2007]. This is justified when the design is done once and can be transferred to other sizes using similarities and achieving a wide range of applications. The claim of doing the design once and having all sizes covered is not the usual case. As mentioned in Chapter 2.2, full similarity is often prevented by a number of reasons. To ensure the functioning of all sizes of the product, Pahl and Beitz have included iterations in their procedure model for size range development (Steps 4 and 5). The iterations can be as easy as re-specifying tolerance grades, which is an example of where this six-step approach, using a basic design, is still very efficient. Significant losses in similarity can lead to a massive redesign of sequential designs because a certain effect might exceed its boundaries of scalability from a certain step factor on. Basically, three different kinds of problems may occur and cause iterations:

1. More than one physical effect is employed in the product, and these different effects are divergent in scaling. This may lead to a change in the governing principle, or, regarding uncertainty, a change in the disturbance or interaction with the highest relative variance. Examples are:
    a. The different growth of mechanical power and cooling in a gearbox: for a totally similar design, the losses are growing in proportion to φ_L^3, cooling power depends on the surface growing with φ_L^3.
    b. The different growth of uncertainty, e.g. production tolerances according to ISO 286 and a size independent variance of the young's modulus, which results in tolerances being the dominant influence on buckling in small sizes, while the variation of material properties are dominant in large sizes [Lotz et al. 2014].
2. Discontinuities can appear in the laws of growth within the size range. This may affect the behaviour of the product in different sizes heavily, or, if anticipated, may cause a major change in design. Examples are:
    a. If the laminar flow wing of an airplane is scaled up while operating under constant environmental conditions, the flow might get turbulent because of the increased Reynolds number, highly increasing drag. This can also happen through uncertainty, for example, if roughness or dirt occurs during use, preventing the flow from being laminar in certain sizes.
    b. If capillary forces are used, scaling up is often not possible. If the flow rate has to be increased, the number of capillaries has to be scaled, not the geometry of the capillaries. This is a massive change in design from the size range point of view.
3. Scaling limits are reached because of technological limitations. These limitations might occur during use or in production. Examples are:
    a. The weight of a structure of the same material increases with its volume (φ_L^3), while the strength only increases proportional to φ_L^2. This causes the structure to collapse under its own weight at some point, as not enough strength was provided for its purpose earlier on.
    b. Scaling up and down may both be critical for casting. Minimum wall thicknesses cannot be under-run, while wall thicknesses above a critical value might lead to shrinkage cavities.

If any problem of this kind appears, the designer has either not utilized an appropriate scaling model (epistemic uncertainty of a mathematical model, also known as mathematical modelling uncertainty) or has not used appropriate product models that include all relevant effects (epistemic uncertainty, also known as product modelling uncertainty). Another reason could be that calculations were performed with neglected variances or incorrect assumptions about model parameters (aleatoric uncertainty). All three types of uncertainty cause a deviation between planned product properties and realised product properties.

This shows the weaknesses of Pahl and Beitz' approach. Uncertainty is not regarded for all sizes in early development stages so decisions that are made in the creation of the basic design may be inaccurate. Inaccurate decisions then lead to iterations in which the designer has to reduce the degree of similarity. This easily happens if various physical effects are used within a product, which happens quite often in complex products and is one of the main reasons for semi-similarity [Pahl et al. 2007]. The other reasons, overriding standards and technological limitations, are also not considered in a methodical way in basic design generation, leading to the same consequences as mentioned previously: inaccurate decisions and semi-similar products. The key results from this analysis are:

- Reduction in the degree of similarity (due to one of the three classes of scaling issue) leads to a greater need for interactions after the scaling process in the Pahl and Beitz methodology
- It is essential that all scaling relevant effects are considered when modelling size dependent product behaviour to create a design with guaranteed functionality in all required sizes.

3.2 Scaling model-related issues (model uncertainty)

To go a bit deeper into the issue of considering all scaling relevant effects to benefit from the size range advantages in the best way possible, the influence of uncertainty has to be examined further. The process of scaling first analyses the product models to find the corresponding similarity laws and growth exponents (Step 2 of the Pahl and Beitz approach). As the examples show, it is often an auxiliary function, a disturbance, interference or incidental quantity that causes the major loss of similarity. Since the similarity laws are generic mathematical models that are directly used to calculate the product properties of sequential designs (see Figure 1), it is absolutely necessary to have a complete analysis and assessment of physical effects of the product model. Detailed analysis and assessment provides information to the designer, reducing epistemic uncertainty. This results in reduced product modelling uncertainty and also decreases mathematic modelling uncertainty in size range development. Approximated laws of growth in semi-similar size ranges are also a source of mathematic model uncertainty.

The lower the epistemic uncertainty in product models and mathematical models, the lower its impact on sequential designs, since the scaling process only links uncertainty in product models of the basic design and mathematic uncertainty in the similarity laws.

Having low uncertainty in the product models of sequential designs, created by scaling, less iterations are needed to ensure the same level of function and quality, since the need for scaling uncertainty reduction is reduced compared to a scaling process involving a high degree of epistemic uncertainty. These correlations are also shown in Figure 2.

Besides scaling model uncertainty, well known parameter uncertainty (aleatoric uncertainty) and its integration into scaling models is possible, as the literature shows, and contributes to more predictable product properties of sequential designs [Lotz et al. 2014a,b], [Vergé et al. 2015].

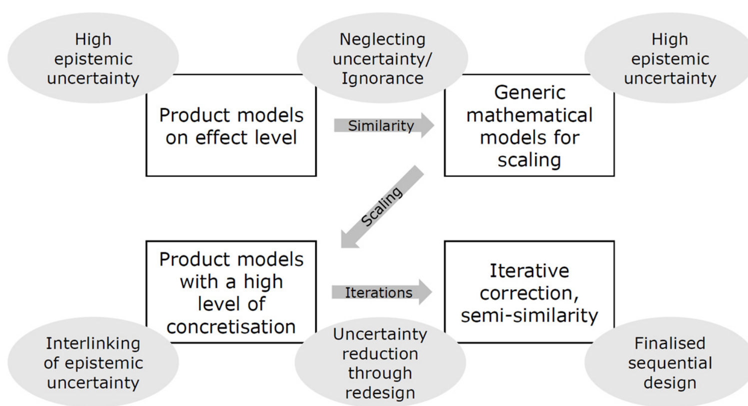

Figure 2. Development cost reduction potentials in size range development due to ignorance and neglected uncertainty

3.3 Implications for size range development

Having the physical issues of size range development described (in Section 3.1) and the issues from model uncertainty within the scaling models analysed means that the implications for a size range development process can be enunciated. The development costs and time will depend upon how many iterations have to be carried out after scaling the basic design. Even more important for mass production is that the iterations do not change the embodiment design of the different sizes too much, but retain the maximum level of similarity. This is essential to retain the cost benefits gained with a size range by using the same technology and production processes [Pahl et al. 2007]. The minimum post-scaling changes will be achieved if a basic design is created that anticipates product behaviour for all sizes in the size range. Anticipating different growth of physical effects, changes in governing principles or leading interactions and disturbances as well as size dependent variances can enable the choice of the most suitable solution for a size range product. This anticipation process (classical frontloading) may start as early as the effect level and should be performed parallel to the rest of the development process. The results are fewer problems, higher cost savings due to retained similarity, and less development cost due to fewer iterations.

This situation has two implications for further research:

1. The potential of emphasizing the anticipation of size dependent behaviour in the early stages of the development process has to be analysed in detail.
2. A modified approach to size range development has to be developed if it becomes necessary.

4. Potential of low-uncertainty scaling processes

Since size ranges are about decreasing costs for a variety of products with identical function but different size [Pahl et al. 2007], the potential of modifying the anticipation in the development process for basic designs refers to costs. Cost savings also provide the motivation for industry to adopt new design processes, especially in a cost sensitive case such as size range development.

The first point was mentioned previously and concerns production costs. The higher the degree of geometric similarity the better. A geometrically similar design does not need significant learning effects for each step size, nor does it need complex preproduction processes - a parametric CAD model is sufficient to derive all necessary documents with very little effort. For the machine operator, every single task is the same, just with bigger work pieces and maybe bigger tools. Losing similarity causes more preproduction work if technology changes are necessary (as stated in Section 3.1), learning effects have to be acquired for different sizes, and possible additional or more expensive processes have to be executed to produce the product in certain sizes. All these effects are qualitatively taken into account in Figure 3.

If modified size range development processes that allow the designer to reduce epistemic uncertainty in the scaling procedure can be developed, the development costs will then be allocated elsewhere in the development process. Iterations will be reduced if scaling uncertainty (both epistemic and aleatoric) is analysed and assessed, and the epistemic part is reduced during the development of the basic design. This is the potential for cost savings in development processes, as in Figure 3.

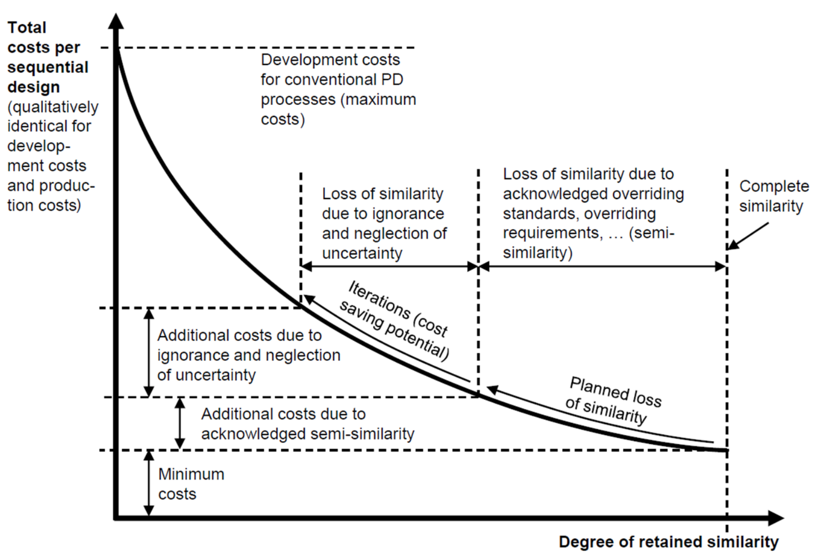

Figure 3. Development cost reduction potential in size range development due to ignorance and neglected uncertainty

If effort is put into designing a robustly scalable basic design instead of iterating around a potentially mediocre basic design, true frontloading is achieved. This reduces costs and development time. The benefit of frontloading in size range development does not apply if complete similarity can be retained and the product properties are not influenced by size dependent uncertainty in a relevant manner. In this case, there is no need to analyse the physical effects before the basic design is completed. Also the - theoretical - case, where a size range is attempted to be developed, but no similarity can be retained, is not a beneficial scenario for scaling model uncertainty reduction through anticipation of size dependent effects, since no information can be transferred efficiently to other sizes of the product and a standard product development process would be the most simple way to achieve the aim. A feasible scope of application that depends on the degree of retained similarity is given in Figure 4, which also shows the effects of reducing iterations.

5. A scaling-integrated product development process

The insights in Sections 3 and 4 mean that new thinking about the size range development process is required. Scaling should be an integrated part of the basic design development process, not just a process that happens after the (reasonable) degrees of freedom are reduced to geometric parameters.
To create a new approach, four components are needed:

- A procedural model for the development process. Since a new approach would concentrate more on finding solutions suitable for scaling and should do this as early as possible, a standard approach like VDI 2221 [VDI 1993] would be a good point to start in further work.
- Models for size dependent modelling of relations between processes and products as well as between product properties to reduce model uncertainty due to neglect of effects. A feasible analysis of size dependent relations between product properties or modules has to be developed in the future. This could be based on design structure matrices [Lindemann et al. 2008] and product property networks [Birkhofer and Wäldele 2009].
- Models for size dependent representation of parameter uncertainty as a source of semi-similarity in product and process properties to allow sound propagation of aleatoric uncertainty. These models already exist [Lotz et al. 2014a,b], [Vergé et al. 2015].
- Methods for assessment of size dependent product behaviour do not yet exist. Assessment of the robustness of a size range over the whole scaling range would be an interesting contribution to a new size range development process, since it would support the choice of solutions that work properly in all sizes produced while not needing design changes.

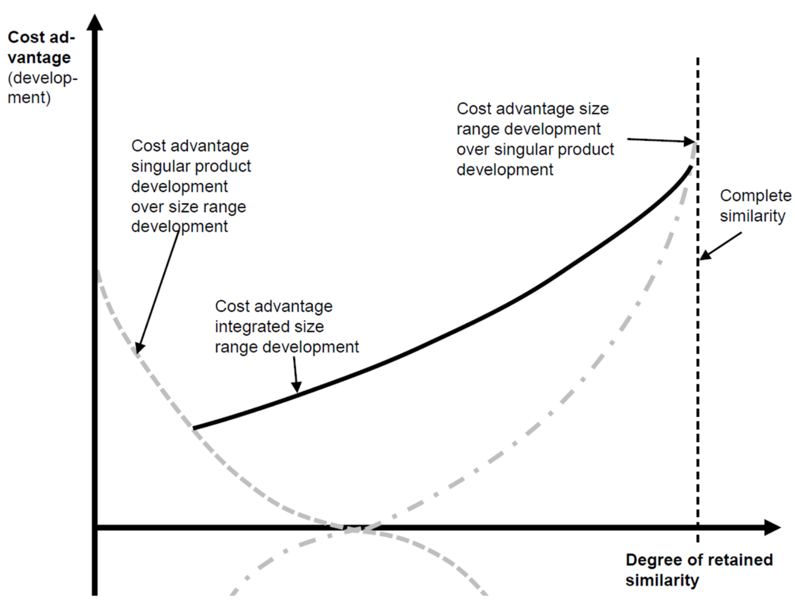

Figure 4. Estimated cost advantages of uncertainty integrated size range development

6. Conclusion

After summarising the basic fields of scaling, size range design, uncertainty and uncertainty scaling, an analysis of the types of scaling uncertainty (epistemic and aleatoric) was given. The analysis of the Pahl and Beitz size range development process showed that a link between different kinds of uncertainty can be found in the transfer from product models of a basic design to the mathematical scaling models, as well as from these to product models of sequential designs. Occurring uncertainty leads to increased costs due to increased semi-similarity.

To prevent the basic design from being insufficient at certain sizes, there is a need for anticipation of effects that cause semi-similarity and their assessment. If anticipation of size dependent behaviour is integrated into the early stages of the product development process, frontloading can be achieved in size range development. This leads to the choice of solutions that retain a maximum level of similarity and therefore are most cost efficient. The additional effort required for anticipation is compensated for in the reduction of iterations during embodiment design for various sizes.

To support uncertainty controlled size range development, future research should be carried out in four areas:

- Definition of a procedural level for uncertainty integrated development of basic designs
- Models to describe size dependent relations between product properties to support the assessment of scaling robustness and the prediction of size dependent product behaviour
- Adaption of methods for concept generation to represent size ranges, not just individual sizes
- Methods for optimization of semi-similar products influenced by parameter uncertainty

Acknowledgement

Thank you to Deutsche Forschungsgemeinschaft (DFG) for funding this project within the Collaborative Research Centre SFB 805.

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