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Virtual Product Development: A method to reduce lead time in New Product Development

A Master's Thesis submitted for the degree of
"Master of Business Administration"

supervised by
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Västerås, 01.08.2016

Affidavit

I, **Kausihan Selvam**, hereby declare

1. that I am the sole author of the present Master’s Thesis, "Virtual product Development: A method to reduce lead time in New Product Development", 68 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Preface

This master's thesis is made as a completion of the Masters in Business Administration. Several persons have contributed with theoretic, practical and intellectual knowledge in support of this master thesis. I would therefore firstly like to thank my supervisor Prof. Dr. Marc Gruber for his time, valuable input and support throughout the entire master period. I would also like to thank the program directors, Prof. Dr. Nikolaus Franke and Prof. Dr. Sabine T. Köszegi, for their advice. Additional thanks and mention is reserved for the program managers Dalibor Babic, MMag.Catherina Purrucker, Petra Hinterndorfer and Katharina Trappel, for bearing with me for the past two years.

I would also like to thank all my colleagues and professors who made these two years enjoyable and enlightning.

Thank you.

Abstract

In today's competitive marketplace, companies, especially in the automotive manufacturing field are under strong pressure to introduce new products frequently to secure their long-term survival and profitability by staying ahead of their competitors. It is not possible for every company, even ones with huge resources, to cope progressively or immediately with the market requirements, due to knowledge dynamics and customer behaviour changes. This increased competition in the market place and reduced product life cycles due to market dynamics force companies to develop new products faster. This also forces companies to develop their knowledge resources quicker. In addition, for many a company, prototyping the new product is a vital activity that can make a huge difference between successful and unsuccessful entry of the said product into the market. physical prototyping is usually very expensive and time consuming , especially if modifications resulting from design reviews involve not only prototype redesign but also tool redesign. The advancement in technology and advanced computers has enabled the use of digital and virtual techniques for prototyping that forgo with costly prototype and production tool manufacturing. A product development platform using virtuality and virtual product development techniques is envisaged to reduce the product design lifecycle time. This platform is then integrated into the modified phase review process developed by Cooper. Focus on automotive industry is prioritised. But the process is suitable for all NPD projects.

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1 Introduction

New product development (NPD) is not only necessary but is also recognised as the cornerstone for the continued financial success of a company [2]. Any new product needs to go through a product development process which would involve atleast the following stages [3].

1. Product conception through idea generation and selection.

2. Product development.

3. Product testing.

4. Product launch.

The specific knowledge and subsequent required skills for the development of new products might often reside in various loctaions and knowledge hubs around the world. Hence it is difficult for firms to collate of all technology needed for new products and processes without extensive collaboration with external parties [4]. To solve this quandary, that every company faces, a development platform or process to advance the knowledge base of the company, through knowledge sharing with external parties, that can be used to reduce time-to-market to new products, is needed. One of the more time consuming part of expanding this knowledge base is validation of the product with relation to quality, performance and cost. Hence a process that can achieve substantial reduction in both production cost, testing and prototyping time is recommended. Virtualisation in NPD has recently made huge headways due to developments in IT related technology [5]. Virtual product development in NPD is now technical reality [6]. Many Automotive and offroad vehicle OEMs have formed partnerships with suppliers to take advantage of their technological expertise in the field of virtual product development [7]. As product development becomes the more complex, supply chain also needs to be more collaborative than in the past. Having this collaboration with a partner with best knowledge rather than partner with least physical distance offer considerable benefit. A study performed by May and carter [8] on virtual development teams in European automotive industry shows that it benefits the OEMs in terms of better quality, reduction in both costs and time to market, for new vehicles.

On the other hand, Stage-Gate system [9] which defines different steps of product development, has come under criticism over its effect on reduction in innovative NPD [10]. Hence a modification of The coopers third generation stage gate process [11] to improve the decision making process and include virtual product development using virtual teams and open innovation models is envisaged.

Organisational structure and strategy changes, that are needed in the matrix organisation, to eliminate decision processes that gives rise to a lowest-common-denominator political compromise in an NPD project is also envisaged.

2 Need for virtuality in New Product Development

Different researchers have slightly different perspective and definitions for product development. But the generally accepted normative for product development is that it is the process that covers the product conception , product design, Product validation, production system design and product introduction processes and start of production. A multidisciplinary approach is needed to be successful in launching new products [12]. In the present environment with quick depreciation of technology and knowledge due to rapid changes in customer needs , development teams encounter very turbulent markets and times. To smoothen the development process where the product requirements need to change rapidly, a rapid idea generation and prototyping process is required. virtual product development provides the tools and processes for such an approach.Virtual product development is a new design, development and evaluation method of integrated product and processing strategies using multidisciplinary simulation and scientific visualization technologies. Adoption of such collaborative engineering tools and technology has significant correlation with NPD profitability [13]. There is also empirical evidence between internationalisation, diversity and a firms capacity for innovation [14]. The requirements set forward in NPD by efficiency and innovation are contradictory in nature. Hence to satisfy both requirements would need a collaborative effort with results based analysis where prototyping and validation of innovative ideas needs to be performed within contracting time scales. this can be achieved through designing virtual customer environments for New Product Development.

When it comes to new product development , involving suppliers helps the firm to gain new competencies while other advantages like risk sharing , faster entry to new markets and resource conservation are also possible [7]. The rate at which the market and technological changes has accelerated tremendously in recent years and this turbulence requires new methods and techniques to launch new products to the marketplace successfully [15].

The most common means of confirming the satisfaction of quality requirements in a new product is through physical prototyping. Despite the high reliability of physical testing, when the boundary conditions are well known, its increased time and cost are a huge dampener in NPD. Also the cost involved with physical testing and validation, tends to kill potentially breakthrough ideas as the boundary conditions for such products are not known and validation of such ideas will logarithmically increase the testing costs [16]. But,a rapid increase in computing power, sophistication of computational methods that capture the environment and requirements, coupled with the modeling of physical phenomena and the ability to match various models and systems, due to standardisation of model formats, are improving the scope of applications and cost effectiveness of virtual prototyping technology at an incredibly fast pace, while also increasing their accuracy and robustness [17]. Virtual prototyping opens up the means to test all probable scenarios for a new product without the additional cost increases of physical testing. This provides a vital tool in prevention of neglect of potential radical breakthrough ideas, as they can be safely tested

3 New product development process

3.1 A standard mechanical product development process

A product engineering process covers the entire life cycle of a product, including all operations for the development, manufacturing, use, servicing and disposal of the said product [18]. Product development manages the creation of the product itself, taking into consideration the different set of boundary conditions. In this way, product development processes includes all the operations necessary to bring new products to market [18].

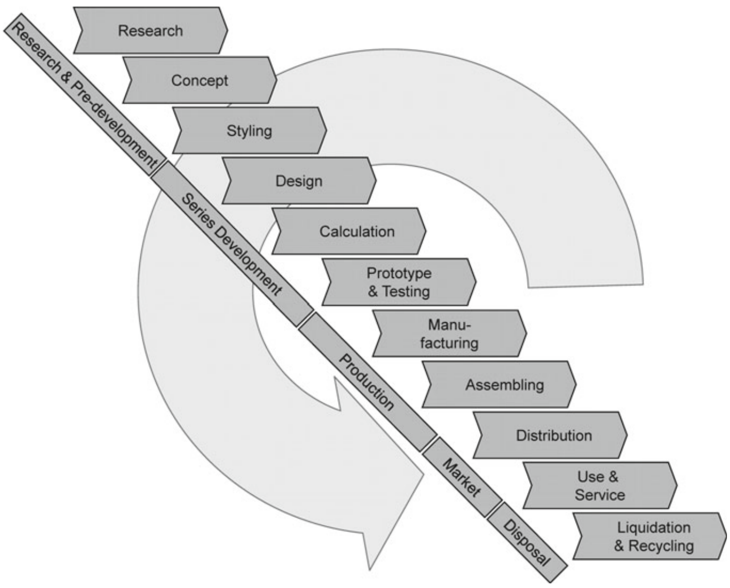

Figure 1: Typical Product Life-Cycle[1]

According to [19] Figure 1 shows a typical product life cycle sequence. Product research encompasses both basic research work and product-specific investigations. The product planning stage is often embedded in the concept phase. In this first development phase, the main characteristics of a new product are defined and evaluated. After the concept phase, the series development includes the styling, the design and a detail engineering phase. The extent of the product

[1]Courtesy: Verein Deutscher Ingenieure:Methodik zumEntwickeln undKonstruieren technischer Systeme und Produkte. VDI-Richtlinie (1993)

testing stage depends on the product type. In the case of automotive engineering processes, the testing stage consists of far-reaching test and optimization work [20]. Next, production-related processes are developed and implemented. After the start of production, the product manufacturing phase represents the last stage in the product creation cycle. The product distribution, use and liquidation (eventually recycling) stages take place in the market. During these phases, marketing-relevant factors, service and customer support have to be considered. Regardless of the specific development tools and methods that are applied, the development process for mechanical products can be divided into five main stages as shown in Figure 2 [21]. In the first stage, the product requirements and specifications are defined. In this stage the description of product characteristics is supported by far-reaching market studies, research into constantly changing customer demands and an evaluation of future legislation-based boundary conditions in target markets.

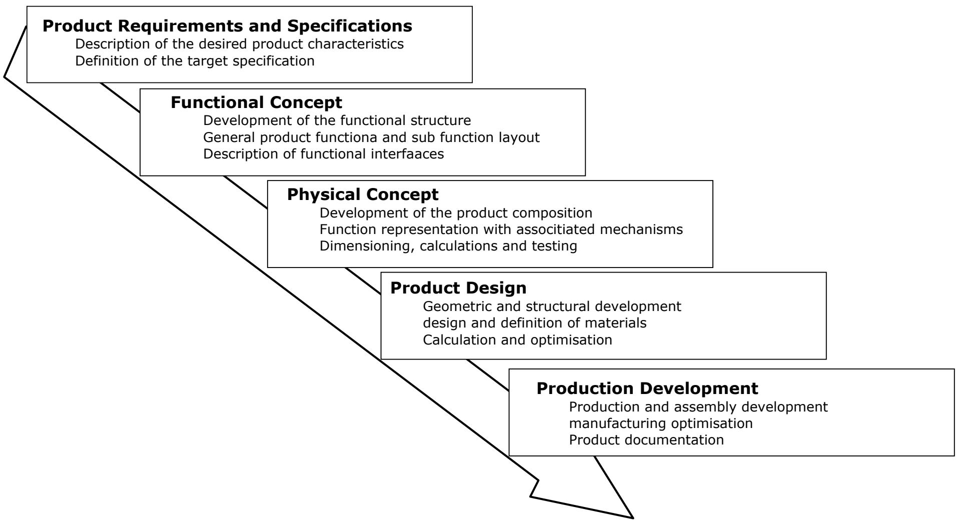

Figure 2: Development process for mechanical products, according to VDI Richtlinie 2221 [3]

[3]Courtesy: Verein Deutscher Ingenieure:Methodik zumEntwickeln undKonstruieren technischer Systeme und Produkte. VDI-Richtlinie (1993)

The second stage of the development process includes the functional concept of the new product. The new phenomenons that are added are assessed to verify their functional configurations. A general product layout describes the definition of functions and sub-functions. All of the interacting requirements of a new product are checked in view of the requirement specifications and other influencing boundary conditions, such as legislation-relevant tasks or production-related influences.

The third stage tackles the physical concept. This stage covers the composition of the product. The new functions are developed with the means of assosiated mechanisms. Besides simulation work, this stage includes the mechanical dimensioning and calculation of components.

The fourth stage handles the product design phase, which is directly dependent on the product concept phase. The geometrical development of all components has to consider the assembly of the product and the interactions of components. The product is verified with definitions developed in the concept phase. Based on knowledge of the product gained during the concept phase, the product components are optimised. The materials are defined in detail, and the product boundaries for the production planning are established.

Finally, the last stage consists of the production-related development. This phase goes hand in hand with the design process because manufacturing boundaries often influence the components design. Thus, the production, assembly and inspection oriented development and the manufacturing-related optimization are performed in parallel and with inputs from product design and related calculations.

While standardised processes of product development provide a framework, in the automotive industry, and especially in conceptual development, significant additional specification and development of new models, methods and tools for conceptual design are necessary [22].

3.1.1 Issues in NPD projects

Even though the standard process for the product development process is linear, the reality of a new product development process matches theory. Some of the most common causes of product development problems [23] are caused by moving product objectives or unexpected technical problems. Especially in new product development where the requirements are not finalised, the performance requirements will be fine tuned as the project moves along. Also product development involves activities with a certain degree of uncertainties, however, it is common that companies allocate resources almost entirely for known project requirements, leaving nothing or very little available for unexpected events.

Issues with physical testing One another major issue with the normal NPD process arises with physical testing. in a normal NPD project, product performance is usually measured using testing of the physical prototype. Physical testing is a time consuming process. the cost of product evaluation is frequently proportional to fidelity and complexity, of the product and test facility availability [24]. The availability of the test system is inversely proportional to the complexity of the test object as shown in Figure 3 [24]. This is a big issue for manufacturers of complex products , such as automotive industries, where the average availability of test components is around 94 %.

That would mean the availability of the total test system is around 50% for testing all product performance requirements. That increases both cost and resources in any new vehicle development.

Physical testing also is one of the biggest culprit in greenhouse gas emissions during product development, especially in automotive industry. One study found out that every prototype for a new vehicle development project adds 3.3 tonnes of CO_2 emissions in testing. Thus reducing physical testing is an environmentally friendly and sustainability necessity.

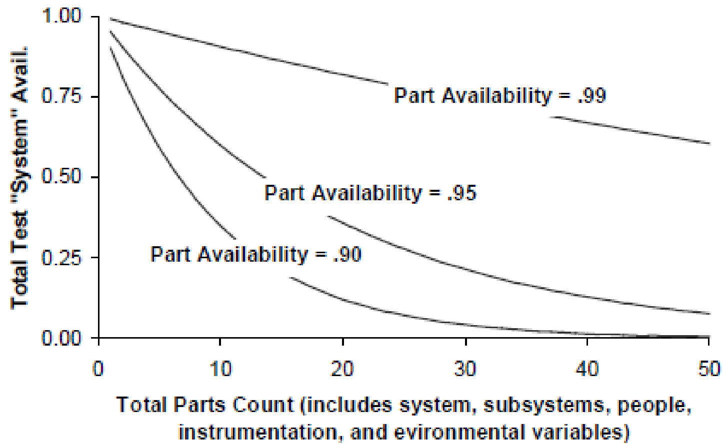

Figure 3: Relationship between test availability and complexity

3.2 Stage-gate Model

3.2.1 General description

Cooper's Stage-Gate model [11], can be seen as a coupling innovation model as defined by Du Preez in 1992 [25], which enables collaborative innovation as well as recognizes interaction between different elements in a product development process and provides for a feedback loop. This model provides an emphasis on integrating the R&D with marketing. The stage-gate model divides the product innovation process into series of stages, which are a set of parallel activities within different stages performed by related organisations, and gates - decision points between the stages where the decision to proceed are taken as shown in Figure 4.

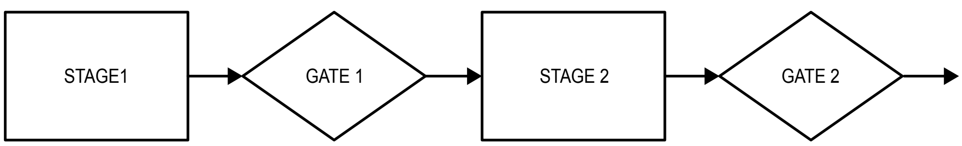

Figure 4: A simplified Stage-Gate flowchart

3.2.2 Stages

Stages are the elements of a project where product development and related analytical and technological research are performed. The near term objective of each stage is to make needed technological or organistional progress and collect the information needed to move the project through to the next gate. Information gained during each stage of the project is used to reduce the uncertainty in technology and economic risk related to the product development process [9]. With this knowledge, the project can make informed decisions that address the challenges related to the project, scientific, technological and economic,and reduce the overall uncertainty of the project. 'Early stages of research and development typically encounter the highest technical risks; the resources in later stages are most often dedicated to overcoming economic barriers to project success' [26].

The Stage-Gate process provides flexibility to gather information, manage risks, and address end-user needs in the timeliest manner. Projects may be initiated at whatever stage is most appropriate. Wherever a project begins, however, it can only be in one stage at a time. Therefore, it is critical that a plan be in place to define the work to be accomplished in each subsequent stage. Project funding may also end at the most appropriate stage.

3.2.3 Gates

Gates are decision points for initiating funding or moving forward with a project [9]. At each gate the following occurs

- A set of criteria is used to judge the progress of the project
- A decision is made as to whether the project should go ahead, be delayed, or stopped
- Approval of funding is made for the next stage
- A path forward for the next stage is presented and approved

Each gate has a unique set of quantitative and/or qualitative criteria for determining whether the project should initiate funding or approve the project into the next stage. Criteria are designed to answer salient questions such as [26]:

- Have critical technical milestones been met?
- Is project on time and within budget?
- Does the concept still have potential to provide benefits to the end-user?
- Does the concept continue to fit with defined goals and strategies?

The current stage of the project is determined by whether it has met all the criteria for preceding gates. As stated earlier, a project may enter the process at whatever stage is most appropriate. However, all previous gate criteria must have been met. Progression through each gate is determined by gatekeepers who are identified at the time the project begins. The gatekeepers determine whether the project moves forward given the information developed in the preceding stage.

3.2.4 Stage gate process in NPD

In a stage gate model the different stages of the product development process can be described with the following process stages

1. idea generation,
2. preliminary investigation,
3. business case preparation,
4. product development,
5. product testing, and
6. product introduction.

But in practice normally stage gate models are mostly used only for the last four stages in the above list. As it is considered that the stage gate processes tend to restrict creativity over structure and hence are not suitable for idea generation process and preliminary investigation.

A NPD process goes through various design stages. The Design Stages are defined levels in the product life cycle and are intended to support a gradual maturity [11]. Each level allows some specific use of the parts and also has established rules to be satisfied by the necessary activities. The purpose of dividing the development work into different stages is to provide a frame for the teamwork. This makes it possible for those concerned to carry out their tasks in a predetermined order.

In normal stage gate approach in automotive industry the four design stages are defined as [23]

- Concept stage - Stage A
- Detailed Design stage - Stage B
- Verification and tooling stage - Stage C
- Production stage - Stage P

The degree of freedom to change the product reduces as we move across the stages as shown in Figure 5. Thus it is important to have a very well defined product by the end of concept stage as this is where most of the changes that can be performed be performed at relatively little additional cost.

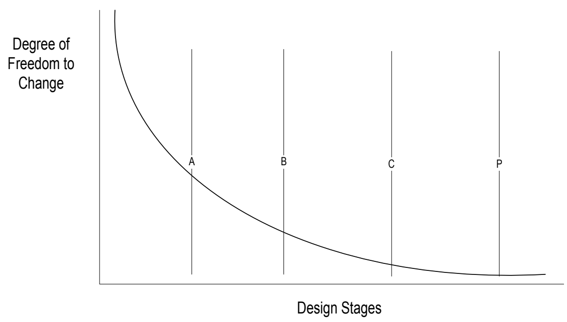

Figure 5: Design maturity versus freedom to change

A normal NPD project is very complex, with sub gates and sub projects for delivery of components and their requirements. Hence normal application approach of the defined stage gate model in mechanical product development, especially in automotive industry, is called the V-model [27]. The V-model, shown in Figure 6 is a graphical representation of the systems development life-cycle. It summarizes the main steps to be taken in conjunction with the corresponding deliverables within product development and validation network.

The V represents the sequence of steps in a project life cycle development. It describes the activities to be performed and the results that have to be produced during product development. The left side of the 'V' represents the decomposition of requirements, and creation of system specifications. This is stages A and B, in the described design stage model. The right side of the V represents integration of parts and their validation. This is stage C and P of the design stages in an NPD project. However, Requirements need to be validated first against the higher level requirements or user needs. Furthermore, there is also something as validation of system models . This can partially be done at the left side also. To claim that validation only occurs at the right side may not be correct. The easiest way is to say that verification is always against the requirements (technical terms) and validation always against the real world or the user needs.

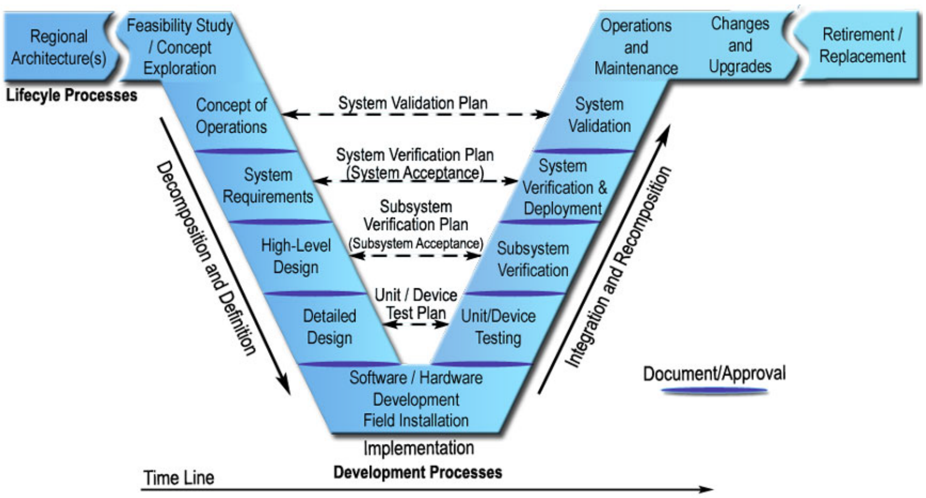

Figure 6: The V-Diagram[4]

3.2.5 Problems with stage gate model

Recently, the Stage-Gate system had been modified and adjusted to fit more to practical reality in different projects, called the Next Generation Stage-Gate [11]. The biggest change is that it has become a scalable process, scaled to fit very different types and risk-levels of projects, from very risky and complex platform developments through to lower risk extensions and modifications. People have recognised that even though risks and consumption of resources is inevitable in any kind of new product development, it is not necessary to go through the full five-stage process.

But even with these improvements there are still criticisms on the stage gate process by it meaning to be project oriented process. There is already growing recognition that stage-gate, while still an important foundation for product development, does not adequately address the interrelated elements that promote successful innovation [28]. Stage-gate focuses on the management of individual projects, which then have to compete for resources in the pipeline. Because stage-gate does not pay attention to links between technology and business op-

[4]Courtesy: US Dept of Transportation

portunities, projects are often little more than extensions of existing products. Another complaint is that in stage-gate process there is the potential for structural organization to interfere with creativity. Some experts believe that overkill of structure can cause creativity and customization to be put on the back burner of importance in an organization. Also stage gate process adds a lot of bureaucracy in the idea-to-launch process. This might lead to consensus based decision at the gates which takes too much time and resources. Also most of the time the decision is based on least common denominator , which again disincentives the potentially breakthrough but risky ideas.

4 Virtual Product Development

Virtual product development is the product development process that utilises the virtues of all IT supported, virtual product and model based processes for the generation of a new product. Virtual product models are computer generated models used specifically for the purpose of optimization of the product and are used for testing procedures in a virtual environment generated to simulate the real environment with the express aim of saving development time and money, while also improving the quality of the final product. There are various categories of virtual models depending on the type of development envisioned. They can include economic models aimed for market and business purposes ,process flow models intended for workflow simulations, Physics and mathematical representations of products in kinematic, parametric or geometric forms [29]. Efficient virtual product development is based on an effective interaction and integration of the various models and systems applied to enable a close cooperation with all participating departments and development partners, both internal and external [29]. Data management is organised in different structures, depending on the requirements of the specific stages in the product development and life cycle.

4.1 Product models and generation

Virtual product development processes are based on product data models, which are able to represent the specific product characteristics. Different needs call for dissimilar product models [29]. In general, the primary methods of product representation can be classified as

- Geometric modeling
- mathematical and parametric modeling
- Feature modeling
- Knowledge-based modeling
- Structure representation

- Technical product documentation

In virtual product development , the process of virtual product generation is divided into two main sections, The development of the virtual product itself, and the generation and optimisation of the virtual production for that particular product. Virtual product development includes all tasks necessary for the creation of product geometry and the implementation of product characteristics. The virtual plant includes the development of all manufacturing related procedures and simulations. In this phase, the operations of production are simulated and optimised within a virtual environment. In addition, the production development takes into account the implementation of supplier, logistics and controlling mechanisms, as well as financial aspects. Optimised virtual product generation processes are based on integrated virtual product models, which include the entire product description.

As of today, In a product development, the virtual product development part of the process contains four main phases [30, 31], The first stage is the CAD modeling where geometry of the product along with its features are created. The second stage includes the development of simulation model. Simulation models are models that are either physical, mathematical or just logical representation of the product, entity, phenomenon or the process as a basis for simulation to verify and validate the product requirements. Mostly the first and second stage are developed in parallel as the personnel involved in the development of these models need specific knowledge and are performed in collaboration. The third stage is the creation of Digital mockup's (DMU) of the product component. DMU allows the description of the product, usually in 3D, for the entire life cycle. DMUs contain both the product structure and simplified geometric models of individual components or assemblies [29]. The complete product model is stored in a single computer repository. Everything is integrated by a digital mockup, the structure is completed and the system defined upstream in the finest detail, which greatly facilitate programming machine tools and assembly robots.The final stage is called the functional DMU or Virtual Mockups (VMUs) [29]. These models consider functional integration of the product, including all of the features and functionality necessary for an effective lifetime operation. These so-called virtual prototypes take functional and physical characteristics into account and enable multibody functional simulations or calculations. These models can also be combined with augmented reality or virtual reality to enable early customer interaction and feedback.

4.2 Data management in VPD

Product lifecycle management (PLM) is the process of managing the entire lifecycle of a product. The lifecycle starts at the idea generation stage, through engineering design and manufacture, to service and maintainance and finally ,disposal of manufactured products [32].PLM tools are used for the integration of people, product data, related processes and provides a product information backbone for companies with relation to their products. The management of all data flow, processes and documents during the development or modification of products across the product life cycle provides the basis for an efficient virtual product generation because complex product structures or product variations create numerous product parameters and a great amount of information [29]. Product data management (PDM) is an important component in the generation of complex product structures in multi-organisational and global collaboration.

Product data can be classified into different categories.

- Product defining data, related to technical requirements, that include all kinds of data relevant to the product specification.
- Product describing data related to technical product documentation are all of the information that can be found in lists.
- Geometry data and other design-based data.
- Information concerning the development process itself, including workflow data, management of resources, data for engineering organization and others.
- Product configuration data include information about possible variants.

4.3 Process changes envisaged with virtual product development

With the help of virtual product development, many changes to NPD product development can be envisaged. Two major changes are the use of front loading and concurrent engineering. These changes help in reduction of development cost and time.

4.3.1 Concurrent design or concurrent engineering

Concurrent design or engineering is a work methodology based on the parallelisation of tasks [33].It refers to an approach used in product development in which functions of designing, manufacturing engineering are integrated to reduce the total time required to bring a new product to the market. Synchronization of individual development steps can be performed with the help of digital mock ups, in which the product is assembled and checked in the context of geometrical requirements and performance requirements. A significant part of the concurrent design method is that the individual engineer has a much bigger sayin the overall design process due to the collaborative nature of concurrent engineering. Giving the designer ownership is claimed to improve the productivity of the employee and quality of the product that is being produced, based on the assumption that people who are given a sense of gratification and ownership over their work tend to work harder and design a more robust product, as opposed to an employee that is assigned a task with little say in the general process

Concurrent design brings with it , its own series of challenges. They include implementation of early design reviews to verify the product validity to requirements, an efficient means ofcommunication between engineers and teams, and opening up of the design process to a wider audience in the design team. A concurrent design process usually requires that accurate and synchronised computer models are exchanged. This is not always easy in reality. If such issues are not addressed properly, concurrent design may not work effectively [34].Even though some activities are linear in nature due to the stage gate model design, concurrent

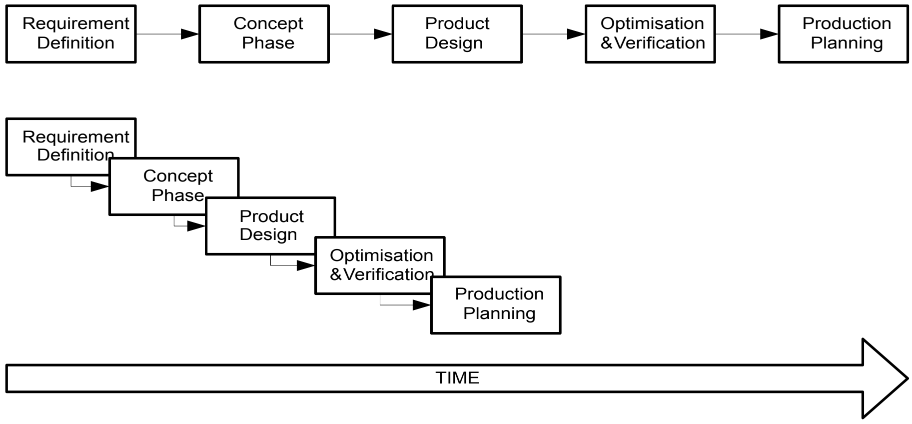

Figure 7: Difference between sequential project as compared to concurrent design project

engineering can provide significant benefits by improving the knowledge base of the company and improved sharing of information.

4.3.2 Front loading

Front loading is used in product feasibility studies, product planning and the beginning of product development. The goal is to define the product requirements and specifications at the earliest possible time, either in requirements phase or in concept phase [35].

Front loading includes robust planning and design early in a project's lifecycle, at a time when the ability to influence changes in design is relatively high and the cost to make those changes is relatively low. It typically applies to industries with highly capital intensive, long lifecycle projects. Though it often adds a small amount of time and cost to the early portion of a project, these costs are minor compared to the alternative of the costs and effort required to make changes at a later stage in the project. With virtual product development during front loading the customer can be used to set the specifications through virtual reality or augmented reality and customer reference groups.

5 Advantages of virtual product development

Academic research [36] has shown significant benefits to be achieved from virtual product development. they include, but not constricted to

- Enables a reduced time to market.
- Allows for early testing.
- Can conduct expensive or impossible tests.
- Reduces the need for a physical prototype.
- Removes geographic boundaries.
- Increases company agility.
- Reduces development costs.
- Reduces the scope and scale of engineering changes.
- Enables full participation by all parties.

5.1 Economic impact of virtual product development

Studies have been performed to verify and advantages of virtual product development. A study performed by Aberdeen Group in 2006 [37] examined 270 companies in united states, and their use of virtual product development process. Aberdeen compared how the companies implemented virtual product development and what kind of consequences they had on project costs, product quality and time to market of the products. The companies were divided into various categories based on the product complexity. The company classification are shown in Table 1

The study divided the companies into best in class , average and laggards based on achievement of set targets at the beginning of the projects. The targets used were product revenue, product cost, development cost, product launch date

Product Complexity	Number of parts	Development Time	Prototype cost
Low	Less than 50	Between a week and year	$ 7600
Moderate	Between 50 and 1000	Between a month and 5 years	$ 58000
High	Between 50 and 10000	Between 1 and 5 years	$ 130000
Very High	Between 1000 and 100000	Between 1 and 20 years	$ 1200000

Table 1: Product complexity based company grouping (Source: Aberdeen Group)

	Best in Class	Average	laggard
Product revenue targets	87 %	66 %	45 %
Product cost targets	87 %	60 %	46 %
Development cost targets	86 %	58 %	45 %
Product launch dates	89 %	64 %	48 %
Development quality targets	91 %	77 %	63 %

Table 2: Measures used for classification

and product quality. Based on aggregate scores incorporating all five metrics, those companies in the top 20% achieved "best in class"' status; those in the middle 50% were "average"; and those in the bottom 30% were "laggard". The best in class manufacturers achieved their target in more that 86% of the projects. Average performers achieved it above 50% of the time, whereas the laggards achieved it in less than 50% of their NPD projects. Table 2 provides more information on the classification.

The integration of simulation and virtual product development in their product development process has significant effect on the results. The use of simulation and virtual product development process by the different class of companies

	Best in Class	**Average**	**laggard**
Design phase	100 %	90 %	78 %
Test Phase	88 %	74 %	69 %
Post Design release	72 %	57 %	53 %

Table 3: Simulation use by different classes of companies

is shown in Table 3 and Figure 8. All best performing companies among the 270 companies involved in the study, that Figure 8 is based on, uses simulation in the design phase. Overall, best in class have a more frequent use of simulation in all phases. One of the primary reasons , stated by the study, for pursuing simulations by the manufacturers early in the product development life cycle was to test product performance virtually. Products that were virtually tested had a higher chance of passing physical prototype testing the first time.

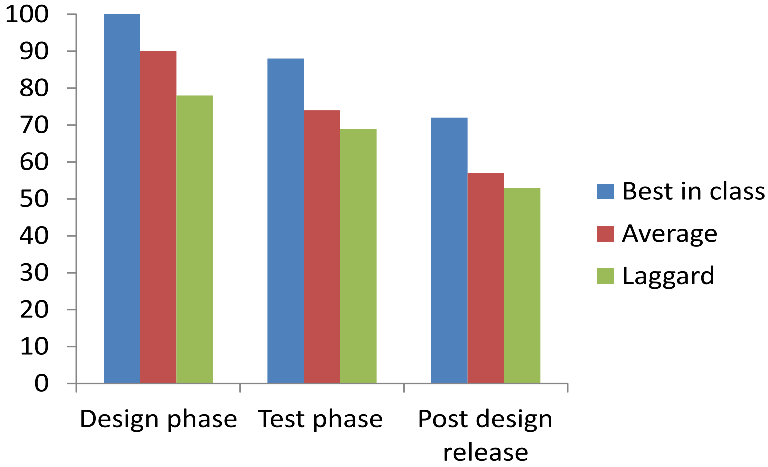

Figure 8: Use of simulation by different companies

The results form this study were quite insightful.The study performed by Aberdeen group highlighted a difference of 1.6 generations of prototype builds between the best in class and an average company. that is for a best in class company it needed only 3 generations of prototype build to deliver product to launch where as an average company needed 4.6 generations of prototypes before product was ready for launch. In companies with very high product complexity, The best in class manufacturers released product to market 158 days earlier with $1,900,000 lower product development costs than average performers. At the opposite end of product complexity spectrum, the best in class manufacturers released product to market 21 days earlier and spent $ 12,000 less on product development costs than average performers.

Another study performed by Ansys in 2011 [38] collected data on return of investment for investments made for virtual prototyping. The result of the study showed that the nominal return on investment rate is 300%. In 2011 IDC announced HPC innovation excellence award for a virtual prototyping program that achieved a return on investment of 1292% [38].

6 Virtual product development advantages among Automotive manufacturers

In order to get an enhanced understanding of the rationalisation for the use of virtual product development in automotive industry, three European based automotive manufacturers approach to virtual product development was analysed. According to software providers Dassault systems, these companies are in the cutting edge in using simulations and virtual prototyping in their product development process .

6.1 Crash simulations performed by company A

In the first company, full vehicle simulations were performed for vehicle safety in crash situations. According to [35] it is possible to perform more iterations of vehicle crash in simulations than by using physical tests. Thus virtual prototyping has improved the crashworthiness of many car designs. Also computer simulations have been faster and cheaper than physical crash tests. The performed crash simulations were FEM based simulations using explicit methods to take into account material deformations and plasticity into consideration.

For one new vehicle development, the company performed 91 iterations on the design with the help of the results obtained from the crash simulations. Because of the importance of automotive crashworthiness, the improvements from crash simulation were verified with two physical prototypes that were built after the 91 iterations were completed. These design changes improved the crashworthiness of the design by 30% for the side-impact crashes, which would be very difficult to accomplish with only physical crash tests. [35].

The statement of the design teams problem solving and learning process provides significant encouragement to virtual prototyping [1]. The design team statement according to [1] was *" In the analysis of prototype crashes of earlier development projects, test engineers repeatedly found that a small section next to the bottom of the center B pillar folded after a side-impact crash. Extensive testing experience suggested that such folding can result in increased crash barrier* *penetration and, as a result, in a higher degree of passenger injury. Based on the knowledge and understanding of the underlying crash dynamics, it was commonly assumed that adding metal would strengthen the folded area and thus provide a higher resistance to a penetrating crash object. As prototype crashes had been costly and difficult to evaluate, engineers felt that it was neither necessary nor cost-effective to verify that assumption. However, since simulation was quick, inexpensive and easy to evaluate, one development team member insisted on a verification test. The entire team was very surprised to find out that strengthening the folded area decreased crashworthiness significantly and initially none of the team members had a plausible explanation. However, after careful analysis of the crash data and a detailed study of the underlying crash physics, they learned that an unanticipated secondary and negative effect caused by the interaction between the folded area and the B-pillar in fact dominated the primary positive effect that they had anticipated. Equipped with this new knowledge, the team conducted a critical reevaluation of all other enforced areas in the automotive body which led to the improvement of the design for all automobiles currently under development."*

when [1] analysed the difference of approach between the two methods (91 crash simulations and 2 physical prototype crash tests), significant advantage of the virtual product development method over physical testing became apparent. The results of the cross reference is shown in Table 4

Development phase	Virtual prototype	Physical prototype
Design	Technical meeting. Less Than 0.5 days	Planning and piece part design. greater than 2 weeks
Build	Data preparation and meshing • small change: 0.5 days • Significant change : 1 week • Complete vehicle: 6 weeks	Design and Construction • Using existing model : 3 months, and $150000 per prototype • new model $>$ greater than 6 months and 600000 per prototype
Run	Crash simulation 1 day simulation	Physical crash 1 week including test preparations
Analysis	Post processing and analysis. 1 day	Data preparation and analysis. 1 to 3 weeks
Total time	2.5 days to 6.3 weeks	3 to 7 months
Total Cost	$5000	$ 300000

Table 4: Difference in time and cost between different methods of crash analysis according to [1]

6.2 Development of new vehicle without physical prototypes at company B

In the development of a new vehicle model and the platform for the new (now defunct) platform for the new series of vehicles at company B, the use of physical prototypes were reduced to only two. This was a forced decision based on hard pressure to reduce cost by reducing the number of prototypes and testing from the parent company. However mule vehicle of earlier models was used to test certain subsystems. [39]

Initially there were string negative reactions for this decision. The initial responce was that it would be a big risk and would significantly lower quality if physical testing was not performed [39]. Hence every product responsible personnel had to go through their tests and prototypes to replace them with virtual tests. Eventually every physical tests were replaced by a virtual test or with a lab test based on previous generation samples. A project was initiated to move from physical prototypes to virtual prototypes. Every test that did not have a virtual test method got a Road to Lab to Math, RLM, project.

The big challenges with these RLM projects were to translate different complex feelings, for example the feeling of closing a car door to measurable parameters from the simulation. In order to be able to translate the attributes based on feelings and driving performance, the need to have experienced employees with knowledge about what to looking for while testing prototype cars became paramount. The task was to break down important goals to measurable parameters. For example EURO NCAP rating requirements were broken down to acceleration levels for different components and sound levels had to be broken down to eigen mode frequencies [39].

The company which depended mostly on physical tests until now had an overwhelming number of test engineers when compared to simulation engineers. Thus moving towards virtual testing also meant a significant change in the organisational structure of the company. The central pillar of their product development process was physical tests with a mule, alpha, beta, gamma and validation tests accounting for five generations of physical prototypes.One big problem with the physical test series was that the results and changes from the alpha series were not tested in the beta series since the prototypes for the beta series had to be ordered long before the alpha series was finished. Since a prototype series takes six months it is very time demanding to go through the testing without being able to include the change made from the earlier series.

Hence moving over to virtual prototyping solved this issue. In fact moving from physical testing to virtual testing reduced the series testing phase from 6 months to 8 weeks. To avoid the problems with physical testing, where changes resulting from one test could not be implemented in the next phase due to supply lead time, the simulations were always performed on the latest geometry. This was done by using synchronisation points where the CAD geometry was frozen. This way all the simulation groups had the same geometric models to perform simulation on. When the simulation was done, they held a vehicle assessment meeting during 1-2 days where all the problems and issues were brought up. After the meeting the simulation engineer worked together with the designer to solve the problems until the next sync time point. the process is shown in Figure 9

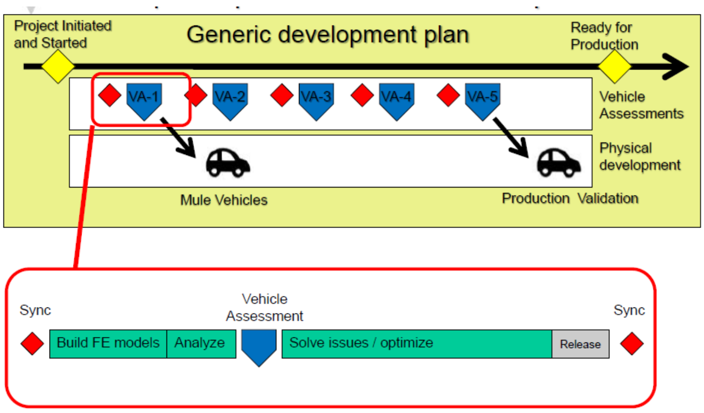

Figure 9: Synchronisation points and time plans

With this strategy, where the sync points formed the spine of the vehicle development project, assessment and analysis was streamlined. Also with lesser hardware prototypes, administration related to purchasing, logistics and testing were eliminated. This resulted in increased time for designers for design work rather than perform administrative tasks and paperwork related to sourcing and prototyping. Further automation in synchronisation of the models, meshing and assembly evaluation further helped reduce time in product development. Moving to virtual prototyping helped in automation of various processes which were manual previously as shown in Figure 10.

The big advantages of this virtual prototyping and virtual product development method, were the reduced overall cost for the development process which was slashed significantly, the shortened time-to-market for the launch,as the vehicle had the shortest development time for the company and the enhanced quality on the product. The developed vehicle received five stars in the EURO-NCAP

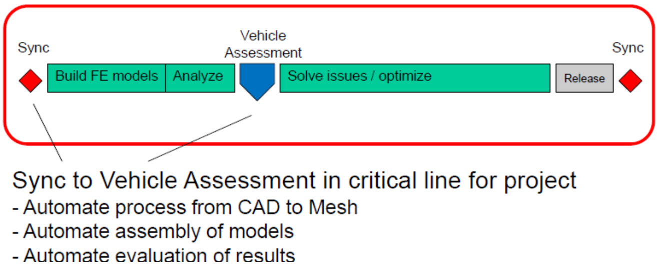

Figure 10: Automation possibilities within the process

safety test, even though it used less than 50% of the physical prototypes as used by the previous model. Another significant advantage was the reduction in late identification of problems usually caused when physical testing was the norm. This reduced stress among the designers and the validation series was most streamlined than in the previous projects

6.3 Zero Prototyping Trajectory in company C

The third company that took an approach towards virtual prototyping , did so for different reasons as compared to the first two. The aim of the company was to deliver high quality premium class vehicles, that combined, reduced carbon emissions along its lifecycle (both during operation and during development and manufacturing), while also being robust enough to be delivered all over the world. To achieve this twin objective they needed to design a vehicle that can run smoothly all over the world, hence be tested in conditions across the world while reducing emissions caused by physical testing. In order to reduce physical prototypes, the company used more Computer Aided Engineering, CAE, and increased the internal knowledge and developed confidence for CAE. This increased CAE usage also generated fast design iterations which lead to shorter product development cycles. increasing the detail CAE also helped them achieve a more robust vehicle.

To achieve a uniform production cycle for the present and future vehicles, a strategy using virtual prototyping was envisaged. The strategy , called 50-30-10, involves developing 50% more products , while reducing the time to market by

30% and reducing tooling changes caused by late design change to 10%. The only means to achieve this goal was through virtual prototyping [40].

Sustainability and reduction of waste has been another key driver behind the move towards virtual prototyping. While developing their latest model, using virtual prototyping, over 7000 crashes were performed and a million and half kilometers of driving were performed. This was the most expansive testing ever performed by the company [40]. But this testing was also their most environmentally friendly testing ever performed by the company. The virtual prototyping technique delivered significant reduction in cost and emissions.

By using virtual prototyping techniques to design the aerodynamics of the car , they were able to achieve excellent aerodynamic performance (C_d of 0.26) without requiring excessive styling compromises. As per the project manager [41], in a recent conference ,"The most significant cost savings when an automaker commits to virtual design comes from avoiding late changes and fixes.Late-discovery and fixes that prompt a one- or two-month delay of the market launch can cost an automaker hundreds of millions of dollars. Problems requiring tooling changes also cost several million dollars. (Improved) ability to design vehicles on cost and time will be enabled using virtual design."

The company intends to reduce physical prototyping to zero by 2020. According to the company, static clay models may cost between $ 500,000 to $1 million per unit and normally they may build two or three models for early testing. Also drivable prototypes may cost between $ 500,000 to $ 1 million per unit (depending on the carryover versus prototype-parts content) and in a normal new vehicle project one might build between 100-200 driving prototypes for physical tests. By performing all these tests using virtual prototype the company expects to develop new vehicles at a much reduced cost by 2020. They have already reduced physical hardware prototyping by 93 % for the most recent modular project compared to the previous one [41].

6.4 Analysis of the case studies

In the case of the three companies, the reason for the use of virtual product development techniques are varied. Company A was forced to look into simulations because physical testing was simply not economically feasible. Company B had severe cost and time pressure forcing it to reduce the number of physical prototypes, whereas Company C made a conscious decision to reduce the environmental impact of its product development process. In all three cases, the companies moved towards virtual product development and simulations as an alternative to physical testing.

All the cases prove that this move away from physical testing has been successful.The move towards virtual testing significantly reduced the need for physical testing , thus reducing the overall cost of the project. Physical prototypes consume much of the project budget and time in any NPD projects. This is especially true for automotive industries, where a physical prototype vehicle could cost anywhere between $500,000 and $1,000,000. The reason for this is because the vehicle is new, It cannot be built in the assembly as the previous model, hence it is a bespoke model where each part has to be manufactured individually and hence is quite expensive. According to Ford management, for designing a single component like intake manifold of an engine, a Ford engineer would create a model of an intake manifold engine part and wait about four months for a prototype at a cost of $ 500,000. Such practices add huge cost to NPD projects. Along with project cost, Virtual product development also saves time. Since manufacturing bespoke parts takes time. Certain individual components can have lead time from anywhere between 4 weeks and 6 months (in the case of complex engine and gearbox parts). If the design is wrong and the mistake is identified only in physical testing, then this could cause severe disruption to the start of production as the tooling also needs to be changed.

Apart from simple financial benefits of reducing physical prototypes, the assessment of the three companies provide us with insight into process changes and knowledge management gains that were brought about by this move that could have a long term beneficial effect for the companies.

- Virtual product development enhances the understanding of the physical properties of the designed product. By using simulations, the engineers achieves the opportunity to understand the strength and limitations of the design more easily. This is not really possible with physical testing as it is pass/fail method. Also as noted in company b , any change that is a result of a physical test is not retested for confirmation. The enhanced understanding creates an opportunity to achieve more optimum solutions for the product and this could be transferred to future products. This is especially true in the case of company A. Thus virtual product development enhances the knowledge base of the company.

- Virtual prototyping actually increases the number of scenarios that are tested and hence provides more valuable information for validation. Since simulations are not as time intensive as physical testing, more scenarios can be simulated in the same time as it takes to perform physical tests. Thus the product can be tested for more conditions and optimised than is possible with physical testing. This enables in delivering a more optimised and robust product already in the first time. Thus reducing the overall lifecycle cost of the product by reducing the running costs and maintenance cost of the product throughout its lifecycle.

- Decreased product development lead-time and increased resource efficiency can be achieved. For each simulation a designer performs by itself reduces the persons idle time while waiting for the physical prototype to be built and tested. This improves the overall resource efficiency of the company. This also reduces the development lead time in general for NPD projects.

- Virtual product development process increases the possibilities of project front loading and concurrent engineering. Simulations performed by engineers can be involved at an earlier stage in the development phase than regular testing. This enables to front load the project with testing on the concepts rather than the detailed design. Also since the testing is performed on different models for different purposes, parallel simulations can take place at the same time. For example a vehicle model can undergo aerodynamic testing and crash testing in the virtual plane simultaneously without much increase in the cost. But this is not true with physical testing, without building another prototype.

7 Integration of Virtual product development in stage gate model

As can be seen from the above case studies, it pays to improve organisational knowledge in virtual product development techniques and using it to front load projects. To use simulation in NPD projects , the stage gate approach has to be modified. In a normal stage gate model in NPD , there are normally six stages and gates. The normal development process can be broken down as shown in Figure 11

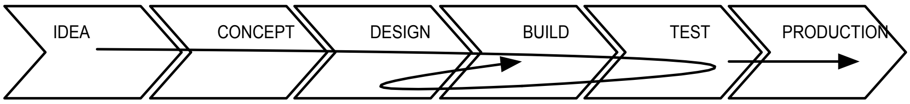

Figure 11: Normal Product development process using stage gate model

In the normal stage gate process, a physical prototype is built. Then the requirements are tested with this prototype. Any kinks or changes needed that are discovered during this testing is then designed and built , either into the prototype or by building a new prototype. More complex and different the product to the present products, the longer this cycle is and more possible that this project will be shelved.

But in the new stage gate process a virtual prototype is designed during the concept phase itself as in Figure 12. The advantage with the virtual prototyping is during concept phase various concepts can be tested with different level of details to test their efficacy. this is not really possible with physical prototypes where the complete detail needs to be modeled. This allows more concepts to be tested, at a faster and cheaper rate.

By developing the virtual prototype already in the idea generation and concept process, we can perform idea assessment, market analysis, product specification in further detail than in later stage prototyping. Also any change that is already implemented here reduces the cost of change significantly.

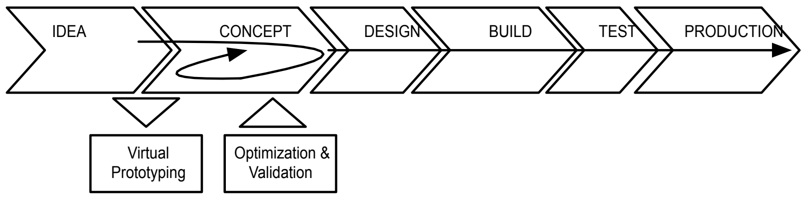

Figure 12: Virtual Product development process using stage gate model

7.1 The process Map

Simulation driven virtual product development will be used in the idea generation and concept phase of the product development process. The problems are front loaded from previous projects and product developments. So the first stage of any product development concept phase shall be customer inputs and previous project reports. Several studies [42] have supported the importance of such systematic learning from knowledge gained through prior projects. In case of virtual product development this knowledge know how would be through a library of product, environment and idea models developed for different simulation purposes.

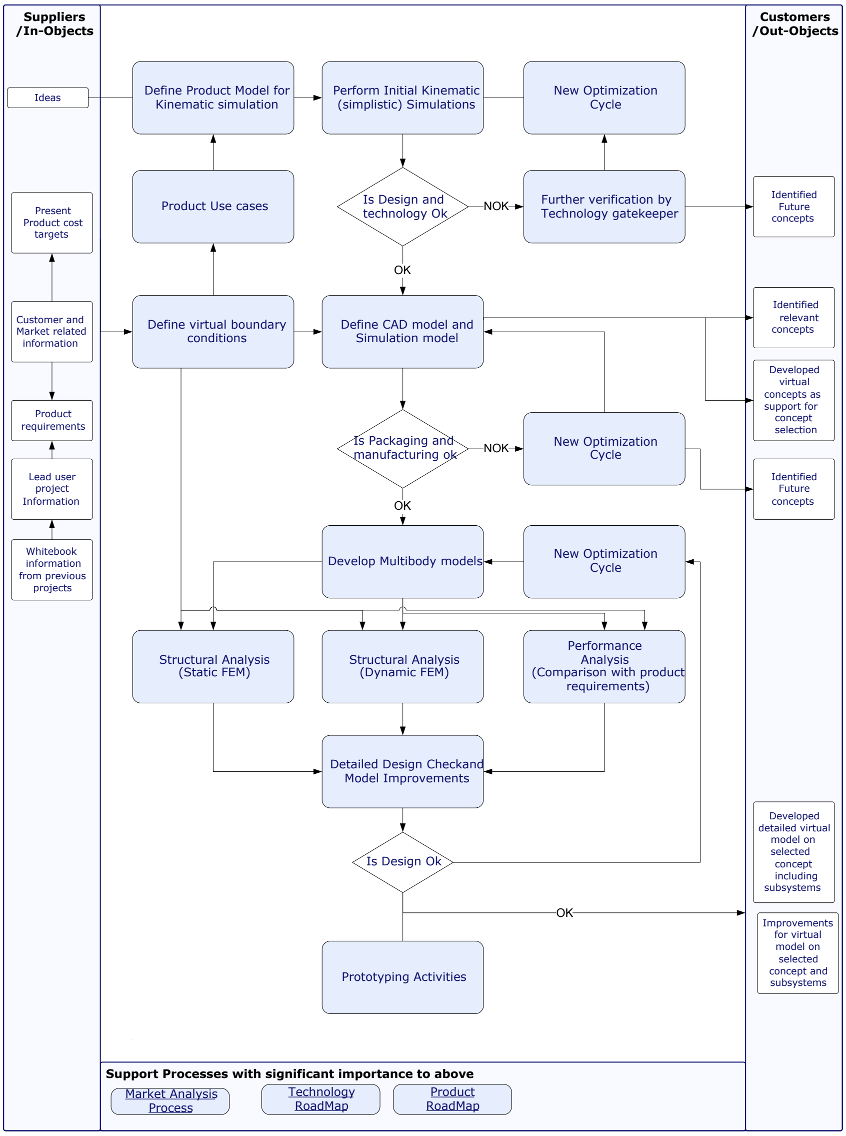

Figure 13: Process map for simulation driven design

7.1.1 Stage A

For any project to be developed from an idea, The idea is initially screened for relevance with the help of a technology gatekeeper and a relationship promoter [43], for relevance with the technology and product roadmaps. Then using the models and know how from previous projects, customer information and needs , the virtual boundary conditions that the product needs to satisfy are developed [44]. The virtual boundary conditions are the requirements that the product needs to satisfy, they can be customer specifications, legal requirements, technological challenges e.t.c. The boundary conditions are necessary for evaluation of a product through objective means. Once the boundary conditions have been defined , they are used for development of product use cases . A use case captures the the requirement on a system about its behavior [45]. The use case describes the system's behavior under various conditions as it responds to a requirement from one the stakeholder. The stakeholder initiates an interaction with the system to accomplish some goal. The system responds, protecting the interests of all the stakeholders. Different sequences of behavior, or scenarios, can unfold, depending on the particular requests made and conditions surrounding the requests. The use case collects together those different scenarios.

In parallel a kinematic or lumped paramter model of the said product is developed from the idea. The kinematic model can be 1 D or 3D in nature depending on type of simulations. Kinematics is the geometry of pure motion - motion considered abstractly. These are the simplest models that can be developed and is best for initial evaluation of models. In essence these models are algebraic models, where the elements are considered to be rigid and are lumped into point masses connected to each other using springs and dampers (In the case of mechanical elements). This simplification reduces the system to a finite dimension. That is the partial differential equations (PDEs) of the continuous time that govern the mechanical products in geometric modeling (CAD and FEM) are converted into ordinary differential equations (ODEs) with a finite number of parameters [46]. Besides the simplicity of the models, these models have other significant advantages. These models are exact representation of the system states. Thus they provide insights into the characteristic behaviour of a system. The simplicity of the models means they can often be solved analytically. They are adequate even if only few data are available. These models transmit enough information to evaluate the advantages of the system product by the idea and the Technology readiness level (TRL) [47] of the said product. Also these models set requirements for the mechanical sub-components of the product and the control, electrical and electronic requirements for the the product. Again by being mathematical (algebraic) models, they can be used in parallel by various teams like mechanical, electrical and control teams. This enables concurrent engineering, which is not really possible with geometric models like CAD models from the start.

The models are then simulated using the use cases and the results are analysed. These simulations are fairly fast in the case of kinematic models. These simulations can be performed in hours rather than days. Most of the requirements, their advantages and disadvantages can be already evaluated in this phase. This reduces time for physical testing, or even with complicated multibody models, in later stages.The promoters then verify the results to see if the product design matches requirements and the concept can be developed further. If the product design is not considered to be appropriate, then the technology gatekeeper evaluates the product model to analyse its advantages over current products and also compares it with the technology and product road map to identify whether the model needs further evaluation or stored for future references.

Then a CAD model is developed for the product. The reason for developing a CAD model in automotive industry apart from doing finite element simulations is to verify the packaging needs and visualisation of the product. In automotive industry especially it is important for a product to look desirable. Hence this is an important step. Once the CAD model satisfies the packaging and visualisation needs it can be said that the product has passed the concept stage. The models used are called stage A models. Next approach is to perform detailed design for the chosen concept and product.

7.1.2 Stage B

In the detailed design stage the virtual product undergoes a multibody modeling approach. Multibody systems (MBS) are technical systems (mathematical models) consisting of different rigid or elastic bodies that are interconnected. The connections may be modeled with classical force elements like spring-dampers or realised by kinematical constraints. Multibody simulation programs are well established and can be found in a variety of industrial sectors, for example in aeronautical engineering or in the automobile industry. In consideration of initial and boundary values, a multibody simulation provides the transient motion of the bodies as well as the forces and moments acting in the connections between bodies. The study of MBS is the analysis of how mechanism systems move under the influence of forces, also known as forward dynamics.

Here the developed CAD model is the input to the design of the multibody model. The multibody model is then subjected to a range of simulations such as finite element analysis (FEM) and performance analysis. FEM allows detailed visualization of where structures bend or twist, and indicates the distribution of stresses and displacements. This can be used to analyse and optimise the Model with respect to fatigue and stress and reduce weight as much as possible. Performance and physics simulation are performed to analyse the performance requirements of the product. Physics simulations are simulations that use mathematical models and use numerical techniques to run the model on the computer. They can be used to solve complex problems and are used to validate complex requirements that simple kinematics models cannot solve.

The models developed are called virtual prototypes. The simulations are screened and the virtual prototype of the product is used for requirement verification and the products and concept analysis. The analysis is performed by the different promoters in the organisation. If the requirements are satisfied then the product can be said to have passed the gate else the model is sent to a new optimisation cycle to achieve the necessary results.

The advantage of the virtual prototypes is that more optimisation cycles can be performed at lesser cost and time than with physical prototypes. When the Virtual prototypes satisfy the requirements then it can be considered that the product has passed the design stage . These models are called stage B models or Detailed development models.

7.1.3 Stage C

Verification and validation are independent procedures that are used together for checking that a product, service, or system meets requirements and specifications and that it fulfills its intended purpose [48].These are critical components of a quality management system such as ISO 9000.

In a normal NPD process, this is the stage where the physical prototype is built and requirements are started to be tested. This provides a significant headache for radical products. As the manufacturing of the product and toolings required might not be up to the requested level. This might cause huge variance in the testing results and might show adverse effects. Also it is too late to make significant changes to the product as the degree of freedom to change is very limited. But one of the major issues , especially in automotive industry, where the product life time runs in years, is that the testing will take a significant amount of time. This is for the simple reason due to the lifetime of the product needs to be tested in a physical manner. Hence for a product with a lifetime of 20 years, the verification testing (Accelerated lifetime tests) could run for upto 6 months [49].

But in case of the new process these tests are already performed on the virtual prototypes. With the use of modern processors and computers these tests can be performed in weeks rather than months. This is a significant reduction in testing time. Also since the verification is already performed in concept and detailed design phase the opportunity for design changes, if needed, is much higher. The main idea of the verification and tooling stage in the new process is to validate the virtual prototype. This is less intensive and more productive than normal physical testing [16, 50, 51].

Also since the product is already optimised through virtual prototyping, it is easier to start the tooling process as the product already has a final design. Thus during design of tooling and production process no surrogation need to be factored in. This reduces the cost of tooling process and also reduces the total cost of the product design and development.

7.2 An hypothetical case study

To understand the principles of the process map and how to implement it in a real NPD project, a case study format is employed. In this case study the process map will be used in a program to develop a powertrain for an electric vehicle. For this study it is assumed that before the start of the project a lead user project was performed to identify the basic requirements of the electric vehicle and these requirements are provided to the powertrain team for choosing the appropriate powertrain.

- The vehicle shall weigh maximum of 1500 kg.The desirable weight is 1000 kg
- The vehicle shall have a range of at least 150 km. The desirable range is 200 km.
- The vehicle shall cost about $15000.
- The vehicle shall have a top speed of atleast 120 km. The desirable top speed is 150 km.
- The vehicle shall be an hatchback that is able to fit a family of 4.
- The vehicle shall have a wheelbase of 2.6 m.
- The vehicle shall be able to operate in all conditions that a normal vehicle can operate.
- The vehicle shall accelerate from 0 to 60 km/hr in 7 seconds. 5 seconds is desirable.
- Shall achieve EURO NCAP 5 star safety rating.

The above requirements even though are well defined on the vehicle level, it still has too many variables that are undefined with respect to the powertrain and are open to many ways of satisfying the requirements. This is where simulation can speed up the process of concept evaluation and detailed design. Even before the start the many questions needs to be answered, a few of which are provided below .

- Should the vehicle be 2 wheel drive or 4 wheel drive vehicle? If 2 wheel drive, should it be front wheel driven or rear wheel driven?
- Should the vehicle be driven by a single motor, 2 motors (Axle motors) or 4 motors (wheel motors)?
- Should there be a gearing between the motor and wheel? if so what is the gear ratio?
- Should There be only a single gear or should there be a gear shift?
- What should be the power of the motor in different configurations?
- What should be the energy capacity of the energy storage system?
- What type of energy storage system should be used?
- Should there be a range extender?

As can be understood from the above questions, there can be anywhere between 10 to 1000 concepts that may or may not satisfy the given requirements. In a normal NPD project, most of the questions will be answered using intuitions and previous experiences. This would work well with a normal incremental product development where the base product is well tested and its fundamentals are well understood within the company. But in case of radical innovation, these stated intuition could result in quite poor results. A good example of that would be the Tesla model S [52]. In a normal fuel driven car, a two wheel drive is more fuel efficient and cheaper than a 4 wheel drive system, because the mechanical system needed to connect all 4 wheels to the gearbox and engine is quite heavy, difficult to assemble and added quite a significant amount of power loss (hence, more thirsty engine) to the power train. Thus Tesla chose a 2 wheel drive system with a single motor for the initial model S. This was a sound decision based on intuition. But the problem is and electric car does not need the same mechanical system to be converted to a 4 wheel drive system. Also having two motors meant that the motors could be smaller and hence cheaper on the long run accounting for economies of scale. Also this enabled better energy recuperation during braking. Thus when Autocar magazine tested the model S P85 (2 wheel drive) with P85D (4 wheel drive) on similar conditions the 4 wheel drive system trumped the 2 wheel drive system in both energy efficiency and driving range, even though the 4 wheel drive is marketed as a sportier car with worse energy efficiency. To identify such issues, it is important to test all possible concepts to identify such issues. Using physical testing would have meant building 100 different concept vehicles at a huge cost. That is one of the reasons, many new products concepts tend to be sub optimal lowest common denominator products are chosen , with an air of it has always been done this way mentality. In the new method using virtual product development process this problem can be eliminated.

7.2.1 Stage A

The first task in the above process is to create the boundary conditions and product use cases from the vehicle requirements. In this case since the requirements of the vehicle is quite specific, it is easy to develop the boundary conditions and use cases. Boundary conditions are toughest scenarios and worst surrounding conditions where the requirements need to be satisfied. These might be the range requirements in the worst environmental conditions and acceleration requirements under the heaviest vehicle configuration for the power train. These boundary conditions must initially atleast be physically recreatable, so that once a physical prototype is built, the physical prototype can be tested in similar situations so as to validate the virtual product model. Hence based on the chosen boundary conditions, the use cases were the boundary conditions can be tested is developed. In this case the use cases might be the acceleration of the car for various gross weight under various road conditions. This use case will relate to the acceleration requirements.

The next step is to create the appropriate kinematic model of the parent product (the vehicle), that can be used to identify the product and sub product requirements. In this case a lumped parameter kinematic model of the vehicle is enough. A lumped parameter model is a simplified description of the behaviour of physical systems into a topological format which contains discrete entities that approximate the behaviour of the system with respect to certain assumptions. in the mechanical domain, the assumption is that the vehicle is rigid whose interaction with the road is based on kinematic joints which represent the wheel and suspension. For different concepts ,different types of these kinematic models might be required. For verifying our concepts of single motor, axle motors and wheel motors, there would be a need three different types of the vehicle kinematic models. They are quarter car model , half car model and the whole car models as described in [53]. These are well defined models in the literature and have been shown to correlate well with reality in most cases. But these models are also very simple (can be generated in 30 minutes) and can be considered to be industry standard in the scientific and research fields.

By combining the product use cases with the concept models, the requirements for various sub components within the powertrain, like electric motor, energy storage system e.t.c , can be obtained. These requirements need to be guessed based on experience, or obtained through trial and error method using physical prototypes. Then these requirements are used to develop the different concept models for these subcomponents. Once this process is done, The designers, engineers and the project managers will have a much better idea of different concepts and can further optimise different concepts. This task shall take few weeks, depending on the computing power available for the project. Normally the complete set of use cases for the complete set of concepts can be run overnight and then the concepts and results can be analysed the next day. This way the ideal concepts can be chosen objectively. there might be some concepts that might not satisfy certain boundary conditions (or requirements) but might provide excellent results for other use cases. It is the responsibility of the technology gatekeeper to make sure this concept is not lost and the knowledge is transferred for future purposes. This stage is normally a concept elimination stage, not a concept selection stage. Hence all concepts that pass the requirements are sent to the next phase of design. There need not be a single overall concept chosen when the gate arrives. This is to avoid choosing the lowest common denominator concept.

At this point the CAD models for the chosen concepts are developed. In most cases the CAD models can be developed in parallel to the kinematic models as these are parallel events. The resources need for both the tasks are dissimilar and hence will be handled by different groups within the project. But in this case , it is better to wait until subcomponent requirements for different concepts have been identified, as the change in requirements would mean changing models. Using the CAD models the packaging and geometry requirements can be analysed. Using this information some concepts can be eliminated.

7.2.2 stage B

This stage is where the CAD models of the concept becomes the basis of the analysis. The CAD models are developed into various relavent multibody or FEM models as per required analysis. In these models the performance of the concepts for the boundary conditions can be revisited. this is called CAE (Computer Aided Engineering). This includes simulation, validation, and optimization of products using the CAD models.

For our analysis the various models that will be generated and analysed shall be

- Stress and dynamics analysis on components and assemblies using finite element analysis, to analyse the component durability during crash and fatigue life.
- Kinematics and dynamic analysis of mechanisms using multibody programs to analyse vehicle dynamics and performance with the chosen concepts and the respective component control systems.
- Acoustics analysis using FEA or a boundary element method , to analyse the interior and exterior noise generation.

- Thermal and fluid analysis using computational fluid dynamics, for cooling and losses calculation within the power train.

In this stage only the most important boundary conditions and the product use cases need be tested. Also requirements that cannot be tested in Stage A are tested here. These simulations generally take a day or two to develop for each concept and about a week or 2 to run. Hence this stage is more time consuming than stage A. Again like in stage A the review process is used to objectively choose the concepts. By the end of this stage there shall be either one or two concepts (or may be a few more, depending on the budget and lead time) left that can be sent for detailed build and physical prototyping. Hence the screening method used in this stage is concept selection rather than concept elimination. Using a concept selection matrix process is recommended here.

7.2.3 Stage C

This is the stage where the physical build and prototyping can take place. Simulations can also be used here to develop the production process and the production tooling for the chosen concepts if only one concept is selected. During the physical testing it is important to replicate only some critical boundary conditions so as to verify the models and not the product itself. Thus the number of physical prototypes built can be reduced to the bare minimum. If stage A and stage B were performed with the best of intentions there would not need to make any late changes in the design and one physical prototype is ideally enough for final verification and validation of the new product.

Thus an electric car is developed in less than three generations of physical prototype using this method which would be better than those stated as best in class by Aberdeen group [37].

8 Organisational pre-requisites for success of the virtual product development process

For successful completion of a product development process using virtual product development process various pre-requisites must be met. The above process is just that, a process. For the process to succeed the organistaion and culture should change accordingly. Various studies [33, 35, 39, 54, 55, 56] have identified critical organisational culture that are seen as a prerequisite for a successful completion of a product development.

8.1 Management involvement and incentivisation

It is of utmost importance that the management is completely involved in the virtual product development process. It is the management teams that play the role of promoters and technology gatekeepers. Hence their involvement is necessary. Incentives might be needed to emphasise of the importance of the simulations and virtual prototyping. They must have the will to overcome organisational resistance to reduction in physical prototyping. This enables an increased usage of simulations among the research and development organization. Therefore, this process should be supported by incentives that shall accentuate the economical , environmental and lead time reducing objectives of the process.

8.2 Target reduction in number of physical prototypes

To move from physical prototyping to virtual prototyping requires a significant change in the organisational structure and culture. Ant change will have significant resistance. To achieve successful transformation requires an establishment of sense of urgency[57]. This can be achieved by setting firm targets and deadlines that are achievable and can act as a quick win. A strategic vision from the management team would motivate employees to understand the importance of the amount of prototypes used and the engineers can more easily prioritize simulations. A reasonable target is to reduce the development timeline for a major product by one year and reducing the total number of physical prototypes that can be built by one.

8.3 Develop interaction between concurrent teams

Virtual product development enables concurrent engineering practices. This requires frequent interaction between the teams in order to always have accurate models for the simulation and continuously compare simulation results to improve the knowledge on the product. There are various PLM softwares in the market that try to automate this process and reduce human error. But the information transfer between designers and analysts are of primary importance as it reduces optimisation cycle and also improves the knowledge base of the company. Hence the automation of this process is necessarily not the best alternative. It also require a clear interaction in the process between simulation groups and physical testing so they can have the use of each other's results and experience as described above. By studying simulations, the engineer gets the opportunity to understand the strength and limitations of the design. The enhanced understanding creates an opportunity to achieve more optimum solutions. It will probably also reduce the communication barriers and enhance the knowledge transfer between different groups within the product development process.

8.4 Clear understanding that this is a front-loaded development process

The whole idea of the new process is to front load the new product development process so as to reduce the time to market of the product. This needs to be understood by the project managers. Resource allocation to the project needs to suit this situation and appropriate resources needs to be allocated as early as possible in the process for any new product development project following the new process map. The earlier the faults are identified the faster they can be solved.

8.5 Obtain necessary resources within physical testing and simulation

Virtual Product Development requires an in depth knowledge and experience for, both the virtual and physical testing. This is necessary so as to be able to develop new advanced methods that can be used to evaluate complex functions that the product needs to perform. The new methods for virtual testing should develop from already developed experience and knowledge of physical testing. Physical testing shall be used primarily for the validation of virtual testing and simulation methods. Hence it is necessary for the management to make sure that the entity performing physical testing does not see virtual testing as its competitor, but as a gradual progression.

8.6 Trust on virtual prototypes

Trust is a significant success factor for implementation of change. Without trust every virtual prototype would require a physical prototype for verification. Without trust each project needs to overcome the organisational inertia caused by the doubt and unnecessary physical testing will occur in order to test requirements, rather than checking the models. Also over reliance on physical testing has significant downsides. There are various factors that affect failure of a product. the more complex the product higher the variance. thus a failure of a product in one physical testing situation does not mean failure in all scenarios and vice versa. Therefore, a single physical test should not have higher importance than simulation results, especially simulations with several iterations behind it, unless it can be proven that the product is incorrectly modeled. Virtual product development requires a organizational will and trust in simulation results. This courage is required both in management, but also among engineers involved in the product development process. It is human nature to distrust new processes. Hence this distrust must not be let to override any anomalous simulation results which might not be obvious in the subjective view of the engineer. Virtual prototyping achieves significant time advantage. Since the time required for each simulation loop is reduced from approximately two weeks to a couple of hours it is possible to do more simulations. Hence it is easier to perform varied simulation to build trust in the simulations.

8.7 Invest in better simulation tools and virtual prototyping methods

Simulation tools keep on improving in leaps and bounds. hence it is necessary for the company to focus on developing internal competence in the latest simulation methods to remain ahead of the curve. Continuous development in simulation tools and methods is needed to reduce the need for physical testing to zero. RLM projects can significantly improve the internal company knowledge in the simulation methods. Beyond state of the art tools that could significantly reduce simulation time needs to also be researched upon. Investment on developing the general knowledge of the company in virtual prototyping methods needs to be prioritised. KPI's for employees should be set that would emphasise such learnings.

9 Conclusion

The product development process from ideas to production contains lots of stages. The stage gate approach is a common approach to simplify and make this process as lean as possible. But a normal product development process has a lot of pitfalls, chief among them is that the product is tested at the very end of a process and hence any changes identified in this is very expensive and time consuming. Thus this inturn sets a conservative approach to new product development.

In this work a method using virtual product development process is developed so as to ride through this issue and front load the product testing to earlier phases. this increase the chances to make changes to the product at a cheaper cost and lesser time. This process envisions methods that can achieve results by reducing the product development time in automotive industries by atleast a third. Also this process envisions a much greater intake of radical ideas as the product risk is significantly reduced by frotloading of the process and availablity of a virtual model form the beginning.

The organisational pre-requisites that shall enable this process to succeed are also mentioned. The success of the virtual product development process depends on the organisations will to overcome teething trust issues with simulations. This is necessary for the success of the process.

10 Further Studies

During the study, other areas whose further research would be significantly improve the presented study were identified. The areas presented in this chapter are beyond the field of the study but would add significant knowledge and improvement to virtual product development based New product development. Two fields of research that have not been included in this steady are big data and augmented and virtual reality. Integrating those methods into virtual product development will provide a significant improvement to the process and considerably reduce the project times.

10.1 Big data and new product development

As per SAS white paper [58], Big data is a relative term describing a situation where the volume, velocity and variety of data exceed an organization's storage or compute capacity for accurate and timely decision making. Successful decision-making will increasingly be driven by analytics-generated insights. And the more accurate and timely these are, the better chance the organisation has a chance to anticipate the future and profit from it. The keys to effective data-driven decision-making, which is a corner stone of virtual product development, is to identify relevant data and the ability to these data from several sources to gain a more comprehensive view and a new insight.

During the product development process in the manufacturing industry, several types of data are generated, often in large volumes, which may be processed and then used as a knowledge toolbox or insight information for the product development teams. Data such as customer insights , competitive intelligence and product performance data, etc. can prove to be of great value for the overall success of the product.

Despite the volume of research available on knowledge management, little work has been carried out in the area of integration of knowledge from the above mentioned data elements, into the product development process. Hence, managing this knowledge sourced from various data sources and using it in the product development process, offers great potential for improving process efficiencies.

For example in the hypothetical case study, customer feedbacks, test engineer feedbacks and workshop and maintainance feedbacks from previous generations of products could be used for setting boundary conditions and product use cases. They might also provide information for idea generation.

10.2 Virtual and augmented reality

Virtual and augmented reality provide additional information to present real world scene. Virtual Reality (VR) is a system of totally immersive environment where the sensors are under control of system controlling the environment and needs a mechanism to feed virtual world to the user. Augmented reality (AR) is where the system augments the real world scene with virtual elements. User maintains a sense of presence in real world at all times. The system needs a mechanism to combine virtual and real worlds. Milgram coined the term 'Augmented Virtuality' to identify systems which are mostly synthetic with some real world imagery added such as texture mapping video onto virtual objects.

User interaction in product development process could tremendously benefit from VR and AR technologies. It could be used for communication between different concurrent teams, test engineers and designers or even designers and customers. Nowadays they are mostly used in marketing purposes more than in product development. But the potential for the use of VR and AR in product development is huge.

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