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Genetic algorithm optimization and robustness analysis for the computer aided design of fixture systems in automotive manufacturing

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Abstract: Fixture Systems (FSs) have great importance in machining, welding, assembly, measuring, testing and other manufacturing processes. One of the most critical issue in FS design is the choice of both the type of fixing devices such as clamps, locators, and support points, (configuration), and their arrangement with respect to workpieces (layout). Several authors deal with the problem of determine the most suitable solution for FSs, often investigating their layout without considering the change of the type of locators. A computer aided design method is proposed to compare and evaluate different configurations for a FS, optimizing the locator type and analysing the roboustness of the solution. A multi-objective optimization based on a genetic algorithm is presented and the selection of the most suitable configuration is performed through the definition of robustness indexes. The effectiveness of the design method is demonstrated for an automotive case study.

Key words: Automotive manufacturing, computer aided fixture design, multi-objective optimization, robust analysis

1- Introduction

1.1- Operating scenario

A Fixture System (FS) is a device composed by clamps, locators and support points to rapidly, accurately and securely position workpieces during the different phases of their manufacturing process. FSs are widely used in various fields of manufacturing (e.g. machining, welding, assembly, inspection and testing) and requirements on FSs are different for each process. For example, in machining, due to the high process forces, compliance of FS has to be accounted for because it is a non-negligible source of error which impacts the workpiece final quality. On the contrary, during an assembly process FS deformation may generally be neglected and FS can be treated as a rigid structure.

FS design is a significant topic for industry since the cost associated with FS can account for 10–20% of the total cost of a manufacturing system [WR1].

Effectiveness of FS design depends both on type and position of locators. Different disposition of the same group of locators and different types of locators placed in the same position lead to very different performances.

In the following, we distinguish between two properties of FS: layout and configuration.

The layout is the result of the application of the principles used to pose the part in the space. It also takes into account position and orientation of locators.

The configuration refers to the set of locator types used to realize the layout. The configuration is the actual implementation of the layout, since a layout is obtainable through the combination of different types of locators.

Table 1 shows the degrees of freedom constrained by locators for some main types of locators used in automotive manufacturing. The Z direction represents the normal to the contact surface or the axial direction of the cylindrical feature.

Degree of Constraint	Locators	Direction of Constraint
1 DoC	Pad Pin/Pocket	Z X or Y
2 DoC	Pin/Hole	X or Y
	Pin/Pocket + Pad	X or Y, Z
	V-Block	X, Y
3 DoC	Pin/Hole + Pad	X, Y, Z

Table 1: Classification of locators

According to the literature, the FS design process can be divided in four steps: setup planning, fixture planning, unit design, and verification [BR, WR2, HV].

During the setup planning, workpiece and technological information are analysed to determine the number of setups required to perform all the manufacturing operations and to define appropriate locating datum for each setup.

Fixture planning defines the datum and the disposition of locators based on the fixing requirements. The number and position of the locating points have to assure that all the degrees of freedom of the workpieces are adequately constrained.

During the unit design, suitable units for locating and clamping the workpieces are designed and produced.

The FS is finally tested during the verification phase, to ensure that it satisfies all the fixturing requirements which drive the design process.

FS design represents a critical task especially in those processes that are characterized by high modularity [AL].

One important example is represented by automotive industry, where accuracy and roboustness of manufacturing processes play a fundamental role, especially in the top class car sector, where very high overall quality is mandatory [SK].

Chassis design, for example, asks for balancing very different design requirements, e.g. static and dynamic performance, safety, lightness, cost. Moreover, a chassis is a complex modular system which can be decomposed in subgroups, differing in materials (e.g. aluminium and cast iron), manufacturing processes (e.g. casting and extrusion) and assembly technologies (e.g. welding, riveting, gluing). Even small misalignments between parts of the frame can lead to reject the total chassis, so that, actually, just a detail optimization of every module permits to achieve the desired targets [CB].

Product design and process design have to be closely integrated, tolerances on parts (functional goals) and assemblies (technological goals) have to be accurately chosen and managed, and FSs have to be specifically tailored and designed.

1.2- Scientific background in Computer Aided Fixture System Design

Since the FS design process is affected by an inherent complexity, Computer Aided Fixture Design (CAFD) tools have been developed in order to support it. Moreover, computer aided techniques could lead to find design issue in the early phase, avoiding expensive late testing and corrections during the development and industrialization phases. This could lead to an improvement in the geometric product tolerance fulfilling functional demands [LL].

The current scientific research on CAFD is focused on two main issues: how to represent and collect the design knowledge about FSs within a computer aided environment; how to implement an engineering procedure for designing FSs in industry.

Many authors have investigated the codification of the design knowledge in a CAE environment and have proposed different integrated approaches to solve such criticism, with a particular focus on fixture design for machining.

Wang et al. [WR1] describe different research aspects that are promising in CAFD: knowledge-related techniques, knowledge modelling, data mining and machine learning. Moreover, they underline the absolute importance of FS design within product/process development and suggest to consider it as a mandatory task for engineers.

Boyle et al. [BR] present a review of over seventy-five CAFD tools focused on the FS design phases they support and on the underlying technology upon which they are based. They conclude that more attention has to be paid on the cohesive integration between the segmented CAFD approaches within a unique framework, in order to enhance the comprehensive understanding of all the basic requirements needed by FSs and to use this understanding to drive the FS design process.

Wang et al. [WR2] propose a method called Case-Based Reasoning aimed at investigating and systemizing the most important achievements in FS design over the past years. Such method draws a procedure to quickly derive conceptual FSs from the representation and systemization of many fixture design solutions and related devices, e.g. depository units.

Hunter et al. [HV] further develop some models for collecting and organizing the FS design knowledge and extending it to many field of application. In particular they present a knowledge template based on the distinction between analytic and synthetic tasks. The knowledge template represents a pattern which defines the most common entities used in FS design for machining.

According to their approach, such knowledge is easily reused in an automatic process [HR] to design fixtures for inspection, assembly or welding.

The implementation of engineering procedures for designing FSs in industry is often treated as a problem of FS layout definition and optimization.

Roy et al. [RS] propose a heuristic algorithm for the automatic selection of the position of locators and clamps for a given workpiece geometry. They also propose the integration of the algorithm within a knowledge-based framework.

Ngoi at al. [NT] state some FS design principles and subdivide a FS in locating, supporting and clamping elements, according to their functions.

Qin et al. [QZ] present a method to design the FS scheme trough the calculation of the influence on the final accuracy given by the fixture elements and the workpiece itself.

Yu et al. [YW] describe an approach for quickly and automatically determining the main clamping points in a FS, starting from the geometry of a workpiece. The procedure consist of the initial projection and extraction of the workpiece boundaries, their simplification, the determination of feasible clamping plans on the workpiece and the selection of the optimal plans.

Wu et al. [WR3] present a geometric analysis for the automated design of the FS layout considering different positions of the locators.

Pelinescu et al. [PW] adopt multiple quality criteria in order to define the best layout for FSs. The final choice depends on a trade-off among multiple performance requirements.

Kaya [K] applies genetic algorithms to draw the best FS layout, considered as supports, locators and clamps, in order to minimize the errors induced by elastic deformation of the workpiece.

Liu et al. [LZ] propose a method to optimize the FS layout in the peripheral milling of a workpiece characterized by low-rigidity.

1.3- Open issues in Computer Aided Fixture System Design

After the setup planning phase there are two common FS design scenarios: in the first, geometric and technological requirements on the part determine both the layout and the configuration. Existing Computer Aided Fixture System design can be very useful here.

In the second case, requirements do not completely determine neither layout nor configuration, so designers rely just on their knowledge and experience to select the best one among alternative solutions. In several situations, however, the layout is imposed by reachability limits of the manufacturing system and the choice of the configuration becomes the discriminating factor for FS design. In such cases, despite the significant number of existing methods and tools cited, FS design is still not fully codified in CAE environments but, especially in small-medium enterprises, deeply based on designers' experience and trial and error approaches.

One notable reason for such lack is that the FS engineering design approaches are very often limited to the investigation of the layout while the configuration is rarely taken into account. The problem of the analysis of different configurations in FS design seems not to be fully addressed even in the scientific literature, due to the inherent difficulties in comparing different locators types. In fact, locators fulfil different functions (e.g. a hole constrains different direction from a pad) and are affected by different tolerances (e.g. a pad and a hole have different dimensional tolerances). As a consequence, computer aided methods tools frequently consider a given configuration and optimize the layout of the locators without considering their functions.

In the present work a computer based design method is proposed to enhance the FS design process and reduce the heavy participation of very skilled and experienced designers.

The method describes how to select the most suitable and robust FS configuration through a multi-objective optimization approach based on an evolutionary algorithm and robustness indexes. A computer aided environment has been also developed for the implementation of the method and validated on an automotive case study.

The paper is organised as follows: Section 2 describes the proposed computer aided design method; Section 3 presents the case study and the results of the robust analysis; Conclusions are finally presented in Section 4.

2- Computer aided fixture system design method

The proposed method integrates numerical and statistical tools and techniques; it consists of four steps, as outlined in Figure 1.

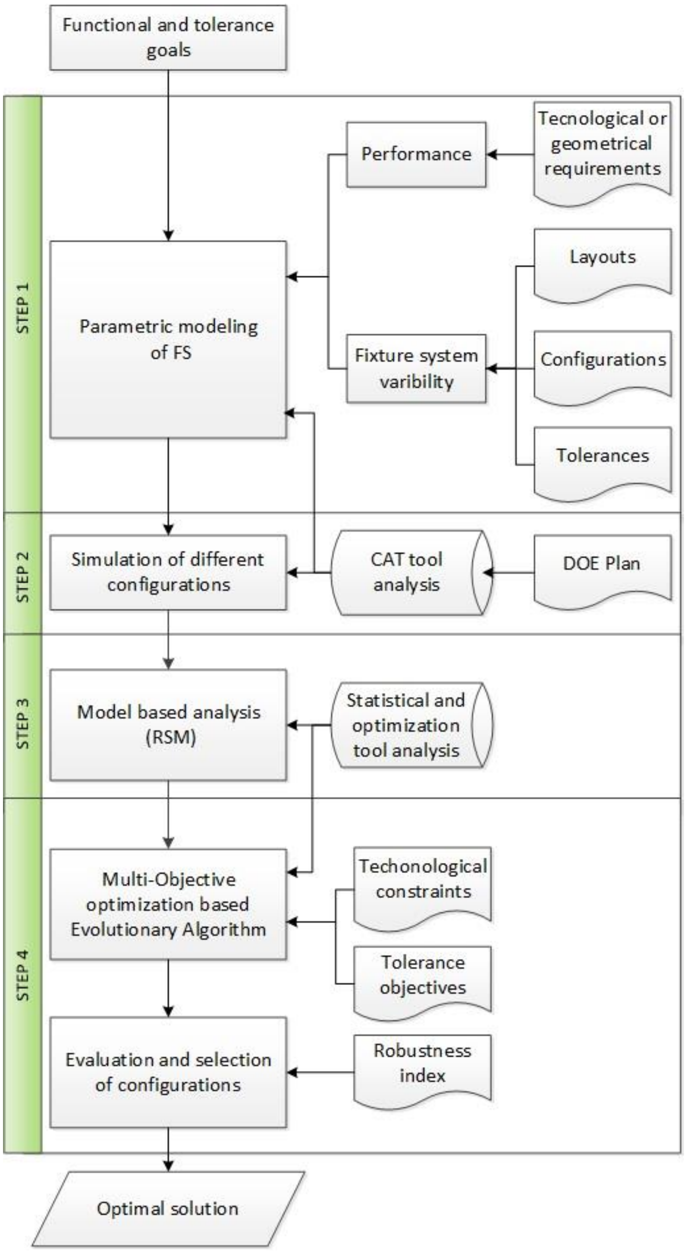


Figure 1: Computer aided design method workflow

FS parametric modelling

The first step deals with the definition of a parametric model, which addresses the functional goals of the FS (e.g. a gap position and orientation measured between two subgroups in a manufacturing process) and the related tolerance fields (i.e. tolerance goals). FS performance is stated through the technological or geometrical requirements. FS variability depends on its layout, configuration while tolerances on locators. Using such information, a Computer Aided Tolerance (CAT) tool allows to define a FS parametric model that represents the output of this step.

CAT numerical simulations

In the second step, the parametric model is used to simulate the different configurations through the statistical variation of the tolerances. This variation can be efficiently organised by means of a Design Of Experiments (DOE) plan, that combines tolerances on every locator through a set of sampling points in the design space defined by the tolerances of locators. In addition, the DOE plan allows to investigate the different interactions between the factors.

In order to accomplish this step a CAT tool is employed. This step outputs a set of numerical simulations of the different FS configurations.

Model-based analysis

After the CAT simulations, a model that correlates the tolerances on the locators with the design objectives is determined. The third step is the development of a FS model-based analysis. The model is obtained fitting a suitable Response Surface (RS) to FS performance. This model is the input for the following optimization step.

Evaluation and selection of the configurations

The last step performs a multi-objective optimization analysis of the model for every FS configuration, in order to identify the most suitable and robust FS design to achieve the functional and tolerance goals.

Starting from the RS and DOE sampling points, an evolutionary algorithm is used to further investigate the design space in order to solve a multi-objective problem: the main goals are to check regions where tolerances can be maximized and, at the same time, they can generate the most suitable gaps between parts. The optimization analysis is subjected to design constraints, due to technological and functional requirements on parts and their manufacturing process (e.g. interference between parts, gap dimensional and geometrical conditions, etc.). As a result, this constrained optimization underlines a feasibility region of the design space, that contains all the tolerance values able to achieve the performance goals and to satisfy the design constraints. Moreover, for each configuration, a Pareto frontier is obtained.

A robust analysis of each Pareto frontier is finally performed, in order to identify the maximum allowable values for each tolerance. The tolerance values t_i of each Pareto point are used to calculate the robustness index *TB*, as expressed in equation (1):

$$TB = \prod_{i=1}^{n} \frac{t_i}{\Delta TL_i} \qquad (1)$$

where *n* corresponds to the number of tolerance types and ΔTL_i is the difference between upper and lower levels in the design space for the *i*-th tolerance. *TB* represents a partition of the feasibility region, in the following called “Tolerance Box”. In particular, for each configuration, the maximum value of *TB* corresponds to the most suitable set of tolerance for the locators. As a consequence, TB_{max} can be used as a robustness index to overcome the difficulties in comparing different locators types.

3- Fixture system design for an automotive chassis manufacturing

FS parametric modelling

The subgroup shown in Figure 2 (on the left) for a top class car chassis is investigated to validate the method proposed. The subgroup is composed of three extruded parts (A, B and C) welded using the MIG technology.

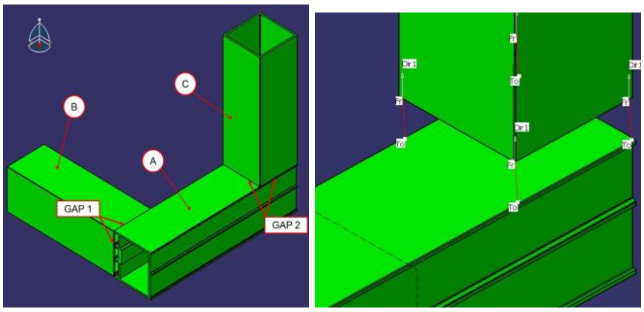


Figure 2: The chassis subgroup investigated (left) and the detail of a measure gap (right)

This welding technology imposes constraints on the relative distances between the functional surfaces of the extruded parts that have to be joined: measure gaps Gap1 and Gap2 shown in Figure 2 on the left. A detail view of Gap 2 measure gap is shown in Figure 2 on the right.

Simulation of different configurations

3DCS CAT software provided by the US Company Dimensional Control Systems (DCS) is used to simulate the dimensional and geometrical variations.

The variation of tolerances on parts and locators are considered along the three directions Y (primary), Z (secondary) and X. Since the subgroup is built of rigid parts, the layout fully comply the 3-2-1 locating principle for every configuration. The software allows the simulation of the fixture system without the need to have the mathematical CAD model, through the representation of the locators, as shown in Figure 3.

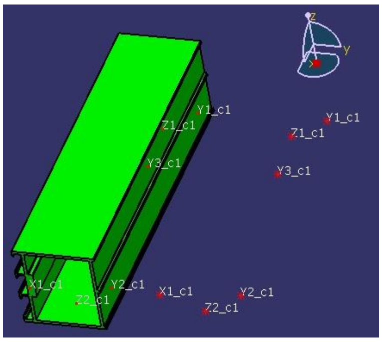


Figure 3: Simulation of the FS by 3DCS software

According to the previous assumptions, the following three system configurations are proposed as a combination of pads and pins, as reported in Table 2.

In particular:

- C1: 6 pads, one for each degree of freedom (3 in Y direction, 2 in Z and 1 in X);
- C2: 4 pads (2 in Y and 2 in Z) and 1 pin/hole mate which restrains two degrees of freedom (X-Y);
- C3: 3 pads (1 in Y and 2 in Z), 1 pin/hole mate which restrains two degrees of freedom (X-Y) and 1 pin/slot mate which suppresses the last degree of freedom (Y).

Configuration	Locators type	Number of locators
C1	Pad	6
C2	Pad	4
	Pin/Hole	1
C3	Pad	3
	Pin/Hole	1
	Pin/Slot	1

Table 2: System configurations

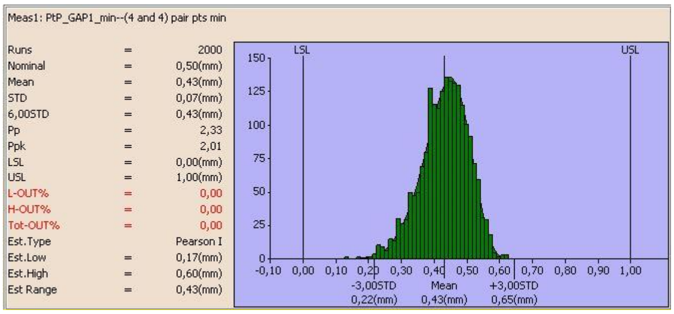
In the following simulations, locators are modelled as contact points allowed to move along the prescribed directions. In particular the pads are subjected to a position tolerance along the related direction (e.g. t_X, t_Y, t_Z). Pins are modelled as contact points which can vary the position within a circular area with the centre on the pin axis (e.g. t_{XY}). This is equivalent to simulate the variation between the coupling pin/hole.

In the proposed CAT model each tolerance range on locators varies from 0 to 2mm, in order to define the maximum admissible values to satisfy the technological and functional requirements.

Two measures are created between the reference part (A in Figure 2 on the left) and the other two parts (B and C in Figure 2 on the left) for the definition of the gaps: the first measure A-B is in Y-direction and the second measure A-C in Y-direction. These two measures are implemented with four couples of point to point measures between the parts, as exampled in Figure 2 on the right. Due to the technological requirements, a nominal value of 0,5mm is set for each gap.

Then, a DOE plan of 200 runs defines a sampling set of tolerances values used as input for the 3DCS simulation.

For every point, the software computes the statistical distribution of the gaps measure on the basis a Monte Carlo algorithm. The output, shown in Figure 4, returns statistical values for every gap measure: minimum and maximum gap values (Gmin and Gmax), mean (μ), standard deviation (STD), Cp, Cpk, etc.



```
Meas1: PtP_GAP1_min--(4 and 4) pair pts min

Runs          =     2000
Nominal       =     0,50(mm)
Mean          =     0,43(mm)
STD           =     0,07(mm)
6,00STD       =     0,43(mm)
Pp            =     2,33
Ppk           =     2,01
LSL           =     0,00(mm)
USL           =     1,00(mm)
L-OUT%        =     0,00
H-OUT%        =     0,00
Tot-OUT%      =     0,00
Est.Type            Pearson I
Est.Low       =     0,17(mm)
Est.High      =     0,60(mm)
Est Range     =     0,43(mm)
```

Figure 4: 3DCS statistical output

Model-based analysis

Multiple runs of the simulation generate a metamodel, which describes the relationship between the variability of the gaps values and the tolerances on the fixture locators. In order to obtain the metamodel, Neural Networks (NN) interpolation was used. NN used method is based on classical feedforward Neural Networks, with one hidden layer, and with an efficient Levenberg-Marquardt back propagation training algorithm and the initialization of the NN parameters is based on the proper initialization approach.

Evaluation and selection of the configurations

The goal of the problem is now to maximize the values of the tolerances of the locators for every configuration; this goal is subject to dimensional and geometrical constraints about the two gaps in order to avoid interference between parts and to obtain the most uniform gaps within a desired range (from 0 to 1mm). This problem is approached as a constrained multi-objective optimization.

Equation (2) expresses the formulation of objectives and constraints for each configuration:

$$\max \bar{f}(t_i) = [t_1, t_2, \dots, t_n]^T \qquad (2)$$

$$t_i \in TL$$

Subject to

$$\mu G_{\min} - 3\sigma G_{\min} \geq 0$$

$$\mu G_{\max} + 3\sigma G_{\max} \leq GapLim$$

$$\Delta Gap = \mu G_{\max} - \mu G_{\min} \leq \Delta GapLim$$

These constraints formulize the following condition for every statistical distribution of simulated gaps:

- absence of interference between parts;
- maximum gap value respecting the design specification: in this case, *GapLim* is set at a value of 1mm;
- condition of gap uniformity, corresponding to the maximum distance between each measure point of the gap: in this case, *ΔGapLim* is set at a value of 0,3mm.

Figure 5 shows the graphical representation of the constraints and the statistical distribution of each gap measure.

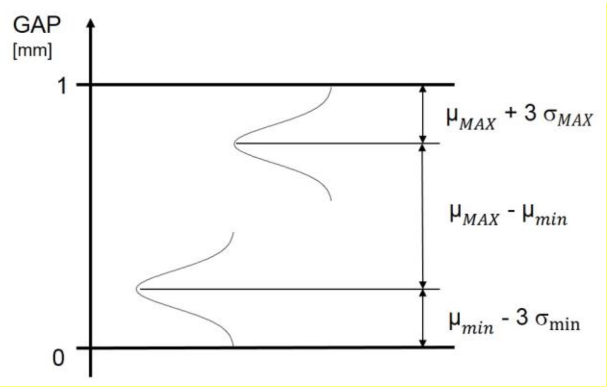


Figure 5: Graphical representation of the constraints

A multi-objective Genetic Algorithm (MOGA) approach is then used to investigate the tolerances design space in order to define a Pareto frontier of the most suitable solutions for each configuration [C, YG]. Every point of the frontier represents Pareto-optimal point, in term of tolerances, which is able to satisfy the functional constraints on the gaps. Figure 6, Figure 7 and Figure 8 illustrate the Pareto front for the three configurations investigated.

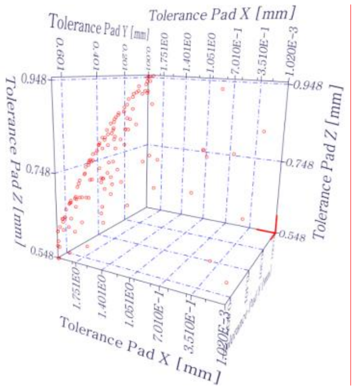


Figure 6: Pareto front for configuration C1

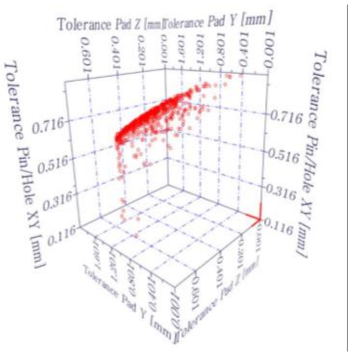


Figure 7: Pareto front for configuration C2

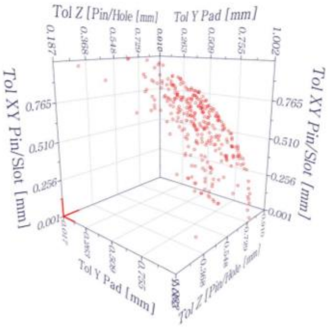


Figure 8: Pareto front for configuration C3

Table 3 presents the values of *TBmax* for every configuration. Moreover, each triad of values of locators tolerances that originates the maximum *TB* can be used to define the maximum tolerance range on locators.

Configuration	*TBmax*	t_i [mm]
C1	0,099	$t_X = 2$ $t_Y = 0{,}64$ $t_Z = 0{,}61$
C2	0,068	$t_{XY} = 1{,}58$ $t_Y = 0{,}54$ $t_Z = 0{,}63$
C3	0,046	$t_{XY} = 0{,}75$ $t_Y = 0{,}71$ $t_Z = 0{,}69$

Table 3: Comparison index TBmax for the three configurations

The output of the multi objective simulation is a frontier of optimal solutions, where at each points corresponds a set of tolerance values. All these results represent suitable solutions in relation to the desired goals and to the constraints. However they cannot lead to an univocal solution and, at the same time, they cannot lead to a comparison between configurations. The difficulties in such a comparison is overcame by mean of a robustness index *TB*, as expressed in Equation 1. In the analysed case, Equation 1 can be simplified as in Equation 3, due to the same width of ΔTL_i for each tolerance, equal to (2-0)mm:

$$TB = \prod_{i=1}^{n} \frac{t_i}{\Delta TL_i} = \frac{1}{\Delta TL^n} \prod_{i=1}^{n} t_i \qquad (3)$$

This index leads to reach two important objectives:

- the *TBmax* underlines a configuration able to maximize the tolerance space for each configuration. In this way, as shown in Table 3, a set of tolerance for t_X, t_Y, t_Z for C1 can be obtained. *tx* can reach the maximum allowable value, equal to 2 mm; *ty* is fixed to 0,64 mm and *tz* to 0,61mm. This means that every combination of tolerances values sets respectively under these limits leads to achieve the uniformity of gaps and their dimensional requirements.

The same for the other two configurations: for C2, t_{XY} is fixed to 1,58mm, t_Y to 0,54mm and t_Z to 0,63mm. For C3, t_{XY} 0,75mm, t_Y 0,71mm, t_Z 0,69mm.

In this way, the *TB* index can be used to set the tolerance range on the locators, in order to maximize them but obtaining uniform gaps values.

- the *TBmax* index represents an objective tool to define the most robust configuration and can be used for its evaluation and selection.

According to such considerations, the tolerance box volume results maximum for C1. It means that, in order to maximized the tolerance on the FS, i.e. its robustness, the configuration C1 leads to respect all the technological and functional requirements with the maximum tolerance range on its locators. The result of this analysis determines the choice of the configuration that better provides the desired performance.

4- Conclusions

The common approach to computer aided FS design is principally based on the evaluation of the layout influence on the overall robustness. Such approach does not consider the effect due to different configurations i.e. the sets of locators adopted to reference parts during their manufacturing or assembly process.

In the present paper the authors consider the problem of extending and deepening the study of the FS design process and propose a computer aided design method aimed at evaluating the effect of FS configuration on its roboustness.

The method integrates numerical and statistical tools and techniques: a dedicated CAT tool has been configured and used to run numerical simulations for evaluating the influence of every tolerance contribution on the final target tolerance for many system configurations, varied according to a DOE plan. Using a CAT tool it has been possible to consider a model-based approach to perform an optimisation analysis.

Since a FS can be considered as a multi-performance system, every FS configuration has been investigated and optimized with a multi-objective genetic algorithm in order to reach the tolerance and functional requirements.

As a result, for each configuration many optimal values for locators tolerances have been obtained in correspondence to a Pareto frontier.

The difficulties in directly comparing different types of locators have been overcame by introducing a robustness index, called “tolerance box” by the authors, that correspond to the volume of a partition of the feasibility region described by every optimal point.

The outputs of this analysis have allowed to define the tolerances values to attribute to the locators aiming to reach the most robust configuration, i.e. to maximize the tolerances values.

The proposed method has been implemented within a computer aided design environment and applied to an automotive case study.

The analysis of different configuration showed that the effects of the tolerances on the locators are highly dependent on the configurations themselves.

Since the investigation of locators type is not addressed during the traditional approach to FS design, a direct comparison with the traditional techniques is not feasible due to different investigation objectives.

Nevertheless, future developments are foreseen: experimental testing will be performed on similar industrial cases to further examine the accuracy of the proposed method.

5- Acknowledgements

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