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# Physics in Design: Real-time numerical simulation integrated into the CAD environment

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**Abstract**

As today's markets are more susceptible to rapid changes and involve global players, a short time to market is required to keep a competitive edge. Concurrently, products are integrating an increasing number of functions and technologies, thus becoming progressively complex. Therefore, efficient and effective product development is essential. For early design phases, in which a large portion of the product cost is determined, it is important that different concepts can be developed and evaluated quickly. An established way of evaluating a design is using numerical methods, such as Finite Element Analysis (FEA). However, setting up numerical simulations in early design phases when concepts change repeatedly is time consuming. This is largely due to the fact that for each design change concepts need to be re-meshed, boundary conditions re-applied and solutions re-calculated. In this paper, a framework is proposed that establishes a real-time connection between the CAD environment and FEA software. Simulation results are automatically updated when the CAD model is updated. Partial re-meshing and smart boundary condition re-application techniques allow for a real-time assessment of design changes. The developed framework is especially interesting for the assessment of multi-physics phenomena in early design phases, as multiple fields can be interpreted by a design engineer that is usually specialized in a specific field.



*Keywords:* Real-time design analysis; Physics in design; GPGPU numerical simulations; Early product development; CAD while engineering.

## 1. Introduction

The current manufacturing industry is confronted by a rapidly changing global market demanding shorter product cycle times, higher quality and lower cost. Due to the global competition, the ongoing technological developments and to keep a competitive edge, manufactures try to integrate an increasing number of functions and technologies into their products. The designers of such complex products have to take aspects of all the different functionalities and technologies into account to construct a well-designed product. Therefore, efficient and effective product development is essential in order to 'design it right the first time'.

According to Tomiyama et al. [1] most design models, like Simon, Pahl & Beitz, Ulrich & Eppinger, etc., define the product development process as a sequence of steps or activities that the manufacturer should employ to design a product. The steps connote a linear process to complete the total design process, involving evaluation, iteration and decision making within each step. Especially in the early (or conceptual) design phases it is important for designers to evaluate different concepts fast and efficient [2]. Adequate evaluation helps designers in making good design decisions, resulting in less iteration cycles between the conceptual and final design phase. Hence reducing the product design time. In addition, good decision making in the early design phases will lower the product costs, as typically decisions made during the first phases of product development affect over 70% of the overall product costs and prove to be crucial to the success or failure of the product [3].

To assist designers in the decision-making process, numerous tools have been developed over the years. In the


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1980s, Computer-Aided Design (CAD) was introduced to facilitate solid modeling that allows for easy access and the manipulation of increasingly sophisticated geometries. The CAD environment currently is an established tool in early product development, helping designers to visualize and share their ideas for new products. Besides CAD, many simulation tools, so called Computer-Aided Engineering (CAE) tools, have been developed to help the development process. This includes tools for Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), mechanism analysis, etc. From these tools the finite element method is perhaps the most frequently used numerical simulation tool for analyzing e.g. stresses, deformation and temperature distributions in models. Two downsides of FEA, and other simulation tools, are that the simulation results depend on (1) the level of expertise of the user and (2) it is relatively time-consuming. For a long time, design and analysis were seen as two different activities [4]. Therefore, simulation tools in general are used during the final phases of product development.

### 1.1. Numerical simulations in early product development

When FEA is used in the final phases of the development of a new product, the standard three phases of FEA: pre-processing, calculations and post-processing are usually performed by several people working in different departments because of the complexity. This is depicted in Fig. 1, in which the arrows represent the directions of communication between individuals and the arrow thickness is a measure for the intensity [5]. This collaborative engineering can be difficult to manage. If the simulations reveal any design flaws, the process of resolving these flaws is relatively slow due to the organizational structure of having multiple people involved. Solving this by good communication and data exchange can only partially reduce this and avoid unnecessary iteration steps that would increase the product-to-market time.

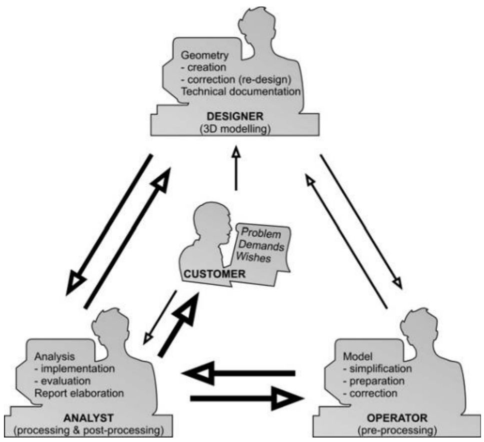


Fig. 1. Work and communication within the current FEA [5].

In order to avoid unnecessary iteration steps and shorten the design time, FEA and other numerical simulations should ideally be incorporated into the early phases of product development [6-8]. However for this to work, simulation tools should be used by the designer of Fig. 1 enabling him/her to make quick design decisions without consulting specialists (e.g. operators and analysts) of different departments.

Setting up numerical simulations in early design phases when products may change repeatedly is time-consuming, due to the fact that for each design change the model needs to be re-meshed, boundary conditions re-applied and solutions re-calculated. Currently the ongoing developments in simulation tools are mainly focused on getting more accurate results faster, whereas simulation results during early product development are mainly used as performance indications of different concepts. Therefore when integrating numerical simulations into the early design phases, the absolute accuracy of the results is subordinated to the simulation speed. A certain error of about 5 to 10% in the simulation results is acceptable if this increases the speed significantly. To achieve a faster simulation, surrogate modeling or metamodeling can be used to create a simplified model of the design. These kinds of models use less computational power compared to numerical simulations in which finite element models are employed, like FEA. However surrogate model selection is problem dependent and a universal method does not yet exist [9]. This makes the simulation results again depended of the level of expertise of the user.

As the computational speed of computers increases steadily, the cost of computational power will decrease. Also the current trend of applying General Purpose Graphics Processing Unit (GPGPU) accelerated parallel computing shows that the more computationally demanding numerical simulations can become even less time consuming [10]. The combination of simplified finite element modelling and low-cost parallel computing makes it possible to establish a real-time interface between the design space and the numerical solution space during early product development phases. This is illustrated in Fig. 2.

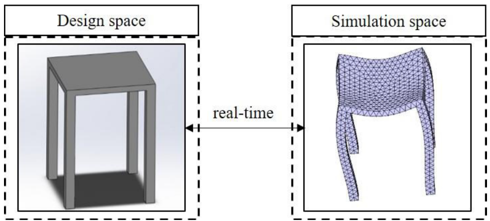


Fig. 2. Real-time interface between the design and numerical solution spaces enabled by simplified finite element modelling.

### 1.2. Goal and outline

The goal of this paper is to present a framework in which numerical simulations are integrated into the CAD environment allowing for real-time simulations during the early product development phases.

This paper is structured as follows. In Chapter 2 the possibility of integrating FEA into the CAD environment is investigated by a demonstrator program. In Chapter 3 the conclusions of this first-proof program are used to define a more detailed framework that is necessary to construct a real-time connection between the design and simulation spaces beyond a live-link. Thus creating a real-time Physics in Design (PiD) environment. Finally, in Chapter 4 the conclusions of this work are presented.

## 2. Physics in Design (PiD) approach

The possibility of integrating FEA into the CAD environment was explored by creating a program that combined a finite element method (simulation space) and a CAD program (design space). The steps that are performed by the two coupled programs are shown in the flowchart of Fig. 3. In the design space, the designer creates a model of the design. The program monitors the model for any modifications of the geometry. When changes are detected the model is automatically send to the simulation space to create an updated simulation result using the new model. To generate the new results, the model first needs to be re-meshed to include the new geometry into the calculations. The boundary conditions and loads are re-applied, and the system of equations is solved obtaining the new solution. This sequence is repeated automatically after each modification to the model geometry.

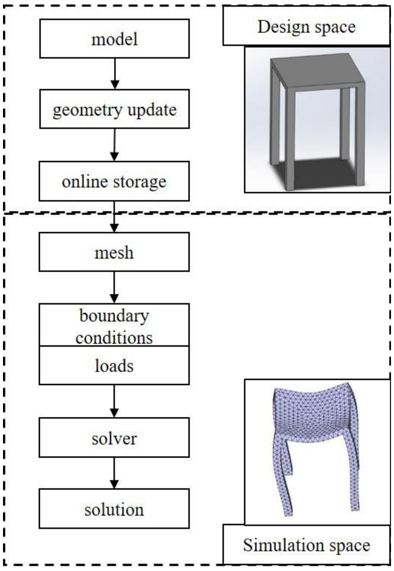


Fig. 3. Real-time coupling between CAD and FEA.

Fig. 4 illustrates a possible product development process of a stool using the aforementioned approach. The simulation results are updated after each CAD model modification. In Step 1 the CAD model of the stool is imported (or modelled) into the design space and the simulation starts by the one-time allocation of boundary conditions and loads. This is indicated by the under construction sign. In this case the bottom of the stool legs were fixed and a downwardly directed distributed load was applied to the top of the seat. When the boundary conditions and load are known the simulation immediately shows the deformation results (magnified), see Step 2. If the designer is not satisfied with the stool's performances or style, the thickness of the seat may be adapted to give it a more robust appearance (Step 3). The changes in geometry are directly transferred to the simulation space when the changes made to the feature are approved in the CAD environment and the new deformation results become immediately visible (Step 4). The designer may now conclude that the new shape of the stool has less deformation. Such easy and fast feedback enables designers to concentrate (and tinker) more on the design and directly interpret the influences of the decisions made in the design process. Designers can freely adapt the dimensions, for instance that of the seat (Step 5), and see the results immediately in the simulation space.

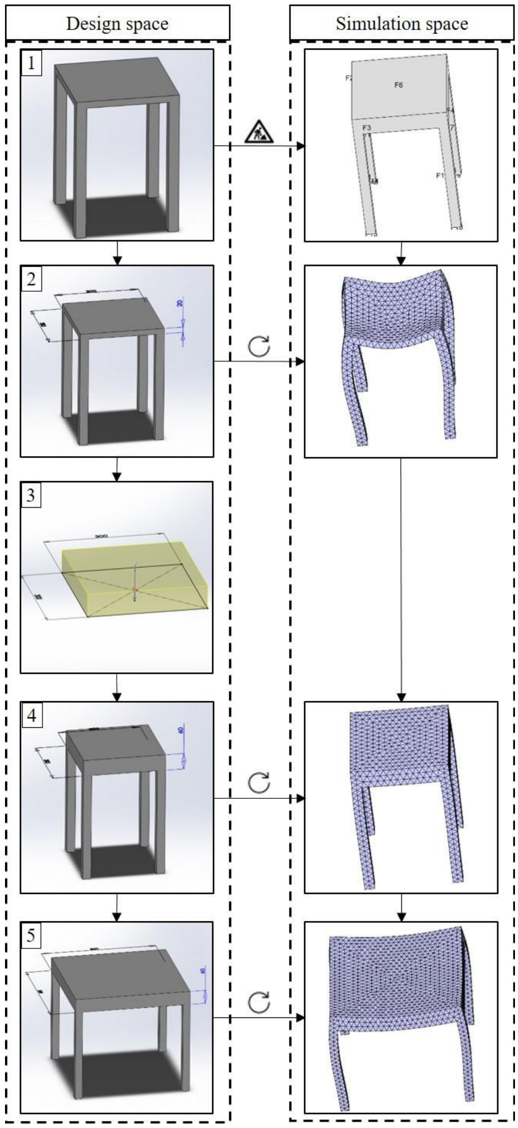


Fig. 4. Real-time integration of the design and simulation spaces.

The presented mono-disciplinary approach shows that the integration of FEA into the CAD environment has potential as a support tool for designers. For CAD models of limited complexity this PiD approach presents the updated simulation results in real-time. Results are obtained within a few seconds of CAD model modification, which is well below the time it takes designers to make changes and interpret the results. The approach also shows that it is possible to automatically obtain new simulation results without the manual re-application of boundary conditions. Notice that the original faces on which a boundary condition is applied, may be repositioned or resized but should not disappear. In the event that a face with set boundary conditions disappears, e.g. when the seat thickness is set to zero, new boundary conditions will have to be applied manually.

When more complex models are presented the serial structure of the program in combination with complete re-meshing and re-calculation hinders the program from updating the simulation results in real-time. Therefore, smart boundary condition and load re-application, partial re-meshing, and intelligent solving are necessary to reduce the computational time. Chapter 3 discusses a more detailed framework for such cases in order to achieve a successful integration of numerical simulations into the CAD environment.

## 3. Real-time PiD framework

In Chapter 2 a first proof was presented of how to merge the design and simulation spaces. The approach showed that the integration requires more implications than just a live-link between the CAD and FEA programs, which is currently supplied by commercially available CAD software [7]. In this study, a framework is developed that accommodates a real-time numerical simulation space by updating the simulation results when the CAD geometry is updated. This framework is presented in Fig. 5 and is an extension of the flowchart given in Fig. 3.

In the following sub-sections the different aspects of the framework are discussed, namely the model preparation (blue box), meshing (red box), the re-application of boundary and load conditions (yellow box) and solving (green box).

### 3.1. Model preparation

The first step is to real-time monitor the CAD model for new features or changes in existing features. Features can be extruded shapes, revolved shapes, extruded cuts, holes, fillets, chamfers, ribs, etc. When the model is modified the simulation space needs to be updated. In the proposed framework, the new CAD model is converted into a triangulated surface mesh (STL-file) and stored online such that it can be accessed by the simulation space. Here the conventional steps of meshing, applying boundary and load conditions, and solving will be performed following a smart and time-efficient algorithm structure. Because new features or modifications to the CAD model usually change the geometry only locally, the CAD model is divided in multiple sections. This procedure is called sub-structuring. By breaking up the model into a number of smaller analyses, computational time is saved. Because only small parts of the model need to be remodeled, while all other parts and their solutions can be re-used. The sub-structuring creates super elements that can be solved independently and thus in parallel using GPU acceleration techniques [11]. Notice that dividing a CAD model into to multiple sub-structures introduces new computational challenges as increased data traffic and computations at the sub-structure interfaces. The computations at the sub-structure interfaces can be minimized using the same nodal arrangement on common interfaces. This puts constraints on how a sub-structure of the CAD model is meshed. This is discussed in the next sub-section.

The sub-structuring of the CAD model is based on the different features that make-up the model geometry. When the model is modified by the designer the difference between the

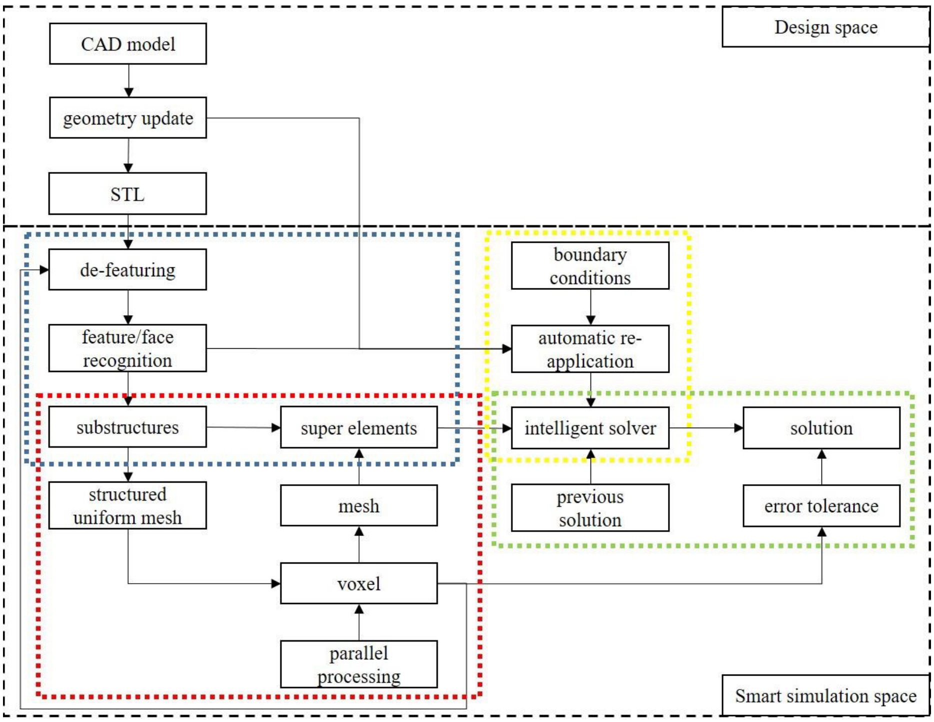


Fig. 5. Framework for real-time Physics in Design (PiD) showing the coupling between design and simulation spaces.

current model in the simulation space and the new model is determined automatically. Only the sub-structures that have been subjected to changes or those that are new are (re-)meshed and (re-) calculated, thus saving computational time.

*3.2. Meshing*

Meshing is an important and time-consuming part in any FEA. It is a commonly known fact that the way the CAD model is modelled will affect the accuracy; e.g. the approximation of the geometry or method of discretization. In general, the accuracy of the model can be improved by (partially) refining the mesh or by increasing the order of the used elements. However, both approaches significantly increase the computational time. Therefore, a trade-off between the level of detail and computational time must be made. Due to the real-time aspect, the subordination of the accuracy and the requirement that the same nodal arrangement is used, the mesh elements and meshing algorithm are simplified and automated.

A 3D structured and uniform mesh is created for each sub-structure of the CAD model based on a voxelization algorithm [12]. The voxel mesh is one of the most effective techniques to reduce the time cost of mesh generation. This type of mesh is normally not used in FEA because of the poor ability to represent curved surfaces, resulting in a decrease of accuracy of the analysis. The decrease in accuracy can be minimized to a moderate error between 5 to 15% if a sufficient number of degrees of freedom is used [13]. Despite the fact that this increases the number of elements, the regularity of the mesh still reduces the mesh generation time by a factor four minimally. In this framework, the time-cost effectiveness is decisive for the choice of this mesh type. The creation of a voxel mesh representation of the CAD model also ensures that the requirement of the nodal arrangement for common sub-structure interfaces is satisfied. The final advantage of a voxel mesh is the natural de-featuring that occurs. The original CAD model is simplified by suppressing detailed features, reducing the computational time of the FEA. This is illustrated in Fig. 6, in which the original CAD model (left) is automatically de-featured in the voxel mesh representation (right). The amount of de-featuring depends on the set voxel size.

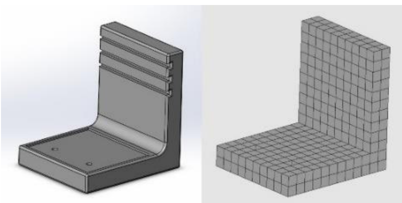

Fig. 6. De-featuring effect of a voxel mesh: left the original CAD model and right the voxel representation of the model.

In practice, the algorithm computes the bounding box of the sub-structure first. The dimensions of this bounding box are rounded to the nearest multiple of the user-defined grid-size. Then optimized octree ray-casting is used to determine if a voxel is inside or outside the sub-structure. On the xy-plane of the bounding box, a 2D grid is created with a grid-point at the center of each voxel. A ray is casted from this center-point parallel to the z-axis up to the opposite side of the bounding box xy-plane. For each ray, all z-coordinates of the intersections between the ray and faces are listed. This list is sorted by increasing value of the z-coordinate. Finally, each voxel center z-coordinate along the ray is compared to the intersection values in the sorted list. The number of values in the list that are greater than the voxel z-coordinate are counted. When this number is odd, the voxel is part of the voxel representation of the CAD model. This creates a low-cost memory and fast mesh algorithm. Due to the parallel structure, each ray can be calculated independently, making GPGPU acceleration possible. This will reduce computational time.

*3.3. Adaptive application of loads and boundary conditions*

Automatic real-time updating of the simulation results requires smart re-application of loads and boundary conditions without user intervention. This relieves the tasks of the user during the simulation process and ensures real-time updating. Of course, the initial application of loads and boundary conditions remains a manual task that requires time and knowledge of the user. The loads and boundary conditions must migrate across the simulation space according to the changes made in the design space. For example, consider the distributed load on the seat of the stool of the previous section. When the height of the seat is modified, the load should still be applied to the top of the seat. Boundary conditions and loads have to be linked to the faces and not fixed to coordinates in space. This can be achieved by face numbering in a prescribed order. Fig. 7 shows a modification of the length of the stool legs, the face numbering however remains identical.

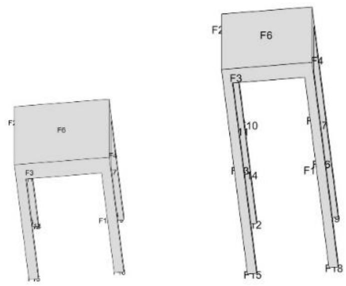

Fig. 7. Face numbering: left before and right after a change of length.

*3.4. Solving and simulation time comparison*

For real-time numerical simulations the number of iterations performed by the solver per model modification should be minimized. This is achieved through (1) partially re-solving and (2) reducing the simulation accuracy. The sub-structuring of the CAD model divides the analysis into smaller sections. Each section creates a super element that can be solved independently. After a model modification, new solutions are only calculated for the adjusted sub-structures. The new simulation result is obtained by substituting the new partial solutions into the previous solution of the simulation, saving computational time.

The simulation time can also be reduced, however this influences the simulation accuracy in two ways. First, due to the proposed simplifications in the mesh generation, the PiD framework causes a deviation of the results compared to conventional FEA. Second, the settings of the numerical solver can be time-optimized. Most FEA use double precision operations to achieve the required accuracy, but many internal calculations do not require this high precision to gain accurate final results. Therefore, a mixed precision method can be used, utilizing low and high precision in different parts of the solver without affecting the final accuracy [8, 14]. Low-precision formats require less memory resources and reduce memory transfers between the CPU and GPU.

Due to the difference in objective between the PiD framework and conventional FEA (i.e. evaluation of design concepts vs. detailed designs) a quantitative time comparison is not fitting. However, some comparisons can still be made. The main time difference is in the mesh generation and solving due to reduced accuracy, going from minutes/hours to seconds. The model preparation time for the first simulation is similar to conventional FEA, but for subsequent simulations the smart re-application of loads and boundary conditions speeds up the preparation significantly.

## 4. Conclusions

Currently in product development processes numerical simulations tools are commonly used in the final phases of product development in which most of the detailing takes place. The simulations are usually not performed by the designer, and thus require good communication and data exchange between the designer, the operator and the analyst to avoid unnecessary iteration steps.

To improve the decision-making process and selection of concepts, numerical simulation tools should also be incorporated into the early phases of product development. Designers should have fast access to numerical simulation results to make the right design decisions quickly. Therefore, this paper presents a framework in which numerical simulations are integrated into the CAD environment and enable real-time simulation results to be displayed in a so-called simulation space.

This Physics in Design (PiD) approach is developed to discover which adaptations, like smart boundary condition re-application are needed to accommodate the real-time updating of simulation results into the simulation space. The approach shows that the integration of FEA into the CAD environment has potential as a support tool for the designer in the early product development phases. The PiD approach presents the updated simulation results in real-time; results are obtained within seconds of the CAD model modification. The PiD approach also shows that it is possible to automatically obtain new simulation results without the manual re-application of boundary conditions and loads. Finally, a framework is presented that incorporates sub-structuring, unformal structured voxel meshes, de-featuring of the CAD model, automatic loads and boundary conditions re-application, and intelligent solving strategies, according to Fig. 5.

Future research will focus on the implementation of all different aspects into a software program and the efficient incorporation of multi-physics simulations capabilities, as this would really benefit design engineers.

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