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ROBUST TOLERANCE DESIGN OF SYSTEMS WITH VARYING AMBIENT TEMPERATURE INFLUENCE DUE TO WORLDWIDE MANUFACTURING AND OPERATION

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1. Introduction

In today's industrial environment products must be developed and brought to market in short time. To shorten the time-to-market between the product idea and the start-of-production various methods were developed over the last decades, which are applied during product development (e.g. concurrent engineering). However, the product developer still has to face additional challenges in modern product development [Liu and Boyle 2009]. In this context, an extended relevance and discussion on quality topics and in particular, Robust Design Methods (RDM), both in industry and research, can be found in recent years [Gremyr et al. 2003], [Liu and Boyle 2009], [Eifler et al. 2013]. These RDMs (which can be principles, tools, methods, metrics etc.) are used to analyze a product in order to reduce the sensitivity of its design parameters towards variation [Eifler et al. 2013].
However, deviations of parts are inherently inevitable due to "axiom of manufacturing imprecision" [Zhang et al. 2011]. Consequently, the product developer has to define appropriate tolerances to limit these dimensional and geometrical deviations and thus, to ensure a certain quality of the entire product [Wartzack et al. 2011]. Therefore, statistical tolerance analyses are widely used in engineering design to quantify the effects of appearing deviations on functional key characteristics (FKCs) of a product [Chase and Parkinson 1991], [Jayaprakash et al. 2012], [Tsai and Kuo 2012], [Walter et al. 2013]. Tolerance analyses lead to significant cost reductions, as only required tolerance ranges may be manufactured [Söderberg et al. 2006]. Unnecessarily narrow tolerance ranges, which lead to high production costs can be avoided or significantly reduced.

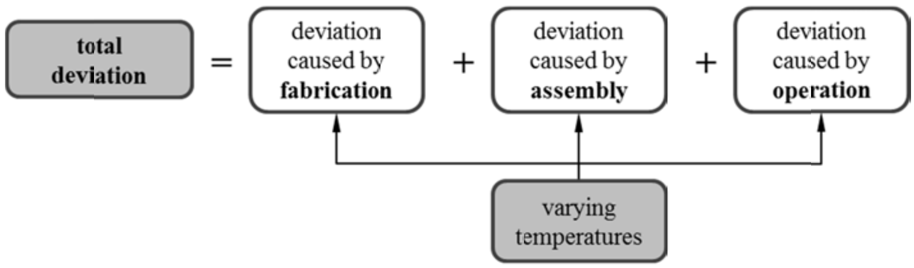

Figure 1. Sum of deviations at different stages of the product development

However, the analysis of only dimensional and geometrical tolerances is not sufficient to evaluate functionality and assemblability of a system and thus, to achieve a robust design. Other aspects, such as deformation, thermal expansion, wear, etc. need to be integrated in tolerance analysis [Chase and

Parkinson 1991], [Scholz 1995]. However, existing approaches only consider the impact of these additional effects.

So the authors claim that a holistic robust tolerance design essentially requires the consideration of both the impact as well as the cause of these deviations. These causes can be both technical (such as forces, friction) and non-technical (the company's choice on the place of production, quality philosophy, qualification of workers, etc.). This is even the more serious, since traditionally product developers hardly take into account non-technical causes during product development and tolerance analyses, particularly.

In this paper the effects of dimensional and geometrical deviations as well as thermal expansions of parts (Figure 1) are analyzed for a simple demonstrator system, which should be manufactured and used at several locations places (with different climate conditions) around the world. Therefore, the current state of the art concerning tolerance analysis taking into account thermal strains is discussed in section 2. The demonstrator system as well as the arising "tolerance design"-challenge are presented in section 3. Section 4 details the statistical tolerance analyses of the demonstrator system both without the consideration of thermal strains (section 4.1) and with the consideration of thermal strains (section 4.2). The results clearly expose, that a robust design (i.e. no problems during manufacturing and use of the system will occur at all considered locations) of the system can only be achieved by considering the cause of the varying thermal expansions, the significantly varying temperature and climate conditions all around the world. Hence, based on the gained results of the statistical tolerance analysis, the tolerances will be re-designed to compensate the different thermal expansions of the system's components and thus, a "worldwide robust tolerance design" is achieved (section 5). The paper closes with a short summary and an outlook on future research activities (section 6).

2. State of the art

The aim of tolerance analysis is to study the accumulation of variations on a geometric attribute of interest [Shah et al. 2007]. Tolerance analysis can be roughly divided into four steps.

First, the relevant Functional Key Characteristic (FKC) has to be selected from the part or assembly to be investigated [Walter et al. 2013]. The selection of the relevant FKC usually happens due to assembly requirements [Shah et al. 2007] or to ensure the latter safe operation of the product [Walter et al. 2011]. The FKC is for example a gap, which is absolutely necessary for assembly. Subsequently, the equation for the FKC must be developed. Thereby, the FKC is the last needed dimension to close a specified loop of dimensional values [Stuppy et al. 2010]. For a one-dimensional problem this leads to relatively simple addition and subtraction of dimensions [Chase and Parkinson 1991]. Third, the FKC is calculated by inserting values for each dimensional value. Thereby, Worst-Case tolerance analysis is a common method where only the two different most extreme possibilities are investigated. The results are the maximum and minimum FKC (i.e. the mentioned gap) [Nigam and Turner 1995]. A more accurate way is to use statistical tolerance analysis with variance-based Monte-Carlo Sampling. To ensure statistical reliability the statistical tolerance analysis calculates several different assemblies with varying deviations for each value. At least 100,000 combinations should be evaluated to gain proper results [Chase and Parkinson 1991]. Forth, the obtained results of the FKC are displayed, examined and interpreted [Stuppy et al. 2010].

According to [Jeang et al. 2002] temperature impact is one of the main causes of product failure. Therefore, thermal strains should be considered in tolerance analysis [Scholz 1995], [Huang 1996]. Recently, the influence of temperature on dimensional values is integrated in tolerance analysis [Jeang et al. 2002], [Laurent et al. 2010].

3. Problem Description

3.1 Demonstrator System

The demonstrator is a bolted connection of three plates (materials: aluminium and polymer) with a bolt (steel), a washer (steel) and a slotted spring pin (Figure 2). Due to manufacturing imprecision the dimensions M_1 to M_6 of these parts are limited by certain tolerance ranges (detailed in Figure 2). The relevant FKC is the distance between the slotted spring pin and the washer. This gap is as relevant for operation as it is for assemblability. To limit the mobility between the three plates and thus, to ensure a sufficient accuracy of the system's geometry, the clearance must be limited. On the contrary, a certain clearance must be given to ensure the assemblability of the bolt connection.

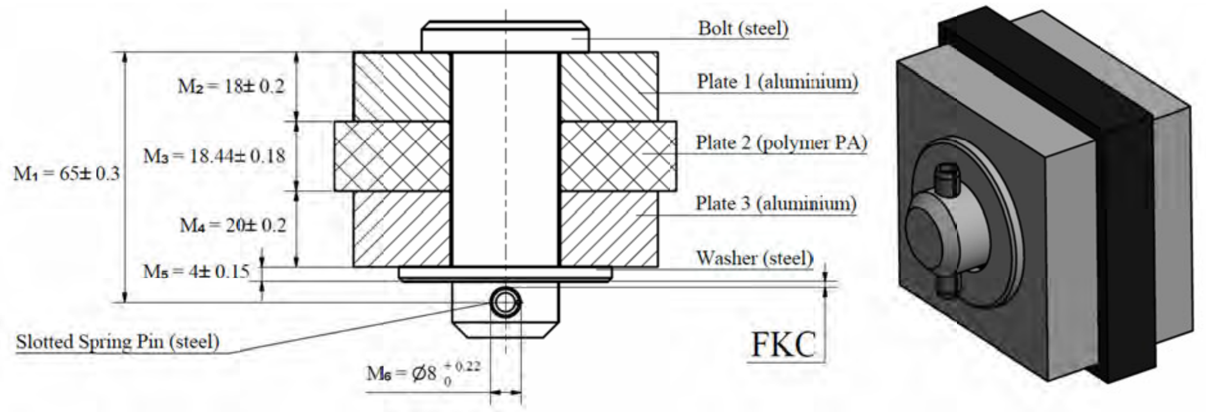

Figure 2. Bolt connection of three plates with corresponding tolerance ranges

3.2 Arising Challenge: Worldwide manufacturing and use of the bolt connection

The authors assume the following scenario: Due to a globally distributed production and distribution of many companies, the bolt connection should be manufactured as well as distributed and thus, used in different locations around the world. However, these locations usually differ in climate conditions, such as significantly varying temperatures.

Nevertheless, the company aims to define a robust tolerance design, which can be manufactured as well as operated in all considered locations, despite the differing thermal expansion of the parts due to the varying temperatures. According to the given requirements of the company, the FKC of the bolt connection must be kept within the range [0 mm; 1 mm] to ensure assemblability and failure-free operation. Figure 3 details the two worst-case and a regular constellation of the FKC. Hence, a statistical tolerance analysis has to be established, which both considers thermal strains and their cause – the varying temperatures all around the world.

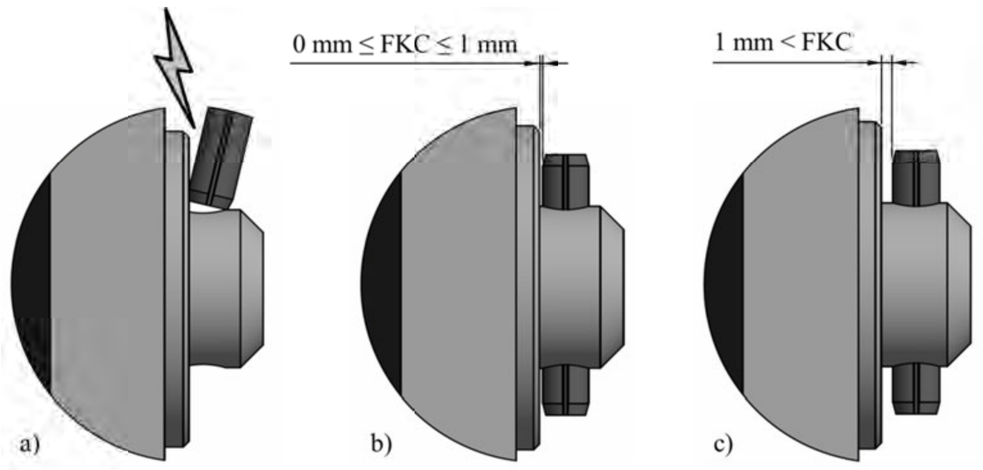

Figure 3. a) negative gap (FKC < 0mm), b) normal gap, c) too large gap (FKC > 1mm)

4. Tolerance analysis of the bolt connection

In order to illustrate the effect of thermal strains on the results of a statistical tolerance analysis, two tolerance analyses of the bolt connection are performed hereafter: without (section 4.1) as well as with the consideration of thermal strains (section 4.2).

4.1 Worst-Case and statistical tolerance analysis (without temperature strains)

According to the tolerance analysis methodology (as detailed in section 2), the FKC is defined and a mathematical relation between this FKC and the appearing deviations M_1 to M_6 must be established. Therefore, a closed one-dimensional vector-chain is used. The resulting relation is:

$$FKC = M_1 - M_2 - M_3 - M_4 - M_5 - \frac{M_6}{2} \quad (1)$$

Thereafter, the FKC can be determined for a large number of virtual bolt connections – the so-called samples. These samples just differ in their parameters, which underlie random deviations and are limited by tolerances. This investigation can be done either by considering only the "worst-case tolerance constellations" or statistically. The two worst-cases for the FKC (minimum and maximum clearance) are determined using the following equations:

$$FKC_{min} = M_{1min} - M_{2max} - M_{3max} - M_{4max} - M_{5max} - \frac{M_{6max}}{2} \quad (2)$$

$$FKC_{max} = M_{1max} - M_{2min} - M_{3min} - M_{4min} - M_{5min} - \frac{M_{6min}}{2} \quad (3)$$

The statistical consideration requires the generation of a large number of virtual bolt connections (samples) and the determination of the FKC for each sample. In this simple case, this analysis was set up with 10 million samples to ensure statistical reliability. Finally, the resulting probability distribution of the FKC is determined and visualized (Figure 4). It also illustrates the worst-case-constellations of the FKC (FKC_{min} = -0.58 mm and FKC_{max} = 1.59 mm), which exceed the given lower limit (FKC = 0 mm) and upper limit (FKC = 1 mm) of the gap. However, the statistical results detail that even more than ±3σ (= 99.73 %) of all produced bolt connections will be within the given limits. Consequently, no re-design of the tolerances would be required in this scenario.

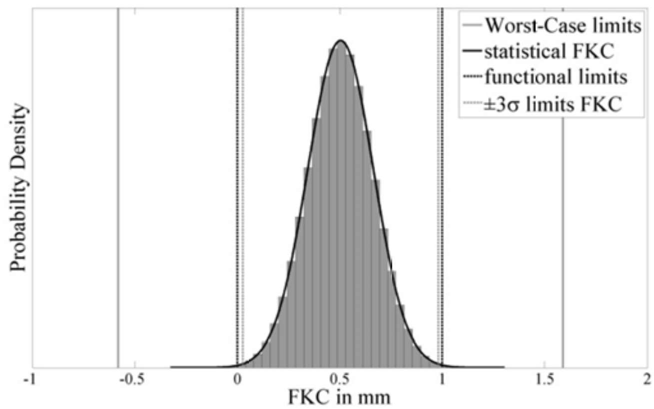

Figure 4. Probability distribution of FKC of the bolt connection (at 20 °C)

4.2 Statistical tolerance analysis (with temperature strains)

As a result of varying ambient temperatures, different materials expand or contract unevenly. This dependency is described by the following equation:

$$L(T) = L_0 \cdot (1 + \alpha \cdot \Delta T) \quad (4)$$

Whereas L_0 is the part's initial length, α is the material-dependent thermal expansion coefficient and ΔT is the difference between initial temperature (corresponding to L_0) and the actual temperature T [Gooch 2007]. Consequently, a variation of the temperature from its reference (usually 20 °C in metrology) will result in a systematic deterministic deviation of the part's dimensions. Further, this systematic deviation causes a mean shift of the resulting probability distribution, which is direct proportional to the temperature difference. Hence, each dimension M_1 to M_6 in equation (1) is modified according to equation (4) and ten statistical tolerance analyses are performed for different ambient temperatures *T*. The resulting probability distributions of the FKC of the bolt connection are shown in Figure 5 for ambient temperatures between -40 °C and +50 °C. These results expose, that a large temperature difference corresponds to an increasing mean shift of the FKC's probability distribution.

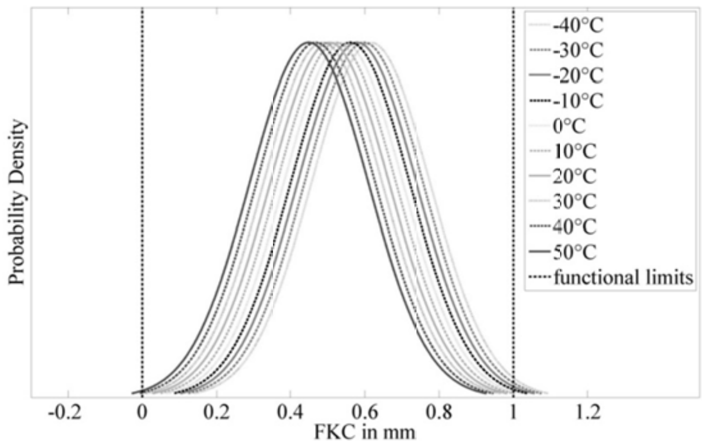

Figure 5. Statistical FKC of bolt connection at certain temperatures between -40 °C and 50 °C

5. Development of a Robust Tolerance Design

In order to develop a robust tolerance design, first the initial tolerance design must be analyzed for manufacturing and use at the relevant locations and thus, the corresponding ambient temperatures. Figure 6 shows the company's choice of six locations for manufacturing and use of the bolt connection, while the associated monthly temperature gradients are listed in Table 1.

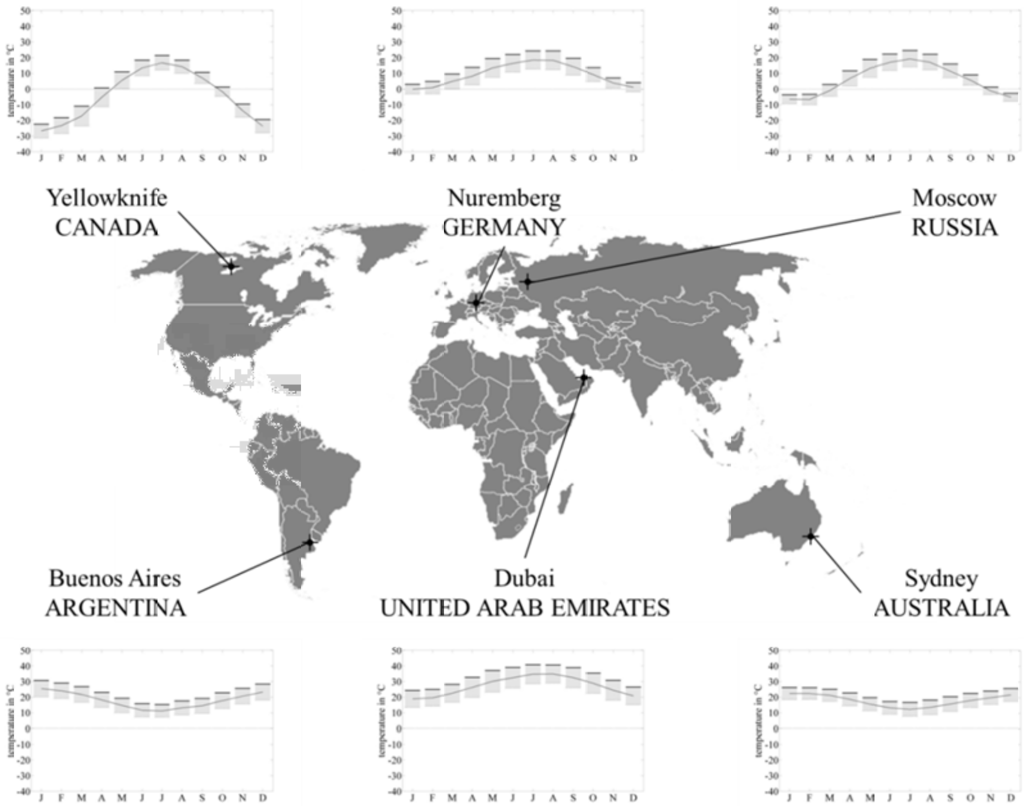

Figure 6. Map with temperature curves at different locations on earth

Table 1. Temperatures at different locations

Months of the year with minimum and maximum average temperature in °C											
Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
Yellowknife, CANADA (62° 27′ N, 114° 24′ W)											
-22.7	-18.6	-11.2	0.4	10.6	18.2	21.1	18.2	10.3	1.0	-9.9	-19.7
-30.9	-28.1	-23.3	-11.0	0.5	8.7	12.4	10.3	3.7	-4.4	-17.7	-27.7
Nuremberg, GERMANY (49° 27′ N, 11° 5′ O)											
2.7	4.5	9.3	13.5	19.1	21.7	24.0	24.0	19.3	13.4	6.8	3.8
-2.9	-2.8	0.4	2.9	7.7	11.0	13.0	12.6	9.1	5.0	0.9	-1.5
Moscow, RUSSIA (55° 45′ N, 37° 37′ O)											
-4.0	-3.7	2.6	11.3	18.6	22.0	24.3	21.9	15.7	8.7	0.9	-3.0
-9.1	-9.8	-4.4	2.2	7.7	12.1	14.4	12.5	7.4	2.7	-3.3	7.6
Sydney, AUSTRALIA (33° 51′ S, 151° 12′ O)											
25.9	25.8	24.7	22.4	19.4	16.9	16.3	17.8	20.0	22.1	23.6	25.2
18.7	18.8	17.6	14.7	11.5	9.3	8.0	9.0	11.1	13.6	15.6	17.5
Dubai, UNITED ARAB EMIRATES (25° 16′ N, 55° 18′ O)											
24.0	24.6	27.9	32.4	36.8	38.8	40.6	40.4	38.7	35.1	30.5	26.2
13.7	14.5	17.0	20.1	23.5	26.1	28.9	29.3	26.3	22.7	18.3	15.4
Buenos Aires, ARGENTINA (35° S, 58° W)											
30.4	28.7	26.4	22.7	19.0	15.6	14.9	17.3	18.9	22.5	25.3	28.1
20.4	19.4	17.0	13.7	10.3	7.6	7.4	8.9	9.9	13.0	15.9	18.4

The temperature information originates from databases and public authorities: *climate.weather.gc.ca*, *wetterkontor.de*, *pogodaiklimat.ru*, *worldweather.wmo.int* and *bom.gov.au*. Table 1 clarifies that at a single location temperature variations of up to 52 °C (Yellowknife) may be expected. A comparison of Yellowknife and Dubai even leads to a temperature gradient of 71.9 °C. Consequently, temperature gradients are of crucial importance for worldwide scrap-free assembly and trouble-free use.

5.1 Statistical tolerance analysis for the different locations

The FKC is determined using a tolerance analysis based on the previously derived relation of the FKC (section 4.2) for each location's individual ambient temperature. Figures 7 and 8 detail the results.

Figure 7. Fulfilment of quality requirements in manufacture and use at the six locations

The results in Figure 8 prove that thermal strains have a significant influence on the scrap rate of the bolt connection during manufacture and use. Then again, the thermal strains depend on the expansion coefficients of used materials (in this case: steel, aluminium and the polymer PA) as well as on the actual ambient temperature. The more the actual temperature differs from 20 °C, the more the upper limit of the FKC is exceeded.

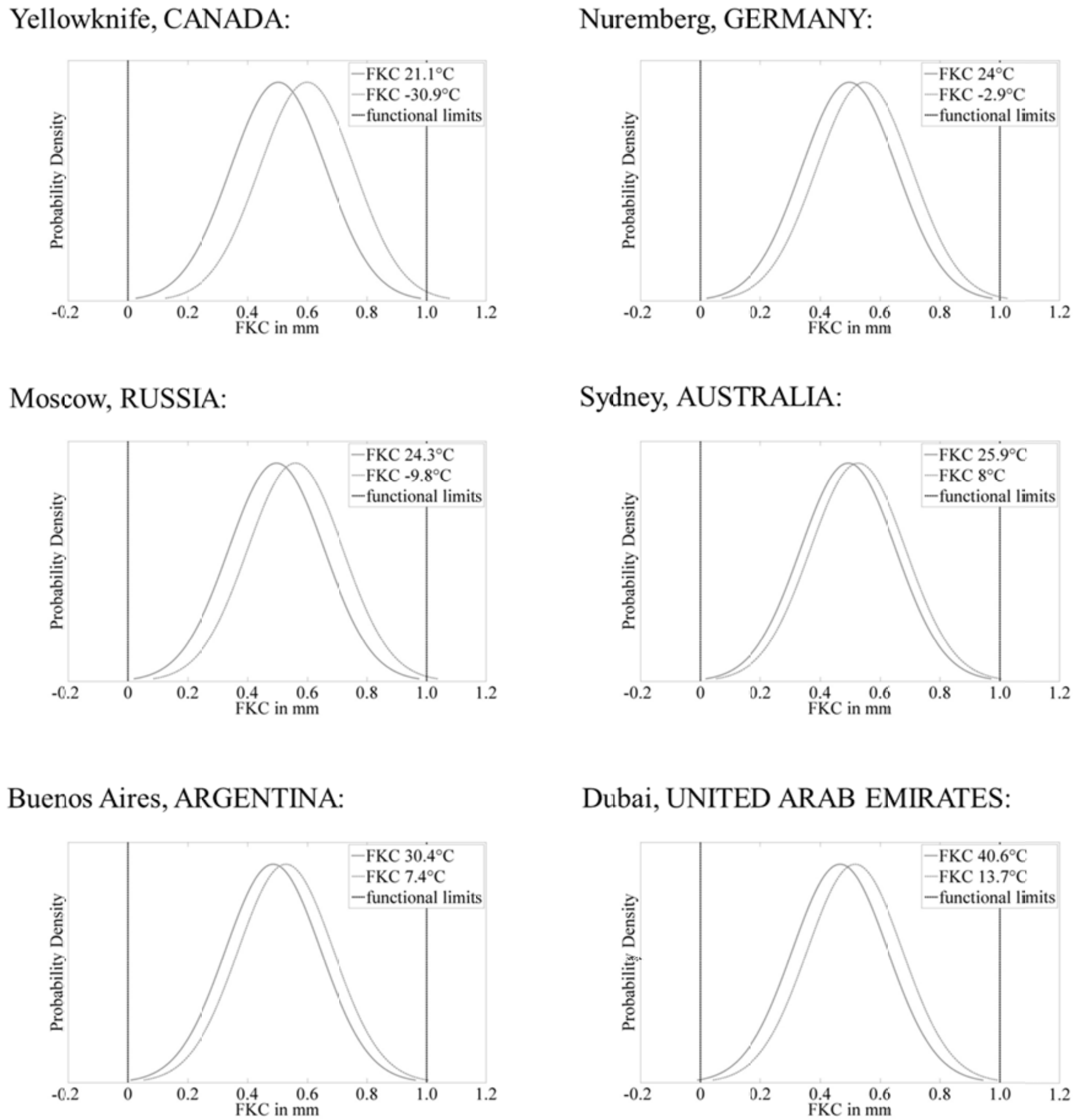

Figure 8. Map with statistical FKC at different locations on earth

The resulting shift of the mean value of the FKC causes a violation of the preselected functional limits of 0 mm and 1 mm at Yellowknife, Nuremberg, Moscow and Dubai. Based on these results a re-design of the tolerances is required.

5.2 Modification of the tolerance design

According to [Jeang et al. 2002], there are three different methods to compensate thermal influences on a certain quality variation:

- Elimination of the thermal effects
- Integration of features for thermal strain compensation in the product
- Construction of a system, that is less sensitive against temperature influences

However, the first two options are very costly, complicated and inefficient to implement [Jeang et al. 2002]. Consequently, a less sensitive product should be achieved. In this case, the robustness of the bolt connection is understood as: The rejection rate of the product's manufacturing and operation becomes less sensitive towards variations. According to the authors' claim in the introduction, this can only be achieved by taking into account the causes for appearing variations, which are in this case the varying ambient temperatures of the six locations, in particular.

The results in Figure 8 evidently show, that for the globally spread manufacturing and operation of the bolt connection, a tolerance adjustment is required. For less complex products (and processes such as manufacturing, assembly, metrology etc.) this re-design can be done manually. However, for more complex assemblies, with respect to production costs, optimization algorithms are highly recommended. For this purpose a mathematical optimization problem can be defined:

$$\max\{tolerance\ range_j\} \quad for\ j = 1 \dots 6 \tag{5}$$

$$subject\ to: FKC_i \in [0\text{mm}\ ;1\text{mm}]\ at\ each\ location\ i \tag{6}$$

In the considered less complex case study of the bolt connection the tolerances can be adjusted manually and optimized towards a robust tolerance design iteratively. The product developer usually can modify: a) the parameters' tolerance ranges and b) the nominal values of these parameters (the so-called mean).

An obvious improvement of the current situation of the "bolt connection manufacturing problem" can be achieved by means of universal narrowing the parameters' tolerance ranges. However, this goes hand in hand with significantly increasing manufacturing costs and may cause production problems due to higher quality requirements. Consequently, the modification of the mean values of parameters must be taken into account. In this case, the probability distributions mainly exceed the upper specification limit of the gap of FKC_{max} = 1 mm (Figure 9a). This means, that in these cases the gap is too large and thus, e. g. the bolt is too long (dimension M_1). So, a mean shift of -0.04 mm of M_1 is applied to centre the probability distributions towards the mean of 0.5 mm of the FKC's upper and lower specification limits. Unfortunately, there still remain some rejects both at the lower and the upper specification limit. Finally, the remaining rejects will be avoided by slightly narrowed tolerance ranges of all dimensions M_1 to M_6. M_5 remains unchanged, as washers are highly standardized parts.

Figure 9b shows the final, ±3σ-conform probability distribution plots for all six locations. The previous as well as the re-designed tolerance specification of the bolt connection are detailed in Table 2.

Table 2. Tolerance specification (before and after)

Name	Dimension	Tolerance range before optimization	Tolerance range after optimization
Bolt	M_1	$65^{+0.3}_{-0.3}$	$64.96^{+0.26}_{-0.2}$
Plate 1	M_2	$18^{+0.2}_{-0.2}$	$18^{+0.17}_{-0.17}$
Plate 2	M_3	$18.44^{+0.18}_{-0.18}$	$18.44^{+0.16}_{-0.16}$
Plate 3	M_4	$20^{+0.2}_{-0.2}$	$20^{+0.17}_{-0.17}$
Washer	M_5	$4^{+0.15}_{-0.15}$	
Bolt's hole	M_6	$Ø8^{+0.22}_{-0}$	$Ø8^{+0.19}_{-0}$

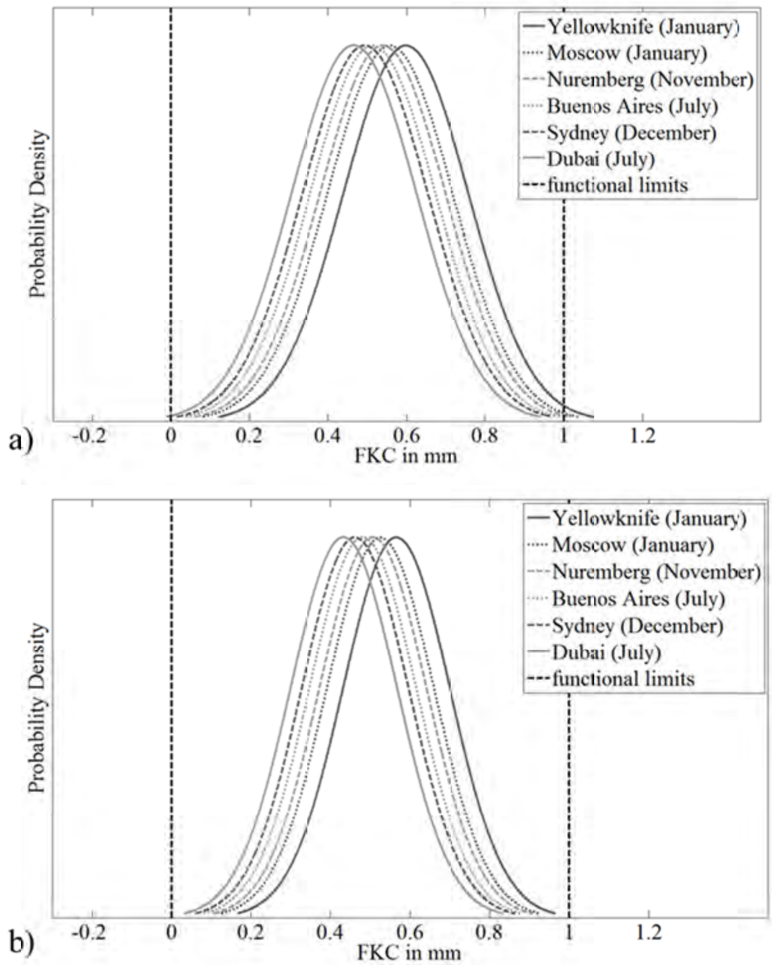

Figure 9. Statistical FKC (temperature depending) before (above) and after tolerance optimization

Finally, a Robust Tolerance Design is achieved. However, in this step, the temperature variation was only considered worst-case for a certain location with the highest and lowest annual temperature. Future investigations aim to consider the statistical probability distribution of the temperatures during a year in more complex assemblies with 3D-vector chains and 3D-thermal expansion.

6. Summary and conclusion

This paper discussed the relevance of a more holistic view on tolerance design in engineering design. Even though thermal strains should be considered, they receive little attention for research. Moreover it is as relevant to consider temperature deviations as to investigate the reasons for their existence (e.g. worldwide ambient temperatures). To illustrate this, a case study of a bolt connection with assembly and usage at different globally distributed locations was performed. It can be seen that already at one single location the annually differing temperatures have a large impact on assemblability and usage. The significance of the temperature effect even grows as different locations on earth are included.

The consideration of thermal strains in tolerance analysis is essential and can be taken into account, relatively easy, by the product developer. Beyond that, the product developer should keep in mind, that tolerance design can link several disciplines, such as classical engineering, quality management, manufacturing planning, procurement and process control. Consequently, the benefit of statistical tolerance analyses can be enormous – in particular abroad of the special field laboratories – if it is used or even discussed on a multidisciplinary wider stage.

In conclusion, a holistic view on tolerance analysis can lead to optimal tolerance ranges considering different effects, such as manufacturing, assembly and use.

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