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A Method of CAD Based Automation and Simulation by the Example of Virtual Stone Chipping Testing

Markus Ernst[1], Mario Hirz[2] and Severin Stadler[3]

[1]Graz University of Technology, markus.ernst@tugraz.at
[2]Graz University of Technology, mario.hirz@tugraz.at
[3]Graz University of Technology, severin.stadler@tugraz.at

ABSTRACT

Frontloading in product development supports the possibility to make important decisions as soon as possible. The dedication of virtual product development tools implicates cost savings by reduction of physical prototype testing. The present publication treats the potential of computer-aided design (CAD) in a specific application to offer changeable, quick and efficient development. The application of the developed methods and tools is shown for stone chipping investigations, which are important for the definition of corrosion protection measures in automotive body design. The automation by use of modern parametric-associative CAD models in combination with high level of knowledge integration enables the creation of simulation tools, which are able to support development processes especially in early stages.

Keywords: virtual testing, parametric-associative modeling, knowledge-based design, macro programming, stone chipping simulation.

1. INTRODUCTION

Nowadays companies are faced with constantly increasing requirements for product quality and that within even shortened development durations. The rising product diversity, permanent changing boundary conditions and the high complexity of products represent an additional challenge, especially in the automotive industry. In order to meet the desire for better quality and still to achieve competitiveness, costs have to be kept minimal and development cycles have to be optimized. These facts can be achieved through the use of modern computer-aided design (CAD) based development methods and tools to ensure flexible, changeable and efficient product creation and production engineering. An efficient and modifiable development of vehicles can be realized with the help of modern IT-based engineering tools. Thus companies can provide the necessary quality of their products in relatively short durations at low costs. A key aspect in vehicle development cycles is to make important decisions as soon as possible. This can be enabled by the so-called frontloading concept. This process describes the integration of computer-aided engineering methods (CAx) in early phase of the product development cycle in order to support important decisions, [2,3], [5–7], [12].

The frontloading approach implicates a reduction of costs in the later development phases. Even if the simulation efforts are increasing, the overall costs can be reduced by application of frontloading concepts. The application of simulations in the course of virtual-prototype-testing reduces the necessary amount of physical-prototype-testing in later phases of the product development cycle. Especially between the styling and the development phases, feedback loops in the course of styling changes can be generated. This advantage saves a lot of time, costs and provides engineering related degrees of freedom in the development process. The application of virtual product development in early stages of the vehicle development cycle supports a partial replacement of expensive physical-prototype-tests. The possible potential of time saving in case of prototype research is visualized in Fig. 1, [2,3], [5–7], [12].

The benefits of virtual product development can be applied to the development of corrosion protection measures in automotive body design. Protection for preventing any type of corrosion attack states an essential influence on the durability of vehicles. In addition, the resale value of used cars can be enhanced by avoiding rust stains resulting from corrosion. Even more dangerous is the

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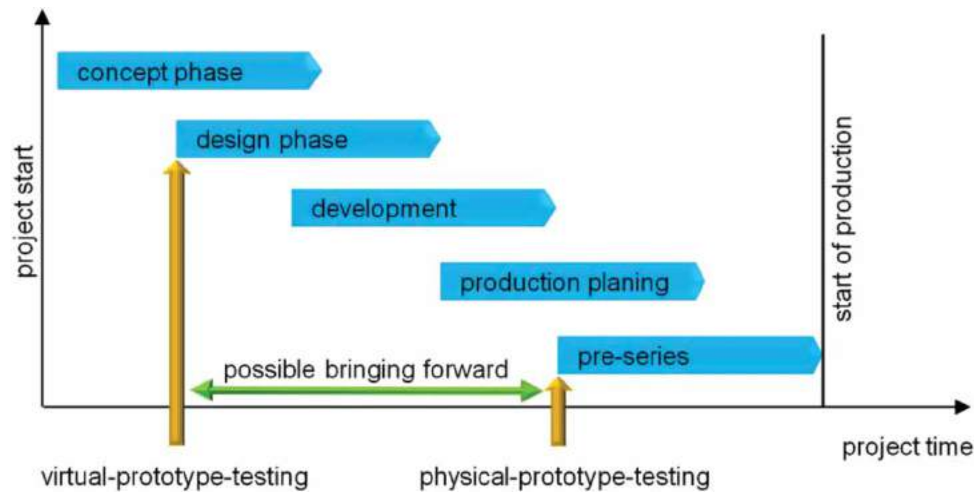

Fig. 1: Time saving through virtual testing, [11].

unexpected component failure because of, stone chipping inducted, corrosion, which implicates safety detraction. In this way, new methods and tools are permanently developed to increase protection against corrosion. Most vehicle manufacturers (OEM) or suppliers of components among the automotive sector already have their own departments to handle this rising challenge, [2].

Stone chipping on vehicle bodies and components is an important issue in the field of corrosion protection in the automotive industry. Stones, which lie on the streets are taken by a preceding vehicle or picked up and stirred up by the own front and rear wheels of the considered vehicle. Because of the rotation of the wheels, the stones are launched due to the increasing centrifugal force and subsequently are forced to impact on components of the vehicle, such as vehicle body, windows, wheels, suspension, underbody, axles and further attached parts. The intensive impact of stones causes erosion of coatings and even to material abrasive. By chemical reactions of metal, water and air, corrosion attacks concerned areas, which can result in to unexpected component failure. For this reason the importance of stone chipping investigations increases in the automotive industry. Multi-layer coatings are applied since a long time in the automotive industry to enhance stone chipping protection, but a widely used application of the measure increases the production costs. Several studies and investigations are concerned with the resistance of coatings or layers as passive protection against failures caused by stone chipping to optimize the coatings and their application methods, [5], [8], [11]. Simultaneously, there also raises the question whether stone chipping can be actively prevented. In today's automotive engineering the most stone chipping tests are performed using physical prototypes. Therefore a gravel road or a scattered gravel prepared path is traversed several times by the concerned vehicle. To enable detailed studies, specific foils or coatings are applied on components such as underbody and vehicle body parts to highlight the areas which are affected by stone chipping. As already mentioned the physical-prototype-testing implicates high costs and limited possibilities regarding redesign cycles because of the relatively late point of time in the vehicle development process. As result of these physical tests, the areas with a high density of stones subsequently have to be protected by the installation of safety precautions, such as covers, films or panels. The entire development process is always associated with high costs and cost-intensive renovations. This fact holds high risk of unforeseen cost pressures especially in late stages of development, [2], [4], [8], [10].

For this purpose the application of stone chipping investigation in early stages of vehicle development, following the scheme of frontloading is very present, which leads to the necessity of an assessment of stone chipping sensitivity in an early development phase. Virtual investigations of stone chipping can be applied as early as possible in the development process. Thus expensive development loops produced by the investigation of physical prototypes could be saved, because stone chipping simulations are able to reduce the number of physical methods. The present approach treats an integration of the corrosion protection issue because of stone chipping from the beginning of the vehicle development process, which enables an early validation and modification of styling concepts, [2].

2. SIMULATION BASED ON 3D CAD

In the automotive industry there are a lot of different ways to offer virtual investigations by the use of adequate simulation tools. The challenge in the present case is to find the ideal method and development environment for the targeted application. In any case, there are different ways to face a stone chipping simulation. It mainly depends on the available input and the desired output, but it is also a question of the desired precision rate and the effort. In the lecture there are some publications which explain the investigation of stone chipping by computer-aided engineering (CAE) based simulations tools, for example computational fluid dynamics (CFD) simulation. For this purpose the main focus of attention lies in the fluid mechanics investigation and the trajectories of different particles. The challenge is to find the optimal point of time to implement a stone chipping investigation in the development process. The floating changeover in vehicle development between styling and engineering is very important in the case of modifiable product development. Especially considering vehicle body styling, early feedback loops secure convertibility regarding the vehicle outer shape. Therefore, the indications of styling and engineering division should be combined as soon as possible in the development process. For this purpose the simulation within CAD environment can be advantageous, because at this point of time the vehicle body geometry is defined by the use of computer-aided styling (CAS) tools and subsequently transferred into a CAD environment. To integrate the stone chipping investigation at this point of time an effective way is to use parametric-associative CAD programs. However, the challenge lies in the complexity of the stone chipping issue. Stone chipping on vehicle bodies depends on many different influencing factors, which in turn affect each other. The challenge in the development of stone chipping investigation is to approximate the simulation as close as possible to reality, and that during early stages of full-vehicle development. This fact requires a detailed consideration of several deciding factors and their evaluation in terms of relevance and necessity regarding the discretized integration into a simulation, [2], [5], [10], [11].

The way to integrate simulation into 3D-CAD models represents a geometrical approach to handle the stone chipping investigation. A main reason for performing automation within CAD is stated by its comprehensive knowledgeware environment, which includes a technology oriented focus on methods and tools for the support of virtual product development. Knowledge-based design uses the integration of mathematical or logical relations into variable geometry models by implementing rules, reactions, formulas or check operations. In this way predefined methods can be applied, which supports the automation of investigations by using simulations. Parameters are used in the CAD program to define the dimensions of the product. Thus the geometry of the object can be changed by the variation of input parameters. The automation of geometry creation or calculation procedures is performed by integrated scripts, such as Visual Basic for Applications (VBA). These macros combine specific routines with the parameters and the knowledge based features to enable an automatized simulation. Through parametric methods, objects are determined in their appearance. The storage of the parameters for the creation of geometry enables their subsequent adjustment and effects a quick and easy modification of the properties. Among associativity the generation of cross-model dependencies between geometries, objects or components is an additional advantage. The combination of these two terms is called parametric-associative design. Their properties provide a structured, easily modifiable, and linked construction, which can be changed by varying parameters of the relationships between objects. This allows rapid, variable construction, because the geometry data and the design models are also saved with the concerning objects, [2], [3], [5–7].

During the alignment of styling and engineering, the consideration of geometrical characteristics is sufficient, because at this stage in the development process the main focus of attention lies on the integration of styling and engineering. The goal is to achieve a satisfying prediction quality within low computational effort. For this purpose it has to be paid attention that during the modeling process of the new approach the most important influencing parameters have to be analyzed and included into the stone chipping simulation.

3. APPROACH OF CAD-BASED STONE CHIPPING SIMULATION

For comprehensive programs and complex simulation structures a separation into different steps is advantageous. Splitting virtual investigations leads to efficient sub-processes, which decrease the duration of the entire simulation process. In case of the present stone chipping investigation the process is organized in three steps, as shown in Fig. 2.

The pre-processing step receives the numerous vehicle body surface elements as input and delivers a merged single surface model. The simulation step includes the geometrical compilation of stone chipping points on the combined vehicle body surface. These points represent those areas, where stone chipping geometrically can appear. The evaluation of these points is generated by the post-processing step, which colors the points as a function of predefined criterions by use of an integrated evaluation system.

To handle a complex simulation tool with a huge data deposition within parametrical CAD environment, the communication and data exchange between users (GUI supported), automated routines (e.g. VBA macros) and the standard functionalities of the applied CAD program can be optimized by using a CAD external database, e.g. Microsoft Excel®, [9]. A possible connection between those components is shown in Fig. 3.

The advantage of the mentioned combination of different tools lies in the separation of working tasks. In this way, the geometrical approach of simulation

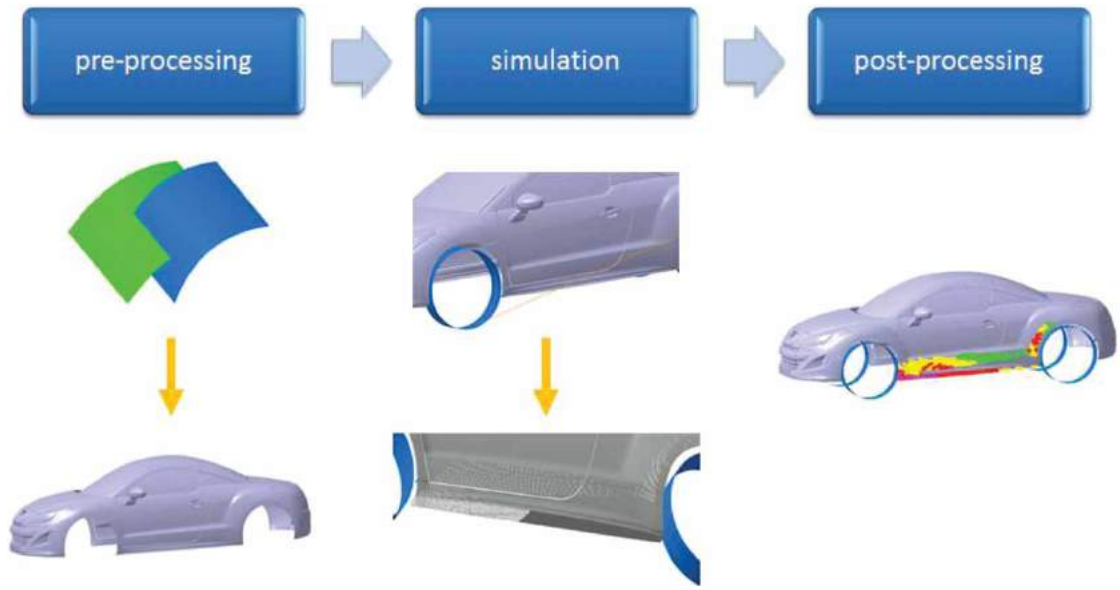

Fig. 2: Tasks of the separated simulation, [2].

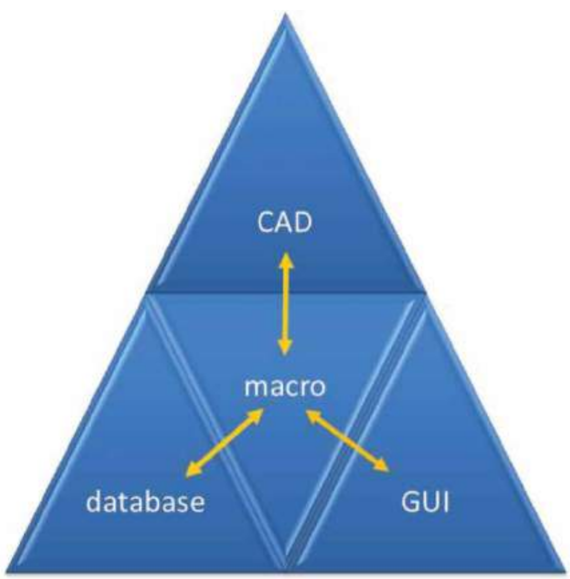

Fig. 3: Communication between the individual interfaces.

within a CAD environment implicates the option to create geometrical objects without actual representation in CAD to reduce computation time. The geometrical data of the created objects can regardless be archived in the database, which is able to reduce the simulation duration noticeable.

3.1. Pre-Processing: A Challenge in View of Product Data Exchange

The pre-processing section includes the data preparation before a simulation can be performed. As a basis for the stone chipping simulation, the vehicle surfaces have to be prepared by creating a shape assembly from the numerous individual vehicle body shape surface elements, exemplary delivered by CAS. Such an assembly, resulting in one big segmented NURBS-surface has to be created each for different variants of styling proposals. To enable an efficient simulation, it proves to be advantageous to provide only one comprehensive surface model. In automotive engineering different software methods and tools are used in particular for the transfer of styling and engineering data. During the concept phase in the development process vehicle body surfaces are designed with the aid of CAD external styling software (CAS). The transfer of geometry information from CAS to CAD can lead to data defects, e.g. tolerance deviations, small gaps or overlapping areas of surface elements. In this way, the joining of such vehicle body surface elements often produces topological errors because of incompatible shapes. These errors can result from the different precision of the diverse programs and the data exchange between them. Of course the option to optimize the product data management by using neutral data formats, such as IGES, or STEP, supports the solution of this challenge. But through the data exchange process, there occur shapes in the three-dimensional space, which lie on top of each other or in a different way, so that they cannot be combined by using the conventional CAD-based functionalities. To avoid assembly errors based on incompatibility of single surface elements, a specific algorithm is included into the present approach. This algorithm bases on automated routines, which are able to combine erroneous and not erroneous surface elements to a comprehensive surface model automatically within the pre-processing step, [2,3], [5–7].

The first step after starting the pre-processing tool is to manually select a few important surfaces of the vehicle body which have to be included in the combined surface. The function of the algorithm takes the first and the second surface of the geometrical set and produces the first assembled surface called join. For this purpose the connectivity criteria of the CAD software is switched off and the deviation value is set maximal. Afterwards the third surface in the geometrical set is added by producing a second join by connecting the first join with the third surface. This approach is explained by handling the challenge to get the correct error to the right time, if an erroneous surface is added to the assemblage. If the joining process delivers, the program removes the erroneous surface and sets the suppress mode true to create a correct join without any error. Finally the program selects that last surface which has been added and switches it into another predefined geometrical set. If joining process does not deliver an error, the previous join and the next surfaces are combined to a new join. In every case the algorithm does not stop and the approach of the program runs until the last surface in the geometrical set. Numerous of industrial applications in automotive body-in-white design have shown that erroneous surfaces, which cannot be added, have been only a few small surfaces like pieces of curves or flanges with high curvature, which have not been relevant for the simulation, [2].

3.2. CAD-Based Simulation of Stone Chipping

After passing the pre-processing step, which delivers the desired vehicle body geometry in shape of assembled surfaces, the actual simulation of stone chipping is performed. First of all the main reasons of stone chipping have to be analyzed. Stones, which lie on the road, are picked up by the tires by following two mechanisms. Either they adhere on the tire surface or they stick in the surface profile. All these stones are subsequently discharged because of the occurring centrifugal force, Fig. 5, [2].

The trajectories of the stones are influenced by a combination of translational and rotational movement of the tire. Judging the reference system in the center of the wheel, the stone moves in a circular motion relative to the reference system. To describe this path, the consideration of the movement of a selected stone in a predefined plane with the aid of a polar coordinate system is appropriate. In order to reduce the complexity, a tire slip is not considered. In the case of a slip-less free rolling wheel the circumferential velocity equals the launching speed of the stone. The launching speed of the stone v_0 is defined as a function of the wheel radius r and the angular velocity ω by the following equation [2]:

$$v_0 = r * \omega \tag{3.1}$$

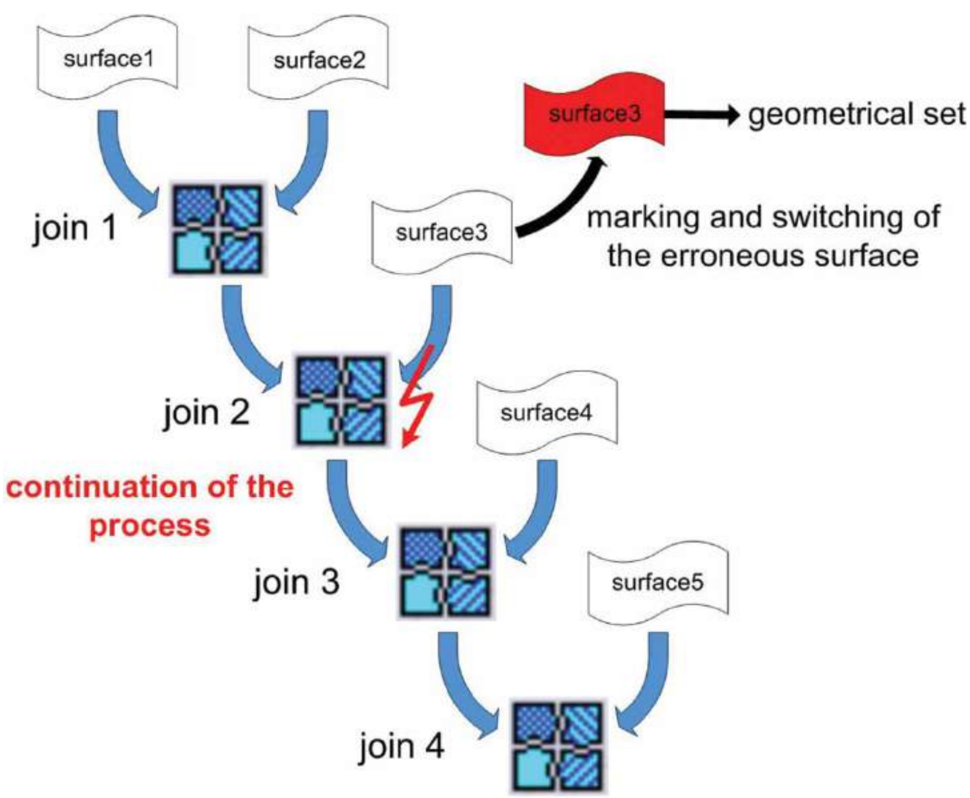

Fig. 4: Principle approach of the algorithm to combine erroneous and not erroneous surfaces, [2].

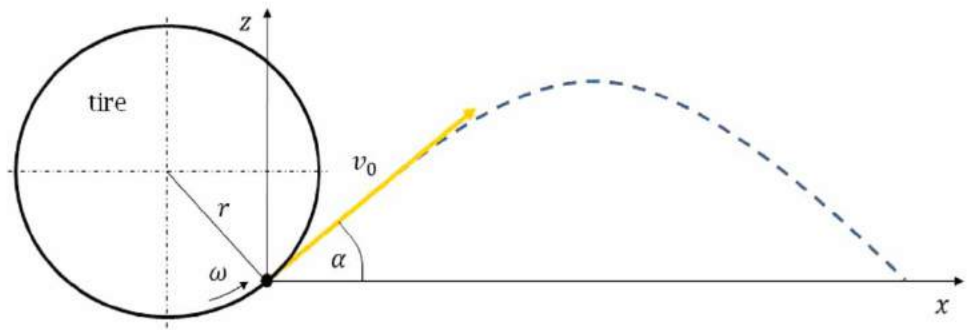

Fig. 5: Launching trajectory of the stone, [2].

The movement of the exemplary stone is effected by a flow field in the air. Looking at a real stone geometry, a large number of forces and moments are affected during the flight due to the complex and irregular geometry. These relationships are difficult to detect and because they are not crucial for a conceptual definition of the trajectory, it is possible to simplify the real conditions to a spherical stone model. Because of the geometrical approach of the present method and relatively small stone dimensions, the flow circulation and accordingly the air drag can be disregarded. In this way, the main influence on the trajectory of the stones is represented by the force of gravity [2]:

$$m * \ddot{x} = 0$$
$$m * \ddot{y} = 0$$
$$m * \ddot{z} = -G = -m * g \quad (3.2)$$

The conversion of equation 2 by integration, cancelling the mass, elimination the time and applying the initial conditions delivers the stone movement in the z-direction as a function of the launching speed, the gravity, the launching angle and the current x-coordinate [2]:

$$z(x) = -\frac{g}{2 * v_0^2 * cos^2(\alpha)} * x^2 + \tan(\alpha) * x \quad (3.3)$$

The simulation tool has to reproduce this launching effect of the stones in an adequate level of detail. For this purpose, a geometrical tire substitution is generated at the beginning of the simulation. Of course a detailed tire model including the kinematic relations in the tread shuffle could provide very exact results of the stone movement, but a representation of the physical conditions including the complexity of tire material and geometry, its movement and deformation would lead to significantly expanded computation effort. Far reaching measurements and simulation of stone chipping behavior results in the cognition, that a simplified modeling of the launching conditions of the stones from the tread shuffle area is sufficient for geometry based representation of the fly paths within a commercial CAD system. As a result of the present approach, a quick creatable geometrical tire substitution model states an efficient way to simulate the concerned behavior in the treated phase of the development process. For an efficient data handling, the user is able to control several tire dimensions and the positioning within a parametric 3D-CAD vehicle model by setting the input data in a specific GUI.

After the definition of the geometrical tire substitution the present approach uses a way to create points on the circumferential surface, which represent the stones that stick in the tire profile or adhere on the surface. An important influencing factor is represented by the actual distribution of the stones on the tire cross section. In the present model, the distribution of stones across the tire cross section is defined by a variable function, edited by user. In addition to the geometric approach to reality of the stone chipping visualization, which provides a statement where the stones hit, an assessment of the damage to the body, launching statistics and impact probabilities are involved. In this way, the distribution of the stones along the tire scope is split into four angle areas, as shown in Fig 6. Each of these areas has a different launching frequency in a defined distance.

In addition, there is also a distribution implemented breadthwise the tire, which is sectioned in ten areas with a constant distance, as shown in Fig. 7. In these areas the user can also choose different launching frequencies, but not before post-processing.

During the simulation the distribution in the tire cross section is constant, but with every point the information of the area where it has been created is deposited. In the following post-processing step the user sets a launching distribution and frequency for the points in each area, which affects the coloring of the impact points. The same procedure is applied for the points along the tire scope, but the distribution for the simulation is not constant. For optical reasons the distribution of the impact points on the vehicle body has to be a constant grid, which is approximated with constant steps across a vertical line from the tire center point. For this purpose the points on the tire have to be distributed by corresponding increment steps. The launching distribution and frequency

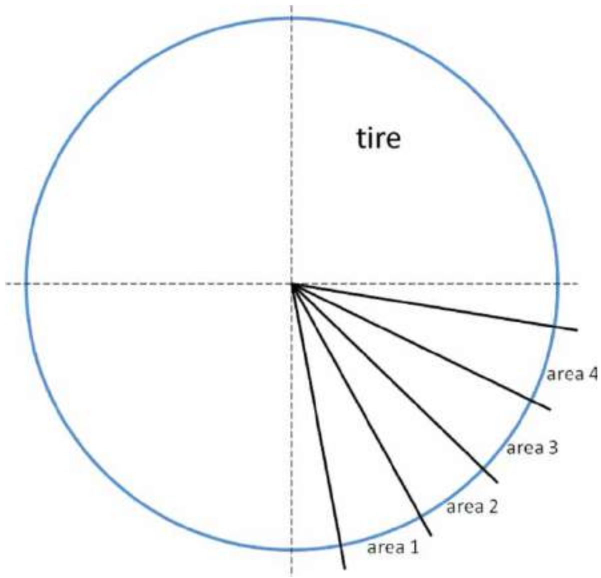

Fig. 6: Four angle areas along the tire scope.

for the points in the four areas along the tire scope are also set in the post-processing. These variants enable an arbitrary implementation of launching possibilities. The selection of the distribution values depends on several factors, such as different road conditions, tire tread, weather conditions, driving behavior, regions etc. In this way, no distribution can be assumed as constant. By use of an effective macro programming, a modifiable increment step range and suitable user guidance via GUI, a variable distribution is integrated into the simulation process.

After the stones are defined as a collection of points on the geometrical tire substitution surface, their launching is visualized by the following algorithm. A computed trajectory of the simulated point movement is intersected with the previously assembled vehicle body surface. The resulting point cloud represents those areas on the vehicle outer surface, which are geometrically influenced by stone chipping. The mentioned method of assembling all single surface patches to one comprehensive body surface plays an important role to achieve unique results. In this way, every launching point on the tire circumferential surface results in exactly one trajectory, which leads to exactly one intersection point on the vehicle body outer surface. To approximate the simulation to real behavior, the trajectories were analyzed. As a result the real life stone chipping trajectory shows a characteristic lying between by two extreme curves. The one boundary curve is represented by trajectories in terms of tangents onto the tire (Fig. 8). That case represents an efficient but relatively vague visualization of the stone paths. A more exact simulation is offered by the implementation of parabolic trajectories instead of tangents (Fig. 9). The definition of this type of curves is accomplished by specific functionalities of the applied CAD system, [1], which enables the integration of parameter-dependent equations into the design environment.

3.3. Post-Processing: Evaluation Regarding Different Aspects

The damage of the vehicle body surface is influenced by different parameters. For example the impact speed, the diameter and the material of the stone affects the impact impulse. But also the vehicle surface temperature, the lack type, the impact angle and the shape of the stones are important factors regarding the material movement of the coating layers. To get a good evaluation the most important factors have to be involved in a proper relation of their damage influence. In the simulation phase, the impact of the launched stones onto the vehicle body is represented by blending the trajectories with the body surface assembly. Subsequently there are possibilities to evaluate the angle of impact onto the vehicle body. This offers a validation by inking the impact points based on the measured angles. This process

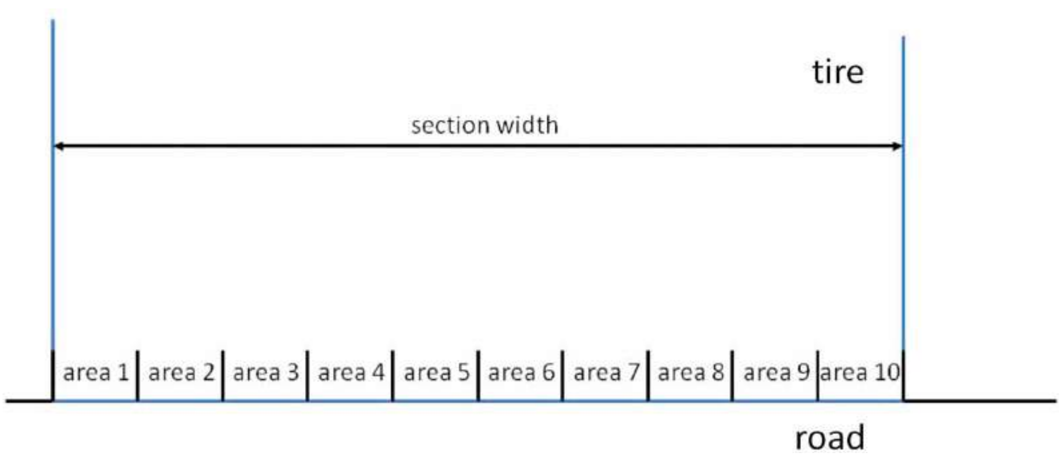

Fig. 7: Ten areas breadthwise the tire.

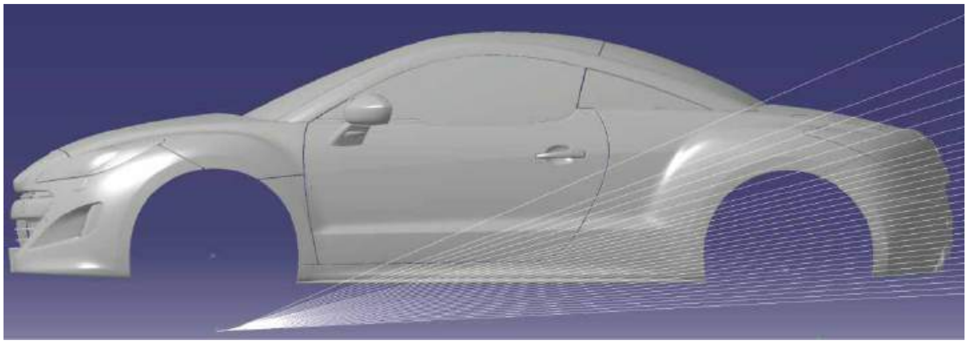

Fig. 8: Simulation by tangents, [2].

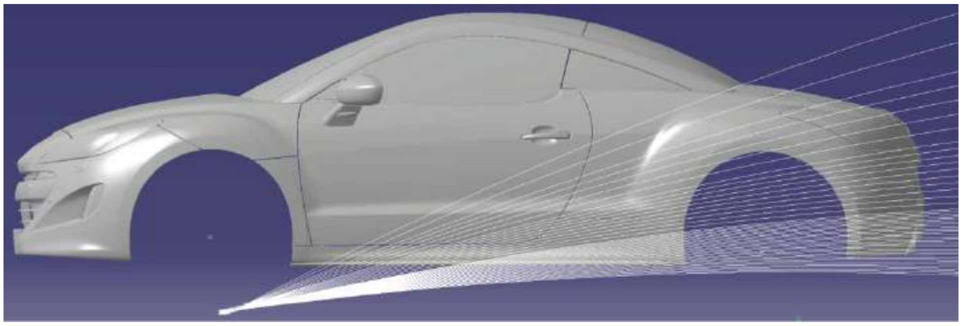

Fig. 9: Simulation by parables, [2].

has been automated by the means of an adequate macro programming, which enables a damage conclusion for the stone impact evaluation in the way of a post-processing tool, as shown in Fig. 10. The result of the stone chipping simulation includes a cloud of points, in which the individual impact spots are colored by the means of the measured impact angle. But also the velocity of the stones and the impact frequency, caused by the stone distribution on the tire in circumference or rather lateral direction are considered. Each of these factors are evaluated by their own and further lay on top of each other with specific relationships. The color scale reaches from green over yellow and red to magenta, in which the green color represents non critical points. With the raising color scale, the magenta colored points highlight very critical areas, [2].

4. INTEGRATION OF THE SIMULATION RESULTS INTO THE DEVELOPMENT PROCESS

The presented approach has been integrated into the automotive development process. Fig. 11 shows the analyses of critical areas, which are characterized by red or magenta colored points in the affected areas. If the responsible expert comes to the conclusion that no critical areas exist or they are present in body parts with sufficiently high stone chipping resistance, the corrosion protection division passes the

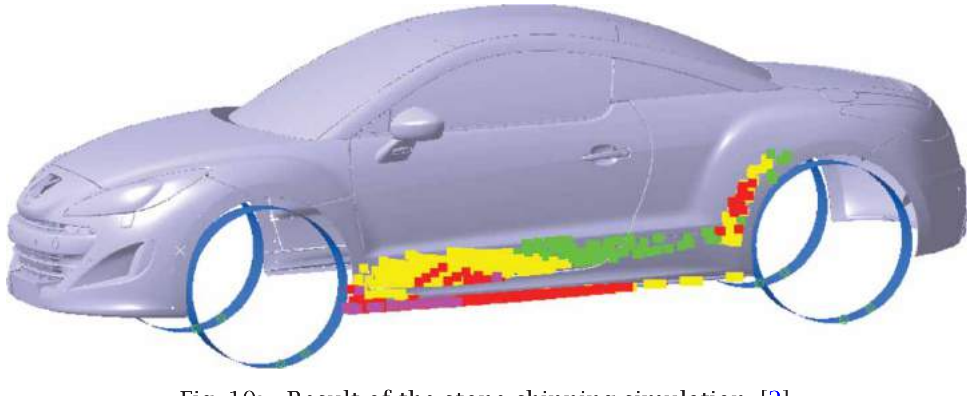

Fig. 10: Result of the stone chipping simulation, [2].

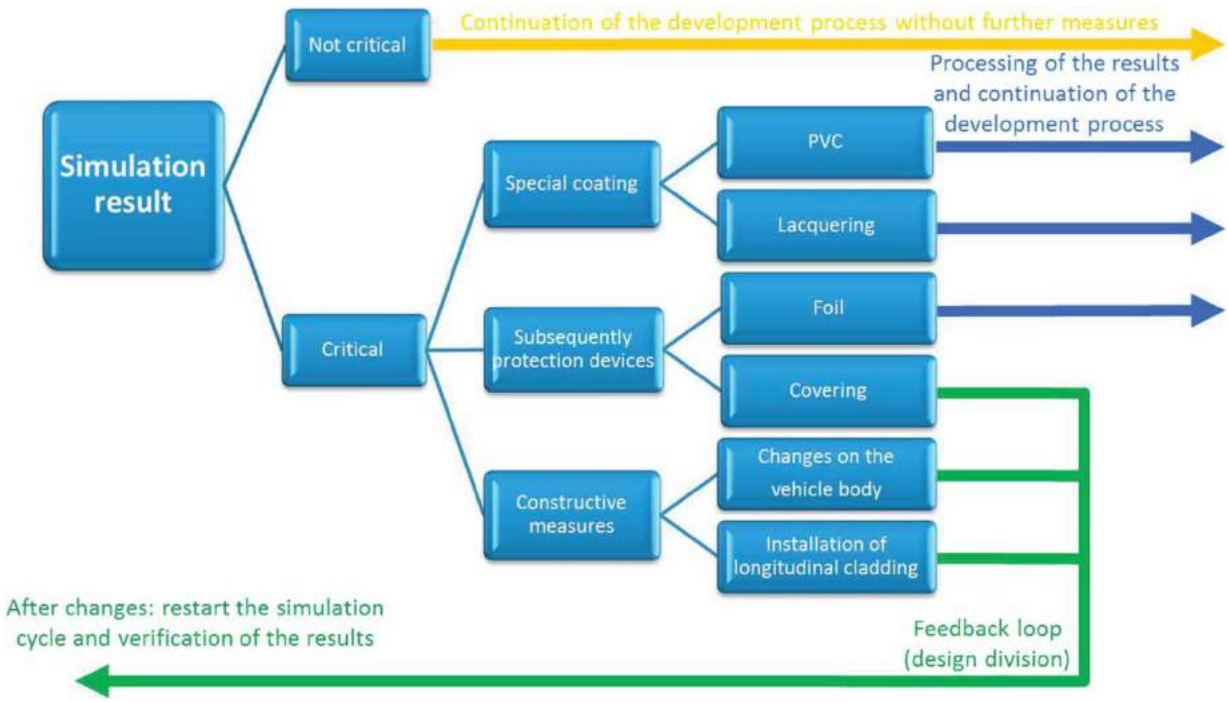

Fig. 11: The use of simulation results in the development process, [2].

vehicle styling with the state in order to the next step in the development process. In case of located critical areas on materials which are less corrosion resistant, the present status of the vehicle body is not declared as in order. After this, additional steps have to be passed through. If special coatings such as PVC, paintwork, or foils as guards are dialed, the results of stone chipping simulation are exported and forwarded to subordinated divisions, such as painting or coating departments. They can exactly locate the critical areas by the data of the point cloud and apply specific protection measures. The definition of specific areas for the application of corrosion protection measures enables a reduced consumption of resources. If the clerk of the corrosion protection division decides for subsequent installation of covers or constructive changes of the vehicle styling, such as vehicle body changes or installing longitudinal cladding, a feedback loop is performed in cooperation with the vehicle body design division. For example, a modification of the side wall precipitation by a few degrees, or an extension of a protective cover beneath the door, could be recommended, which is in turn implemented and verified by the relevant styling or design division. These modifications in the styling can be confirmed or changed by alternative proposals. In both cases a stone chipping simulation is carried out and the results are compared before and after the passage of the loop. This process implementation of the present approach of virtual stone chipping enables the definition of stone chipping protection in an early stage in the vehicle development process, [2].

5. CONCLUSION

The implementation of virtual development tools supports effective development processes and represents a promising way to react to the increasing pressure based on the high requirements in the automotive industry. Due to new generated engineering methods it is possible to save costs and development time by shifting important decisions to earlier stages of the development process. This effect results from the compliance of arrangements in the case of frontloading. For that purpose a combination of CAD and automation is indispensable. The present publication includes an application of problem-oriented automated knowledge-based engineering methods within commercial CAD software. The present virtual evaluation of stone chipping represents an interesting application of enhanced geometry based simulation, which is able to support automotive development processes within a virtual environment. This enables an effective indication of the areas affected by the stone impact, the frequency of the stone launching and the damage due to the impact angles of the stones. Due to the applied GUI and automation, stone chipping investigations are enabled with low cost and work effort. The tool has been applied in an industrial application. The accuracy of the simulation could be verified in the course of hardware prototype tests. Through the integration of simulation in the early phases of the vehicle development, change loops in the case of vehicle body design are supported. Based on the results a decision aid for the subsequently performed installation of protection measures is offered. In this way, unforeseen or too late recognized change of the vehicle body, usually associated with high costs, can be avoided.

LIST OF PARAMETERS

v_0	[km/h]	launching speed
r	[m]	wheel radius
ω	[s-1]	angular speed
m	[kg]	mass
$\ddot{x}$	[m/s^2]	acceleration along x-direction
$\ddot{y}$	[m/s^2]	acceleration along y-direction
$\ddot{z}$	[m/s^2]	acceleration along z-direction
G	[N]	force of gravity
g	[m/s^2]	gravity
$z(x)$	[m]	distance along z-direction
x	[m]	distance along x-direction

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