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Individualizing Locator Adjustments of Assembly Fixtures Using a Digital Twin

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Implementing the concept of a Digital Twin in full production provides enough data on each individual assembly for real-time control of production processes. Taking advantage of this opening, this paper proposes individualized locator adjustments as a new method to improve the geometrical quality of assemblies. In this method, all locators in the assembly fixture can be adjusted for each individual assembly based on the scan data of the mating parts of that assembly. The optimal adjustment of every locator for each individual assembly is obtained using an optimization algorithm and non-rigid variation simulation tools (computer aided tolerancing tools). This method is applied to three industrial cases and geometrical variations and the mean deviation from nominal positions are compared to non-individualized adjustments and also when there are no adjustments. The results show that applying this method, an improvement of up to 81% in geometrical variation and 78% in the mean deviation of assemblies can be obtained compared to assemblies without adjustments. These improvements are 60% and 57% higher than non-individualized adjustments of locators for the variation and the mean deviation, respectively. Moreover, a modification on the optimization algorithm has been proposed that reduces the amount of required adjustments.

1 Introduction

Geometrical variations and deviations in parts and assemblies cause functional and aesthetic problems in products [1]. Therefore, a considerable amount of money and work is usually spent to utilize new technologies to minimize variations and deviation of products. There are different techniques that try to reduce the effects of part variations in the final assemblies, techniques that are labeled Geometry Assurance [2]. One of these techniques that has being used in industry since mass production started is locator adjustments. This technique is getting more attention in new production systems such as implementing a Digital Twin in assembly lines. For instance, a new Digital Twin concept in the production phase of welded assemblies has been proposed by Söderberg et al. [2] and is named Smart Assembly 4.0. Based on this concept, Figure 1, the scan data of all produced parts before assembly are available and can be used to improve the geometrical quality by different techniques, such as selective assembly [3, 4], weld sequence [5] and locator adjustments.

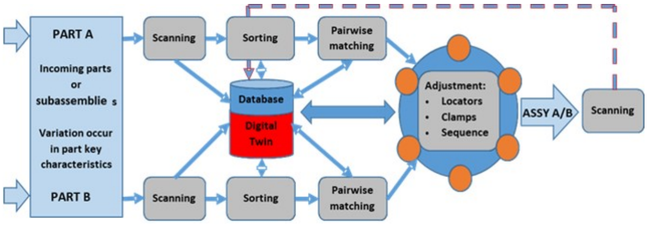

Fig. 1: The proposed concept of Smart Assembly 4.0 by Söderberg et al. [2].

Although locator adjustment of assembly fixtures is getting more attentions in new production systems, there are some gaps and limits in the existing applications and studies of this technique. Section 1.1 gives a brief introduction to this technique and reviews studies that has focused on it. In Section 1.2 then, the limits of the existing approaches are clarified and it is explained that how this study is going to

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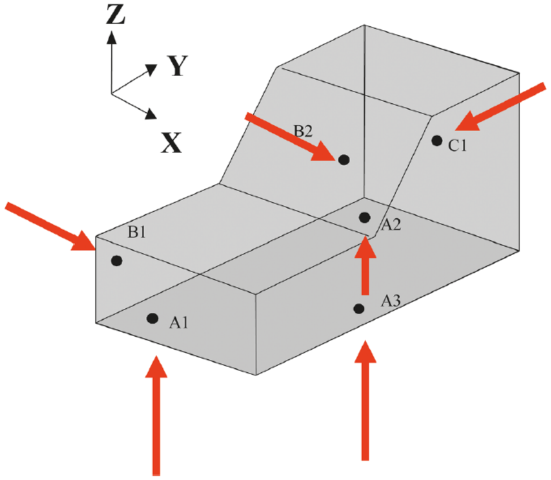


Fig. 2: 3-2-1 locating scheme for rigid parts [6].

remove them by presenting a new approach.

1.1 Locator Adjustments

Locator adjustment is a technique that increases the geometrical quality of assembly products by applying minor adjustments to locators of assembly fixtures. Each part has six degree of freedom that consist of three translation and three rotations around x,y and z axes. These degrees of freedom should be locked by some locators in a fixture. A common locating scheme for rigid bodies is 3-2-1 which is illustrated in Figure 2. If the part is not rigid, which applies to most of sheet metal parts, some extra clamps are also used to withstand external forces such as gravity to position the part into a desired position. These clamps are referred to as support points. The goal of locator adjustments is to reduce the geometrical variations and deviations of the final assemblies by applying some minor adjustments to these locators and support points. The adjustment for each locator or support point can be made only in the direction that it locks the movement of the part.

Locator adjustment is also referred to as Shimming [7] and Trimming [8]. Shimming is used when a thin slip or wedge of metal is added to the locator of fixture manually. There are usually some standard shims in different thicknesses and the required thickness is traditionally defined based on previous experiences or trial and error. Recently adjustable locators are also presented and produced [9]. Utilizing these types of locators, there would not be need for shims anymore.

There are some studies that have determined the amount of required adjustments by simulation of assembly process. Lindkvist et al. [8] proposed a Virtual Trimming toolbox in a variation simulation program to optimize the amount of required adjustment for each locator in a fixture. In this method, the inspection data from the parts produced during the pre-production phase form the input of the procedure. Using these data and the variation simulation tool, the final geometry of the assemblies can be predicted by simulating the assembly process. Then, by applying an optimization algorithm, the optimal adjustments can be calculated so that the final deviations are minimal. However, this toolbox is limited to rigid assemblies. Consequently, it is limited to adjustment of only six locators and when there are more than six locating points (support points) in the assembly, this method cannot be utilized. Forslund et al. [6, 10] has utilized this tool box to define the required adjustments for assembly of ballads in a turbine rear structure.

Beckmann et al. [11] developed a metamodel-based method to calculate the required locator adjustments in each locator. To prepare this model, they performed a sensitivity analysis of the assembly model. Then, a metamodel is generated out of the simulations. In the case of geometric deviations in the assemblies, the metamodel can be used to predict the outcome for different adjustments and the proper adjustment can be determined. Another procedure to calculate the required adjustments is developed by Germer et al. [12], and is referred to as Virtual Measurement Data Analysis (VMDA). Their method is based on the statistical data measurements on the previously produced assemblies and computer-aided tolerance tools. If the need for adjustments arises, they can predict the outcome of different locator adjustments using the simulation tool. Keller [7,13] presented a method for adjusting locators by measuring the locator forces and using them in control system before joining the parts. The application of this method is, however, limited to batch of assemblies and it does not utilize the scan data of mating parts for prediction of adjustments.

1.2 Scope of the paper

The application and studies of locator adjustments have been limited to adjustments for a batch of assemblies. In other words, adjustment of the locator had been carried out for a batch of assemblies not for each individual assembly, although the geometry of individual parts can vary between the defined tolerances. As a consequence, the existing approaches of locator adjustments cannot compensate for the variation of parts. This limitation also can cause reduction of geometrical quality for some individual assemblies, although it improves the overall quality of the batch of assemblies.

Another important limitation in existing studies is that there is not a criterion to calculate the limits of the adjustments that can be applied. The limits are usually based on previous experiences or trial and error. A disadvantage of this type of limiting is that these types of limits are not examined for generating residual stresses or plastic deformations that later may cause fatigue problems in the structure of the car-body. Therefore, they may reduce the geometrical deviations, but may introduce undesired residual stresses. Another disadvantage is that this type of limitations, restrict the maximum improvement of the assembly. All locators do not have the same effect on the assembly, but limiting all of them to the same level is, in fact, limiting the maximum improvement that can be achieved.

The limits and gaps in the existing applications and previous methods of locator adjustments are summarized in the following list.

- Applications and studies are limited to one adjustment in each locator for all assemblies or a batch of assemblies.
- Some undesired residual stresses and plastic deformation may be generated because of adjustments since the residual stresses and the maximum produced stress has not been considered as a limiting factor in adjustments.
- The scan data of mating parts as real-time production data have not been utilized in the prediction of the adjustments in previous studies.

This paper proposes individualized adjustments of locators in assembly fixtures within the concept of a digital twin. It means that the adjustment of locators is performed for each individual assembly based on the simulation results of a digital twin that is generated by utilizing real-time scan data of the produced parts. Therefore, this new approach can compensate for the part variations by adjustments which is not possible by existing methods. As a result, the improvement in final results can be considerably greater than traditional methods. Moreover, this study considers the residual stresses and the maximum stress during the assembly as the limiting factors for adjustments. The advantage of this type of limitation is that the maximum improvement in the assembly can be achieved without generating undesired residual stresses and plastic deformations that can be produced in other methods. In addition, this paper proposes a modification in the optimization algorithm that reduces the amount of required adjustments while the amount of improvement will not reduce.

Section 2 of this paper presents the developed method to calculate the adjustments for individualized adjustments. To be able to compare the results of individualized adjustments with non-individual adjustment, a method for calculating the required adjustments in non-individual adjustments is also developed and presented in this section. In Section 3 the outcome of applying both non-individualized and individualized adjustment to three industrial cases are presented. Thereafter, in Section 4, the results are compared and discussed. Moreover, the practical issue of applying the presented method are discussed.

2 Method

To make the adjustments individualized, the geometry of each individual part should be known. Some techniques have been recently developed to calculate the deformed shape of each part by taking some pictures from it [14]. Taking advantages of the provided data by these techniques, the deformed shape of each part can be provided before assembly as real-time production data to generate a digital twin for each physical assembly before starting the assembly procedure [15]. Thus, the assembly procedure can be simulated for the digital twin using variation simulations. Afterward, using an optimization algorithm, the adjustments for the digital twin will be obtained. Finally, these adjustments will be applied to the real assembly. This procedure is illustrated in Figure 3.

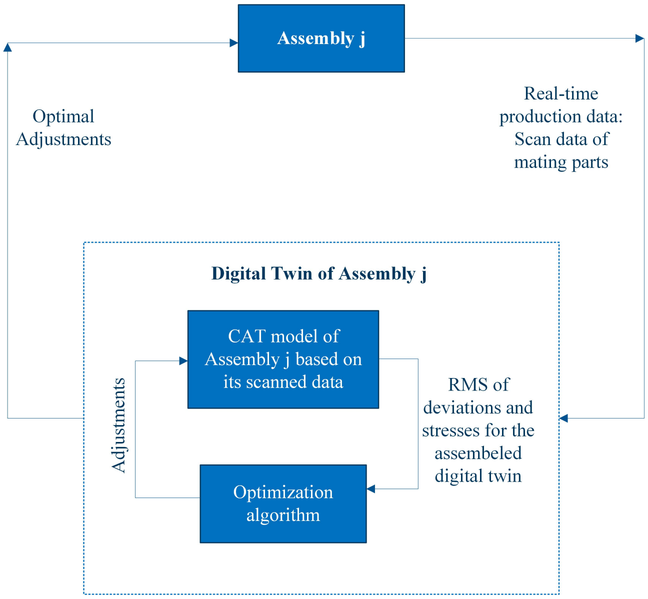


Fig. 3: Procedure of utilizing a digital twin for each assembly to individualize the locator adjustments

In this method, the real-time interaction is to get the scan data of each mating part of the physical assembly and giving the exact amount of adjustment to the fixture for clamping the parts before assembly. Data fusion is also performed to utilize data of different pictures to generate the deformed shape of the part. In addition, simulation of deformations of each assembly and calculating the maximum stress during the assembly process is a multi-dimension simulation. Therefore, the presented system has the characteristics of a digital twin [16, 17].

This section discusses how the scan data of each part can be used to generate the digital twin and the optimal adjustments for that digital twin can be obtained. After generating the digital twin, the optimization problem of finding the optimal amount of required adjustments for every locator and support point of each assembly should be solved in individualized locator adjustments. The optimization problem in non-individualized adjustments is to find the optimal adjustments for every locator but for the entire batch of assemblies. This section presents a method for each problem. Firstly, criteria for evaluating the geometrical quality for an assembly and for a batch of assemblies are defined in Section 2.1. Section 2.2 introduces the maximum stress and residual stresses as constraints of the problem. Then, generation of the digital twin of each physical assembly and utilizing it for simulating the assembly procedure in a variation simulation program is discussed in Section 2.3. Afterward, the optimization problem is formulated in Section 2.4. Section 2.5 presents the details of the utilized optimization algorithm to solve the problem. Finally, Section 2.6 presents a modification on the optimization procedure that reduces the required adjustments while it keeps the improvement the same.

2.1 Objective

In both individualized and non-individualized adjustments, the objective is to maximize the geometrical quality of the products after assembly. Thus, definition of geometrical quality should be clarified. Individualized adjustments treat each assembly separately. Accordingly, there is a separate optimization problem for each assembly and the geometrical quality for that assembly will be considered as the objective to be maximized. One the other hand, in non-individualized adjustments the entire batch of assemblies are treated the same. So, there is one optimization problem for the entire batch and the geometrical quality should be defined as a criterion for the entire batch.

The criterion for assessing the geometrical quality of a single assembly can be deviation of a point from its nominal position. To consider the quality of the whole geometry of the assembly, the root mean square (RMS) of deviation of different points is considered and is presented by RMS_{dj} as it is illustrated in Equation 1. In this equation, d_{ij} represents the magnitude of deviation of point i from its nominal position in the jth assembly and n is equal to the number of all nodes of the meshed geometry. Therefore, this study meshes the whole geometry of assembly into small elements. Accordingly, the RMS of deviation of all nodes from their nominal values is considered to be the objective of optimization in individualized adjustments.

$$RMS_{dj} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(d_{ij})^2} \tag{1}$$

In order to evaluate the geometrical quality of a batch of assemblies, variation and mean deviation of dimensions in the entire batch are considered as the criteria. The variation is usually considered to be six times the standard deviation [18]. Equation 2 demonstrates the mathematical representation of this parameter.

$$6s_i = 6\sqrt{\frac{1}{N-1}\sum_{j=1}^{N}(d_{ij}-\bar{d}_i)^2} \tag{2}$$

Where

$$\bar{d}_i = \frac{1}{N}\sum_{j=1}^{N} d_{ij}$$

In this equation, the number of assemblies in the batch is represented by N. Variable d_i represents the magnitude of deviation of point i from its nominal position and $\bar{d}_i$ is the mean deviation of that dimension. To acquire a better view of the variation of the entire assembly, the surfaces of the parts are meshed into small elements. Then, deviation of every node of the meshed geometry from it nominal value can be calculated. Thereafter, the root mean square (RMS) of variations and mean deviations in all nodes of the assembly can be considered criteria by which to evaluate the geometrical quality. This is presented in Equations 3 and 4.

$$RMS_v = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(6s_i)^2} \tag{3}$$

$$RMS_m = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\bar{d}_i)^2} \tag{4}$$

In these equations, n is the number of defined nodes in the assembly. RMS_m is considered as the objective of optimization for non-individualized adjustments. Hence, it also leads to lower variations in the batch of assemblies.

If there are some areas that are more important in the assembly, such as inspection areas, a finer mesh can be applied to those areas so that they influence the RMS more. Another way is to give a larger weight to nodes of those areas.

2.2 Constraints

The locators in a fixture can be adjusted to a limited extent. The limits are defined based on the magnitude of undesired residual stresses and plastic deformations due to the adjustments in the assembly. Tensile residual stresses can be added to the applied stresses in presence of external tensile loading and become detrimental. Compressive residual stresses are beneficial for fatigue strength of the assembly. However, they are undesired when they are large in magnitude due to the instability that they can generate trough creep or by redistribution [19].

A common approach to limit the adjustments in previous studies and practice is to define a limit for all locators based on experience. Nevertheless, all locators do not have the same effect on the produced stresses. Therefore, considering the same limit for all locators will reduce the potential improvement of the assembly. Moreover, there is no guarantee that those limits will not generate undesired residual stresses because this is not usually examined.

To overcome this limitation, this study adds the residual stresses and the maximum stress during the assembly to the constraints of the problem. Therefore, the limits of adjustments can be looser without making stress problems. The advantage of this addition is that the most potential improvement can be obtained without breaking the stress limits. In addition, it prevents generating residual stresses that can be produced in the other methods.

2.3 Generating the digital twin

The goal of having a digital twin for each physical assembly is to simulate the assembly procedure and predict the deviations and stresses. Deviations and stresses are influenced by a large variety of parameters. Part variations, the stiffness of parts, locating schemes and weld properties are some of these parameters [20]. The final variation and deviation of the product can be simulated using inspection data on the part level, joining process information and locating schemes. This kind of simulation is usually referred to as Variation Simulation or Computer Aided Tolerancing (CAT) in the automotive industry [21]. There are some commercial programs for this purpose, including RD&T (Robust Design and Tolerancing) [22] and 3DCS (3 Dimensional Control Systems) [23]. The techniques utilized in RD&T for variation simulation include Finite Element Analysis (FEA) and Monte Carlo simulation. Moreover, implementing the Method of Influence Coefficient (MIC) reduces the calculation cost of the simulations [24]. This technique is also combined with contact modeling to improve accuracy [25].

RD&T program is utilized in this study to generate a digital twin for each physical assembly and predict the stresses and deviations of that assembly. To attain this goal, the first step is to generate a model in the program that includes all deformations of the mating parts. This is possible by modeling the nominal parts and meshing the model. Thereafter, deviation of each part in each node will be added to the model. Having the mechanical properties of the parts, locating schemes and joining procedure the assembly procedure can be simulated for that digital twin.

RD&T does both rigid and non-rigid variation simulations. This study utilizes non-rigid simulation with contact modeling to acquire higher accuracy in prediction of the quality of assemblies and to be able to consider and adjust more than six locating directions for each part. In non-rigid simulation, parts are allowed to deform when they are positioned. Hence, the stiffness of parts and clamping force are considered in the simulation. The spring-back forces and resulting deformation are then calculated by the program, utilizing FEA and MIC methods. Therefore, results are more reliable and accurate in the non-rigid simulation [25, 26]. To calculate the residual stresses, an FEA simulation is conducted after each variation simulation to deform the parts from their free shape before assembly to their deformed shape after spring back (that is determined by variation simulations) and the stresses are calculated.

Some assumptions made for variation simulation by this tool are that deformation is in the linear elastic range, fixtures and welding tools are rigid, the thermal deformations are negligible, the material is isotropic and the stiffness matrix remains constant for deformed part shapes. The detailed procedure and method of variation simulation in RD&T is illustrated in [18, 26].

2.4 Optimization problem

Individualized locator adjustments is an optimization problem with objective of minimizing deviations of each assembly from its nominal geometry. These adjustments, however, should not generate undesired residual stresses and plastic deformations in the assemblies. Hence, two constraints are added to this problem that limit the maximum von Mises stress during the assembly procedure (S_{max}) and the maximum residual stresses (S_{res}). S_{res} can be limited separately for tensile and compressive stresses. However, this study considers von Mises stresses that includes both compressive and tensile residual stresses. The stress limit for the maximum stress ($S_{max-allowable}$) can be a factor of yield stress of the parts based on the utilized design standards in a company. The stress limit for the residual stresses ($S_{res-allowable}$), however, is normally lower than $S_{max-allowable}$ and can be defined in design phase based on the properties of the assembly and its application. These constraints are added to the optimization problem as two penalty functions [27]. If the stresses are less than their limits they do not add to the objective function, but if they become larger than the limits, a penalty will be added to the objective. The mathematical representation of the optimization problem of individualized adjustments is shown in Equation 5.

$$\begin{aligned} \min(RMS_{dj}(X_j) + \alpha \max(0, \frac{S_{max}(X_j) - S_{max-allowable}}{S_{max-allowable}}) \\ + \beta \max(0, \frac{S_{res}(X_j) - S_{res-allowable}}{S_{res-allowable}})) \end{aligned} \tag{5}$$

$$X_j = \{x_{j1}, x_{j2}, x_{j3}, \ldots, x_{jL}\}$$

Subject to:

$$a < x_{jk} < b$$

RMS_{dj} is the RMS of deviations of all nodes of jth assembly, L is the number of locators in the assembly fixture and a and b represent the minimum and maximum amount of adjustments that can be applied, respectively. The number of all assemblies in the batch is indicated by N. α and β are the penalty coefficients and they will be selected based on the range of stresses and deviations so that the penalty is roughly ten times the objective [27].

The optimization problem should be solved for each assembly (for $j = 1, 2, 3, \ldots, N$) in individualized locator adjustments. As a result, each assembly will have an optimal X at the end and the results can be applied during the production. For non-individualized adjustment one optimal X will be found so that RMS_m is minimal for all assemblies. The stresses in the penalty functions are S_{max} and S_{res} among all assemblies of the batch.

2.5 Genetic algorithm

A real-coded Genetic Algorithm (GA) is utilized to solve the optimization problem, since the amount of adjustment can be any real number between the limits. GA is an evolutionary algorithm. In this algorithm, firstly a population of random solutions for the problem will be created, known as initial generation. Thereafter, the next generations will be generated by giving fitter solutions of previous generations higher chances to combine and mutate. This procedure will continue till the solutions are evolved enough to satisfy the convergence criterion.

2.5.1 Selection

In each iteration of GA some individuals should be selected for crossover and mutation to generate the new solutions. The selected solution referred to as parents and the new solutions are named children. This study utilizes roulette wheel method [28] for selection of parents. In this method, each solution gets a probability for being selected based on its fitness. Equation 6 presents the relation of this probability and fitness of each solution. N in this equation represents the population size of the algorithm.

$$p_i = \frac{f_i}{\Sigma_{(j=1)}^{N} f_j} \tag{6}$$

To select a solution, based on the p_i each solution is associated to an subinterval from interval of zero to one. Therefore, a random number between zero to one will be generated. The solution that the random is in its interval will be selected for crossover or mutation.

2.5.2 Crossover

In crossover operation usually two children will be generated out of two parents. A common method of performing this operation in real-coded GA is to calculate an arithmetic combination of the parents [29]. Equation 7 illustrate this type of crossover.

$$z_1 = x\zeta + y(1-\zeta), \;\; z_2 = y\zeta + x(1-\zeta) \tag{7}$$

In this equation z_1 and z_2 are the children, x and y represent the parents, and ζ is a random number between zero and one.

2.5.3 Mutation

The mutation operation for real numbers can be conducted by several methods. The utilized method in this study is referred to as non-uniform mutation. In this method a random number between the limits of the optimization parameters will be added to the selected solution for mutation. If the result is still between the limits it will substitute the previous solution. If it is less than the lower limit, the lower limit will substitute the solution and if it is larger that the upper limit, the upper limit will be considered as the mutated solution [29].

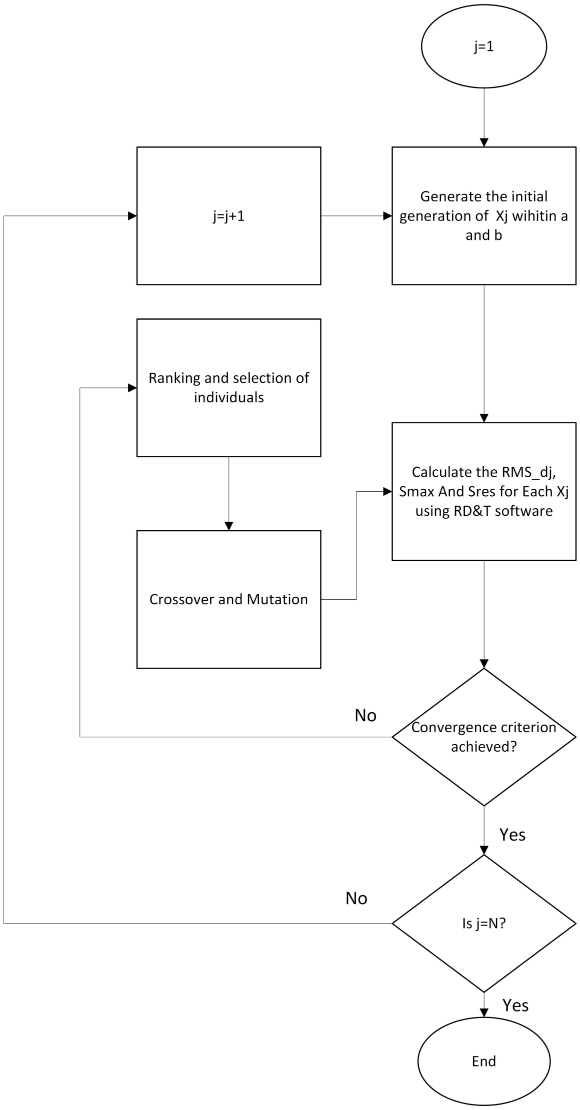


Fig. 4: Flowchart of non-individualized locator adjustments

2.5.4 Implementation

The flowcharts of the presented methods to solve non-individualized and individualized adjustments are depicted in Figures 4 and 5, respectively. To perform the optimizations, two MATLAB codes are developed for the optimization algorithms. Thereafter, an interactive connection between the MATLAB and RD&T programs is established. For each function evaluation, MATLAB calls the RD&T program to run the simulation for a given input of adjustments of locators. After the simulation, the RD&T program returns the result of that adjustment to MATLAB. The algorithm then stops when the convergence criterion is satisfied. The convergence criterion is if the best solution in the population does not improve after 50 iterations. The crossover and mutation rates for optimization are considered 0.8 and 0.05 respectively based on previous research [29].

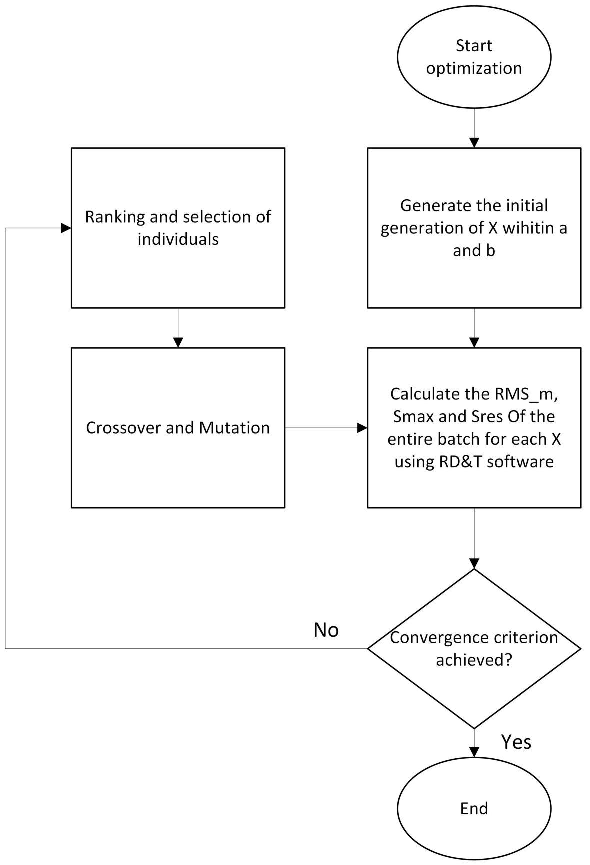


Fig. 5: Flowchart of individualized locator adjustments

2.6 Considering zero adjustments in the initial generation

The situation when locators are in their nominal position and no adjustment is applied is considered to be zero adjustments. The initial generation in GA is usually created by generating random numbers between the boundaries for each solution. However, one of these solutions in the initial generation is considered to be the zero solutions. In other words, to create the initial generation of GA, the whole population are random numbers between boundaries except one of them in which x_{jk} for all ks are zero. This modification in the optimization algorithm is performed because of two reasons. First, it avoids finding solutions that reduce the geometrical quality compared to the situation when no adjustment is applied. Because when the zero adjustments exist in the initial population, only individuals with better fitness can be qualified as the solution. Second, it leads to finding the results that require less adjustments. There are usually a couple of local optima that can be found as the final results. When there is a zero adjustment in the initial generation, the local optima that are near zero adjustments get a greater chance to show off and compete with other optima. Therefore, to evaluate the effect of considering zero adjustment, it is considered in the initial generation of each individualized optimization and the results are compared to solutions obtained without this consideration.

3 Results

In order to evaluate the results of the proposed method of geometry assurance, this method is applied to three industrial cases. These cases are modeled in the RD&T program. The assembly circumstances including the locating scheme during welding and measurement, weld properties, weld sequences and material properties are applied as boundary conditions of simulation. Figure 6 presents the developed models of the three cases. In this figure, the arrows represent the locating scheme of each model. If the number of locators are more than six for each part, the extra locators are referred to as support points. In RD&T the first six locators are indicated by red and the rest by orange to differ between master locating points and support points. Figures 6a, 6c and 6e present the locating schemes of fixtures that are used for the assembly, for case 1,2 and 3, respectively. The white spheres are indicators of the spot welds in these figures. Figures 6b, 6d and 6f demonstrate the applied locating scheme during measurement of deviations.

A batch of 25 assemblies ($N = 25$) is considered for each case to evaluate the variation and mean deviation of the entire batch when the adjustments have been applied. Therefore, for every component of each case, 25 deformed parts are considered for assembly. The limits of adjustments are considered to be -4 and 4 millimeters for a and b, respectively. The limits that are using in industry for shimming of these parts are -2 and 2 milliliters. Nevertheless, they are extended here because of having the stress constraint.

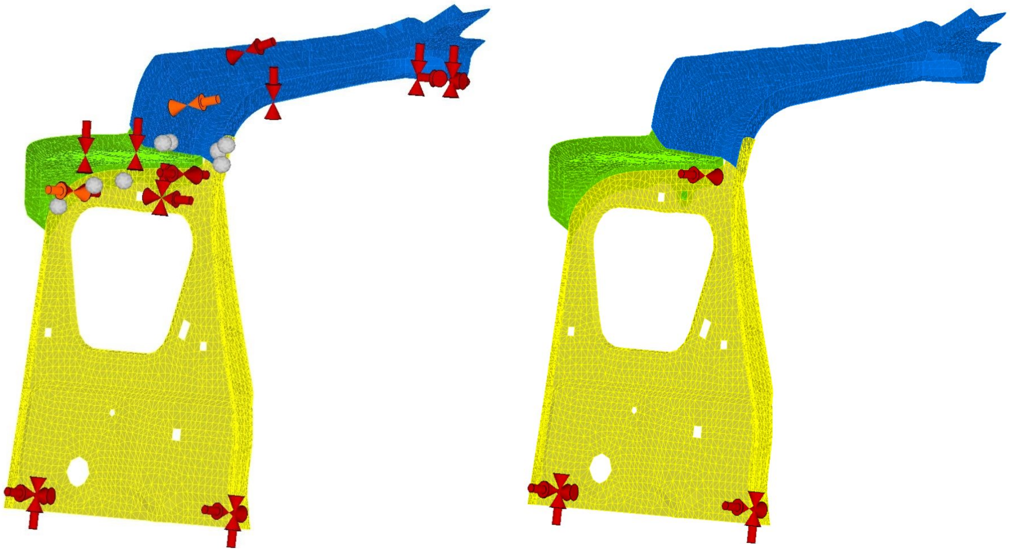
The number of optimization parameters is equal to the number of all locators (L) in each assembly. Therefore, the first case has 20 optimization parameters, the second case has 19 and the third case has 12. The mesh size is 5040, 17247 and 5610 nodes for the first, second and third case, respectively. The amount of $S_{max-allowable}$ and $S_{res-allowable}$ are set to 320 MPa and 10 Mpa, respectively , for all cases based on internal standards of the car manufacturer and allowable stresses [30]. The penalty coefficients, α and β, are also set to 100 so that the value of penalty is roughly ten times of RMS_{dj} for stresses that are generated in defined limits of adjustments. The population size of 200 is considered for the genetic algorithm used for optimization of each case.

Figures 7, 8 and 9 show the RMS_{dj} for all js without any adjustments, when non-individualized adjustments are applied and upon application of individualized adjustments for case 1, 2 and 3, respectively.

The RMS of variation and mean deviation (Equations 3 and 4) of the entire batch without any adjustment, after applying non-individualized adjustments and after performing individualized adjustments are presented in Table 1 for different cases. The percentage of improvement in RMS_v and RMS_m for non-individualized and individualized adjustments are also listed in this table.

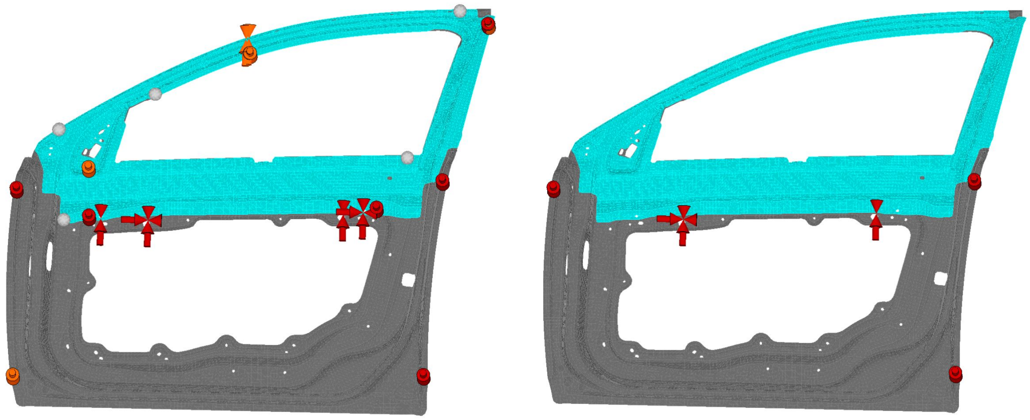
4 Discussion

The results show that applying the presented method for individualized adjustments of locators can improve the geometrical quality of assemblies 3 to 4 times higher than



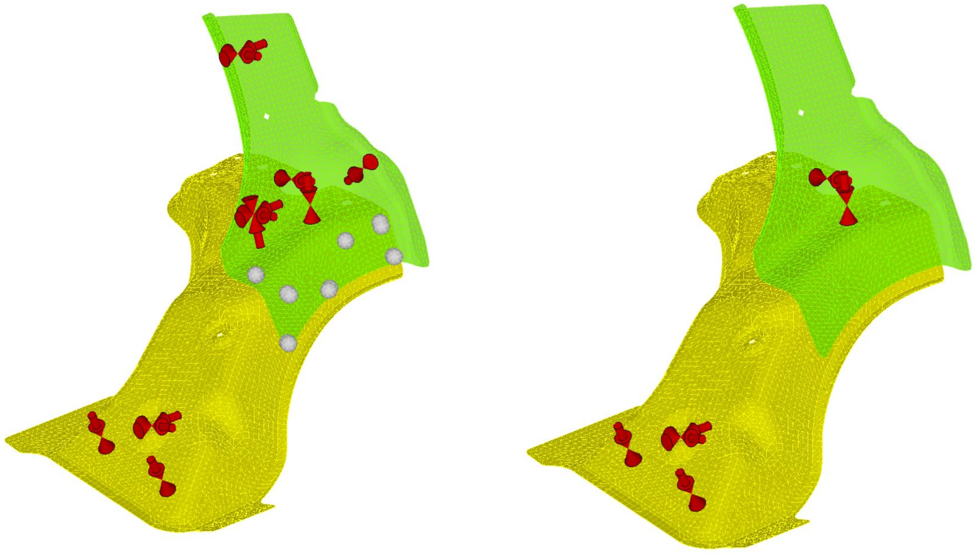
(a) Locating scheme of the first sample case before welding

(b) Locating scheme of the first sample case for measurements



(c) Locating scheme of the second sample case before welding

(d) Locating scheme of the second sample case for measurements



(e) Locating scheme of the third sample case before welding

(f) Locating scheme of the third sample case for measurements

Fig. 6: Models of sample cases in RD&T program

Table 1: RMS of variation and mean deviation of batch of assemblies without adjustments, with non-individualized adjustments and with individualized adjustments

Case	Quality Criteria	Without adjustments	Adjustments without digital twin		Adjustments with digital twin	
			RMS	Percentage of improvement	RMS	Percentage of improvement
1	Variation	1.53	1.22	20	0.29	81
	Mean Deviation	0.36	0.27	25	0.08	78
2	Variation	1.19	1.11	7	0.55	54
	Mean Deviation	0.32	0.27	16	0.16	50
3	Variation	1.42	1.08	24	0.46	68
	Mean Deviation	0.29	0.24	17	0.11	62

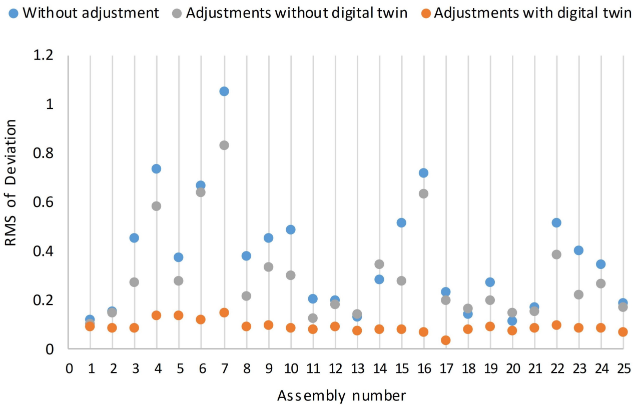


Fig. 7: RMS of deviation for each assembly without trimming, with non-individualized trimming and with individual trimming for case 1

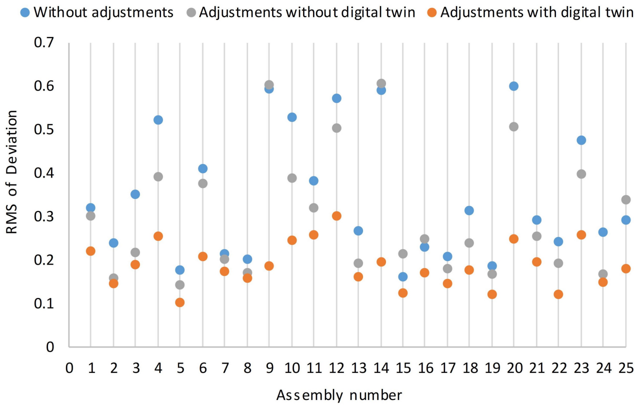


Fig. 8: RMS of deviation for each assembly without trimming, with non-individualized trimming and with individual trimming for case 2

non-individualized adjustments. This improvement is in both terms of variation and mean deviation of assemblies.

As shown in Figures 7, 8 and 9, RMS_d has been improved for all assemblies when individualized adjustments are applied. However, when non-individualized adjustment are applied to assemblies, RMS_d for some assemblies has worsened than when there are no adjustments. It means that applying non-individual adjustments can improve the overall quality of assemblies but may cause some assemblies to have lower quality. One the other hand, applying individualized adjustments improves the geometrical quality of every assembly.

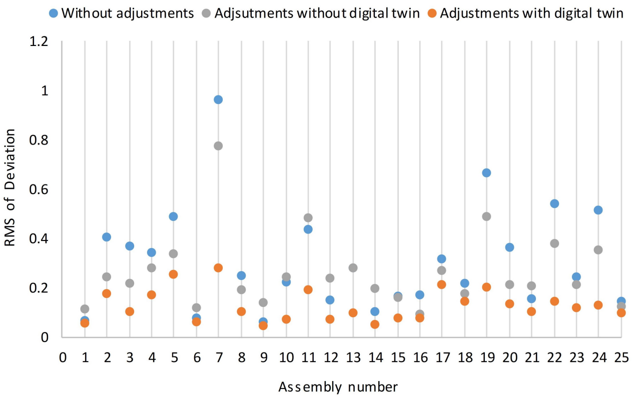


Fig. 9: RMS of deviation for each assembly without trimming, with non-individualized trimming and with individual trimming for case 3

Since the utilized optimization algorithm is a metaheuristic optimization algorithm, there is no guarantee that the obtained solutions are global optima. Nevertheless, the goal of this paper is to evidence the potential of individualization in locator adjustments. Hence, the obtained results can be acceptable for this goal.

Implementing the technique presented can also result in a cheaper production process. Since applying this technique improves the geometrical qualities of assemblies considerably, the mating parts can have relatively looser tolerances of production. This translates into production that is less expensive.

4.1 Effect of considering zero adjustments in initial generation

The results of applying the modification that was proposed in Subsection 2.6 are discussed in this subsection. The

Fig. 10: Sample of adjustable locator that can be developed for individual trimming [9]

individualized adjustments for all cases are calculated both by considering zero adjustments and without this modification. To compare the results, the range and average amounts of adjustments are listed in Table 2. The number of zeroes in the final adjustments are also compared for both scenarios. Because having more zeros in the final results means lower numbers of locators needed to be involved in the adjustments. Moreover, the percentage of improvement obtained by each scenario is presented for the comparison. To make the conclusion more robust, the optimal adjustment for every case is calculated ten times by each method for every case. The average results are listed in Table 2 for all cases.

As shown in Table 2, considering zero adjustments in the initial generation leads to having additional zeroes in the final adjustments, i.e. it results in fewer adjustments for approximately the same improvements. In addition, the average of all adjustments is also less when zero solution is considered. Accordingly, applying the proposed modification reduces the adjustments required for the same amount of improvements.

4.2 Practical issues

The presented method in this paper is based on this assumption that having adjustable locators in assembly fixtures is practically possible. This possibility has been proved in other studies. Erdem et al. [9] have developed a possible configuration of adjustable fixtures. Figure 10 and Figure 11 depict illustrations of these locators that are designed for the automotive industry fixtures.

The elapsed time of the optimization for each case mostly depends on the simulation time for each function evaluation and varies for each case. The elapsed time of calculations for the individualized adjustments was approximately 5, 12 and 6.5 hours for the first, second and third case respectively. This time for non-individualized method was 2, 4 and 2.5 hours for first, second and third cases, respectively. Since there would be a couple of hours between scanning process of parts and assembling them, the time elapsed does not make any delay in production process.

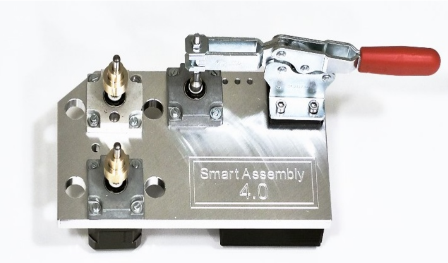


Fig. 11: Sample of adjustable locator that can be developed for individual trimming

4.3 Future research

Adjustment of locators for each individual assembly based on the scan data of the produced parts is a new idea and can be improved further in future studies to be implemented in new production systems in the Digital Twin concept. Improvement of the optimization time elapsed can be studied by utilizing some surrogate functions and metamodels. Moreover, implementing an intelligent agent can be studied along with the simulations to observe the predictions of simulations and inspected data of assemblies. Another area of future research is to apply some deep learning algorithms to observe the errors of simulations by comparison of measurement data of produced assemblies and prediction of simulations.

5 Conclusion

Adjustment of locators for each individual assembly in the concept of a Digital Twin was proposed in this study. This technique can be implemented in a smart assembly line where the locators are adjustable by a generating a digital twin from scan data of mating parts for each assembly. To calculate the optimal adjustment of every locator for each assembly, an optimization algorithm is utilized along with variation simulation (CAT) tools. The objective of optimization was considered to be the geometrical deviation of each assembly. However, it also results in a considerable improvement in variation and mean deviation of all assemblies. The maximum stress that can be generated during the assembly is also constrained by adding a penalty function to the objective function to prevent undesired residual stresses and plastic deformations due to adjustments. The main contributions of this paper are as follows.

- Proposing and studying individualized locator adjustments by presenting a method, applying the method to three industrial cases and evidencing the potential improvements resulting from this technique compared to non-individualized adjustments and without adjustments.
- Preventing generation of plastic deformations and undesired residual stresses by limiting the maximum residual stress and the maximum produced stress during the assembly.
- Presenting a modification in the utilized optimization algorithm that reduces the required adjustments for the same improvements.

Table 2: Effect of considering zero adjustment in initial generation on the final average results

Case	Status	Number of zeros in the final adjustments	Average of optimal adjustments	Range of optimal adjustments	Percentage of variation improvement	Percentage of mean deviation improvement
1	With zero adjustments	107	0.15	1.2	80	77
	Without zero adjustments	77	0.19	2.0	78	73
2	With zero adjustments	89	0.27	3.8	53	45
	Without zero adjustments	41	0.36	3.8	49	43
3	With zero adjustments	48	0.26	2.4	68	59
	Without zero adjustments	27	0.31	3.1	65	58

The results of applying this technique in three industrial cases confirm that an improvement of up to 81 percent in the variation and 78 percent in the mean deviation of the entire batch of assemblies can be obtained. It can also be concluded from results that:

- Individualized adjustments can improve the geometrical quality of the assembly batch 3 to 4 times higher than non-individualized adjustments.
- Applying individualized adjustments results in a better geometrical quality for all individual assemblies while for non-individualized adjustments the quality of some assemblies may become worse.
- Having the zero solution in the initial generation of the optimization algorithm can reduce the total amount of adjustments that are required for the same amount of quality improvement.

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