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Virtual Experimentation, R&D Performance and Learning: The Impact of Information Technology on Brazilian Industry

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ABSTRACT:
Experimentation and tests using physical prototypes or computer simulation are practices used in the development of various industrial products. The aeronautical, automobile, mechanical, naval, petroleum and microelectronics industries have been using one or both of the techniques mentioned for a very long time. The aim of this research is to describe and interpret the experimentation modes currently used in Brazilian industry and their impact on R&D performance and on the respective learning process. Using a detailed empirical study developed in General Motors do Brasil’s Technological Center (automobile industry) and in the research centers financed by Petrobrás do Brasil (petroleum industry), the gains in speed and reduction in costs when it comes to developing new products become obvious. Besides this the flexibility provided by the use of computer simulation allows for more efficient learning, with better results in the problem solving process.

Keywords:
Computer Simulation, R&D performance, Learning, Automobile Industry and Petroleum Industry

INTRODUCTION
Over the years experimentation techniques or tests have served two major purposes:
i) To define a pre-product (prototype), subordinated to the characteristics assumed in the project and to prepare it for reproduction when orders are received (airplane, ship) or for mass production (molds, automobiles, parts, etc) or;
ii) Use the process and pre-product for anticipating and correcting problems.
According to Clark and Fujimoto (1991), “Our clinical and statistical evidence reveals two contrasting paradigms of prototype development: prototype as early problem detector or prototype as a master model. European high-end specialists view the engineering prototype as a master to be copied by the production model. In contrast, the Japanese car makers, regard the prototype as a tool for finding and solving design and manufacturing problems at early stages of product development”. Recognizing the importance of experimentation as an inherent activity for validating the development of new products is at one and the same time both an exercise in good sense and one of humility. If acquired knowledge and experience were the only prerequisites necessary for preparing a product there would be no need for such a large amount of effort and so much investment to be ploughed into this technique. In other words experimentation in the shape of prototypes, molds or mathematical models for computer simulation are the material representations of the limitations from which human beings suffer when it comes understanding reality.
As Simon (1955) so well puts it, “the simplifications applied by this organism (the human being) to the real world for the purpose of taking decisions introduce discrepancies between the simplified model and reality; and these discrepancies, in turn, serve to explain many of the phenomena of organizational behavior”.
In addition to the statements made, there is also the experimentation process seen as a learning opportunity, based on the act of making mistakes without causing significant damage to the whole production chain. According to Thomke (1998), “my empirical findings also suggest that such an experimentation strategy can sometimes benefit from getting the prototype wrong the first time, a strategy that contradicts prior work in product development which often prescribes “getting it right the first time””.

The evolution of computer graphics, informatics, engineering and other inter-disciplinary sciences has allowed experimentation to be carried out by the interface between men and machines, which simulates a real environment and allows those involved to interact with the same. This new interaction concept is called virtual reality. Virtual reality has applications in architecture, medicine, entertainment, computer graphics, production planning and control, plant layout planning, preparing prototypes, simulation and training (Netto et al, 1998). In this way it is possible to simulate situations that would be physically impossible to capture in the real world, or would be economically impractical to reproduce under normal working conditions.

Currently a given industrial experiment can be carried out in different ways (e.g. computer simulation, quick prototype building) and there is an optimum economic change point between those ways that reduce cost and the time taken for product development (Thomke, 1998). This fact allows for a similar experimentation management basis to be used in different industries where tests are started in virtual environments and then later completed using physical prototypes that are submitted to specific usage conditions.

This work shows that in Brazilian industries, where there has been a rapid development of computer simulation, this has had a significant impact on R & D performance. First, because the costs of the project have been reduced by reason of the number of conventional prototypes that have been economized, and because the speed of the new product development (NPD) cycle has increased. Secondly, the flexibility provided by computer simulation means that a greater variety of experiments can be assessed, thereby increasing knowledge regarding the operating behavior of the product. Thirdly, virtual experimentation, when understood as an art form, has allowed adaptations in its use, which have respected Brazilian cultural characteristics and resulted in differentiated strategic practices.

The paper is divided into three parts. In the first section we describe the GMB’s virtual experimentation process. The next section relates the virtual experimentation process in the Brazilian petroleum industry. The last part concludes with observations for practice and theory.

**METHODOLOGY**

Two major, internationally well-known industries were analyzed and two distinct experimentation and test practices were researched:

a) Virtual experimentation carried out in the automobile industry, using computer simulation and three dimensional representation, to show the effect on the vehicle as a whole, or on isolated components, when they are submitted to specific forces (knocks and collisions);

b) Experimentation carried out in the petroleum industry to assess the operational working conditions of offshore oil platforms using physical or virtual prototypes submitted to simulated wave tests in ocean tanks or numerical tanks.

We collected information from interviews with specialists in simulation from the industrial and academic world, from interviews with engineers and those responsible for the tests done in the research centers we studied, and by observing the experimentation process in General Motors do Brasil’s technological experimentation and testing center in Sao Caetano do Sul (Sao Paulo – Brazil), at the Underwater Technology Laboratory of the Federal University of Rio de Janeiro (UFRJ), the Sao Paulo Technological Research Institute (IPT) and the Numerical Offshore Tank (NOT) of the Department of Naval Engineering in the University of Sao Paulo’s Polytechnic School (EPUSP). After 5 months of dialogue, 10 semistructured interviews and 10 people interviewed we were able to understand and describe the current experimentation and test processes carried out in these centers, how these processes differ from the practice in other similar centers throughout the world, and their influence on the development of new products. By request, all the confidential data was omitted (e.g. how many car crashes were simulated), but this limitation did not affect the conclusions.

**AUTOMOBILE INDUSTRY**

Although the ability to project, test and analyze technical and scientific concepts with the help of computerized resources has been delighting the world of Research and Development (R & D) for years, only recently has it reached a relevant stage of performance, thanks to technological advance and the evolution of simulation techniques. As a result, professional
engineering journals are increasingly reporting on projects with significant R & D performance improvements attributed to the use of advanced computer simulation (Thomke, 1998).

General Motors do Brasil’s (GMB) Technological Center started its plans for using virtual experimentation in 1996 with an emphasis on the application of structural analyses for correcting problems. In 1997, virtual experimentation started to be a part of the new product development cycle for the Celta and Corsa automobile projects. It also started being used for impact simulation for determining the crashworthiness of automobiles (their capacity for deforming on impact). Since 1998, simulation has been part of other phases in new product development and in 1999 simulation tests of virtual thermodynamics were introduced. In 2000 they started simulating sudden and sharp changes in direction and since 2001 they have been simulating comfort (how the automobile rides).

The area responsible for the analyses and simulations on automobiles currently compromises 14 engineers who use leading-edge technological resources, specifically the LS-DYNA3D software for simulating collisions three dimensionally and NASTRAN for linear simulations. The strategy employed by the Brazilian subsidiary has meant that it become specialized in segmented analysis models, thereby differentiating it from other units in the group that use complete, complex and less flexible models.

A Description of Virtual Experimentation

According to Cooper (1983), “The testing stage is a validation of the product’s design and features in use. Product prototypes are tested within the company to determine that no technical flaws exist. In parallel, a customer test of the product is conducted”.

GMB’s virtual experimentation process is divided into four phases as shown in Table 1. This method of working is applied to all vehicles. The only thing that changes is the intensity of the load involved according to the type of vehicle (saloon, pick-up or bus) or the total weight of the automobile.

<table>
<thead>
<tr>
<th>Conception Phase</th>
<th>Development Phase Intermediary 1</th>
<th>Development Phase Intermediary 2</th>
<th>Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Overall performance</td>
<td>• Durability</td>
<td>• Noise and vibration</td>
<td>• Physical prototype</td>
</tr>
<tr>
<td>• Airflow</td>
<td>• Crash</td>
<td>• Airflow</td>
<td></td>
</tr>
<tr>
<td>• Vehicle dynamics</td>
<td>• Comfort</td>
<td>• Passenger protection</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 – Phases in GMB’s Virtual Experimentation

Source: Prepared by the author

In the conception phase the platforms of previous similar vehicles are used, with their respective performance indicators. This is for the initial design of the product that will be submitted to specific virtual tests. In this phase the characteristics of the vehicle are defined in accordance with market demands, performance parameters, components, materials, costs, time, production process to be used and the design of the vehicle.

The vehicle dynamic test submits the virtual prototype to a series of brusque maneuvers, involving a change of direction at high speed, in order to evaluate the response efficiency of components such as the steering, tires, shock-absorbers and the differential axle. In this stage the results of the simulations are periodically compared with field tests to evaluate the correlation of the theoretical model with the average reality of the maneuvers as carried out by various drivers. Currently this correlation is at 92%. The results of the simulation are passed on to GMB’s component suppliers, who take advantage of this and other stages in the test cycle to improve their products. This is a type of strategic alliance provided by the experimentation model, which strengthens the ties between the automobile manufacturer and its suppliers on a worldwide level. In certain circumstances suppliers are involved on site, making modifications to the components during the tests. The airflow test at this phase consists in simulations using two-dimensional models and focusing exclusively on airflow.

During the Intermediary 1 development phase, an evaluation is made of the resistance of the vehicle’s components when they are submitted to specific and controlled forces in accordance with normal working conditions for the vehicle in question or in predefined impact situations. The conditions of the surface of the test track are constantly checked against the characteristics of Brazilian roads. By bringing together the finite element models, the limits of mechanical resistance and the expected life of
these components can be calculated using software developed internally by GMB. Here again the results are periodically compared to those from traditional tests. An example of this is the appearance of a structural crack that is forecast to happen after 24,000 kms of use but which happens after just two minutes of simulation. This same fault was only seen after 4 months, or 30,000 km of traditional testing.

It is during this phase that crash simulations are carried out to assess how the vehicle and its components deform when they are submitted to various types of collision with different obstacles. Generally speaking, government norms on collision establish minimum standards of safety, which over the years have been added to and substituted with the more demanding requirements put together by independent bodies in Europe (European New Car Assessment Programme – EuroNCAP http://www.euroncap.com) and in the United States (Insurance Institute for Highway Safety – IIHS http://www.hwysafety.org). As a result of these tests, safety classifications are put together comparing the vehicles of the various manufacturers. These classifications are publicly available for each category of vehicle (mini-van, saloon, utility truck) and periodically published by the independent bodies, thereby forcing the manufacturers to exceed the minimum standards demanded by local legislation.

In accordance with EuroNCAP, impact tests are divided into:

i) Head-on collision
A collision between a minimum of 40% of the front part of the vehicle at a speed of 64 km per hour with a fixed deformable barrier measuring 1000 mm x 540 mm.

ii) Side collision
A collision between a Trolley with a deformable front measuring 1500 mm x 500 mm at a speed of 50 km per hour with the side of a stationery vehicle.

iii) Collision with a pedestrian
A collision between the front part of the vehicle at a speed of 40 km per hour with an adult or child pedestrian.

iv) Collision with a post
A collision between the side of a vehicle placed on a platform moving at a speed of 29 km per hour with a rigid post measuring 254 mm in diameter.

The simulations carried out on a computer reproduce the effects of the different types of collision on components. When we were collecting the information we observed the consequences of a head-on collision using the Meriva automobile, in accordance with EuroNCAP norms. The collision was reproduced on the computer at a speed that was noticeable to the human eye, using three-dimensional effects. From the screen, where the loads originate and how they evolve during a collision in the car as a whole or in the tested-to-destruction parts (parts that are destroyed in low velocity collisions to save the vehicle as a whole, reduce the cost of repairs, and ensure that it can be safely repaired, e.g. the bumper) can be traced, in order to assess the operational limits of their mechanical resistance and their energy absorbing capacity. These effects could not even be captured if TV cameras were used. Depending on the results, new parts or new materials may be used, thereby helping define the design of the tooling that will be used in the production process.

The whole system is attached to the CAD platform, which allows for components to be redesigned and incorporated into the production process. An example of an operational limit is the definition of the limit of plastic strain of 18% for panels; this can be graphically visualized. The comfort test is carried out by experts in the subject who, when they drive the vehicle on specific tracks, assess it according to the comfort criteria from the driver’s point of view. With simulation, the same journey can be made using a virtual automobile.

**R&D Performance, Learning and Physical Prototype**

In the Intermediary 2 development phase the components, materials, structure and their consequences on the passengers in the vehicle are jointly assessed. Previous individual results are used. Noise and vibration tests assess the main sources of noise in the vehicle: the support structure of the engine, the exhaust system and insulation. These assessments are based on fluid mechanics models (the study of water and air features under specific conditions) and the tests are carried out by inserting air and measuring the sound pressure, in order to track the sources of the noise and its path. Since the condition of Brazilian roads changes constantly, adjustments to the materials or the designs of various components become necessary, even for world projects, in order to ensure that the performance indicators fit the new circumstances.
Airflow tests are based on Thermodynamics and the experiments are carried out using the temperature of the air entering the engine according to the outside temperature, thereby assessing the engine cooling system. Simulations are carried out on three-dimensional models with the focus on the relationship between airflow and temperature. Tests relating to protection for passengers in the vehicle aim to guarantee a minimum survival rate of 75%, based on statistics taken from autopsies carried out on the victims of automobile accidents. The principal parts of the human body that are assessed are: head and neck, thorax, legs and upper limbs and the leg (knee) and lower limbs. For the design and specification of automobile parts and components, assessments are made of the rates of deceleration to which body parts may be submitted.

The final tests are carried out in a traditional way, in other words, an impact using a physical prototype, containing dummies (human prototypes) for passengers. All previous results are compared with the real collision, with the occupants of the vehicle being substituted for dummies made of a special material that allows for a comparison to be made of the injuries caused to their vital regions (head, neck, thorax and legs) and the consequences on human beings. Virtual experimentation makes many contributions. The productivity gains in the development of new products, when compared to the conventional process, can be seen in Table 2. Reductions in time and cost are significant when the number of physical prototypes that are saved during the process is considered.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Computer simulation (per iteration)</th>
<th>Conventional method (per iteration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Design</td>
<td>CAD (creation and/or alteration of a part in three dimensions)</td>
<td>CAD (creation and/or alteration of a part in three dimensions)</td>
</tr>
<tr>
<td></td>
<td>2 hours.</td>
<td>2 hours.</td>
</tr>
<tr>
<td>2. Construction</td>
<td>Preparation and integration of the data base</td>
<td>Design and construction of the model</td>
</tr>
<tr>
<td></td>
<td>30 minutes</td>
<td>5 days</td>
</tr>
<tr>
<td>3. Test</td>
<td>Simulation of the structure’s durability</td>
<td>Durability on the test track</td>
</tr>
<tr>
<td></td>
<td>2 minutes</td>
<td>6 months</td>
</tr>
<tr>
<td>4. Analysis</td>
<td>2 minutes</td>
<td>5 days</td>
</tr>
<tr>
<td>5. Average time of NPD¹</td>
<td>24 months</td>
<td>36 months</td>
</tr>
<tr>
<td>6. Prototypes economized</td>
<td>Corsa 1999 Project – 6 prototypes</td>
<td>-</td>
</tr>
<tr>
<td>7. Average economy from the</td>
<td>US$ 800,000</td>
<td>-</td>
</tr>
<tr>
<td>reduction in number of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>prototypes¹</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 – Comparison between NPD using virtual experimentation and the conventional process

Source: Prepared by the author
Source: General Motors do Brasil
ⁱResults obtained after the new vehicle has been developed

Innovation

The test procedures and software used are the same for all of General Motors’ subsidiaries worldwide. However, reduced investments available for equipment and labor forced the Brazilian subsidiary to become creative. The turbulent Brazilian economic environment demands flexibility and agility because in Brazilian culture late replies to urgent market demands are unacceptable. The complex and slow, conventional virtual experimentation model was adapted to local circumstances using segmented modules that allow for independent analyses without the need for complete simulation of the model. Therefore simulations and analyses are four times faster than when the conventional procedure is used. This competitive advantage contributed to the fact that GMB has become a point of reference within the corporation and is asked to carry out virtual experiments on projects developed by other subsidiaries and by the Head Office itself.

PETROLEUM INDUSTRY
The major part of Brazil’s petroleum production is obtained from deep-water oil wells. Petrobrás, the state petroleum company, is the owner of this differentiated technology that in some cases operates in depths of water greater than 2000 meters. Ocean exploration is carried out using static tankers or platforms, located mainly in the oil fields off the coast of the State of Rio de Janeiro. The projects for these platforms or tankers are ordered by Petrobrás and the tests are carried out in centers that have different technological competences. Figure 1 shows the ideal experimentation and testing cycle that can now be used because of the recently inaugurated technological installations. As can be seen, the ideal cycle starts with definitions of the depth of drilling, an estimate of production and the environmental characteristics at the location, as supplied by Petrobras as preliminary parameters for the basic platform project. The pre-project is arrived at after consulting the library of projects already carried out and adapting them. With the pre-project put together, the basic tests are carried that will validate the numerical coefficients to be used in the NOT simulation (virtual tank). After obtaining the results of the simulation tests on the platform structure, and on the anchoring points and oil production connecting lines, a test of the final hydrodynamic configuration is carried out in UFRJ’s ocean tank (physical tank) using a scale model platform prototype.

A Description of Experimentation and Testing Cycle

The IPT carries out various types of test for supplying and creating the coefficients for the numeric models of the NOT, which are not available in any literature and are difficult to measure. The initial platform or tanker model undergoes the following tests:

i) Test of a capsized model
   Stability test carried out on a submerged and overturned prototype to assess the action of wind by substituting air for water in the ratio 1:19.

ii) Self-propulsion test using a scale model
   Optical systems for measuring movement assess the degree of oscillation of the prototype with the hull of the model moving along the IPT test tank (280 m x 6.6 m x 4.4 m deep), with or without the influence of waves. This test is used exclusively for ships that will move under their own power.

iii) Captive model
   Wave, current and wind tests carried out on the prototype to determine the parameters for the numeric model. For example: waves returning after hitting the platform legs form other waves that might reach heights that could affect its deck.

iv) Stationary model in waves
   Wave impact tests on a stationary model. For example: to avoid lateral oscillation greater than 14° (exclusively for tests on
platforms).
v) Taking on water
Test on the model involving it being flooded with water.

After the coefficients have been defined in the basic tests, hydrodynamic model simulations are carried out in the NOT, where, using three dimensional computer graphics and in real time, the traction forces that occur in anchor and oil production lines under the influence of currents and when the platform is being moved are reproduced. The results are adjusted for the characteristics of the final hydrodynamic configuration test that will be carried out in the tank in the Ocean Technology Laboratory. In addition, mathematical models allow for simulation of environmental conditions without the physical restrictions imposed by tests carried out in tanks (problems caused by the reduction in the physical scale or the maximum possible depth limit), thereby increasing the possibilities of extending the experiments to include situations that have as yet never occurred.

The atmospheric conditions for oil exploration in Brazil make the tests carried out in the ocean tank different. It allows for the simulation of hydrodynamic phenomena of the marine environment in layers up to a depth of 1500 m and preprogrammed variations in the wind of 12 m per second, unlike similar tests in Norway and Holland that only reach a maximum depth of 1000 m. Currently, at 40 m long, 30 m wide and 15 m deep, it is the deepest tank in the world, with a capacity of 23 million liters of water and the possibility of carrying out tests with exploration platforms, ships, tugs, prototypes of marine vehicles and for training divers, etc. The experimentation model and tests used by the laboratory combine virtual experimentation (generator of sea wave profiles) with classic prototype work (scale model of an oil platform).

Reproduction of sea conditions is carried out by measuring the waves for a period of a year in the place the platform is to be located. From this investigation a histogram is put together containing the frequency of the appearance of waves and their height and direction (one way or multi-directional). This will serve as information for supplying the computerized system used for generating waves in the tank.

The waves are generated by 75 independent paddles placed lengthwise in the tank, and capable of producing movements at various angles. Across the tank there are shock-absorbing beaches that are responsible for dissipating the energy of the waves, thereby avoiding them returning to the test area and contaminating the measurements. The waves are tested, measured and calibrated in accordance with a predetermined profile, before the model is put into the tank for the test. Figure 2 shows a view of the tank’s wave generator.

The model platform shown is constructed in accordance with scale studies on the dynamic effects in the ratio 1:64 (64 times smaller). In the theory used, time scales are the square root of the geometric scale, i.e. 1: 8 (8 times smaller). Measuring equipment is installed with accelerometers, infrared sensors and cameras to assess movement in the body of the model. Figure 3 shows the model of an offshore platform ready for hydrodynamic configuration testing in the tank.

The operating and survival limits of the platform are defined as the practical operational results. The operating limits reflect the normal uninterrupted working conditions of the platform when submitted to waves of between 4 and 5 meters, depending on the place where it is located. The survival limit reveals the collapse condition of the platform when submitted to the impact from waves that only occur once every ten or every hundred years. In Brazil waves that occur once every ten years are 7 meters high, while waves that occur every hundred years vary between 13 and 15 meters.

Innovation

The ocean tank was only recently installed (2003) and there are still no relevant data regarding its impact on the NPD cycle. Once again, the scarcity of resources is the fount of creative inspiration. Given the impossibility of investing in sophisticated wind tunnels or super-computers, Brazilian research centers innovated their procedures. Tests carried out using models submerged in water substitute conventional experiments in wind tunnels, thereby obtaining flexibility and a considerable margin of safety, by substituting air for water (9 times denser). A cluster of 120 computers processing in parallel substituted the super-computer and made simulation possible. The NOT is considered unique in the world and reproduces the environmental working conditions of oil platforms by means of mathematical scale models in 3D. This resource contributes to an increase in the efficiency of oil extraction from current reserves and simulates how platforms will operate under conditions as yet unexplored, with extraction occurring at a depth of 3000 m.
Figure 2 – Test tank with wave generator

Figure 3 – Offshore platform prototype for hydrodynamic testing.
CONCLUSION
This research was carried out with companies that are considered to be representative industrial examples for the R & D community, and which use the latest state of the art technology and are internationally recognized. This reinforces how integrative and essential the participation of the experimentation and testing stage is to the new product development process.

The influence of information technology resources allows experiments to be carried out, communicated and concluded, thereby emphasizing the essential technical competences of each scientific center, without geographic restrictions. The use of simulated computer experimentation, with three-dimensional graphical resources, allows for the reproduction in real time of phenomena imposed on virtual products, and the proven reduction in costs and product development cycle times. The simulation technique allows environmental conditions that are difficult or impossible to reproduce physically to be tested and extrapolated, by anticipating future operating configurations for the products. Besides the gains in process cost and speed, the results of the mathematical models prove the potential of the theories being used (thermodynamics, hydrodynamics). Despite the significant advances in and reliability of virtual experimentation physical prototypes are still necessary for the total or partial validation of the mathematical models used, thereby producing a mixed experimentation strategy that combines the physical with the virtual. In both industries, the main purpose of the testing and experimentation phase is a reduction in errors and an increase in the chances of success for other new products to carry out their operational functions.

The competitive advantage of using simulation in R & D is not only restricted to the mathematical models used, but lies also in the capacity to integrate and interact in the learning process. The existence of a test stage allows all of the most advanced technological resources to be used, thereby making the learning task, and the capacity for the company to learn, easier, because the consequences of an error are diluted in the virtual environment. In this way the trauma of the error is avoided and, on the contrary, it is managed in order to improve the production process. The gains obtained from this method of learning go beyond the industrial frontiers and are applicable in other areas such as health, finance, education, energy, etc.

Virtual experimentation allows for a combination of the flexibility of new technologies and the cultural abilities inherent in each nation. This combination allows for adaptations in the way technological concepts and resources are used, thereby giving rise to unique and differentiated strategies. In this sense this is where globalization gives way to regionalization.

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