CHALMERS

Air Tightness in Car Coupe

Master's Thesis in the Applied Mechanics

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Department of Applied Mechanics
Division of Vehicle Engineering and Autonomous Systems
Road Vehicle Aerodynamics and Thermal Management
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
[The picture displays a Volvo V40 with a magnifier that metaphors the goal of this project is to develop a leakage detecting method]

Department of Applied Mechanics
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ABSTRACT

This thesis presents developing work about air leakage detecting method for Volvo car body. The purpose of this project is to find out an efficient and effective way of detecting the air leakage point in car body that meets all the requirements given from Volvo Car Corporation. The whole project contains investigation work about air leakage detecting methods existed in all industries nowadays and a complete air leakage detecting system was developed based on the current requirements the company provided.

To achieve the goals, the group firstly conducted deep investigation of the problem, including find out the root of the problem and the effect of the problem. Meanwhile, requirements and desires from the company were gathered, analysed and translated into requirement specifications in order to fully understand the purpose of the project. Based on the preparation work, the group carried a thorough market research regarding air leakage detecting methods which are applied in other competitiveness automobile companies and industries. Later on, a set of evaluating system were applied to scientifically estimate each methods found. Depended on the methods evaluation result, the group decided to proceed with methods that involve in devices-aided. During the concept development phase, different concepts were generated based on the benchmarking result or combined from each other and later on being eliminated according to systematic evaluation procedures, which involved in Weight Decision Matrix and Kesselring Matrix. It is worth mentioning that the concept development phase is a circulation between concept generation and concept elimination, i.e. new concepts were generated from last elimination and passed to next elimination with old remaining concepts.

At last, three different concepts fit in three different testing circumstances were raised and explained in detail. Along with the conclusion of the development results, the group also provided the company with cost estimation for each concepts.

Key words: *air leakage, detecting method, concept development*

Contents

Abbreviations:

VCC	Volvo Car Corporation.
NVH	Noise, vibration and harshness
mbar	Millibar.
°C	Degree Celsius.
CFD	Computational fluid dynamics.
L (G)	General leakage amount in complete car.
L(A,L(B),L(C),L(D)	Amount of leakage found at each points A,B,C,D.
B1, B2	Concepts generated based on combination.
A1, A2, ……..A9	Concepts generated from Morphological matrix.
C1, C2, C3	Final concepts.

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Preface

This master thesis was performed at Tightness Group, Body & Trim Department at Volvo Car Corporation (VCC) in Gothenburg during the first half year of 2014. The supervisor for the thesis has been Jari Söderström, Technical Special B&T at Dept. 93130 at VCC, and the examiner has been Lennart Löfdahl, professor from Applied Mechanics from Chalmers University of Technology.

Doing master thesis in a big company is both exciting and challenging experience for us. It was never an easy journey, but luckily, we were not alone on the way. That is why we would like to thank all the people that helped us and shown a beacon of light.

We would like to express our gratitude to our examiner Lennart Löfdahl for his advice and tips. His support and continuous feedback motivated us throughout the project and was essential for the success of the project.

Specially, we would like to thank our supervisor Jari Söderström, Claes Annerstedt, Göran Nyman and other colleagues in Tightness Group. They kindly provided us with valuable information and guided us towards the right path. The tremendous support from them helped us go through the toughest period.

At last, we appreciate the help from VCC. Especially the colleagues from Device Supporting Office, Timo Nyberg and Tommy Gundersen. They offered us a lot of help and positive inputs that inspired us to accomplish this project.

Finally, it should be noted that the thesis could never have been conducted without the great patience and understanding from our families and friends.

Thank you for your interest and hope you will enjoy the following reading.

Göteborg August 2014

Wuwei and Ganesh

1 Introduction

In this introducing chapter, the company Volvo Car Corporation is described with its existing products and current situation in the market. Further on the problem which is raised by the company and given to the project group is fully analysed and defined. At last, the scope and aim of the project is explained.

1.1 Company

Nowadays, as the customers are demanding for higher quality and less energy-consumption cars, the Volvo Car Corporation (*VCC*) has always endeavoured to provide better cars that could enlarger its usability and meanwhile lower the environmental impact. As a world's leading automobile company in pursuing safety cars, Volvo Car Corporation is focused on development, production and sale of sport utility vehicles, station wagon, sedan, compact executive sedan and coupes.

In year 1927, the company was founded in Gothenburg, Sweden, which was created as a subsidiary company owned by SKF. 7 years later as SKF sold most of the shares of the company, Volvo Cars was owned by Volvo AB until 1999, when it was acquired by the Ford Motor Company. But a Chinese domestic automobile company Zhejing Geely Holding Group acquired Volvo Cars since 2010 from Ford until now. Since then, Volvo Cars' has boosted its sales in China, United States, etc., with its best-selling car models: XC60, V50, V70, XC90, C30, S40, etc.

1.2 Problem definition

While increasing sales in market, the VCC has received customer complaints constantly regarding car wobbles and unpleasant noise generated at high speed, bad smell goes into car body when driving in air polluted area.

As the problem is addressed clearly many times by customers and the company, the project group has investigated deeply into the problem by breaking down the problem into details to find the root of the issue. Understanding the root cause of a problem may reveal solutions that would not otherwise be considered when a more narrow view of the problem is used (Liker, 2006). The analysis of the root cause concerning VCC's problem with air leakage was conducted by a Fault Analysis Tree, which is shown in Figure 1 below.

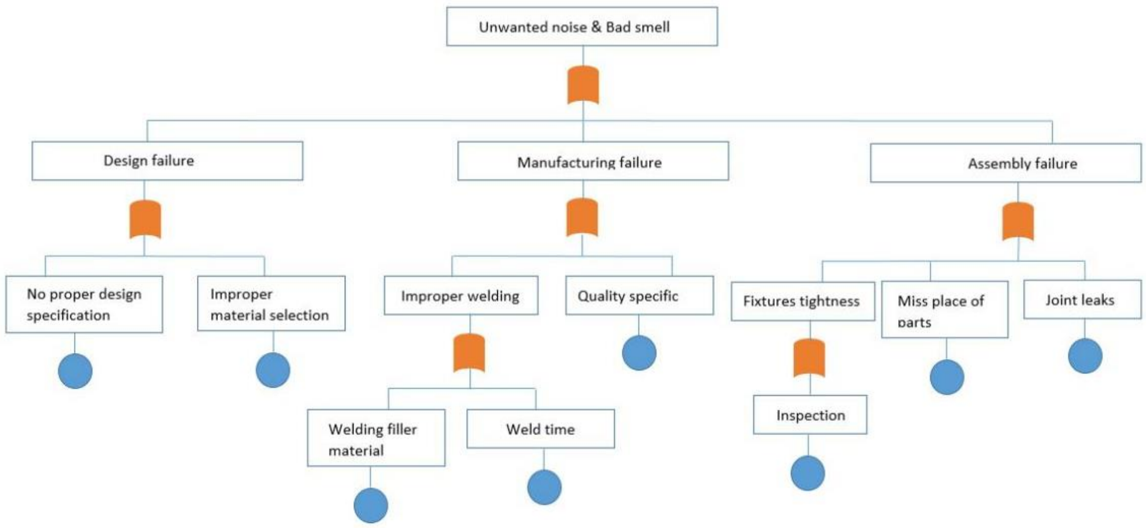


Figure 1 Fault analysis tree

By performing this Fault Analysis Tree, it is not hard to find that the reason for causing the problem is the air tightness failure in car body which results in air leakage into car. While the root causes of the air leakage are due to design failure, manufacture failure and assembly failure during the car developing, manufacturing and assembling phases. So the complete problem definition of this project became:

The Volvo cars are not able to provide completely air-tightness car bodies due to failures in developing, manufacturing and assembling phases.

1.3 Scope & aim

Based on the problems the company is facing, VCC provided a series of constraints and expectations of the desired output could be, which is listed as follows:

- We are looking for a more efficient way of detecting the leakage points compared to existing method.
- We want to know how other car companies' dealing with air leakage problem.
- We want to get wide scope of the current existing leakage detecting methods.
- The method should be able to measure the individual parts of car body.
- The method should be able to measure a complete car body without damaging any parts.
- The method should have long lifecycle and should not cause any negative physical effects like injuries, noise, and toxic gas to the operator.

- The method should be able to carry out by only one operator.
- If possible, the method could show the leakage trail of a leakage point.
- If possible, the testing result could be able to update in system automatically for feature reference.
- If possible, the method could be conducted without physical cars.

Along with the listed points and the problem definition from Chapter 1.2, the aim of the project was formulated as follows:

The aim of the project is to conduct a broad research of leakage detecting methods that exist in car companies or other industries and develop an efficient and effective way of detecting the air leakage point in car body that meets all the requirements given from Volvo Car Corporation.

2 Methods & Approach

In order to achieve the aim, the project was planned and structured into four different phases according to stage gate model by Cooper “The new product process: a decision guide for management” (Cooper, 1988). To confirm the correctness of the approach and to review the deliverables obtained from each phase, two different gates were provided at the ends of first two phases, which are illustrated in Figure 2. The figure shows the overall project approach and the outputs obtained from every phase. Later parts of this chapter describe about each phase in general along with a summary of the work conducted.

Figure 2 The stage-gate process

2.1 Market analysis

Once the problem was studied in detail and identifying its root causes, along with user needs & expectations, the benchmarking of techniques followed by analysis of competitor’s status were conducted. Knowledge on current market situation was obtained through interviews and observation methods for collection of user data. This provided a better understanding of the problem statement. This phase was set to be completed by the first gate where the benchmarking result was presented. Detailed information about this process is presented in Chapter 3.

2.2 Concept development

In order to optimize the best concept which could solve the mission statement, several brainstorming sessions were conducted. The brainstorming sessions led to a creative and design oriented approach and utilized sketches in generating the concepts. Many concepts generated which were optimized later on by stepwise eliminations in order to select the best suited concept (Liker, 2006).

This phase was initiated by analysing the customer problems and translating the customer needs into requirements and desires, which will lead to the development of possible fulfilling solutions to their expectations. The concepts were created and developed by using a morphological matrix, which is presented in Appendix E. These generated concepts were later evaluated and screened based on comparison with each other and most importantly against the requirements.

During the evaluation, new concepts were also generated by the combination of eliminated concepts. Concepts which did not meet the customer needs were removed and the rest where ranked by using Kesselring Matrix. This phase was completed by the second gate where the final concepts were presented. The concept development phase is further described in Chapter 4.

2.3 Evaluation & Conclusion

After the selection of final developed solution, various tests were conducted and evaluation was performed in order to check if the final solution has fulfilled the requirements and desires of the users. Further, costs were analysed and the performance of the products were tested in various areas and surroundings. Conclusion was performed by comparing the final concepts with the requirement specification. In order to represent the difference and benefits achieved by the final concepts, the entire process was described in Chapter 5 and Chapter 6.

Documentation was performed at every stage for the preservation of data and essential details. Finally the data was carefully sorted and documented during optimization of results. All the essential data was compiled into the report.

3 Market Analysis

In this chapter, a deep market research was carried out regarding air leakage detecting method applied in other competitiveness automobile companies and other industries. 10 detecting concepts were found and fully analysed based on their performance in identifying air leakage in reality. A structured comparison of these 10 concepts was provided in order to get clearer understanding of a feasible testing method in this project.

As it was required by Volvo Car Corporation, a profound market analysis needs to be conducted in order to get a deep comprehend of the problem and obtain an overall picture of how other car companies and industries deal with the same leakage problem. Based on the market analysis, the background of the problem will be clearly shown and it might enlighten the group with concepts generation which will be carried later on.

Before the actual market research, the definition of leakage in this project was elaborated in Chapter 3.1. Secondly, the market research scope that matches this project was brought forward in later chapter. Lastly, the benchmarking result was stated in detail by means of listing and analysing the 10 air leakage detecting methods that were found in all industries, which was followed by a structured comparison of the existing 10 methods. The flow chart of this phrase can be seen in Figure 3.

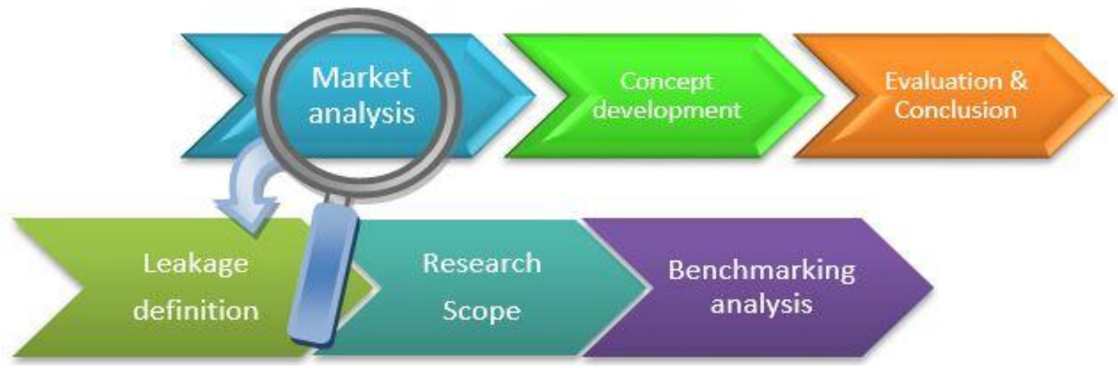


Figure 3 Market research workflow

3.1 Leakage definition

The process of identifying an air leakage flow is called air leakage detecting. Air leakage requires the measurement of very small flow rates of a gas. However, leak flow can be described as volume leak flow or mass leak flow. Volume leak flow is the rate of volume change over time, i.e., the air is measured in volume units over time. Mass leak flow is the rate of mass change over time, such as grams per minute or milligrams per second. It is not hard to see that the correlation between volume and mass leak flow is given in the equation as follows:

$$m = Q \times p \qquad (3.1)$$

In this equation, m is mass flow, Q is volume flow and p is the density of the air, which is measured in milligrams per cubic centimetre *(Sagi, Hemi, 2014).*

Since the previous air leakage tests were been carried in volume flow by VCC, this project work will continue using the same measurement method and standard unit, i.e., litre per second (l/s).

3.2 Market research scope

Since air leakage is a newly aroused concern to automobile industries in recent years, so not much previous work or references can be found at present. To deal with this problem, the project group on one hand contacted related personnel contacts in other car companies regarding air leakage issue, on the other hand, the group looked into other industries, like container, construction, bullet train, air crafts and submarine, to get wider information source of this issue. The market research scope can be seen as following Table 1:

Table 1 Market research Scope

Equipment	Test Methods	Industries
Ultrasonic detector	Soap bubble	Car companies
Air flow detector	Fluorescent	Bullet train
Thermal camera	Smoke	Air crafts
	Stethoscope	Submarine
	Water bubble	Container
		Construction

3.3 Benchmarking results

Based on the market research scope stated above, the project group found various air leakage detecting concepts that are existed on the market and still under usage, which were sorted into 10 different kinds as listed below:

3.3.1 Bubble immersion concept

In the bubble immersion test, the component which needs to be air leakage checked is firstly attached onto a fixture and sealed to reach an enclosed space before it is immersed into water. The operator looks for a stream of bubbles and observes the size of them escaping from the testing piece in a certain time (As shown in Figure 4). Water property, operator attention and the quality of the sealing area make this test very time-consuming and messy *(Sagi, Hemi, 2014).* But, however, due to the low instrumental cost and handy testing equipment, this concept is still under usage. It is not hard to see that the bubble test could only be used to identify the point of a leak other than the quantity of leakage *(Production Leak Testing, 2014).* Several variations of this concept includes: using special liquid that can immerse more bubble other than water, using vacuum to reduce the water pressure on the part.

Figure 4 Bubble immersion

3.3.2 Pressure decay concept (air compressor)

The pressure decay test device works on a given control volume of pressure in an enclosed space and calculates leak flow rate. When operating the pressure decay device, enough time should be allowed for a steady decay to develop. It is a temperature-sensitive test since air density depends on the pressure and temperature *(Sagi, Hemi, 2014).* Moreover, the larger the tested volume, the less sensitive the instrument will be. In general, it is a method to identify the quantity of leak instead of the point of leak with a very common, relatively simple and low cost technique.

Figure 5 Air compressor

3.3.3 Trace gas concept

In the trace gas concept, the testing piece is pressurized with a trace gas like helium, halogen and hydrogen. The concentration of the trace gas leaking out around the testing piece will be later on measured *(Sagi, Hemi, 2014)*. The trace gas used in this method is inactive, which is environmental-friendly and will not damage the testing piece. However, the trace gas is expensive. It might cost more than $100,000 on continuous test operations per year. Plus the sensitivity of the method differs vary depending on the operator, tracer gas used and the type of instrument *(Production Leak Testing, 2014)*. This method should be used as a pre-screen in combination with other detecting method other than being used as a final qualification leak test (See Figure 6).

Figure 6 Tracer gas sniffer

3.3.4 Soapy water spray concept

By applying soap solution to joints and pressurized the testing piece, it is easy to identify some bubbles coming out. The more bubbles, the larger the leak. It is a simple method to for pinpointing multiple small leaks in a specific area *(How to implement leak detection techniques in compressed air, 2012)*. But it can be very time-consuming and messy (See Figure 7).

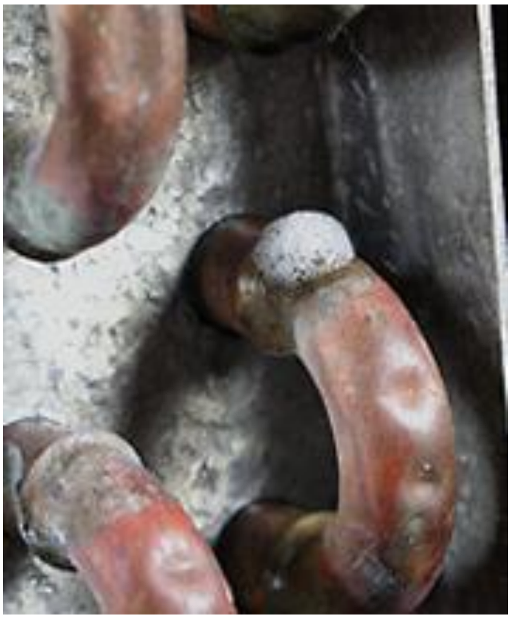


Figure 7 Soapy water spray

3.3.5 Fluorescent addictive concept

In this concept, the fluorescent is injected into the system with oil and detected by using an ultra violet lamp in a dark environment. It is an effective maintenance tool for quick testing by revealing the trace of leak (Guide to good leak testing, 2009). However, the additive must be cleaned off after the leak test, so it adds more time-consuming work afterwards. This method has been used to check aircraft fuel tanks and fluid systems for leaks (See Figure 8).

Figure 8 Fluorescent addictive concept

3.3.6 Ultrasonic detector concept

The ultrasonic detector is a newly developed device that could detect the ultrasonic wave launched by an emitter and suggest a signal by beeping sound *(How to implement leak detection techniques in compressed air, 2012)*. By keeping the emitter inside the closed testing piece and moving the receiver slowly around the surface, it is possible to hear sound frequency difference by bare ears. According to different kinds of testing pieces, the strength of the emitter could be adjusted, same as the sensitivity of the receiver. Depending on their sophistication, an ultrasonic detector cost between $750 to $5,000 (See Figure 9).

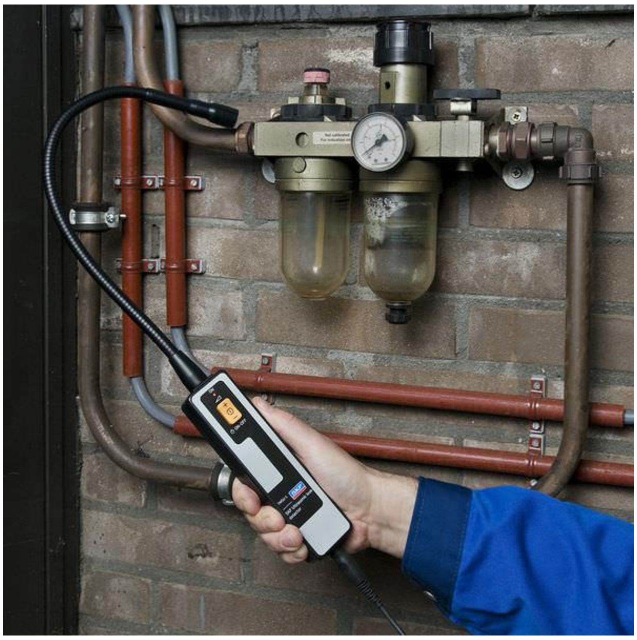


Figure 9 Ultrasonic detector concept

3.3.7 Stethoscope listening concept

This is the simplest and oldest way of testing. The stethoscope probe will be placed close to the pressurized testing piece and move along with the suspect leaking point. The operator is possibly to hear hissing sound different when it reaches a leaking point *(How to implement leak detection techniques in compressed air, 2012)*. It requires the whole working environment to be extremely quiet. However, it could not indicate how big is the leakage, but pointing out where the leakage locates (See Figure 10).

Figure 10 Stethoscope Listening

3.3.8 Air flow detector concept

Air flow detect concept relies on the air flow sensor, where the testing piece is pressurized and the air leakage will be identified directly by using an air flow meter, or known as air flow detector. The air supply is not isolated from the testing piece, thus the flow out is equal to the flow into the part as measured by the air flow detector *(Production Leak Testing, 2014).* This method can not only identify the leak point but also indicates the quantity of the leak (See Figure 11).

Figure 11 Air flow detector

3.3.9 Thermal image camera concept

Thermal Image Camera has been applied to construction industry to check air leakage in buildings for many years. Based on detected temperature differences, thermal camera can create a crisp image by showing the colour changes of the testing piece. Some advanced type of thermal camera can also make it possible to read the temperature value of a specific point (*FLIR Systems, I, 2011)*. According to the group's survey, this method has not been used in any automobile industry (See Figure 12).

Figure 12 Thermal image camera

3.3.10 Manual sense concept

Manual sense is a primitive way to test air leakage. This concept needs the operator to touch or approaching the testing piece by hand. But according to experienced test engineers, this method could be applied to some quick check but not reliable test results since it requires high physical demand to the operator. Moreover, it can be sometimes dangerous if the hand reaches sharp edge without noticing (See Figure 13).

Figure 13 Manual sense

3.4 Benchmarking result comparison

As people are limited in their capacity to process information, it is essential that we conduct evaluation according to scientific a set of evaluating system. In this project, the group applied Weight Decision Matrix (Pugh Matrix) and Kesselring Matrix to evaluate the 10 market research results. To reach the same evaluating value on the final concept, same system will be later on used on Concept Elimination phase as well (See Chapter 4).

3.4.1 Weight decision matrix

Weight Decision Matrix, also known as Pugh Matrix, is to evaluate and prioritizes a list of options. The group fist established a list of weighted criteria according to this project and then evaluated each option against those criteria.

In order to get the overall criterion that are important to this project, the group conducted a brainstorming session, which invited colleagues and supervisors to join in. After deep analysis and discussion based on the project requirements, 10 criterion were chosen, i.e. Usability, Accuracy, Time saving, Long lifecycle, Cost, Maintenance, Operator safety, Support device, Number of parts measured and Damage occurrence.

The next step is to evaluate each choice against each criteria. As shown in Table 2, we established a baseline. For each criterion, we rated each other alternative in comparison to the baseline, using scores of better (+1), same (0), or better (–1). At last, we summed up each option’s rating by the weight and scaled them according to the Importance in Percentage (Table 3).

As it is clearly shown in the Appendix A, the criterion with the highest scale are the most important, while the criterion with the scale of 1 has the least importance. This Weight Decision Matrix will continue to be used in later Concept Elimination phase.

Table 2 Weight decision matrix

WEIGHT DECISION MATRIX													
Criterion	A	B	C	D	E	F	G	H	I	J	sum	sum/total	Scale
A - Usability	-	1	0.5	1	1	0.5	0	0	1	1	6	13.30%	4
B - Accuracy	0	-	1	1	1	1	0.5	1	1	1	7.5	16.70%	5
C - Time saving	0.5	0	-	1	1	0.5	0	1	1	1	6	13.30%	4
D - Long lifecycle	0	0	0	-	1	0.5	0	0	0	0.5	2	4.40%	2
E - Cost	0	0	0	0	-	0.5	0	0.5	0	0	1	2.20%	1
F - Maintenance	0.5	0	0.5	0.5	0.5	-	0	0	0	0	2	4.40%	2
G - Operator safety	1	0.5	1	1	1	1	-	1	1	1	8.5	18.90%	5
H - Support device	1	0	0	1	0.5	1	0	-	1	1	5.5	12.20%	4
I - No. of parts measure	0	0	0	1	1	1	0	0	-	1	4	8.90%	3
J - Damage occurance	0	0	0	0.5	1	1	0	0	0	-	2.5	5.60%	2

Table 3 Importance in scale

Importance in %	Importance in Scale
0% - 3.8%	1
3.8% - 7.6%	2
7.6% - 11.4%	3
11.4% - 15.2%	4
15.2% - 18.9%	5

3.4.2 Kesselring matrix

The Kesselring Matrix is a visualization technique that allows different variant to compare with each other. In this matrix, the decision is made by using the most important evaluation criteria with weight factors and a grade scale.

As we can see from the Table 4, each concept is graded on each criteria and been multiplied according to the criterion's weight. The total score is summed up and ranked in order. The method with the highest merit value was ranked as number one, i.e. Ultrasonic Detector. A clearer Kesselring matrix could be seen in Appendix B.

Table 4 Kesselring matrix

KESSELRING MATRIX											
Criterion	Leakage Detecting Methods										
	Weigh	Ideal		1. Ultrasonic		2. Thermal Image		3. Fluorescent		4. Air flow detector	
		Grade	Total	Grade	Total	Grade	Total	Grade	Total	Grade	Total
A - Usability	4	5	20	5	20	5	20	4	16	5	20
B - Accuracy	5	5	25	4	20	4	20	4	20	4	20
C - Time saving	4	5	20	5	20	5	20	3	12	4	16
D - Long lifecycle	2	5	10	4	8	3	6	1	2	3	6
E - Cost	1	5	5	5	5	3	3	3	3	4	4
F - Maintenance	2	5	10	4	8	4	8	1	2	4	8
G - Operator safety	5	5	25	5	25	5	25	3	15	5	25
H - Support device	4	5	20	5	20	2	8	1	4	3	12
I - No. of parts measure	3	5	15	5	15	5	15	3	9	4	12
J - Damage occurence	2	5	10	5	10	4	8	4	8	4	8
Total		160		151		133		91		131	
Total/Ideal		1		0.94375		0.83125		0.56875		0.81875	
Ranking		-		1		2		10		3	

Criterion	5. Smoke Gun		6. Tracer Gas sniffer		7. Stethoscope		8. Soap Bubble		9. Water Bubble		10. Manual Sense	
	Grade	Total	Grade	Total	Grade	Total	Grade	Total	Grade	Total	Grade	Total
A - Usability	5	20	4	16	3	12	3	12	2	8	4	16
B - Accuracy	3	15	4	20	3	15	3	15	3	15	2	10
C - Time saving	2	8	4	16	2	8	2	8	5	20	2	8
D - Long lifecycle	1	2	3	6	4	8	5	10	5	10	5	10
E - Cost	4	4	3	3	4	4	4	4	4	4	4	4
F - Maintenance	2	4	1	2	4	8	4	8	4	8	5	10
G - Operator safety	4	20	3	15	5	25	4	20	5	25	5	25
H - Support device	3	12	2	8	3	12	2	8	2	8	3	12
I - No. of parts measure	3	9	4	12	1	3	1	3	1	3	3	9
J - Damage occurence	4	8	4	8	4	8	3	6	2	4	5	10
Total	102		106		103		94		105		114	
Total/Ideal	0.6375		0.6625		0.64375		0.5875		0.65625		0.7125	
Ranking	8		5		7		9		6		4	

A - Usability	
Value	Grade
2 person hard	1
2 person easy	2
1 person hard	3
1 person easy	4
1 person very easy	5

B - Accuracy	
Value	Grade
Roughly	1
Less accurate	2
Medium	3
Accurate	4
Very accurate	5

C - Time saving	
Value	Grade
> 1 day	1
1 day	2
0,5 day	3
1 hr	4
< 0,5 hr	5

D - Long lifecycle	
Value	Grade
Replace every 1 yr	1
Replace every 3 yrs	2
Replace every 5 yrs	3
Replace every 10 yrs	4
Never replace	5

E - Cost	
Value	Grade
>100,000	1
50,000 - 100,000	2
20,000 - 50,000	3
10,000 - 20,000	4
< 10,000	5

F - Maintenance	
Value	Grade
Once a day	1
Once a week	2
Once a month	3
Once a year	4
Never	5

G - Operator safety	
Value	Grade
Very dangerous	1
Dangerous	2
Medium	3
Safe	4
Very safe	5

H - Support device	
Value	Grade
More support device	1
2 support device	2
1 support device	3
depends upon	4
No support device	5

I - No. of parts measured	
Value	Grade
Single part	1
Two parts	2
Several parts	3
More parts	4
Complete car	5

J - Damage occurance	
Value	Grade
More damage	1
Damage	2
Little damage	3
Neither or	4
No damage	5

However, this matrix result only reflects over the result other than points out which concept is the best. Since there could be very small difference between the ranked concepts, uncertainties in the weight factors or an uneven balance between the grades (from 1 to 5).

As the Kesselring Matrix result shows, the top three concepts are all with devices-assisted other than manual detecting. It gave the project group a hint that the better solution might lies in optimizing the detecting device.

4 Concept Development

Different aspects of current market solutions and customer needs were analysed through the interviews. The target product specifications were developed by brainstorming the conceptual design and potential technological solutions based on the interviews. A stepwise screening of the proposed specifications was carried out in order to develop the best concept which meets the product requirements.

4.1 Requirement specification

The requirement specification was developed to understand the expectations and needs of customers to build the final concept for the solution. This requirement specification was used as a central document during the whole project. According to Ulrich and Eppinger (2012), customer needs leads to a huge margin for subjective interpretation and requires to be translated to measurable terms. Such specifications have to be updated and changed when new circumstances and restrictions are revealed, making it to an imperative document to reach a successful product (Ulrich, 2012).

Design specifications were formulated by translating the customer needs and wishes, derived from the market analysis (See Chapter 3), into requirements in measurable terms. These requirements were listed and categorized based on the data collected through interviews, observations and questionnaires. Some of the parameters essential to make the product functional were to be added to the list apart from the customer requirements. A total of eight requirements and desires were identified. This was done in collaboration with VCC. To be able to follow up on the customer requirements, measurable target values and evaluation methods were specified and discussed. Appendix C.

A proper hierarchy was created and more important requirements were differentiated from less vital ones. Each requirement was rated to be either a requirement or desire. By this way, evaluation of competing concepts was made more reliable and clear, through motivation of choices. This makes important targets easy to follow.

4.2 Concept Development Process

"He who chooses the beginning of the road chooses the place it leads to. It is the means that determines the end" - Harry Emerson Fosdick

The quote well emphasizes the importance of selecting the right concept from the beginning. By using different product development methods, the team generated an alternative solution concept in response to the needs and requirements identified throughout the process. The concept development was structured and divided into four different steps which is illustrated in Figure 14.

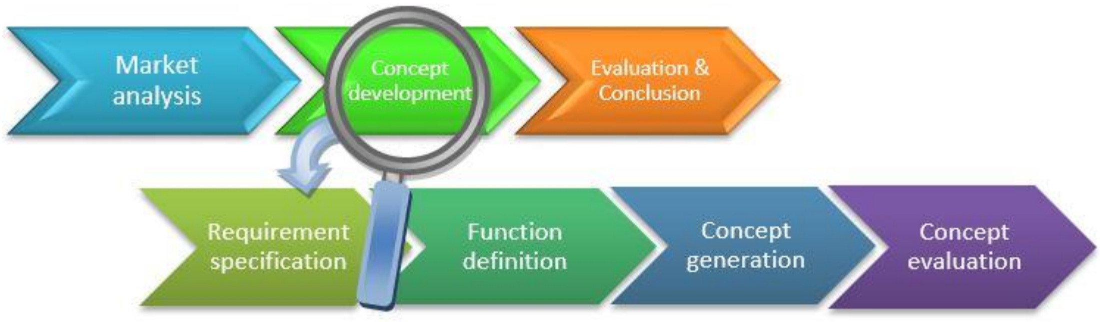


Figure 14 Process of Concept Development phase 1

With the knowledge from the previous projects, these steps were selected, in order to fit the project as recommended in the books, The Value Model (Lindstedt, 2003) and Product Design and Development (Ulrich, 2012).

During concept generation, the process followed was, the set-based approach in relation to lean development. This enables the development of the final solution through the convergent process (Liker, 2006).

The concept development phase was initiated with wide range of concepts gathered through brainstorming sessions. There were eight concepts generated during concept generation stage and these were passed through three stages for a step wise screening. Further, the concepts were assigned different colour codes. The blue circles represent the concepts generated from the morphological matrix and through brain storming, while the concepts which did not fulfil the requirements where removed. These are represented through red circles. Yellow circles represent concepts newly generated by combining and improving eliminated concepts in between stages. Finally, green circles represent the concepts which had been chosen after optimization to fulfil the requirements of the users. Figure 15 could express this process vividly.

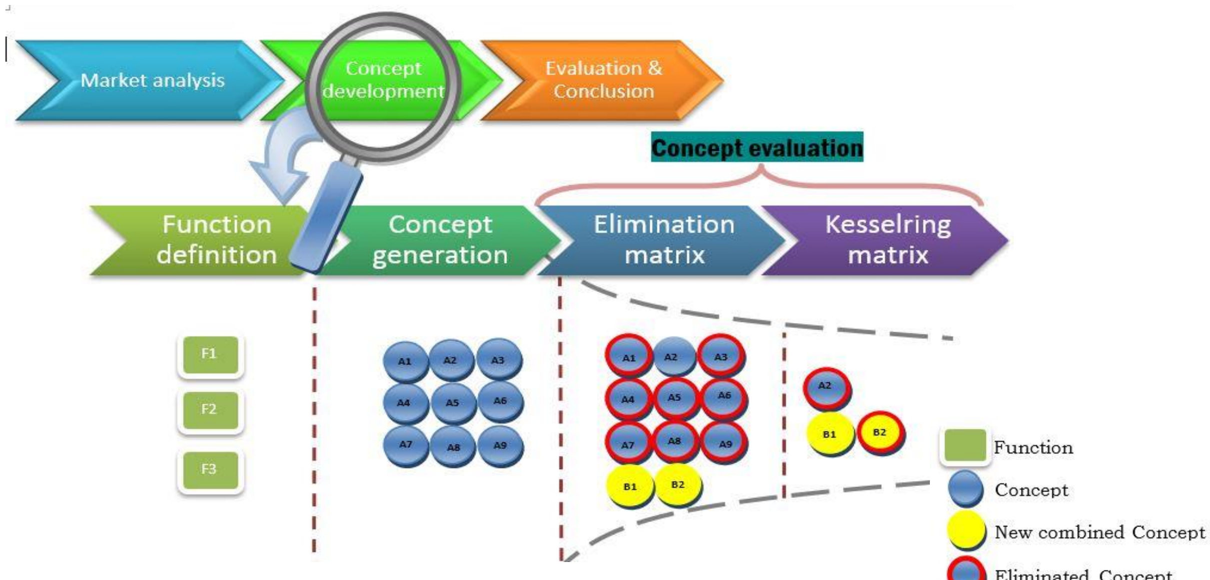


Figure 15 Process of Concept Development phase 2

4.2.1 Tests

To truly understand the problem and focus the concepts on right track, tests were conducted frequently. Initially the company practiced tests were analysed and demerits of the tests were inferred. Then the novel tests were implemented and practical implications were studied. Based on the level of feasibility of the tests, appropriate test was chosen.

4.2.1.1 Existing physical test method:

In the pre-production stage of a car, different part and complete car is been tested for leakages. In Volvo Cars Corporation (VCC), the traditional method they follow for checking leakages is by passing compressed air of 1.5 Mbar through the parts to be tested. When checking the side mirrors, the mirrors are loaded on to the top of a wooden box, compressed air is passed from wooden box through the bottom of the mirror. While this being carried out smoke is passed on the outers, leakage is found when the smoke is move away from the surface of the mirror. The physical model of the test is presented in the Figure 16.

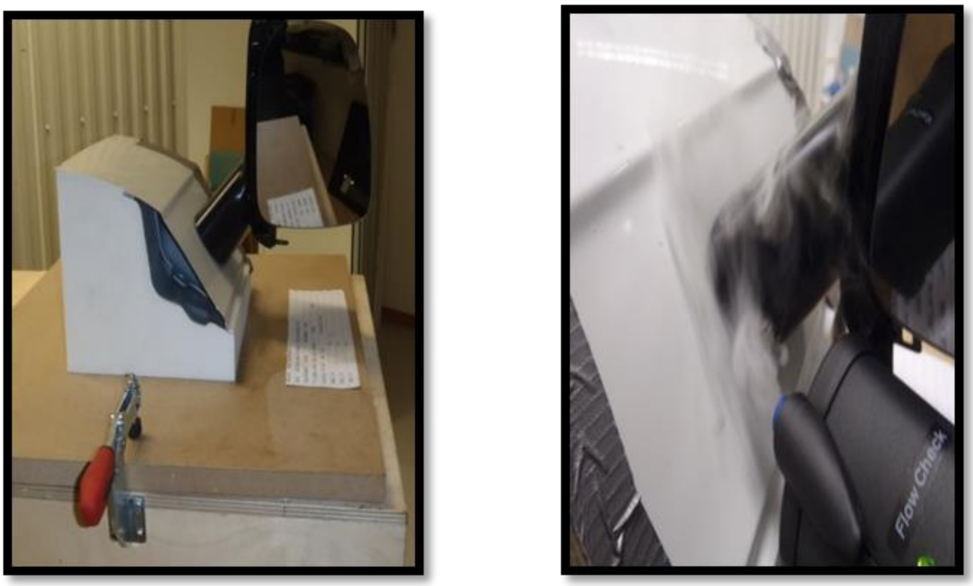


Figure 16 Compressed air test along with smoke gun on side mirror

The car doors are fixed to the wooden fixture and compressed air is passed through the fixture in to the car door. Now the smoke gun is been brought near the door corners and handles and by inferring the upward movement of the smoke the leakage points are been diagnosed.

While checking the whole car for the leakages, the front window of the car serves is fixed with a specially designed fixture through which compressed air is passed through the entire car body. By moving the smoke gun or moving the hand through body the leakages are been diagnosed.

The general demerits of this physical testing done by VCC are that the tests leakage points in the car body could be identified but not the amount of leakage in leakage point. Another disadvantage is that the testing thoroughly depends on the level of sensory perception of the individual performing the tests.

4.2.1.2 Testing devices introduced

Idea Generation

Before the idea generation phase, the supporting devices in VCC is been tested for developing novel concepts in air leakage testing.

Different varieties of Ultrasonic, airflow detectors and thermal camera were tested and they were evaluated based on their accuracy, time lag and effectiveness when used. The types of tests and their procedures were designed based on the type of machine chosen which is showed in Table 5.

Table 5 Instruments tests conclusion

Tests	Device Version	Y/N
Airflow Detectors	GHA 598	🟠
	GHA 716	🟠
	GHA707	🟠
	Sensirion	🟢
Ultrasonic Detectors	Airflow ultrasonic	🟠
	Sonic wave ultrasonic	🟡
Thermal	Thermal Camera	🟡

🟢	Focus more
🟡	Need further invesigation
🟠	Eliminated

The types of the physical test developed are discussed below along with their physical construction, methodology along with their merits. They are:

Sensirion:

Sensirion is used in finding out the right amount of air leakage in each and every point can be found.

Operating range:

The car body part to be checked for the leakage is fitted in a fixture and compressed air of 1.5 Mbar is passed through the part. The surface of the part under testing is checked by moving the Sensirion along the specimen’s surface. The sensirion is actually connected to the computer through a USB port. While moving the sensirion over the surface, a corresponding graphs appears on the computer screen with help of the software supported by Sensirion.

Appearance of the peak on the graph corresponding to the Sensirion movement would give us the leakage point and the amount of leak at the point.

Advantages:

- Identifies accurate leakages along with quantity of leakage at each point.
- Simple testing procedure.
- Graphically shows the leakage quantity and stores easily.

Disadvantages:

- More time taken for finding the leakages in a complete car.
- Maybe need an additional operator to keep track of the graph during testing.

Ultrasonic detectror:

Detect leakages air through sonic waves produced by emitter, which is been detected by a receiver.

In this method, the emitter of the ultrasonic equipment is kept inside car at various positions and the receiver is moved manually outside the car. When a leakage is identified the high frequency sound through the head phones which is detected by the receiver, (thereby the output of this detection would in the form of disrupted sound waves represented in a graph, shown in the desktop).

Advantages:

- Identifies accurate leakages.
- Simple testing procedure.

Disadvantages:

- More time taken for finding the leakages in a complete car.
- Cannot identify the quantity of leakage.

Thermal Camera:

The purpose of the thermal camera is to detect the temperature difference on different surfaces.

Operating range: -20°C to 450°C.

Hot or cold air along with compressed air is continuously sent into the car until a certain set temperature is attained uniformly throughout the interior of the vehicle. Using a thermal camera on the exterior surface of the vehicle, the point of leakage can be easily identified by either a dark red spot (when hot air sent inside) or a dark blue spot (when cold air sent inside).

The Figures below show the leakages in the car body, under the working principle when passing the hot air inside the car, in which the red colour indicates the leakage and blue colour represents the cold metal surface of car body.

Figure 17 represents the leak in the seal on passenger front door. The plus sign pointer represents the amount of heat that has been escaping at that point with temperature 33.2°C. The green colour represents its position in the range of 29°C to 39°C, which is represented in the figure below.

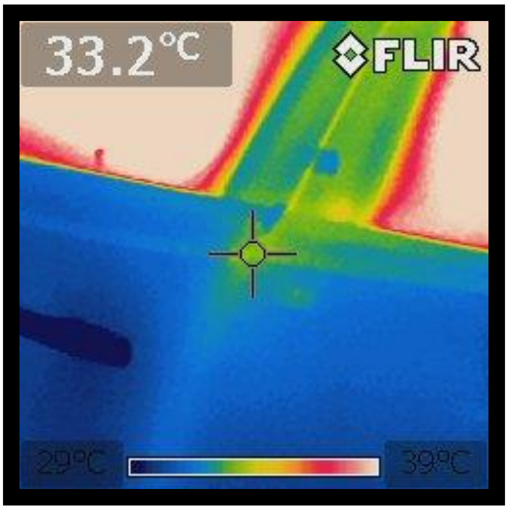


Figure 17 Leakage point between the front and rear door on Volvo 40

Figure 18 represents the leakage on the rear bumper. The plus sign pointer represents the amount of heat is been escaped that the point with temperature 33.9°C. Which is comparatively less when compared other points on the bumper. As the colour red is more on the other points, which has the highest range of heat leakage.

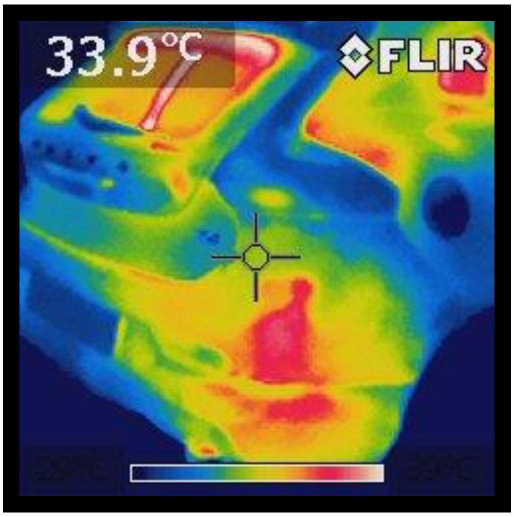


Figure 18 Leakage on the rear bumper on Volvo 40 using thermal camera.

Advantages:

- Identifies hidden leakages.
- Short time taken for finding the leakages in a complete car.
- Simple testing procedures.

Disadvantages:

- Not accurate.
- Needs external devices and proper fixture for compressor attachment.
- Long preparation time is needed before testing.

Table 6 illustrates the comparison for the three device described above. 7 important criterion are measured for each device. From Table 6, it is not hard to judge that all three kinds of device get their merits and shortcomings. Hence, how to use each of them in the right circumstance become an essential question for the group to consider.

Table 6 Device comparison

	Criterion	Thermal camera	Sensirion	Ultrasonic detector
1	No. of operators	1	1 or 2	1
2	Support equipment	Air compressor, fixture, heat blower	Air compressor, fixture, laptop	No
3	Preparation time (min)	5	10 + 5	5
4	Test time (min)	10 - 15	> 30	> 30
5	Test site	Windless, dark	Windless	No
6	Accuracy	★★	★★★	★★★
7	Alternative methods	Cool /Hot	No	No

4.2.2 Function definition

We devised a functional definition in order to decompose the problem into sub-problems using a Black Box model. This helped us in understanding the problem in detail and obtain the right product with all the required specific functions.

The air leakage detection system is kept as the Black box system (Figure 19) and its inputs and outputs were identified. In order to understand the problem, the black box model was developed into a system function chart, in which the leakage detection sub-functions were also included with respect to the connections between them. This chart together with the black box model can be seen in Appendix D. With the help of the chart. The problem was approached by grouping the sub-problems into three main functions which are Detect leakage, Identify amount of leak and supporting device.

Brainstorming was done by pivoting on these three functions to come-up with the sub-solutions, which eventually lead to develop the concepts using the Morphological tool.

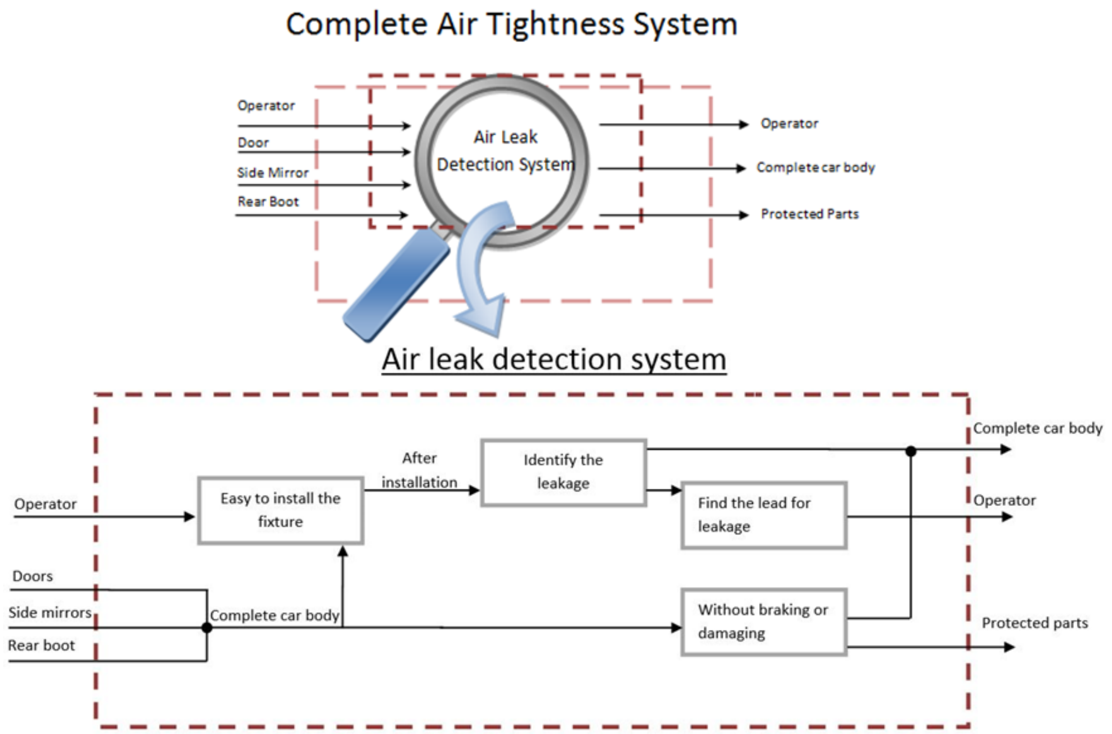


Figure 19 Function system chart

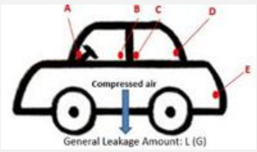
4.2.3 Concept generation

A concept can be defined as both an “approximate description of the technology, working principles, and form of the product” as well as a “concise description of how the product will satisfy customer needs” (Ulrich & Eppinger, 2012). Concept generation is the process by which all of the possible (probable and improbable) solutions for a problem are identified by using various methods such as Morphological matrix et al. (Ulrich, 2012). During the morphological matrix the sub-solutions were generated based on the three main functions identified from the chapter In order to find sub-solutions for the three main functions research was done exploring both external research, such as published literature, existing products, competitor’s research and internal research. In which internal focus methods were further executed through brainstorm sessions and assigning individual assignments within the team. Later, the ideas were visually represented to the project partner which helped understanding and communication of different concepts. Feedback was taken from the project partner after each brainstorming session, thus resulting in new perspectives and new concepts.

Different sub-solutions were found from the external research and internal research and these sub-solutions were brought together using a morphological matrix, where the sub-solutions were summarized facilitating the cross fertilization of the solutions to define a system concept (Ulrich, 2012). The matrix can be studied in Appendix E. Theoretically, hundreds of concepts can be generated from this but considering the feasibility constraints and time constraints, only a few concepts that were generated were shortlisted. Complementary to the morphological matrix, brainstorming meetings were carried out to add new ideas to the collection of concepts. At the end we were ended up with 9 potential concepts which were subject to further optimization were generated Table 7.

In order to show how these concepts work, we chose Concept A1 (Foam bubble with water test equipment) and Concept A2 (Air flow detector optimization) to be described in detail in the following text.

Table 7 List of generated concepts

LIST OF GENERATED CONCEPTS					
No	**Detect leakage**	**Identify amount of leak**	**Supporting devices**	**Concept name**	**Picture**
1	**Foam/Bubble**	**Pressure meter**	**Foam spray**	**A1. Foam / Bubble with water test equipment**	
2	**Air compressor**	**Air flow detector**	**Fixture**	**A2. Air flow detector optimization**	
3	Fluorescent	Amount of light emission	Container	A3. Light detecting	
4	X- Ray vision	Air flow detector	Laptop	A4. X-ray vision	
5	Electric waves	No	Fixture	A5.Electrostatic wave	
6	Thermal scan	Thermal camera	Heaters / Coolers	A6. Thermal camera	
7	Ultrasonic	Ultrasonic reader	No	A7. Ultrasonic	
8	Fluorescent	No	Container	A8. Florescent spray	
9	Air compressor	Pressure meter	Stereoscope	A9. Air compressor with stethoscope	

Foam bubble with water test equipment (A1)

This concept was inspired from the soap bubbles gun. The concept is a combination of foam, pressure meter and foam spray based on the three functions from Morphological matrix. The car which needs to be tested is place in a closed room, foam spray is then used to apply the foam evenly and perfectly around the car. Later, when the pressure is passed inside the car, the foam applied on the leaking surface will lead to bubble popping or create a hollow surface by moving the foam away from that point. Then with the help of pressure meter, the amount of pressure developed at those points can be found easily. See Figure 20.

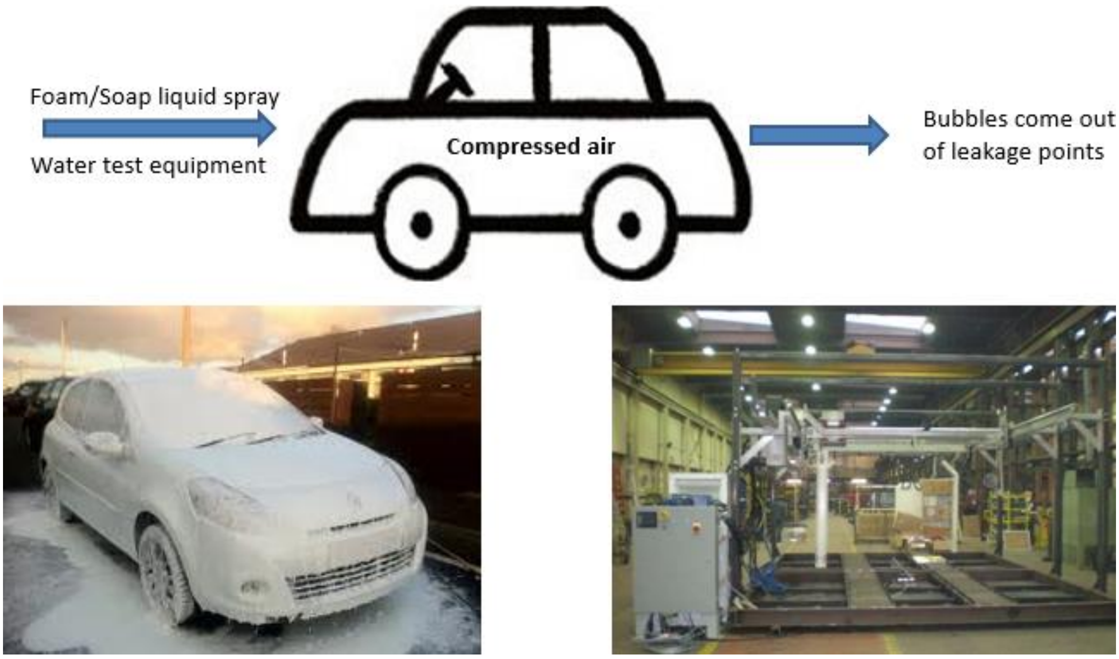


Figure 20 Concept A1: Foam bubble with water test equipment

Air flow detector optimization (A2)

This concept works on the combination of air compressor, air flow detector and fixtures, in order to carry the testing. The testing was conducted by passing the compressed air into the car through the window with the help of a fixture, from which we can also know the amount of pressure passed in and the total amount of leak L(G) and then detect the leak by the help of airflow detector around the car. Each leakage point: A, B, C, D with their leakage quantity: L(A), L(B), L(C), L(D) will be detected by air flow detector and then summed up to get an overall detected leakage amount. By comparing the difference with total leakage amount L(G), it is not hard to calculate the remaining undetected leakage amount. Figure 21 can illustrate how this concept works.

Calculation of undetected leakages:

L (A) + L (B) + L (C) + L (?) = L (G)

L (?) = L (G) – L (A) – L (B) – L (C)

L (?) = L (D) + L (E)

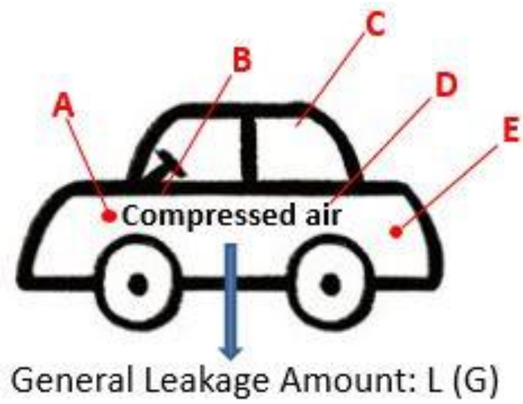


Figure 21 Concept A2: Air flow detector optimization

All the 9 potential concepts which were subject to further optimization were generated, which were all summarized in the Appendix F. The figure indicating the inception of these concepts was also made.

4.2.4 Concept evaluation

The generated concepts developed from morphological matrix were evaluated using comparative decision making, thus finding the best possible solution which would require the least amount of costs i.e. extending the amount of resources for the longest possible period. Narrowing down the concepts based on the competitiveness of each concept during the concept evaluation phase results in a concept that will obviously have the highest potential for becoming the best product by meeting all of the customers' requirements in the best possible way (Ulrich, 2012).

The concept evaluation was done in steps; Elimination Matrix, Kesselring Matrix. To end the evaluation with the best concept, which will be discussed further. During this process, the concepts were not only eliminated but new concepts were also generated from combination of concepts which have been eliminated.

Elimination Matrix:

The elimination matrix is used in the evaluation process to narrow down the amount of concepts which does not fulfil the customer's crucial requirements. The main aim of the matrix is to eliminate the concepts based on performance (function), simplicity / geometry /ergonomics which were drawbacks of the products and devices involved in the concept, to decide if the concepts needed to be further developed or kill or any combinations can be done, before continuing to final evaluation Table 8.

Table 8 Elimination based on the requirements

1.Performance (functions)		
	1.1	Solution able to measure the current & feature leakage problems
	1.2	Able to measure individual parts of the car body
	1.3	Able to measure the complete car body
	1.4	Single solution for both individual part & complete car test
	1.5	Should show the trail of the leakage point
	1.6	Represent the amount of leakage at a point
	1.7	Represent the amount of leakage in a complete car body
2. Simplicity / Geometry / Ergonomics		
	2.1	Maximum people needed to operate
	2.3	Maximum time for installation
	2.5	Minimum people needed to install
	2.6	Easy to operate

This initial methodical procedure is considered as a crucial step as it reduces the total time taken by generating concepts by combination of concepts before taking all the evaluated concepts into Kesselring matrices. Hence, the 9 concepts that were shortlisted from the concept generation were narrowed down to 3 concepts. From which concept “A2. Air flow detector” was selected directly from further development and remaining “B1. Thermal & Sensirion” and “B2. Thermal & Ultrasonic” was generated from the combination of A9, A6 and combination of A9, A7 optimization based on their performance against the rest. The concepts elimination matrix can be seen in the following Table 9, which could be seen clearer in Appendix G as well.

Table 9 Elimination Matrix

	1. Performance (functions)						2. Simplicity / Geometry / Ergonomic				Feasible	Decision	Comments	
	1.1	1.2	1.3	1.5	1.6	1.7	2.1	2.3	2.5	2.6				After further investigation
A1	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	No	There are better solutions for this concept. Needs investigatio	Kill
A2	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Need further development	Yes
A3	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	No	There are better solutions for this concept. Needs investigatio	Kill
A4	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	No	No	There are better solutions for this concept. Needs investigatio	Kill
A5	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	No	No	Yes	Kill - Don't know how to implement	Kill
A6	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Could be combined with other concepts / Kill	Kill
A7	Yes	Yes	Yes	Yes	yes	yes	Yes	Yes	Yes	Yes	Yes	Yes	Could be combined with other concepts / Kill	Kill
A8	Yes	Yes	Yes	Yes	yes	yes	Yes	Yes	Yes	No	No	Yes	Could be combined with other concepts / Kill	Kill
A9	Yes	Yes	Yes	Yes	yes	yes	Yes	No	Yes	No	No	Yes	Further development and combined with A6	Kill
B1	New combined concepts												Conbination of A9 and A6	Yes
B2													Conbination of A9 and A7	Yes

Kesselring Matrix:

For further evaluation of the three chosen concepts, Kesselring matrix was used. In a Kesselring matrix, each concept has been evaluated based on the weightage of the criteria which was developed during the benchmarking, instead of comparing the concepts to a reference concept. The method of Kesselring matrix has been proven to provide more accurate evaluation than the earlier methods, since each criteria differs in importance. This implies that before one starts to evaluate, a process to determine the relative importance has to be done, where one way is to use a weight decision matrix (Persson, Pettersson, & Johannesson, 2004). With the help of weight decision matrix along with the Kesselring matrix, the concepts were scaled down to two high potential concepts which are presented in Appendix H. Where the concept "B1 Thermal & Sensiroin" was ranked first with total score of 152, followed by concept "B2 Thermal & Ultrasonic" with total score of 136. The "B1 Thermal & Sensirion" has highest grades in accuracy, time consumption, safety, ease of measurement of number of parts and no damage accrued on the testing car or car body part. The only criteria where it got low grade when compared to other criteria was cost. Since the grade is higher when cost is compared to ideal weightage. Hence, it satisfies the cost criteria. See Table 10.

Table 10 Kesselring Matrix

KESSELRING MARTIX

Criteria	Methods								
	Weigh	Ideal		A2. Airflow detector		B1. Thermal & Sensiron		B2. Thermal & Ultrasonic	
		Grade	Total	Grade	Total	Grade	Total	Grade	Total
A - Usability	4	5	20	3	12	4	20	4	16
B - Accuracy	5	5	25	4	20	5	25	3	15
C - Time saving	4	5	20	3	12	5	20	5	20
D - Long lifecycle	2	5	10	4	8	5	10	5	10
E - Cost	1	5	5	5	5	3	3	3	3
F - Maintenance	2	5	10	4	8	4	8	3	6
G - Operator safety	5	5	25	5	25	5	25	5	25
H - Support device	4	5	20	3	12	4	16	4	16
I - No. of parts measured	3	5	15	5	15	5	15	5	15
J - Damage occurence	2	5	10	5	10	5	10	5	10
Total		160		127		152		136	
Total/Ideal		1		0.79375		0.95		0.85	
Ranking		-		3		1		2	

5 Final Result

Depended on the systematic concept evaluation result as discussed in Chapter 4, the group refined three final concepts which are suited for three different testing requirements and circumstance. As shown in Table 11, the three concepts were named as C1, C2 and C3 respectively, along with their involved device and testing conditions.

Table 11 Final three concepts

	Concept 1 (C1)	Concept 2 (C2)	Concept 3 (C3)
Device Involved	Thermal camera, Sensirion, heat blower, air compressor	Thermal camera, Ultrasonic detector	Ultrasonic detector
Testing Conditions	For reference car test in car developing phase	In customer site without any heater or air compressor	In production line for quantity car body check
Advantage	Quantify of leakage	Handy and easy	Time-saving

The three concepts with their complete testing procedures were explained in detail in the following text.

5.1 Final C1: Thermal camera + Sensirion

This concept is designed for the circumstance when a reference car model needs to be tested in company completely with some essential equipment like air compressor, heater and computer with Sensirion software. The main detectors are thermal camera and Sensirion air flow detector. It not only helps to pin-point the exact leakage area, but could also suggest the quantity of leakage, which is much needed in reference car for further development phase. The testing procedures for this concept are explained as follows:

1. Place the car in a cool and dark environment; Put on the door fixture and connect to the air compressor; Put one heat blower inside car;
2. Turn on the heat blower and until the car interior body reaches 50 degrees; Meanwhile, put the air compressor into 1.50 mbar;
3. Check the car surface with the thermal camera; find out colour difference in the camera image which indicates the possible leakage area and mark it out;

4. Connect Sensirion to the laptop; Scan the particular surface where was marked in Step3;

5. Pay attention to the Sensirion graphic which is shown on the laptop; Check the peak point of the graph, which indicates the exact leakage point and the leakage amount;

6. Save the graphic of Sensirion result; Do three more similar tests around this area; Find out the average leakage amount;

7. Add the leakage quantity of all the detected points on (A); Compare it to the leakage figure shown on the air compressor (B); If A<B, it means there are some other leakage points remaining detected;

8. Continue following Step 4 to Step7 until A reaches closely to B.

The merit of this concept is that instead of applying Sensirion right in the beginning for complete car checking, which will cost numerous time and labour work, we use the thermal camera to mark out the suspicious leakage areas and later on use the Sensirion to specially check these areas. As a consequence, the efficiency and accuracy of the whole car checking is largely increased.

Additionally, with the help of the Sensirion software, which could show accurate leakage amount for certain point, the requirements of the leakage quantify is being fulfilled.

5.2 Final C2: Thermal camera+ Ultrasonic detector

This concept could be used when a tester is invited to visit a customer site and conduct a quick leakage point identify test for problem cars. The main detectors are thermal camera and ultrasonic. Compared to C1, this concept does not require the need for air compressor, fixture for doors or even laptop; instead, all it needs are thermal camera and ultrasonic detector. The testing procedures for this concept are described as follows:

1. Judge by the environment temperature of customer site; Turn on the car air conditioner if outside temperature is high, e.g. 35 degrees; Vice Versa;

2. Heat / Cool the car until the interior and exterior temperature reach a difference of at least 15 degrees;

3. Use the thermal camera to check the colour difference from the image; Mark our the suspicious areas;

4. Put the Ultrasonic emitter inside the car and use Ultrasonic receiver to scan around the marked areas; Pay attention to the beeping frequency difference (When it detects a leakage, the Ultrasonic receiver will emit more frequent alarm);

5. Carry similar test for two other times to identify the leakage points.

This concept is specially designed for problem cars in the customer site, where you might not be able to get other equipment like air compressor, heat blower and fixtures handy. Only thermal camera and ultrasonic detector could afford to carry this test.

However, unlike concept 1, this concept can only find out the exact leakage point, other than the amount of leakage. But it saves time and does not require some heavy, big equipment, so it is recommended to use in the customer site where only the leakage point is required to be detected.

5.3 Final C3: Ultrasonic detector

This concept is designed especially for the car air leakage test in the production line, where it requires doing very fast and numerous times of check. In this circumstance, the quantity of air leakage is no longer a demand; however, the time consumption for each car test becomes important. Depended on the particularity of this testing condition, the group proposed to only use the Ultrasonic detector to conduct test in this circumstance, which was fully illustrated by the following steps:

1. Put the Ultrasonic emitter inside each car and turn on the signals;
2. Scan the car surface with Ultrasonic receiver, especially the suspicious leakage areas where were identified in Concept 1 under reference car checking result.
3. Continue doing the same test procedure to find the exact leakage point.

According to the test conditions of production line, it demand the tester to use the least time to find out the most leakage point. So air compressor, heat blower are not suitable to apply into this concept. However, in Concept 1, when a reference car is being tested before massive production, the most possible leakage area will be identified and pass on to the later production line tests. As a result, the tester does not need to check the entire car body with the Ultrasonic detector, which will reduce the consumption of checking time.

6 Evaluation & Conclusion

The Chapter 6 includes a summary of the most important conclusion drawn from the project progress, around the final solution. The conclusion is based on the evaluation, which is divided into two steps. Performance test of final solution on existing solution and cost estimation. Also, some of the most important learning outcomes from this solution will be discussed.

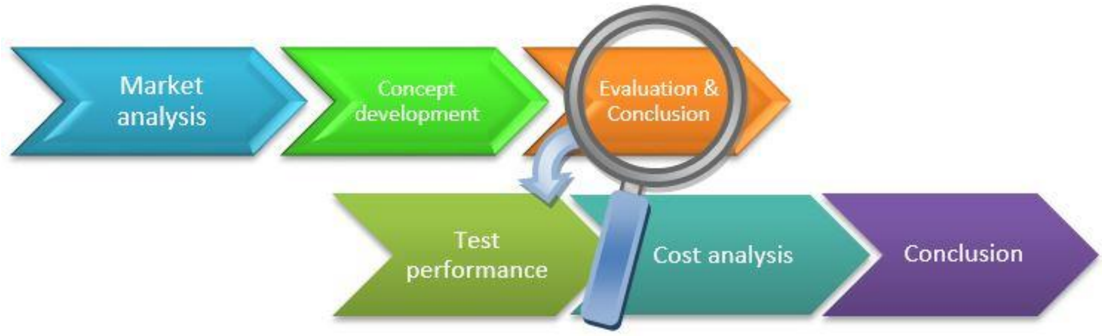


Figure 22 The process of evaluation phase

The proposed final solutions meet the customers' requirements and have potential to solve the existing and future problems. Apart from other solutions developed during the project. Solution "C1. Thermal & Sensirion" has the highest priority of satisfying the customer's criteria and needs.

6.1 Test performance

In order to verify the statement above, a test comparison was performed with the existing solution. All the possible requirements which are needed to be examined and evaluated are considered the most important during this test. Some of the requirements like usability, operation safety, number of parts can be measured and damage occurrence is evaluated by visual inspection and other testing procedures. Other kind requirements include some of the main targets; Accuracy (Roughly/very accurate), time saving, (yes/no), Maintenance(short time /long time) and maximum number of people and time needed to install (1/2) were measured and compared with existing solution by performing Simple tests. Also to have strong statement and prove for the requirements like accuracy, time saving on installation and operation, the test was conducted twice by two different operators to have the standard values.

Main criteria on which the comparison were considered importance were shown in Table 12

Table 12 Tests comparison

Criteria	Previous solution	C1. Thermal & Sensiron	C2. Thermal & Ultrasonic	C3. Ultrasonic
Usability	One person hard	One person easy	One person easy	One person easy
Accuracy	★	★★★	★★★	★★
Time consumption	0.5 day	< 2 hours	< 1 hour	< 0.5 hour
Lifecycle	1 year	5 years	5 years	5 years
Maintenance	Once a year	Once 2 years	Once 2 years	Once 2 years
Safety	Not Safe	Very safe	Very safe	Very safe
Support device	Air flow meter reader	Air Compressor/ Heaters	No support device	No support device
No. of parts measured	Complete car	Complete car	Complete car	Complete car
Damage occurrence	Some damage	No damage	No damage	No damage

6.2 Cost analysis

The cost analysis is required by the company to estimate the right device model and suppliers in terms of benefiting the time efficiency and cost savings. According to VCC representatives, the budget plan for purchasing the needed device is under discussion. Based on the budget limitation, the group carried out a wide benchmarking on the best suppliers who provide products with high quality and reasonable price. Additionally, the device's properties were taken into consideration when comparing the products.

As Table 14 shows, 4 devices need to be purchased by the company. They are: Thermal camera, Sensirion, Ultrasonic detector and Heat blower. However, since one of the essential equipment – Air compressor already exists in VCC in a good working condition, it was not taken into the cost estimation process.

Table 13 Bill of material

No.	Device	Supplier	Models	Cost
1	Thermal camera	FLIR	FLIR i7	18,150 SEK
2	Sensirion	SENSIRION	Low-Pressure-Drop Flow Meter SFM3000	1,377 SEK
3	Ultrasonic detector	SDT270	Ultrasonic Detector SDT-270	27,000SEK
4	Heat blower	CADET	Cadet RCP402S 4000W 240V Garage Heater	1,777 SEK
			Total	**48,200 SEK**

6.3 Conclusion

The proposed solution fits to the mission statement of this project," Air Tightness in Car Coupe" that meets all the requirements of the customer and by this project the brand value of Volvo cars will be increased to a higher level. A summary of the evaluation results is presented in Table 14. As we can see from Table 14, by implementing the new concepts, all the requirement specifications are being fulfilled.

Table 14 Summery of evaluation results for some of the requirements

Requirements	Evaluation results
Solution able to measure the current & feature leakage problems	The solution meets both the present and feature problems
Single solution for both individual part & complete car test (Target value = 4 of 5)	It is possible (Target value =5)
Represent the amount of leakage at a point	With the help of Sensirion the amount of leak at a specific point can be measured
Easy to store the data	The end result can be easily updated/stored in the system
Maximum people needed to operate (2)	One operate is needed
Maximum time for installation (15mins)	Installation time is reduced to 10 mins
Maximum people needed to install (2)	One person is enough
Should not cause any bad effects to the operator	No chemical or toxic gas are used
Endure maximum temperature 120°C	Maximum temperature will be 40°C
Endure minimum temperature - 50°C	Minimum temperature under -20°C

According to VCC representatives, this solution is a strong potential way to do the testing in upcoming production in addition to the existing testing methods. The work that was done within this project confirms that the company who ordered the development is satisfied with the result.

7 Future Work Recommendation

This master thesis was done by a group of two, with tremendous help and guide from internal VCC and university examiner Professor Lennart Löfdahl. By meeting most of the requirement specification, the end result satisfied the goal of this project. However, due to time and resource limitation, the group found some more areas that could be further investigated and improved.

7.1 Sound effect development of Sensirion

As it was introduced in Chapter 5, air flow detector – Sensirion could be used to identify the accurate point of leakages along with its leaking at each point. Since the Sensirion needs to be operated along with a computer software through a USB port, it requires at least two operators to cooperate: one for scanning the car surface with Sensirion device, the other one checks the instant air flow graph appeared on the computer screen and remind his/her co-worker when it comes to the peak of the graph.

However, according to project requirement, only one operator is needed to carry the whole testing phase. So the optimization development work for Sensirion testing becomes essential. In order to cut the needed operator number down to one, the group came up with an idea, i.e. programme the Sensirion software to make it provide a sound effect when the graph figure exceeds some certain amount of leakage.

In that case, only one operator is needed to handle the Sensirion testing by scanning the surface of the car and meanwhile paying attention to the beeping sound given by the computer. Both labour and time investment could be largely reduced after implementing this method.

So, the group strongly recommend the company to look into this sound effect optimization for Sensirion in the future development work.

7.2 Virtual testing investigation

Right from the beginning, an extra investigation work was required by the company, i.e. to check whether it is possible to detect air leakage point through simulation programs like CFD (Computational fluid dynamics). The group conducted a serious of investigation including VCC internal discussion with CFD specialists and external search via Internet. According to VCC CFD specialists, it might be possible to find the leakage points by adjusting some tolerance features in doors and simulate in CFD.

However, due to time and resource limitation, the investigation of virtual testing was not completely conducted. If possible, it is recommended for the company to look into more fluid dynamic simulation software.

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Appendices

Appendix A: Weight Decision Matrix

WEIGHT DECISION MATRIX													
Criterion	A	B	C	D	E	F	G	H	I	J	sum	sum/total	Scale
A - Usability	-	1	0.5	1	1	0.5	0	0	1	1	6	13.30%	4
B - Accuracy	0	-	1	1	1	1	0.5	1	1	1	7.5	16.70%	5
C - Time saving	0.5	0	-	1	1	0.5	0	1	1	1	6	13.30%	4
D - Long lifecycle	0	0	0	-	1	0.5	0	0	0	0.5	2	4.40%	2
E - Cost	0	0	0	0	-	0.5	0	0.5	0	0	1	2.20%	1
F - Maintenance	0.5	0	0.5	0.5	0.5	-	0	0	0	0	2	4.40%	2
G - Operator safety	1	0.5	1	1	1	1	-	1	1	1	8.5	18.90%	5
H - Support device	1	0	0	1	0.5	1	0	-	1	1	5.5	12.20%	4
I - No. of parts measure	0	0	0	1	1	1	0	0	-	1	4	8.90%	3
J - Damage occurance	0	0	0	0.5	1	1	0	0	0	-	2.5	5.60%	2

Importance in %	Importance in Scale
0% - 3.8%	1
3.8% - 7.6%	2
7.6% - 11.4%	3
11.4% - 15.2%	4
15.2% - 18.9%	5

Appendix B: Kesselring Matrix

KESSELRING MATRIX																						
Criterion	Leakage Detecting Methods																					
	Weigh	Ideal		1. Ultrasonic		2. Thermal Image		3. Fluorescent		4. Air flow detector		5. Smoke Gun		6. Tracer Gas sniffer		7. Stethoscope		8. Soap Bubble		9. Water Bubble		10. Manual Sense	
		Grade	Total	Grade	Total	Grade	Total	Grade	Total	Grade	Total	Grade	Total	Grade	Total	Grade	Total	Grade	Total	Grade	Total	Grade	Total
A - Usability	4	5	20	5	20	5	20	4	16	5	20	5	20	4	16	3	12	3	12	2	8	4	16
B - Accuracy	5	5	25	4	20	4	20	4	20	4	20	3	15	4	20	3	15	3	15	3	15	2	10
C - Time saving	4	5	20	5	20	5	20	3	12	4	16	2	8	4	16	2	8	2	8	5	20	2	8
D - Long lifecycle	2	5	10	4	8	3	6	1	2	3	6	1	2	3	6	4	8	5	10	5	10	5	10
E - Cost	1	5	5	5	5	3	3	3	3	4	4	4	4	3	3	4	4	4	4	4	4	4	4
F - Maintenance	2	5	10	4	8	4	8	1	2	4	8	2	4	1	2	4	8	4	8	4	8	5	10
G - Operator safety	5	5	25	5	25	5	25	3	15	5	25	4	20	3	15	5	25	4	20	5	25	5	25
H - Support device	4	5	20	5	20	2	8	1	4	3	12	3	12	2	8	3	12	2	8	2	8	3	12
I - No. of parts measure	3	5	15	5	15	5	15	3	9	4	12	3	9	4	12	1	3	1	3	1	3	3	9
J - Damage occurance	2	5	10	5	10	4	8	4	8	4	8	4	8	4	8	4	8	3	6	2	4	5	10
Total		160		151		133		91		131		102		106		103		94		105		114	
Total/Ideal		1		0.94375		0.83125		0.56875		0.81875		0.6375		0.6625		0.64375		0.5875		0.65625		0.7125	
Ranking		-		1		2		10		3		8		5		7		9		6		4	

A - Usability	
Value	Grade
2 person hard	1
2 person easy	2
1 person hard	3
1 person easy	4
1 person very easy	5

B - Accuracy	
Value	Grade
Roughly	1
Less accurate	2
Medium	3
Accurate	4
Very accurate	5

C - Time saving	
Value	Grade
> 1 day	1
1 day	2
0,5 day	3
1 hr	4
< 0,5 hr	5

D - Long lifecycle	
Value	Grade
Replace every 1 yr	1
Replace every 3 yrs	2
Replace every 5 yrs	3
Replace every 10 yrs	4
Never replace	5

E - Cost	
Value	Grade
>100,000	1
50,000 - 100,000	2
20,000 - 50,000	3
10,000 - 20,000	4
< 10,000	5

F - Maintenance	
Value	Grade
Once a day	1
Once a week	2
Once a month	3
Once a year	4
Never	5

G - Operator safety	
Value	Grade
Very dangerous	1
Dangerous	2
Medium	3
Safe	4
Very safe	5

H - Support device	
Value	Grade
More support device	1
2 support device	2
1 support device	3
depends upon	4
No support device	5

I - No. of parts measured	
Value	Grade
Single part	1
Two parts	2
Several parts	3
More parts	4
Complete car	5

J - Damage occurance	
Value	Grade
More damage	1
Damage	2
Little damage	3
Neither or	4
No damage	5

Appendix C: Requirement Specification

		Requirement (Criterion)	Target value	Justification	Evaluation / Verification	R/D
1.Performance (functions)	1.1	Solution able to measure the current & feature leakage problems	Yes	Volvo	Past test results & Physical tests	R
	1.2	Able to measure individual parts of the car body	4 of 5	Volvo	Physical tests	R
	1.3	Able to measure the complete car body	4 of 5	Volvo	Physical tests	R
	1.4	Single solution for both individual part & complete car test	4 of 5	Volvo	Physical tests	R
	1.5	Should show the trail of the leakage point	4 of 5	Volvo	Physical tests	D1
	1.6	Represent the amount of leakage at a point	Yes	Volvo	Physical tests	R
	1.7	Represent the amount of leakage in a complete car body	Yes	Volvo	Physical tests	R
	1.8	Easy to store the data	Yes	Volvo	Benchmark & Physical tests	R
	1.9	Store the end result data automatically	4 of 5	Volvo	Physical tests	D2
2. Simplicity / Geometry / Ergonomics	2.1	Maximum people needed to operate	2	Volvo	Physical tests	D3
	2.2	Minimum people needed to operate	1	Volvo	Physical tests	R
	2.3	Maximum time for installation	10 min	Volvo	Physical tests	R
	2.4	Maximum people needed to install	2	Volvo	Physical tests	D4
	2.5	Minimum people needed to install	1	Volvo	Physical tests	R
	2.6	Easy to operate	Yes	Volvo	Physical tests	R
	2.7	Easy to carry while customer visit	Yes	Volvo	Physical tests	D5

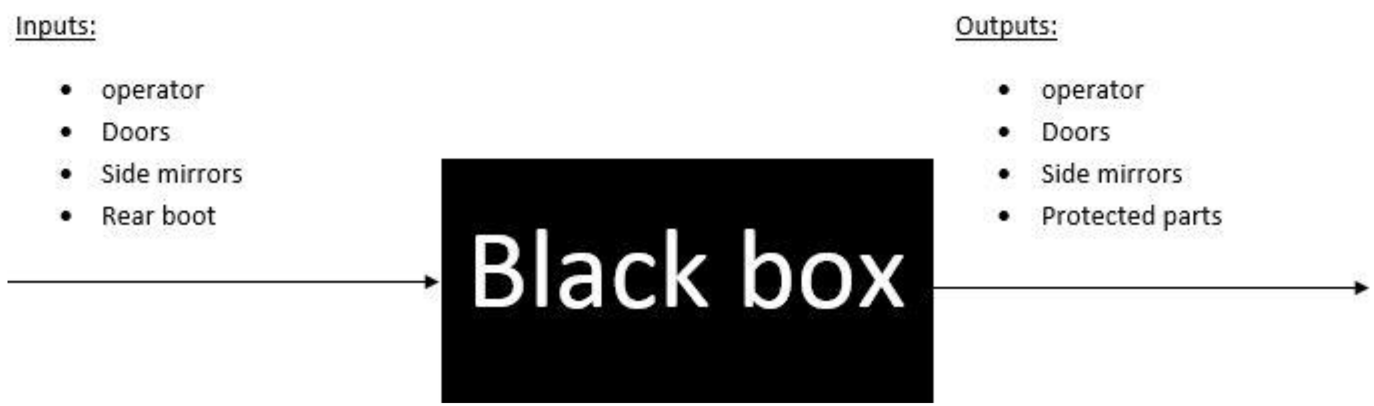
3.Properties	3.1	Should not cause any bad effects to the operator	Yes	Volvo	Physical tests	R
	3.2	No damage in the car exterior while testing	Yes	Volvo	Physical tests	R
	3.3	No damage in car interior while testing	Yes	Volvo	Physical tests	R
	3.4	Endure maximum temperature	120C°	Volvo	Physical tests	D6
	3.5	Endure minimum temperature	-30 C°	Volvo	Physical tests	D7
4.Durability	4.1	Long life of the device	5 years	Volvo	Calculations & estimates	R
	4.2	Free maintenance	Yes	Volvo	Calculations & estimates	D8
5.Environm et	5.1	Should not cause any bad effects to the surrounding / workplace	Yes	Volvo & Law (restrictions)	Properties and study	R

R=Requirement ("must"), D=Desire ("should") with its associated importance factor from 1-5, where 5 is the greatest importance.

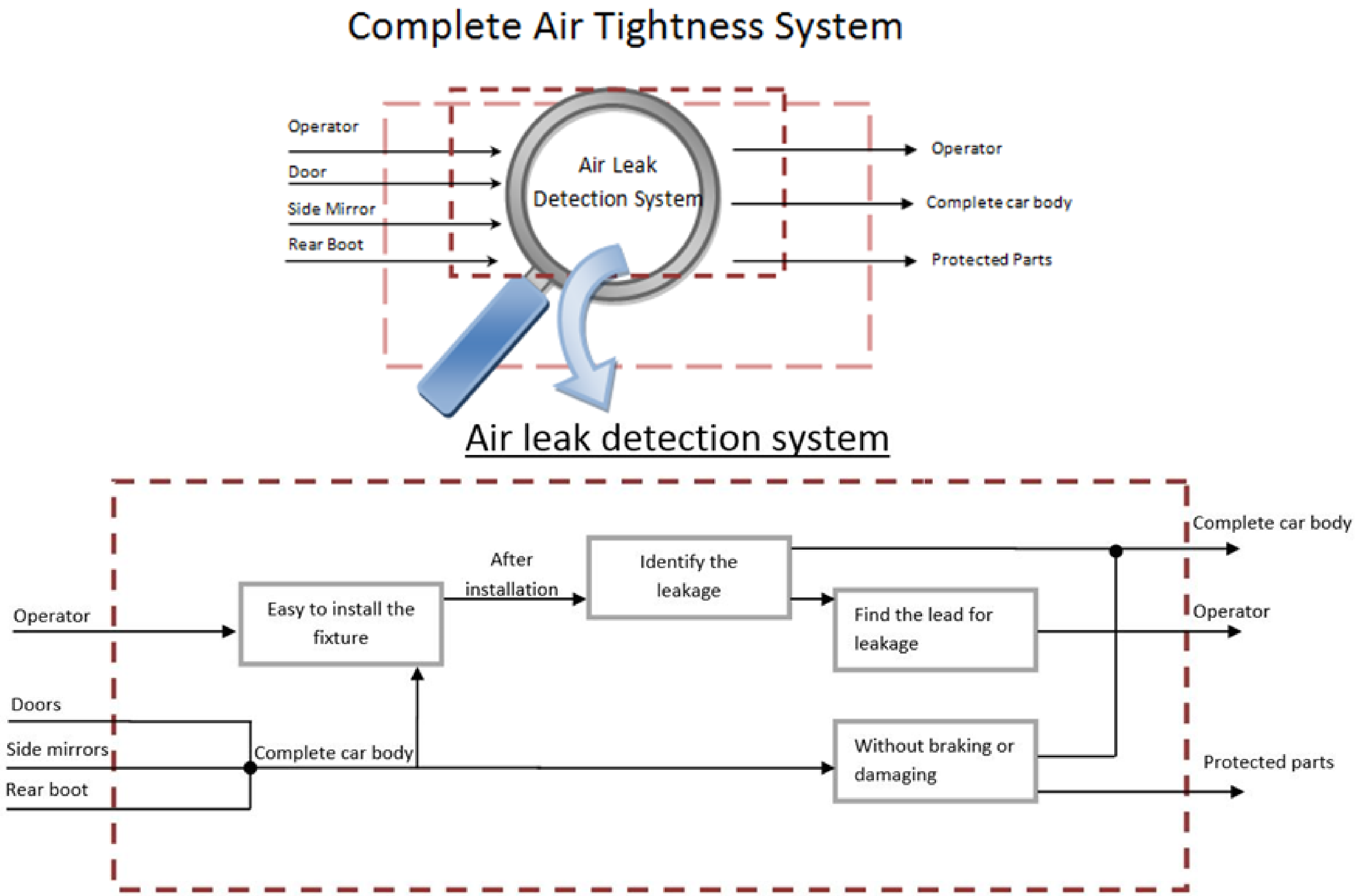
The above specifications listed covers the air tightness in car body, which task is to find out the leakages in the car body (individual part of the car body or the complete car body). This refers to identifying the air leakages device. Which shall be developed to prevent the unwanted leakages in the vehicle's and increases the comfort level to the customers and the brand value of the company.

Appendix D: Black box & Function system chart

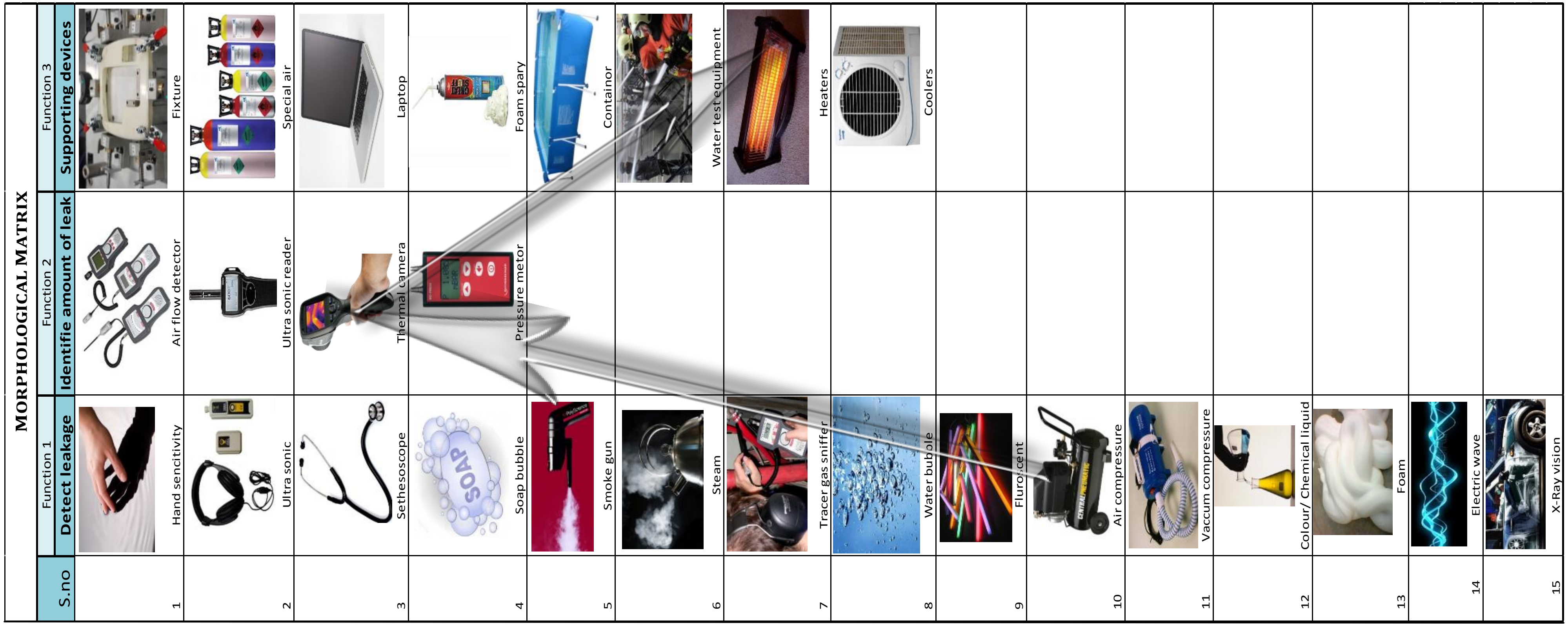
Black box



Function system chart



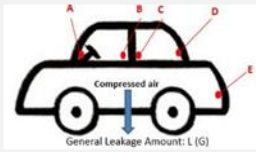
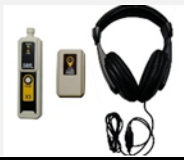
Appendix E: Morphological Matrix



MORPHOLOGICAL MATRIX

S.no	Function 1 Detect leakage	Function 2 Identifie amount of leak	Function 3 Supporting devices
1	Hand sencitivity	Air flow detector	Fixture
2	Ultra sonic	Ultra sonic reader	Special air
3	Sethesoscope	Thermal camera	Laptop
4	Soap bubble	Pressure metor	Foam spary
5	Smoke gun		Containor
6	Steam		Water test equipment
7	Tracer gas sniffer		Heaters
8	Water bubble		Coolers
9	Fluroscent		
10	Air compressure		
11	Vaccum compressure		
12	Colour/ Chemical liquid		
13	Foam		
14	Electric wave		
15	X-Ray vision		

Appendix F: Summary of generated concepts

LIST OF GENERATED CONCEPTS					
No	**Detect leakage**	**Identify amount of leak**	**Supporting devices**	**Concept name**	**Picture**
1	**Foam/Bubble**	**Pressure meter**	**Foam spray**	**A1. Foam / Bubble with water test equipment**	
2	**Air compressor**	**Air flow detector**	**Fixture**	**A2. Air flow detector optimization**	
3	Fluorescent	Amount of light emission	Container	A3. Light detecting	
4	X- Ray vision	Air flow detector	Laptop	A4. X-ray vision	
5	Electric waves	No	Fixture	A5.Electrostatic wave	
6	Thermal scan	Thermal camera	Heaters / Coolers	A6. Thermal camera	
7	Ultrasonic	Ultrasonic reader	No	A7. Ultrasonic	
8	Fluorescent	No	Container	A8. Florescent spray	
9	Air compressor	Pressure meter	Stereoscope	A9. Air compressor with stethoscope	

Appendix G: Elimination Matrix of generated concepts

Elimination Matrix														
	1. Performance (functions)						2. Simplicity / Geometry / Ergonon				Feasible	Decision	Comments	
	1.1	1.2	1.3	1.5	1.6	1.7	2.1	2.3	2.5	2.6				Results
A1	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	No	There are better solutions for this concept. Needs investigation	Kill
A2	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Need further development	Yes
A3	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	No	There are better solutions for this concept. Needs investigation	Kill
A4	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	No	No	There are better solutions for this concept. Needs investigation	Kill
A5	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	No	No	Yes	Kill - Don´t know how to implement	Kill
A6	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Could be combined with other concepts / Kill	Kill
A7	Yes	Yes	Yes	Yes	yes	yes	Yes	Yes	Yes	Yes	Yes	Yes	Could be combined with other concepts / Kill	Kill
A8	Yes	Yes	Yes	Yes	yes	yes	Yes	Yes	Yes	No	No	Yes	Could be combined with other concepts / Kill	Kill
A9	Yes	Yes	Yes	Yes	yes	yes	Yes	No	Yes	No	No	Yes	Further development and combined with A6	Kill
B1	New combined concepts												Conbination of A9 and A6	Yes
B2													Conbination of A9 and A7	Yes

Colour Code	
	Ready for Kesselring Martix
	Needs further development before
	Combine or Kill
	Killed

Number of Kill	8
Number of Yes	1
New combined concepts	2
Total number of concept	11

Appendix H: Weight Decision & Kesselring Matrix

WEIGHT DECISION MATRIX													
Criterion	A	B	C	D	E	F	G	H	I	J	sum	sum/total	Scale
A - Usability	-	1	0.5	1	1	0.5	0	0	1	1	6	13.30%	4
B - Accuracy	0	-	1	1	1	1	0.5	1	1	1	7.5	16.70%	5
C - Time saving	0.5	0	-	1	1	0.5	0	1	1	1	6	13.30%	4
D - Long lifecycle	0	0	0	-	1	0.5	0	0	0	0.5	2	4.40%	2
E - Cost	0	0	0	0	-	0.5	0	0.5	0	0	1	2.20%	1
F - Maintenance	0.5	0	0.5	0.5	0.5	-	0	0	0	0	2	4.40%	2
G - Operator safety	1	0.5	1	1	1	1	-	1	1	1	8.5	18.90%	5
H - Support device	1	0	0	1	0.5	1	0	-	1	1	5.5	12.20%	4
I - No. of parts measured	0	0	0	1	1	1	0	0	-	1	4	8.90%	3
J - Damage occurance	0	0	0	0.5	1	1	0	0	0	-	2.5	5.60%	2
										Total	45		

Importance in %	Importance in Scale
0% - 3.8%	1
3.8% - 7.6%	2
7.6% - 11.4%	3
11.4% - 15.2%	4
15.2% - 18.9%	5

KESSELRING MARTIX

Criteria	Methods								
	Weigh	Ideal		A2. Airflow detector		B1. Thermal & Sensiron		B2. Thermal & Ultrasonic	
		Grade	Total	Grade	Total	Grade	Total	Grade	Total
A - Usability	4	5	20	3	12	4	20	4	16
B - Accuracy	5	5	25	4	20	5	25	3	15
C - Time saving	4	5	20	3	12	5	20	5	20
D - Long lifecycle	2	5	10	4	8	5	10	5	10
E - Cost	1	5	5	5	5	3	3	3	3
F - Maintenance	2	5	10	4	8	4	8	3	6
G - Operator safety	5	5	25	5	25	5	25	5	25
H - Support device	4	5	20	3	12	4	16	4	16
I - No. of parts measured	3	5	15	5	15	5	15	5	15
J - Damage occurence	2	5	10	5	10	5	10	5	10
Total		160		127		152		136	
Total/Ideal		1		0.79375		0.95		0.85	
Ranking		-		3		1		2	

A - Usability	
Value	Grade
2 person hard	1
2 person easy	2
1 person hard	3
1 person easy	4
1 person very easy	5

B - Accuracy	
Value	Grade
Roughly	1
Less accurate	2
Medium	3
Accurate	4
Very accurate	5

C - Time saving	
Value	Grade
> 1 day	1
1 day	2
0,5 day	3
1 hr	4
< 0,5 hr	5

D - Long lifecycle	
Value	Grade
Replace every 1 yr	1
Replace every 3 yrs	2
Replace every 5 yrs	3
Replace every 10 yrs	4
Never replace	5

E - Cost	
Value	Grade
>100,000	1
50,000 - 100,000	2
20,000 - 50,000	3
10,000 - 20,000	4
< 10,000	5

F - Maintenance	
Value	Grade
Once a day	1
Once a week	2
Once a month	3
Once a year	4
Never	5

G - Operator safety	
Value	Grade
Very dangerous	1
Dangerous	2
Medium	3
Safe	4
Very safe	5

H - Support device	
Value	Grade
More support device	1
2 support device	2
1 support device	3
depends upon	4
No support device	5

I - No. of parts measured	
Value	Grade
Single part	1
Two parts	2
Several parts	3
More parts	4
Complete car	5

J - Damage occurance	
Value	Grade
More damage	1
Damage	2
Little damage	3
Neither or	4
No damage	5