Systematics for development of dimensional characteristics of automotive industry products

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Abstract: The definition of a product's dimensional characteristics is a challenge in project development in the automotive industry due to its construction complexity, in which several components from different development areas and suppliers must interact in a final product. Dimensional characteristics are understood as being those related to tolerances, gaps, fit, matching between parts, product specification and control charts. In order to allow the product to be assembled without the need of further adjustments and within the time determined for its assembly, it is necessary that all these characteristics be specified, verified and confirmed in the individual parts and in the composed assemblies of those parts. This study proposes a system that enables the identification, evaluation, definition and control of dimensional characteristics in the development of a new product, from the initial phases of the project to the mass production, using different tools and concepts of tolerance analysis. The system is exemplified through its application in two actual production cases (taillight and front-end) in a car assembly company.

Keywords: tolerance analysis, variability, deformable assemblies, dimensional management, assemblability.

1. Introduction

The increase in global competition due to the growth of previously unknown brands and their arrival in new markets forces automotive companies to launch products with increasingly shorter development periods. These products must be differentiated in terms of innovation and quality, which compels assembly companies to work with more modern and complex styles from the perspective of manufacturability. Hammett, Wahl and Baron (1999) add that, as the product life cycle becomes shorter, assembly companies place great emphasis on the development of new products.

The positive results in productivity achieved by companies that adopted lean manufacturing systems have made their implementation essential from the standpoint of competitiveness. Added to that demand is the constant effort to reduce the number of hours necessary to assemble a vehicle. The main action to introduce of such improvements has been a better integration of the development resources in the design and product development processes by means of practices such as simultaneous engineering, design for assembly and partnerships with suppliers.

In his analysis of product development engineering processes in automotive companies, Fallu (2004) shows that, in an attempt to improve the product development process and engineering quality, many automotive companies implemented and continue to implement several initiatives aiming at enhancing discipline in the engineering process and thus meeting costs, deadlines, and satisfaction and quality targets.

The concept of dimensional development is introduced in this scenario as a tool to support product and process development systemically and systematically with focus on dimensional quality, a characteristic of great importance to the final product quality and the operational efficiency of automotive companies.

This study proposes a systematics that enables the identification, evaluation, definition and control of dimensional characteristics in the development of a new product, from the initial phases of the project to mass production, using different tools and concepts of tolerance analysis. Dimensional quality is understood as all dimensional characteristics of individual parts and assemblies that allow a planned assembly, without rework and further adjustments in the factory floor. For the final consumer, dimensional quality represents equipment with good aesthetics and proper functioning, without noise or unexpected failures.

2. Product and process development in the automotive sector

The initial phases of product development do not involve the manufacture of parts, requiring only the development of the product's concepts and drawings for the manufacture of prototypes. As it is an initial phase of the development, different design and manufacture concepts must be decided upon based on the premises of the project. The simultaneous engineering groups start to work in this phase to check the project for manufacturing feasibility and quality of the product concept. Figure 1 exemplifies the main assemblies and corresponding areas involved in the development of a new concept. Simultaneous engineering groups are established, among other reasons, to try to solve process and product problems integratedly, with specialists from different company areas working together to avoid development errors.

The automotive product is made up of several correlated components and each construction element has its variability index. If the sum of variabilities of the final product is not evaluated or calculated, it may represent a chronic manufacturing problem resulting in potential inconveniences to the internal client, such as manufacturing, or to the final client that buys the product.

A great flow of technical information coming from various areas and departments with different, or even conflicting, feasibility needs must converge in the product drawings. It is essential to have clear interfaces in order to define premises and register information within subsystem development areas, involving even the suppliers, since all components must interact when performing their functions in the final product. Figure 2 exemplifies other departments involved in the product development process.

Due to positive results in productivity, companies are forced to plan or update their new processes according to concepts of lean manufacturing (WOMACK; JONES, 2003). In order to meet such premises, each assembly operation must occur according to a plan, following the assembly sequence, movements, fastening sequence, final assembly time and quality. An unsuccessful assembly operation due to difficult or impossible fitting between parts, or even an assembly whose adjustment results do not meet product specifications will generate rework during the operation or, in the worst case, rework at later points of the assembly line. Deming (1990) complements that the rework cost represents only part of the cost generated by low quality. Low quality causes decrease in productivity along all the production line, and some faulty products end up in the consumer's hands.

Another relevant factor for the productivity of automotive companies is the reduction in assembly time. Great attention has been devoted to the elimination of unnecessary operations and movements that do not add value to the product. Rework caused by bad product or process specification has direct influence on assembly time due to the additional adjustment and rework time. Before production starts, the dimensional characteristics of the set of components that make up the product must have been specified, evaluated, detailed in drawings and verified concerning manufacturability by means of simulations in the future process condition.

The development of the production processes begins almost at the same time as the initial product concepts, due to the need to analyze the technical feasibility of manufacturability. The technical discussion generated at this phase is of the utmost importance to foresee the dimensional behavior of the product, because in order to define assembly reference points and functional relations it is necessary to evaluate the whole vehicle assembly concept and how its components will interact.

The launch phase represents the challenge of verifying if the product manufacturing condition is adequate, as well as identifying new problems under permanent operation

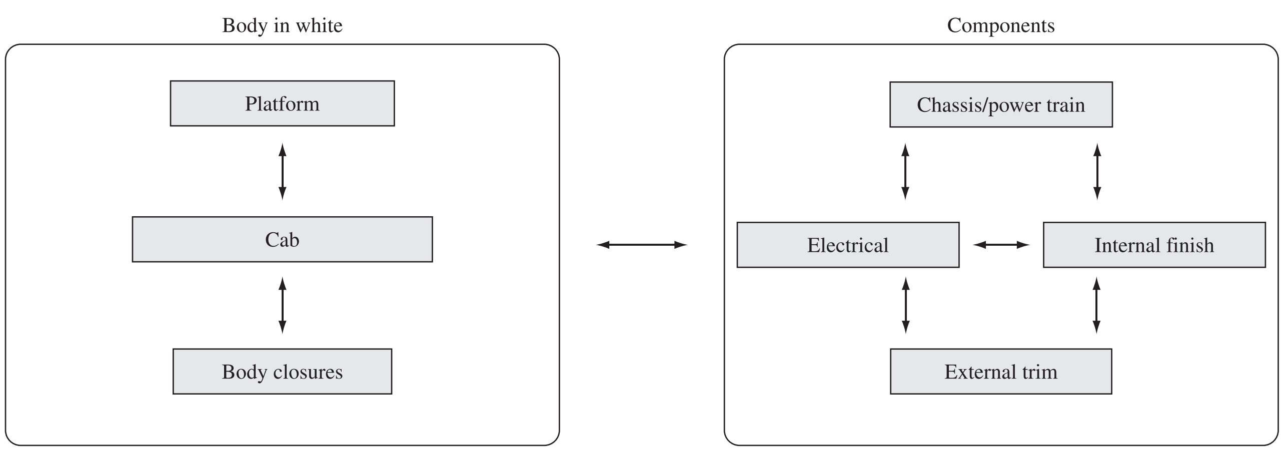

Figure 1. Main development groups of automotive components.

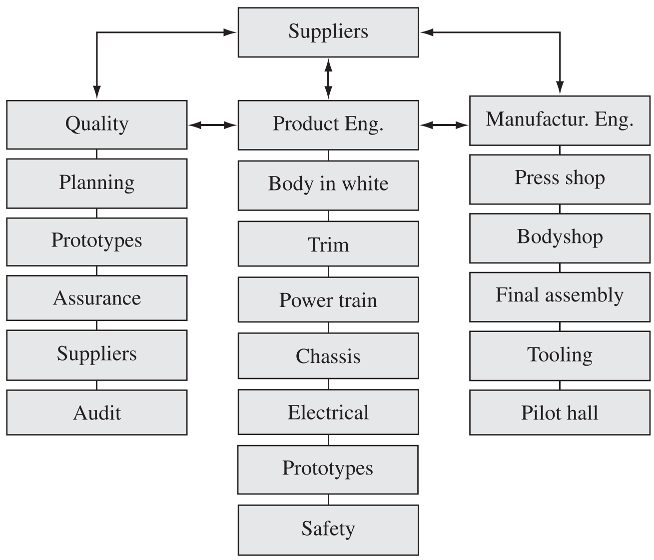

Figure 2. Involvement of other departments in product development.

conditions. Great emphasis is placed by the administration on the stabilization of component manufacturing processes within product and quality specifications, due to the necessity to meet project deadlines and introduce the product in the market. Given the complexity of developing a product such as a full vehicle, the lack of evaluation of dimensional quality problems during the project results in a great number of problems in the launch phases, since traceability of potential problems that should have been discussed in the concept development phase is lost.

Deming (1990) stresses that quality should exist in the product since the project phase. Every product must be regarded as being part of a whole. After the plans are being executed, it may be too late. According to Gerth and Baron (2003), the design, stamping, assembly and launch groups, as well as suppliers of tool, assembly equipment and stamped parts can interact better in a formalized structure with the proper methodology.

3. Dimensional analysis tools in product and process development

The development of a dimensional analysis requires basic knowledge about dimensional concepts and analysis tools. Dimensional concepts are related to variation control techniques, that is, the dimensional behavior of components and techniques to represent and identify tolerances. The analysis tools are composed of numerical and/or geometrical analyses of different kinds performed by commercial software. The tool is selected according to the analysis need or the possibility of investment and available resources.

Every manufactured component has dimensional variation. In the case of the automotive industry, variability control is important for it enables stable processes and good productivity values. Knowledge about variability is important for the product designer in order to foresee the dimensional behavior of the part in relation to the vehicle assembly.

Parkinson (1995) examined how engineering models can be used to develop robust projects that tolerate variation. These models can predict performance and control the effect of variability on the project. Lee (1998) exemplifies how dimensional variation in body in white and body closures is a critical factor related to the functionality and to the productivity of the assembly process. Low dimensional integrity will cause functional problems such as water leaks, wind noise and excessive effort to close the doors. High dimensional variability in body in white or body closures will also result in assemblability problems in the adjustment processes with consequent low productivity results.

Dimensional data evaluation software is available in the market and can produce dimensional reports with high accuracy, including reports about several production batches, thus facilitating comparison and evaluation of information about the dimensional status of components. It is important that the designer uses the evaluation techniques properly, so that the values can be adequately taken into consideration in the project.

The Cp and Cpk indices represent statistical indicators of dimensional variations and deviations. The importance of these indicators is that they numerically represent what a process is capable of producing in relation to dimensional tolerances and they differentiate the natural process variation from a random deviation. Thorough knowledge of such information is of great importance for tolerance analysis, since it defines variability characteristics of individual tolerances that will be input in the calculation, thus having direct influence on the result.

In a study about the development of a methodology to allocate tolerances at a minimum manufacturing cost, Kawlra (1994) explains that, with the increasing emphasis on quality, the product community has constantly reduced dimensional tolerance values to obtain better assemblies. In his research about capability indices for a functional relation, Bulba (2003) described suitable values for Cp and Cpk, which currently are 2.0 and 1.5, respectively.

A project normally starts with the drawings in their nominal value, but it is the designer's responsibility to assign tolerance values in the drawings according to construction, functional and manufacturing requirements of the product. In the case of an automotive product, each component has interfaces or adjustments with several other components and all of them are subject to variations in the six degrees of freedom. This fact makes it a complex task to assign tolerances to the physical characteristics of the product on the products drawings. As a result, the common practice in the drawings is to define tightened general manufacturing tolerances in order to avoid possible manufacturing or product assembly problems.

According to Chase and Greenwood (1998), adequate use of dimensional tolerances for manufactured parts is recognized by the industry as a key element in the efforts to improve productivity. Modest efforts in this area can yield significant cost reductions with little investment.

The geometrical language, or GD&T (Geometrical Design & Tolerancing), is regulated by norm ASME Y14.5 of 2009 and is composed of a language and a symbolic representation to indicate dimensional requirements of parts and assemblies in a clear and standardized way, thus facilitating communication among specialists. It has been used for many years by the aeronautical industry and the American automotive industry. ASME Y14.5 – 2009 is similar to norm ISO 1101 GPS.

The Cartesian language employs the global coordinate system, which has three orthogonal planes crossing the vehicle in the X, Y and Z axes. The global coordinate system is related to how the components are located in space. The location of the component references in the three orthogonal axes allows the exact location of the components to be identified in the vehicle project. It also allows the location of references in space for the elaboration of the manufacturing process and of dimensional control devices, within a unified coordinate system.

In the product development process, the individual parts of a vehicle are developed with dimensional tolerances designed to meet the technical, functional, manufacturing feasibility and quality requirements. These components from different development areas or even different companies must converge in the final product. From the dimensional aspect, this integration results in the sum of individual dimensional variations. In order to design a tolerance analysis model, all components that influence the results of the calculation must be identified. This identification should take into account product components, assembly sequence and process sequence. The resulting final variation is a function of the sum of the variations that compose it, and this sum is called tolerance chain.

In the past 30 years, several authors have researched different tolerance analysis concepts and methods. Specifically in the 1990s there were a great number of publications due to the development of computational techniques for tolerance analysis. Hong and Chang (2002) conducted an extensive research about the state of the art in tolerance analysis based on the review of many publications. Shen et al. (2005) reviewed and compared four tolerance analysis methods.

According to Lee (1998), one of the efforts made to improve dimensional quality and keep costs at competitive levels is to apply tolerance analysis to product and process projects. Tolerance analysis is important to check if the sum of tolerances proposed for the components is acceptable for a product based on verified specifications.

The concept of worst-case tolerance analysis is based on the sum of variations of the components, with each of them at the maximum individual tolerance allowed. In this way, the sum of the values is arithmetic. The problem in this kind of calculation lies in the fact that hardly ever are all components at the maximum tolerance at the same time. The result of the calculation has quite a wide range of variation and is often not feasible in the product design.

The main characteristic of statistical tolerance analysis is to consider the variability of all components that make up the chain. Hence, all components will hardly ever be at their maximum tolerance simultaneously. In this case, each element is represented by an individual statistical variation. Even if the variation value of one of the components is higher than the allowed limit, the value of another component will absorb this excess since it is below its limit or in the opposite direction of variation. Statistical analysis can be made by using numerical integration methods or evaluations with the Monte Carlo method, based on random generators.

Degrees-of-freedom analyses presuppose that all variations are linear, that is, they occur on the same orthogonal plane. If a measurement is not on the studied plane, it will be necessary to project its variation to the plane under analysis. Analyses in one degree of freedom allow quick evaluations, since their modeling is simpler when compared to other types of analysis. The modeling should, however, follow criteria similar to those of more complex analyses in order to ensure the correct construction of the model.

Analyses in the three degrees of freedom have been developed due to the physical characteristics of automotive components, with variations normally occurring in the three orthogonal directions. As a result, variation of one component in one orthogonal direction exerts influence on another direction if the surface of the components has a complex profile. Analyses in the three degrees of freedom also allow product variation to be visualized by using animation tools.

Tolerance analysis with mathematical models is based on the premise that the contribution of each component is related only to its individual tolerance and that these elements are not deformed by the forces generated in the assemblies. The concept of deformable assemblies or compliant assemblies takes into account the resistance and deformation of the parts.

It is difficult to predict variations in the body in white assembly process and, for this reason, based on the deformable assembly concept, the measurement tolerances should be defined only after evaluation of the process results and/or of an advanced vehicle. The initial values are estimated based on the experience of previous projects and will be confirmed or revised in the pre-series vehicles.

Hammett, Wahl and Baron (1999) described the functional assembly concept for complex assemblies that take into consideration the criteria of flexibility of metallic parts as an alternative to the sequential method of component approval. Gerth and Baron (2003) explain the functional assembly concept adopted by American companies, which consists in ensuring that components are within the process field, rather than the tolerance field. Majeske and Hammett (2000) complement that non-rigid components may have their shape modified during an assembly process.

It may be convenient to wait to define the dimensional characteristics in the launch phases, as actual product and process data can be used. However, it is essential that the product concept is conceived and evaluated in the virtual phase considering the allowable process variability.

Gerth and Baron (2003) add that a vehicle body in white is the most complex system to design and produce. It requires the coordination of many separate groups (design, stamping, assembly and launch, as well as suppliers of tools, assembly equipment and stamped parts) concerning deadline restrictions to build a manufacturing system that is not well understood.

4. Dimensional development systematics applicable to the automotive project

The application of tolerance analysis to the automotive project requires the adoption of a systematics to enable the identification and organization of dimensional data according to the product concept and to the process sequence. Figure 3 proposes a model for the tolerance analysis process.

Tolerance analysis is a very useful tool to predict the dimensional behavior of a product under process conditions. But the guarantee of effectiveness in the actions identified by the tolerance analysis tools goes beyond the numerical analyses. It is necessary to have a work method that will ensure the identification, analysis and implementation of actions to correct critical dimensional characteristics. This process is called dimensional planning. Figure 4 presents the dimensional planning process proposed in this study.

According to Craig (1996), dimensional planning is an engineering methodology combined with computer simulation tools used to enhance quality and reduce costs due to robust design and controlled variation. The objective of dimensional planning is to create project and processes that absorb as much variation as possible without affecting product function.

The sum of the dimensional variation of individual components that will have influence over a product characteristic occurs through the contact or interface between parts during an assembly or production process sequence. Careful evaluation of these interfaces represents an opportunity to identify potential dimensional problems.

Interface evaluation consists in identifying all contact points between parts and evaluating, in the three orthogonal directions of the global coordinate system, the effect of this contact on the dimensional behavior of the product, bearing in mind the dimensional variation. This evaluation enables the future behavior of the component to be predicted based on dimensional factors other than the tolerances. These factors are identified as assemblability, dimensional stability, compensation of dimensional variation and possibility of adjustments.

Dimensional variation may occur in any orthogonal or composed direction. As a consequence, in order to make a full evaluation and identify potential problems in the six degrees of freedom, assemblability must be evaluated once in each orthogonal plane and in both directions of variation. The proposal for the interface evaluation process is represented in Figure 5.

There is not yet a mathematical model or software capable of identifying potential problems in assemblability, adjustability, stability and compensation of dimensional variations caused by the dimensional characteristics of the assemblies.

The product drawings can be considered the main control documents, as they are the reference and source of information for all other dimensional control documents used to measure the product. In their turn, the dimensional control documents can be identified as those of parts, of assemblies or even of the complete body in white, and are applied to components manufactured internally (Make) or provided by suppliers (Buy). Their purpose is to define the exact points that will be controlled by the measurement machines. There are also documents that define the product control points in process, and which will be the base for the design of these means.

Checking the conformity is a final and important phase in the dimensional development process so that the simulated results can be compared with the actual product variability results in the production. It is possible to make a critical analysis of the input values versus the output values of the calculations, which allows the specialists to learn more and the variability parameters to be corrected for further analyses.

Once the systematics for dimensional planning, tolerance analysis and interface evaluation are identified, it is still necessary to demonstrate how these systematics are integrated within a project system focused on dimensional quality. Figure 6 presents the consolidation of the dimensional development process in the project of automotive products proposed in this study.

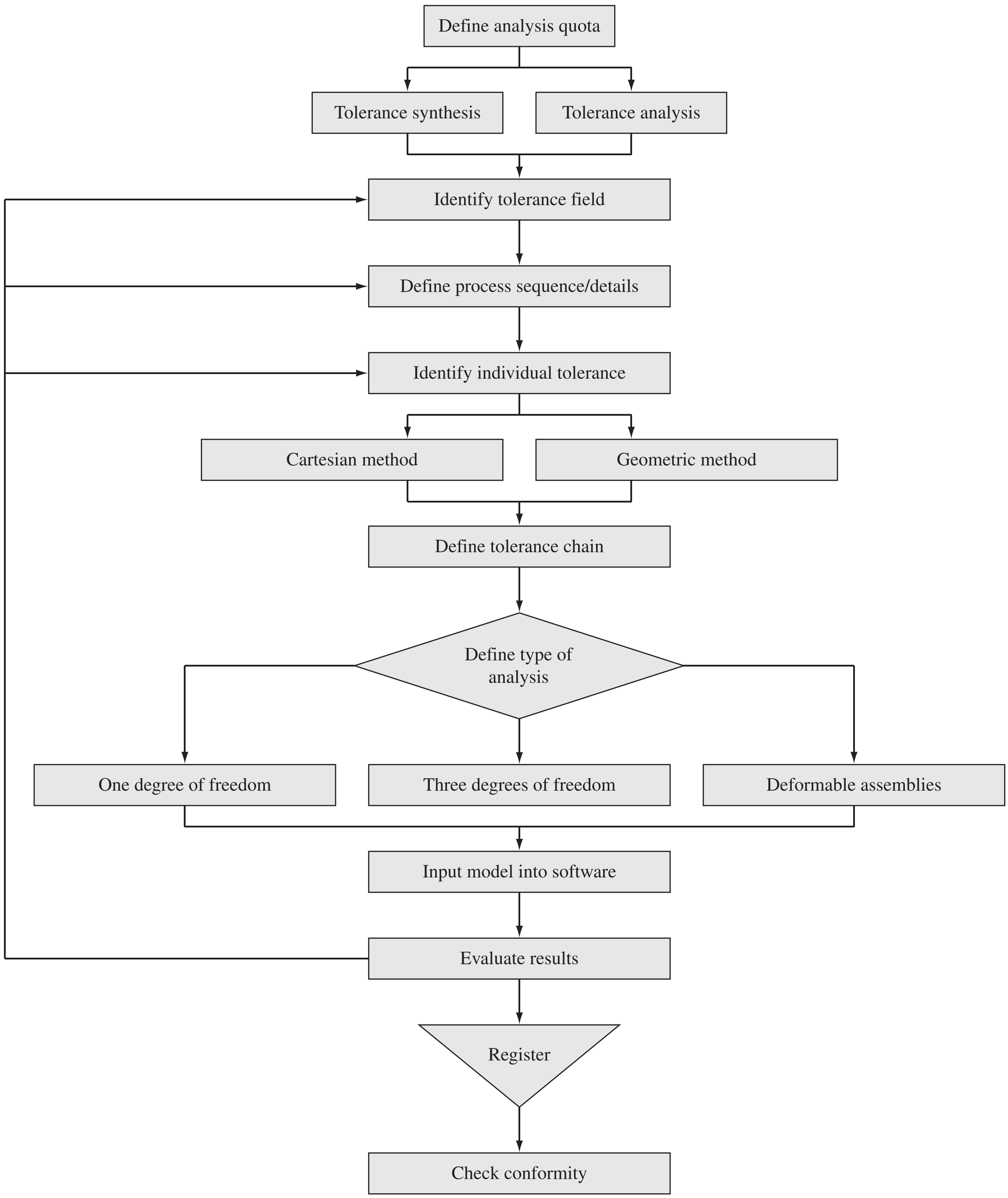

Figure 3. Tolerance analysis process.

5. Examples of application of the dimensional development process

In order to exemplify the proposed systematics, as well as to evaluate the improvements obtained with its application by means of the correct and premature identification of problems that could occur when the vehicle is assembled, two cases of a vehicle assembly company are presented: taillight and frontend.

5.1. Taillight

Quality premises: The characteristic to be evaluated is flushness between the taillight and the tailgate external sheet due to potential adjustment problems in process and demerits in the audit grade. A –0.5 mm deviation will not cause demerit in the quality inspection due to the conditions of visual evaluation in process.

Product concept: The product is composed of a taillight fixed to the tailgate with screws. There are three fastening

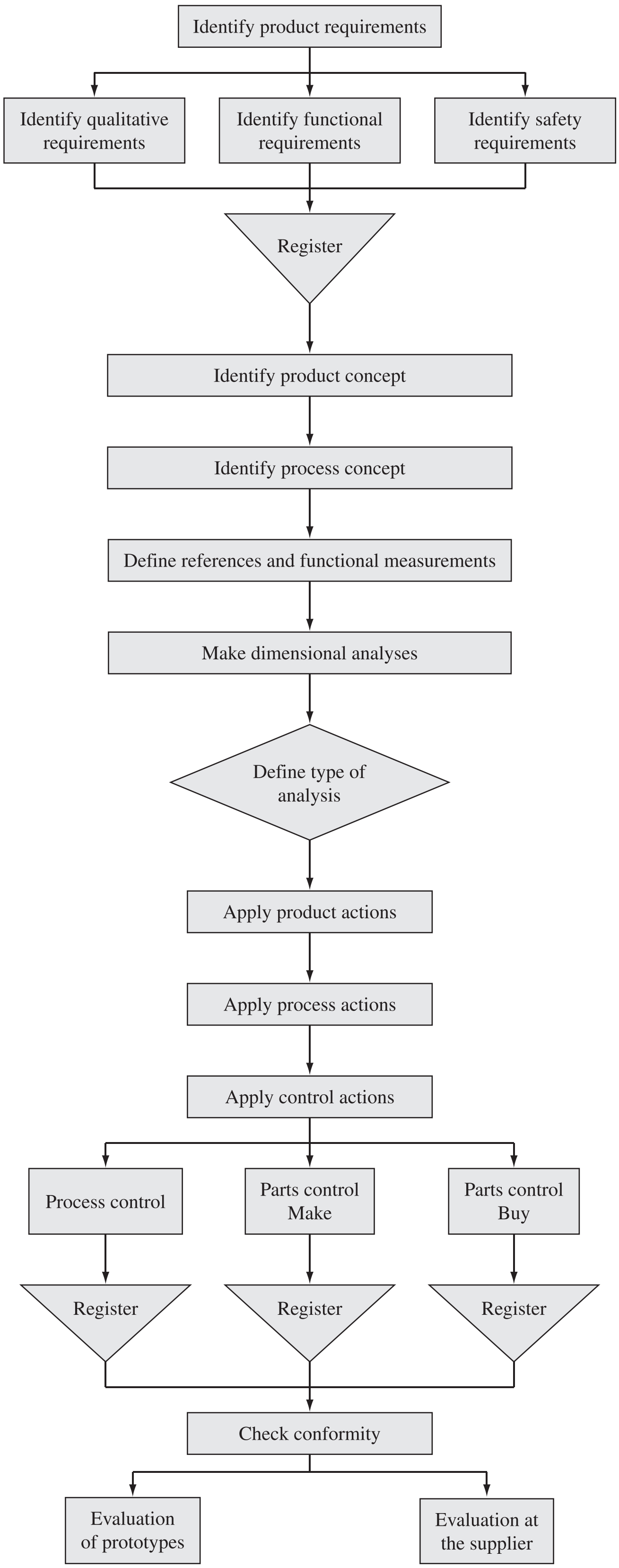

Figure 4. Dimensional planning process.

points in the internal part of the tailgate assembly. Sealing around the fastening points prevents water and dust leaks.

Process concept: The manufacturing process of the tailgate starts by joining the two external sheets, which are welded in a specific operation station. In the next operation, the taillight brackets are glued in their internal side. The assembly is then fixed to the internal sheet through the klinching process.

Process sequence:

1. The external sheet assembly is formed by welding the upper external sheet with the lower one.

2. The external sheet assembly is formed by adding the bracket closure part.

3. The tailgate assembly is formed by joining the internal sheet with the external assembly in the klinching station.

Process references: After the process sequence is indicated, it is necessary to identify the reference points of the parts and to check their use in the process. This evaluation will identify where and how exactly the parts are supported. This information will be used later to define the tolerance chain.

Tolerance chain: The study of the component references identified their use to form the assembly. Based on that study, it is possible to define the tolerance chain, composed of the sum of variations of the different processes and dimensional tolerances at the points of contact between the parts. Figure 7 represents the tolerance chain for the taillight.

Tolerance analysis in one dimension: Based on the tolerance chain described in the previous item, data were input in the statistical calculation software in one dimension.

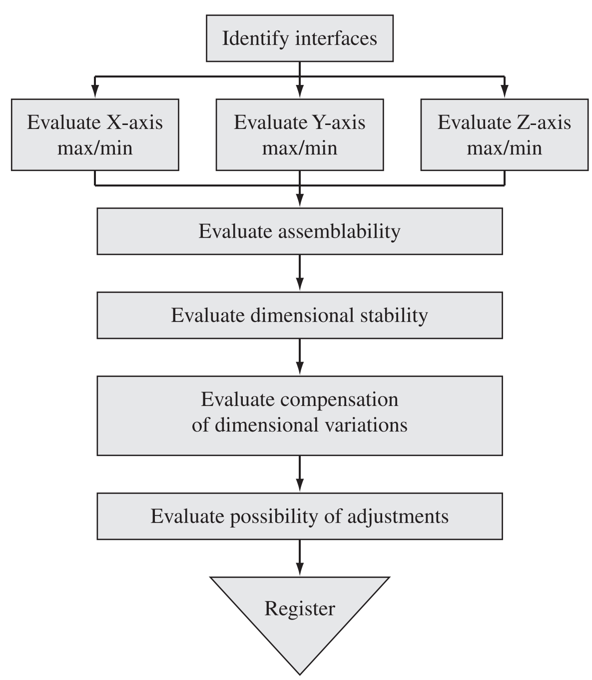

Figure 5. Interface evaluation process.

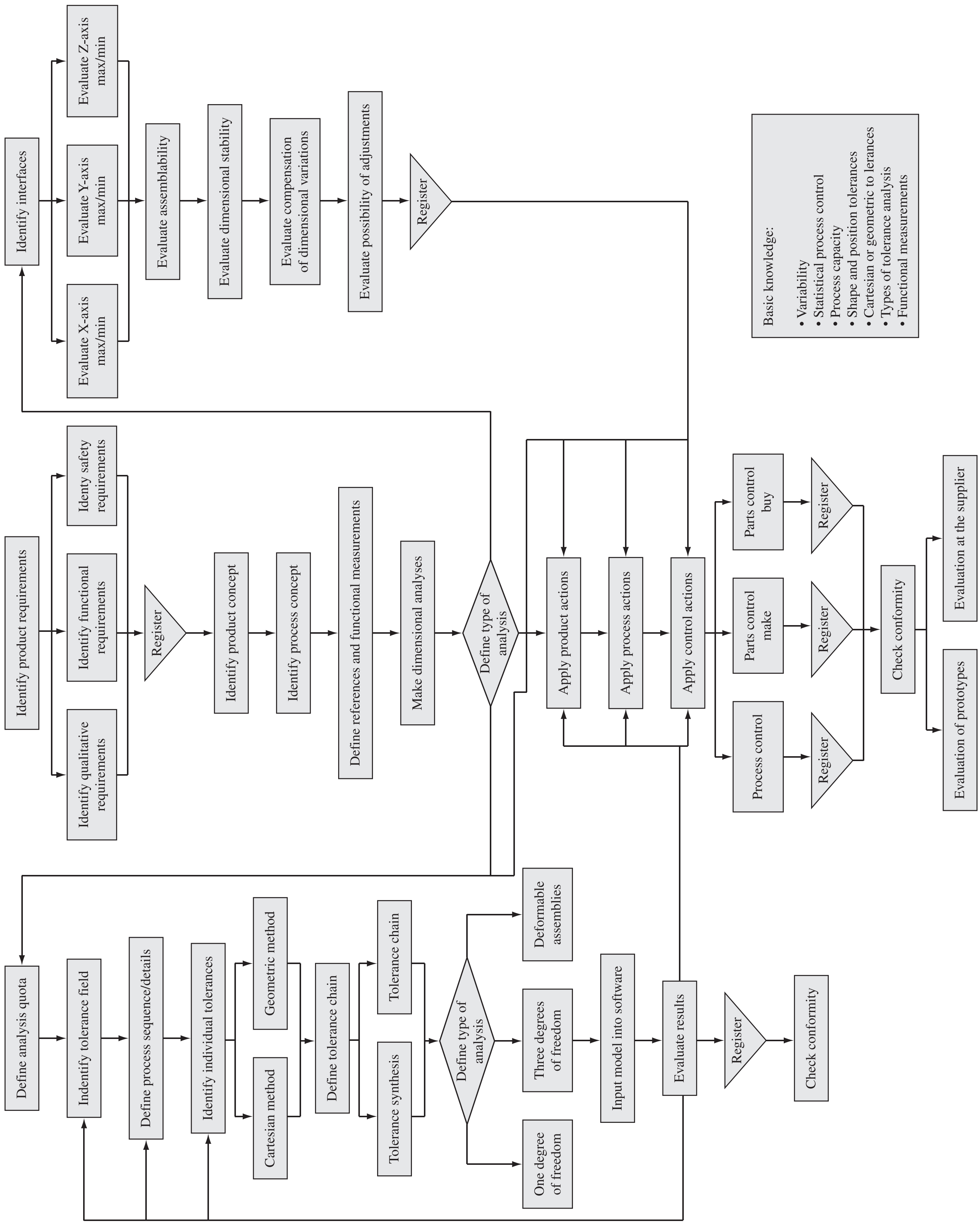

Figure 6. General process of dimensional development in the automotive project.

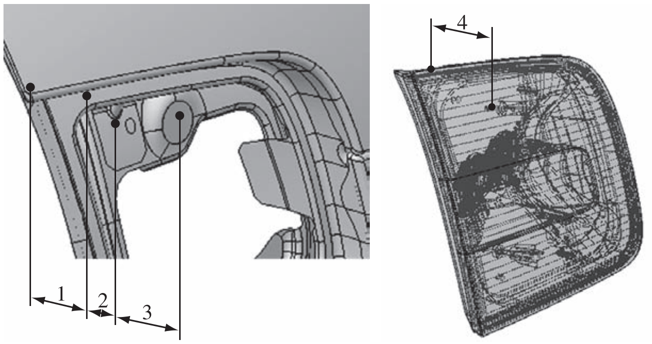

Figure 7. Tolerance chain.

The calculated value is ±2.5 mm in the worst-case condition (arithmetical) and ±1.49 mm in the statistical condition, resulting in a figure of 39% of the vehicles within the specification for a tolerance field of 0; –0.5 mm.

Tolerance analysis in three dimensions: The result of the simulation was +2.2; −1.8 mm, with 32.5% of the production volume within the specified flushness value.

Deformable assemblies: As the assembly has stamped parts that are later welded, the influence of the process devices or of a component with a thicker sheet can change the dimensional condition of the tailgate. The welding operations of the external sheets, klinching, drilling and adjustment of the taillight fastening plane are subject to the influence of component elasticity and of different adjustments of the devices.

Interface evaluation: Table 1 shows the potential problems indicated by the application of the interface evaluation systematic.

Correlation between predicted problems and those identified in the production phase: By comparing the potential problems identified in the interface analysis and the actual problems identified during the production process, it is possible to verify which of the predicted problems actually occurred in the process. Table 2 correlates the problems predicted during the project and those identified in the production phase.

5.2. Frontend

The second example is the case of the frontend, specifically the adjustment between the headlight and the fender. The concept of this product has a high quality level required by the design specifications, which must be guaranteed in the process.

Quality premises: The quality premises for the assembly of the frontend in relation to the adjustment between the headlight and the fender are the shape adjustment in the y-direction and the gap adjustment in the x-direction. In this study, the adjustment in the y-axis between the headlight and the fender will be exemplified. Design tolerance for the adjustment between the parts is ±0.5 mm in relation to the drawing specification that places both components in flushness condition.

Product concept: The product is composed of a frontend assembly, formed by the plastic support, the headlight and the crossmember, which is fixed to the body in white by screws in the upper and lower side members. The body in white is supplied ready with the fenders previously adjusted in their position.

Process concept: The process concept of the frontend module is formed by a frontend assembly composed of a plastic support, crossmember and headlight, which is pre-assembled in a specific pre-assembly line and later sent to the final assembly. In the final assembly this module is fixed to the body in white with screws. The body in white supplied by the bodyshop is already painted and the fenders are assembled and adjusted by geometry devices in relation to the doors and the hood.

Process sequence: Once the analysis objective is defined, the process sequence is evaluated. The product assembly process begins in the bodyshop during the assembly of the fenders on the body in white, with process devices, to ensure they are positioned correctly in relation to the doors and the hood. The body in white is then sent to painting before receiving the frontend in the final assembly.

Process references: The assembly references are found in the adjustment regions of the fender and in the positioning regions of the body in white. In the assembly of the frontend, the assembly device uses the references on the plastic support and the holes on the fenders for the assembly on the body in white.

Tolerance chain: Based on this reference study, it is possible to define the tolerance chain, which is composed of the sum of variations of the different processes and dimensional tolerances at the points of contact between the parts. Therefore, starting from one of the points of the quota to be analyzed, one goes through the dimensional tolerances of individual parts, the references and the process sequence, which will be added sequentially, until the second point is reached. Figure 8 represents the tolerance chain for the frontend.

Tolerance analysis in one dimension: The calculated value is ±3.05 mm in the worst-case condition (arithmetical) and ±1.9 mm in the statistical condition, resulting in a figure of 67% of the vehicles within the specification for a ±0.5 mm tolerance field.

Tolerance analysis in three dimensions: The result of the simulation was +2.6; −3.2 mm, with 47.4% of the production volume within the product specification.

Analysis of deformable assemblies: As the assembly has stamped parts that are later assembled on the body in white, the influence of the process devices and the elasticity of the components may change the adjustment condition

Table 1. Interface evaluation.

Interface Evaluation					
Part under evaluation:	**Taillight**				
Parts with interface	**Axes**	**Item**	**Criteria**	**Description of potential faults**	**Actions**
Tailgate	x	1	Assemblability	Taillight may be difficult to assemble in the x-axis due to variation of the corresponding gap in the tailgate, in the z-axis.	Analyze tolerances in the x- and z-axes to compare variation with assembly gap.
		2	Stability	Taillight is fixed to the internal panel by three screws. It must remain stable after torque is applied to assemble the screw.	Four fastening points should be used to facilitate the adjustment. With three points, despite the defined plane, it is difficult to adjust the four corners of the taillight.
					Tailgate internal sheet should have adequate thickness so that it will not yield when torque is applied.
		3	Compensation of variations	Taillight is fixed against the internal panel, being adjusted with the external panel; variation in taillight and tailgate assembly will hinder taillight adjustment.	Analyze tolerances to check the final result of variability and identify necessity to modify the concept.
		4	Adjustments	The fastening concept does not provide possibility of adjustment in the x-axis. With 3-point fastening, the taillight is unstable despite the support plane provided by the three points, because the adjustment occurs in four corners.	Analyze tolerances to check the final result of variability and identify necessity to modify the concept.
	y	5	Assemblability	Variation in the relation between the position of the fastening hole and the matching line of the tailgate with the taillight may make assembly difficult. Consider variation between fastening holes.	Analyze tolerances to compare variation with assembly gap.
		6	Stability	No problems were identified.	
		7	Compensation of variations	Compensation of tailgate and taillight dimensional variation must be absorbed by the assembly gap of the taillight in the internal tailgate.	Analyze tolerances in the y-axis to compare variation with assembly gap.
		8	Adjustments	Assembly gap must have adjustment field as well as absorb component variation.	Analyze tolerances in the y-axis to compare variation with assembly gap.
	z	9	Assemblability	Variation in the adjustment region for the taillight fastening point can hinder the assembly due to small gap.	Analyze tolerances in the z-axis to compare variation with assembly gap.
		10	Stability	No problems were identified.	
		11	Compensation of variations	Gap between taillight and tailgate in the assembly and in the fastening points must be checked to confirm the capacity to absorb variations without hindering the assembly.	Analyze tolerances in the z-axis to compare variation with assembly gap.
		12	Adjustments	Assembly gap must have adjustment field as well as absorb component variation.	Analyze tolerances in the z-axis to compare variation with assembly gap.

Table 2. Correlation between problems predicted in the interface analysis and those identified in the assembly line.

Axis	Problems predicted in interface evaluation	Problems identified in process
x	Taillight may be difficult to assemble in the x-axis due to variation of the corresponding gap in the tailgate, in the z-axis.	Taillight does not fit in the corresponding space in the tailgate.
	Taillight is fixed to the internal panel by three screws. It must remain stable after torque is applied to assemble the screw.	
	Taillight is fixed against the internal panel, being adjusted with the external panel, variation in taillight and tailgate assembly will hinder taillight adjustment.	All manufactured vehicles require taillight adjustments.
	The fastening concept does not provide possibility of adjustment in the x-axis. With 3-point fastening, the taillight is unstable despite the support plane provided by the three points, because the adjustment occurs in four corners.	The taillight is positioned "outwards" after assembly in almost all vehicles (outwards in relation to the tailgate surface).
y	Variation in the relation between the position of the fastening hole and the matching line of the tailgate with the taillight may make assembly difficult. Consider variation between fastening holes.	Sometimes all the fastening gap is used and it is still not possible to adjust the taillight in the y-axis.
	Compensation of dimensional variation in tailgate and taillight must be absorbed by the assembly gap of the taillight in the internal tailgate.	The taillight touches (in width, in the y-axis) the internal side of the tailgate and it is not possible to adjust it to the external line.
	Assembly gap must have adjustment field as well as absorb component variation.	Sometimes all the fastening gap is used and it is still not possible to adjust the taillight in the y-axis.
z	Variation in the adjustment region for the taillight fastening point can hinder the assembly due to small gap.	
	Gap between taillight and tailgate in the assembly and in the fastening points must be checked to confirm the capacity to absorb variations without hindering the assembly.	
	Assembly gap must have adjustment field as well as absorb component variation.	

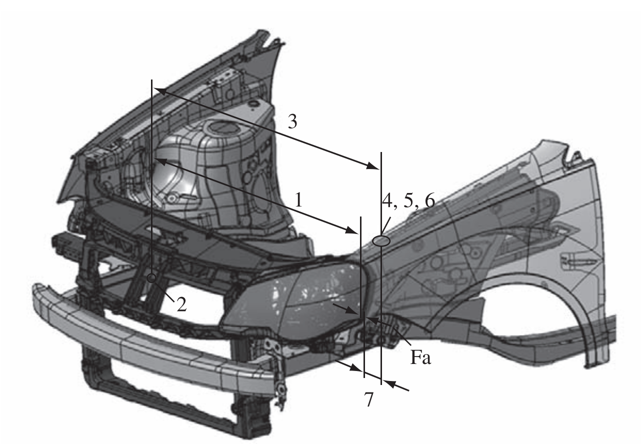

Figure 8. Tolerance chain.

of the fenders. Tolerance analysis defined the necessary value for the functional measurement between the fenders, but these values can only be confirmed under production conditions. A comparative with similar processes may aid in the decision about the adequate value.

Interface evaluation: Table 3 shows the potential problems indicated by the application of the interface evaluation systematics. The evaluation of interfaces allowed nine other relevant potential problems to be identified concerning dimensional characteristics.

Correlation between predicted problems and those identified in the production phase: By comparing the potential problems identified in the interface analysis and the actual problems identified during the production process, it is possible to verify which of the predicted problems actually occurred in the process. Table 4 correlates the problems predicted during the project and those identified in the production phase.

5.3. Verification of conformity

In order to verify conformity, actual data were collected from products in process condition. Due to the evaluation conditions in process and during vehicle manufacture, it was not possible to use any measurement device. Data were collected by means of visual evaluation immediately after the components were assembled and before any adjustment.

Visual evaluations have little accuracy and, for this reason, a criterion was defined for the evaluation of adjustments. Due to the difficulty in differentiating the variation, a step of 0.5 mm was adopted. This measurement criterion is not very accurate, but it is useful for the comparison with the simulation data. The visual condition is similar to the evaluation made by the audit inspectors. Figures 9 and 10 show the results for the taillight and frontend cases, respectively.

Table 3. Interface evaluation

Interface Evaluation					
Part under evaluation:	**Headlight**				
Parts with interface	**Axes**	**Item**	**Criteria**	**Description of potential faults**	**Actions**
Frontend	x	1	Assemblability	Gap between headlight housing and frontend is necessary to avoid assembly problems.	Check with tolerance analysis the plastic support and headlight variation versus the assembly gap.
		2	Stability	Fastenings guarantee stability in x. Frontend must have structural rigidity.	Check rigidity of the plastic support in the design and prototypes.
		3	Compensation of variations	Upper fastenings must have a gap to absorb headlight variations; lower fastenings do not allow variations to be compensated in the x-axis	Check with tolerance analysis the plastic support and headlight variation versus the assembly gap. Analyze tolerances of the matching between headlight and fender in order to define tolerance of the components in the lower region.
		4	Adjustments	Headlight fastening concept does not allow adjustment of the lower fastenings. Upper fastenings must have a gap to absorb variations and allow adjustment.	Check gap with peripheral components in order to define headlight adjustment. Analyze tolerances of the matching between headlight and fender in order to define tolerance of the components in the lower fastenings.
	y	5	Assemblability	Gap between headlight housing and frontend is necessary to avoid assembly problems.	Check with tolerance analysis the plastic support and headlight variation versus the assembly gap.
		6	Stability	Fastenings guarantee stability in y.	--
		7	Compensation of variations	Variations of the headlight and plastic support assembly must be absorbed with assembly gap.	Define variability between headlight fastening points with tolerance analysis. Define dimensional tolerance between headlight and plastic support fastening points.
		8	Adjustments	It is necessary to provide a gap for adjustment beyond dimensional variations.	Check gap in the headlight perimeter and frontend assembly to add the difference to the result of the tolerance analysis of the fastening points.
	z	9	Assemblability	Gap between headlight housing and frontend is necessary to avoid assembly problems.	Check with tolerance analysis the plastic support and headlight variation versus the assembly gap.
		10	Stability	Lower fastenings guarantee stability for the headlight; upper fastenings are flexible.	Define position tolerances for the plastic support and the headlight fastenings.
		11	Compensation of variations	Headlight will be assembled with device (verify). Flexible fastening points of the upper headlight fastenings absorb variation. It is necessary to identify the gap in the lower fastenings to compensate variations in assembly with device.	It is necessary to evaluate variability of the plastic support and the headlight in order to check the necessary gap.
		12	Adjustments	It is also necessary to provide gap for adjustments.	It is necessary to evaluate variability of the plastic support and the headlight in order to check the necessary gap for adjustment.

The data in Figures 9 and 10 demonstrate that the variability values in process remained similar to the simulated values under the conditions of one and three degrees of freedom, thus indicating a good correlation between the simulation and the actual variability results. Evaluations in the three degrees of freedom may present variation results greater than those in one degree of freedom, due to the influence of one orthogonal direction over another in association with the physical characteristics of the components. As a result, an increase in the variability value is observed.

It is important to stress that the dimensional problems mentioned were related only to the aesthetic characteristics of the vehicles, due to demanding style specifications and to the quality audit concept adopted by the company, but analyses can also be used to evaluate safety items.

Table 4. Correlation between problems predicted in the interface analysis and those identified in the assembly line.

Problems predicted in interface evaluation	**Problems identified in process**
Gap between headlight housing and frontend is necessary to avoid assembly problems.	In some assembly operations, the whole assembly gap was used and it was not possible to adjust the headlight in the y- and x-axes.
Fastenings guarantee stability in x. Frontend must have structural rigidity.	Difficulty to guarantee adjustment of the headlight gap with the fender in the x-axis due to the elasticity of the frontend fastening point.
Upper fastenings must have a gap to absorb headlight variations; lower fastenings do not allow variations to be compensated in the x-axis.	All vehicles require headlight adjustments after the frontend is assembled on the body in white with the assembly device; upper fastenings are loosened to allow adjustment.
Headlight fastening concept does not allow adjustment of the lower fastenings. Upper fastenings must have a gap to absorb variations and also allow adjustment.	Difficulty to guarantee adjustment of the headlight gap with the fender in the x-axis due to the elasticity of the frontend fastening point.
Gap between headlight housing and frontend is necessary to avoid assembly problems.	In some assembly operations, the whole assembly gap was used and it was not possible to adjust the headlight in the y- and x-axes.
Fastenings guarantee stability in y.	
Variations of the headlight and plastic support assembly must be absorbed with assembly gap.	Most vehicles require headlight adjustments after the frontend is assembled on the body in white with the assembly device; fastenings are loosened to allow adjustment.
It is necessary to provide a gap for adjustment beyond dimensional variations.	
Gap between headlight housing and frontend is necessary to avoid assembly problems.	Most vehicles require headlight adjustments after the frontend is assembled on the body in white with the assembly device; upper fastenings are loosened to allow adjustment.
Lower fastenings guarantee stability for the headlight; upper fastenings are flexible.	
Headlight will be assembled with device (verify). Flexible fastening points of the upper headlight fastenings absorb variation. It is necessary to identify the gap in the lower fastenings to compensate variations in assembly with device.	Most vehicles require headlight adjustments after the frontend is assembled on the body in white with the assembly device; upper fastenings are loosened to allow adjustment.
It is necessary to provide gap for adjustments.	

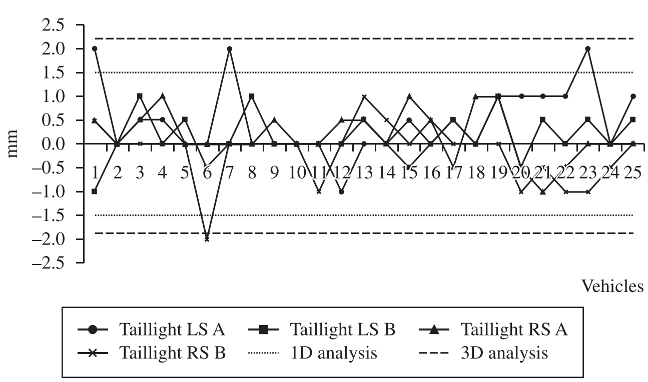

Figure 9. Correlation between calculations in one and in three dimensions with measurements in the assembly line for the taillight example.

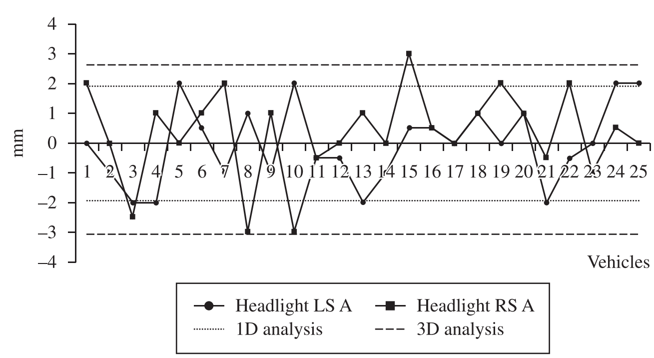

Figure 10. Correlation between calculations in one and in three dimensions with measurements in the assembly line for the frontend example.

Even if a dimensional evaluation may occasionally not be absolutely accurate, due to availability of data, its application allows the identification of critical factors so that actions can be adopted in the project as early as in the concept phase.

6. Conclusion

The application of the dimensional development systematics proposed in this study, which includes dimensional planning, tolerance analysis and interface evaluation, allows early identification of dimensional problems during the project that could potentially occur in the production, as well as the identification of critical requirements for product and process dimensional control. Its systemic application along the entire automotive project enables product and process development to be aided in a disciplined way with a focus on dimensional quality.

As important as the applied systematics is the designers' knowledge about concepts and languages for the representation of tolerances, concepts about the dimensional behavior of products such as variability, and analysis tools provided by different types of software. The role of the dimensional analysis expert is to use adequately all languages, concepts and tools presented in this study so that suitable and reliable analysis models can be designed.

Dimensional development plays an important role in product and process development aiming at efficient design and manufacture of vehicles, without late product modifications or rework along the assembly line, thus allowing a balanced production with good quality results.

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