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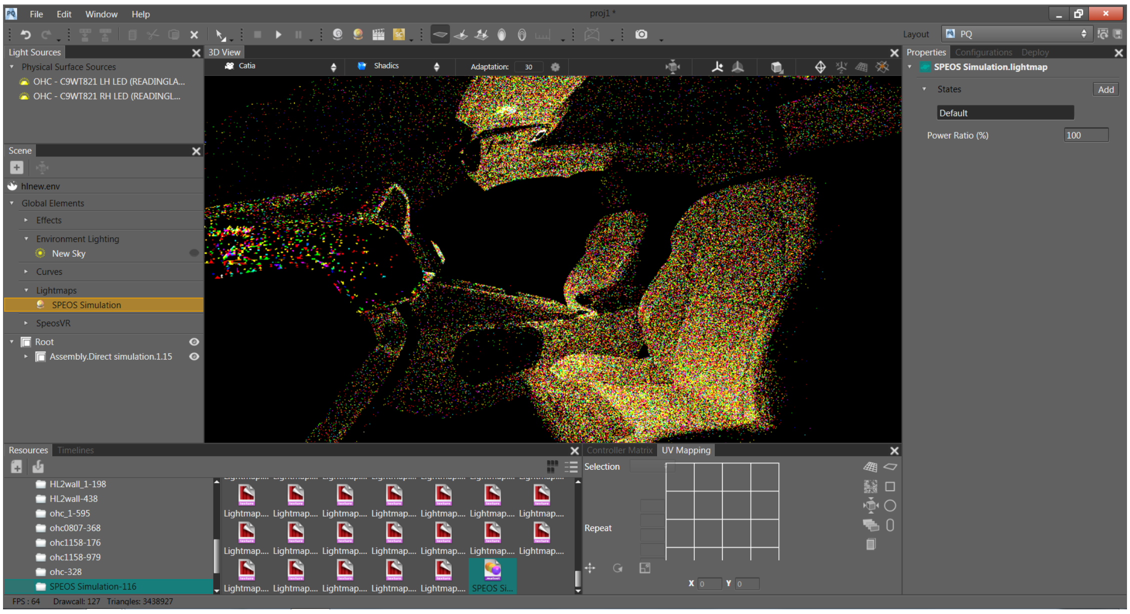

Virtual verification of illumination

Master's thesis in Product Development

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Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Master's thesis

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Dynamic behaviour of lights

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Master's Thesis
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Abstract

Illumination content in the cars is increasing all across the automotive industry to solve various customer problems, and also for aesthetic purposes. It is not only an aesthetically pleasing premium design feature but also a means of communication with the user. To stand out in the current competition, having an excellent illumination content with great execution is of utmost importance. This also means that the perceived quality of light by users should be appreciable. The high lead time and huge costs involved with physical prototypes demand a better way of working; therefore, working with virtual prototypes is necessary. With increasingly complex illumination content, and to find out issues earlier in the product development phase, virtual verification on the concepts is paramount, because this way might reduce the overall cost of product testing. This virtual verification would be more reliable if the car software that is coded for the illumination functionality can be included, i.e., logic verification, in the verification process.

The purpose of this thesis is to investigate a few software that can support the virtual verification of dynamic illumination. This thesis work also aims to identify a logic verification method that can be integrated into the virtual verification software and to draw a technology roadmap to implement the solution at Perceived Quality Illumination(PQI), Volvo Car Group(VCG). To address the problem of logic verification, the authors have investigated different logic verification methods. This thesis, therefore, investigates the contemporary methods of virtual verification at VCG with the intent of improving the current way of working.

The results consisted of the critical analysis of interviews, which led to requirement lists. It also consists of comparisons between different software and different logic verification methods based on experiments and data from interviews.

In conclusion, performing simulations and verifying the different requirements at the right stage of the product development phase helps to reduce the lead time of the project. The tool to be used for logic verification purposes is MIL up to DSM5, and SIL, after that, should be put into use. Because of SPEOS's high fidelity simulation results, it should continue to be in use. The software to be used for dynamic illumination verification with the ability to include SIL is Unity. A proposal for the virtual verification process across the timeline of the VPDS has been presented, considering the situation at VCG.

Keywords: virtual verification, lean methodology, perceived quality, product development, technology road map

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Ranga Raju Mohanapu & Dhivya Shanmugam, Gothenburg, December 2019

Contents

List of Abbreviations

AA	Approval Acceptance
CAD	Computer Aided Drawing
DSM	Design Surface Model
FDJ	Final Data Judgment
FSM	Functional state machine
GPU	Graphics Processing Unit
HIL	Hardware in Loop
HPC	High Performance Computing
MIL	Model in Loop
PC	Program confirmation
PD	Product Development
PQ	Perceived Quality
PQI	Perceived Quality Illumination
SIL	Software in Loop
VCG	Volvo Car Group
VP	Verification Prototype
VPDS	Volvo Product Development System

1 Introduction

In this chapter, a description of the company, and the background to the master thesis will be presented. The following content also outlines problem description, establishes the aim of the work, presents the limitation of the work, and finally presents the research questions to be answered.

1.1 Volvo Car Group

Volvo Car Group(VCG) is a car manufacturer offering premium vehicles and was founded in 1927 in Gothenburg, Sweden. The brand is known for safety while providing the freedom to move in a safer, sustainable, and in a personal way, which is more distinct for the brand [1].

The VCG's cars design is influenced by modern Scandinavian design. The design naturally integrates nature through its choice of colour, materials, and illumination in the interior having more simplistic design yet premium and functional [2].

The illumination content has been increasing in the past years, adding value to the customer. Some of the illumination features are ambience interior light, active bending light, dipped beam, home safe light, and cornering light. The headlight has a distinctive shape like a hammer, also called Thor hammer headlight which marks uniqueness to the brand [3].

1.2 Perceived Quality Illumination department

The section Craftsmanship within the Volvo Car Group is a part of Craftsmanship and Durability centre, which contains Perceived Quality Geometry & Appearance, Material, Surface Finish & Illumination and Solidity. The different attributes within Perceived Quality are presented in Figure 1.1.

The Perceived Quality Illumination (PQI) department defines requirements that should reflect customer needs. It also evaluates how a customer perceives the car and sets requirements on various light components in both the exterior and interior of the car, to provide a sophisticated experience for their customers. The requirements are set both for static and dynamic lights behaviour. The three important aspects around which the requirements set are:

1. Homogeneity of light properties on both the lit surfaces (the surface on the light source) and the distributed light, where the light hits the ground or other surfaces
2. Synchronization between different light sources
3. Harmony between the interior light sources and materials

The PQI validates the requirements by validating the light properties and functionality of its light components for which they are designed. This validation is done at the prototyping phase, where they are physically verified.

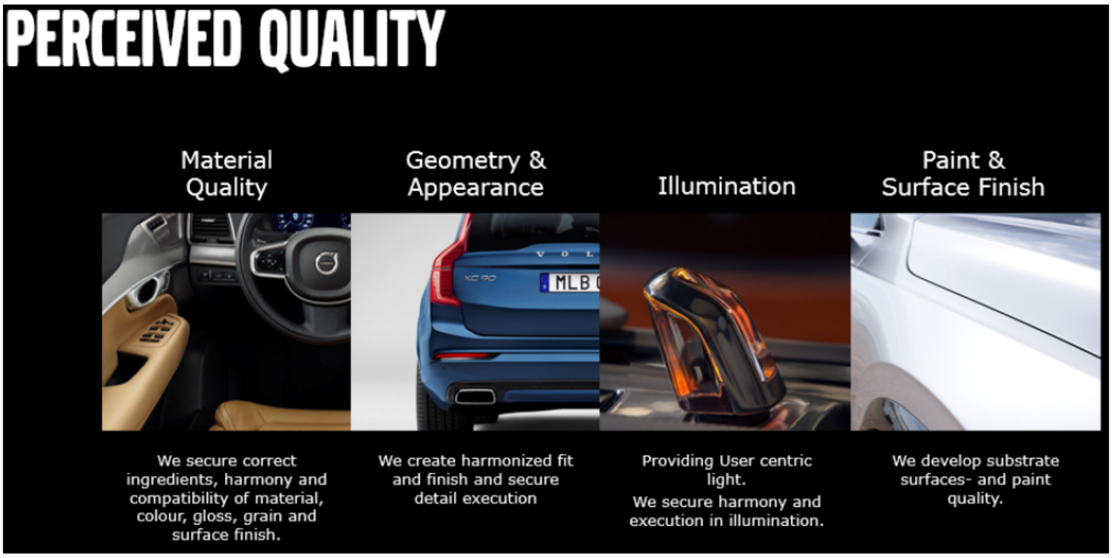


Figure 1.1: Perceived Quality

1.3 Background to Master Thesis

Illumination content in the cars is increasing all across the automotive industry to solve various customer problems and also for aesthetic purposes as shown in this Figure 1.2 where interiors of the car are lit up to see clearly. It is not only an aesthetically pleasing premium design feature but also a means of communication with the user. For example, in Figure 1.3 (look at the white arrow), car welcomes the users with its light content, with a carpet like light which aids the users to see the ground in dark environments. To stand out in the current competition, having an excellent illumination content, and better quality of light along with excellent execution is of utmost importance.

In a competitive environment where customers demands are dynamic, the development of new products and processes has become the centre point of any product development activity. Companies that make their products available faster in the market are the one who gains significant market share [4].

Figure 1.2: Lighting up interiors and Aesthetics

Figure 1.3: Carpet like lighting to welcome users

For the companies to reduce the lead times, they have to adapt to new technologies in order to stay relevant in the market and make profits [4] [5]. Technology is one of the crucial resources for an organization in order to lead the competition. Due to this fact, an organization should acquire or develop leading technologies and develop a strategy for managing technology [4]. In the efforts of making the products reach the market faster, the testing phase should also be expedited. To make sure all the engineering components are working as intended, rigorous testing is required on a complete car with all systems, both hardware and software in place. But very often, testing involves high costs. So, virtual verification of engineering systems has become an essential enabling factor in the new product development process for minimizing product time to market and carrying costs [6].

Valid, reliable, fast and cost-efficient methods to conduct virtual verification of design frameworks are essential to keep up with rising consumer expectations at optimal product development costs [7]. In the automotive industry, virtual verification of illumination systems is critical for designing the optical parts including but limited to lamps, indicator light, mirror light and dash light. Simulations are relatively cheaper and can be performed in a short time when compared to prototype-based evaluation methods [8].

Virtual prototypes are used because they cost less and save money in the long run [9]. Usage of virtual prototypes come with many advantages such as:

1. It can also be used in a virtual environment where any scenario like day/night conditions can be simulated. This increases the quality because numerous alternatives can be tested in quicker and inexpensive ways [9]
2. they are sustainable options by not wasting resources such as manual labour, tools and material [9]
3. It enables the identification of issues earlier in the product development phase. Therefore, more designs can be tested and verified; hence quick feedback can be given to the implementation teams (the teams which realize the concepts). Since the product development time is crucial it helps in reduction of time [9]

In a new car project, for the physical verification of PQI requirements, the team requires physical prototypes of light components which would roughly take ten weeks from the date of ordering. In the case of complete vehicle evaluation, it would roughly take 16 months from the stage when the engineering team begins the work. Due to design iterations and complex light behaviours, huge costs are involved in physical prototyping. This is because it takes time to build the physical prototypes and very often they are expensive and arrive late in a project. Therefore, there should be a superior way to verify illumination content of the car virtually, akin to how advanced dynamic finite element analysis software serves as a medium to simulate, visualize and verify the physical products digitally with regards to the structural analysis of the geometries to save costs [11].

Static simulations were conducted mostly to perform virtual verification of vehicle interior and exterior lighting [10]. There is also dynamic behaviour of illumination, which is ramping up or down of light intensity. Static simulations represent a simple model of the engineering system, and therefore real-time dynamic simulations are essential to product reliability and accurate output [10]. However, substantial transformation in the operational process, improved knowledge and skills, and more computational power are some requirements that are needed for the successful transition from static to dynamic simulations [12].

The organization's ability to adapt and implement in-house developed or acquired technologies will be dependent on its strategy for technology management [13]. These strategies must identify which technologies are essential for the company's technical capability and how this knowledge can be used to improve its products and processes [4]. The technology roadmaps of the company have the potential for supporting development to ensure that the company's current and future needs are synchronous with the strategy [14].

In this thesis project, the focus is on to find new digital tools and processes and to develop a technology roadmap to improve VCG's car testing methods via virtual verification. VCG has certain options to choose from and with this thesis project they hope to understand which path will likely pave their way into virtual verification of illumination.

1.4 Problem Description

In the current scenario, VCG uses software called *SPEOS* to verify the illumination virtually, but it has limitations. It is not very easy to test and validate dynamic illumination functionality with this software. Even though physical prototypes can be used to verify dynamic illumination functionality, it is expensive to rely on physical prototypes due to the considerable lead time and material costs. There is no way to verify the car software or logic that is coded for illumination functionality before the first physical prototype arrives. There are tools in the market which have the potential to fulfil the needs of PQI, which needs further investigation. Therefore problem description for the master thesis is then as follows:

How can we do virtual verification of dynamic behaviour of light which is accurate and can be done in earlier phases of product development and how to make a transition from the current way of working to virtual verification of dynamic illumination?

1.5 Aim

The thesis project aims to investigate a few software that can support the virtual verification of dynamic illumination. This thesis work also aims to identify a logic verification method that can be integrated to the virtual verification tool and to draw a technology roadmap to implement the solution at Perceived Quality Illumination(PQI), Volvo Car Group(VCG). This technology roadmap includes a timeline and the steps to be taken between the transitions from the current way of working to dynamic simulation and also proposes which tool to be used along the product development phase.

1.6 Limitations

The thesis work is limited to investigate only Ansys Optis products, i.e. *SPEOS* and *VRXperience* and *Unity*, as VCG has collaborations with these companies already. Throughout the thesis work, several issues will be discovered which are important to achieve the aim. These issues will not be solved. The work will not include developing solutions to optimize the process with regards to working with simulating tools or developing the tools with required computational capabilities for the simulation environment. The work will not consider how other automotive companies are conducting their virtual simulations. The thesis research lasts 5.5 months of 40 hours per week. The financial resources are limited to what the VCG and the university are willing to sponsor, so there is no specified money allotted for this thesis work.

1.7 Research Questions

- Which kind of tool whether visualization tool or simulation tool should be used at each stage of the product development process?
  Simulation is approximated representation of reality, and this requires tremendous computational resources. Based on the available resources, this question will answer depending on the situation which kind of tool will be useful. This question will also highlight the logic verification methods that could be used.

- Which properties of static simulation tool are significant, to be present in the dynamic simulation tool?
  The static simulation tools offer only a few features, but they are important, and reliable for virtual verification of illumination. This question will probe if static simulations are important in the near future, and it helps in guiding the creation of the requirement list for the dynamic simulation tool.

- What are the risks involved in the transition from static simulation tool to dynamic simulation tool?
  By investigating this question, VCG hopes to understand if there are any issues with dynamic illumination simulation tools. If there are any, then what are they. Since static simulation software is highly reliable, can dynamic simulation have the same standards as the former?

- Which other stakeholders apart from Perceived Quality Illumination will be benefiting from the solution?
  With this question, VCG can evaluate if only PQI is the only stakeholder or are there any other departments in VCG that can benefit from thesis results and conclusions. From the economic aspect, it is in the best interest of VCG, that more departments use the same tool for their purposes.

2

Theory

In this chapter, the theory that is necessary to be familiar with when reading this thesis is outlined. It assists the reader in understanding the content, and this is where some of the information in the thesis work derives from.

2.1 Illumination terms

The illumination terms required to understand the master thesis report have been described under this section.

Colour temperature - Colour temperature is the temperature measured by a visible light-emitting body, and it is denoted in kelvin. The colour temperature is usually represented as cold or warm. The colour temperature is dependent on the metal and the degree to which the metal is heated [15].

Colour Rendering Index (CRI) - CRI is the numerical value representing the actual or natural colour of the object by an artificial light source. The numerical value varies from 0 to 100. 100 denotes high CRI, and 0 denotes low CRI as shown in this figure 2.1 [16].

Figure 2.1: CRI [16]

Intensity - The quantity or strength of light that a light source radiates in a particular direction which is also referred to as luminous intensity [17].

Light leakage - Light leakage is the escaping or leaking of light from defects or holes in the light component or surrounding body where there is a deviation of light appeared from the expected light appearance [18].

Glare - Glare is a visual perception and sensation caused by excess levels of brightness. Glare causes difficulty to human beings in seeing due to excess levels of bright artificial light. An example of bright artificial light is the vehicle's headlights in the night [19].

Light intensity homogeneity - The uniformity in the intensity of light emitted by a light source [20].

Colour homogeneity - The uniform colour spread of the light source with even colour temperature on the illuminated surface. The colour is homogeneous if the values measured are contained within the elliptical surfaces as shown in the Figure 2.2, according to standards defined by the International Commission on Illumination (CIE) 1931 colour space [21].

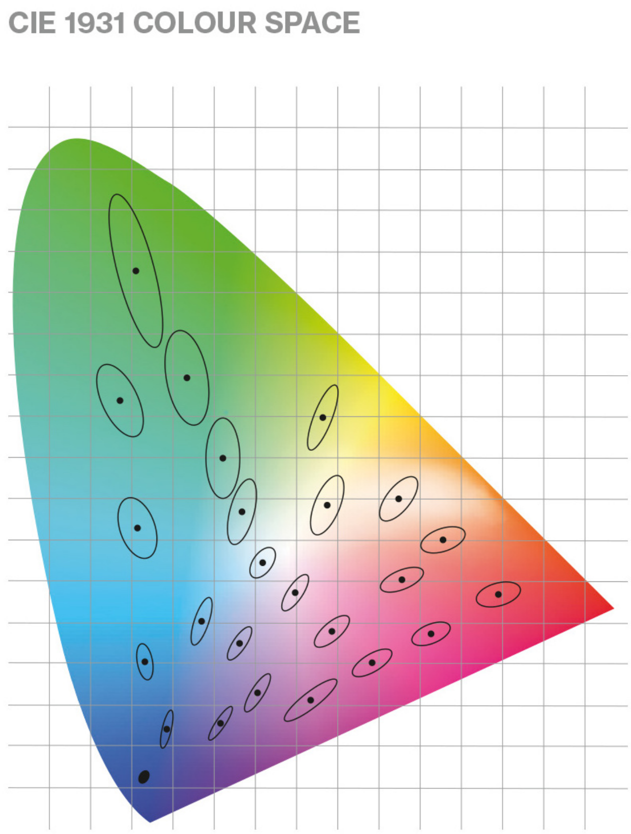


Figure 2.2: CIE 1931 colour space [21]

Synchronisation - Synchronisation is the coordination of the different light sources in terms of intensity, ramping effect, and timing.

Flicker - Flicker is the fluctuation in the intensity and brightness of a light. It is commonly caused due to voltage fluctuations or other external devices [22].

Optical System - Optical systems refers to the combination of elements such as lenses, mirrors, light sources and prisms that add up to make one whole optical part such as vehicle's headlight [23].

Photometric Analysis - Photometry is the science of the measurement of light, in terms of its perceived brightness to the human eye [24].

Human Eye Adaptation - Adaptation of the human eye refers to the capability of the retina of the eye to various luminous intensities of light [25].

Ramping effect - Ramping effect is the change in the intensity of light in several steps. The degree of change in intensity can be an incremental effect or decremental effect.

2.2 Verification terms

The verification terms that are required to understand the master thesis report have been described under this section.

Simulation - In product development, simulation is the process of building and testing the real-life product or process virtually in a user-controlled environment. The results of the simulation model will be used to analyse the performance of the product or process virtually [26].

Visualization - The high fidelity simulation results are numbers, and they need to be presented visually in a way for a human to understand. These numbers are represented into visual terms by use of computer graphics [27].

Static simulation - The simulation of light where light properties such as intensity and colour are not changing with time, i.e. static. By static simulation of lights, PQI department of VCG means that the simulation is executed for lights that are not in motion.

Dynamic simulation - The simulation of light where light properties such as intensity and colour are changing with time and hence dynamic behaviour is exhibited.

2.3 Other common terms

Perceived Quality (PQ) - Perceived Quality is the perception of the customer on the quality of aspects like geometry, performance, material, design and illumination [28].

Continuous Integration - Continuous integration refers to the incorporation of small changes to the system in a frequent manner. The system after each minor change will be tested to see if the change has broken down the system [29].

Driving Simulator - The driving simulator is a simulation technique which is used to monitor the driver's attention and behaviour to any changes made to the interior or exterior of the vehicle [30].

Virtual Reality - Virtual Reality refers to the use of computers in creating a simulation environment. Unlike the traditional graphical user interface, Virtual Reality provides the users with a feel of real 3D world experience [31].

Augmented Reality - Augmented Reality refers to the integration of virtual elements for the enhancement of the user's perception of the real world while maintaining the experience given to the user as real as possible [31].

Graphics Processing Unit - A graphics processing unit is a chip or electronic circuit which is used mainly to control and enhance the performance of videos and graphics. A graphics processing unit can render images at a faster pace due to parallel processing when compared to the central processing unit [32].

2.4 Background on Perceived Quality Illumination (PQI) Requirements

PQI has requirements on the following aspects:

1. HOMOGENEITY of light properties on both the lit surfaces (the surface on the light source) and the distributed light, where the light hits the ground or other surfaces
2. SYNCHRONIZATION between different light sources
3. HARMONY between the interior light sources and materials

PQI Requirements can be classified as Static light and Dynamic light requirements.

Some examples of PQI static light requirements are:

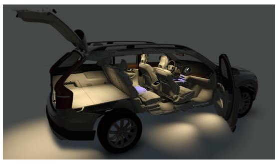
1. colour temperature (warm or cold), Figure 2.3a
2. light leakage in the light sources should not occur, Figure 2.3b
3. lights should not glare users, Figure 2.3c
4. homogeneity of light intensity in light components, Figure 2.3d
5. colour homogeneity on distributed light on the ground in this Figure 2.3e

(a) Colour Temperature

(b) Light Leakage

(c) Glare

(d) Homogeneity Intensity



(e) Colour Homogeneity

(f) Colour Rendering Index [49]

Figure 2.3: Requirements

6. high colour rendering index (CRI) which means light has same properties as natural light(sun or fire) which represents colour in a natural way, Figure 2.3f [49]

Some examples of dynamic requirements are:

1. synchronization of different lights (synchronization in terms of timing, i.e. delays between the light sources should not occur)
2. ramping effect of lights
3. flickering of lights should not occur

2.5 Contemporary process and timeline

In this section, the contemporary way of verification at PQI will be presented.

In a car new project, for the physical verification of PQI requirements, the PQI team needs prototypes of physical light components. This would roughly take about ten weeks to arrive from the date of ordering and to do a complete vehicle evaluation, a physical car with the hardware (i.e. Mechanical, Electronic and Electrical) and software is required. First such car is a Verification Prototype (VP) which would take approximately 16 months from Program Confirmation (PC) stage according to VPDS, see Figure 2.4 and practically there are delays.

Now every time a significant design change is made, for example, a change of new LED source or light guide, a new prototype of the light component should be ordered which has to be verified and approved by PQI. This means high costs are involved in prototyping.

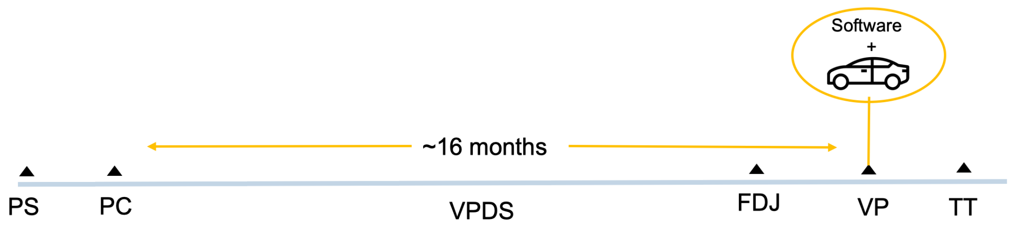


Figure 2.4: Volvo Product Development System Timeline

Often in the physical cars, there are deviations from the design intent due to various reasons such as manufacturing problems or unintended behaviours due to logic flaws in the software. Further, any design changes at later stages in the project would mean high costs or worst case; some cannot be fixed within the project time frame.

In the current scenario, the virtual verification of static lights is being done. This way of working is known as static verification method where light properties are not time-dependent, i.e. there are not changing as time progresses and simulation is known as static simulation.

The timeline of VPDS, see Figure 2.5, where the gate from PC to FDJ spans about 11 months, and to perform the light simulations, geometry models with appropriate materials and *SPEOS* light components are required. Based on this data, partial simulations are done at DSM5 and AA1, and the complete simulations of the car are available before FDJ.

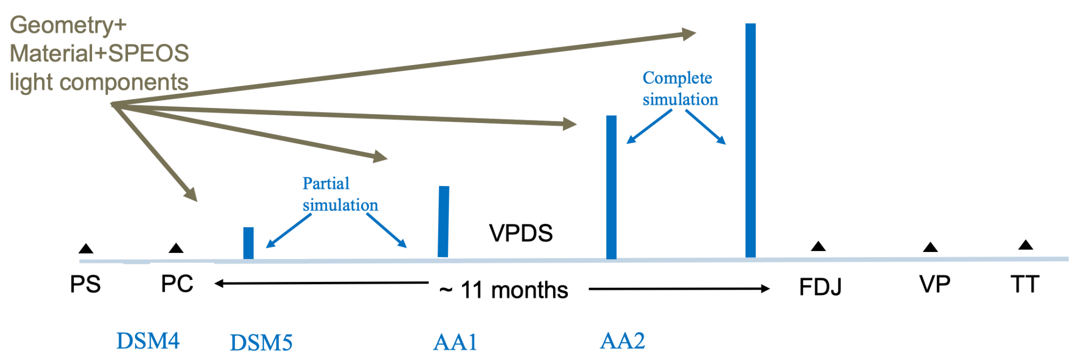


Figure 2.5: Timeline

SPEOS is a light simulation software provided by Ansys Optis. This software supports physics-based high fidelity light simulations which produces good quality images with 360 degree viewing possibilities as shown in these Figures 2.6 and 2.7. It offers many other features where different scenarios, such as the day or night environments, can be evaluated. One can also adjust the intensity of light sources and check if they satisfy intended design requirements. The *SPEOS* software estimates the optical performance of systems, and the illumination to improve the product's efficiency to save physical prototyping time and costs, [33]. This software can be used to get accurate photometric analysis.

Figure 2.6: *SPEOS* simulation result showing interior front side

Figure 2.7: *SPEOS* simulation result showing interior front side from different point of view

This software, in combination with CAD software such as CATIA V5, can be used to prepare a simulation and obtain a result. In the data preparation, materials with appropriate optical properties, meaning it contains data about how the light will interact with a particular surface, are connected to the geometries. The simulation results are generally called as .sv5 files. One kind of .sv5 file is called as a .sv5 component which contains light sources and appropriate optical material applied on to geometry. The other one is .sv5 simulation result which contains other car geometries, light sources(.sv5 components) and appropriate optical materials [34].

But there are many limitations using *SPEOS* software, as full customer experience cannot be evaluated. To elaborate:

1. it can only have fixed viewpoints per simulation so viewpoints cannot be moved after simulation
2. cannot zoom in the scene to get a closer look into results(images)
3. the simulation is computationally intensive, meaning it takes a few days to weeks in a cluster of computers to give out the simulation results
4. the dynamic behaviour of lights like the ramping effects of lights and synchronization of different lights cannot be evaluated

There are also several variants in one project and several projects run in parallel. To verify all the variants of car projects, a high-performance computational ability and manual work are required. There is also a lack of verification method to test and evaluate the car software (logic) that is built into the hardware for light behaviour. Further, the problem can be divided into two independent problems see Figure 2.8. One problem aims to find a solution(software) that can support high interactivity, has high fidelity light simulation and displays dynamic behaviour of illumination. The other one aims to find a method to verify the implemented logic. Both of the independent solutions combined would solve the main problem. With this information, the technology roadmap can be suggested.

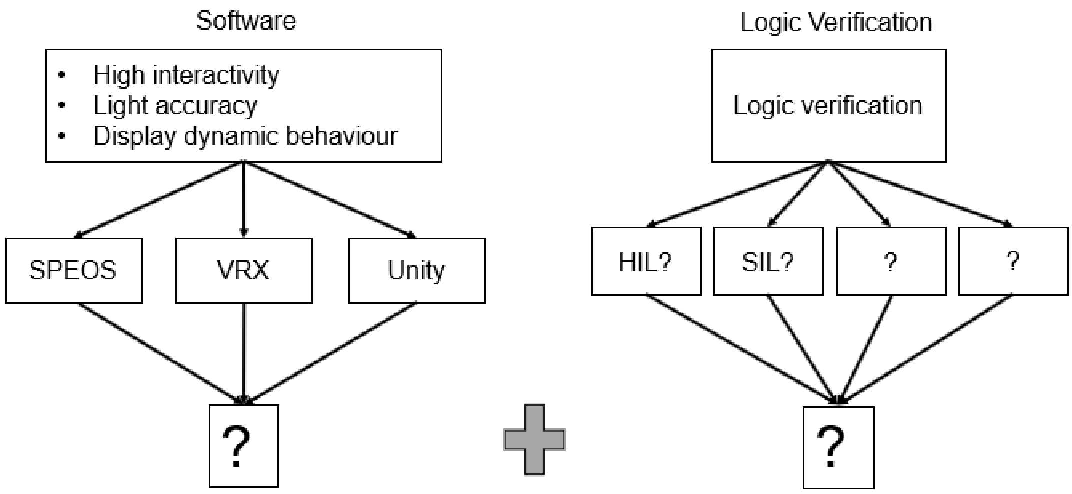


Figure 2.8: Independent Problems

2.6 Scalable Product Architecture (SPA) Platform

The two most common types of car projects within VCG are new model project and model year change projects. The current cars are built under a platform called SPA, which is known for flexibility and efficiency [35]. Figure 2.9 shows the flexibility of the SPA platform. In parallel to the current projects, a new platform called SPA 2 is being developed, which will have the capability to accommodate advanced computing [36]. This master thesis study was concentrated on the platform SPA 2 as most of the future cars will be launched in this platform.

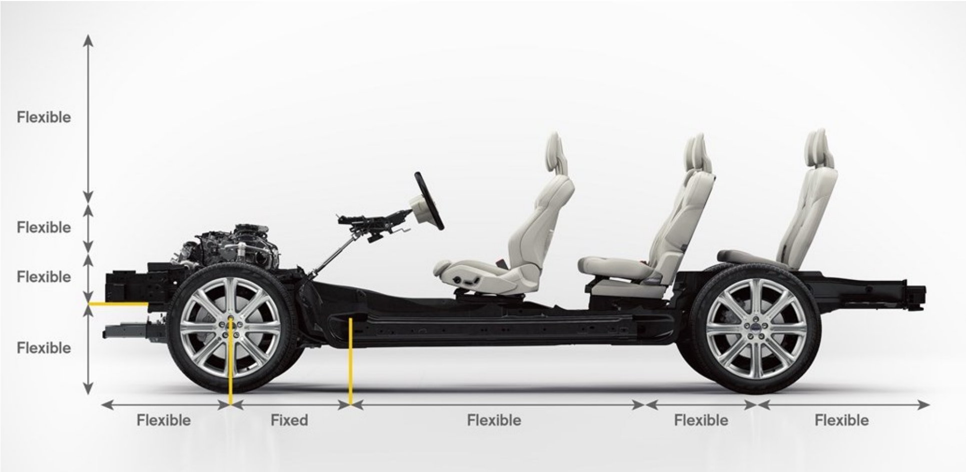


Figure 2.9: SPA platform [37]

2.7 Volvo Product Development System (VPDS)

The VPDS consists of four phases, namely Program Strategy Phase, Concept Phase, Engineering Phase and Industrialisation Phase. The phases that were focused for the master thesis project for optimisation of the time and efficiency for PQI are Concept phase, Engineering phase and Industrialisation phase, as these are the phases when PQI verifies. The specific gates that are important for PQI are PC, FDJ, VP and TT. Figure 2.10 is a brief picture showing the crucial phases, gates and the areas relevant for this master thesis study.

The specific areas that were concentrated on the master thesis project are Function Selection, Mechanical System Development & Integration, Software Development, Electrical Hardware Development and Prototypes, Tools & Builds. This is because all the phases mentioned above give input information for PQI verification.

PQI gives input to the functions involving light components in the concept phase and the specific gates Program Start(PS) and Program Confirmation (PC). Mechanical System Development & Integration has the release of CAD components in the concept and engineering phase, which are input to PQI to start the work.

The Engineering phase is the most critical phase for PQI, which required optimisation of the process as the dependencies with other streams are high in this phase. The Engineering Phase spans for approximately 11 months, starting from the gate PC to FDJ (Final Data Judgement). The Engineering Phase is also the phase in which the concepts are engineered to software and hardware.

Software and Electrical Hardware have the crucial releases in this phase which serves as an input to PQI. The software releases that were focused for optimisation are E1, E2 and E3. The Electrical Hardware releases were not crucial in this case, as the signal requirements written in Elektra were the main focus. Elektra is an online database that stores requirement on signal management concerning software and electronics in the Volvo cars. Although, hardware releases were considered on a few occasions depending on the situations.

In the ideal case scenario, FDJ is the gate where PQI should be ready with simulation results of the final virtual models and verifying the virtual model of the entire car with virtual lights. In the practical case scenario, due to delayed inputs from other streams, the virtual verification of illumination is delayed even after FDJ. The critical phases in the Industrialisation phase are VP (Verification Prototype) and TT (Tooling Trial). PQI verifies the illumination requirements in the physical car in this phase.

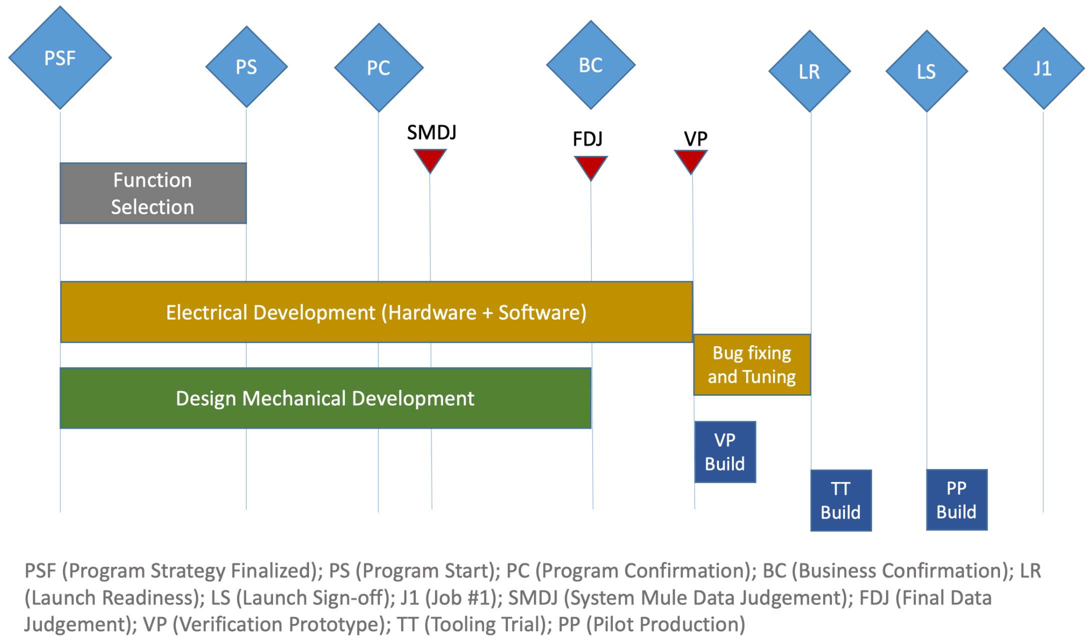


Figure 2.10: VPDS

In the ideal case scenario, PQI should be able to verify the illumination requirements of the physical car in VP and TT. However, the light components most often are not connected in the electrical architecture due to delays in the software releases and the physical verification by PQI is done after VP until TT.

2.8 Continuous Integration Framework

Continuous Integration is abbreviated as CI, and it is an agile practice to integrate the software development process continuously several numbers of times in a day [38]. This practice allows having faster feedback as the software is tested on a periodical basis, which allows the developer to correct the errors at the initial stages, which reduces the lead time of development of software [38].

Continuous Integration system allows the persons involved to be able to view the status and the corrections made to the software. The history of corrections can also be viewed by members involved in the system. One important benefit of CI is to help identify errors in the software at the initial stages so that the errors can be corrected in the software [38].

"The SW in HIL is updated every 4 hours i.e. continuously integrated."

- Stated by HIL Setup interviewee & CI training

2.9 Virtual Verification

In this section, the software tools and logic verification methods investigated for the master thesis study has been presented.

The software options presented below are *VRXperience* and *Unity* and the logic verification options presented are HIL (Hardware In Loop), SIL (Software In Loop), MIL (Model In Loop) and FSM (Functional State Machine).

2.9.1 Software tools

As mentioned previously in the Limitations section, the scope of the master thesis is to investigate only two software that is *VRXperience* and *Unity*. The capabilities of the software will be introduced in this chapter.

2.9.1.1 VRXperience

VRXperience is a software developed by Ansys Optis. This software offer services to quickly simulate and visualise the early phase light designs and their effects on the illumination. In this way, one can create a virtual customer experience in terms of perceived quality to foresee any faults in appearance. This software can be used for the optimisation of the perceived quality of the product, which will reduce the need for several and high-cost prototypes. The software can also be used to secure the reliability and the feasibility of the manufacturing and assembly processes without any increase in costs [39]. *VRXperience* has several capabilities, such as:

- to import various relevant CAD formats
- allows physics renders
- supports photometry
- allows testing different concepts of lighting
- supports variant management which is testing different lighting and material configurations

- can import *SPEOS* results to view in head-mounted displays

It has different modes which can be used for different purposes. They are *VRXperience* progressive mode, Raytrace mode and Shadics mode. For this master thesis, only Progressive mode and Shadics mode is applicable, since Raytrace mode is not used for perceived quality purposes, which is presented later in this section. Different modes offer different accuracy levels. There is a trade-off between simulation accuracy and speed of simulation and interactivity with the model [40]. The layout of *VRXperience* tool is shown in this Figure 2.11. The contents of the picture are purposefully not clear because it is confidential information.

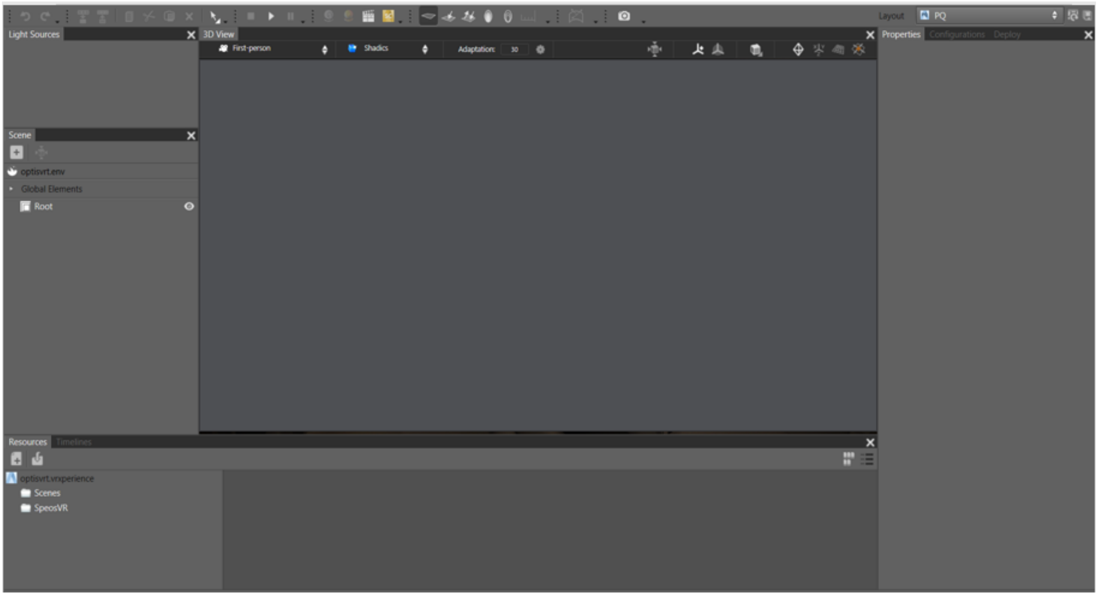


Figure 2.11: VRXperience layout

2.9.1.1.1 Progressive mode

Progressive mode is a mode in the *VRXperience* software where the simulation is performed as time progresses, meaning that it starts with a noisy image where light has not taken many bounces. The noise disappears after a few seconds as light bounces multiple times off different surfaces. This mode uses an approximation of the *SPEOS* algorithm used with High-Performance Computing(HPC). The *SPEOS* algorithm is highly accurate Monte-Carlo simulation which consists in sending rays from each pixel of the sensor(viewpoint) until one of the stopping criteria is reached. The stopping criteria can be, for example, an option to choose 1000 bounces off the surfaces or 100000 of rays from a light source to a sensor or vice versa. The simulations run on the Graphics Processing Unit(GPU) and it supports up to 2 GPUs on parallel. It also allows the user to move within the scene, which means it supports multiple viewpoints. This mode can also be used to create videos [40].

2.9.1.1.2 Raytrace mode

Raytrace mode uses Deterministic Raytracing algorithm, which is less accurate than Monte-Carlo. Therefore the results of the simulation are comparatively faster than the Progressive mode. This mode is used to create the simulation of reflections which allows performing visibility studies. This mode, for example, can be used to validate the mirror reflections or used to look at the interference caused by material reflection. Since validating the reflections are not in the scope of PQI, the raytrace mode has not been studied in further [40].

2.9.1.1.3 Shadics mode

Shadics mode, unlike Progressive mode, is optimised for speed; therefore, only allows for 0 or 1 bounce of light. In this way, high interactivity with the model is achieved at a very low accuracy compared to the Progressive model. This mode allows to import of various CAD formats which include only geometries, or *SPEOS* simulations results called as .sv5 Linked Export(*SPEOS* Formats) which contains geometries, light sources and material files. By importing different files consisting of different formats, one can prepare the *VRXperience* model, which can be used to create different configurations with lights and materials. The same model can also be used for progressive mode [40].

2.9.1.2 Unity

Unity is a gaming software developed by Unity Technologies. Due to high demands in the automotive industry for virtualisation, Unity has developed a platform for automotive and manufacturing, based on already existing gaming software. With their real-time 3D creative development platform, one can visualise automotive products and build interactive and virtual experiences [41]. The layout of the Unity tool is shown in this Figure 2.12. The contents of the picture are purposefully not clear because it is confidential information.

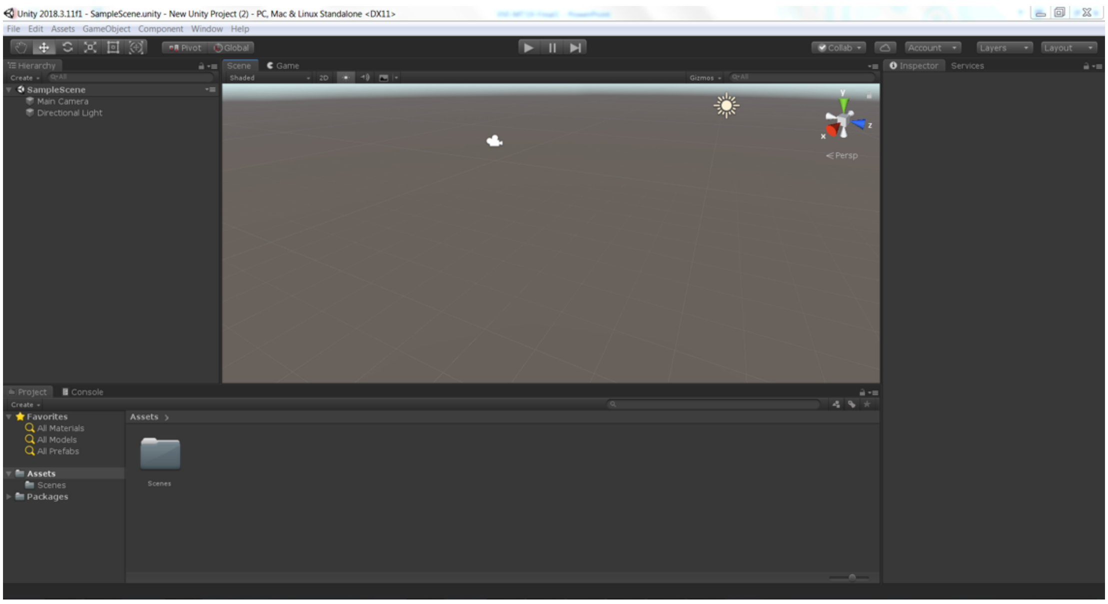


Figure 2.12: Unity Layout

2.9.2 Logic Verification Methods

In this section, the different logic verification methods are presented. Those methods that were are at VCG have been considered for the master thesis study.

2.9.2.1 Model In Loop(MIL)

Model in Loop is a testing method used in early phases of control system design (controller). This is to test whether the mathematical logic is working or not in a simulated environment. Software components are modelled in Simulink/MATLAB environments to test the mathematical logic. It is a faster way to visualise the mathematical logic since everything can be done on a computer. Iterations of the same would yield with better control system designs. This method does not involve any physical car hardware and hence way cheaper than HIL testing [42].

2.9.2.2 Software In Loop(SIL)

The Software in Loop is a testing method where code that is embedded in the ECUs is used. This code is generally generated from the controller that is designed in an earlier phase of a control system. Car hardware is not used in this type of testing instead of simulated environments(computers) are used. With this type of testing, one can save costs by identifying issues earlier by faster iterations and also quickly verify if the software will work in simulation of reality. [42].It does have support to Continuous integration framework.

2.9.2.3 Hardware In Loop(HIL)

Hardware in Loop is a testing method where hardware components along with software are used to test integration issues. The verification of functions and testing is done on full vehicle systems. HIL testing is done after individual subsystems have been tested in MIL and SIL. Hardware (ECUs) of several subsystems are connected along with actuators, sensors and computers, which are used to simulate the real environments [42]. It does have support to Continuous integration framework.

Figure 2.13: HIL setup shows various controllers connected and display of results of testing in the screen

2.9.2.4 Functional State Machine(FSM)

Functional state machines at VCG are used to visualise and verify the high-level functional requirements. FSM is not a testing method but a visualisation method. This is created by the use of functional programming, which is a programming style that can be applied in many languages such as Lisp, Python, C#. Functional programming is a way to explain the computer how to treat the computations, what is the problem, and how it should solve without going into the specifics of the solution [43]. Hence this allows high-level abstraction. For example, in this Figure 2.14 "Door closed" and "Door Open" are states of the system. When they get triggered by the triggers such as "UNLOCK by key" or "User closes the door" the door opens and closes. Here in this example due to this way of programming, it does not consider how actuators of doors are activated, or sensing of key happens. Which means actual industrial implementation(software and hardware) is not considered, and hence this does not represent reality.

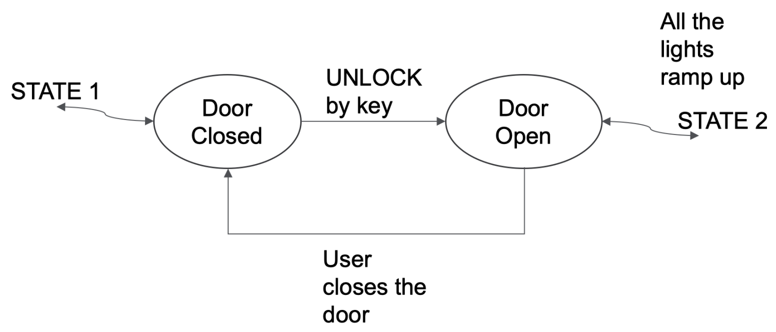


Figure 2.14: FSM

2.9.3 Other virtual verification methods

Some of the other identified virtual verification methods from other areas within VCG have been presented here.

2.9.3.1 VRX Dynamic Driving Experience

VRX Dynamic Driving Experience software is used to visualise the logic built in Simulink for the logic verification of functions for headlights. The different lighting conditions such as day and night conditions can be set in the software, and the light simulations can be visualised on the screen. The simulations of light do not represent reality.

2.9.3.2 Ergonomic CAVE

DELTAGEN software is used to operate the CAVE (Cave Automatic Virtual Environment) VR system. Eight projectors are used to simulate the physical world, and various eye sensors are used. The CAVE VR system at VCC has only one light condition which is bright sunlight mode and the roads are flat and do not have any bumps. There is a problem with the modification of the simulation environment of the CAVE due to lack of knowledge transfer and management methods.

2.9.3.3 Driving Simulator

Driving simulator is used to test the functions in the car, and this simulator is used to verify the logic used in the car. The fidelity of the light simulation result is low since the screen does not represent the real light quality. A whole network of car connections needs to be built in order to use the car software into this network which is complicated and expensive.

2.9.3.4 Virtual car connected to Unity

Virtual car is a mixed reality environment meaning both virtual reality and real environments are used. In this physical car is driven with a VR environment in conjunction where virtual objects are input in the virtual environment. To this, the physical car responds to the objects and reacts to the input objects in the virtual environment. The interviewed group is mainly testing active safety features. Unity is used as a medium between virtual and real environments. The signals are integrated from the physical car software to virtual environments. The signals from the physical car's are the steering wheel, speed, gear, opening of the door. In future, more signals are to be integrated into Unity from the physical car. The capability of the VRX software is analysed to test Advanced Driver Assistance Systems (ADAS) like LiDAR (Light Detection and Ranging) and RADAR (Radio Detection and Ranging).

3
Methodology

In this section, an overview of how the research was conducted and the methods that were used in the study will be presented.

This is a master thesis in collaboration with a company where one of the authors had no prior relationship with the company in question and other author has previously worked as a summer worker during summer of 2018. Since one of author worked in the same department for about five weeks, the work and result could have been biased marginally. Nevertheless, the authors can be considered as outsiders who are collaborating with employees at the company, which reduces the likelihood of any bias towards the result presented in this thesis. A level of bias could still happen since collaboration with employees has occurred, who could introduce bias in favour of the company when discussing some topics. This potential risk of bias needs to be considered when analysing the results of this thesis work.

3.1 Identifying the needs of PQI

Developing a technology roadmap for a dynamic virtual verification method involves understanding the existing problems of simulating tools, and contemporary processes that are followed to verify the cars. This understanding is crucial because user/PQI needs can be understood from this activity.

The needs of PQI were identified by conducting physical workshops, i.e. observations on physical cars on the competitor cars and Volvo cars to understand how PQI department sets and verifies their requirements. Different logic verification methods that are followed at VCG on the car, such as BOX cars and HIL rigs were also investigated. This investigation hopes to give a way of reducing cost and improving the perceived quality without an increase in costs. This activity was followed by numerous semi-structured and unstructured interviews with the people such as Function owners, System architects, Software developer and Light designers concerned with lights. The interviews helped authors to understand the needs and requirements of all the stakeholders. In parallel to the interviews knowledge on software SPEOS, VRX and Unity were acquired from their respective manuals. The methodology followed for the above explanation is presented below.

3.1.1 Research Approach

Research is the careful or diligent search [44] for the problem and make its root cause analysis. Problem identification is a key activity in any research endeavour and hence it important to find the cause of problems. By identifying the source of the problem, one can choose from a range of methods to investigate the problems and solve it [45]. There are two ways to do it; one is qualitative research, and the other is quantitative research.

3.1.1.1 Qualitative research

Qualitative research is often described as non-quantitative in characters such as texts, visual, fieldwork, observations, internet sites and interview transcripts. The aim of qualitative research to elicit something that is hard to explain or cannot capture. Since the data produced from qualitative research are often words or visual images, it is hard and time-consuming to analyse the data, which makes qualitative research more suited for small-scale studies [45] [46].

3.1.2 Data Collection methods

In this section, three different data collection methods are presented. There are different approaches when collecting data, and the scope of the data collection process is resource-dependent. In order for the collected data to mean something, it must be analysed and evaluated.

3.1.2.1 Observations

The collection of data on events in an actual and natural situation is known as observation. This kind of research can be divided into systematic observations and participant observations. Quantitative data is produced as a result of systematic observations. So, when using this observation method, the requirement is that the data to be collected systematically, so that the produced data is consistent between observations and independent on who is performing the observation. Participant observations are used to produce quantitative data which gather information about different social groups or social behaviours. There are different type of participant observations, where the researcher can choose to be a part in the observation event a secret or chose to be part of a group and making the role of observer known to everyone involved. Another form of participant observation is known as fieldwork. Fieldwork is when the observer takes part in activities as they happen in the field. In order for fieldwork to be an effective observation method, the researcher immerses themselves in the activities to gain insights and collect information. It is therefore important to ensure that the presence of the observing researcher does not intrude the situation taking place in any way. There is an issue of perception, which is it is heavily dependent on the researchers' personal bias towards data collection. This issue can be overcome by methods such as proper documentation about the same things in an observation event. This issue is generally done by having a discussion amongst the researchers about the observation that data on the same things will be collected so that data is consistent among all the researchers. [45]

For this master thesis project, they are called as physical workshops with cars where authors involved themselves in analysing how the cars perceived quality of illumination is verified. BOX cars were also investigated. These are the setup where hardware is assembled without the outer body of the car, and it is tested for integration issues on the complete vehicle. These BOX cars are built even before first verification prototypes are built. These investigations gave a first-hand experience and gained insights into what is lacking in contemporary ways. This method, therefore, took a considerable amount of time.

3.1.2.2 Interviews

An interview is the most commonly used qualitative research methods where the researchers approach the respondents and conduct in-depth interviews to understand their views on a specific topic [47]. Interviews can be helpful to the researchers to get in-depth and insightful information for a research question. Interviews can be classified into three different types: structured interviews, unstructured interviews, and semi-structured interviews. In structured interviews, the researcher prepares a set of questions to ask the respondents. All respondents will be asked the same questions and in the same order. Structured interviews help the researchers to compare and analyse the different responses received from different respondents for the same given set of questions. In unstructured interviews, questions are not prepared before the interview, and there is no formal or orderly way to conduct the interview. Semi-structured interviews have characteristics of both structured and unstructured interviews where the researcher prepares a set of questions ask to the respondent before the interview, and also the researcher ask additional follow-up questions during the interview to get more clarification on certain response. In all these types of interviews, the researcher must be open-minded and should not express any disagreements when the response received from the respondent conflicts with their ideas [47].

Semi-structured and unstructured interviews were conducted in this research project, and all the respondents are concerned with lighting and illumination technology. The respondents include function owners, system architects, software developer, and light designers. The interviewers were open-minded and have not expressed any disagreements while conducting the interviews even when the response conflicts with their insight. The different responses received from different respondents were compared and analysed using the KJ analysis method.

In this master thesis project, several unstructured interviews were conducted to understand the overall process within VCG regarding virtual verification of illumination and to understand every phase, what is being done in that phase and who is involved.

The interviews were conducted to identify the following.

- the virtual verification methods for other areas within VCG
- the possible logic verification methods that could be used to conclude with a verification method used internally
- the software used in different departments in Volvo Cars so to analyse if those software could meet the virtual verification needs of PQI
- the signals associated with light components and how the requirements for signals are written and what the requirements contain

3.1.2.3 Literature Study

A literature study is a comprehensive study performed to get a comprehensive insight into a particular research topic, before starting a new project in the same research area. A comprehensive literature study provides theories, interpretations, concepts and general principles relevant to the undertaken project [48]. The main objective of the literature study is to aid researchers to get a deeper understanding of the relevant research project and to learn about the state-of-the-art techniques that have emerged to solve the problem at hand.

Performing a literature study consists of several steps [48]. The first step in the literature study is to state the specific research objectives for the undertaken project. The second step is to develop and evaluate the study protocol, where the strategy to conduct the literature study will be developed and evaluated. The third step is to unbiasedly find the primary studies, systematic reviews, and meta-analyses relevant to the current research objectives. The sources of data to perform the third step in the literature study are the university digital library, peer-reviewed journal articles, peer-reviewed articles in conference proceedings, and books published by reputed publishers. The fourth step is to identify the studies that directly address the problem at hand from the pool of data available from the previous step. The last step in the literature study process is to extract and report the required information that can be directly associated with the research objectives [48].

The literature study, following the steps as mentioned above, was carried out to fulfil the current research objectives. The data for the literature study were mostly collected from the Chalmers University digital library and Google Scholar. The keywords that were used while looking for studies that directly address the problem at hand include virtual prototyping, perceived quality, product development, virtual verification, lean methodology, and technology roadmap. The validity and reliability of the information in the literature were ensured by mostly considering the peer-reviewed articles in reputed journals and conference proceedings. The validity and reliability of the data taken from other sources were ensured by comparing the data across multiple sources.

3.2 Defining Requirements

Requirements in a product development context are present to guide the researchers in a direction and gives a way to evaluate the solution. They are used to manage a complex task by giving a purpose to the problem statement. In this way, the researchers can communicate towards a common target. The requirements are not static since depending on the information at any point of time they change. Having established requirements at the start of the project provides a target, which in turn will help in gaining more knowledge about the problem. However, one should be willing to accept the changes that arrive due to increased knowledge.[50]

3.2.1 KJ analysis

KJ analysis is otherwise known as Affinity diagram. It is a management technique which is used to collect, cluster and categorise the unorganised information into a few pieces of organised information that is easy to follow. This method helps to analyse the data visually, where the connections between one information to other information can be seen visually. The larger chunks of information are categorised into small clusters to track and visualise the information [52] [53].

In this thesis project, KJ analysis was done to analyse the data gathered from the interviews conducted. The interviews were categorised into different topics, and each topic was given ranks according to the importance value of the topic. Figure 3.1 is an example of KJ analysis for SPEOS.

SPEOS (Rank:1)			
Capability	File formats	Problems	Material Scan
We can do the ies profile simulation in SPEOS and import to VRX	XMP- Define surface light, there will be uniform distributed light on the surface, whereas in reality it is not uniform.	If the path is too long for the export, then the error message appears.	A physical sample, for scanning in the early phases for the early samples, one sample for grain and texture, and another sample for colour is required.
A separate simulation required to identify the light leakage because it may appear too bright as adaptation has to be adjusted	brdf does not store pattern, only stores optical information, jpeg file gives pattern. It is recommended to use colour and light variation from brdf, and pattern from jpeg.	Exports the CATIA file from the Teamcenter into SPEOS and changes the material properties	Extract spectrum from colour scan brdf and apply in the texture/gloss scan brdf
Adaptation value depends on the candela per m2. It needs experience to set adaptation value.		The axis system (X-axis and Y-axis) needs to be known in order to position the components.	
Next SPEOS version will have box lights with the ies profiles hidden.		The lights components are positioned manually.	

Figure 3.1: Example of KJ Analysis

Based on observations on both competitor's and VCG's car, such as BMW and Volvo V90 respectively and interviews with key stakeholders, the needs on physical verification were noted down as physical verification requirements. This list was then updated to include things that are not possible by physical verification and exclude the things which are not possible to perform virtually, either because of unreliability or due to shortage of computational resources available at VCG. The updated list was then translated as virtual verification requirements which eventually became requirements on software. The interviews conducted with the key people concerning with logic verification methods resulted in a requirements list. In this way, requirements were used to help manage complex tasks and to communicate between the different stakeholders of a project. These two requirement lists were used to eliminate the concepts and arrive at conclusions.

In total three requirement lists were generated, which consisted of firstly, physical verification requirements, that is used to verify the physical car presently at VCG, secondly, software requirements which was framed during the master thesis study to evaluate and compare the different software, and thirdly, logic verification requirements list, which are used to evaluate and compare the different logic verification methods. The physical verification requirements are the basis of framing the software and logic verification requirements. These requirement lists were primarily analysed using KJ analysis of qualitative interviews because KJ analysis provides a framework on how to analyse such data.

3.3 Generation of concepts

As mentioned in Limitations, there were only two software to consider. So these software were put to the test by using the lean methodology principal. For this, experiments were made in SPEOS and VRXperience to verify the software requirements. The lean methodology was applied to carry out experiments in VRXperience where experiments were smaller in size. This was done to ensure there is no waste of time and authors would learn from small experiments and eventually improve on them.

As mentioned before in the above sections, all the logic verification methods were analysed using interview notes and literature gathered. No experimentation was possible due to the lack of resources for SIL. For the HIL, MIL and FSM methods, interview notes were deemed to be enough material to generate concepts.

3.3.1 Lean Methodology

Lean methodology assists the organisations in achieving their strategic objectives more efficiently and sustainably. The lean methodology is founded on two pillars, including continuous improvement and respect for people [51]. Continuous improvement is a process of streamlining work processes by finding the factors slowing down the system. Continuously making changes to improve the system is the best way to reduce the volume and cost of waste.

3.4 Evaluation of concepts

The software in consideration and different logic verification methods were evaluated using Pugh's Matrices and Kesselring Matrices. After these results were gathered and based on the results conclusions were made. In this section, the product development tools such as Pugh matrix, Kesselring matrix and KJ analysis, Technology Roadmap used for the master thesis study are presented.

3.4.1 Pugh Matrix

The Pugh matrix is a relative evaluation method where a reference is chosen randomly, and all other alternative concepts are compared to this reference. A set of criteria is formulated from the requirements list. This evaluation determines if, for each criterion, a concept is better or worse than the reference [50].

Company name	Pugh Matrix			
Authors	Created: Date			
Criteria	Alternative1	Alternative 2	Alternative 3	Alternative 4
Criteria 1	REF	-	-	-
Criteria 2	REF	-	-	-
Criteria 3	REF	+	+	+
Criteria 4	REF	+	+	+
Criteria 5	REF	+	+	+
Criteria 6	REF	-	-	+
Criteria 7	REF	0	+	+
Criteria 8	REF	0	+	+
Criteria 9	REF	-	-	-
Net score		0	2	9
Rank	-	3	2	1

Figure 3.2: Example of Pugh Matrix

This method allowed to compare different concepts in their early phases and hence this was used. It was difficult to quantify their performance initially because the alternatives were similar and did not give an entire idea on which were worse. By comparing them to one another, it gave authors a deeper insight into the weakness and strengths of the different concepts. Figure 3.2 is an example of Pugh Matrix for software.

3.4.2 Kesselring Matrix

The Kesselring matrix is a scoring method; unlike the relative evaluation method, the concepts are given different scores based on their performance for several predetermined criteria instead of comparing the concepts with a chosen reference. The criteria were also given weights which further increased the accuracy and resolution of the results. The method uses a theoretically "ideal" solution, which is given the highest scoring for all the criteria. The ideal solution is then used as a point of reference to determine how well or worse each concept fulfils each criterion [50].

This method was used when more knowledge was available with the aim to improve the accuracy of the result compared to the Pugh matrix. The weighting and the scoring allowed larger differences in the total scores, which gave a better picture of which concepts were worse and which were better. Figure 3.3 is an example of Kesselring Matrix for software.

Company name	Kesselring Matrix								
Authors	Created: Date								
Criteria		Concepts							
		ideal		Alternative 1		Alternative 2		Alternative 3	
	w	s	m	s	m	s	m	s	m
Criteria 1	4	5	20	5	20	3	12	2	8
Criteria 2	5	5	25	1	5	3	15	5	25
Criteria 3	1	5	5	1	1	3	3	5	5
Criteria 4	2	5	10	1	2	5	10	4	8
Criteria 5	4	5	20	1	4	4	16	5	20
Criteria 6	3	5	15	5	15	5	15	1	3
Total		30	95		47		71		69
Rel tot			1		0.4947368		0.747368		0.726316
Mean		5	15.83333	2.333333	7.8333333	3.833333	11.83333	3.666667	11.5
Deviation		0	5.833333	1.777778	6.4444444	0.833333	3.555556	1.444444	7.333333
Median		5	17.5	1	4.5	3.5	13.5	4.5	8
Ranking			-		3		1		2

Figure 3.3: Example of Kesselring Matrix

3.5 Elimination of concepts and Developing the remaining concept

After the critical analysis of the results from different evaluation methods, the weaker concepts were eliminated, and the remaining concept was developed to strengthen the concept further. This development of the remaining concept was, however, in a theoretical sense and hence no proof of concept has been generated. The conclusion was made using technology roadmap which laid out plan on which software in combination with a logic verification should be used.

3.5.1 Technology Roadmap

A technology roadmap is a high-level flexible strategic plan that provides specific technology solutions for an organization to be executed over a certain period to achieve stated technological objectives [54]. A strategic plan is critical for introducing new technological processes within the organization. Three main phases have to be followed while implementing the technology roadmap. These phases include the preliminary phase, development phase and follow-up phase [54].

In the preliminary phase, the main technical objectives of the project are determined. In the development phase, the technical requirements to fulfil the objectives are carefully determined, and the technology roadmap is formed. Some minor changes to the established technology roadmap can be made during the follow-up phase based on the progress.

In this project, a technology roadmap to conduct dynamic virtual verification was developed by thoroughly understanding the contemporary processes that are implemented currently to virtually verify the engineering design systems and also the existing problems associated with static simulations.

4
Experiments in VRXperience and SPEOS

The software, *VRXperience*, was tested to check if it fulfils all the requirements on the software. The requirements on the software are presented in the Results chapter. To test the *VRXperience* software, either data was be prepared in it or import existing *SPEOS* simulations into *VRXperience*. Initially, the required CAD models have been downloaded from the Teamcenter; a database of CAD models. They were imported into CATIA V5 to prepare the data by following a manual that is available at PQI. Preparation of the data includes removing the unnecessary data for light simulation and applying proper materials which their respective surface optical properties. Removing the excess details will ensure the model remains at a reasonable size to manage the available computational resources.

The CAD models that were used in this experiment are shown in Figure 4.1: two front seats, Overhead console(OHC) consisting of reading light components, the front bumper of the car, one Headlight with thor hammer, IP console with steering wheel and the roof of the car with polestar logo on it. A High Dynamic Range Image(HDRI) was used, and it was obtained from *VRXperience* software suppliers.

The results of simulations in *VRXperience* and *Unity* were compared to *SPEOS* simulations results. As discussed before *VRXperience* has two modes which offer different accuracy and interactivity levels. *VRXperience* Shadics mode has a feature called as light mapping or baking of light. A lightmap is a data structure used in the light mapping. A lightmap provides lighting effects such as global illumination. It is a pre-computed result of a *SPEOS* simulation carried out in local computer or cluster of computers with High-Performance computing. The simulation is carried out depending on the size and accuracy required for the situation. Baking of light is done to save the computation time. While baking of light offers the advantages, it cannot be used in every scenario. If the illuminated area is known, and there will not be any change in the area since there are no moving parts, then baking can substantially reduce the computational time of the simulation. Consider the case where overhead reading lights are illuminating the seat surfaces with uniform intensity. In this situation, as the illuminated area is known and it will not change since the light component location and seat positions are constant for a given percentile of human occupying the seat.

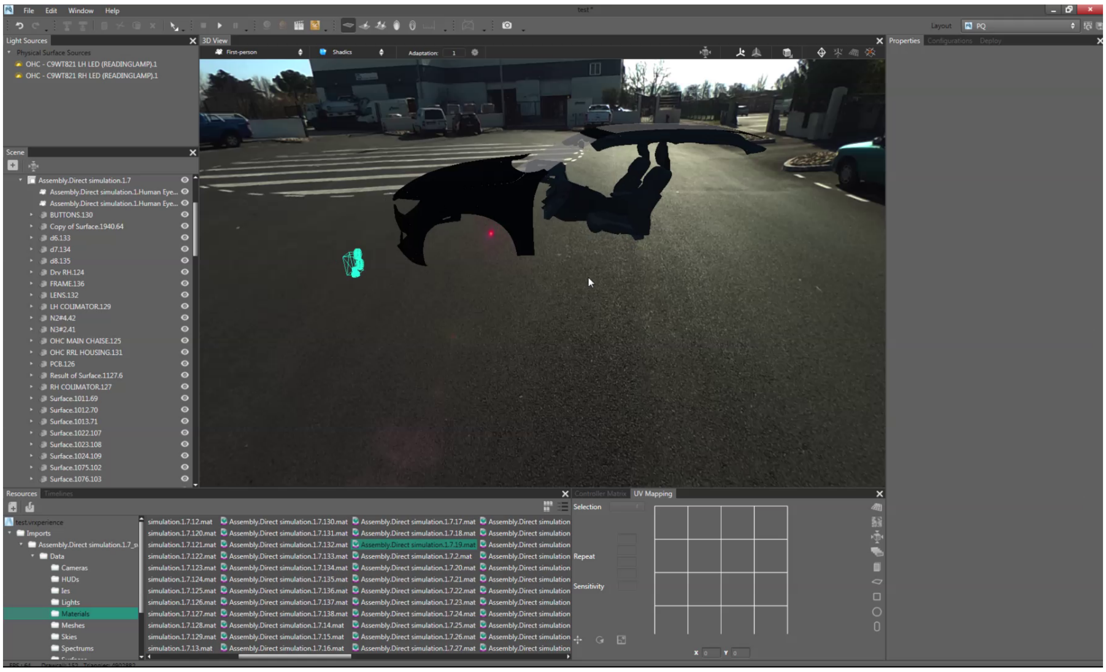


Figure 4.1: CAD Models

For the same model the mode was changed to Progressive mode then light rays are shot from a light source to sensor(viewpoint of the user) or sensor to the light source. If the light rays are shot from light source to sensor, then it is called as Direct Simulation, and it is used when complex light guides/components exist in the scene which requires hundreds or thousands of bounces off the surface to capture the actual behaviour of light. Conversely, if there are simple light components which do not need hundreds or thousands of bounces of light, then light rays are shot from the sensor(viewpoint of the user) to light sources which bounce off all the available surface in the scene. The results can be viewed in the results section.

Unity has similar features of VRXperience except it does not support some light components data. Due to delay in information on Unity models internally, much of the experimental studies could not be made in Unity. Based on theoretical information available on Unity webpage [55] and from interviews with VCG unity users the results are analysed and conclusions are made.

5
Results

In this chapter, the results of the thesis are presented. Initially the requirement lists for physical verification and virtual verification has been presented and then results of comparison between different software and different logic verification methods has been presented.

5.1 Physical Verification Requirements

The requirement list consists of physical verification requirements which are used to verify if the light components, software and functions are in place by several requirements mentioned below. Some of the significant physical verification requirements are as follows:

- Light timing and synchronisation
- Glare
- Colour Rendering Index
- Light intensity

5.2 Virtual Verification Requirements

The virtual verification requirements consist of the logic verification method requirements and software requirements.

5.2.1 Logic Verification Method Requirements

The chosen logic verification method should satisfy the following requirements:

- **High Fidelity of the system, consider hardware latencies**
  The logic verification method shall be of high fidelity which includes the hardware latencies. It shall be connected to the software in the ECU of the car. The system also considers the capabilities of the hardware and unforeseen circumstances that could have an impact on the software and the hardware, and thereby produce high fidelity results.

- **Early logic verification**
  The logic verification method shall be able to verify the logic early in the product development process. Since faster feedback, results in faster correction of

errors and thereby accommodates time for improvement.

- **Easy to Modify the logic**
  The logic verification method shall be of an easily modifiable structure, that is the logic shall be simple to modify easily. The more complex it is to modify the logic, more resources would be required for compensating the complexity of the structure.

- **Take fewer resources to build the setup**
  The logic verification method shall take fewer resources than the current resources to build the setup as this directly involves time and costs.

- **Take less time to build the setup**
  The logic verification method shall take less time to build the setup than the current setup, which can reduce the lead time of the project and facilitate early verification.

- **Support to the Continuous Integration Framework**
  The logic verification method shall be able to support continuous integration framework as the software in the car are continuously integrated every 4 hours enabling giving feedback if there are errors in the code by verifying logics.

5.2.2 Software Requirements

The chosen software should satisfy the following requirements:

- **Photometric Analysis**
  The software shall have the capability to perform photometric analysis. The photometric analysis will provide results which humans can perceive.

- **Light simulations and light accuracy**
  The software shall be able to follow the physics of light in simulations, thereby providing high accuracy in the simulation results.

- **Real time rendering**
  The software shall provide the ability to perform real-time rendering to verify the dynamic behaviour of lights.

- **Interactivity**
  The software shall support high interactivity with the CAD model so that it is easier to move around the model in any degree.

- **Variant simulation**
  The software shall provide the features to perform simulations of several variants such that less manual settings are required.

- **Stability of the tool**
  The software shall be stable, i.e. the tool should be free of errors and bugs.

- **Support logic verification system**
  The software shall have the support to integrate logic verification tool so that a separate tool is not required to verify and visualise the logic.

- **Display complex dynamic light behaviour**
  The software shall be able to display complex dynamic light behaviour as dynamic simulations are an important part of the entire verification process.

- **Support *SPEOS* formats**
  The software shall be able to support *SPEOS* formats, as the fidelity of *SPEOS* software is high. This requirement is crucial since the model preparation is done in *SPEOS* currently and may not change in the near future. Even though the software can simulate dynamic light behaviour with good light quality, it should support *SPEOS* formats.

- **Support CAD formats**
  The software shall support different CAD formats as the geometries that shall be received from different departments of VCG shall be CAD files.

- **Support material library**
  The software shall support material library of different formats as a number of file formats are required, which contributes to different specifications like colour, gloss, texture etc. of one material.

- **Support VR**
  The software shall be able to support VR such that the simulations can be viewed in a virtual environment.

- **Support AR**
  The software shall be able to support AR such that the simulations can be augmented on a real environment.

- **Customizable**
  The software shall be customisable as different settings may be required for the different simulations, and this shall be customised in the software.

- **Take less time for model preparation for PQI**
  The software shall have the features and user-friendly interface such that the software shall take significantly less time than the current software used for model preparation of PQI.

5.3 Software

The following results have to be comprehended, considering the constant computational resource in mind.

The evaluation of different alternatives was done using Pugh matrices. This evaluation was done using 15 different criteria. The round 1 and round 2 results of the Pugh Matrices for software are shown in figure 5.1 and figure 5.2 respectively. To make sure that the results from the first Pugh matrix were robust, two different rounds of the evaluation were conducted with different reference concepts each time. The comparison between different rankings of the concepts was made to see if there was a consistency in the results. After these two different rounds of Pugh, concepts which scored low continuously were eliminated.

VRX Progressive mode: The Progressive mode has scored lowest among the alternatives, as shown in figure 5.1 and figure 5.2. It performs similarly to SPEOS or offers no advantages on half of the listed criteria. As discussed in section 2.8.1.1.1, Progressive mode can simulate the light with high fidelity and longer result yielding time, compared to Shadics mode and Unity. Owing to that reason, having the support to logic verification system and displaying complex dynamic light behaviour maybe not be possible, since, it will be a delayed simulation result, it cannot match real-time requirements. Similarly, having the support to VR and AR, would not be recommended since the simulation result has to load for every change in viewpoint. The result on the head mount display is loaded on local computer resources, and therefore it takes a lot of time to render the result. Therefore it would consume more time for verification and hold still at a viewpoint would be impractical.

Similarities between SPEOS and VRXperience: Ansys Optis have developed the SPEOS and VRXperience modes, and they have not provided the ability to customise the software, and therefore customisation is not an option. Similarly, they all have the same properties in terms of material library management and support to AR.

Unity: Unity is found to have better support for the material library and has an option to customise the software from the interview with the VCG internal Unity users. Furthermore, it does better in many other criteria and hence gets the best rank in both the Pugh's rounds. The Unity users at VCG have given a positive review on its stability on the matters concerned with PQI, and hence it scores more than others. This tool also supports the logic verification system and takes less time in model preparation for PQI. This is because this software is in use in VCG other departments, and the same model can be requested for PQI use.

Volvo Car Group and Chalmers University of Technology	Pugh Matrix			
Created by: Ranga Raju Mohanapu & Dhivya Shanmugam	Created: 2019-05-15			
Criteria	SPEOS	Progressive	Shadics	Unity
Photometric Analysis	REF	-	-	-
Light simulations and light accuracy	REF	-	-	-
Real time rendering	REF	+	+	+
interactivity	REF	+	+	+
variant simulation	REF	+	+	+
Stability of the tool	REF	-	-	+
Support logic verification system	REF	0	+	+
Display complex dynamic light behavior	REF	0	+	+
Support SPEOS formats	REF	-	-	-
Support CAD formats	REF	+	+	+
Support material library	REF	0	0	+
Support VR	REF	0	+	+
Support AR	REF	0	0	+
Customizable	REF	0	0	+
Take less time in model preparation for PQ ill	REF	0	-	+
Net score		0	2	9
Rank	-	3	2	1

Figure 5.1: Pugh Matrix Round 1 for Software

Volvo Car Group and Chalmers University of Technology	Pugh Matrix			
Created by: Ranga Raju Mohanapu & Dhivya Shanmugam	Created: 2019-05-15			
Criteria	SPEOS	Progressi	Shadics	Unity
Photometric Analysis	+	+	0	REF
Light simulations and light accuracy	+	+	0	REF
Real time rendering	-	-	0	REF
interactivity	-	-	0	REF
variant simulation	-	-	0	REF
Stability of the tool	0	-	-	REF
Support logic verification system	-	-	0	REF
Display complex dynamic light behavior	-	-	0	REF
Support SPEOS formats	+	+	+	REF
Support CAD formats	-	0	0	REF
Support material library	0	0	0	REF
Support VR	-	-	-	REF
Support AR	-	-	-	REF
Customizable	-	-	-	REF
Take less time in model preparation for PQ ill	-	-	-	REF
Net score	-7	-7	-4	
Rank	3	3	2	1

Figure 5.2: Pugh Matrix Round 2 for Software

Photometric Analysis: The photometric analysis is worse in all the alternatives compared to SPEOS. In VRXperience modes, it is still developing, and in Unity, it is in research stages, according to their website [56]. For a given computational resource to attain a higher speed of simulation result and greater interactivity with the models, one needs to forego light simulation accuracy. Therefore, light accuracy and light simulation are worse than SPEOS.

Real time rendering: The features such as real-time rendering and interactivity with the model are better in all the alternatives compared to SPEOS because these features comprise the accuracy of the light simulation. However, it is worth noting that Progressive mode is significantly better than SPEOS because it renders the images faster than SPEOS. Nevertheless, the real-time rendering feature in Progressive mode does not represent reality. Similarly, variant simulation is better in VRXperience modes and Unity because of their ease of changing the variants.

Similarities betweeen VRXpereince - Shadics mode and Unity: The Shadics mode and the software Unity share more or less the same advantages over other alternatives. They score differently against some criteria, such as support for VR. Even though Unity ranked first in both Pugh's rounds, it is not entirely apparent how Unity is better and by what margin. Therefore to understand the difference between net scores of Unity and Shadics Kesselring Matrix has been used.

Although Pugh Matrices gave a direction towards the final solution, it is better to weigh the criteria to get a robust solution. Pugh Matrix inherently assumes that all the criteria are equally important, whereas Kesselring Matrix with weights uses a nearly perfect ideal solution and compares all the available alternatives to that ideal solution. Figure 5.3 shows the results of the Kesselring matrix for software.

After performing Pugh Matrix evaluation, support for logic verification system and display complex light behaviour are combined. Since one was a consequence of others and rest all the criteria, have been retained, and further evaluation using Kesselring Matrix has been made. From the interviews, literature study and experiments in VRX and SPEOS, the most important criteria are how well all the relevant CAD formats and material library are supported. Good photometric analysis, light simulation and light accuracy are the following essential criteria. Other essential criteria include real-time rendering, high interactivity with the model, has to support to logic verification system and all the SPEOS formats and takes less time to prepare models for simulation for PQI. The least important include the if they support variant simulation, the stability of the tool, support VR, AR and option to customise.

Volvo Car Group and Chalmers University of Technology		Kesselring Matrix				
Created by: Ranga Raju Mohanapu & Dhivya Shanmugam		Created: 2019-05-15				
Criteria		Concepts				
		ideal	Speos	Progressive	Shadics	Unity
	w	s	s	s	s	s
Photometric Analysis	4	5	5	3	2	NA
Light simulations and light accuracy	4	5	5	5	2	2
Real time rendering	3	5	NA	2	5	5
interactivity	3	5	1	3	5	5
variant simulation(time)	2	5	1	3	3	4
Stability of the tool	2	5	5	2	3	5
Support logic verification system	3	5	NA	NA	5	5
Support SPEOS formats	3	5	5	3	3	1
Support CAD formats	5	5	4	5	5	5
Support material library	5	5	5	3	3	4
Support VR	1	5	1	NA	5	5
Support AR	1	5	1	1	1	5
Customizable	1	5	1	1	1	5
Take less time in model preparation for PQ ill	3	5	3	3	3	5
Total		200	127	117	138	149
Rel tot		1	0.635	0.585	0.69	0.745
Mean		5	3.08333	2.8333333	3.28571	4.30769
Deviation		0	1.75	0.8888889	1.22449	0.95858
Median		5	3.5	3	3	5
Ranking			3	4	2	1

Figure 5.3: Kesselring Matrix for Software

Progressive mode did worse than all other alternatives. It does not have proper photometric analysis compared to SPEOS because the algorithm in Progressive mode is set to have compromised the accuracy for light related features considering the constant computational resources. For the same reason and due to delayed simulation result, the support for logic verification system is not applicable. Due to rendering the images slowly the support for VR, AR also affected negatively because for every change in the point of view the result has to be computed which takes time and hence it may be not possible to use the VR or AR mode. It is not a stable tool compared to SPEOS or Unity since there were problems while conducting experiments with this mode which did not yield results in some scenarios. It neither has a good variant simulation support nor good interactivity with the model, and it does not have the option to customise compared to Shadics and Unity.

SPEOS also follows the same trend as Progressive except it not better than other alternatives at realising the ultimate goal of achieving faster simulation results and able to verify the dynamic light behaviour. Even though it scores more than Progressive mode because it has stable support SPEOS formats and material library management. Nevertheless, it scores less than Shadics and Unity in interactivity with the model, variant simulation time, support to VR & VR and customisability.

Shadics is worse than SPEOS and Progressive mode at photometric analysis and light simulation accuracy. It does not have support to AR since these features are in development. Shadics can support VR which are limited to view only SPEOS simulation results. Also, Shadics does not have good support compared to SPEOS for SPEOS formats which makes the results not represent the reality and hence the score is negatively affected.

After a thorough evaluation of Kesselring Matrix, both Shadics and Unity remained.

5.4 Logic verification method

Evaluation of the different alternatives for logic verification was done using Pugh matrices. This evaluation was done using six different criteria which can be seen in figure 5.4. To make sure that the results from the first Pugh matrix were robust, four different rounds of the evaluation were conducted with different reference concepts each time. The comparison between different rankings of the concepts was made to see if there was a consistency in the results. After these four different rounds of Pugh, concepts which scored low continuously were eliminated. The figures 5.4, 5.5, 5.6 and 5.7 shows the round 1, 2, 3 and 4 Pugh matrix results for software.

Volvo Car Group and Chalmers University of Technology	Pugh Matrix			
Created by: Ranga Raju Mohanapu & Dhivya Shanmugam	Created: 2019-05-15			
Criteria	HIL(REF)	SIL	MIL	FSM
High Fidelity of the system, Consider Hardware Latencies	REF	-	-	-
Early logic verification	REF	0	+	NA
Easy to Modify the logic	REF	+	+	NA
Take less Resources to Build the setup	REF	+	+	+
Take less time to build the setup	REF	+	+	+
Support to the Continous Integration Framework	REF	0	-	-
Net score		2	2	0(NA)
Rank	2	1	1	3

Figure 5.4: Pugh Matrix Round 1 for Logic verification method

Volvo Car Group and Chalmers University of Technology	Pugh Matrix			
Created by: Ranga Raju Mohanapu & Dhivya Shanmugam	Created: 2019-05-15			
Criteria	HIL	SIL	MIL	FSM
High Fidelity of the system, Consider Hardware Latencies	+	REF	-	-
Early logic verification	-	REF	+	NA
Easy to Modify the logic	0	REF	+	NA
Take less Resources to Build the setup	-	REF	+	+
Take less time to build the setup	-	REF	+	+
Support to the Continous Integration Framework	0	REF	-	-
Net score	-2		2	0(NA)
Rank	4	2	1	3

Figure 5.5: Pugh Matrix Round 2 for Logic verification method

Volvo Car Group and Chalmers University of Technology	Pugh Matrix			
Created by: Ranga Raju Mohanapu & Dhivya Shanmugam	Created: 2019-05-15			
Criteria	HIL	SIL	MIL	FSM
High Fidelity of the system, Consider Hardware Latencies	+	+	REF	-
Early logic verification	-	-	REF	NA
Easy to Modify the logic	-	-	REF	NA
Take less Resources to Build the setup	-	-	REF	0
Take less time to build the setup	-	-	REF	0
Support to the Continous Integration Framework	+	+	REF	0
Net score	-2	-2	REF	-1
Rank	3	3	1	2

Figure 5.6: Pugh Matrix Round 3 for Logic verification method

Volvo Car Group and Chalmers University of Technology	Pugh Matrix			
Created by: Ranga Raju Mohanapu & Dhivya Shanmugam	Created: 2019-05-15			
Criteria	HIL	SIL	MIL	FSM
High Fidelity of the system, Consider Hardware Latencies	+	+	+	REF
Early logic verification	-	-	+	REF
Easy to Modify the logic	-	-	+	REF
Take less Resources to Build the setup	-	-	+	REF
Take less time to build the setup	-	-	+	REF
Support to the Continous Integration Framework	+	+	0	REF
Net score	-2	-2	5	REF
Rank	3	3	1	2

Figure 5.7: Pugh Matrix Round 4 for Logic verification method

HIL needs many resources (both human and non-human) to build the setup, meaning to connect all the mechanical hardware and software according to HIL team at VCG A.4. It takes more space and time to build one. Hence, it was not very easy to maintain and modify the system. In contrast, FSM was a method to visualise the high-level requirements but did not provide a way to verify the implemented system. Even though it ranked as second in some Pugh rounds, it was because it is not applicable for some criteria such as early logic verification and easy to modify the logic. Therefore, it does not satisfy the requirements to be a logic verification system, and hence it is eliminated.

After Pugh rounds, Kesselring matrix with weights was used to evaluate the remaining alternatives HIL, MIL, SIL to increase the resolution and see which concepts were weaker. HIL could have been eliminated after Pugh rounds, but the further evaluation did not consume much time, so it was carried on, and it gave a better understanding to make a strong case for a virtual future. Figure 5.8 shows the Kesselring matrix result for logic verification.

Volvo Car Group and Chalmers University of Technology	Kesselring Matrix								
Created by: Ranga Raju Mohanapu & Dhivya Shanmugam	Created: 2019-05-15								
Criteria		Concepts							
		ideal		HIL		SIL		MIL	
	w	s	m	s	m	S	m	s	m
High Fidelity of the system, Consider Hardware Latencies	4	5	20	5	20	3	12	2	8
Early logic verification	5	5	25	1	5	3	15	5	25
Easy to Modify the logic	1	5	5	1	1	3	3	5	5
Take less Resources to Build the setup	2	5	10	1	2	5	10	4	8
Take less time to build the setup	4	5	20	1	4	4	16	5	20
Support to the Continous Integration Framework	3	5	15	5	15	5	15	1	3
Total		30	95		47		71		69
Rel tot			1		0.4947368		0.747368		0.726316
Mean		5	15.83333	2.333333	7.8333333	3.833333	11.83333	3.666667	11.5
Deviation		0	5.833333	1.777778	6.4444444	0.833333	3.555556	1.444444	7.333333
Median		5	17.5	1	4.5	3.5	13.5	4.5	8
Ranking			-		3		1		2

Figure 5.8: Kesselring Matrix for Logic verification method

Confirming to the Pugh's rounds HIL did worse than SIL and MIL on four out of six criteria. That is, building the setup has lead time due to physical prototypes arriving late in the product development phase. The setup takes vast resources than other alternatives to build, and it is tough to change the logic via hardware. Also, it is worth emphasising that it is expensive compared to other methods. 5.8

After HIL elimination, the remaining alternatives are SIL and MIL which were used to make conclusions.

6
Discussion

This thesis project was entirely conducted at the company, and the authors were located in the same department as the company supervisor. The collocation of the authors and the supervisor has been an advantage for this thesis. Firstly, it expedited the process by enabling the authors to meet all interviewees in person, to gather the required information. Secondly, it made the thesis work possible by giving the authors access to the company's databases that stored all the information and resources such as computers. Consequently, there could be a basis for the result of the thesis.

The choice of the method to answer the research questions was limited to observations, qualitative interviews and literature study. These choices were made primarily because the fundamental knowledge to do the thesis work did not exist. The fundamental knowledge in consideration involves people across from different departments who can provide information about specific technologies. Quantitative interviews could have also been a complementary approach to qualitative interviews. A significant amount of time was invested in creating the fundamental knowledge, so there was not sufficient time left to do that. Also, it was impossible to create a questionnaire without any knowledge on the subject, and quantitative interviews are confirmatory. This thesis work did not require to confirm any hypothesis but to find out the issues that need to solve to achieve the aim. A suitable alternative approach to interviews could have been focus groups where a group of participants would be given a topic to discuss freely, and organisers would take notes on the discussions. Due to lack of sufficient time, this could not be done and also it was impossible to foresee that the information was spread across the different departments of the VCG.

The choice of using semi-structured interview was used since, as previously mentioned in methodology chapter allowed the interviewees explore what they considered necessary for virtual verification of dynamic illumination, while at the same time staying within specific predetermined topics. This kind of interview technique worked well and allowed for the identification of essential issues to achieve the aim. However, a drawback of this approach was a difficulty to sometimes link specific discussions to virtual verification of illumination and many people from different departments had to be contacted to make a connection to virtual verification of illumination. This difficulty arose due to the interviewees did not know how to guide the authors with the information. This is believed not to have affected the identification of essential issues since as the knowledge grew, authors could make connections and make conclusions. The authors' inexperience of probing can, in large part, have affected this, and the problem could have been reduced through better-interviewing techniques. All the interviews were documented by hand, which means missing out the documentation of crucial information might have happened accidentally. An alternative approach could have been that all the interviews should have been audio-recorded and later convert them into readable transcripts. However, this would have consumed most of the thesis time frame. The authors feel that this kind of documentation worked out well because only a few times they had to revisit the people and ask them the same questions. Heavy cross-department dependency delayed the information flow for the thesis work.

The choice to conduct experiments was to get deeper insights into the abilities and shortcomings of the software. Because of the lack of fundamental knowledge, a significant amount of time was spent in accessing the information via interviews. The created knowledge base, however, helped to propel the work forward faster in the later phases of the thesis work. A considerable amount of time was spent in model preparation, meaning large size CAD models that take up a lot of memory space have been prepared. Due to this importing time of models into VRXperience was huge, which was not so productive. This happened due to not following a lean methodology. After many failed attempts adapting small experiments and continuous improvement mindset, the work improved. Only a few parts have been used in experiments which could have biased the results.

Much time, had been spent in VRXperience software which led to the identification of more issues compared to Unity. Due to unavailability and complexity to work Unity models in VCG, experiments could not be done in Unity software. This was due to the inability to operate the Unity because of restrictions internally in VCG, delayed the work in Unity software. However, most of the technical information had been accessed from the Unity experts in VCG and from Unity's website. This, however, in reality, when implemented, might vary from theoretical information. So the current results should be validated in future by doing somewhat similar experiments in Unity.

The experiments might have been delayed due to the availability of only one computer to conduct experiments. Not only that but also only one Teamcenter account was working, and only one laptop was available for data preparation. More experimentation might have highlighted more issues. However, the cooperation between the authors and supervisor, whose Teamcenter account was being used, worked well with little time waste. The most important experiments in VRXperience were conducted on the computer provided by suppliers with higher computational power than available at VCG. So careful considerations have to be taken on results on estimating how it works out in VCG. Nevertheless, due to lack of human resources in one key department, the demo SIL has not been able to be produced.

Lastly knowledge barriers of the authors' might have affected the thesis work. The authors primarily had a background in mechanical engineering with little or no knowledge in expert level software and electronics domains. However, the cooperation with most of the interviewees has worked well, and they were able to delineate the subject matters so that authors can conclude it. Every criterion in evaluation somehow points to low computational resources which made it difficult for the authors to make the criteria independent of each other. This was solved by carefully defining each requirement and having consistent meaning terminology across the thesis.

7 Conclusion

As discussed earlier, the solutions for the two problems stated are

1. Tool to be used for logic verification is MIL upto DSM5 and thereafter SIL
2. SPEOS should be still used because of its high fidelity simulation results
3. Software to be used for dynamic verification with the ability to include SIL is Unity

For logic verification, MIL should be used in the early phases after the gate PC as the design content, functions and the signals would be immature. MIL should be used in the phases of refinement and in some cases development. The results from MIL could be given as an initial feedback to the respective people working with functions, light designs, signal etc.

For virtual verification, there is no one software that can simulate the light with high fidelity and high interactivity in a fast way due to limitation on computational abilities. Therefore, a combination of two software should be used to verify the different requirements virtually.

After DSM5, Unity should be used along with SIL, where SIL is for logic verification purpose and Unity is for visualisation purpose. Unity is a tool used internally at VCG for other purposes and it is possible to customise the tool. The customisation is possible because a significant percentage of the tool is a programming environment where the functions can be coded in the tool, along with delays and specifications of the hardware. Since, Unity is a visualisation tool, it can be used to visualise how the behaviour of lights would be and when the behaviour will be displayed. One benefit of using Unity is, it can benefit multiple stakeholders, as Unity is being used for several purposes including light and other areas within VCG.

Since Unity is a tool used for visualisation purpose, for the verification of light quality and fidelity, SPEOS should still be used. This is because it produces high fidelity simulation results that can be viewed with human eye adaptation. Therefore, visualising the simulation result is as viewed in the physical environment. It is suggested that PQI does partial simulations in the beginning phases upto AA1 (Apperance Approval 1) as all the light components may not be received at this point of the product development phase and the light components may not be complete in design due to complexities. The complete simulations are suggested to be performed from AA1 upto FDJ as the light components would be received in those stages.

The Figure 7.1 shows the proposed verification process that optimises the time of PQI according to the results obtained from the master thesis study.

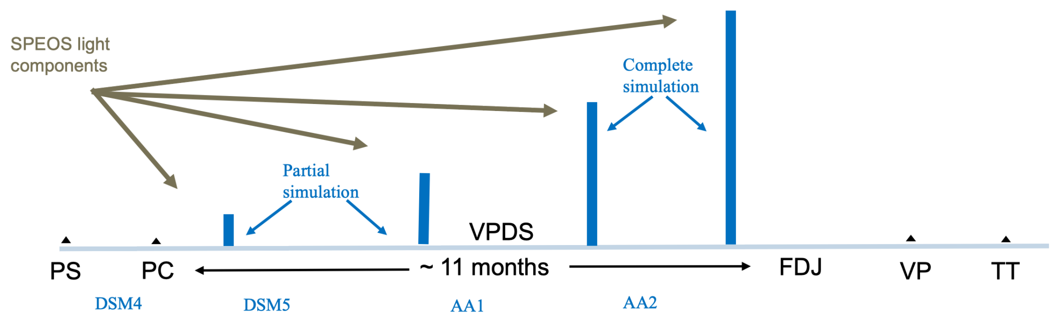


Figure 7.1: Proposed verification process with VPDS

The other logic verification methods such as HIL and FSM does not fulfil the requirement criteria due to factors like feasibility, fidelity and time.

The other software VRXperience compared in this study had some problems which have to be improved before it can be used. A few improvements have to be made, as certain features are missing or have a problem of not integrating well with SPEOS files. Also, the stability of the tool is low, and therefore, using the tool at a phase where the tool is evolving may not be a long term solution. So, VRXperience software was eliminated from the choice between Unity and VRXperience until the problems are fixed. Another reason for the elimination of VRXperience was because ANSYS Optis had a demo of SPEOS Standalone software which has the features of both VRXperience progressive and SPEOS. But SPEOS Standalone software has not been tested, as it was introduced to authors to the end of the master thesis study. Due to uncertainties in the release of new software and the instability of the software, VRXperience was eliminated.

As a short term solution until the issues are resolved, the above stated process of verification should be followed for efficiency.

8 Recommendations for future work

The investigation on how the continuous integration framework for the activities performed by PQI could reduce the manual tasks significantly and automate the process. The software is continuously integrated in Volvo Cars and this should also be applied to the other different processes at VCG as this will reduce the lead time significantly. It will also eliminate human errors as manual updates may not be efficient, as there could be new updates for geometry, light components, materials etc. Also, manually checking all the updates and verifying may lead to errors.

The automation of linking SPEOS materials with geometry should be investigated as majority of the time is spent in model preparation. Every time there is an update of new components or materials, it is manually updated in the current scenario. In the future, automation will lead to reduced lead time.

Also, evaluation of different scenarios and the car variants that need to be verified by PQI should be investigated. The investigation is required so that a standardised process could be established for new projects, model year changes, facelift, and for the different models and level of content in the car.

In the practical scenario, there is a delay in the development of software in most cases and this could lead to project delays. To overcome this, an investigation must be carried out on how the functions can be defined early and how the VPDS could be adapted to have the functions defined early in the process with the consideration of iterative feedback from the other functions (Function Owners, Attribute Owners, Designers, System Architects etc.) within VCG.

A periodical check on the updates from VRXperience or ANSYS Optis would help PQI to know on what directions to take when buying the software or renewal of the licenses. Also, the capabilities of SPEOS Standalone software should be investigated, as it was introduced towards the end of the master thesis project.

The Unity team and PQI within VCG are recommended to work closely. The collaboration is recommended to continuously follow the Unity development work and give feedback to the Unity team, so the required features for PQI could be coded in Unity.

Bibliography

[1] Company | Volvo Car Group. (2019). Company. Accessed on: October 6, 2019. [Online] Available at: `https://group.volvocars.com/company`.

[2] Volvocars.com. (2019). The Scandinavian Sanctuary | Volvo Cars. Accessed on: November 12, 2019. [Online] Available at: `https://www.volvocars.com/intl/discover-volvo/the-scandinavian-sanctuary`.

[3] Volvocars.com. (2019). Lighting | Lighting | S60 2019 | Volvo Support. Accessed on: October 27, 2019. [Online] Available at: `https://www.volvocars.com/mt/support/manuals/s60/2019/lighting/lighting`.

[4] Wheelwright, S. and Clark, K. (1992). Revolutionizing product development.

[5] Teece, D. (1996). Firm organization, industrial structure, and technological innovation. Journal of Economic Behavior & Organization, 31(2), pp.193-224.

[6] Wickman, C., Söderberg, R. and Lindkvist, L. (2003). Toward non-nominal virtual geometric verification by combining VR and CAT technologies. Geometric Product Specification and Verification: Integration of Functionality: 7th CIRP International Seminar on Computer-Aided Tolerancing, P. Bourdet and L. Mathieu, Eds. Dordrecht: Springer Netherlands, pp. 301–310.

[7] Katare, S., Reddy, D., Ourchane, A. and Nammalwar, G. (2017). Towards a One Day Frame Model Build. SAE Technical Paper.

[8] Németh, Z., Veres, Á. and Nagy, B. V. (2012). Simulations for optical design and analysis – Digitale Bibliothek Thüringen. Mechanismentechnik in Ilmenau, Budapest und Niš, pp. 135–144.

[9] Rix, J., Haas, S. and Teixeira, J. (2016). Virtual Prototyping. New York, NY: Springer.

[10] Liu, S. et al., (2008) Multi-physics multi-scale modeling issues in LED. ICEM 2008: International Conference on Experimental Mechanics, vol. 7375, p. 737507.

[11] Ansys.com. (2019). Structural Analysis Software | FEA Analysis| ANSYS Structural. Accessed on: October 27, 2019. [Online] Available at: `https://www.ansys.com/products/structures`.

[12] Jakica, N. (2018). State-of-the-art review of solar design tools and methods for assessing daylighting and solar potential for building-integrated photovoltaics. Renewable and Sustainable Energy Reviews, vol. 81. pp. 1296–1328.

[13] Philbin, S. (2013). Emerging Requirements for Technology Management: A Sector-based Scenario Planning Approach. Journal of technology management & innovation, 8(3), pp.7-8.

[14] Phaal, R., Farrukh, C. and Probert, D. (2004). Technology roadmapping—A planning framework for evolution and revolution. Technological Forecasting and Social Change, 71(1-2), pp.5-26.

[15] Westinghouselighting.com. (2019). Color Temperature (Kelvin). Accessed on: November 17, 2019. [Online] Available at: http://www.westinghouselighting.com/lighting-education/color-temperature.aspx.

[16] Westinghouselighting.com. (2019). CRI - Color Rendering Index. Accessed on: November 27, 2019. [Online] Available at: http://www.westinghouselighting.com/lighting-education/color-rendering-index-cri.aspx.

[17] Sciencedirect.com. (2019). Luminous Intensity - an overview | ScienceDirect Topics. Accessed on: November 27, 2019. [Online] Available at: https://www.sciencedirect.com/topics/engineering/luminous-intensity.

[18] Sciencedirect.com. (2019). Light Leakage - an overview | ScienceDirect Topics. Accessed on: November 17, 2019. [Online] Available at: https://www.sciencedirect.com/topics/engineering/light-leakage.

[19] Lrc.rpi.edu. (2019). What is glare? | Light Pollution | Lighting Answers | NLPIP. Accessed on: November 17, 2019. [Online] Available at: https://www.lrc.rpi.edu/programs/nlpip/lightinganswers/lightpollution/glare.asp.

[20] Goodworkint.com. (2019). Homogeneity: the base of good lighting - Good Work Internacional. Accessed on: November 17, 2019. [Online] Available at: https://www.goodworkint.com/en/homogeneity-the-base-of-good-lighting/.

[21] Xal.com. (2019). LED - Colour homogeneity. Accessed on: November 27, 2019. [Online] Available at: https://www.xal.com/en/know-how/led-colour-homogeneity/.

[22] ERP Power. (2019). LED Light Flicker | ERP Power. Accessed on: November 17, 2019. [Online] Available at: https://www.erp-power.com/document/led-light-flicker/.

[23] Encyclopedia Britannica. (2019). Optical system. Accessed on: November 17, 2019. [Online] Available at: https://www.britannica.com/technology/optical-system.

[24] Thearender.com. (2019). Photometric analysis | Thea Render. Accessed on: November 17, 2019. [Online] Available at: https://www.thearender.com/features/photometric-analysis/.

[25] Stockman, A, Langendörfer, M.,Smithson, H. E., Sharpe, L. T. (2006). Human cone light adaptation: From behavioral measurements to molecular mechanisms.

[26] Encyclopedia Britannica. (2019). Computer simulation. Accessed on: November 17, 2019. [Online] Available at: https://www.britannica.com/technology/computer-simulation.

[27] Visual Components. (2019). Simulation vs. Visualization - what's the difference? - Visual Components Blog. Accessed on: November 17, 2019. [Online] Available at: https://www.visualcomponents.com/insights/blog/simulation-vs-visualization-difference/.

[28] Snoj, B., Pisnik Korda, A. and Mumel, D. (2004). The relationships among perceived quality, perceived risk and perceived product value. Journal of Product & Brand Management, 13(3), pp.156-167.

[29] Thoughtworks.com. (2019). Continuous integration | ThoughtWorks. Accessed on: November 24, 2019. [Online] Available at: https://www.thoughtworks.com/continuous-integration.

[30] Vienne, F., Caro, S., Désiré, L., Auberlet, J., Rosey, F., et al. (2014) Driving simulator: an innovative tool to test new road infrastructures. TRA - Transport Research Arena, Apr 2014, Paris, France.

[31] Web.tecnico.ulisboa.pt. (2019). Virtual Reality : Introduction. Accessed on: November 17, 2019. [Online] Available at: http://web.tecnico.ulisboa.pt/ist188480/cmul/introduction.html.

[32] Sciencedirect.com. (2019). Graphics Processing Unit - an overview | ScienceDirect Topics. Accessed on: November 17, 2019. [Online] Available at: https://www.sciencedirect.com/topics/engineering/graphics-processing-unit.

[33] Ansys.com (2019). SPEOS Optical System Design Software | ANSYS. Accessed on: July 10, 2019. [Online] Available at: https://www.ansys.com/products/optical/ansys-speos.

[34] SPEOS. (2018). ANSYS Optis. (*Software manual*)

[35] Volvocars.com. (2019). "Designen flyttar gränserna för oss". Accessed on: November 24, 2019. [Online] Available at: https://www.volvocars.com/se/volvomagasin/artikel/designen-flyttar-granserna-for-oss.

[36] Your future Volvo will burst with computing power | Volvo Car Group. (2019). Your future Volvo will burst with computing power | Volvo Car Group. Accessed on: November 24, 2019. [Online] Available at: https://group.volvocars.com/news/future-mobility/2018/your-future-volvo-will-burst-with-computing-power.

[37] Media.volvocars.com. (2019). Press Material - Images - Volvo Cars Global Media Newsroom. Accessed on: November 24, 2019. [Online] Available at: https://www.media.volvocars.com/global/en-gb/media/photos/list.

[38] martinfowler.com. (2019). Continuous Integration. Accessed on: November 24, 2019. [Online] Available at: https://www.martinfowler.com/articles/continuousIntegration.html.

[39] Ansys.com (2019). ANSYS VRXPERIENCE. Accessed on: July 10, 2019. [Online] Available at: https://www.ansys.com/products/systems/ansys-vrxperience.

[40] VRXperience. (2019). ANSYS Optis. (*Software manual*)

[41] Technologies, U. (2019). Automotive, Transportation & Manufacturing | Unity. Accessed on: June 25, 2019. [Online] Available at: https://unity.com/solutions/automotive-transportation-manufacturing.

[42] Bergström, D. and Göransson, R. (2016). Model- and Hardware-in-the-Loop Testing in a Model-Based Design Workflow. Lund University, LUP Student Papers. Accessed on: November 24, 2019. [Online] Available at: https://lup.lub.lu.se/student-papers/search/publication/8776530.

[43] Sturm, O. (2011). Functional Programming in C# : Classic Programming Techniques for Modern Projects.

[44] Merriam-webster.com. (2019). Definition of RESEARCH. Accessed on: October 15, 2019. [Online] Available at: https://www.merriam-webster.com/dictionary/research.

[45] Denscombe, M. (2014). The Good Research Guide for small-scale social research projects.

[46] Saldana, J. (2011). Fundamentals of Qualitative Research.

[47] C. Boyce and P. Neale, "Conducting In-Depth Interviews: A Guide for Designing and Conducting In-Depth Interviews for Evaluation Input," Pathfind. Int., vol. 2, no. May, pp. 1–16, 2006.

[48] P. Cronin, F. Ryan, and M. Coughlan, "Undertaking a literature review: a step-by-step approach," Br. J. Nurs., vol. 17, no. 1, pp. 38–43, 2008.

[49] Willing, R. (2019). Energy Efficiency and CRI. Rich Brilliant Willing. Accessed on: November 27, 2019. [Online] Available at: https://richbrilliantwilling.com/blogs/light-reading/15947112-energy-efficiency-and-cri.

[50] Almefelt, L. (2017). The Requirements Specification - Methods, guidelines, applications. Chalmers University of Technology (*Lecture Notes*).

[51] P. Åhlström and C. Karlsson, "Change processes towards lean production," Int. J. Oper. Prod. Manag., vol. 16, no. 11, pp. 42–56, Jan. 1996.

[52] Sciencedirect.com. (2016). Affinity Diagram - an overview | ScienceDirect Topics. Accessed on: October 27, 2019. [Online] Available at: https://www.sciencedirect.com/topics/engineering/affinity-diagram.

[53] UX Articles by UIE. (2004). The KJ-Technique: A Group Process for Establishing Priorities. Accessed on: October 27, 2019. [Online] Available at: https://articles.uie.com/kj_technique/.

[54] M. L. Garcia and O. H. Bray, "Fundamentals of Technology Road mapping," Sandia National Laboratories. 1997.

[55] Technologies, U. (2019). Automotive, Transportation & Manufacturing | Unity. Accessed on: June 25, 2019. [Online] Available at: https://unity.com/solutions/automotive-transportation-manufacturing.

[56] Technologies, U. (2019). Automotive, Transportation & Manufacturing | Unity. Accessed on: May 02, 2019. [Online] Available at: https://unity3d.com/unity/roadmap.

A

Appendix

A.1 KJ Analysis

A.1.1 Rank 1 - Unity, SIL, SPEOS, HIL and VRX Progressive mode

Unity (Rank:1)			
Capability	Light sources	Signals	Communication
Unity is a 70% programming environment and 30 % tool where the tool can be built according to preferences	Default ight sources are available in Unity	Can integrate signals (trigger points) to the software	Can accept file over Ethernet
Unity is more used as a tool to visualise the design intent and does not follow the physics of light as of today	Default light sources is used	Unity integrates signals from the physical car software	Can be connected using Ethernet
Used only for visualization purpose	Reproduce patterns by the placement of texture near the light source		Open API (Application Programming Interface)
Nothing should be hardcoded, because it cannot be changed. You have a separate visualization software and separate input controls like mouse and touch pad.			
Used to verify design intent			
The support on IES is on the roadmap			
Ray tracing is possible feature to explore the realistic light behaviour			
Can use codes available for free			
Real time visualizations are possible do not know about simulations.			

Figure A.1: Unity

SIL (Rank:1)
To avoid bench rig use only the SIL
The SWs are in VBF(Volvo Binary Format)
Support CI of application on complete vehicle level
No physical ECU HW
GUI serves debugging and fault tracking

Figure A.2: SIL

SPEOS (Rank:1)			
Capability	File formats	Problems	Material Scan
We can do the ies profile simulation in SPEOS and import to VRX	XMP- Define surface light, there will be uniform distributed light on the surface, whereas in reality it is not uniform.	If the path is too long for the export, then the error message appears.	A physical sample, for scanning in the early phases for the early samples, one sample for grain and texture, and another sample for colour is required.
A separate simulation required to identify the light leakage because it may appear too bright as adaptation has to be adjusted	brdf does not store pattern, only stores optical information, jpeg file gives pattern. It is recommended to use colour and light variation from brdf, and pattern from jpeg.	Exports the CATIA file from the Teamcenter into SPEOS and changes the material properties	Extract spectrum from colour scan brdf and apply in the texture/gloss scan brdf
Adaptation value depends on the candela per m2. It needs experience to set adaptation value.		The axis system (X-axis and Y-axis) needs to be known in order to position the components.	
Next SPEOS version will have box lights with the ies profiles hidden.		The lights components are positioned manually.	

Figure A.3: SPEOS

HIL (Rank:1)		
Capability	Problems	Software
The test are done from bottom up, i.e. units, components, ECU, domain, box car.	It takes long time to setup the rig.	The SW in HIL is updated every 4 hours i.e. continuously integrated.
The results produced are the replication of the real time scenario.	Difficult to track down the nodes specific to light signals.	
The test rig tests are important as it represents the real case scenario.		
All the SW and ECU should be available to setup the HIL		
If there is a fault in the rig, the fault will be there in the production car.		
The car shown on the visualization screen does not represent the real case scenario only in terms of appearance.		
The HIL setup is removed after car is relesed into the market		
It can be accessed from home. You can download the files on your local computer and basically run it from home.		

Figure A.4: HIL

VRX Progressive (Rank:1)				
Capability	Problems	Possibility	Material Scan	File formats
Each frame is calculated in VRX from SPEOS data.	If the path is too long for the export, then the error message appears.	Want to test if VRX can support ADAS features like LiDAR, RADAR	Extract spectrum from colour scan brdf and apply in the texture/gloss scan brdf	brdf does not store pattern, only stores optical information, jpeg file gives pattern. It is recommended to use colour and light variation from brdf, and pattern from jpeg.
R2 release update May 2019: Switch on and off light in shadics, different configurations, interpolate configurations from timeline. R2 will not handle multi-GPU.	If you have some exported .sv5 files, then the .sv5 components will not be imported. There is an intellectual property issue.		A physical sample, for scanning in the early phases for the early samples, one sample for grain and texture and another sample for colour is required.	

Figure A.5: VRX Progressive mode

A.1.2 Rank 2 - MIL, VRX Shadics mode, FSM, Signal, and VPDS

MIL (Rank:2)	
Capability	Problems
The VRXperience files are exported to the Simulink. The signals are sent from Simulink to VRXperience.	Not so robust, not accurate.
Simple and functional Simulink models can be built to test and verify the logic.	The virtual tests are not the exact representation of the real world and there might be changes.
Used for the purpose of Visualization of logics.	
This more like design intent than verifying the actual car software.	
Simulates different scenarios for the headlights.	

Figure A.6: MIL

VRX Shadics (Rank:2)			
Capability	Problems	Material Scan	File formats
Real time can be done with Shadics	If the path is too long for the export, then the error message appears.	Extract spectrum from colour scan brdf and apply in the texture/gloss scan brdf	brdf does not store pattern, only stores optical information, jpeg file gives pattern. It is recommended to use colour and light variation from brdf, and pattern from jpeg.
R2 release update May 2019: Switch on and off light in shadics, different configurations, interpolate configurations from timeline. R2 will not handle multi-GPU.	If you have some exported .sv5 files, then the .sv5 components will not be imported. There is an intellectual property issue.	A physical sample, for scanning in the early phases for the early samples, one sample for grain and texture and another sample for colour is required.	

Figure A.7: VRX Shadics mode

FSM (Rank:2)	
Capability	Problem
Visualisation tool	Low fidelity of light
Early in the VPDS	
Used to verify design intent	
Developed in Unity	
Logics are coded and the system responds to the coded logics.	

Figure A.8: FSM

Signal (Rank:2)
CEM sends the signal to the light sources
Finding relevant signals is important
Add FMU for additional signals

Figure A.9: Signal

VPDS (Rank:2)	
Internal	External
FO should start giving input at the concept phase.	Lights are designed by suppliers and they share the updated components via email, encrypted file sharing system and internal (Volvo Cars) sharing folders.
PQI needs to give feedback on the fucntions written by FO	Request suppliers to provide ies profiles and spectrum.
Materials that are included in the design phase do not have optical properties.	The SPEOS data is not updated during the gates. GDL, suppliers need to be contacted and for them to provide the files it can take many days.
The material document is sent by the material team to the illumination in order to check the right material when simulating.	
Time taking to change the optical material property to each component.	

Figure A.10: VPDS

A.1.3 Rank 3 - ECU

ECU (Rank:3)		
Requirements	Software	
	Internal	External
Generic requirements on lamps for suppliers, slight differences in animations and such, less than 10 %.	Volvo Cars defines how we want to communicate and what signals we want it send and how it should respond.	Software developed by suppliers cannot be modified by Volvo. The ECUs do not have a smart system, it behaves as programmed according to the signals received.
Requirements are written in Elektra	The system is designed in such a manner that when there is a signal that should activate the interior lights, it passes through the exterior light layer.	The ECU developed by suppliers have SW that can be changed only by the supplier.
Latencies of hardware could be found in the Elektra.	There is only one SW for all the modules and the CEM communicates with each ECU/module/HW with separate parameters or signals.	

Figure A.11: ECU

A.1.4 Rank 4 - Illumination content and FMU

Illumination Content (Rank:4)
Variant management

Figure A.12: Illumination Content

FMU (Rank:4)
FMU (Functional mockup units) physical representation of sensor data. Connect to matlab directly and not only autosar.
FMU could be something to test at a basic level.
Overall sketch of the functions, dependencies, which lights can be simplified without actually affecting the behaviour of the function.

Figure A.13: FMU

A.1.5 Rank 5 - Driving Simulator, SPEOS VR and VR

VRX Driving simulator (Rank:5)
Not so robust, not accurate.
Used for the purpose of Visualization

Figure A.14: Driving Simulator

SPEOS VR (Rank:5)
The VR adjusts to the aspect ratio of the window but the other surrounding parts are displayed when viewing with VR and when taking pictures out of it, it looks dispositioned.

Figure A.15: SPEOS VR

VR (Rank:5)
Verification before FDJ is necessary and VR will help this to avoid errors.

Figure A.16: VR