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This paper analyzes the impact of the virtual tool 'crash simulation' on automotive R&D over the last 35 years. The research carried out in this context identifies and investigates distinct phases respectively stages of the potential of crash simulations based on the Finite Element Method and the stages' impact on automotive R&D in-depth.
In a study of German Original Equipment Manufacturers' (OEM) utilization of crash simulations, the evolution of this tool is explored and its impact on productivity and problem-solving investigated. We draw upon literature about crash simulations in car development projects, the utilization of crash simulations in related tasks, and recent literature about the overall impact of crash simulations on automotive R&D. The significance of the tool 'crash simulation' for the OEMs is emphasized by means of corresponding landmark projects. Our study is based on qualitative research based on 29 in-depth interviews with experts from all of the major German OEMs and experts from the US-American academia. Our analysis results in partitioning the tool's evolution into five phases. Each phase is characterized by its impact on automotive R&D. The phases induced profound changes either in productivity or in the ability of problem-solving. Understanding these profound changes and its triggers holds the key to better understanding the potential of virtual simulation tools and the requirements necessary to unlock this potential.

1. Introduction

In the highly competitive automotive industry it is crucial for carmakers to conduct research and development (R&D) fast and efficient. Therefore, the industry is constantly searching for tools, instruments and processes which allow to significantly improve the effectiveness of development work. Design for crashworthiness[1] of a car is such an instrument: it is not only an important factor determining the marketability of a new car, but also a necessary legal requirement.[2] Especially in the automotive triad United States, Europe, and Japan, legal requirements, consumer tests (e.g. Euro-NCAP[3]), and assurance classification tests impose serious crashworthiness requirements on new car development projects. Thus, fast and efficient design for crashworthiness can give carmakers a competitive advantage over their competitors.

Traditionally, carmakers relied solely on physical destructive testing of prototypes to achieve and verify crashworthiness. In recent years, virtually destructive tests of cars in the computer, or 'crash simulations', supplemented the physical destructive testing-only option. By now, virtual crash tests outnumber their physical counterparts by magnitudes in new car development projects. The relevance of crash simulations in vehicle development is also

[1] Crashworthiness is a term describing the ability of a vehicle to protect its occupants in survivable crashes.
[2] For European consumers, safety (together with reliability of the car) is the most important aspect when buying a new car. (Euro NCAP/MORI 2005)
[3] NCAP is the abbreviation of 'New Car Assessment Program'. Euro-NCAP is the consumer test for the European market.

impressive, e.g. at DaimlerChrysler's Chrysler Group: 70 percent of Chrysler's daily simulation computations are crash-related simulations (Hampton AutoBeat 2002).

The automotive R&D tool 'crash simulation' takes its origin in the military domain in the 1960s and is at present the predominant simulation computation throughout the automotive industry. More than four decades of evolution of the tool 'crash simulation' molded R&D in the automotive industry and, at the same time, the industry molded the tool's evolution.

Similarly to the evolution of the tool 'crash simulation', Schrage discusses the role of spreadsheet software as a simulation tool for the financial industry (Schrage 2000). Spreadsheet software decreased costs of financial models that once 'cost thousands of dollars, to pennies'. It raised productivity of financial departments by magnitudes, but at the same time, the simulation tool allowed firms to ask totally new questions. Eventually, spreadsheets became 'a mirror of reality' for companies.

Analogously, Galison analyzes the impact of the virtual tool 'Monte Carlo simulations' on microphysics and its importance for problem-solving[4] (Galison 1997). Monte Carlo simulations were assigned to problems too complex for theory and too remote for experiment. Galison concludes that without Monte Carlo simulations as a virtual tool, the material culture of late-twentieth-century microphysics is not merely inconvenienced, but does not exist.

Similar to these examples of virtual tools, 'crash simulations' do not merely had the potential to enhance R&D productivity by magnitudes, but at the same time, the tool allowed R&D engineers to increase problem-solving by raising questions, which they had never been able to ask before, e.g. which influence an incremental structural change would have on the overall crashworthiness of the car (Becker et al. 2005, Thomke 2003). Without crash simulations, contemporary new car development projects would not merely be inconvenienced, but would not be possible. Hence, over the last four decades, the tool 'crash simulation' revolutionized the R&D process in the automotive industry.

1.1 Aim of the Study

This paper analyzes the impact of the virtual tool 'crash simulation' on automotive R&D over the last four decades. The research carried out in this context identifies and investigates distinct phases respectively stages of the potential of crash simulations based on the (explicit) Finite Element Method (FEM) and the stages' impact on automotive R&D in-depth.

Based on our study of German Original Equipment Manufacturers' (OEMs) utilization of crash simulations, we explore the evolution of the tool 'crash simulation' and investigate its impact on productivity and problem-solving. We draw upon literature about crash simulations in car development projects, the utilization of crash simulations in related tasks, and recent literature about the overall impact of crash simulations on automotive R&D. Corresponding landmark projects emphasize the significance of this tool for the OEMs. Our study is based on qualitative research based on 29 in-depth interviews with experts from all of the major German OEMs and experts from the US-American academia.

Our analysis results in partitioning the tool's evolution into five phases. Each phase is characterized by its impact on automotive R&D. The phases induced profound changes either in productivity or in the ability of problem-solving. Understanding these profound changes and its triggers holds the key to better understanding the potential of virtual simulation tools and the requirements necessary to unlock this potential.

1.2 Research Methodology

The explorative and descriptive nature of this work demanded for qualitative research based on expert interviews. Semi-structured expert interviews provided primary data source of this thesis with 29 interviews (21 on-site and 8 telephone interviews). All but 7 interviewees are from the seven major German OEMs (Audi, BMW, DaimlerChrysler, Porsche, Volkswagen, Opel and Ford of Germany). Five interviews were conducted with companies providing the crash simulation software or services related to automotive crash simulations. The two remaining interviewees were chosen from academia (both from M.I.T.).[5] In addition, secondary data sources such as literature findings, previous research results, company press releases, and internet research were employed.

Each OEM was contacted by phone first after studying publicly available information on the R&D department concerned and analyzing publications on crash simulations from the OEM. All German OEMs agreed to participate in the study. Before visiting the companies an outline of the topic and the authors' interview guideline were sent to the interviewees. Thus, interviewees were able to prepare for the meeting and, if possible, to provide text documents or other artifacts of crash simulations, which match the topic. Each expert had distinguished experience in crash simulations and was hierarchically situated between middle management and senior management. The on-site interviews took two hours on average, with some interviews taking up to four hours. The procedure in the eight telephone interviews was similar to those in the on-site interviews. On an average, the phone interviews took one hour.

Through multiple interviews with different experts many different perspectives were outlined to the authors. Such a variety of perspectives ensures valuable insights, reliable results, and constructs validity of the data.

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[4] 'Problem-solving' measures the ability to solve problems (in R&D) by means of the current state of technology.

[5] These two interviewees from M.I.T. were chosen due to their extensive knowledge of crash simulations and the FEM, and their local proximity to the authors.

2. Evolution of Crash Simulations

Automotive safety bases on two aspects: active safety (to prevent accidents, e.g. suspension system), and passive safety (only relevant when a crash occurs). Crash simulations only regard the latter. In case of a vehicle accident, occupants get injured from one of two causes: from the contact of the occupant with the structure (e.g. collision of the head with the steering wheel) or from unreasonably high deceleration loads (e.g. resulting in bone fractures or organ rupture). Nowadays, to assess the behavior of a car in a crash, R&D engineers perform both, physical destructive tests and virtual crash tests. Virtual crash tests, or crash simulations, are relatively new: the first automotive crash tests originate in the 1970s. In the beginning, many different simulation methods competed with each other (e.g. analytical methods, hybrid methods, implicit and explicit finite element methods), but over the years the explicit finite element method (FEM) became the preponderant tool for automotive crash simulations (Bigi 1990). The explicit FEM discretizes the structure (the car or car component) in space and time. The result is a mesh of elements. The more elements the mesh contains, the higher the fidelity of the simulated structure.[6] The set of equations representing the interactions of the elements in the mesh is calculated for each discretization step. The overall result is derived from the outcome of each step-by-step (element-by-element) calculation.

In this paper, we follow the longer trajectory in the evolution of crash simulations. In order to fully explore and describe the changes caused by crash simulations, we divide the evolution of this specific tool into five phases. Each phase is characterized by a basic shift in R&D engineers' understanding of the tool 'crash simulation'. Each phase had an impact on R&D productivity and/or on solving R&D problems (by addressing problems which formerly had been impossible to solve), thus increasing the ability of problem-solving.

2.1 Origins in the Military Domain

Since the 1960s, US-national laboratories developed the explicit FEM and applied it to crash events (Haug et al. 1986). It was not until the 1970s that supercomputers enabled engineers to intensify work on the FEM (Figgins 2002). Due to the high costs for the required hardware (the supercomputers), a solely governmental effort is quasi inherent for the evolution during this period. Only projects of national interest were subject to a sufficient financial support. Furthermore, these projects focused on problems, which posed serious difficulties to conventional physical destructive testing: these crash simulations covered mainly impact, penetration and explosion issues. The US-national laboratories investigated problems, which formerly had been unsolvable or far too expensive to test. An event impossible to test is, e.g., the impact of a small meteorite on the outer shell of a space station, or the rapid expansion of a gas bubble in a nuclear reactor core accident, whereas an event too costly is, e.g., the impact of an airplane on a nuclear power plant containment.

Example: aircraft impact on nuclear power plant in 1983
A landmark study at that time was the impact of a military aircraft at high speed (200m/s) on the concrete safety containment of a nuclear power plant. The impact causes local stresses and destruction beyond the elastic limit and the safety containment is subject to a potentially damaging high frequency response. The structure of the impacting aircraft is of no interest, it solely serves as a load-time diagram to charge the safety containment. 60 elements model the safety containment and took 33 hours of CPU time on a VAX 11/780 machine for 22 milliseconds of crash duration with the explicit FEM (Haug et al. 1983).

Impact on R&D
The goal of this era was to find and validate an alternative to physical destructive testing (Scharnhorst 1987, Haug 1981). The purpose of these first applications of the FEM was not to increase productivity in military research, but to solve problems which formerly had been impossible to solve. It is just impossible to physically test the impact of a small meteorite with a satellite or the rapid expansion of a gas bubble in a nuclear reactor core accident. Thus, FEM crash simulations enabled the R&D engineers to conduct more diverse experiments. As a result, researchers were able to solve new problems and eventually to develop better products (in this case: safer structures). Thus, the phase from the 1960s to the early-1980s was an era of improving the degree of problem-solving in R&D – the productivity in the safety assessment of structures was of no interest. These simulations draw the automotive industry's attention to crash simulations in the 1970s (Haug 1981).

2.2 The Early Phase in the Automotive Industry

This section discusses advances in crash simulations in the automotive industry from the first car component crashes in the early 1970s, to the first full body frontal crash using the explicit finite element approach in the mid-1980s (see the

[6] The number of elements determines the granularity of the model. Additionally, other important factors are the quality of the elements and the description of the interactions of the elements (mesh quality) (Khalil and Du Bois 2004).

next section), which is considered to be the pivotal point in automotive crash simulations.

Since 1970, engineering journals reported exceedingly about virtual methods for crash simulation in the automotive industry (Scharnhorst et al. 1986). The reason for the advent of crash simulations is seen in both, the newly emerged possibilities due to the availability of the first supercomputers and suitable software, and the necessity for car component evaluations at an early project stage (i.e. before building the first physical prototypes), e.g., in automotive lightweight construction (Schelkle 1983). Whereas at the beginning of this phase R&D engineers employed many different simulation methods (e.g. implicit and explicit finite element method, finite difference method), the research during these 15 years indicated that the explicit finite element method is the solely appropriate for automotive crash applications.

Example: side member of a Porsche in 1983

The goal of this project was to investigate the absorption of the kinetic energy in a crash by elastic and plastic deformations. Symmetrical reasons allowed the side beam model to consist only of the front half of the structure lengthwise and a quarter of the cross section. In total, 96 elements were modeled with the program Abaqus on a Cyber 175 supercomputer. The simulation led to a detailed analysis of the kinetic energy consumption of each element. Formerly, such an analysis was only possible by manually measuring the degree of deformation of the side member after the crash. With these measured values, R&D engineers calculated the degree of kinetic energy absorption by plastic deformations. In contrast, with virtual testing, the R&D engineer could read out the exact amount of plastic and elastic deformation for each element. Nevertheless, the crash simulation in this example suffered from oversimplification of the (shell) elements, and from an unrealistic perfection of the side member's geometry. (Schelkle 1983)

Impact on R&D

As a result of the possibility to study the energy consumption of single components in detail, R&D engineers were able to improve their understanding of the physical phenomena during a crash. Thus, this period from the first car component crashes in the 1970s to the mid-1980s was a period of learning for R&D engineers. Due to crash simulations, R&D engineers could study the behavior of the structure (e.g., folding, buckling) arbitrarily slow, thus allowing for a more detailed analysis of the mechanics. As a result, R&D engineers changed the way they looked at certain problems and started asking new questions, e.g., whether a slightly modified shape of the structure would influence the overall crash result. At the same time, R&D engineers gained trust in the tool crash simulation. This is especially important, because many R&D engineers had strong reservations to trust a virtual experiment. Nevertheless, the processing time of one simulation was too high for the industrial application of crash simulations and did not fulfil the industry's demand for an overnight calculation. Additionally, the crash algorithms were error-prone and complicated. As a result, the costs for the finite element calculation were too high as well. The inability to fulfil the industry's requirements (overnight calculation at reasonable costs) and the lack of appropriate software and hardware brought automotive crash simulations to a standstill in the late 1970s to early 1980s (Khalil and Du Bois 2004, Scharnhorst et al. 1986, Schelkle 1984, Schelkle 1983).

2.3 The Breakthrough for Crash Simulations

In the mid-1980s upcoming vectorized supercomputers (e.g. Cray X-MP, or Cyber 205), improvements in code processing (e.g. introduction of the constant time step for the explicit FEM, change from scalar code to vectorized code), the encouraging results from the early phase of automotive crash simulations, and the need to find alternatives to physical prototype testing led to the first full vehicle crash simulation in 1986. Although different approaches for the first full vehicle crash simulation were made at the same time in the US, Japan, and Europe, and it is not quite sure who succeeded first, it was Eberhard Haug from ESI Group to publish first in 1986 in the course of the 'Forschungsgemeinschaft Automobiltechnik' (FAT)[7] working group (Khalil and Du Bois 2004, Haug et al. 1986). The FAT set two goals for the simulation: accuracy (to predict the mechanical behavior of a car body in a crash) and efficiency (to perform this simulation overnight).[8]

Example: Volkswagen Polo in 1986

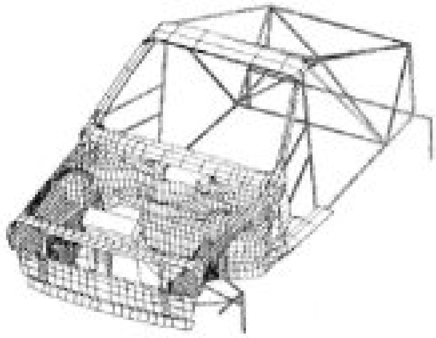
The major goal of this landmark study was to assess the degree of energy absorption of one particular element of the total kinetic energy in a crash. Furthermore, the project served as a test for the explicit integration of equations of motion, for the treatment of contact problems, for the analysis of geometrical and material non-linearities, and for an evaluation of the state-of-the-art supercomputers (Scharnhorst et al. 1986).

The model of the Volkswagen Polo consisted of 5661 finite elements, which mainly represented the front structure of the car, see figure 1. The available hardware prohibited the usage of more elements. After several improvements of the hardware and software platform, the simulation took 4 hours for 60 milliseconds of crash duration on a Cray 1/S

[7] The FAT was founded in 1983 and included all seven German automotive assemblers: Mercedes-Benz, Volkswagen, BMW, Porsche, Audi, Opel and Ford of Germany.

[8] To the FAT's project similar approaches at that time were, e.g., Benson and Hallquist 1986, Chedmail et al. 1986, Nilsson 1989.

machine (Haug et al. 1986).



Source: Haug et al. 1986 (p. 494, figure 3)

Figure 1: FEM computer model of the Volkswagen Polo for a frontal crash simulation, program Pam-Crash.

Impact on R&D

The strength of crash simulations in comparison with physical testing is the assessment of displacements for each element, whereas physical testing is predominant in obtaining the values for acceleration forces. Crash simulations have the advantage, that they do not only capture the effect (as in destructive testing), but that they also capture the cause. During the simulation, the R&D engineer can directly influence the cause and observes the effect at the (more or less) same time. Furthermore, crash simulations provide a detailed analysis of the absorbed energy for each element, thus contributing to a problem which has long been the target of destructive testing. In addition, a benefit of crash simulations is the possibility to change the point of view ex post, whereas in physical testing positions of cameras and measuring points in the vehicle have to be defined ex ante. Thus, if the crash results in an unanticipated collapse of a component, a crash simulation still provides the data and a suitable point of view, whereas often in physical testing exactly that particular spot was not covered by a camera or measuring point. The FAT's work proved that crash simulations, by pointing out the relative improvements, are reliable for the analysis of two consecutive design changes (Seiffert and Scharnhorst 1988, Scharnhorst et al. 1986).

The simulation of the Volkswagen Polo in 1986 emphasized the potential of crash simulations for the automotive industry (Scharnhorst 1987). Crash simulations

- decreased time and effort needed to evaluate design alternatives,
- delivered at least promising results for the accuracy of the obtained crash data, and
- decreased the persistence of R&D engineers' design ideas (due to shorter feedback cycles).

2.4 Paradigm Shift in Crash Simulations

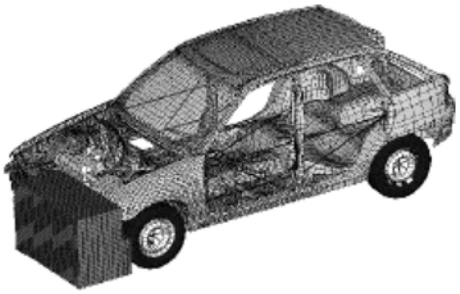
The simulation of the Volkswagen Polo in 1986 marked the pivotal point in automotive crash simulations. Hitherto, crash simulations had merely been feasibility studies.[9] Now, in the late 1980s, the phase of the productive usage of crash simulations began. This became possible mainly due to gains in computation power, which roughly followed Moore's Law[10], advances in crash software (especially in contact modeling and meshing; both are relevant for the interactions of the elements in a crash), improved material models (e.g. modeling of aluminum alloys), and, perhaps most important, the ability to visualize the outcome of the calculation with graphics or animated movies. This visual representation facilitated the human-machine interface and consequently built R&D engineers' trust in the tool 'crash simulation'.

Example: Opel Astra in 1990

In 1990, shortly before the start of production of the new Opel Astra in Germany, the German car magazine 'Auto, Motor und Sport' (AMS) launched a new consumer crash test. This test led to a significantly increased loading of the vehicle structure. Instead of a frontal crash with 50km/h and 100 percent overlap of the rigid barrier, the AMS test demanded for a frontal crash with 55km/h and 50 percent overlap rigid barrier, see figure 2.

[9] In fact, hitherto engineers working on virtual simulations were often regarded as scientists conducting a 'virtual adventure' rather than as R&D engineers (Khalil and Du Bois 2004, Haug et al. 1986).

[10] Moore's Law bases on the famous statement of Intel's co-founder Gordon Moore in 1965, who predicted, that every computer performance related quantity doubles every 1.5-2 years (Moore 1965). Thus, the possible performance of, e.g. crash simulations, grows at the same rate.



Source: Böttcher et al. 2005 (p. 2, figure 1)

Figure 2: Opel Astra front impact on rigid barrier with 50 percent overlap in 1990.

Due to the time pressure, it was not possible to improve the car's design by means of physical testing only. Thus, R&D engineers massively employed crash simulations – and succeeded. It turned out, that the increased crash load could be absorbed by two measures, firstly by extending the cross member (which was already developed for a variant of the Opel Astra with a higher motorization), and secondly by strengthening the A-pillar. Thus, crash simulations productively influenced the vehicle R&D process. The crash model consisted of 70,000 elements and took about 2 days of computation time on a Cray machine for 110 milliseconds of crash duration.[11]

Impact on R&D
In the beginning 1990s, the OEMs started to reap the benefits from their simulation efforts. Crash simulations, compared with physical testing, allowed for fast and cheap assessment of vehicle crashworthiness, as described in the example given above. OEMs began to simulate very early in the vehicle development project, and thus front-loaded their car development process. These early, fast design iterations significantly improved productivity in vehicle development. Industry experts see the start of the productive usage of crash simulations about 1990. In the mid-1990s, principal design decisions are already based on virtual simulations, and at the end of the decade the industry considered the reduction of necessary physical prototypes in vehicle development to be feasible (Holzner et al. 1998).

2.5 New Challenges for Today's Crash Simulations

In passive safety, crash simulations helped to advance the safety of vehicles, though crash simulations are based on optimal behavior of the involved factors (e.g., error-free material descriptions, exact position of the passengers in the car) in a crash event. Thus, crash simulations had only been a coarse approximation of reality. At the end 1990s, R&D engineers began to take reality into consideration, e.g. by the consideration of randomness in vehicle accidents through varying simulation conditions, by modeling the human body instead of modeling dummies (which are mere surrogates for the human body), or by consideration of the influence of the production process (e.g. deep drawing) on the material behavior in a crash. Furthermore, increasing time pressure on product development performance let to an assessment of the organizational integration of crash simulations (i.e. if the simulation department should be situated as an independent department or integrated into an existing one). Though the 'traditional' tasks of crash simulations gained further importance, these considerations indicate a process of rethinking in the R&D departments. At the end of the century it became more and more important how to exploit the potential of crash simulations most efficiently and which other tools could be used to take reality more precisely into consideration.

Example: Opel Astra in 2003 in comparison to the 1998 model
The example given emphasizes the advancements in crash modeling, but does not represent e.g. scatter of crash conditions. Figure 3 juxtaposes the 1998 and the 2003 Opel Astra crash model. The advancements in the content of crash models (e.g. the interior, restraint system, or dummies) are apparent. Over a period of 5 years, from 1998 to 2003, the fidelity of crash models has increased considerably.[12]

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[11] This example is based on a personal communication at Opel, Germany, and on Böttcher (Böttcher et al. 2005).

[12] One R&D engineer reported in one of the interviews conducted with the German OEMs, that he encountered some problems in modeling a car in the very early 1990s. He called the software company providing the crash program and his counterpart answered, that modeling 8,000 elements is indeed challenging, but not too complex. The R&D engineer corrected himself and clarified, that he does not want to model 8,000 elements, but 80,000. Thereafter, the line went silent for some seconds. This anecdote illustrates well, that even the producers of the tool crash simulation had problems to keep up with the rapid evolution of the tool, and that crash simulations have long been an adventure rather than the result of engineering and computation skills. One main outcome of this period is the demystification of crash simulations.

(a). Opel Astra 1998.

(b). Opel Astra 2003.

Source: Böttcher et al. 2005 (p. 3, figure 2)

Figure 3: Comparison of crash model contents for 1998 and 2003 Opel Astra.

The thin lines behind the steering wheel in the 1998 model substitute the dummies. The 2003 model already included dummies, controls and instruments, restraint systems, and the fuel tank. Especially the integration of the dummies into the crash model was an important step for the R&D engineers. The number of elements increased by a factor of 12 over a period of 5 years, from 114,414 elements in 1998 to 1,398,435 elements in 2003. Instead of using a single supercomputer, the simulation ran on a Linux cluster.

Impact on R&D
With such highly detailed crash models, R&D engineers were able to reduce the number of physical prototypes needed in new car development projects. At the same time, R&D engineers were able to perform much more design iterations at a marginal amount of money in comparison to physical testing. A study in 1998 yielded, that the total time for one simulation takes about 2.5 days to 6.3 weeks and costs typically less than US$5000 whereas one physical prototype iteration takes about 3.8 months to more than 7 months and costs more than US$300,000 (VP&S 2004, Böttcher et al. 2005, Thomke 2003).

3. Results

The need for solving new problems initiated the utilization of the FEM for crashworthiness assessment. In the beginnings, crash models contained only 60 elements, as mentioned in the description of the phase 'Origins in the Military Domain'. The automotive industry recognized the potential of crash simulations with the FEM, and began modeling single components of cars. Crash model sizes increased over the years, roughly following Moore's Law, and by 2004, crash models already contained 1.5 million elements. Industry experts anticipate that this development of computation power will continue.

Thus, the question of the future is not, whether the technical capabilities in crash simulations advance further, because this will inevitably be the case with growing computation power. The question is rather, what influences the application of crash simulations in the future (when a lack of computation power does not hamper crash simulations anymore). Thus, OEMs have to find a way to improve the utilization of crash simulations in their R&D process. The future utilization of crash simulations depends foremost on three aspects: a technical, an organizational, and a legal aspect.

3.1 Technical Aspect

Crash simulations with the explicit FEM approximate reality by thousands of finite elements. At present, explicit FEM crash simulations contain about 1.5 million elements. Every element is by itself an approximation of reality and relies on certain parameters, which characterize the finite element. These parameters are, e.g., material descriptions, integration points, or the contact algorithm (modeling the interactions between the elements). A change of one parameter, e.g., of the material stiffness, affects all parameters, thus its effect multiplies thousandfold. The crash simulation department of a major OEM experienced this effect in the mid-1990s.[13] The simulation department had tried to verify the load-time diagrams provided by the physical testing department for a certain car model. After some iteration of simulating and modifying the initial model set-up,[14] they succeeded and obtained the same results. However, when they presented their results to the head of vehicle development, it turned out that the crash simulation department had simulated the wrong car model by mistake - but had still obtained the 'right' results for the other car. This is a fruitful example emphasizing the caution necessary when working with the explicit FEM. Many small changes of parameters may unintentionally lead to, as in this example, another car. Furthermore, another technical downside is the likelihood of a 'software bug'. The larger the crash models, the more lines of code are included, and the higher the likelihood of a bug among millions of lines of code. One of the challenges for crash simulations in the next few years will be to address these technical deficiencies.

3.2 Organizational Aspect

The value of each tool depends on how it is put into usage. The integration of crash simulations in a standardized automotive R&D process determines the value of this tool for the OEMs. The principle decision where to integrate the crash simulation engineers in the R&D process (e.g. in rivalry to the physical crash testing department) determines the effectiveness of the tool 'crash simulation'. The integration of the tool depends not only on its position in the R&D process, but also on the way how R&D engineers use it. Many OEMs encounter the phenomenon, that nevertheless how much computer power they provide to the R&D engineer, the latter will use it up in 'an astonishingly short lapse of time' (Haug 2004). This phenomenon is well known from economics: *If all you have is a hammer, everything looks like a nail. (Bernard Baruch, statesman and financier, 1870-1965)* Thus, if your only tool is a powerful Linux cluster, then make sure your FEM model fills up the entire memory and uses all the available CPUs (Marczyk 1999).[15] Thus, it is necessary for OEMs to continuously review the proportionality of the output of crash simulations to the efforts. Otherwise, OEMs risk that their R&D engineers work suboptimal.

3.3 Legal Aspect

At present, due to legal regulations, it is not possible to fully substitute physical prototype testing with crash simulations. As a result, OEMs cannot fully exploit the potential of crash simulations to increase productivity. Furthermore, due to lacking reference models of human bodies for explicit FEM simulations, legal authorities still demand cars which are 'safe' for dummies (which are merely mechanical surrogates of humans). As a result, OEMs have no financial benefit from exploring the potential of explicit FEM simulations of humans (e.g. in the future the assessment of acceleration loads on organs would be possible). Thus, legal regulations 'force' the OEMs to build cars which are safe for dummies, but the safety of real occupants remains suboptimal.

Acknowledgement

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[13] This example is based on a personal communication by Professor Bathe from M.I.T. in October 2005.

[14] Often R&D engineers have to run some inaugurational simulations in order to calibrate the crash model.

[15] Or, how a R&D engineer from a major German OEM put it: 'Wir sind immer so, dass nichts mehr geht.'

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