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Systematic Method for Axiomatic Robustness-Testing (SMART)

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Abstract

SMART (Systematic Method for Axiomatic Robustness-Testing) is a method for the development of robust and reliable products. It combines elements from the robust design methodology with a holistic approach by using Axiomatic Design (AD) and the Taguchi Method (TM). These two methods were established and expanded by N.P. Suh (1990) (AD) and G. Taguchi (1949) (TM). SMART is based on the chronological sequence of the four phases of the Product Development Process (planning, conception, design and development) according to the VDI Guideline 2221. Using this chronological basis, the three process steps (System, Parameter and Tolerance Design) of the Taguchi Method are classified and integrated accordingly. The AD method is applied to the systematic examination of the robustness of designs.

During the conceptual stage, one or more designs are generated by means of AD. AD also helps analyze the design's complexity from the perspective of possible design modifications, thus assuring robust solutions. If a design has already been generated but needs improvement as things developed, AD is used as well. The design may not necessarily be changed in its basic structure but is examined in terms of its complexity. The results of AD support the setup of the P-Diagram according to Taguchi either after the conceptual stage or the design stage of the product.

The following step is the Design of Experiments (DoE) of the product's design parameters and noise factors that occur during its utilization. Testing may either be carried out by virtual or real tests. After analyzing the results of the tests, the design should be optimized accordingly in order to increase the robustness. A predicted reliability determination is possible as well.

The last step is the adjustment of the tolerances of the design for cost optimization purposes. After a final robust design has been established, the actual durability and reliability of the design can be determined on the basis of reliability testing using Design for Reliability (DFR) methods.

Basically, SMART can be used both in the initial stages as well as in the more developed stages of the development process.

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1. Introduction

Product requirements grow with customer requirements. Thus, systems become more complex, but the demands for quality, reliability, safety and energy efficiency increase. In order to meet these requirements, the priority must be on the designing of robust products and their Design Parameters (DP) in the Product Development Process (PDP).

Here, a design can be realized by different DPs to meet customer requirements, Customer Attributes (CAs), or Function Requirements (FRs). The target of robust product development is to find the setting levels of DPs, in which the Ideal Functions (IFs) are insensitive to Noise Factors (NFs). This means that the spread of IFs has to be independent of the spread of the DPs (Yang, 2007). Here, for example, a DP of the design B determines a greater spread of the FR as a DP of design A; see Figure 1. In this example, the design B would be preferable for a robust design of the FR.

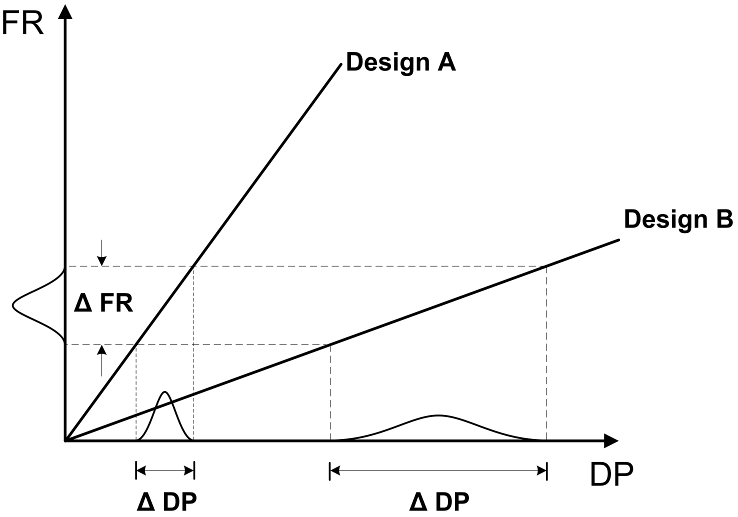


Figure 1. Robust-Design of an FR distribution from two designs (Suh, 2001)

For this purpose, two aspects must be considered. On the one hand, DPs need to be defined so that the possible design is insensitive (robust) to the NFs they are exposed to in practice. Second, whether an optimum of these parameters exists with regard to the product or the CAs must be clarified.

In order to clarify these aspects during early stages of product development, a systematic approach is required. The Systematic Method for Axiomatic Robustness Testing (SMART) is an approach with which robust products can be designed. In this case, SMART is oriented to the established methods of Robust Design methodology (Bergman, 2009) and combines Axiomatic Design (AD) of N. P. Suh [1990] and the Taguchi Method (TM) by G. Taguchi (1949). In addition, SMART applies other methods, such as Design of Experiments (DoE) or tolerance analysis. Those are components of both Design for Six Sigma (DFSS) as well as Design for Reliability (DFR) (Matthew, 2014). Using these methods, SMART may design reliability-centered robust products.

2. Guideline VDI2221 and Robust Design Methods

2.1 Guideline VDI2221

Guideline VDI2221, Verein Deutscher Ingenieure (VDI) [Association of German Engineers], recommends an approach to developing and designing new products. Figure 2 (VDI, 1993)

shows a flow chart for this procedure at the bottom. The four stages describe the chronological sequence which has to be done to design a successful product in its development process.
The four phases of Planning (Phase I), Conceptual Design (Phase II), Embodiment Design (Phase III) and Detailed Design (Phase IV) are of primary importance. These four phases represent the chronology of SMART, as illustrated in Figure 2.

In order to get from one phase to the other, the previous one must be completed. Several iterations within a phase are possible to achieve the desired goal.
The commonly-used design stages in the industry can also be assigned to the respective phases. Therefore, the labels A-, B-, C-, D-Sample and Start-of-Production (SOP) are used. A-Sample represents a conceptual design which can be used as a functional sample and for concept validation. B-Sample is equal to A-Sample. However, it is suitable for first testing in the overall concept and on the test. The mounting dimensions conform to the series. C-Sample is equal to B-Sample, but it safely achieves the specifications (tasks). Its parts consist of standard tools and near-manufacturing process. D-Sample is a design which consists of standard parts for the series and complies with the quality requirements which are statistically validated (Hab, 2013).

At the end of the System Design Phase, which corresponds chronologically to the Conceptual Design, the A-Sample is available. It is prepared to confirm the design concept and is not suited for durability testing. At the beginning of the Parameter Design Phase, which corresponds chronologically to the Embodiment Design, the A-Sample as well the B-Sample are available. The final B-Sample can be created at the end of the Tolerance Design Phase, Detailed Design Phase, which could also be used for durability testing; see Figure 2.

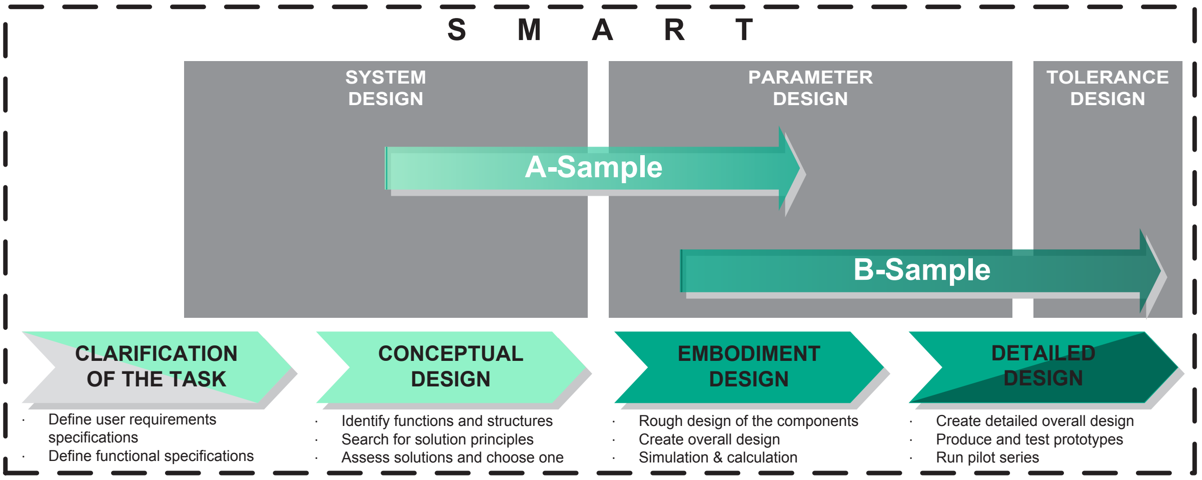
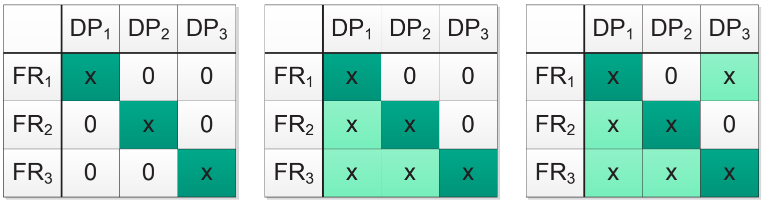


Figure 2. Three phases of Taguchi and SMART and the four phases after Guideline VDI2221 as a chronology

2.2 Taguchi Method

The Taguchi Method (TM) is a method of Robust Design methodology and was developed by G. Taguchi in the 1950s. Originally, the motivation was designing robust processes. Over the years, however, this method gained more and more importance for designing robust products. In his approach, Taguchi describes developing these products according to the three phases of development System Design (SD), Parameter Design (PD) and Tolerance Design (TD) (Fowlkes, 1995). Here, in the SD phase, the concept is developed regarding the product requirements. This phase can be chronologically assigned to the part of the Clarification of the Task phase and the Conceptual Design phase according to Guideline VDI2221; see Figure 2. If the concept or the design is already defined, the DPs can be determined and examined in more detail in the second phase, PD. This phase can be chronologically assigned to the Embodiment Design and partly to the Detailed Design of Guideline VDI2221.



	DP_1	DP_2	DP_3
FR_1	x	0	0
FR_2	0	x	0
FR_3	0	0	x

Uncoupled Design

	DP_1	DP_2	DP_3
FR_1	x	0	0
FR_2	x	x	0
FR_3	x	x	x

Decoupled Design

	DP_1	DP_2	DP_3
FR_1	x	0	x
FR_2	x	x	0
FR_3	x	x	x

Coupled Design

Figure 3. Comparison of the three design matrices according to the AD

Once the design parameters are identified to the extent that an optimum of the setting can be found, this phase is completed by the robustness analysis. Thus, the next step is the final phase, TD. In TD, a compromise must be found between the design tolerances and the design costs which are needed for the manufacturing process of the overall design (Fowlkes, 1995). Here, the design tolerance limits can either be further restricted or, ideally, expanded. Only at the end of the TD phase, when the robust design has been finally determined in terms of cost optimization and action can steps for implementation be recommended.

2.3 Axiomatic Design

AD is a Robust Design method for a structured and goal-oriented structured approach in the research, development and design. It can be classified according to its basic approach in the Design Systematics in VDI2221 to VDI2225 and VDI2206 (Morgenstern, 2009). In general, AD is a tool for managing the complexity of development (Tasi, 2009).

P. Milling (Milling, 1981) describes the complexity with the example of non-linearity whereby the complexity of a system increases as the number of elements and their links as well as their functionality increase. However, it must be noted that in today's developments, the complexity is enforced due to product and cost requirements and thus cannot always be avoided. Therefore, a compromise between these two aspects must be found, with the result that the complexity cannot be avoided. In this case, an Uncoupled Design, see Figure 3, cannot be achieved in most designs.

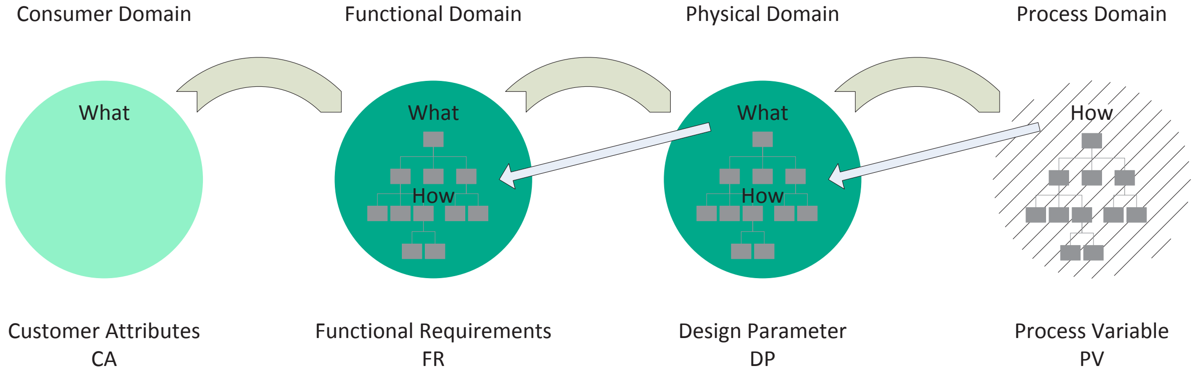


Figure 4. Four domains of the design world (based on Gumus, 2005)

The basis of AD consists of four domains (Consumer, Functional, Physical and Process Domain), see Figure 4. Using the Zig-Zag Method, one can jump back and forth between the domains to create the reconciliation for the subsequent domain. With the question "How can we achieve it?" the step to the next, correct domain is made. The question: "What does one achieve?" is oriented in the opposite direction, i.e. to the left domain; see Figure 4 (Suh, 2001).

Using AD, the relationship between the FRs and the DPs are described. This has the great advantage that a system or design is described at the functional level. For the following link, which describes the interference between the FRs and the DPs, the Design Matrix is selected as the representation of the form; see Figure 3, (Park, 2006).

If, at the beginning, no design or concept, SD phase, exists, a design can be converted to an Uncoupled Design by AD. This means that a feature request is to be implemented only through a DP. This has the distinct advantage that it can be designed independently of the other DPs. If you cannot avoid complexity in the system, these can be identified and described through the Coupled Design. If a design can be described almost in the structure of a Decoupled Design, one attains the information that there is at least one sequence in which the DPs must be implemented to ensure that the functional independence of the FRs involved is guaranteed. AD can be used as a stand-alone method for designing robust products. Due to the identification of complex contexts, AD should also be integrated only as an aid of a functional system analysis in SMART. Distinction must be made as to whether a design has already been in existence or a new design needs to be developed. Thus, AD has to be adjusted in his approach to the respective phase, System Design Phase or Parameter Design Phase, see section 3.

3. Systematic Method for Axiomatic Robustness-Testing (SMART)

SMART is based on the chronological sequence of the PDP of the VDI Guideline 2221 and at the three phases SD, PD and TD according to Taguchi. On the one hand, the systematic product development is guaranteed by the PDP and, on the other hand, it allows the introduction to the product development by the three successive phases of development.

3.1 System Design Phase in SMART

The basis of AD consists of four domains (Consumer, Functional, Physical and Process Domain). The Consumer, the Functional and the Physical Domain are significant for SMART. Defining process variables so that they can be ignored is not relevant for the design of robust products. As a first step, the Functional Requirements (FRs) and their respective Design Parameters (DPs) should be defined from the Customer Requirements (CRs). Immediately after that, the Design Matrix is set up; see Figure 5. The Design Matrix is reviewed by the Independence Axiom to see if it is satisfactory: If that is not the case, a detour over the reorganization of the Design Matrix must be taken, if possible. The reorganization can be done with algorithms by Suh, Lee, Acclaro or Benavides (Benavides, 2011 and Lee, 2006). Only if that effort proves unsuccessful should the affected DPs be redefined or new design levels in the Design Matrix implemented, in order to remove couplings.

If there are several designs, and hence several Design Matrices, they must be compared with each other using the Information Axiom in the interest of finding the best design. This could be implemented by testing or using probability calculations.

The transition into the second phase, the Parameter Design Phase, is made when the information content is satisfactory. Otherwise, a new loop in the System Design must be performed until a satisfactory A-Sample design has been defined.

AD in System Design Phase is used for designing a possible uncomplicated and Decoupled Design, ideally an Uncoupled Design. These DPs and their FRs can still be sufficiently redefined in the design phase with a link.

In the first step, you need information about the specifications that are assigned to the product's FRs is needed, in which the customer demands are listed. Subsequently, the FRs are weighted at the top level. Important and in the further step, all possible DPs can be listed using a morphological approach in order to design the respective FR contribution determined to realize a satisfactory low complexity. With the help of Independence and the Information Axiom, the decision can be made on a satisfactory design thereafter. During the definition of FRs and DPs, the two axioms should be considered by the system designer by default; otherwise more DPs would need to be determined and checked again with the above axioms. The Independence Axiom states that the FRs should be independent. The Information Axiom states that the information content of the design is to be minimized (Suh, 2001).

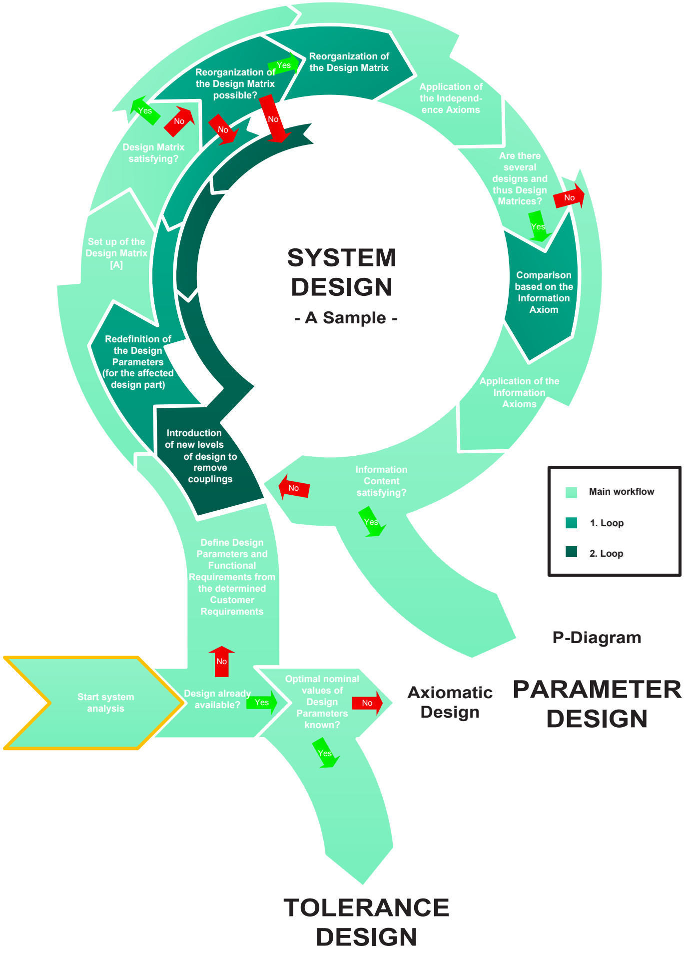


Figure 5. SMART – System Design

Developing more designs or concepts is recommended, so it may be a possible recourse in further product development of an alternative design.

3.2 Parameter Design Phase in SMART

The entry into the Parameter Design Phase of SMART can be made directly, if a concept or a design already exists and the optimal DPs are yet to be found; see Figure 6. In the case of entering directly at a later stage of the product development, AD should be used to reveal any design errors or to improve the given design; see Figure 6.

AD in the Parameter Design Phase is generally used for functional system analysis of the existing design. It is used only if SMART is applied at a later stage of the product development. As in the System Design, the FR-DP pairs can be set up using the Zig-Zag method. Depending on the development stage, the links of the identified FRs and DPs are available only when logically derived and verified using the laws of physics: If a prototype already exists, they are confirmed by DoE. The logical derivation can be expressed by the question: “Has DP been designed so that FR is affected?“

In addition, the Design Matrix is set up and, by using the Independence Axiom, the decision is taken whether the design is satisfactory. If the design is unsatisfactory, any design errors should be detected and improved. Following that, it can be transferred via the P-Diagram in the Taguchi experimental design to determine the robust design.

The mutual connecting hub is the P-Diagram. It illustrates the relationship between the Signal Factors (SFs), the Control Factors (CFs), the Noise Factors (NFs) and the desired Ideal Function (IF) (Fowlkes, 1995). The main advantage of this classification is the structural identification of the DPs according to their characteristics and functional connections. Therefore, AD may serve as a kind of filter. Due to the definition of DPs in AD all CFs can be identified through Customer Requirements or the requirements list. As a consequence, the remaining parameters can be assigned to the SFs and NFs.

In the next step, the TM describes the DoE based on the results of the P-Diagram. As mentioned previously, the P-Diagram represents a holistic consideration of all incoming and outgoing variables of the system. Under certain circumstances, not all factors can be considered for the DoE. Due to the fact that some critical factors are already identified with AD, investigating these should be preferred. The experiments are carried out and the results analyzed. If an optimization and a technical feasibility are both possible, the A-Sample design can be optimized by means of the experimental results. At this chronological step, the B-Sample is defined. The robustness of the B-Sample design is verified by confirmation experiments. However, when there is no prospect of an optimization or technical feasibility of the design, the P-Diagram needs to be examined again. In concrete terms, this means that the P-Diagram should be complemented with new findings from the first loop and possibly unrecognized factors should be added to the new DoE.

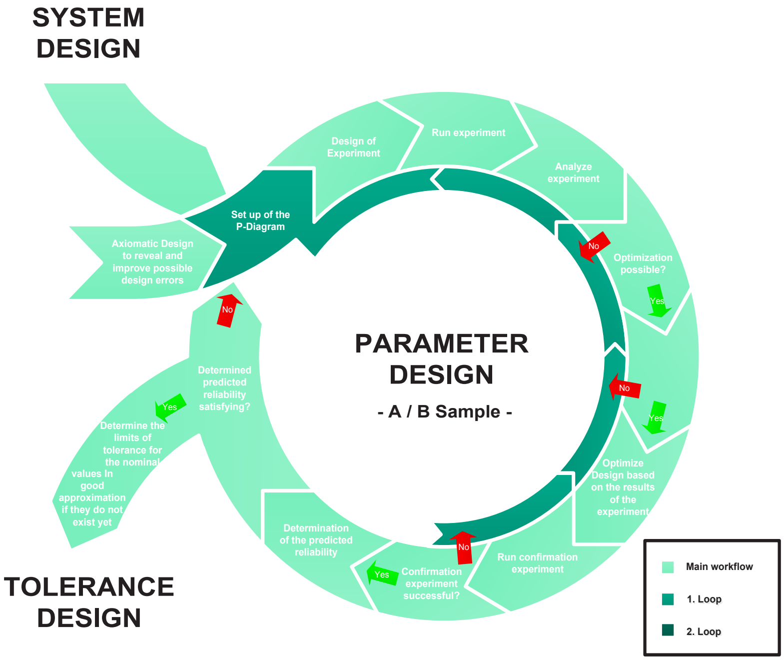


Figure 6. SMART – Parameter Design

The conclusion of the Parameter Design is carried out by one or more confirmation experiments. The way into the last phase, Tolerance Design, is open when the completion of the confirmation experiments is successful. Otherwise, another iteration must be carried out. The confirmation experiments could be carried out either by real or simulative experiments. It should be noted that the simulative experiments must be validated at a later time. At this chronological step, the B-Sample is defined. A predicted reliability determination is also possible after successfully completed confirmation experiments. At this state of the defined design, the reliability can be predicted to random failures and fatigue failures, which are based on simulation models. According to the predicted reliability, a first assumption of the reliability test-strategy can be given.

3.3 Tolerance Design Phase in SMART

The last stage of SMART can be entered either through successful confirmation experiments or directly with the knowledge of an optimal parameter setting, TD, commences. First, however, tolerance limits for the nominal values in good approximation need to be established for the given optimal parameters, if they do not already exist.

At the beginning, the Loss Functions of the design tolerances according to Taguchi should be set up; see Figure 7. Afterwards, the design tolerances which are sensitive to changing performances, should be narrowed. These design tolerances can be both manufacturing tolerances and process tolerances. With regard to the definition of the tolerance limits, a good compromise between narrowing the tolerances and the technical feasibility should be found. What follows is a cost optimization by expanding other tolerances which are not sensitive to changing performances. Steps of action regarding the design of the product can be recommended, if a good compromise between robustness, costs and technical feasibility is found.

After a final robust design has been established, the actual durability or reliability of the design can be determined and the more detailed reliability test-strategy can be provided on this basis.

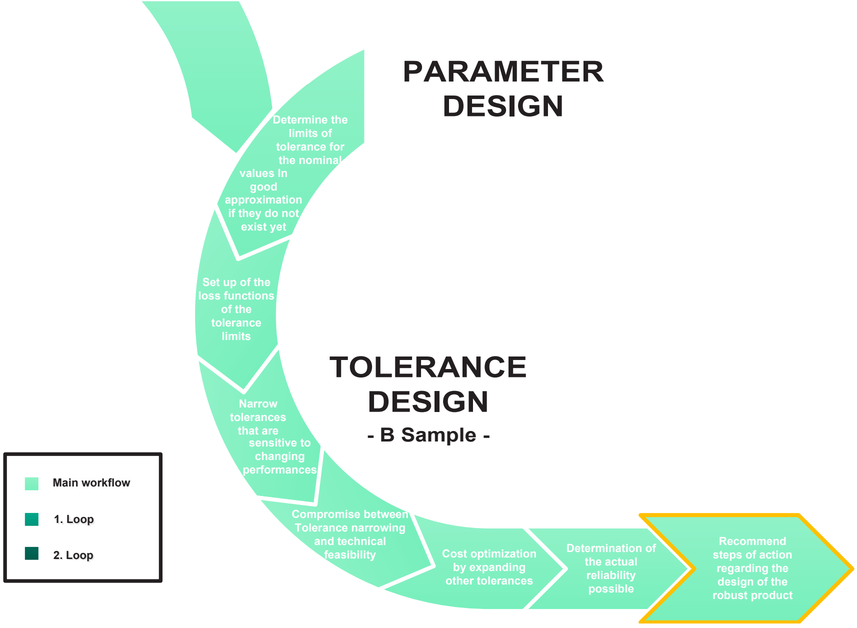


Figure 7. SMART – Tolerance Design

3.4 The holistic method

Figure 8 illustrates the overall layout of SMART and gives a more detailed approach. SMART is illustrated in the shape of a circular roadmap, which will help to improve the comprehensibility of the basic procedure. More detailed views and descriptions of the various phases are presented in the previous subsections.

The starting point of SMART lies in the middle of Figure 8. If there is no design available as SMART begins, the roadmap leads the way into the System Design. In this phase, the circular loop is run iteratively until the desired design is determined.

The transition to the second circular loop, PD, is represented by the P-Diagram according to Taguchi. Additionally, it is also used as an entry into SMART at a later stage of the PDP. The objective of this loop is a robust setting of the DP. If the objective is achieved, the path leads into the last phase of SMART, TD. This stage of development could also be entered directly. The tolerances of the design are optimized in this final stage with respect to the cost aspect.

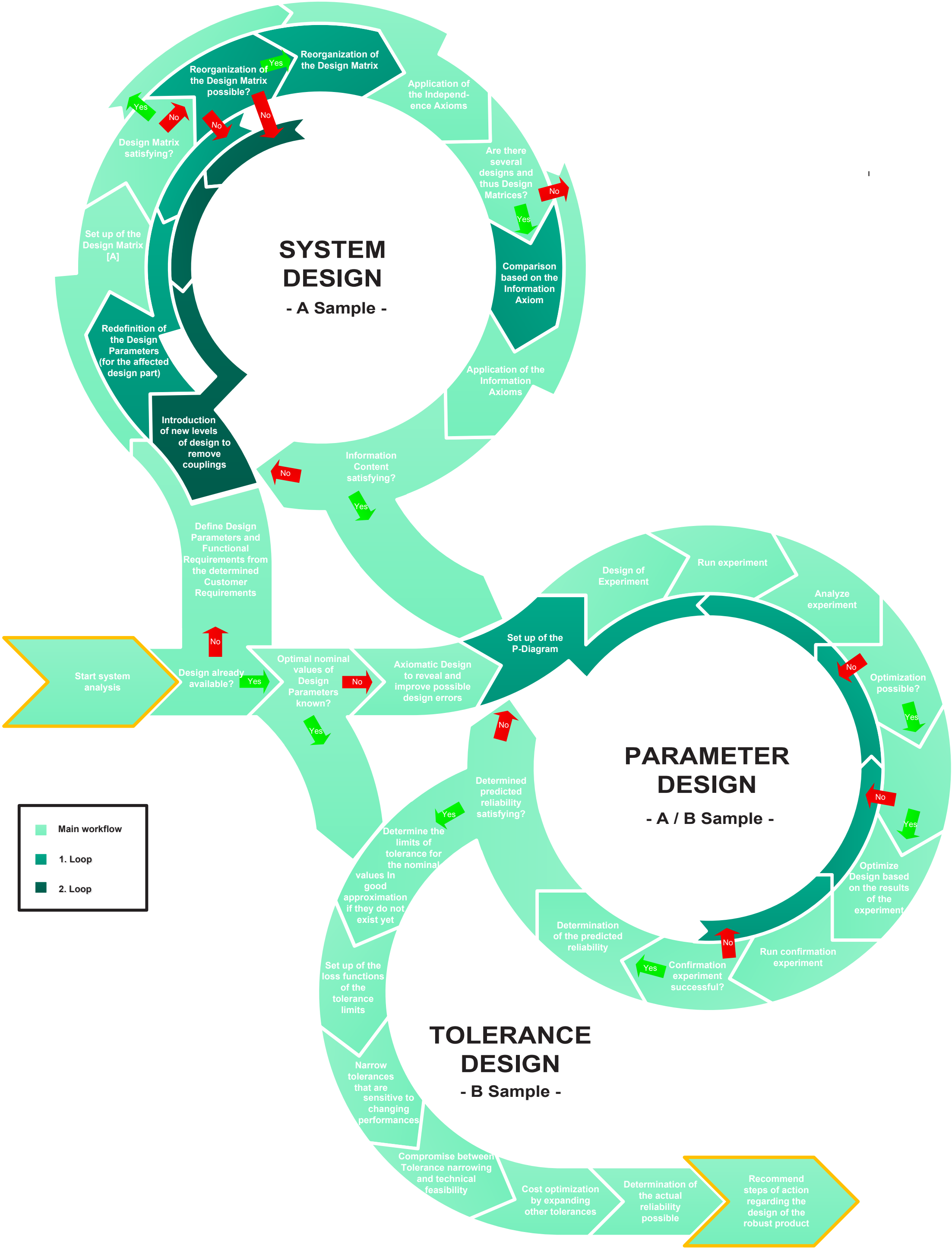


Figure 8. SMART – Overview

More specifically, this means some of the tolerances could either be narrowed or, at best, be widened. Additionally, at the end of the PD, as well as at the end of the TD, the reliability of random failures and fatigue failures can be determined. Furthermore, the reliability test strategy can be provided.

4. Discussion

SMART is based on established methods and procedures according to VDI2221 and the TM. In addition, it integrates the Robust Design method AD. Hence, SMART refers to already successfully applied methods and experiences. Compared to the known and established methods, SMART goes even further by adapting and combining these methods to a holistic approach.
AD was developed by N.P. Suh et al. as a Robust Design method that can be used independently. However, AD is not transparent when applying it to today's products. A complex design cannot be ruled out with regard to the aspects of implementation of Customer Requirements and cost minimization. Additionally, the application of AD to a complex design cannot be implemented without a considerable amount of time. Therefore, AD has to be adjusted according to its approach. Within SMART, AD is used as a system analysis tool. With the aid of AD, a design can be analyzed on a functional level, in order to achieve a Decoupled, ideally an Uncoupled, Design. Furthermore, AD contributes to a better system understanding with respect to its functions and reveals possible design errors if necessary.

Another great advantage of SMART is the TD procedure. The TM specifies ways of implementation, which, however, require a more detailed description. A clear tolerance design procedure has yet to be described sufficiently.

Two conflicts of objectives have been discussed in the approach of SMART. On the one hand, a compromise between the complexity and the given conditions for development must be found. The need for high functional density with low possible design space forces the developer to design complex products. On the other hand, the technical feasibility conflicts with complexity. A robust optimum of the DPs, ready for manufacturing, cannot always be achieved. Thus, the technical feasibility should always be checked in the Parameter Design phase. In addition, the process tolerances that result from the manufacturing must also be considered during the definition of the production tolerances. SMART considers these aspects and leads the user to initial steps in designing robust products in early development stages. No additional effort during the implementation of the product is given in later phases.

If, for example, the DPs are not yet known or cannot be defined, SMART enables the DPs to be defined in early development stages without great financial effort. This frontloading is supported by appropriate simulation models. Since sensitive DPs are already identified by the simulation and the confirmation experiments, real experiments could be planned better and reliability can be predicted more accurately. This allows the testing costs to be reduced as the system behavior regarding resilience can more likely be estimated early in the design process.

5. Conclusions and future research

In this paper, SMART is presented as a holistic and reliability-oriented method for the design of robust products. SMART is based on and combines the two established methods of the VDI2221 guideline as a chronological sequence with the four phases of the PDP and the TM with the three phases of the offline quality control. In addition, SMART arranges the Sample Phases to the respective phases of the chronological sequence of the VDI2221 guideline as well to the three phases of the Taguchi Method. In this way, SMART allows the integration of existing experiences from verified procedures, on the one hand and, on the other, the entry into the respective phase and therefore the entry into the use of SMART.

In addition, AD is adjusted to the given development stage. It has been shown how AD can be applied to achieve the goal of a robust design.

It should be noted that SMART provides a way to find not only an optimized robust design but also a compromise in terms of costs and technical feasibility (manufacturing), which will be discussed as well.
SMART is applied to a technical design and has been situated in the PD phase so far, which allows all the described steps to be successfully confirmed. In the next step, the TD phase is applied and further developed to describe the previously mentioned compromise in detail.
Finally, the method should be verified in its overall approach based on a technical example.

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