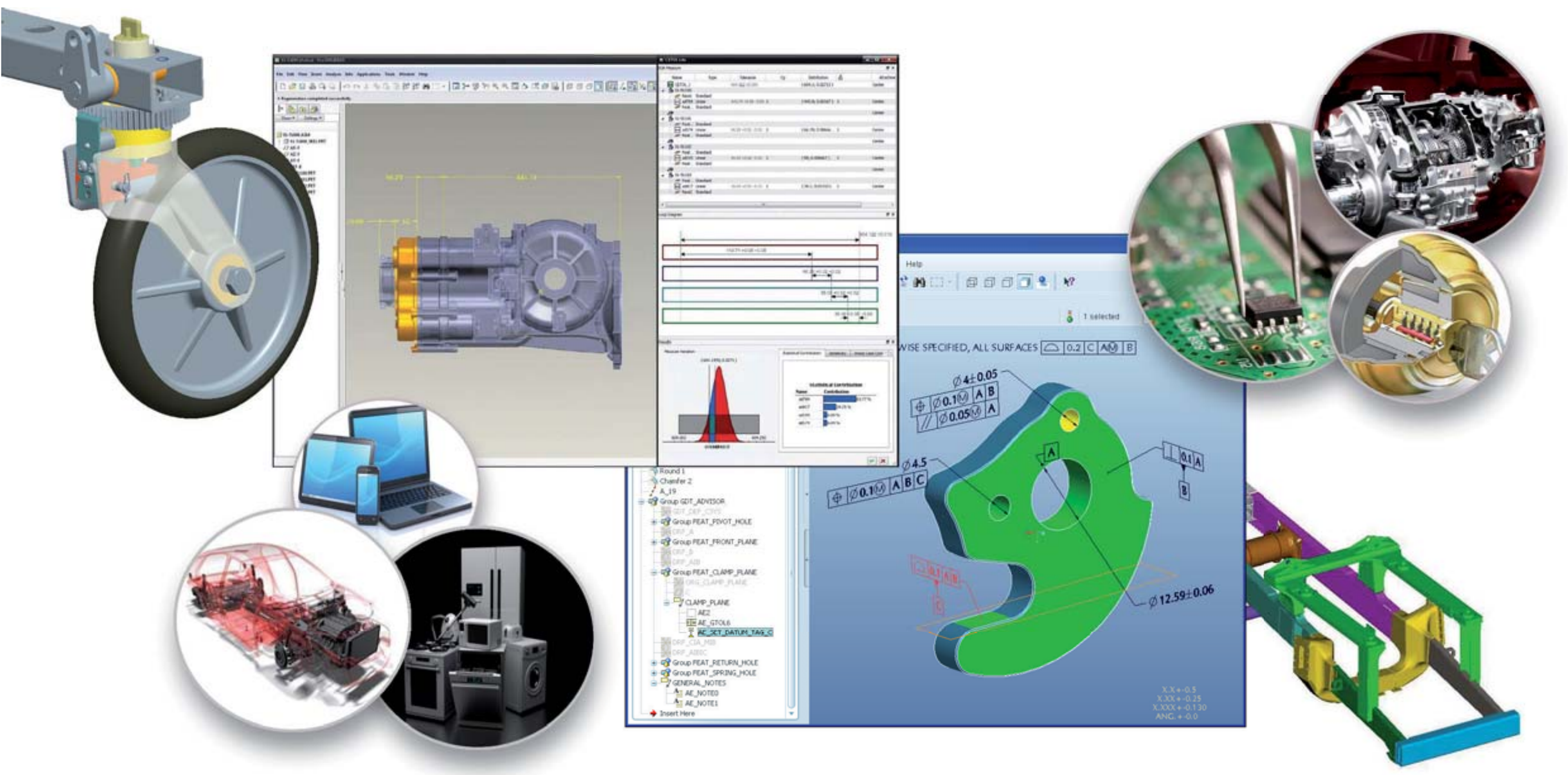
How to reduce cost and increase quality

Effective Tolerance Management

ENGIN SOFT



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Summary

1. The cost of imprecision

This title could seem provocative, but it is a matter of fact: any manufactured object will differ in both shape and dimensions from the idealised conception of its designer. Whilst these differences do not necessarily have immediate consequences for each part in isolation, they become significant as we manufacture many of them, and begin to integrate them into more complex assemblies.

Tolerance has tangible effects upon users, goods and manufacturers. Some effects are insignificant; others have functional, aesthetic, emotional and economic consequences, and may even give rise to unintended consequences.

1.1. The cost of imprecision for the user

Certain types of tolerance can safely be ignored, and may not even be noticed. For example, it is not usually a problem if our building is smaller or larger than planned. Although the difference may be quite large in absolute terms, it does not affect the building's aesthetic quality and function.

But, for example, a tap which drips because the sphere inside it is some hundredths of a millimetre smaller than necessary will require repair or replacement. In this case, accepting the tolerance would lead to irritation or possibly consequential damage. Although the tolerance in the manufacturing process is small, it demands a response with real economic consequences for the consumer and, inevitably, the manufacturer.

Furthermore, our perception of quality is often associated with the level of precision with which an object is manufactured, regardless of the actual technological content. For example, a mobile phone will provide a sense of quality and technological excellence simply by possessing a rigid shell, well-defined edges, flush-fitting joints and micrometric gaps between its moving parts – even though these attributes are purely aesthetic.

To understand the emotional impact linked to dimensional imprecision, we could also consider a well-known example from the automotive sector. Almost everyone would agree that a car appears to be well-constructed if the closing of its doors is smooth, requires little force and produces a precise and subdues noise. This mix of positive sensations can be achieved through good control of dimensions and shapes in the manufacture of the door and the vehicle body. If the closing of the doors feels vague, or requires excessive force or generates a harsh and metallic noise then we have the sensation that the entire car is badly constructed. These sensations are known to influence consumer purchasing decisions.

The effects of tolerance may be very evident in the purchase of replacement parts, in the automotive and other sectors. Consumers will frequently economise by purchasing such components from suppliers other than the original equipment manufacturer. However, if such parts do not comply with the dimensional accuracy specified by the original designer this can lead to assembly problems and time-consuming adjustments. This means additional expense in the repair shop. When such problems occur the decision is often to purchase again, buying original and more expensive parts!

There are thousands of examples we could provide, involving countless everyday goods: we deal with the effects of tolerance in the products we use on a daily basis, but these problems only become familiar when they cause us frustration or require additional costs to resolve.

1.2. The cost of imprecision for the manufacturer

Dimensional imprecision is a well-known and important topic for people dealing with series production. Failing to understand and comply with the necessary level of tolerance in manufacturing can lead to serious financial and therefore business consequences. Pursuing an unnecessary high level of precision may lead to additional expense, whereas inappropriate low precision can lead to; loss of reliability and quality, loss in assembly and warranty costs. In an ideal situation, quality control will notice that the goods do not comply with the dimensional requirements. In this case, you can promptly intervene to find and resolve the cause of the problem. If the cause is not identified promptly, it can lead to interruption in production, and therefore delay product delivery. Depending on the details of the contracts, manufacturers might incur penalties, client dissatisfaction and even forced price renegotiation.

In addition to the cost of imprecision, defects in the shapes and dimensions of supplied parts might be missed by quality control. This case is not so rare, especially if the quality control is conducted on limited samples. In situations where large volumes of the products are placed in the market, the damages may be very significant. To avoid risk or guarantee functionality, the manufacturer may have to replace or fix defective products and invest heavily to recover brand reliability.

The damage produced by badly-chosen or executed manufacturing tolerance is linked to product value. If we consider large numbers of cheap products or small numbers of expensive products, the expense required to rectify problems can easily jeopardise the survival of a business.

An economic estimation is obviously difficult to determine, because mistakes are never advertised by companies. We can approximately predict tolerance damages by referring to car manufacturer recall statistics. Between 1st January to 10th October 2012, foreign brand cars recalled in Italy for defective parts or systems totalled 623,539 (UNRAE data). There are various reasons for these recalls: blocked circuit breakers, sheared bolts, electrical short-circuit risks, accidental contacts. Most of the problems are electrical, but there are mechanical problems too. We can estimate that at least 25% of the recalls were necessary because of dimensional or assembly errors.

In this case, tolerance issues would be responsible of about 156,000 interventions. Based on a reasonable estimate of the median cost of intervention (parts and labour) leads to an estimated total direct cost in excess of 30 million Euros, in only ten months! Brand damage occurs as well, which is difficult to estimate although the consequences can be severe. In early 2010, Toyota stock fell so severely due to reliability and quality concerns that its market capitalisation reduced by twenty-five billion dollars.

It might seem obvious, but the above account shows that controlled component tolerance is not an abstract quality objective, but an issue with very real consequences for business. The effective management of dimensional tolerance can result in competitive advantages and avoid significant costs in rectifying damages.

2. Introduction to GD&T

GD&T stands for **Geometric Dimensioning and Tolerancing**; a system of symbols and variation guidelines increasingly used in describing the size, shapes and permitted variation of components and products destined for production.

2.1. The history

The history of GD&T started a century ago, and its utility became more and more relevant starting from the Second World War. In this period the USA produced and delivered across the Atlantic Ocean a huge quantity of components and parts to help the Allies in their war effort. Many of these components, despite being produced according to the relevant design specifications, could not be installed due to assembly problems.

After the war, a commission of government representatives, companies and universities analysed the problem of how best to guarantee the satisfactory assembly and function of a product. The result was the development of a language for systematically describing geometric dimensioning and tolerancing – this language is known as GD&T.

2.2. GD&T advantages

In practice, the aim of the GD&T is to communicate to the manufacturing department the degree of accuracy and precision with which components have to be made.

Each component of a finished product is the result of a chain of different subsidiary processes, and each one has a different degree of variability, or imprecision. The result of this situation is that, when the process is completed, the manufacture component does not have the exact geometry and dimension specified in the initial design.

So GD&T is useful for specifying the limits within which the manufactured parts may deviate from their idealised or nominal dimensions. If the real component exceeds these acceptability limits, it would be necessary to reject the design during the quality control phase.

Therefore, if the design requires the specification of manufacturing tolerances, which it invariably does, this also implies that the production process needs a dimensional control system to verify that they are respected. Now we understand that tolerancing is directly linked to production cost: if you increase the precision of components (reducing tolerance values), you will have to implement a more precise and expensive manufacturing process. This will also require more precise tools and measuring methods in the quality control phase, possibly requiring more highly-skilled employees: all these elements contribute to an increase in production costs.

It is also obvious that a tolerancing policy is required, since operating without appropriate criteria would mean a decrease in product quality, either functionally or aesthetically.

It will now be clear to you that a correct and conscious use of GD&T has to perfectly balance two opposite requirements:

1. on the one hand, GD&T must be used to specify adequate tolerances to guarantee product assembly, function and aesthetic performance.
2. on the other hand, GD&T should not be used to specify too high a degree of precision, which would over-constrain the manufacturing and assembly process and lead to unnecessary costs.

3. Geometric dimensioning and tolerancing: complementary aspects

3.1. Dimensional tolerancing

A designer knows that a component's nominal dimensions will never be perfectly reproduced by the manufacturing department, no matter how precise and accurate the production will be.

For example we are now considering the block represented in the Figure 3.1.

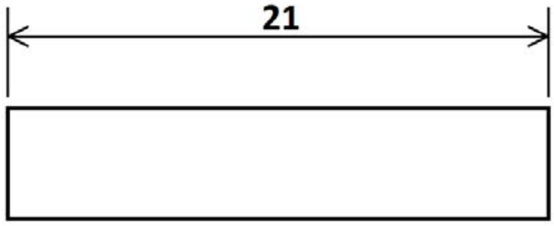


Figure 3.1

The designer decided that this component will have a nominal length of 21 mm, but he knows that this length will never be exactly this in the finished item because of imprecision in the manufacturing process.

However, the item won't necessarily be rejected, since users will be able to use it without problems if the actual dimension is very similar to the nominal one. But what does "very similar" mean?

The answer can be found in the definition of dimensional tolerancing: the range of values in which a component dimension (linear or angular) is acceptable. In the design it is usually on the edge of the related figure, with the symbols "+" and "-", as showed in the Figure 3.2.

The designer writes in the project which dimensions and tolerances are acceptable for the component (so "very similar" to the projected one). In this example, the length has to be between 20.98 mm and 21.01 mm.

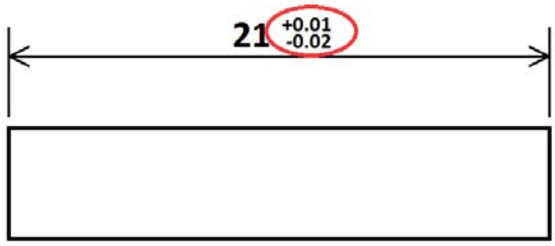


Figure 3.2

The designer is specifying that if the manufactured component has a length of, for example, 20.97 mm or 21.02 mm then it would have to be rejected. Of course the designer must have a means of deciding what limit to specify for this dimension – a topic that will be considered later. But once the decision is made, GD&T will enable the designer's intentions to be clearly specified for the manufacturer.

3.2. Geometric tolerancing

Simple dimensional tolerancing present some problems. First they could provide non-standard tolerancing limits. For example, considering the positioning of a hole in a plate, as shown in the Figure 3.3. The designer has specified the location and tolerance of the centre of the hole, rather than its edges, and done this in two mutually-perpendicular directions.

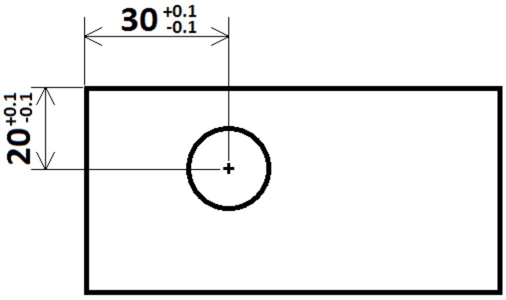


Figure 3.3

These two linear tolerances together specify that the axis of the hole could acceptably lie anywhere within an "acceptability area" which, in this case, is a square with its centre at the nominal point and with 0.2 mm sides. Any holes located within this area are acceptable (Figure 3.4).

Actually this configuration provides an ambiguous performance requirement. Points in the square are acceptable as much as 0.141 mm from the nominal point, provided that they are in the corners of the "acceptability square".

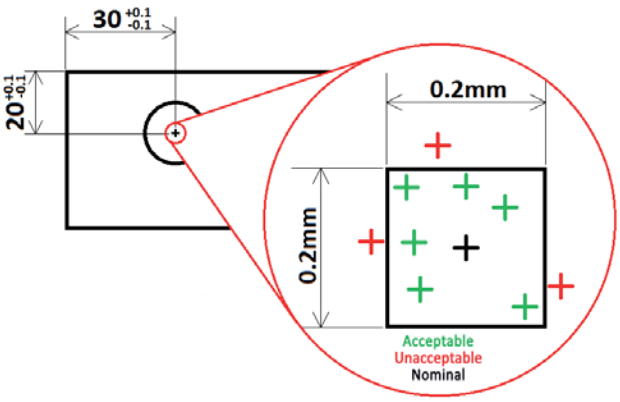


Figure 3.4

However, there are points that are closer to the nominal, but unacceptable because they are not in these corner regions. This paradox exists because linear dimensional tolerancing has been applied independently in two directions, but it is evident that the correct position of the hole most probably ought to be evaluated considering their combined effects.

This paradox cannot be resolved using two dimensional tolerancing in this manner. If this designer wishes to limit the deviation of the centre of the hole from its nominal value then such a scheme will always lead to some acceptable designs being rejected (if the two tolerances are drawn too tightly) or some unacceptable designs being accepted (if the two tolerances are too loose).

For example, if the designer wants the hole axis to be at a distance lower than 0.141 mm from the nominal axis, using two dimensional tolerancing of 0.100 mm lead to reject some correct configurations (Figure 3.5).

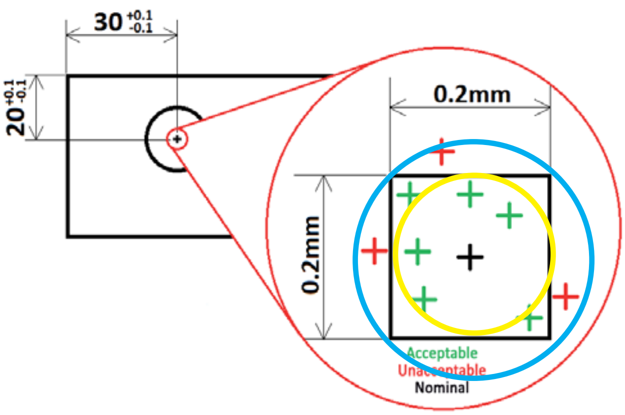


Figure 3.5

We can solve this ambiguity by defining a geometric tolerance in a circle, centred round the nominal point (not a square). The circle will include all the acceptable axis positions.

Geometric tolerancing establishes an implicit link along coordinated directions. It's evident that geometric tolerancing is important to permit a designer to accurately specify that a hole should be "not too far" from the nominal point. Such a scheme will enable the designer to request that the distance of the manufactured hole axis should be no more than 0.141 or 0.100 mm from the nominal value without any subjectivity in its interpretation.

4. Functional Dimensions

Most products available on the market are assemblies of multiple individual components. Tolerances assigned to individual components have a crucial role in guaranteeing the assembly and correct functioning of the finished product.

Product compliance, if not related to aesthetic factors, is the conformity of one or more of its dimensions to prescriptions for the assembled system: these are named functional dimensions. All products have this characteristic, no matter the sector, the material (polymers, metals, ceramics, glasses) or the function.

If we consider the watch locking mechanism, represented in the Figure 4.1.

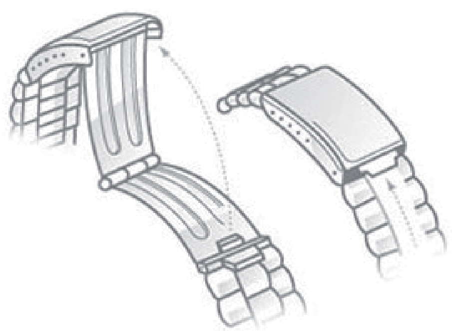


Figure 4.1

It is made of two elements of pressed steel, acting as balancers. These two elements have to contact each other through a small "hanger", on which a form of hook operates to fasten the watchstrap and secure it in place. This is shown in the Figure 4.2.

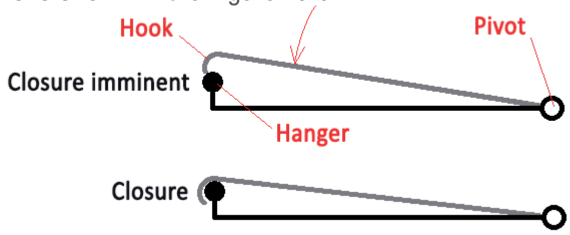


Figure 4.2

Hanger and hook must be positioned in a precise way that, during the closing movement, a small degree of interference (Figure 4.3) can provide an elastic deformation to the hook that once closed will firmly lock the hanger and will avoid accidental openings.

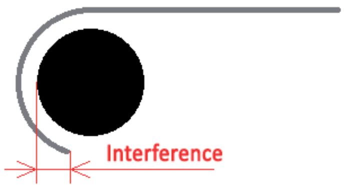


Figure 4.3

The effective operation of the strap depends on this interference: for this reason it is called functional dimension. It has to be carefully controlled because:

- → If it is too strong, the strap will not close, and the user could damage the strap by attempting to force it.
- → If it is too weak, the strap might close, but would open too easily.

In this particular case, the functional dimension will depend on various factors such as:

- → Distance between the centre of the hanger and the pivot
- → Radius of the hanger
- → Offset between hanger balancer and hook balancer
- → Play between pivot and balancers
- → Distance between the centre of the hook and pivot
- → Hook internal range
- → Hook angular rotation

The interaction of these dimensions is called the dimensional stack-up. These dimensions interact with each other and they enable us to calculate the functional dimension. Along this dimensional chain, single tolerances are combined and propagate, leading to increasing uncertainty in the value of the functional dimension.

Tolerance analysis is a calculation process that quantifies the effects on the precision of the functional dimensions of tolerancing and uncertainty sources in the dimensional chain.

Tolerances propagate because of an elementary mechanism: contact between assembled component surfaces. Since these surfaces are **differently disposed in the space** (three-dimensional problem), **differently contoured** (flat or curved) and **differently paired** (contact between point and surface, or surface and surface, or surface and hedge etc.) the combination of their tolerances is a very complex problem.

Setting up mathematic expressions calculating functional dimensions depending on the tolerancing in a three-dimensional context is almost impossible. To do this accurately would take far too long for a manufacturing company, and soon becomes almost impossibly complex mathematically. Whilst solving this complexity through conventional tools may (to all intents and purposes) be impossible, with some deep simplification we may be able to approximate it.

5. Tolerance stacking

Technical offices that deal daily with good production and tolerance analysis often simplify this general problem into a two dimensional or even a one dimensional plan. This operation transforms the original dimensional chain in a series of stacked linear quotes, each one with its own tolerance value.

Let's analyse a simple application, for which we will later analyse the risks and implications of our simplification.

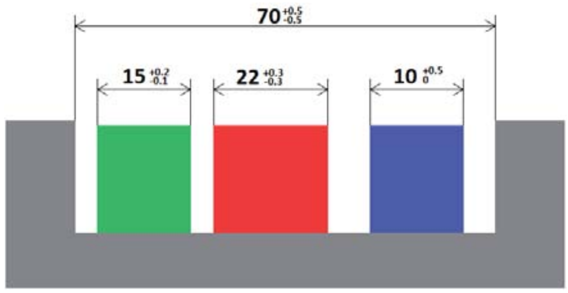


Figure 5.1

Figure 5.1 represents three blocks located in a "U" shaped main block. We decide that the functional dimension of this system is the play between the last block and the right side of the main block, when they touch each other and lean against the left side (Figure 5.2).

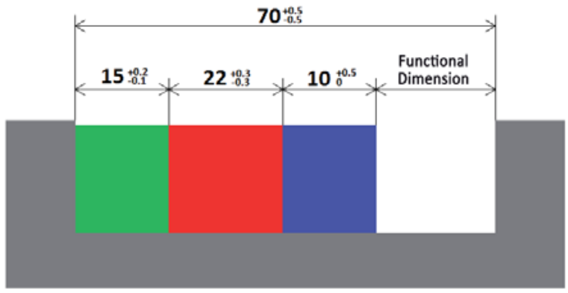


Figure 5.2

This functional dimension controls the ability of the assembled system to contain an eventual fourth block.

The study of one-dimensional tolerance propagation aims, in this case, to correlate the play between dimensional properties of the single blocks and the main block with those ones of the functional dimension.

The functional dimension's nominal value is:

Functional dimension=70-15-22-10=23mm

Maximum and minimum values can be determined for the functional dimension, expressing each component dimension with the related variability limits, so that:

MAX=(70+0.5)-(15-0.1)-(22-0.3)-(10-0)=23.9mm

MIN=(70-0.5)-(15+0.2)-(22+0.3)-(10+0.5)=21.5mm

6. Two-dimensional approach

We have observed that the one-dimensional tolerance analysis of an assembled product is not very difficult. Even for objects a little more complex than blocks, we could easily solve this problem, though a little mental effort and the use of a spreadsheet.

But in reality nothing is one-dimensional and nothing has a perfect geometry.

To illustrate this concept, let's consider an assembly made from different blocks as shown in Figure 5.1.

For each block the only variability is the width, and we have seen how it can be used to calculate the functional dimension. This is a one-dimension schematization. In reality, each block has many different sources of uncertainty, more than those ones shown in the Figure 5.1. Each block differs in both height and corner angles; its edges aren't perfectly aligned (as in the figure), but have an irregular shape. So, what consequence does each block's mono-dimensional variability have in the functional dimension? It is shown in the Figure 6.1.

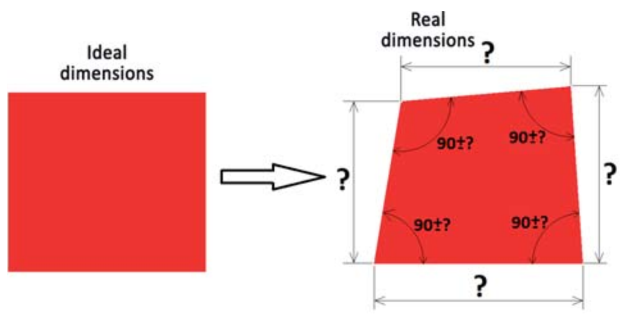


Figure 6.1

Here we find that the contact among blocks doesn't occur on a contact side, but on a contact point, in which the position depends on each component's geometry.

The functional dimension doesn't depend on four simple linear dimensions, but on the points of contact which themselves will depend on the different angles and lengths.

This example clearly explains how moving into a two-dimensional scheme causes a lot of problems, even if these elements are very simple. Moreover, we have to consider that the configuration of this system is not standard because the contact point's positions will themselves depend on how the system was assembled.

We can analyse this topic matching Figure 6.2 and Figure 6.3:

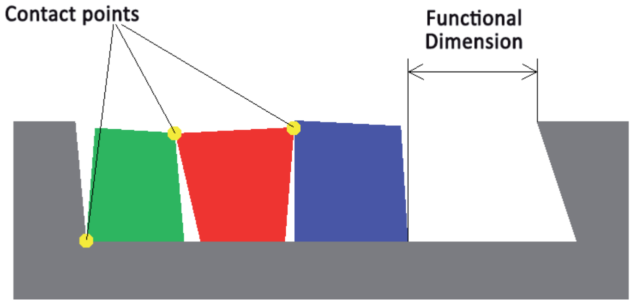


Figure 6.2

In these two schemes, the contact points positions are completely different, as well as the functional dimension. This is an important implication, because we have to perform a separate analysis for each of the different configurations to calculate the same functional dimension.

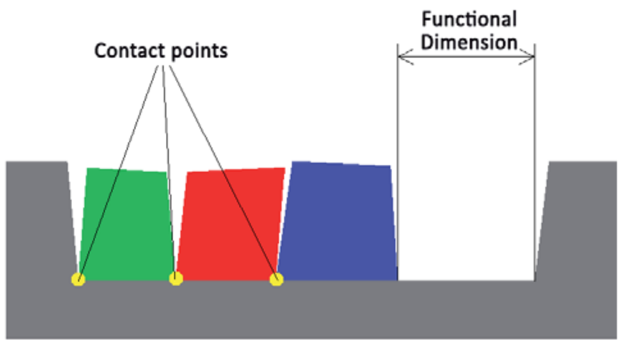


Figure 6.3

7. Three-dimensional schematization

Now we are going to extend the analysis to the third dimension: obviously this problem is more complicated than the two-dimensional analysis; each block has now a variability involving the inclination of all edges, in each of the rotational dimensions and size variation in its own three dimensions (height, length, width).

Furthermore, any functional dimension still depends on the assembly process. By way of example, Figure 7.1 illustrates a sequence of operations made to assemble the object:

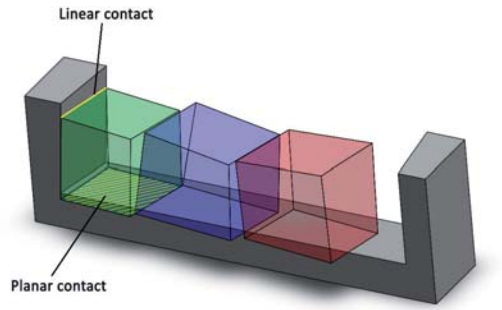


Figure 7.1

1. each block stands on the horizontal surface of the main block, by a plane contact with this element.
2. each block touches the closest surface to the left, by a linear contact with this element.

Here the choice of sequence is ambiguous and deeply affects the result. In this case, we have chosen to put in contact the lower surfaces of each block first, because gravity forces the interaction.

Figure 7.2 is a representation of the functional dimension of this system.

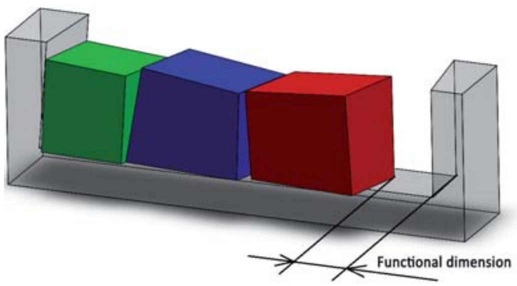


Figure 7.2

The choice of points was done in an arbitrary fashion to get the closest points to measure from: this arbitrary choice obviously has an influence on the final result.

Hopefully you've noticed, without going into any detailed equations, how seemingly trivial problems of analysis can become deeply complex and hard to solve when extending these analyses to the second or third dimension - even for assembled products with very simple geometries.

8. Worst Case Analysis (WCA)

In the paragraph dedicated to the one-dimensional tolerancing, we determined the variability of the functional dimension: using simple calculations, we defined two limits per dimension (the highest and the lowest), compatible with their range of variability.

To calculate this variability, we summed every quote of the chain in accordance with two combinations:

1. summing all the lowest dimensions
2. summing all the highest dimensions

In this way, we've obtained two values for the functional dimension, representing the limits of its range of variability.

This calculation approach is called Worst Case Analysis (WCA) and it means calculating the functional dimension using the two most unfavourable combinations that could occur, and determining the highest variability.

Although this concept is correct, this approach presents several implications: statistically it considers that each possible combination of quotes in the dimensional chain has the same probability of occurrence, or at least, it considers the implausible combination of the worst possible combination of errors.

For instance, consider a factory is manufacturing the assembled product mentioned above. Suppose that the production line is split up into four different manufacturing departments, each producing a different type of block and a fifth assembly department receiving the other department's production output on pallets. Each pallet contains the type of block from its corresponding manufacturing department. Our analysis is equivalent to assuming that the assembly department chooses to assemble all the smallest components for one functional dimension, and then all the largest components for another functional dimension.

Obviously these situations are extremely unlikely to happen in reality, because the choice of the components will be random and even if there are components at the limit of their acceptable dimensional range, they will be unlikely to be combined with similarly extreme parts – such parts will most probably be combined with others possessing dimensions within their permitted limits, diluting the consequences of the extreme part.

Nevertheless, the Worst Case method of analysis guarantees complete certainty, since every possible conceivable combination has been considered. Unfortunately, this also typically leads to very high production costs, in an attempt to reach such a high precision of machining standards to guarantee that no possible combination of parts will fail to satisfy the required functional dimensions. In practise it is more convenient to reduce your process' precision and costs, and reject a small proportion of your final products.

All rejected items represents a cost, but if we deal with thousands or millions of parts, this cost is smaller than the savings due to a more economical production process (i.e. few rejected items per million, if using a "six sigma" approach).

9. The statistical approach

We have just discussed manufacturing for the WCA approach is very expensive because it considers the very worst possible combination of individual part dimensions. In practice, we can usefully treat the problem quite differently, using a statistical approach.

In fact, when parts are manufactured within their permitted tolerance, the majority of them will have dimensions close to some mean value, with a decreasing proportion having dimensions at greater distances from this mean. This means that it is more probable that the real dimensions are closer to the median value of the variability range rather than far from it. To clarify this concept, we can analyse the cylindrical component shown in the Figure 9.1:

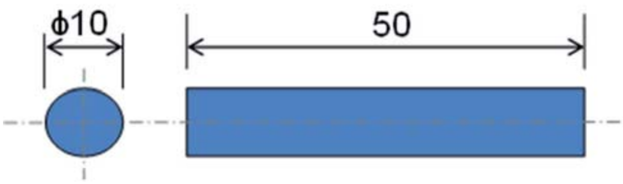


Figure 9.1

For example, the defined dimension is 50mm long. We know that during the production process, the intended length won't be reflected in every item. Suppose that our manufacturing process is set up to produce parts with a mean length which matches the nominal value: we know that considering a sufficiently big statistical sample of real parts, that there will be a statistical dispersion around the nominal value, which has a normal distribution and a standard deviation. This is a direct consequence of the width of the tolerance range chosen by the designer (Figure 9.2.). But it is not the only possibility.

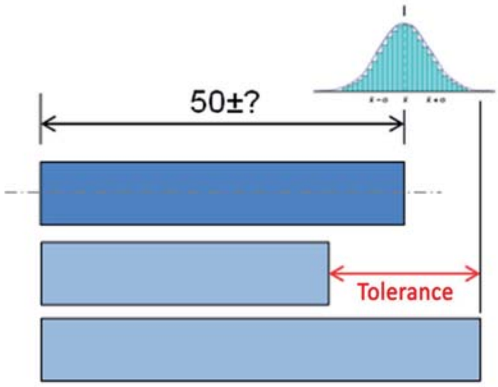


Figure 9.2

Observing the chart of the distribution, we know that statistically, most of the samples have a value very closed to the medium value (nominal), while smaller numbers of the item differ by greater amounts from the nominal.

Since this characteristic is common in every dimension (even if sometimes the distribution is not perfectly normal), we have to add component variances to calculate the variance in the functional dimension. This is very different from the Worst Case Analysis, in which you add the maximum deviations.

Using the statistical approach, we can also recognize which tolerances are responsible for the biggest contribution along the dimensional chain, enabling the designer to make the appropriate corrections early in the design phase.

In effect, the statistical approach enables the designer to deal with the most likely combination of errors, rather than the worst possible combination. Furthermore, where the distribution of the component tolerances are known, it permits a quantification on the likelihood of success, which can be set to correspond to the allowable risk of the assembly being imperfect.

Compared to a Worst Case approach, the Statistical approach will permit the use of wider tolerances, leading to reduced production costs without significantly diminishing product quality. It also permits the prediction of the percentage of wasted parts that we might expect once production begins.

10. Sensitivity Analysis

When we set up a model of tolerance analysis, we are setting up a kinematic model of the functioning of the assembled system, since we are including every dimension of the dimensional chain (with the related variability range), we are defining each functional dimension (with the related acceptance range) and which surfaces will be in contact with each other.

It means we are mathematically defining how the functional dimensions can vary as the component dimensions in a dimensional chain vary (the variability that is limited by the tolerancing range we defined for each dimension).

For instance, we can consider again a simple system formed by several blocks (Figure 6.3):

What effect does each block's dimensions have on the functional dimension? In this simple example it is evident that if one block has a longer dimension, the functional dimension would decrease by the same amount. This phenomenon can mathematically be explained through the sensitivity analysis:

$$Sensitivity = \frac{functional\ dimension\ variation}{variation\ along\ the\ dimensional\ chain} = -1$$

This value is negative because an increase of the dimension along the chain produces a decrease of the functional dimension; and it is unitary because variations are of the same amount (if one block lengthens by 1 mm, the functional dimension decreases by 1 mm).

On the contrary, if each block maintains the same dimensions, but the main block has different dimensions, we would obtain the following sensitivity:

$$Sensitivity = \frac{functional\ dimension\ variation}{variation\ along\ the\ dimensional\ chain} = -1$$

In this case the sensitivity is positive because fixing each single block's dimensions and increasing the main block length leads to an increase in the functional dimension; and it is unitary because an increase of 1 mm in the length of the main block produces a 1 mm increase in the functional dimension.

The above mentioned example is a simplified version of the sensitivity analysis. In this case we can suddenly recognize the results because the analysis model has got simple linear lengths, placed in series, with a perfect planar contact between all the adjacent surfaces.

However, any other assembled system is more complex than this example, with tolerancing on the edges (for example tolerancing on parallel or perpendicular surfaces) and geometric tolerancing (profile or shape tolerancing). In these cases the sensitivity analysis becomes a kinematic problem, and it is difficult to solve it, because we have to consider that all the contact points move among every component, varying each dimension of the dimensional chain.

Even from this analysis you will see how useful it is to have a tool that is able to analyse sensitivities since it enables us to understand where and how much to intervene, to adjust the nominal (mean) values of functional dimensions.

Combined with a statistical analysis that is able to predict their variance, this information massively strengthens the ability of the design process to deal with production variability.

11. Statistical contribution analysis

Analysing the chain of tolerancing, we can usually benefit from using both the sensitivity analysis and the statistical contribution analysis.

Quality control requires us to discard any parts for which a functional dimension lies outside the design acceptance limits. Considering the functional dimension shown in Figure 11.1, we would need to discard those parts in the red "tails" of the probability density function.

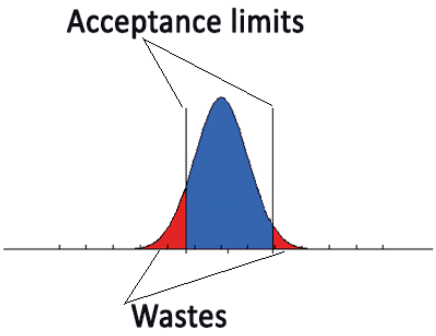


Figure 11.1

The chart represents the distribution of frequency in a generic functional dimension: values in blues are included in acceptance limits; the red ones are over these limits and have to be rejected. We are supposing now that among all assembled products, 70% of them are acceptable, but 30% of them have to be rejected.

Which part tolerances made the biggest contribution to the number of discarded assemblies? The statistical contribution analysis can give the answer.

We can clarify this concept considering a complex production. In this case the situation is represented in the Figure 11.2.

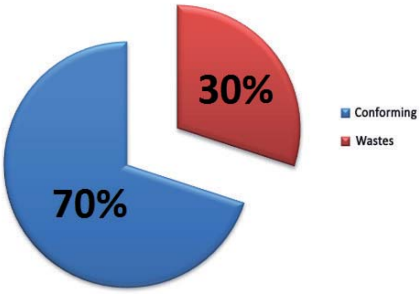


Figure 11.2

The statistical contribution analysis related to the 30% of waste assemblies is represented in the Figure 11.3:

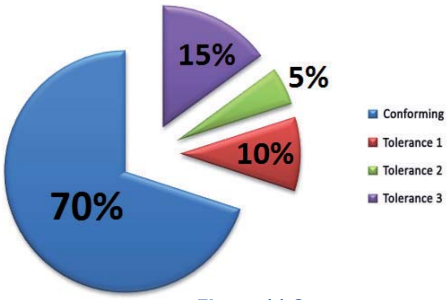


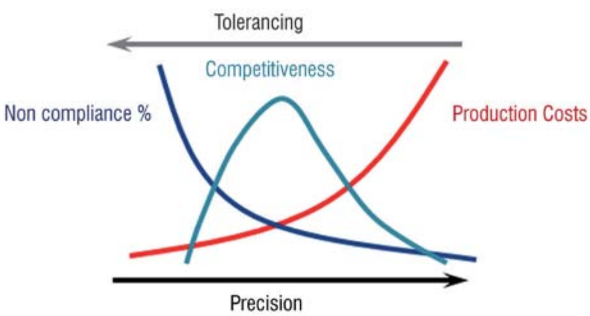
Figure 11.3

The chart shows that not every tolerance in the dimensional chain is equally responsible for the out-of-limit assembly. We notice that most of waste is caused by variability of “Tolerance 3”, while “Tolerance 2” doesn’t contribute so significantly to the rejected parts.

Aiming to reduce the percentage of waste, you will have to act on “Tolerance 3”, because it would provide the best improvement to the production process.

12. CETOL 6σ: an essential tool for analysis and optimisation

We have just analysed all theoretical aspects of dimensional and geometric tolerancing, so we now have to understand how designers, production controllers and quality controllers can avoid or, at least reduce to acceptable limits, cases of faultiness caused by imprecision in the manufacturing process.



It is not only a technical matter because decisions about tolerance specification will affect defect rates, production costs, warranty claims and business reputation. These all have a direct effect on business profitability. In some sectors these errors are not allowed (because of regulations or the very high costs of defects), but for all the other sectors we have to define a strategy for tolerancing that balances costs and advantages.

You can only really understand the relationship between part tolerances and assembly performance by finding **the mathematical relationship that analytically links the non compliance percentage to the individual part dimensions their related tolerances.** Tolerance analysis is the set of operations that lead to this law.

We can easily understand how important it is **to find these relations, to find them correctly** and **to use them to your advantage.** Without a correct tolerance analysis, you risk the production of an excessive percentage of waste, or the production of a small number of defects but at an unacceptably high production cost.

Tolerance analysis leads to an understanding of how imprecision in component manufacture stacks up to determine the dimensional properties of the assembled product.

This operation seems easy, but in the practice it is a long and complex task. You need precise analyses of **geometries** and their **external interactions** remembering that ASME and ISO laws on tolerance specifications, with appropriate mathematics to compute the extremely complex way in which the multiple parts combine in three dimensions.

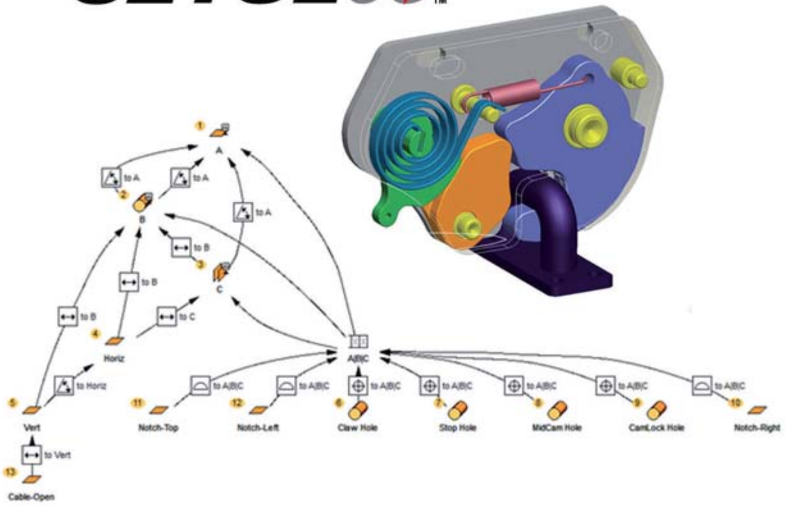
A manual analysis of tolerancing on a three-dimensional assembled system with a medium complexity is, to all intents and purposes, impossible.

For this reason, in the majority of cases, tolerance analysis has been carried out with great simplification of the real problem and dealing with only the largest effects.

The CETOL 6σ software addresses these potentially misleading simplifications and provides a straightforward environment to tackle the full three-dimensional analysis of interacting part tolerances. The software builds the mathematical model which relates the functional dimension and their variances to the component part tolerances and variances, computes the sensitivities, statistical contributions and (if required) conducts a worst case analysis too. These are exactly the tools that you require to efficiently deal with tolerance issues at all stages in the product delivery process, from the initial specifications through each stage of the design and manufacturing process and onwards into the whole life management of the product.

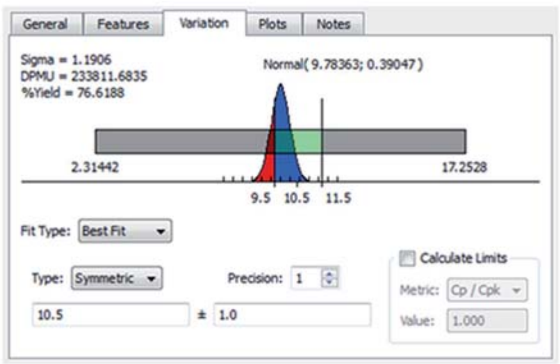
At the core of this capability are CETOL 6σ's unique algorithms for computing the kinematics of arbitrarily-profile contacting surface – "precise constraint technology." These equations empower CETOL 6σ to compute the effect of part dimensions and their variances on the functional dimensions, permitting a comprehensive understanding of the tolerance problem for any assembly.

The user simply defines the manner in which way components interact each other, and CETOL 6σ handles the mathematics seamlessly, within the standard CAD interface.



This approach means that you only have to **analyse the assembly process**, and in particular the geometrical details that physically determine positions of parts. Implementing this analysis within CETOL 6σ is easy because it is done within the CAD interface (Solidworks, Creo, CATIA V5), involving the selection of pairs of interacting surface directly on their CAD representations.

CETOL 6σ's mathematics ensures that any possible interaction between pairs of surfaces can be represented – every real interaction type can be implemented in a straightforward and intuitive manner.



At the end of this virtual assembly process you have a numeric model. At this stage, the user only has to apply tolerancing precisions to the details selected in the "virtual assembly" phase, which can be both dimensional and geometrical.

This operation is easy and fast, because it is only a transcription into CETOL 6σ of the usual tolerancing prescriptions present in the design. In accordance to the ASME's standard, CETOL 6σ's database covers all the possible cases of tolerancing. In fact, if GD&T has previously been specified directly on the CAD model then it can be imported into CETOL 6σ, used within the CETOL 6σ mathematics and directly updated whenever the CETOL 6σ data is changed by the user!

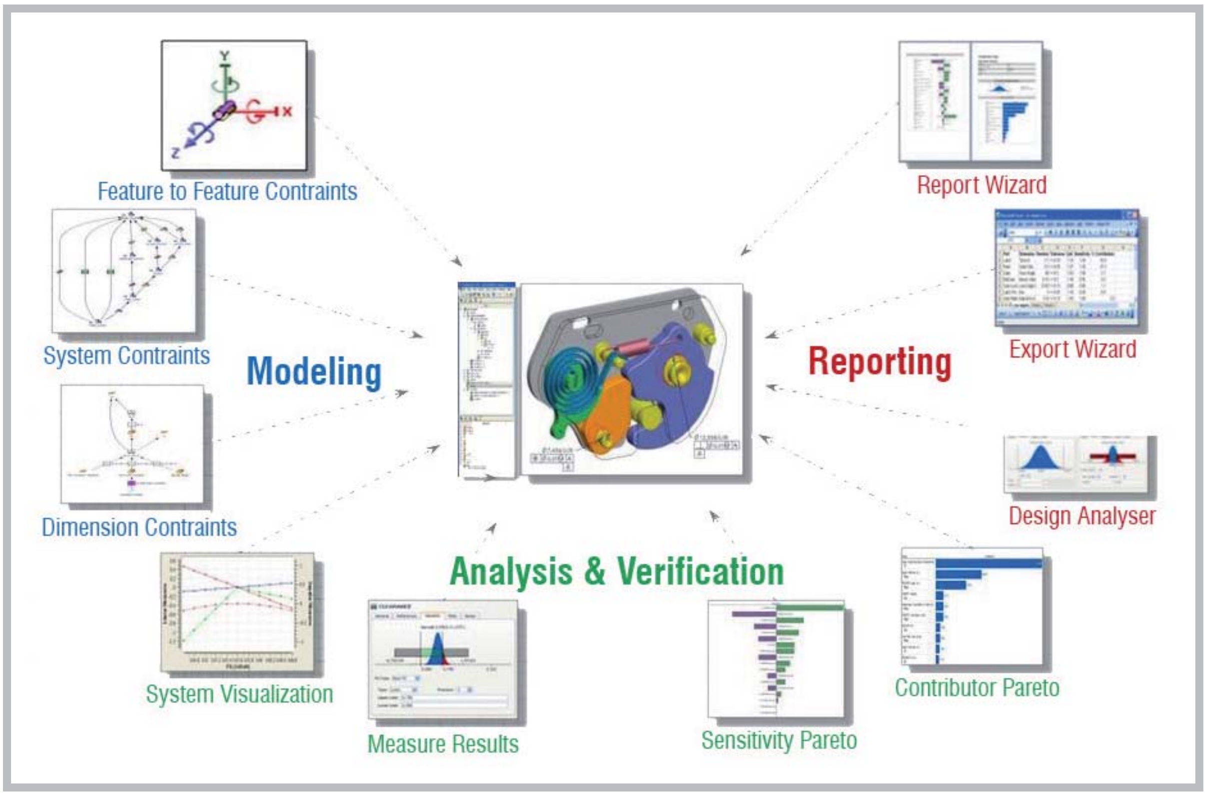
The last step is to identify all the functional dimensions of the assembled system for which we wish to analyse **dispersion**. You can define these functional dimensions by selecting the surfaces directly involved on their CAD geometries, and the problem is formally completed by supplying appropriate acceptance limits to each functional dimension.

It is important to emphasise the significance of CETOL 6σ's mathematical approach. All other tolerance analysis tools working in three dimensions use a Monte Carlo approach. This involves the definition of assembly rules that cannot compute the sensitivities of functional dimensions to changes in part dimension. Their assembly technique just amount to rules for how parts approach each other into contact, and their calculations involve the creation of large numbers of variant parts embodying the statistical distribution of the their dimensions. To compute the variance in their functional dimensions, these parts must be brought together in random combinations to directly explore the resulting functional dimension distributions by subsequent statistical analysis. Such approaches lead to very long calculation times and do not yield either the precision of CETOL 6σ or the same analytical information.

CETOL 6σ uses a **numerical technology** that enables you to make the same analysis in very short time, maintaining both a high level of precision and reliability.

This impressive speed makes it suitable for repetitive analyses, even directly in optimisation problems.

CETOL 6σ provides an excellent presentation of statistical results. It summarises and represents in an **ordered and accessible** manner all the fundamental indicators that check eventual defects linked to manufacturing tolerance. It analyses the causes of potential problems and helps you to choose the **most effective and economic remedies.** In particular, determining the statistical contributions and conducting the sensitivity analysis becomes a natural and intuitive operation that fully characterises the problem.



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