https://doi.org/10.52326/jes.utm.2023.30(4).02
UDC 621.9:681.518

COMPARISON AND EVALUATION OF CLASSICAL METHODS OF DIMENSIONAL CHAINS THEORY AND THEIR MODERN ANALOGUES

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Received: 11. 02. 2023
Accepted: 12. 05. 2023

Abstract. The requirements for the quality, reliability, and cost-effectiveness of engineering products and engineering production itself are constantly improving. As a result, there is an increasing demand for the quality of design and technological preparation of production, which includes classical dimensional analysis as its foundation. The Classical Method of dimensional analysis calculation represents a comprehensive set of computational and analytical actions carried out during the development and analysis of projects and technological processes, including: the construction of specialized dimensional diagrams for projects and technological processes, the identification and recording of interconnections between all dimensional parameters, the identification of dimensional chains, verification, and the establishment of rational sizing methods in drawings. Dimensional analysis involves a significant number of procedures and actions. The time required for dimensional analysis is substantial, ranging from 10 to 50 hours for a single technical drawing or technological process. At the same time, the use of Modern Methods for calculating dimensional chains will allow us to determine, after a thorough evaluation of manufacturing conditions at each production stage (operation), leading to a reduction in the manufacturing cost of parts. The increased workload of the evaluation process can be compensated by using databases and appropriate software that operates interactively with the user. This will also lead to a reduction in the labor intensity of dimensional analysis of projects and technological processes through automation.

Keywords: *calculation of tolerances, classical methods, simulation, modern programs, tolerance analysis, tolerance limit.*

Rezumat. Cerințele de calitate, fiabilitate și rentabilitate pentru produsele inginerești și pentru producția inginerească în sine sunt în mod constant îmbunătățite. Ca rezultat, există o creștere a cererii pentru calitatea proiectării și pregătirii tehnologice a producției, care include analiza dimensională clasică ca fundament. Metoda clasică de calcul a analizei dimensionale reprezintă un set cuprinzător de acțiuni computaționale și analitice efectuate în timpul dezvoltării și analizei proiectelor și proceselor tehnologice, incluzând: construcția diagramelor dimensionale specializate pentru proiecte și procese tehnologice, identificarea și înregistrarea interconexiunilor dintre toți parametrii dimensionali, identificarea lanțurilor

dimensionale, verificarea și stabilirea metodelor raționale de dimensionare în desene. Analiza dimensională implică un număr semnificativ de proceduri și acțiuni. Timpul necesar pentru analiza dimensională este semnificativ, variind de la 10 la 50 de ore pentru un singur desen tehnic sau proces tehnologic. În același timp, utilizarea metodelor moderne de calcul a lanțurilor dimensionale permite o evaluare minuțioasă a condițiilor de fabricare la fiecare etapă de producție (operațiune), ceea ce conduce la o reducere a costului de fabricare a pieselor. Volumul crescut de lucru al procesului de evaluare poate fi compensat prin utilizarea bazelor de date și a software-ului corespunzător care funcționează interactiv cu utilizatorul. Acest lucru duce, de asemenea, la reducerea volumului de muncă a analizei dimensionale a proiectelor și proceselor tehnologice prin automatizare.

Cuvinte cheie: *Calculul toleranțelor, metodele clasice, simularea, programele moderne, analiza toleranței, limita toleranței.*

1. Introduction

Dimensional analysis of structures is a crucial stage in the dimensional advancement of structures, as it allows you to identify the relationship of components and assembling units that make up the machine, determine methods for achieving the required accuracy of the machine, analyze the correctness of setting dimensions and tolerances on the drawings, improve the manufacturability of the design, establish the sequence of assembly of the machine and its assembly units, Figure 1 [1].

The purpose of dimensional analysis is to ensure the quality and manufacturability of products, their elements, workpieces, obtain the dimensions and maximum deviations necessary to fill in technological maps, setup sketches, control programs, calculate cutting conditions, time standards.

Dimensional analysis of assembly is a set of calculation and analytical procedures executed in the development and analysis of assembly and technological methods of machining, including: construction of special dimensional schemes of technological processes; identification and fixation of the relationships of all dimensional parameters, including the use of graph theory; identification of dimensional chains of structures and technological processes; confirmation and establishment of rational ways of sizing in the drawings; assignment ample and necessary amount of technical specifications; nominations of reasonable parameters, the minimum required benefits; verification estimation of the possibility of ensuring drawing dimensions and technical requirements; calculation of

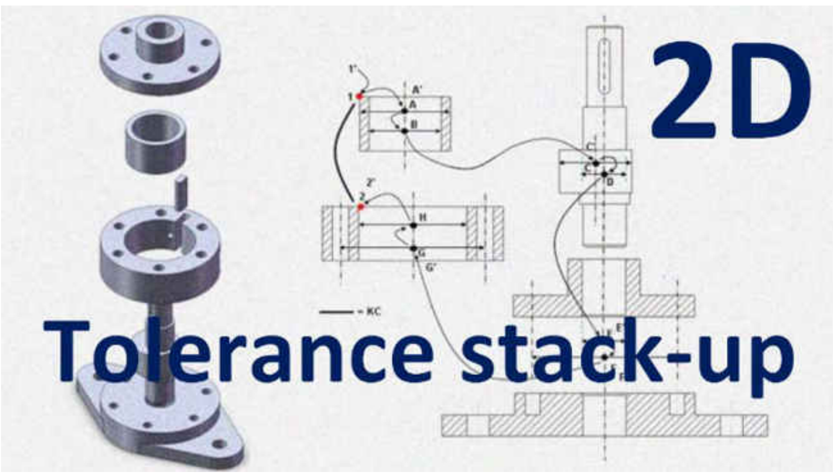

Figure 1. Tolerance stack-up Example [1].

average and minimum allowances; determination of nominal values of operating dimensions; calculation of coating depth, nitriding thickness and other parameters.

Dimensional analysis involves many actions. The complexity of dimensional analysis is very significant - dimensional analysis of one design or one technological process can take from 10 to 50 hours.

The solution to the problem of reducing the complexity of the dimensional analysis of machines and technological processes is possible based on its automation. In mathematical modelling of dimensional chains of assembles and technological processes, graph theory is used, which makes it possible to connect theoretical positions with computational algorithms implemented on a computer. The most advanced methods for automated calculation of operating dimensions, location deviations based on dimensional chains are the methods proposed by Ivashchenko [2], Mordvinov et al. [3], Smetanin et al. [4] and several other authors.

Their main advantage is a reduction in time and an increase in the quality of design; The main disadvantage is the need to generate dimensional schemes and graphs in manual mode, which makes it difficult to implement these techniques in production (Figure 2) [5].

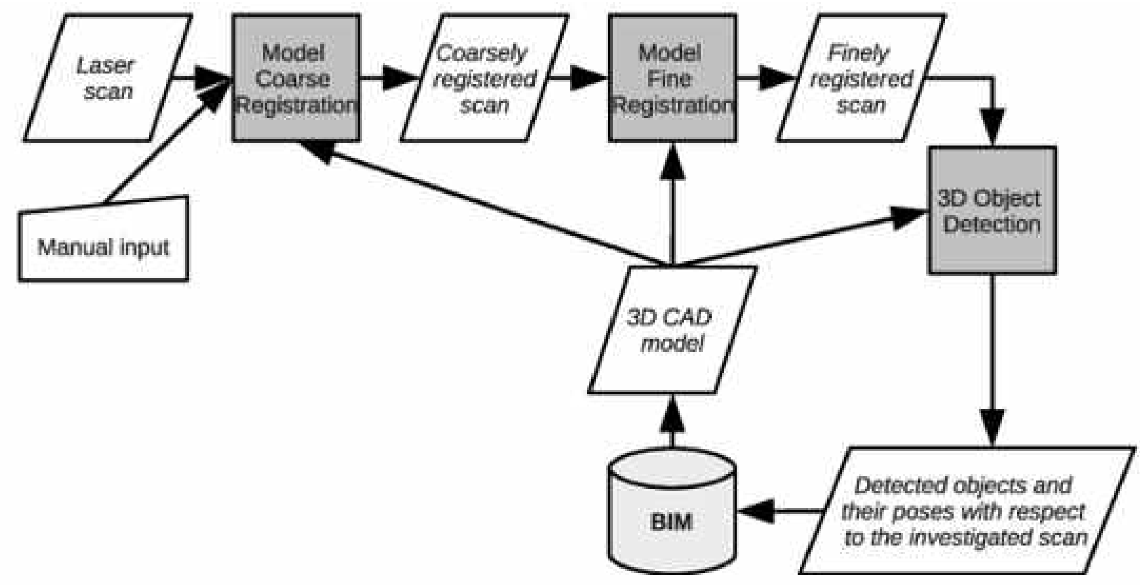

Figure 2. The process of studying 3D elements of the model using laser scanning [5].

A more advanced technique is the "Tolerance Analysis" [6] module in Autodesk Inventor (Figure 3).

The advantage is that it is not necessary to build dimensional schemes, but it is very laborious due to the need to calculate and organize digital and graphic data that are manually entered using special “windows” to be able to perform the calculation. To automate the dimensional analysis more fully, a computer program “Tolerance Tools” has been developed [6].

The solution of variants of one problem provides for the possibility of using the originally entered information for multiple repetition of the solution when the calculation conditions, the utility of dimensional parameters, or a minor change in the composition of operations in the checklist of initial datasheet change.

To ensure ease of coding, information about the assembly unit, part, workpiece, and technological process of machining is presented in the form of geometric models that have only flat and cylindrical surfaces.

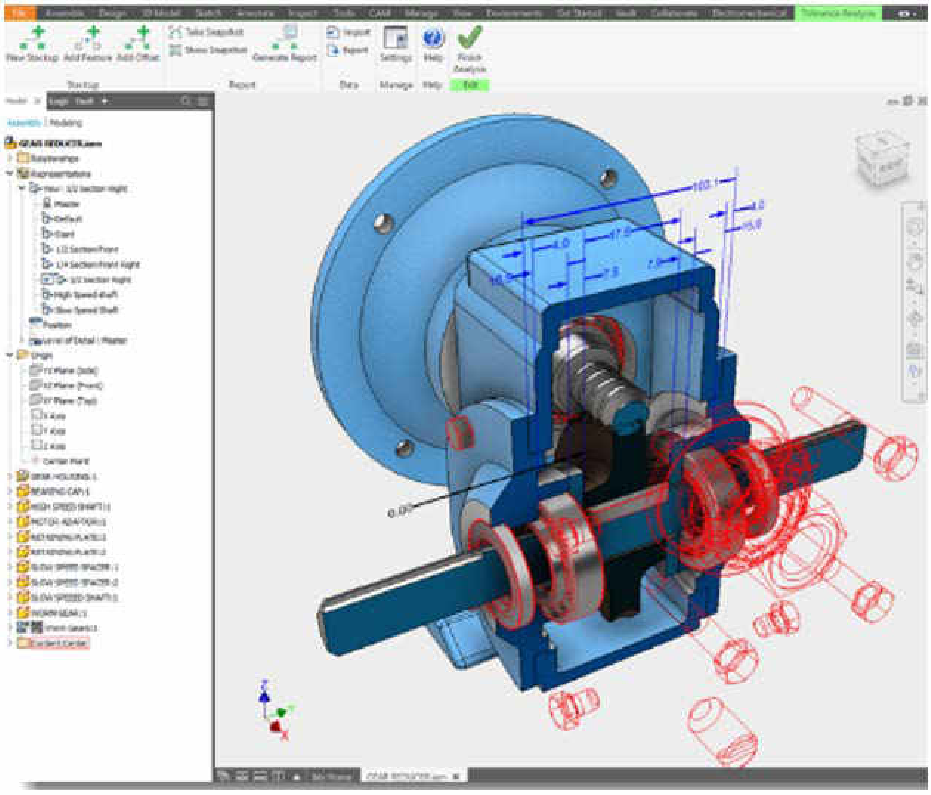

Figure 3. "Tolerance Analysis" module in Inventor [6].

2. Classical methods the theory of dimensional chains and analysis

When designing mechanisms, machines, instruments, and other products, designing technological processes, choosing measurement tools and methods, and operating products, it becomes necessary to conduct a dimensional analysis, with the help of which the correct ratio of interrelated dimensions is achieved and permissible errors (tolerances) are determined. Dimensional analysis is performed using the theory of dimensional chains [7,8]. A dimensional chain diagram is an equivalent of interrelated dimensions that form a closed contour and determine the optimal position of the surfaces or axes of one or more parts. Dimensional chains diagrams graphically in the form of graphs (Figure 4).

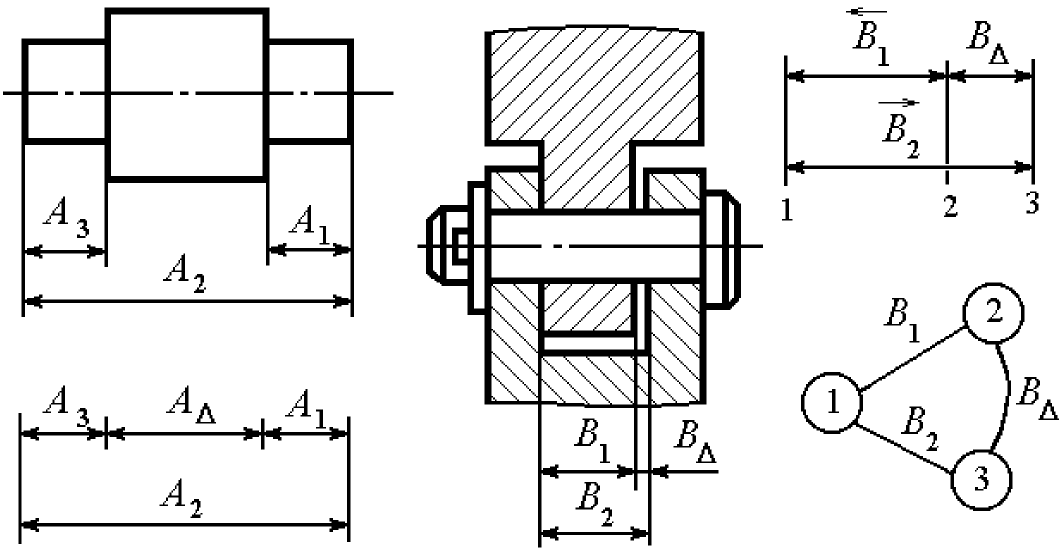

Figure 4. Example of a dimensional chain diagram, graph schema [7].

The dimensions that form a dimensional chain are called its links. The links of the dimensional chain can be any angular or linear parameters: diametrical dimensions, distances between surfaces (axes), gaps, tensions, overlaps, variance in the shape and position of axes, etc.

All dimensional chains consist of two or more links, one of which is closing, the rest are components. The link is called the closing link, to which the basic requirement of accuracy is imposed, which determines the quality of the product in accordance with the specifications.

To perform dimensional analysis, in addition to the dimensional scheme, an equation of dimensional chain is constructed, derived from the condition of closure Eq. (1):

$$c_1A_1 + c_2A_2 + \ldots + c_{m+}n + Am_{+n} = 0 \quad (1)$$

where:

$A_1, A_2, \ldots, A_{m+n}$ – the nominal values of all links in the dimensional chain;

$c_1, c_2, \ldots, c_{m+n}$ – the coefficients that characterize the degree of influence of a link's variation on the change of the closing link, or the transmission ratios.

In dimensional chains with parallel links (linear chains) Eq. (2):

$$|c_1| = |c_2| = \ldots = |c_{m+n}| = 1 \quad (2)$$

In planar and spatial dimensional chains (general case) Eq. (3):

$$c_i = \frac{\partial A_\Delta}{\partial A_i} \; (i = 1, 2, \ldots, m+n) \quad (3)$$

If a growth in the constituent link leads to a growing in the closing link, the transmission ratio is positive; if it leads to a decrease, the transmission ratio is negative.

2.1. Problems solved using dimensional chains

The calculation of dimensional chains is necessary when solving the problems of designing, manufacturing, and operating a wide class of products (machines, mechanisms, instruments, devices, etc.). Using the theory of dimensional chains, the current design, technological issues can be solved:

- Establishment of geometric and kinematic connections between the dimensions of components; calculation of nominal dimensions, variances, and dimensional tolerances.
- Calculation of precision standard and formulation of requirements for machinery and their parts.
- Analysis of the correctness of sizing and parameters on the current datasheets of parts.
- Determination of interoperation parameters and tolerances.
- Justification of the order of technical processes in the production and assembly of parts.
- Rationale and computation of the required precision of fixtures.
- Choice of means and techniques of measurements, calculation of achievable measurement accuracy.

A complete calculation of dimensional chains is carried out in the process of developing the working design of the machine, preliminary calculations should be made during the constructive development of the technical design. All issues resolved through the assistance of dimensional chains are divided into two types: direct and inverse. direct task. According to the calculated value and the tolerance or deviations of the master link, the basic values, tolerances, maximum deviations of all the constituent links of the dimensional chain are determined. Such a task relates to the design calculation of a dimensional chain. Reverse problem.

According to the established nominal values, tolerances and maximum deviations of the constituent links, the standard value, tolerance, and maximum deviations of the closing loop are determined. Such a task refers to the verification calculation of the dimensional chain.

The main task is direct, since it allows solving the main problem in the design of the machine - to determine the parameters of the constituent links that ensure the accuracy of the closing link of the machine or part.

The inverse problem is solved if it is needed to check the correctness of the conclusion of the direct issue or those accepted without calculating dimensions and tolerances.

2.2. Full interchangeability method and maximum-minimum method

The method has significant advantages, including simplicity, clarity, low computational workload, a complete guarantee against defects due to inaccuracies in the mating link, and the absence of the need to allow for even a small percentage of risk in the calculations.

The use of this method will allow us to obtain:

- simple and cost-effective assembly.
- the possibility of organizing in-line assembly.
- the possibility of wide cooperation between industries.
- the simplicity of manufacturing spare parts and supplying them to consumers.
- the possibility of selective control.

Scope - in large-scale and mass production, with a small tolerance of the closing link and a small number (up to five) of the constituent links of the dimensional chain, with multi-link dimensional chains with a large tolerance for the closing link. The disadvantage of the method is that the tolerances of the constituent links are smaller, all other things being equal, than with all other methods, which may turn out to be uneconomical. If the accuracy of the closing loop of the dimensional chain is achieved by the method of complete interchangeability, then the calculation of dimensional chains using the maximum-minimum calculation method is applied, Figure 5 [8].

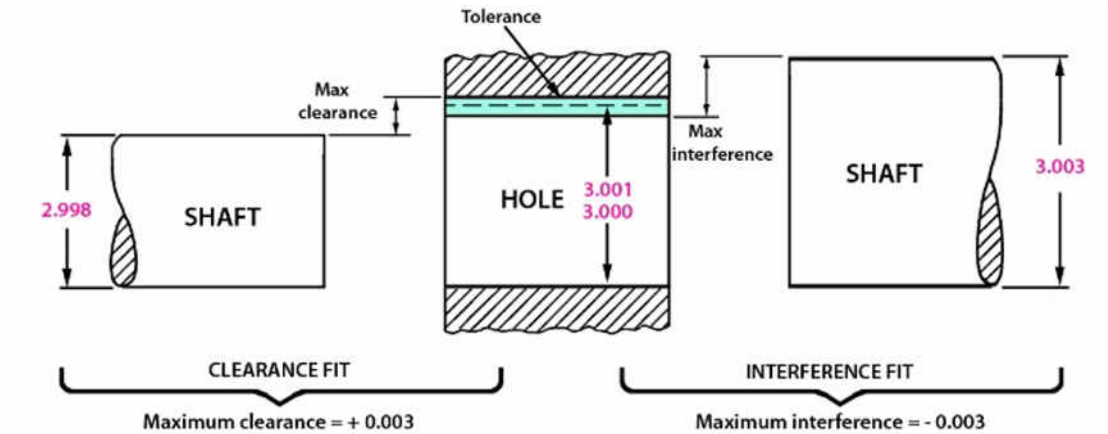

Figure 5. Maximum-minimum deviations [8].

The maximum-minimum method assumes that the assembly receives parts with limiting dimensions in combination, in which all increasing links will be the biggest limiting dimensions, and reducing links will be the minimum ones. Therefore, the parameter of the closing loop will be max or min, the likelihood of which is very minor.

The method leads to large margins of accuracy, and the calculated tolerance values obtained by this method often do not correspond to the specified ones. If we proceed from the tolerance of the closing link, then the tolerances of the constituent links turn out to be unnecessarily tight. If they proceed from the tolerances of the constituent links, then the calculated tolerance of the closing link is greater than the specified one.

This method has great benefits - simplicity, clarity, low complexity of computational work, a full assurance against marriage due to the inexactness of the closing loop, no necessity to permit even a minor degree of uncertainty in the calculation.

The maximum-minimum method is financially viable only for Dimensional chains with a small number of precise component loops. In other cases, the required precision in the manufacture of parts may go beyond not only economic, but also practically achievable accuracy.

The method should be used to solve design and verification problems in the terms of single-unit and small-scale fabrication of products, in the design of single component, for initial calculations of an ancillary aspect, and in cases where even a negligibly small chance of the closing link parameters going beyond the permissible limits is unacceptable [9].

2.3. Group interchangeability method

Parts are connected without fitting and regulation. The calculated value of the tolerance of the component link increases several times to an economically viable manufacturing tolerance.

After manufacturing, the parts are sorted according to their actual dimensions into groups within the design tolerance and are assembled into the corresponding groups using the method of complete interchangeability. It is possible to achieve high accuracy of the closing link with appropriate tolerances of the component links.

The scope of application is mass and large-scale production with small-link (3-4 links) dimensional chains with high accuracy of the closing link.

The disadvantages of the method are an increase in the volume of work in progress, additional costs for checking, sorting, and marking parts, and some complication in the supply of spare parts.

The calculation of dimensional chains using the group interchangeability method can be carried out using the maximum-minimum method or the probabilistic method.

The calculation includes the replacement of the design tolerances of the constituent links with production or technological tolerances, which may exceed the design tolerances by several times.

To ensure the necessary precision of the closing loop, the component links are sorted into groups according to actual sizes, and the scatter field of the sizes of each group must be equal to the design tolerances of the component links.

2.4. Fitting method

The required accuracy is achieved through the fitting of a pre-designed component called a compensator, onto which a specific allowance is applied during mechanical processing for assembly.

It ensures the possibility of achieving high precision in the closing link while maintaining economically feasible manufacturing tolerances for the constituent links.

Application area: single and small-scale production, multi-link dimensional chains with a high-precision closing link.

Disadvantages of the method: significant increase in assembly cost and time, difficulty in standardization and mechanization, complexity in production planning.

It provides the ability to adjust the closing link not only during assembly but also during operation, as well as the possibility of automatic adjustment of precision [10].

Application area: all types of production requiring high precision in chains.

Disadvantages of the method: potential complexity in product design, increased number of components, and assembly complications due to the need for adjustment and measurements.

3. Modern analogues of dimensional chains and analysis

Nowadays, most of the production process is devoted to reference literature: quality standards, tables, etc. As a result, it takes a long time to launch a new part or machine into production. This situation is unacceptable from the point of view of economic competition and in the conditions of the rapid development of society and technology. In addition to general computerization and automation, but also the increasing use of computer technology, not only the problem of digitizing reference information, but also the problem of developing programs for managing this information is becoming increasingly relevant.

Debugging and replacing some algorithms with others, depending on the production conditions and the development of methods for calculating dimensional chains, Figure 6.

Computer-based simulation utilizing contemporary software - Tolerance Tools

Autodesk® Inventor® Tolerance Tools is a special addon, the one-dimensional tolerance tools software aiding in gaining a better insight into the influence of mechanical fit and performance through the combined dimensional changes, Figure 7. A one-dimensional tolerance stack-up Implies that the distance under examination, along with all contributing dimensions affecting its modification, are aligned in one vector direction.

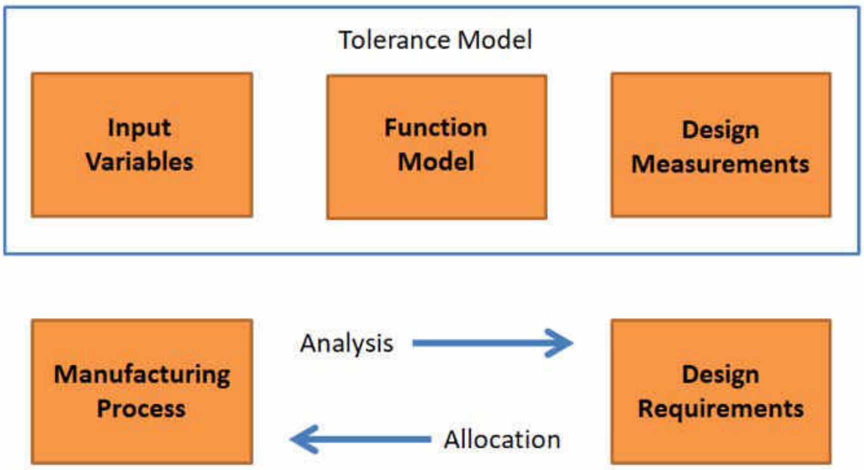

Figure 6. Methods for calculating dimensional chains.

One vector modification of the plane along the stack-up direction is constant; angular modification of the plane concerning of other is not measured. At times, the impacts of angular modification are disregarded, that it is crucial to validate the analysis.

The aim of tolerance design is to account for the permissible modification in every part to ascertain whether the engineering demands are fulfilled during assembly. Tolerance analysis aids in achieving the following: ensuring fits better excluding the necessity for manual calculations and tables, determining the optimal tolerances this will allow us to minimize fabrication costs, enhancing the requirement quality, and finishing of your final product.

Tolerance Analysis tool sustains of Worst Case method (Figure 8), the individual parameters are placed at any of the maximum, or minimum deviations to make the stack up distance as bigger or as smaller as admissible (Figure 9), general Statistical (Figure 10), and Root of the Sum of Squares method (Figure 11).

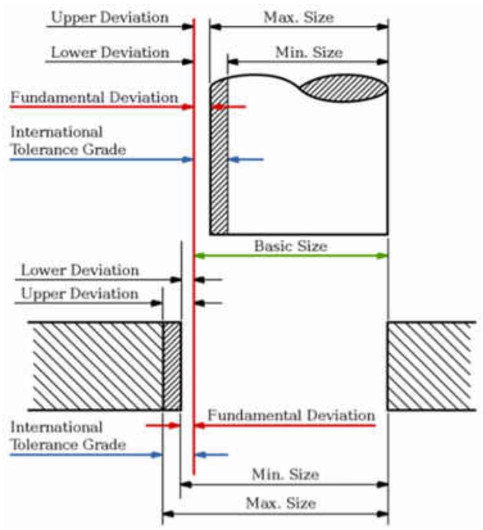

Figure 7. Tolerance Deviations and Sizes [11].

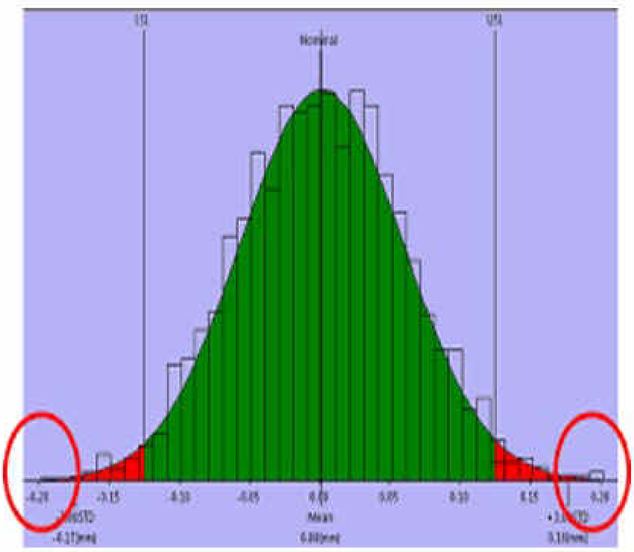

Figure 8. Worst Case method [12].

The Worst Case method does not including the deviation of the individual parameters. As an alternative, it presupposes that - all components have been manufactured at the maximum allowable limit of acceptance to bring in to assemble. Worst Case method forecast the utter upper and lower limits of the stack up distance.

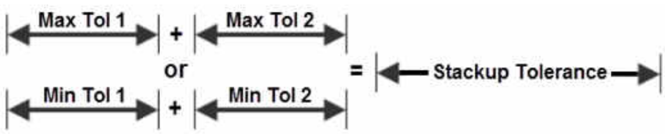

Figure 9. Components of overlay tolerance [13].

The standard variation computed for the normal distribution of each parameter is derived from equation Eq. (4):

$$C_p = \frac{UTL-LTL}{6\sigma} \quad (4)$$

From where:

- UTL – Upper Tolerance Limit;
- LTL – Lower Tolerance Limit;
- σ – standard variation distribution.

Solving by the standard variation yields Eq. (5):

$$\sigma = \frac{UTL - LTL}{6 * C_p} \quad (5)$$

The modest pretense of C_p=1.0 stems from the assumption of a fabrication process that places the variation of tolerances at +/- 3 standard variation from center line of the tolerance area, this is assumed to be the average, so that the possibility of a part respect the necessary tolerances is 99.7 %.

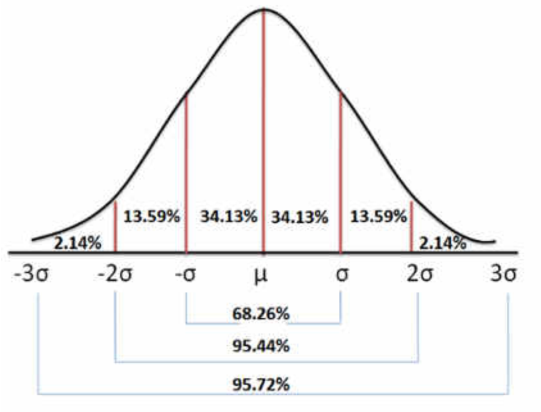

Figure 10. Statistical Method [14].

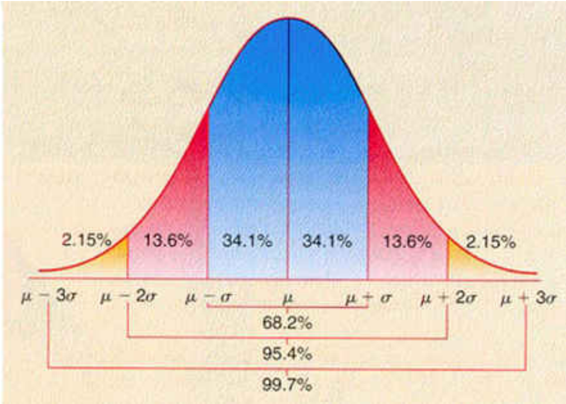

Figure 11. Root Sum of Squares Method [14].

Tolerance Analysis assumes, for all statistical evaluations, that manufacturing aims for the center line of the tolerance area. As a result, that mean is at the center line of the tolerance area. Root of the Sum of Squares analysis applies the principles of the statistical analysis method relate to the previous component but with certain clarify assumptions to facilitate computations using tolerances such as standard variations [15].

The main presupposition is that the proportions of each tolerance, to their respective standard variations on the dimension and the stack-up outcome became an equal. For a Root of the Sum of Squares method, Tolerance Analysis suppose a C_p of 1.0 for all parameters and the develop stack up limits.

4. Conclusions

Dimensional analysis of projects and technological processes represents a set of calculation and analysis procedures carried out during the development and analysis of machining:

- Construction of special dimensional diagrams for technological processes.
- Identification of dimensional chains in projects and technological processes.
- Assignment of reasonable tolerances and necessary minimum reserves.
- Calculation of average and minimum reserves.

Dimensional analysis involves a significant number of procedures and actions. The time required for dimensional analysis is substantial, ranging from 10 to 50 hours for a single technical drawing or technological process. Reductions in the labor intensity of dimensional analysis.

Conflicts of interest: The author declares no conflict of interest.

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Citation: Lealin, S. Comparison and evaluation of classical methods of dimensional chains theory and their modern analogues. *Journal of Engineering Science* 2023, 30 (4), pp. 20-30. https://doi.org/10.52326/jes.utm.2023.30(4).02.

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