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Original Article

ACTIVE DIMENSIONAL CONTROL OF LARGE-SCALED STEEL STRUCTURES

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ABSTRACT
The article discusses the issues of dimensional control in the construction process of large-scaled steel structures. The main focus is on the analysis of manufacturing tolerances. The article presents the procedure of tolerance analysis usage in process of design and manufacturing of large-scaled steel structures. The proposed solution could significantly improve the manufacturing process.

Keywords: large-scaled steel structures, dimensional quality, tolerances, statistical dimensional control, measurements, shipbuilding.

INTRODUCTION

The ever-increasing requirements for dimensional quality of prefabricated components force measurement processes to resign from passive dimensional control (which finds the state with essentially no possibility of changing) in favour of active control, having influence on the formation of the desired features of prefabricated components.

The use of active control allows, among others, carrying out the analysis of the impact of measurement error (estimated by standard deviation) on an ongoing basis on the dimensional quality of prefabricated structure components. The concept of such control is shown schematically in Figure 1.

The basic idea of the solution presented in the figure above is the systematic complementation of tolerance equation of a given chain with actual dimensions (obtained through the measurement process) and the analysis of the impact of the results obtained on the final (dependent) dimension of a given dimensional chain.

In order to present the concept further in this document its basic components will be discussed: tolerance equations with dimensional chains issues and the process of analysis.

TOLERANCE EQUATIONS

In assembly process of each type of structure, also large-sized, some dimensions depend on others. These are called dependent dimensions. The literature also specifies the terms: result dimen-

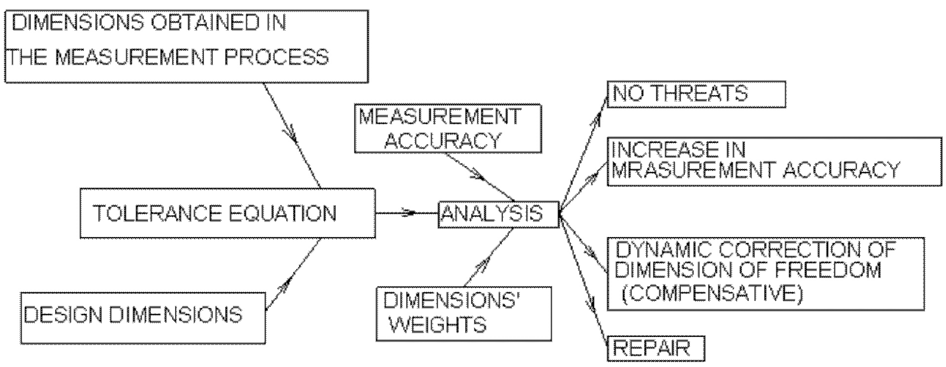

Fig. 1. The concept of active dimensional control

sions, closed dimesions and total dimensions. The interrelation between dimensions can be described analytically using the following equation:

$$Z = F(X_1, X_2, ..., X_n) \quad (1)$$

where: Z – dependent tolerated dimension,
X_i – independent i-th tolerated dimension, $i = 1, ..., n$.

Function (1) can be interpreted as:
- the relationship between actual dimensions,
- the relationship between random dimensions of known probability distributions.

Thus, when calculating tolerated dimensions the following methods may be used:
- deterministic,
- stochastic.

Tolerance equation based on deterministic model

Among deterministic methods of calculating tolerated dimensions there are three different methods:
- differential calculus method,
- arithmetic method (also called min-max method, border case method, worst case method) ,
- logarithmic method.

Differential calculus method is based on the study of dimensional function (1) increase. It is a general method, used in all arithmetic operations. It is particularly effective for cases of non-linear form of the function (1). The equation for dependent dimension tolerance developed on the basis of differential calculus method takes the following form:

$$T_Z = \sum_{i=1}^{n} |Q_i| \cdot T_{X_i} \quad (2)$$

where: T_Z – dependent dimension tolerance,
$Q_i = \dfrac{\partial F}{\partial X_i}$ – influence coefficient for the i-th independent dimension,
F – dimensional function,
T_{X_i} – i-th independent dimension tolerance.

Coefficient Q_i determines the impact of independent dimension X_i changes on dependent dimension Z changes. Values of Q_i coefficients are determined based on nominal dimensions.

In order to determine the upper and lower deviation of dimension Z it is necessary to group all independent dimensions, separating them into two groups:
- increasing dimensions marked with index from 1 to k,
- decreasing dimensions marked with index from $k + 1$ to n.

Using the above division the upper and lower deviation can be calculated from the following equations:

$$z2 = \sum_{i=1}^{k} Q_i \cdot x2_i + \sum_{i=k+1}^{n} Q_i \cdot x1_i$$
$$z1 = \sum_{i=1}^{k} Q_i \cdot x1_i + \sum_{i=k+1}^{n} Q_i \cdot x2_i \quad (3)$$

where: $z2$ – upper deviation of dependent dimension Z,
$z1$ – lower deviation of dependent dimension Z,
$x2_i$ – upper deviation of i-th independent dimension X_i,
$x1_i$ – lower deviation of i-th independent dimension X_i.

The arithmetic method is based on the analysis of extreme values achieved by simple arithmetic operations (addition, subtraction) on the tolerated dimensions. However, in case of multiplication, division and roots, logarithmic method is used. Formulas for selected operations on tolerated dimensions are given in Table 1.

A detailed description of the above methods of tolerance calculations along with calculation examples can be found among others in [2, 3, 4].

Tolerance equations based on stochastic model

Deterministic rules for determining tolerance equations are based on the following statement: *"threshold values of independent component dimensions cause threshold values of dependent dimensions"* [2]. It is obvious that actual independent dimensions generated in manufacturing process may be considered as random variables with specified probability distributions. Given the nature of the most common statistical distributions, it can be easily seen that the probability of occurrence of dimension value near their threshold value is rather low. It can be concluded that the tolerance calculations using deterministic methods do not meet the practice and significantly reduce required tolerances of components.

Table 1. Operations on tolerated dimensions

Operation	Tolerance function	No
$A_{a1}^{a2}+B_{b1}^{b2}=(A+B)_{a1+b1}^{a2+b2}$	$T_{A+B}=T_A+T_B$	(4)
$A_{a1}^{a2}-B_{b1}^{b2}=(A-B)_{a1-b2}^{a2-b1}$	$T_{A-B}=T_A-T_B$	(5)
$A_{a1}^{a2}\times B_{b1}^{b2}=(A\times B)_{A\times b1+B\times a1}^{A\times b2+B\times a2}$	$T_{A\times B}=A\times T_B+B\times T_A$	(6)
$k\times A_{a1}^{a2}=(k\times A)_{k\times a1}^{k\times a2}$	$T_{k\times A}=k\times T_A$	(7)
$\left(A_{a1}^{a2}\right)^2=(A^2)_{2\times A\times a1}^{2\times A\times a2}$	$T_{A^2}=2\times A\times T_A$	(8)
$\sqrt{A_{a1}^{a2}}=(\sqrt{A})_{\frac{a1}{2\times\sqrt{A}}}^{\frac{a2}{2\times\sqrt{A}}}$	$T_{\sqrt{A}}=\frac{1}{2\times\sqrt{A}}\times T_A$	(9)

Much more realistic results can be obtained by using statistical methods for the tolerated dimension calculations. In addition, a major advantage of these methods is achievement of much larger fields of independent dimensions tolerances. The paper [4] derived the formula for the coefficient showing the increase value of tolerance of components determined using stochastic methods in relation to deterministic methods:

$$G=\frac{\sqrt{m-1}}{k_{œ}} \tag{10}$$

where: m – number of chain components,
$k_{śr}$ – average value of variation coefficients of dimension chain components.

Variation coefficient is expressed by the following formula:

$$k_j=\frac{6\cdot\sigma_j}{T_J} \tag{11}$$

where: σ_j – standard deviation of the j-th dimension distribution,
T_J – tolerance of j-th dimension.

Tolerance increase coefficient G should be greater than one ($G > 1$) for the calculation of tolerance based on stochastic model was justified.

In statistical method of determining the tolerance, independent tolerated dimensions are considered to be independent random variables of any probability distributions, which are characterized by corresponding standard deviations:

$$\sigma_Z=\sqrt{\sum_{i=1}^{n}Q_i^2\cdot\sigma_i^2} \tag{12}$$

where: Q_i – influence coefficient for i-th independent dimention,
σ_i – standard deviation characterizing i-th independent dimension.

Assuming that the variation of all dimensions can be characterized by a normal symmetrical distribution, tolerance function developed on basis of (12) takes the following form:

$$T_Z=\lambda\cdot\sqrt{\sum_{i=1}^{n}Q_i^2\cdot T_{X_i}^2} \tag{13}$$

where: λ – correction coefficient, $\lambda = 1$ for normal distribution.

In the case where distributions of certain considered dimensions differ from the symmetric normal distribution, the value of correction coefficient should be greater than unity. In the literature, the proposed values range from 1.4 to 1.8.

In situation where independent dimensions have different known probability distributions, for determining tolerance equations the relation taking into account variation coefficients of particular dimensions should be used:

$$T_Z=\frac{1}{k_Z}\sqrt{\sum_{i=1}^{n}\left(\frac{\partial Z}{\partial X_i}\right)^2\cdot k_{X_i}^2\cdot T_{X_i}^2} \tag{14}$$

where: k_Z – variation coefficient of dependent dimension Z,
k_{X_i} – variation coefficient of i-th independent dimension X_i.

The variation coefficient, for example, has a value of 1.0 for a normal distribution, 1.225–1.414 for the triangular distribution to c.a. 1.732 for the uniform distribution.

Analysis of dependent dimension distribution is often difficult, therefore, in the calculations in most cases of approximate methods are used. They are based on the so-called. threshold theorem, which states that the dependent dimension distribution of tends asymptotically to a normal distribution, regardless of independent dimensions distributions, when the number of the independent component dimensions of dimensional function dimensions is large enough (at least four components).

COMPENSANTION CELLS IN DIMENSIONAL CHAINS

It is known that the dimension chain is a closed set of subsequent, connected to each other (common databases) dimensions that describe the position and orientation of the elements of the geometrical structure of large-scale structures and form a closed circuit.

For example, in shipbuilding (large-scale structures) the dimensional chain consists mostly of compensation cells, also known as dimensions of freedom. The values of these dimensions of freedom can be varied within a set range during an ongoing production process. They are supposed to compensate for the deviation of particular cells of a given dimension chain. The dimensions of freedom mainly include technological reserves and the size of welding joints. Dimensions of freedom can be seen as an independent chain cells, dimension of which shall be equal to zero.

Rules for the use of technological reserves depend on the technology of hull production and measurement techniques used in a shipyard There are mainly two types of reserves:

- prefabrication (“cutting off” in section prefabrication process),
- assembly („cutting off” in process of assembly of sections and blocks into a hull on a slipway or in a dry dock).

In rare cases, one can find also treatment reserves on bent elements. Location of those reserves mainly depends on:

- production technology,
- assembly sequence,
- structural and operational properties of a given element and the entire hull.

Currently, most shipyards, including Polish shipyards, use, technological reserves to a greater or lesser extent. This is an unfavourable situation, since this considerably extends the construction cycle of the hull, and increases energy and material expenditures. Particularly troublesome is significant the increase in engagement of lifting equipment - section, which holds the assembly reserve must be initially set to cut the reserve off and then re-positioned for assembly.

CALCULATIONS OF TOLERANCES OF COMPONENT DIMENSIONS

In the process of determining tolerances of component dimensions based on the deterministic and statistical model, the following calculation methods are used:

- The method of equal tolerance – consists in calculating the tolerances of chain component cells on the assumption that tolerances of all component cells are equal.

$$T_{X_i} = T_{X_2} = \ldots = T_{X_n} = T$$

Thus the calculation uses the following relationships:

– in deterministic model:

$$T_Z = \sum_{i=1}^{n} \left(\left| Q_i \right| \cdot T \right) \tag{15}$$

where:

$$Q_i = \frac{\partial F}{\partial X_i}$$

F – dimensional function,

X_i – independent i-th tolerated dimension.

– in statistical model:

$$k_Z^2 \cdot T_Z^2 = \sum_{i=1}^{n} \left(Q_i^2 \cdot k_{X_i}^2 \cdot T^2 \right) \tag{16}$$

- The method of equal accuracy class – consists of calculating the tolerance of component cells depending on the size of nominal dimension of the component cell. In this method it is assumed, that accuracy class coefficient “*h*” is approximately constant for all chain cells. The value of dimension tolerance in this method can be presented as:

$$T_{X_i} = h \cdot \sqrt[3]{X_i} \tag{17}$$

where: h – accuracy class coefficient

The calculation uses the following relationships:

– in deterministic model:

$$T_Z = h \cdot \sum_{i=1}^{n} \left(\left| Q_i \right| \cdot \sqrt[3]{X_i} \right) \tag{18}$$

– in statistical model:

$$k_Z^2 \cdot T_Z^2 = h^2 \cdot \sum_{i=1}^{n} \left(Q_i^2 \cdot k_{X_i}^2 \cdot \left(\sqrt[3]{X_i} \right)^2 \right) \tag{19}$$

The unknown in equations (18) and (19) is a coefficient “*h*”. After it is determined the tolerance of particular cells can be calculated according to formula (17).
The method of equal accuracy is used when analyzing dimensional chain there are dimensions with significantly differing nominal values.

- Method of equal effect – consists in identifying the component cell tolerance with the assumption that change in tolerance of resultant cell is equally dependant on the value of the product of the partial derivative of a given cell multiplied by tolerance of this component cell. For a parallel chain, this method is no different from the method of equal accuracy class.
- The method of least costs – is to calculate the component cells tolerance at minimal costs of manufacturing a component or at minimal costs of its assembly. This method requires knowledge on the function of manufacturing costs of a given component according to changes in tolerance of a given dimension.

Detailed description of these methods can be found, among others, in positions [2, 3, 4].

A simple example of determining tolerances of component dimensions for dimensional chain presented in Figure 2. The values of particular dimensions are presented in Table 2.

The chain equation (dimensional function) in this case takes the following form:

$$b = \sum_i a_i \quad i = 1, 2 ,... , 8$$

In the calculations method of equal tolerance (formulas (16) (16)) and method of equal accuracy class were used (equation (17) (18) (19)). Partial derivatives (impact coefficient) for particular dimensions are equal to one. The calculations were made for the deterministic and the stochastic models. It was assumed that the distributions of chain component cells are identical according to the normal distribution. The results obtained are summarized in Table 3.

The presented example illustrates benefits of using statistical method of determining tolerance – significant increase in tolerance of complement cells of dimensional chain.

ANALYSIS OF TOLERANCE EQUATIONS IN ACTIVE DIMENSIONAL CONTROL

This analysis should be carried out in two stages. It begins by identifying an independent dimensional chain of danger coming from the position of measurement result in uncertainty field for a given cell (Fig. 3).

This is done based on weight of determined dimension. The weight is determined in the design process of production technology for the specific structure. If the risk is high, re-measurement of higher precision should be done, or the item is to be sent for corrections.

The second stage is to determine the impact of the resulting independent dimension on the dependent dimension. This is achieved by checking the following condition:

$$T_Z \geq T_{Z_R} \tag{20}$$

where: T_Z – tolerance of dependent dimension determined on design stage,
T_{Z_R} – tolerance of dependent dimension determined on actual (real) data.

Value T_{Z_R} is determined on the basis of design tolerance equation through exchange of design data for actual real data acquired during an ongoing production process.

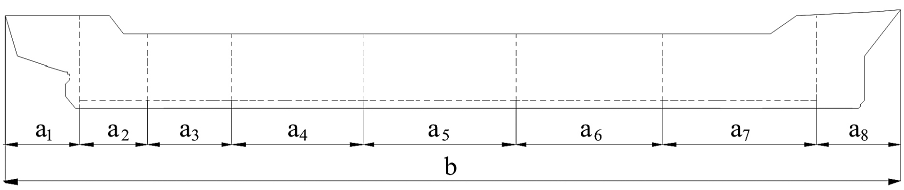

Fig. 2. The basic dimensional chain of a ship’s hull

Table 2. Dimensions of the basic dimensional chain of a ship hull

Component	b	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
Dimension [m]	$150.0^{+0,200}_{-0,200}$	12.5	11.2	14.4	24.1	24.1	24.1	25.6	14.0

Table 3. Results of the determination of component dimensions tolerances of dimensional chain of ship hull

Method	Model			
	Deterministic		Stochastic	
Equal tolerance	$a_1 = 12.5^{+0,025}_{-0,025}$	$a_2 = 11.2^{+0,025}_{-0,025}$	$a_1 = 12.5^{+0,070}_{-0,070}$	$a_2 = 11.2^{+0,070}_{-0,070}$
	$a_3 = 14.4^{+0,025}_{-0,025}$	$a_4 = 24.1^{+0,025}_{-0,025}$	$a_3 = 14.4^{+0,070}_{-0,070}$	$a_4 = 24.1^{+0,070}_{-0,070}$
	$a_5 = 24.1^{+0,025}_{-0,025}$	$a_6 = 24.1^{+0,025}_{-0,025}$	$a_5 = 24.1^{+0,070}_{-0,070}$	$a_6 = 24.1^{+0,070}_{-0,070}$
	$a_7 = 25.6^{+0,025}_{-0,025}$	$a_8 = 14.0^{+0,025}_{-0,025}$	$a_7 = 25.6^{+0,070}_{-0,070}$	$a_8 = 14.0^{+0,070}_{-0,070}$
Equal accuracy class	$a_1 = 12.5^{+0,022}_{-0,022}$	$a_2 = 11.2^{+0,021}_{-0,021}$	$a_1 = 12.5^{+0,062}_{-0,062}$	$a_2 = 11.2^{+0,060}_{-0,060}$
	$a_3 = 14.4^{+0,023}_{-0,023}$	$a_4 = 24.1^{+0,027}_{-0,027}$	$a_3 = 14.4^{+0,065}_{-0,065}$	$a_4 = 24.1^{+0,077}_{-0,077}$
	$a_5 = 24.1^{+0,027}_{-0,027}$	$a_6 = 24.1^{+0,027}_{-0,027}$	$a_5 = 24.1^{+0,077}_{-0,077}$	$a_6 = 24.1^{+0,077}_{-0,077}$
	$a_7 = 25.6^{+0,028}_{-0,028}$	$a_8 = 14.0^{+0,023}_{-0,023}$	$a_7 = 25.6^{+0,079}_{-0,079}$	$a_8 = 14.0^{+0,064}_{-0,064}$

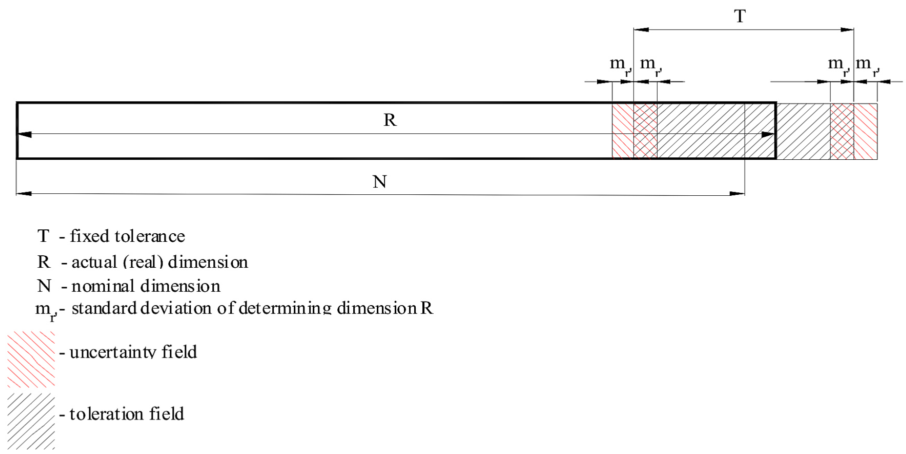

Fig. 3. Position of dimension in relative to nominal dimension

In case the condition (20) is met, a decision should be made to direct the item to the next stage of production. Otherwise actions should be taken resulting from Figure 1, which are:

- increase measurement accuracy,
- perform correction of dimensions of freedom (compensative),
- send the item to repairs.

Various tasks should be performed in the order presented. When one does not produce the intended effect, or they are unsatisfactory, one should move to the next activity. It should be noted that the adjustment of dimensions of freedom should be carefully analyzed technological, strength and economic terms. Economic issues concern mainly labour-intensive welding process involving a change in the size of welding gaps. For example, the relationship between man-hours and the distance between elements when welding T-joints is presented in Figure 4 [2].

As it can be seen from the above chart, excessive increase in the size of welding gaps significantly extends the welding process.

Dimentional weights

Active dimensional control requires determining the weights of component cell of all dimensional chains making up the ship hull. Its goal is to set limits for "diverging" a given chain cell from the fixed tolerance.

Weights of particular cell result mainly from these types of:

- contract,
- strength,
- proper functioning of the machinery and equipment fitted into hull structure,
- associated with block equipment of the hull,
- technological, minimizing fit mounting of the structure.

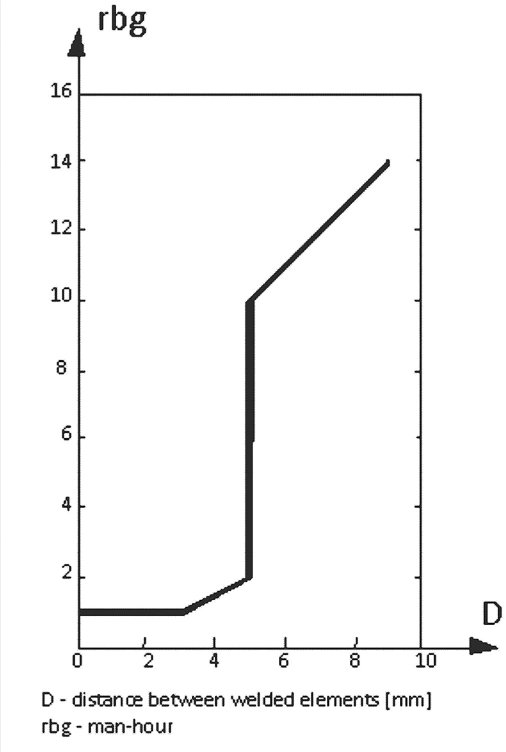

Fig. 4. Relationship between the workload of welding and distance between welded elements [2]

Particular groups of demands determining weights of dimensional chains cells constitute a separate complex research topics. Issues concerning determining tolerance limits are discussed, among others, by works [9].

MATHEMATICAL DESCRIPTION OF APPLIED PRODUCTION TOLERANCES

In practice of production plants manufacturing large-scale steel structures, it is common to encounter a situation, when tolerances are set on the basis of years of experience and only in small degree do they result from calculation analysis. In such cases application of active dimensional control requires performing mathematical description of applied tolerances.

The description should be performed starting from the ultimate dimension of the structure, such as a ship, through dimensions of smaller and smaller groups of elements, to the individual components. Proceeding according to this policy is recommended by most researchers and engineers dealing with these issues. This way of tolerance preparation is called "top down" method, but it can also be found in the literature under the term "from the whole to the detail method" or "modern synthesis of dimensional chains". The advantages of establishing tolerances according to this rule are discussed in detail, inter alia, in [9].

The development of mathematical description of applied tolerances and synthesis of results that are received when the description is complemented with real values may bring simultaneously a lot of information concerning, among other things, manufacturing process control.

Stages of proceedings

The mathematical description process should start with identification of dimensional chains of the whole hull strength and determining the relationships between them. This task can be accomplished through the graphs of dimensional chains hierarchy (Fig. 5). By creating various graphs one should come from "the top" independent dimension (e.g. the length of the cable) and then divide it into dimensions of sections, subsections and down to individual elements. Detailed fragmentation of the dimensions of the hull structure is the only way to allow the analysis of dimensional changes in different phases of the technological process.

Based on graphs equations of toleration of all dimensional chains must be developed. This can be divided into two stages involving determining tolerance of dependent dimension on the basis of applied tolerances of independent dimension. In the first stage the calculation should be performed based on a deterministic model. In case when the condition:

$$T_Z \geq T_D \tag{21}$$

where: T_Z – currently applied tolerance of dependent dimension,

T_D – tolerance of dependent dimension determined based on deterministic model,

is not met, go to step two – make calculation using a statistical model, and check the condition:

$$T_Z \geq T_S \tag{22}$$

where: T_S – tolerance of dependent dimension determined on basis of statistical model.

When the condition (22) is not met it is necessary to immediately analyze the controlled technological process to identify hazards arising from this fact. Process discussed above is presented schematically in Figure 6.

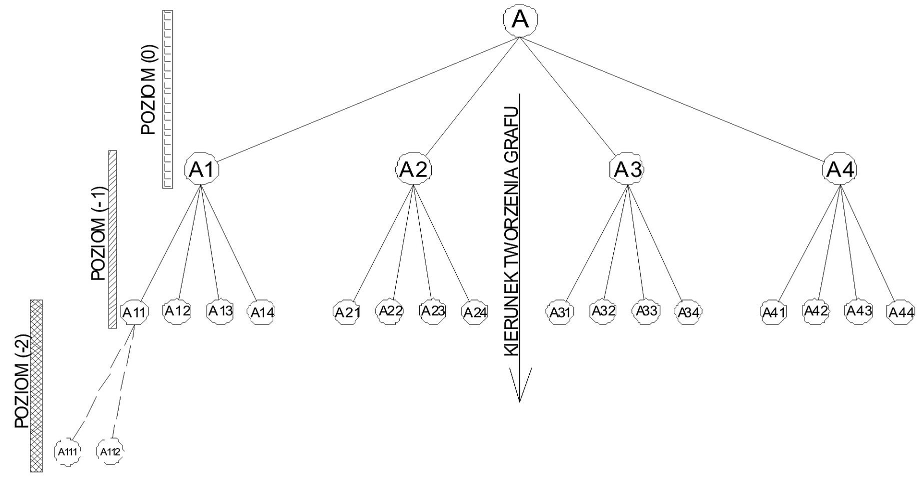

Fig. 5. The graph of dimensional chains hierarchy

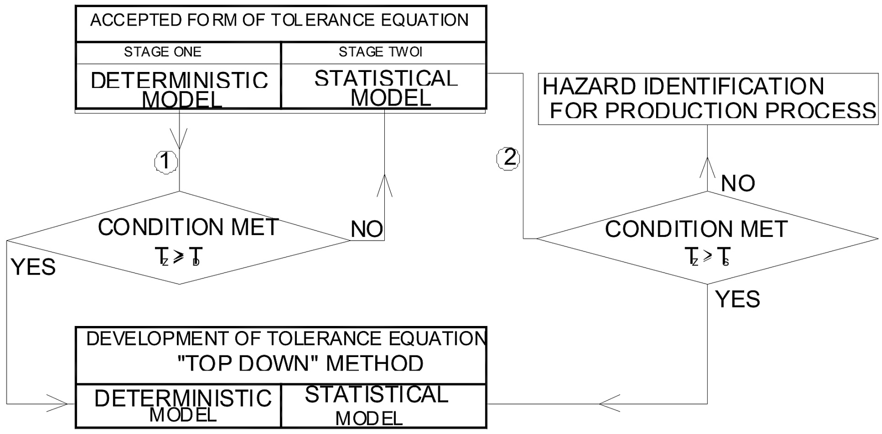

Fig. 6. Procedure of mathematical description of manufacturing tolerance

The mathematical description of tolerance demonstrates the ability of the manufacturing process due to the dimensional quality. If it is greater than the applied tolerances, it is possible to reduce or even, in some cases, eliminate the technological reserve.

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