WARRANTY RISK MANAGEMENT FOR THE CONSUMER DURABLE MANUFACTURERS

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ABSTRACT

Warranty is a contractual obligation for maintenance upon failures of sold items during a warranty period. Warrantors utilise warranty as a strong promotional tool. Although warranty can bring some benefits, it involves various types of risks that may lead to negative impact (such as economic loss) on the warrantor. Systematic analysis of such risks can protect warrantors from potential losses. Based on a critical and comprehensive analysis of the existing warranty literature, very few studies discuss warranty risk management (WaRM). This thesis therefore aims to investigate WaRM from several perspectives and it makes contributions to the literature and practice, as shown below.

- A WaRM framework was developed. The framework was thoroughly analysed.
- A questionnaire was designed to gain an in-depth understanding of WaRM. From analysing the survey in the UK automotive industry, the following findings were obtained
  - the most commonly used tool for identifying warranty hazards is the root cause analysis technique;
  - the most commonly used tool for assessing warranty risks is the failure mode effect and criticality analysis technique;
  - the top contributors to warranty incidents and costs were human error related, which mainly include: (1) human error at different stages of product life cycle; (2) product modification at suppliers and original equipment manufacturer (OEM); (3) customers' fraud (4) insufficient collaboration between parties (suppliers, OEM and warranty services providers). Based on these findings, two generic warranty hazard taxonomies were designed.
- Selection of methods to mitigate WaR (warranty risk) is important but includes uncertainty. The thesis investigates the warranty risk mitigation process and analyses the main criteria that can be influenced. A selection method is developed based on the joint application of the cumulative prospect theory (CPT) and the analytic hierarchy process method (AHP).

The new method can guide decision makers to the selection of mitigation methods over their conflicting views and their attitudes towards risks.

- A warranty policy includes both warranty price and duration. Optimisation of warranty policies is therefore vitally important. The thesis also developed a CPT-based warranty model to optimise warranty price considering the warrantor's and buyers' risk attitudes. A numerical example is provided to illustrate the proposed models and the sensitivity of the profit to different risk attitudes for the parties. Accordingly, the main findings are: (1) The warrantor's risk attitude has less impact on the profit compared to the buyers' risk attitudes; (2) the increase in the repair cost may lead buyers to accept higher warranty price; and (3) the higher the buyers perceive the product failure rate, the more likely they will be willing to buy the extended warranty.

The theoretical implications of this thesis are listed as follows:

- Develop a framework for WaRM.
- Determine the top contributors to warranty hazards and hence two taxonomies were developed.
- Develop a decision model to select the optimal mitigation plan to respond to the emergent warranty risk.
- Develop a mathematical model to optimise warranty price considering the buyer and warrantor point of views towards the expected repair cost and claims cost, respectively.

The practical implications of this thesis are listed as follows:

- The WaRM framework will provide warranty practitioners with the required guidelines to manage warranty risks.
- The result of using the streaming data as an early warning tool has shown its efficiency in highlighting the warranty issues.
- The warranty hazards taxonomies might help warranty practitioners in improving the process, procedures or technologies which are required to reduce the occurrence of warranty risks.

- The development of WaRM-CPT model may aid the decision makers in selecting the optimal mitigation plan to respond to an emergent warranty risk.
- The determination of the optimal warranty price can be achieved when the warrantor and buyers views are considered. To this end, a mathematical model is provided.

A LIST OF THE PUBLICATIONS

Journal paper (Published)

Aljazea, A.M. and Wu, S., (2019). Managing risk for auto warranties. *International Journal of Quality & Reliability Management*, 36, 7, 1088-1105. [Developed based on Chapters 3 & 4]

Journal paper (Submitted)

Aljazea, A.M. and Wu, S., (2019). Warranty Price Optimisation Based on the Cumulative Prospect Theory. *Journal of the Operational Research Society*.Under review. [Developed based on Chapter 6]

Conference papers (Published)

Aljazea, A., Luo, M. and Wu, S., (2018). Mitigating Warranty Risk for Automotive Industry, *the 10th IMA International Conference on Modelling in Industrial Maintenance and Reliability (MIMAR)*. Manchester, UK, 13-15 June 2018. [Developed based on Chapters 5]

Aljazea, A. and Wu, S., (2019). A Framework of Warranty Risk Management, *the Ninth International Conference on Business Intelligence and Technology*. Venice, Italy, 5-9 May 2019. [Developed based on Chapters 3]

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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

ACRONYMS

FTC	Federal Trade Commission
UCC	Uniform Commercial Code
WaRM	Warranty risk management
DMs	Decision makers
AHP	Analytic hierarchy process
CPT	Cumulative prospect theory
QFD	Quality function deployment
CRM	Customer relationship management systems
SLA	Service-level agreement
WSP	Warranty service provider
OEM	Original equipment manufacturer
NFF	Non-fault-found
FBNR	Faulty but not reported
MCDM	Multi-criteria decision-making
MAUT	Multi-attribute utility theory
MHDIS	Multi-Group Hierarchical Discrimination
OM-AHP	Orders-of-magnitude AHP
FRW	Free replacement warranty
PRW	Pro-rata warranty
ISO	International Organization for Standardization
GAN	Generalised activity networks
DSM	Design structure matrices
SWOT	Strengths, Weaknesses, Opportunities, and Threats
FMEA	Failure mode and effect analysis
FMECA	Failure mode and effect criticality analysis
ERP	Enterprise resources plan
SNS	Social network services
USGS	United States geological survey
SVM	Support vector machine
NB	Naïve Bayes
JDL	Joint directors of laboratory
VIN	Vehicle identification number
API	Application programming interface
PDS	Product design specification
ANP	Analytic network process
RI	Random index
FTA	Fault tree analysis

NOTATIONS

Chapter 5	
$\boldsymbol{x_i}$	Outcome
$\boldsymbol{\pi_i}$	Decision weight of the ith outcome
$\boldsymbol{v}(\cdot)$	Value function
$\boldsymbol{d_i}\ (\boldsymbol{i}=\mathbf{1},\dots,\boldsymbol{m})$	Set of the mitigation plans.
$\boldsymbol{c_i}\ (\boldsymbol{i}=\mathbf{1},\dots,\boldsymbol{m})$	Cost incurred due to using the ith mitigation plan.
$\boldsymbol{c}^{\mathbf{ref}}$	Reference point for the costs $c_i,\dots,c_m$ of the mitigation plans.
$\boldsymbol{s_j}\ (\boldsymbol{j}=\mathbf{1},\dots,\boldsymbol{n})$	States of the emerged warranty risk.
$\boldsymbol{p_j}\ (\boldsymbol{j}=\mathbf{1},\dots,\boldsymbol{n})$	Probability of the jth state of the emerged warranty risk, where $\sum_{j=1}^{n} p_j = 1$.
$\boldsymbol{h_k}\ (\boldsymbol{k}=\mathbf{1},\dots,\boldsymbol{q})$	Criteria that may be influenced if the jth state has occurred.
$\boldsymbol{z_{ik}}$ $(\boldsymbol{i}=\mathbf{1},\dots,\boldsymbol{m})$ $(\boldsymbol{k}=\mathbf{1},\dots,\boldsymbol{q})$	Initial judgements of the decision makers, when applying the ith mitigation plan to mitigate the impact of the warranty risk on the kth criterion.
$\boldsymbol{z_k^{\mathbf{ref}}}\ (\boldsymbol{k}=\mathbf{1},\dots,\boldsymbol{q})$	Reference point for the kth criterion values. In this research, the average of the z_k values is used as a reference point (Terzi et al., 2016).
$\boldsymbol{I}^{\mathrm{c}}, \boldsymbol{I}^{\mathrm{r}}$	Importance degree of the cost (I^{c}) compared to the result (I^{r}) with respect to each mitigation plan, where $I^{\mathrm{c}} + I^{\mathrm{r}} = 1$ and $0 \leq I^{\mathrm{c}}, I^{\mathrm{r}} \leq 1$.
$\boldsymbol{G_i}$	Prospect value of the mitigation plans results.
$\boldsymbol{V_i}$	Value of the costs of the mitigation plans.
$\boldsymbol{Y_i}$	Overall prospect value of the mitigation plans.
Chapter 6	
$\boldsymbol{K}(\boldsymbol{t})$	Maximum number of warranty claims within time period $(0,t)$
$\boldsymbol{N_i}(\boldsymbol{t})$	The number of claims occurred Buyer i within period t
$\boldsymbol{p_i}(\boldsymbol{n},\boldsymbol{t}) = \boldsymbol{P}(\boldsymbol{N_i}(\boldsymbol{t}) = \boldsymbol{n})$	Probability that there are n claims
$\boldsymbol{c_r}$	Repair cost from the buyer's perspective
$\boldsymbol{c_w}$	Handling a warranty cost from the warrantor's perspective
$\boldsymbol{c_p}(\boldsymbol{t})$	price per product item of selling extended warranty with period t
$\boldsymbol{r_p}(\boldsymbol{t})$	expected number of warranty claims and the reference number of warranty claims

CHAPTER 1: INTRODUCTION

Warranties have been used to protect buyers from fraud and faulty products since the early sixteenth century (Murthy & Djamaludin, 2002). Warranties at this time were uncomplicated verbal agreements; the products they guaranteed were simple and produced by local people who addressed product failures directly. In the late nineteenth century, the basis of the exploitation theory of warranty emerged, where the warranty terms were designed in favour of the warrantor while the buyer had few rights and could assume the full risk of purchase. When faced with this type of warranty, the buyer may feel that the warrantor has no confidence in its products (Murthy 2002). In the early twentieth century, the Federal Trade Commission (FTC) was established to control the sale of goods. In 1952, the Uniform Commercial Code (UCC) was introduced to determine the rights of each party involved in the sales of goods, with warranty being a focus (Murthy & Djamaludin, 2002).

Although this code specified some rights for both parties, the buyer remained burdened with the risk of product failure. Because of these shortcomings in the UCC, the Magnuson-Moss Warranty Act was introduced to make American consumers aware of their rights and to improve the quality of warranties. The new act aimed to improve the warranties, under the assumption that if the warrantor provides a good warranty, the buyer will feel that the product is of good quality. This process is known as the signal theory of warranty. In this theory, when the product becomes more complex and its performance harder to evaluate, the duration of the warranty can be used by the consumer to assess the reliability and quality of the product (Spence 1977). Recently, a warranty has been considered an insurance policy and a repair contract, conforming to the investment theory of warranty. By this theory, the buyer invests in a warranty to reduce potential failures. Additionally, the warrantor can introduce conditions on how the product should be used, thus avoiding responsibility for damages incurred from product misuse. Now, warranties are often required by certain legislation, for instance, the products sold in the European Union must have a 2-year warranty (Wu 2014).

A warranty is then defined as a contractual obligation provided by a warrantor (manufacturer or other parties, such as warranty service agents) to a client (firms, governments, or customers) for a period of time after the product has been sold (Murthy 2002). A warranty, on one hand, is perceived by the customer as insurance and protection against potential product failure early in the product's life cycle. On the other hand, the warrantor provides an extended warranty to signal the reliability and quality of the product. In other words, a long warranty duration may indicate good product reliability and quality from the buyer's perspective (Heal 1976; Heal 1977).

1.1 Significance of the research

Although the provision of warranty services can bring some benefits, it involves different types of risks that can affect the whole business. Due to market pressure and customer demands, manufacturers work to achieve two main factors: (1) producing reliable products with a high level of quality, and (2) timing the product launch to precede or coincide with those of their competitors. The estimation of future warranty costs is hindered by these factors, as they often increase the degree of uncertainty in product performances in field tests.

Potential warranty risks can then be sourced from product-related issues, logistics-related issues, warranty servicing-related issues, customer-related issues or information-related issues. As such, managing such risks efficiently can protect or reduce the fiscal consequences of product failure, which may accumulate to billions of dollars. For example, Warranty Week estimates the warranty claims for the carmakers went up sharply in 2017 with around $53 billion compared to the same period in 2016 (Warranty Week 2017). *Volkswagen* paid around 17.55 billion euro (equivalent to nearly 9% its revenue) for warranty claims in 2017 (Warranty Week 2017)[1].

These costs are mainly from the expenses of the labour and spare parts required to rectify the failures of the products. The estimation of such costs

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[1] Available at: https://www.warrantyweek.com/archive/ww20190711.html, Access date: 11 Oct. 19.

becomes more challenging as the products become more complex and the warranty durations longer. Hence, considering warranty risks at the early stage of the product life cycle is imperative to avoid or reduce the occurrence of such risks. This research therefore will establish the concept of warranty risk management (WaRM) by developing a generic WaRM framework, determining the top contributors to warranty hazard, mitigating warranty risk and finally optimising the warranty policy as one of the top contributors to warranty hazard.

1.2 Knowledge gap

There are a large number of warranty publications that concentrate on the financial planning of warranty such as forecasting the number of warranty claims and then estimating the associated costs. WaRM, however, receives very little attention and is just mentioned as a side section in conference papers such as Díaz (2011) and Costantino (2012). Therefore, there is a need to establish the concept of WaRM and develop the related frameworks and models in order to aid warrantors to reduce the impact of warranty risks.

1.3 Objectives and research questions

This research aims to establish the concept of WaRM in the durables industries, specifically in the automotive industry. To this end, the following objectives are planned:

1) To analyse WaRM literature comprehensively.
2) To obtain an in-depth understanding of the existing practices of WaRM in the automotive industry in the UK, specifically focusing on procedures and tools used to manage warranty risk.
3) To develop a generic WaRM framework.

    Q1: How do manufacturers manage warranty risk? What are the existing tools used to identify warranty hazards and manage the associated risks in the UK automotive industry? What are their limitations?

4) To design a taxonomy for the top contributors to warranty incidents from two perspectives: product life cycle perspective and warranty chain perspective.

Q2: What are the top contributors to warranty incidents and costs in the UK automotive industry?

5) To develop a warranty decision model to aid warranty decision makers (DMs) in assessing and mitigating warranty risk.

   Q3: Under the conflicting views of decision makers for the methods of mitigating warranty risk, how can a method of selection of risk mitigation be developed?

6) To develop a model that optimises warranty policy by considering the warrantor's and buyers' risk attitudes towards the profit and repair cost, respectively.

   Q4: How can one optimise warranty policy if the utility of a warrantor and buyers towards the profit and repair cost, respectively, is different?

1.4 Thesis structure

The focus of this thesis is on WaRM, starting from the conceptualisation and then following through to framework design, hazard identification, risk mitigation and finally optimisation of the warranty policy as a source of the warranty hazards. These subjects will be discussed in the chapters of this thesis as follows.

Chapter 2 provides a comprehensive analysis of literature regarding warranty management and its relationship with other areas, such as engineering, marketing, etc. Warranty risk is reviewed from three perspectives: warrantor, warranty services provider (WSP) and customer. Additionally, the literature on adopting big data techniques and social media data for risk identification is reviewed in order to employ these techniques in warranty hazard identification. Other literature related to the sources of warranty hazard is thoroughly analysed from three perspectives, namely: product life cycle, warranty chain and human error. In order to develop a warranty decision model for warranty risk mitigation, existing multi-criteria decision-making tools are reviewed, particularly those tools considering the uncertainty of outcome. Lastly, the existing literature considering risk preferences of the DMs in optimising the warranty policy is reviewed.

Chapter 3 analyses existing tools and procedures in areas similar to WaRM, such as insurance and supply chain risk management. These examples will aid in constructing the WaRM framework. Additionally, investigation of existing practices and tools used to manage warranty risk in the durable industries, specifically the automotive industry, will be provided. Based on the analysis of the questionnaire data, the WaRM framework is designed considering the importance of adopting an advanced technique of early-stage warranty hazard demonstrate its superiority as an early warning tool. It is then fused in the framework with the existing data (e.g. warranty claim data) by the data fusion technique in order to improve the accuracy of outcome prediction.

Chapter 4 is mainly focused on determining the top contributors to warranty incidents and costs. This chapter starts by analysing the potential hazards stated in the literature. Then, a questionnaire was designed and circulated to the DMs who work in the automotive industry in the UK to obtain understand better the existing warranty hazards in the industry. Accordingly, the warranty hazard taxonomy was designed from two perspectives: the product life cycle perspective and warranty chain perspective.

Chapter 5 proposes a warranty decision model to aid in the selection of an optimal warranty risk mitigation plan. When the risk has occurred, different criteria can be affected such as warranty cost, manufacturer reputation, environment health and human safety. In this chapter, the analytic hierarchy process (AHP) method is adopted to assign weights to the criteria that are difficult to quantify. Additionally, AHP is adopted to obtain the initial judgements of DMs representing different departments, such as engineering, marketing, after-sale, finance, etc. Since the weights given to those criteria are affected by the DMs’ risk attitudes, the cumulative prospect theory (CPT) is adapted to address issues such as reference dependence, utility evaluation and probability distortion. The reference point is proposed in two scenarios: the deterministic reference point and the dynamic reference point. In the dynamic scenario, the DM will be able to determine the optimal warranty risk mitigation policy by considering different check-ups during the warranty period. A numerical example is provided to illustrate the proposed models.

Chapter 6 develops a warranty model to determine the optimal warranty price, considering the risk attitudes for both the warrantor and the buyer with respect to the profit and warranty repair cost. In this chapter, the willingness of the buyer to purchase the extended warranty is determined based on the buyer's valuation of the product, their perception of the product failure rate and the offered warranty price. Once the proportion of buyers who are willing to buy the extended warranty is determined, the warrantor will compute their profit accordingly. While the cost of warranty claims generated from the warrantied products is uncertain, the warrantor may compute the prospective value of such costs in order to determine the certainty profit equivalent. In this chapter, a numerical example is proposed to illustrate the sensitivity of profit to the following factors: (1) risk preferences of both the buyers and the warrantor, including risk aversion, risk-seeking and loss aversion towards warranty repair cost and profit, respectively; (2) the length of warranty duration; (3) the cost of repair per claim for buyers and (4) the buyers' perceptions of the product failure rate.

Chapter 7 provides a summation of the main findings of this thesis and offers suggestions for future work.

CHAPTER 2: LITERATURE REVIEW

In this chapter, the existing literature that is relevant to each of the thesis's chapters will be presented. Primarily, literature pertaining to warranty, risk management and its tools as used in the warranty field, WaRM, top contributors to warranty hazards, warranty mitigation and warranty price optimisation will be reviewed. Subsequently, commentary on the existing work will be discussed and gaps in the knowledge will be identified.

2.1 Overview

This chapter covers warranty management in Section 2.2 and risk management in Section 2.3, followed by WaRM in Section 2.4; subsequently, warranty hazard identification is discussed in Section 2.5, and warranty risk assessment and mitigation are presented in Section 2.6. A review of the multi-criteria decision-making methods and CPT is presented in Section 2.7. In Section 2.8, different warranty policies and some works on warranty price optimisation are reviewed. A summary of the existing works is offered in Section 2.9.

2.2 Warranty management

In this section, the concepts of product warranty and warranty management will be investigated.

2.2.1 Products

In our daily lives, we use different kinds of products that assist us in dealing with difficulties and to facilitate our work. Products are not limited to tangible or physical items, but they can be ideas, knowledge or a combination of tangible and intangible components. Products can be classified into the following groups (Murthy, 2006):

1) Consumer non-durables, including products with short life spans, such as processed foods. These products are generally inexpensive and, hence, are not covered by warranty.
2) Conventional products, such as cars, appliances and computers, which are generally bought as single items. These products vary in terms of their complexity and, hence, the degree of uncertainty in their performance

varies considerably. They are sold under warranty imposed by law, such as the two-year warranty that is standard in European countries.

3) Commercial and industrial products. These are sold as single items or in batches of *n* items and characterised by a relatively low number of buyers and manufacturers. Examples include large agricultural machines, large-scale computers, drilling machines used in construction, and machines used in the health sector, such as X-ray and MRI scanners.
4) Products bought by the government. A prime example of this is military equipment, such as fighter aircraft. This group of products are sold to very few buyers. They are characterised by high complexity and their use of the latest technologies.

This thesis's main focus is on conventional products, in particular, consumer durables and the automotive industry is provided as an example. As such, the following paragraphs provide a brief background to this industry.

Cars are defined as wheeled vehicles that are mainly used for transportation and operates on roads (*Oxford English Dictionary).* They can be categorised, based on their structures, into passenger cars, trucks, buses, etc. They can be further categorised, based on the source of energy used, into petrol, hydrogen, diesel, electric, hybrid, etc. The industry's first foray into mass production occurred with Ford in the early twentieth century. The industry has since grown rapidly in the United States, where major automakers, such as General Motors, Ford and Chrysler, produce millions of cars annually. Table 2-1 presents information about the number of cars produced annually by various countries.

Each car may be viewed as a system comprising over 15,000 components[2], which can be further deconstructed into several sub-systems, including body, engine, chassis, transmission, electrical, cooling, controls, exhaust, safety, fuel and lubrication. Each sub-system can itself be deconstructed into lower hierarchical levels, such as assemblies, sub-assemblies, components and

[2] Available at https://auto.howstuffworks.com/under-the-hood/trends-innovations/car-assembling2.htm. Accessed date: 02 Oct. 2019.

parts; for example, a car's engine consists of several components,[3] including the crankshaft, cylinder head and flywheel.

Table 2-1: Annual worldwide car sales; source: VAD[4]

Region	2018	2017	2016	2015	2014	2013
Europe (EU+EFTA)	15,624,500	15,631,700	15,131,700	14,201,900	13,006,500	12,308,200
Russia*	1,800,600	1,595,700	1,425,800	1,601,200	2,491,400	2,777,400
USA*	17,215,200	17,134,700	17,465,000	17,386,300	16,435,300	15,531,600
Japan	4,391,200	4,386,400	4,146,500	4,215,900	4,699,600	4,562,300
Brazil*	2,475,400	2,176,000	1,988,600	2,480,500	3,333,400	3,579,900
India	3,394,700	3,229,100	2,966,600	2,772,700	2,570,500	2,554,000
China	23,256,300	24,171,400	23,693,400	20,047,200	18,368,900	16,303,700
Combined:	68,157,900	68,325,000	66,817,600	62,705,700	60,905,600	57,617,100

Normally, automotive products are sold with after-sale services included, such as maintenance, installation, upgrading and training. In other words, the buyer may assess the physical product along with the after-sale services as a total package that he or she can compare it with other competitive products, in terms of the performance and after-sale services. After-sale services play a critical role in buyer satisfaction (Ullah et al., 2018). The provision of after-sale services may increase the profitability of the warrantor in various ways, such as the revenue obtained by extending the life of the product and the sale of the extended warranty.

In terms of the above services, the focus in this thesis is on warranty and extended warranty. According to Murthy & Djamaludin (2002), warranty plays a vital role for both manufacturers and buyers, since it is provided as an integral part of the products' purchase transaction.

2.2.2 Product warranty

Warranty, as defined in Chapter 1, is an obligation provided in writing and/or orally by a warrantor to a buyer for the purpose of ensuring a product or service against failure. In other words, it is a contractual agreement between

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[3] Available at: http://www.darcast.com/engine_components.html. Accessed date: 02 Oct. 2019.
[4] Available at: https://www.vda.de/en. Accessed date: 02 Oct. 2019.

the warrantor and buyer, which specifies the buyer's responsibilities, the product's performance and restrictions, etc. Warranties provided as an integral part of the sold product are known as 'normal' or 'base' warranties. They can be also sold separately and, hence, may be called 'extended' warranties or service contracts, which the buyer can choose to purchase or not (He et al., 2017).

Warrantors and buyers may perceive the role of warranties differently. Buyers consider it a tool to protect their rights against any failure that may emerge during the warranty period, provided that the warrantied item is appropriately used. In particular, the warranty contract usually states that product failure will be repaired or replaced with a new product, provided the failure has not occurred through misuse on the part of the buyer. Additionally, the buyers may consider warranty as a source of information about the product's reliability, which may be inferred from the offered warranty period.

For the manufacturer, warranty functions as a protective mechanism against false claims raised by buyers. The expected performance of the product and the warranty's limitations are therefore stated in the warranty contract. The manufacturer may also use the warranty as a promotional feature, since buyers may infer the reliability of the warrantied item from the advertised duration of the warranty. This is particularly true of new innovations characterised by high levels of uncertainty.

2.2.3 Warranty management

Managing product warranty from a strategic perspective requires DMs to consider the warranty's implications for the business overall from the early stages of a product's life cycle. The management of warranty can therefore be discussed from two aspects: technical and commercial. The technical aspects include the product's design and manufacture. With regard to managing the commercial aspects, DMs may consider two critical factors: warranty price and duration, which each play an important role in marketing the product. Additionally, the provision of a competitive after-sale service can maintain buyers' satisfaction and sustain their loyalty (Ullah et al., 2018).

To discuss the importance of the warranty from a strategic perspective, the relationship of warranty to other departments within the industrial organisation will be investigated. The paragraphs that follow will discuss the warranty's relationships with engineering, marketing, logistics and after-sale, see Figure 2-1.

(1) Warranty and engineering

As mentioned above, the early stage of the product's life cycle is crucial in determining the product's reliability and quality, which, in turn, affects the future warranty cost (Murthy & Djamaludin, 2002). In other words, the manufacturing of reliable products leads to a reduction in warranty cost, as they require less maintenance and spare parts, compared to unreliable products. The target product reliability and quality may be determined by the engineering department. As such, these crucial elements, which affect future warranty claims costs, will be discussed.

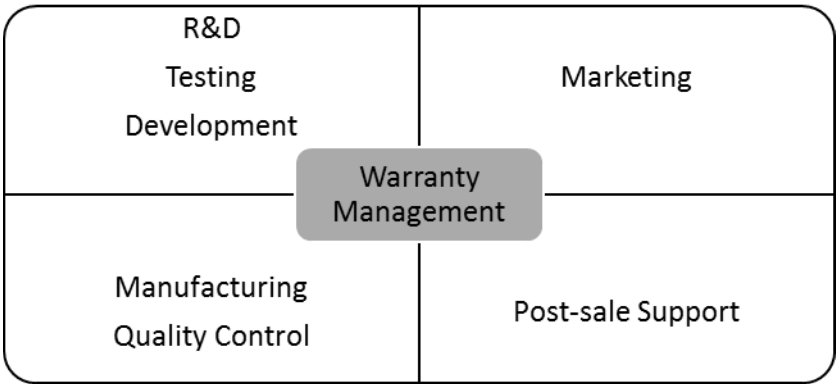

Figure 2-1: The relation between warranty management and the whole business[5]

Product quality

Product quality is defined as follows:

'The group of features and characteristics of a saleable good which determine its desirability and which can be controlled by a manufacturer to meet certain basic requirements'.[6]

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[5] Source (Blischke & Murthy, 1992)
[6] Available at: http://www.businessdictionary.com/definition/product-quality.html. Accessed datae: 02 Oct. 2019.

'Product quality is the totality of features and characteristics of a product that satisfies the stated or implied needs'.[7]

Product quality can have a direct effect on buyers' satisfaction. As such, high-quality products may lead to repeat sales, positive word-of-mouth and buyers' loyalty. Product quality can be observed through several dimensions, as follows (Murthy & Blischke, 2006; Razak et al., 2016):

- Performance: A product's performance is evaluated based on its functional properties; for example, fuel consumption and power, among other properties, are key properties of cars' engines.
- Conformance: This is defined as the degree to which a product's performance meets a pre-specified performance standard. By contrast, non-conformance is the degree to which a product's performance deviates from the pre-specified performance standard.
- Durability: This is a measure of a product's life span. Most products, if not all, deteriorate over time. Although proper care for the product (e.g., regular maintenance) throughout its useful life may extend its life, it will eventually become defunct.
- Serviceability: This measure is used to determine the extent to which the product can be repaired and to measure the speed with which a faulty product can be restored to its intended functionality.
- Perceived quality: This is the buyer's subjective impression of a product's quality.

Product reliability

Product reliability may be perceived by buyers as the product's performance, successful operation, absence of faults and dependability (Melchers & Beck, 2018). The Consumer Report[8] published in October 2017 reports various car brands which were ranked by the buyers based on their overall reliability, see

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[7]ISO 9000. Available at: http://www.fao.org/3/W7295E/w7295e03.htm#TopOfPage. Accessed date: 02 Oct. 2019.

[8] Available at: https://www.autonews.com/assets/PDF/CA1126931019.PDF. Accessed date: 02 Oct. 2019.

Table 2-2. From the manufacturer's point of view, product reliability is defined as the likelihood that the product will perform its intended function for a period of time if it is not misused.

In the literature, reliability has been discussed from various perspectives, such as reliability modelling, reliability engineering, reliability analysis and optimisation, reliability management and reliability science. In this thesis, reliability analysis and reliability management are discussed, since warranty risk is primarily related to these two areas.

Table 2-2: Cars reliabilities (Consumer Report, 2017)

Rank	Brand	Reliability score
1	Toyota (14 models)	80
2	Lexus (8 models)	77
3	Kia (8 models)	71
4	Audi (7 models)	68
5	BMW (6 models)	62
6	Subaru (6 models)	60
7	Infiniti (4 models)	60
8	Buick (4 models)	59
9	Honda (6 models)	59
10	Hyundai (5 models)	59

(2) Warranty and marketing

As mentioned above, product warranty plays an important role in the marketplace. It is offered as a promotional and protective mechanism for use by the warrantor and buyer, respectively. For example, in the automotive industry, warranty was provided for 90 days in 1930, and the warranty period had been increased to seven years or 100,000 miles by Suzuki in 2002. Over time, manufacturers, such as Hyundai, Kia and Mitsubishi, offered longer warranty durations of up to ten years (Gorzelany, 2018), see Table 2-3.

Table 2-3: Warranty coverage for different brands. (Gorzelany, 2018)

Brand	Basic Coverage Year/km	Powertrain Coverage Year/km	Corrosion Coverage Year/km
Volkswagen	6/72,000	6/72,000	7/100,000
Hyundai	5/60,000	10/100,000	7/Unlimited
Genesis	5/60,000	10/100,000	7/Unlimited
Mitsubishi	5/60,000	10/100,000	7/100,000
Kia	5/60,000	10/100,000	5/100,000
Jaguar	5/60,000	5/60,000	6/Unlimited
Infiniti	4/60,000	6/70,000	7/Unlimited
Tesla	4/50,000	8/Unlimited	--
Lincoln	4/50,000	6/70,000	5/Unlimited
Cadillac	4/50,000	6/70,000	6/Unlimited

To understand the relationship between warranty and marketing, this thesis will focus on the buyer purchasing process, since it is a core element of the marketing programme's design process. The purchase process can be as follows:

1) Determining the buyer's needs: Buyer's needs can be triggered by advanced technology and functions of new innovations, or by promotional tools that lead the buyer to expect certain features as standard.
2) Acquiring information about the intended product: The buyer may mainly collect information about the product's reliability and quality to assuage their uncertainty regarding the product's performance.
3) Comparing different brands in terms of price, reliability, specifications, warranty and other post-sale services.
4) Purchasing the product.
5) Using the product.

6) Evaluating the product's reliability and quality: After using the product, the buyer may be able to evaluate the product performance and after-sale services including warranty.
7) Future actions: If the buyer is satisfied with the product's performance and after-sale services, they might repeat-purchase the product and convey a positive word-of-mouth reviews to other potential buyers. Otherwise, the buyer may consider another competitive product, on the basis of product performance or after-sale services.

Chu & Chintagunta (2011) studied the four economic theories (insurance theory, sorting theory, signalling theory and incentive theory) that pertain to warranty provision. They empirically examined the role of warranties in the automotive and computer server markets, based on the assumptions of these theories. They found that the main role of warranties in both markets is to provide buyers with insurance against faulty items (insurance theory) and that warranties of different durations work as a sorting mechanism for buyers with different quality evaluation tendencies and various levels of risk aversion. The results also indicate that they are not used to signal quality (signalling theory) or to incentivise manufacturers to reveal or improve their products' quality (incentive theory). This result is inconsistent with that of Boulding & Kirmani (1993), who suggested that, in general, consumers' responses to warranties confirm the behavioural assumptions of signalling theory.

Furthermore, in the context of perceiving a longer warranty period as a signal of good quality, Liao et al. (2015) studied warranty policy and its effects on a buyers' behaviour from the buyer's perspective. This study incorporates manufacturers' warranty services and consumer heterogeneity into a model and develops three market settings with which to study the impact of warranty on manufacturers' profits. Products with warranties have higher prices in the marketplace which, in turn, can enhance their profitability. Moreover, product warranty plays a significant role in remanufactured products, and profits are highest when new and remanufactured products are provided with differentiated warranties (Liao & Li, 2016; Alqahtani & Gupta, 2017). Ye & Murthy (2016) proposed a menu of two-dimensional warranties to meet various consumer choices.

However, the product warranty has a negative impact on the product price, whereby the warranty service cost is added to the manufacturing cost. Thus, warrantied products are usually more expensive (Blair & Innis, 1996). To maximise profits in the presence of costs resulting from warranties' obligations, Aggrawal et al. (2014) developed a mathematical approach to obtain optimal price and duration for products sold with a base warranty.

2.3 Risk management

The risk management system has been implemented for several decades in various sectors, such as supply chain risk management and risk management in finance. In industrial organisations, including automakers, risk management plans are established to address unexpected and undesirable events. However, preventable faults may continue to occur, due to weaknesses in the implementation of risk management. In this section, the definition of risk management and its main elements will be discussed.

There are many definitions of risk management, which vary according to the specific areas that it serves. In the engineering field, for example, the risk is related to the expected loss (Lirer et al., 2001). ISO/IEC (2002) defined it as a combination of the probability of an event and its effects. However, in researching warranty management, uncertainties beyond the probabilities should not be overlooked.

Although risk management definitions may vary, several characteristics remain consistent, as follows (Aven, 2016):

1) Potential for loss.
2) Uncertain outcomes.
3) Decisions required to manage the nature of the risk: loss or uncertainty.

Accordingly, risk management is a systematic approach to determining the best action to take under uncertainty through the performance of several processes, beginning with risk planning, hazard identification, risk assessment action and monitoring. To apply risk management efficiently, it is essential that the risk management culture be developed throughout the organisation.

Generally, risks mainly consist of causes and effects. The former is known as a threat, which is defined as the *events* that potentially produce loss, whereas a *consequence* is defined as the outcome or loss that ensues when the threat has become actualised (Alberts & Dorofee, 2009), see Figure 2-2. Known risks are those harmful occurrences the probabilities and impacts of which can be anticipated. These risks are acceptable as trade-offs for the potential opportunities that can be achieved. By contrast, unknown risks are difficult to estimate and, thus, are difficult to manage.

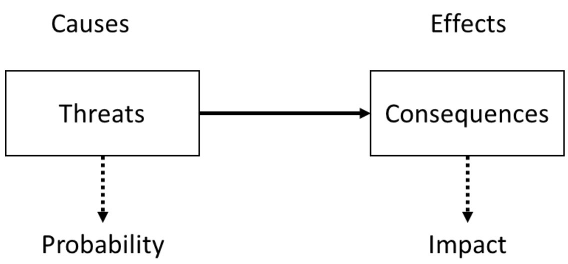

Figure 2-2: Risk components; Source (Alberts & Dorofee, 2009)

Risk management is comprised of five stages: risk planning, hazard identification, risk assessment, risk evaluation and risk mitigation.

2.4 Warranty risk management (WaRM)

WaRM can be defined as the process of identifying, assessing, evaluating and responding to risks that are likely to emerge during the period of the warranty programme. As mentioned above, the purpose of risk management is to maximise the probability of acceptable events in the warranty programme and simultaneously reduce, avoid or control the unacceptable ones. It deals with uncertain events that, if they were to occur, would have a negative impact on the warranty's objectives. If such risks occur, they are analysed so that their causes may be understood. Accordingly, the manufacturer must respond to these risks by taking certain measures, such as improving product quality and reliability, recalling failed products, updating the warranty risk plan, etc (Motabar et al., 2018).

In the literature, WaRM is rarely discussed and is only mentioned as a side topic by some works. For example, Díaz & Márquez (2011) investigated the interaction between warranty and other departments in an industrial organisation and included the necessary stages in a framework for warranty management by adopting generic tools developed for project management, such as cost-risk-benefit analysis. Costantino et al. (2012) adapted the quality function deployment (QFD) methodology to understand buyers' needs. As such, warranty issues were prioritised based on QFD, and the riskiest activities are ranked accordingly. González-Prida & Márquez (2012) proposed a warranty management framework outlining the main issues that should be considered to achieve a warranty programme and accurately assess buyers' satisfaction. Zhou et al. (2017) propose a Bayesian approach to detect the reliabilities related issues at the early stage of the product life cycle and reduce the need for extensive warranty claim data.

To ensure a robust WaRM system, reliable data are essential. As such, with the development of data warehousing and data mining techniques, it is possible to collect data from different sources, and then integrate them and build a big picture of different hazards, with which the assessment and analysis of risks stemmed from different sources becomes possible. As such, an in-depth understanding of warranty risk and further development of WaRM methodologies may reduce warranty costs and enhance the manufacturer's profit. Nevertheless, based on a critical and comprehensive review of the literature, very few publications have investigated WaRM. In the following sections, WaRM will be reviewed from different points: the manufacturer's perspective, the warranty service provider's perspective and the buyer's perspective.

2.4.1 Risks from a manufacturer's perspective

Warranty is a type of insurance that secures the rights of both manufacturers and buyers against the faulty functionality of products purchased under warranty terms during the warranty period. Specifically, it functions as a mechanism to protect manufacturers against claims resulting from the misuse of products as well as against buyers' fraud. In addition, it assures buyers' rights to claim against items that fail to satisfactorily perform their intended functions. Moreover, warranty is also used as an essential tool in dispute resolution between two parties (i.e., warrantor and buyer).

The p rovision of very high-quality products may reduce future warranty claims, but may also increase the products' sale prices, and, consequently, the sales volume may decrease. Manufacturers therefore require trade-offs between products' quality and sale prices to retain a strong competitive position in addition to reducing warranty costs. Otherwise, poor-quality products may lead to several faults in the product, which may incur huge expenses. These faults, in some cases, may be crucial, particularly those associated with safety. For example, Takata's defective airbags caused eight deaths and over one hundred injuries. Takata consequently had to pay a $25 million fine, $125 million in compensation for casualties and $850 million to some automakers who issued a massive recall (Paul Lienert, 2017).

Warranty risk from the manufacturer's perspective can be categorised into three groups, namely: (1) Manufacturer-related risks (2) WSP-related risks and (3) buyer-related risks (Table 2-4). In the subsections that follow, these groups will be briefly discussed.

(1) Manufacturer-related risks

Manufacturer-related risks can also be divided into two groups: the first group includes the internal risks that can generally be predicted and controlled. The second includes external risks that the warrantor can partially manage. For example, the occurrence of an earthquake may be expected, but cannot be controlled. Additionally, terrorist activities are considered an uncertain risk, with consequences that are difficult to predict.

With regard to the internal risks, product reliability and quality are deemed to be internal hazards. This is mainly determined based on decisions taken at the early stage of the product's life cycle, which has a direct effect on warranty costs. Although engineers conduct several tests to ensure products' reliability, they rely on limited information and, hence, the degree of uncertainty may remain high.

(2) WSPs-related risks

WSPs' activities are considered one of the main contributors to warranty risks from the warrantor's point of view. WSPs may cause significant risks to the warrantor from two aspects: WSPs fraudulent activities and buyers' dissatisfaction. Kurvinen et al. (2016) report that the greatest proportion of fraudulent claims may be attributed to service agents who gain higher revenues if they process more claims. With regards to buyers' dissatisfaction, some warranty service centres care little about buyers' satisfaction. This issue may result from poor service quality, long repair times or lack of respect for buyers. Buyers may then be dissatisfied and disseminate negative word-of-mouth reports verbally or in writing on social network platforms, for example. Hence, decreased sales volume rates may ensue. Service centres, as a part of the after-sale service, are therefore among the critical factors that influence buyers' purchasing decisions. Hence, the establishment of robust customer relationship management systems (CRM) would result in increased sales volume rates.

(3) Buyer-related risks

Manufacturers clearly state the following points in their warranty policies to ensure protection against future disputes or fraud that may arise:

- The start and end dates of the warranty period.
- Proof of purchase.
- Usage limitation.
- Parts covered by warranty, such as spare parts, labour and logistics.
- The warranty provider's right to review the item within the warranty period.

However, some buyers pursue a variety of fraudulent activities. Kurvinen et al. (2016) categorised such activities into four groups as follows:

(a) Refund or replacement

In such cases, a buyer will claim faults in the product's performance although it works as expected. Their aim is to have this item replaced with a new one or to obtain a refund.

(b) Avoidance of service costs

Buyers try to access out-of-warranty service despite their products have exceeded the warranty period.

(c) Earning more

Buyers claim to replace unentitled items in order to resell them and earn money from these fraudulent activities.

(d) "SLA improvement"

Buyers cheat by claiming a better service than they are entitled to.

Table 2-4: Examples of warranty hazards from different perspectives*

Product-related hazards		**WSPs-related hazard**	**Buyer-related hazard**
Internal hazards	External hazards		
• Product design • Reliability • Warranty cost • Business strategy • Management process • Security of information • Warranty policy • Machine breakdowns	• Political policy • War • Financial Crisis • Exchange rate fluctuation • Terrorism • Supplier bankruptcy • Broken contract • Raw parts scarcity • Supply interruptions • Market requirements • Inaccurate demand • Order fluctuation • Urgent orders • Products damaged in transits	• Agent fraud • Low service quality • Mismanagement • Maltreatment with buyers • Delay in service	• Buyer fraud • Delay in informing failure • Not attending a protective maintenance

*Sources: (Chopra & Sodhi, 2004; Wu, 2011; Chen et al., 2013; Kurvinen et al., 2016)

2.4.2 Risks from the warranty service provider's perspective

Products are mostly sold by dealers or sales channels that often provide warranty services. The provision of such services involves some risks, which can be divided into two groups (Figure 2-3). The first group includes the internal risks, such as scheduling tasks, and hence more repair time is required, lack of knowledge, technicians turnover, etc. The second group, the external risks from the WSP’s perspective, includes manufacturers’ and buyers’ fraud, political issues, etc. Warranty policy generally states several conditions that must be verified before the maintenance or replacement of faulty products is granted. Once these conditions have been met, WSPs must carry out the required services. The following risks therefore must be given greater consideration (Afshar-Bakeshloo et al., 2018):

1) Mismanagement: this type of risk has a severe impact not only on the warranty services but also on the overall business. Scheduling, for example, is highly important in determining an accurate time for defective items’ maintenance.
2) Lack of knowledge: some service centres may recruit unqualified technicians to reduce wages at the expense of quality. Hence, the brand’s reputation may be compromised, and buyers might consider changing in favour of competitors’ products.
3) Technicians’ issues: several issues affect the time required to repair faulty items, such as technician turnover, imperfect estimation of required spare parts, availability of required hardware and software, etc. Such activities are examples of risks that prevent warrantors from achieving the warranty objectives, as well as negatively affecting the overall business.

Buyers can be a source of the warranty risk to WSP since they may use some fraudulent activities, which have already been discussed in the previous section. Moreover, WSPs can be influenced by manufacturer’s fraud (Murthy & Jack, 2017). For example, the manufacturer may delay or deny some claims in order to reduce the warranty cost provided by the WSPs.

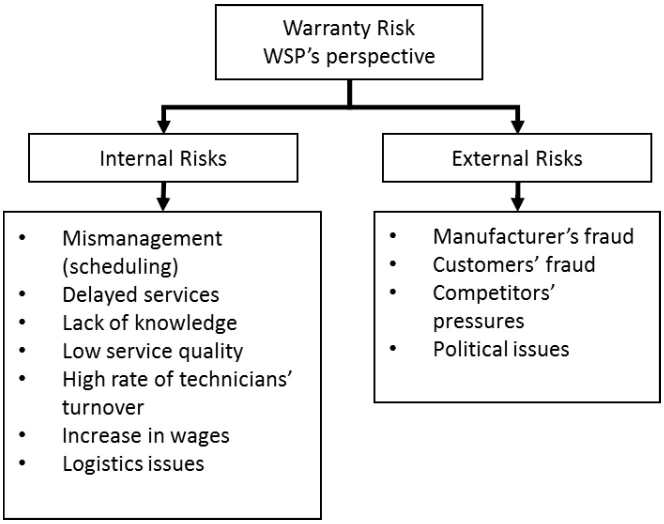

***Figure 2-3: Potential risks from the WSP's perspective*[9]**

2.4.3 Risks from a buyer's perspective

The buyer's perception of a product's reliability and quality is a critical factor in the purchasing decision (Li et al., 2019). Warranty is therefore provided to mitigate their concerns regarding the product's possible future failure. Hence, poor warranty services may lead to customers' dissatisfaction regardless of product performance.

Warranty fraud is another risk from the buyer's point of view. Kurvinen et al. (2016) identified two ways in which buyers can be affected by warranty fraud:

1) *Extra costs*: warranty providers (WSPs, agents, etc.) may charge the buyer for services that are covered by the warranty policy. They may also cheat them in terms of benefits provided in an extended warranty form.
2) *Poor service*: buyers might be treated negatively or their demands may be ignored. Moreover, tardiness or poor execution in delivering the service may result in buyers' dissatisfaction.

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[9] Sources: Chopra, S. & Sodhi, M. S. (2004). Managing risk to avoid supply-chain breakdown. *MIT Sloan management review,* 46(1)**,** 53, Wu, S. (2011). Warranty claim analysis considering human factors. *Reliability Engineering & System Safety,* 96(1)**,** 131-138, Chen, J., Sohal, A. S. & Prajogo, D. I. (2013). Supply chain operational risk mitigation: a collaborative approach. *International Journal of Production Research,* 51(7)**,** 2186-2199, Kurvinen, M., Töyrylä, I. & Murthy, D. P. (2016). *Warranty Fraud Management.* New Jersey: John Wiley & Sons.

WSPs must therefore maintain their relationships with their buyers by ensuring that their products are of a high standard in addition to fulfilling the warranty policy terms in the after-sales stage.

The importance of warranty data

When a product has been sold, engineers often use warranty claims data as the main source of field data to improve the product's performance. Additionally, it may be used to analyse buyers' needs or expectations about the product.

Generally, warranty data can be classified into two main groups as follows, see, Figure 2-4:

- *Warranty claims data*: Such data are collected from the claim and repair service carried out for the warrantied products.
- *Supplementary data*: This refers to the data gathered from different sources, such as design and development systems, manufacturing and marketing systems, etc. Buyers' feedback, which can be posted on the Internet, is a valuable source of information. Nowadays, this is one of the primary sources from which streaming data may be obtained.

Warranty data are the primary source of data that aid engineers in suggesting the optimal warranty policy, as well as plan warranty services and spare part preparation. They provide information on the actual operation and usage of the product. Such data are more useful than those obtained from laboratories since they provide field reliability data (Wu, 2012). Several points should be considered before using warranty data to estimate a product's reliability: (1) warranty claims data are usually incomplete and (2) they are only collected at the early stage of the product's life cycle, and, thus, little information might be yielded regarding the product's future reliability.

The importance of warranty data is not limited to the current product, but it is also used to develop new products. Suzuki et al. (2001) stated that warranty claim data is essential for the following reasons:

- It can provide early warnings about bad design, poor production processes, faulty components or inferior materials.

- It can yield observations of new product development, whether or not the objectives are achieved.
- It can provide good insight into product reliability and compare products to those of competitors.
- It can anticipate future warranty claims.

Blischke et al. (2011) categorised different kinds of data into the following groups:

- Product-related data: This includes failed parts, fault mode, product age and usage at the time of failure.
- Buyer-related data: This includes the environment of operation, usage intensity, maintenance, etc.
- Service agent-related data: This includes maintenance issues, the decision of whether to replace, repair or refund and data related to service costs.
- Market-related data: This includes the degree of reliability and quality and the prices of competitors' products. This data is critical for optimising warranty pricing strategies.

Wu (2012) claimed that several issues associated with warranty data should be taken into account:

- Aggregated data: for example, claims grouped based on the product's age (e.g. 0–30 days) and then sent to the analyst.
- Data lags: such delays might result from sales or reporting processes, as these take time for verification before submission.
- Incomplete censored data: warranty data that is characterised by right-censored data caused by the expiration of the warranty period.

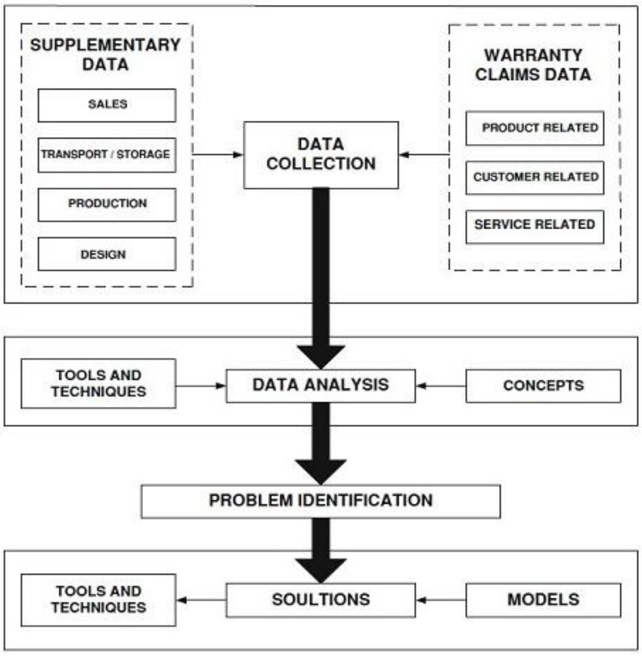

Figure 2-4: Collecting warranty data from various sources; source (Blischke et al., 2011)

Data quality is an essential element in warranty data, because of its implications for the results' accuracy. Mahlamäki et al. (2016) studied the importance of the quality of maintenance data for the results' accuracy of their proposed models (EPSi) and tool (EPSitor) to predict extended warranty costs. The proper extraction of warranty data is also crucial for providing information that may be utilised for improving products, as mentioned before. Jeon & Sohn (2015) used association rule analysis to extract useful information from warranty data by defining the relationship between the production data and failure data during the warranty period, which helps the manufacturer to determine the required improvements.

Several papers have been published in the area of warranty data analysis. Wu (2012) reviewed publications on this topic from 2005 to 2012 and classified them into five groups: (1) publications related to early detection and reliability, (2) suggestions for development, (3) field reliability estimation, (4) warranty claim prediction and (5) warranty claim estimation. Additionally, warranty data analysis publications had been fully covered by Chukova et al. (2005).

2.5 Warranty hazard identification

The body of literature on warranty is vast and is mainly focused on financial planning issues, such as the estimation of warranty costs and the number of future warranty claims and determination of the optimal warranty policy, etc. (Mondal et al., 2003; Huang & Zhuo, 2004; Kestle & Cudney, 2010; Akbarov & Wu, 2012; Wu & Akbarov, 2012). Warranty hazard, however, has received little attention. In this section, therefore, existing literature on warranty incidents and warranty costs will be analysed from the product life cycle and warranty chain perspectives. The contribution of human error to warranty incidents and warranty cost will also be reviewed, Figure 2-5.

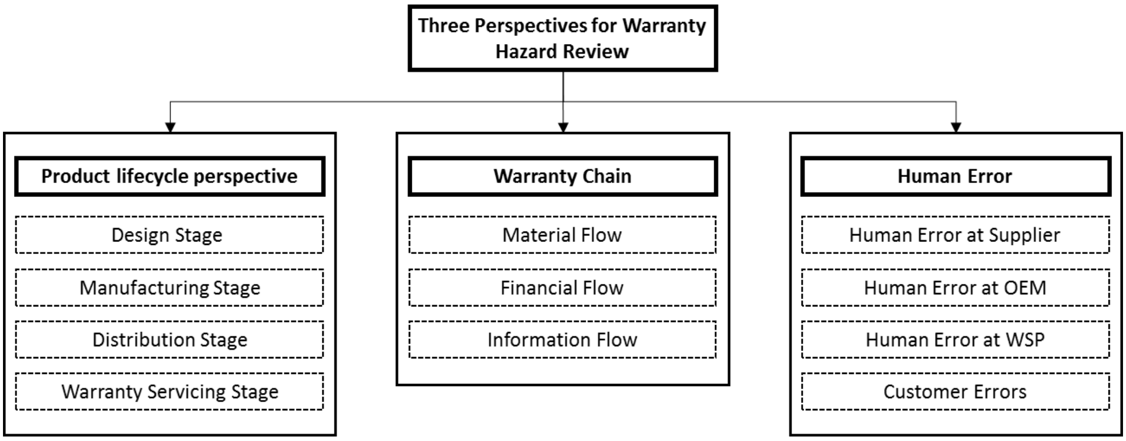

Figure 2-5: Review of warranty hazards

2.5.1 Product life cycle perspective

Several efforts have been made to improve warranty management from the product life cycle perspective. For example, Wu (2012) listed several causes of warranty claims and divided them into four groups: (1) hardware failures, (2) software failures, (3) human errors and (4) organisational errors. Sundin et al. (2010) carried out case studies to investigate the use of warranty as a strategic tool for improving integrated product/service engineering. Murthy & Blischke (2000) highlighted the importance of warranty-related strategic decisions and then identified several hazards associated with such decisions. Chen & Chien (2007) also improved the prediction of warranty costs by considering those non-failure-related hazards that affect warranty costs from the product life cycle perspective.

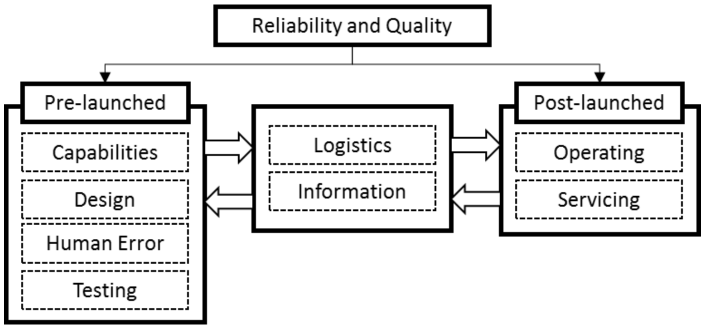

Figure 2-6: Review of warranty incident contributors

Warranty incidents are mainly triggered as a result of issues with product reliability and quality, which can be divided into pre-launched and post-launched groups (Figure 2-6). The first group includes the capabilities at play in the manufacturing and assembly process, product design, human error and testing or system validation processes. The second group includes operating- and servicing-related hazards that contribute to warranty incidents.

The warranty survey report (2007) showed that the highest contributor to warranty hazards is the lack of capabilities in the manufacturing and assembly processes at manufacturers and suppliers. This problem may result from a lack of communication between parties (original equipment manufacturer (OEM) and supplier) to validate approaches to manufacture or assembly. Other factors, such as workers, machines and the authorisation level given by the OEM to the suppliers, can also play a critical role in managing this problem.

At the design stage, product reliability is a crucial factor in warranty, as it determines future warranty claims and the required service resources. Dussauge et al. (1992) stated that, at the product design stage, 80% of future products' costs are determined. It is primarily influenced by the decisions made at the design stage, including (product concept, R&D, manufacturing planning). Such decisions typically involve two or more groups with different interests. As such, their perspectives on reliability issues will differ, in terms of acceptance sampling, testing, warranty and insurance, etc. Ríos Insua et al. (2018) have developed a framework based on adversarial risk analysis to address the conflict among decision makers. The impact of the reliability on warranty has received considerable scholarly attention. For example, Murthy (2006) reviewed the role of product reliability in warranty costs and proposed a framework for managing product reliability. Gurel & Cakmakci (2013b) analysed the impact of product reliability on warranty through a study conducted in a large company in the electrical industry. Product reliability is also considered to be the cornerstone of forecasting warranty.

Additionally, products' reliability is influenced by manufacturing-related issues, such as manufacturing assembly processes, as mentioned above. To mitigate this problem, Shelley Xie & Hsieh (2002), for example, developed a new algorithm that minimises deformations resulting from welding and clamping. Manufacturing process capability and operational disruption can negatively influence the provision of warranty. These problems may occur because of insufficient response to changes, particularly during the early stage of the product life cycle (Khan et al., 2008; Yeh & Fang, 2015). Another manufacturing-related issue is that the variability in the manufacturing process results in some products' failure meet the quality standards. Murthy & Djamaludin (2002) termed this type of product quality "nonconforming", with the rest of the products termed "conforming". Díaz et al. (2012b) suggested several quality issues that should be considered before offering warranty contracts.

Warranty claims are increased as a result of design- and manufacturing-related issues. Some of these issues can be addressed if they are known during the diagnostic process, whereas others cannot be resolved due to difficulties in determining the fault, known as non-fault-found (NFF). This issue is quite common in warrantied products that are influenced by the design and manufacturing processes from one side and by buyers' interventions from the other side. This problem has received considerable attention. For example, Qi et al. (2008) reviewed and presented the causes and effects of the NFF problem in electronic products. Studies of the impact of product design on products' reliability as well as quality are numerous (Gurel & Cakmakci, 2013a; LU & ZHANG, 2013; Díaz & Márquez, 2014; Jain et al., 2014; Azadeh et al., 2015).

Once the warranty policy has been determined, planning for warranty logistics is then crucial to achieving the warranty programme objectives. The successful provision of warranty services depends on the effectiveness of warranty logistics. The potential hazards of logistics on warranty can include (1) the location of service centres; (2) the capacity of each centre and its requirements for technologies and personnel skills; (3) planning to own or outsource these centres; (4) transportation of the required material for warranty services; (5) spare parts inventories, whether for control or allocation; (6) jobs scheduling, and (7) decisions taken as to whether to repair or replace (Murthy et al., 2004). Wu (2012) also identified several logistics-related issues that have caused warranty claims, such as damage during delivery and missing product accessories.

As such, the provision of the warranty can be directly influenced by the aforementioned factors. For example, the availability of spare parts has a direct impact on the required service time for repairing or replacing faulty items. Management of spare parts and inventory, however, involves several difficulties, such as demand volatility, seasonality, short product life cycles, rapid technological advancements, and fluctuations in buyers' demand (Johnson, 2001; Wong & Hvolby, 2007). Such difficulties imply that greater effort should be invested in accurately planning and forecasting the requirements for spare parts. Sarfaraz et al. (2014) studied the impact of obtaining spare parts for warranty assistance on the assembly line. Based on several criteria and alternatives that determine such decisions, the authors applied the fuzzy AHP to address such problems.

When the purchased product under warranty has failed to perform its intended function, it is sent/brought to the warranty services centre to be replaced or repaired. As such, some warranty-related risks can be triggered by the WSP, including long service time and low service quality. Ahmad & Mohsin Butt (2012) listed the main criteria that should be considered in providing warranty or after-sale services: (1) spare parts availability, (2) adequate warranty terms, (3) technical support, (4) pricing and (5) service support.

The quality level of warranty services is one of the main factors that can directly impact buyers' satisfaction. Izogo & Ogba (2015) studied the impact of service quality and concluded that it has a significant impact on buyers' satisfaction and loyalty. Sabbagh et al. (2017) also investigated the various influences of product quality and service quality on buyers' satisfaction in the presence of warranty in the automotive industry. The authors concluded that the moderating role of warranty is that the relationship between service quality and buyers' satisfaction is strengthened by the warranty's presence, whereas the relationship between product quality and buyers' satisfaction is insignificant in the presence of warranty as a moderator. Wu (2012) stated that some WSP-related issues could increase warranty claims, such as poor internal training programmes and inadequate access to product information.

Despite the above hazards affecting buyers' satisfaction, WSPs can trigger other hazards affecting warranty cost, such as fraudulent activities. In some cases, they consider this fraudulent activity to be their main source of revenue (Kurvinen et al., 2016). The authors claimed that the highest rates of fraudulent claims are found among warranty service agents. The Association of Certified Fraud Examiners carried out a survey in 2014 and concluded that 5% of manufacturers' revenues are lost as a result of fraud activities.

2.5.2 Warranty chain perspective

Regarding supply chain risk management, Tang & Musa (2011) reviewed the chief supply chain risks and classified them into three main groups: (1) material flow risks, (2) financial flow risks and (3) information flow risks. This category is adopted to give DMs a holistic view of the potential contributors to warranty incidents from the warranty chain perspective.

The material flow risk in warranty refers to warranty incidents resulting from the movement of materials (e.g., spare parts, sub-systems, etc.) from one party to another. For example, shipping products between parties (suppliers, OEM, dealers and buyers) can have an impact on product reliability and may cause product damage.

In warranty management, information and data can be gathered internally or externally. External sources may include warranty service agents systems and retailers systems, while internal sources may include the marketing, manufacturing and engineering units, in addition to the information collected for decision-making purposes during the feasibility stage of the product's life cycle (Blischke et al., 2011). Such data were categorised by Blischke et al. (2011) into the following groups:

- Product-related data: faulty parts, failure mode, product age and usage at failure, etc.
- Buyer-related data: the environment of operation, usage intensity, maintenance, etc.
- Service agent-related data: maintenance issues, such as whether to replace, repair or refund. Another example is the data related to service cost and its quality.
- Market-related data: the reliability and prices of competitors' products, in order to optimise the pricing and strategic planning of warranty services.

The primary source of such data is warranty claim data (claim data and supplementary data, see Figure 2-4. In the literature, warranty data and information have received considerable attention. Wu (2012) reviewed the analyses of warranty data and classified them based on the usage of such data into five groups: (1) early detection and reliability, (2) suggestions for development, (3) field reliability estimation (4) warranty claim prediction and (5) warranty claim estimation. Before this period, publications about warranty data analysis had been fully covered (Chukova et al., 2005). Obtaining information from warranty data involves, however, several risks, which impede the availability of data at the required time. For example, Amoo Durowoju et al. (2012) identified several of these risks including information security and disruption, information accuracy, information accessibility and information efficiency.

Financial flow risk associated with warranty refers to those activities that cause an increase in warranty costs. Such activities result from non-failure-related expenses, such as shipping, administration, labours, exchange rate, etc. These expenses increase warranty costs, though warranty incidents are not increased. Some non-failure-related warranty events were discussed by

Kakouros et al. (2003) to determine the cause of increasing warranty costs at the Hewlett-Packard Company (HP), while no reliability issues were recorded.

2.5.3 Human error

Generally, human error can be intentional or unintentional and has an impact on warranty incidents and warranty costs. It varies from one party to another, and its level of contribution to warranty incidents is also varied.

For suppliers, human error can have an impact on product reliability, due to unauthorised changes in product design for some components. When these components are sent to the OEM for assembly, further human errors may arise.

For OEMs, although the manufacturing process is often mechanised, human intervention is still necessary for processes such as welding and clamping (Shelley Xie & Hsieh, 2002). Consequently, products' reliability and quality are influenced by such interventions and, hence, the number of future warranty incidents is expected to be high in the event that such a process may have been improperly performed.

For WSPs, human error is also a critical factor that may have a negative impact on both warranty incidents (e.g., service quality, diagnostics-related issues, etc.) and buyers' satisfaction (e.g., technical support, service time, buyer care, etc.). Khan et al. (2014) stated that one of the main contributors to NFF claims is the problem of improper diagnosis on the part of technicians.

Customers' errors account for a significant proportion of all contributors to warranty incidents. Wu (2011) distinguished two types of customer-caused warranty risk that affect warranty cost. The first is 'non-faulty but reported' (NFBR), which refers to buyers who have nothing to claim but report a failure, nonetheless. In this case, failure might be reported due to misuse, non-failure or other human factors. The second type is 'faulty but not reported' (FBNR), and refers to buyers who might eventually report but only after several intermittent failures during the warranty period. This type of warranty risk constitutes a significant proportion of full warranty claims and is considered one of the main reasons for NFF, particularly, in the electronics industry (Qi et al., 2008; Erkoyuncu et al., 2016).

Mithu & Saha (2016) stated that many warranty claims are due to failures caused by misuse or lack of knowledge on the part of buyers. They developed two models to determine two types of warranty claims: fatal failures and intermittent failures caused by buyers.

Further warranty hazards can be triggered by buyers who are uninterested in completing the preventive maintenance programme, which is a proactive approach aimed at protecting manufacturers from extra warranty costs and extending the product life cycle (Kim et al., 2004). They might pay little attention, due to different reasons, such as preventive maintenance being borne by customers or inconvenient scheduling of check-ups. Having a good preventive maintenance system can extend products' life cycles, keeping maintenance costs within acceptable ranges, as well as reducing warranty costs which, in turn, yield benefits for both manufacturers and buyers (Moghaddam & Usher, 2011). Due to the costs of preventive maintenance, Chen & Chien (2007) developed a framework to examine the impact of such costs on both the manufacturer and the buyer for the products sold under the free-replacement renewing warranty policy. This framework can save costs by assisting in the selection of optimal preventive action.

Some buyers pursue a variety of fraud activities, which drive warranty costs up. For example, Kurvinen et al. (2016) categorised such activities into four groups as follows:

a) *Refund or replacement:* In such cases, buyers claim that there is a fault in the product's performance despite the fact that it is working as expected, with the aim of obtaining a replacement or a refund.
b) *Avoiding service cost:* Buyers try to get out-of-warranty services when their products have exceeded the warranty period.
c) *Earning more:* Buyers claim to replace unentitled items in order to resell them and earn money from such fraudulent acts.
d) *"SLA improvement":* Buyers cheat by claiming a better service than they are entitled to.

2.5.4 Other works

In addition to the above research, there are some other works worth reviewing. Díaz and Márquez (2011) applied the cost-risk-benefit analysis approach in order to improve the warranty management programme. Costantino et al. (2012) adapted the QFD methodology to understand customers' needs in relation to warranty services. As such, warranty issues were prioritised based on the customers' perspective.

2.6 Warranty risk mitigation

Once a warranty risk has been assessed, the DMs must select a suitable plan to mitigate such a risk. The difficulty with the warranty risk mitigation decision is the interplay between warranty management and several departments within the organisation (e.g., engineering, marketing, logistics, etc.), as well as external parties, such as suppliers, warranty services providers, buyers, etc. Due to such relationships, the selection of the optimal warranty risk mitigation plan is conducted amidst uncertainty and risk.

To better understand the above-mentioned steps in the WaRM plan, a brief discussion of WaRM will be given. Subsequently, the methods that can be adapted to select the optimal mitigation plan, such as multi-criteria decision-making (MCDM) methods, will be discussed.

According to ISO 31000, risk management is defined as a set of activities and methods employed to direct and control the risks that can affect an organisation's ability to achieve its objectives (Purdy, 2010). Such activities can be grouped into five main stages: (1) risk planning, (2) hazard identification, (3) risk assessment, (4) risk evaluation and (5) risk controlling and monitoring. These steps are adapted to WaRM, and in this section, the focus is on the mitigation of warranty risks.

During the risk planning stage, it is essential to specify the responsibilities involved in managing and responding to risks. As such, the warranty risk plans are often determined at the risk planning stage to efficiently respond to these risks in the event that they are actualised.

In the literature, warranty risk mitigation has not been discussed yet. However, these risk mitigation studies are discussed in other disciplines such as supply chain risk management, finance and projects. Chen et al. (2013) examined a collaborative approach including suppliers' collaboration and customers' collaboration to mitigate supply, demand and process risks. The author found that collaboration between parties has effectively reduced the respective supply chain risk. Rajesh et al. (2015) developed a method based on a combination of grey theory and digraph-matrix methodologies to quantify various supply chain risk mitigation strategies. Kumar Dadsena et al. (2019) proposed an integrated fuzzy model based on failure mode and effects analysis (FMEA) approach to select a risk mitigation strategy on the trucking industry.

In projects risks, Connor et al. (2019) proposed and examined legal strategies for mitigating the financial risk of energy infrastructure projects. Other mitigation strategies were proposed to mitigate the disaster risks based on the study of the three prominent Australian disasters (de Vet et al., 2019). (Noori et al., 2018) developed a new resilience metric to determine the maximum investment in bildings risks mitigation.

2.6.1 Multi-criteria decision-making (MCDM) tools

Since the mitigation of warranty risk is a decision problem, some models can be adapted to the selection of the optimal warranty risk mitigation plan. In this section, the common MCDM will be reviewed.

MCDM methods are extensively used in different fields, such as financial risk, supply chain risk management and decision-making. Due to the difficulties and complexities of various problems and the importance of making appropriate decisions, many researchers and experts in finance have been forced to employ analytic decision-making tools in their decisions. Zopounidis & Doumpos (2002) discussed the applications of MCDM in financial risks such as credit cards and bankruptcy, corporate performance evaluation, country risk assessment, the selection of portfolio and management and financial planning.

Various MCDM methods are used in such studies, including AHP, multi-attribute utility theory (MAUT), Elimination and Choice Expressing Reality (ELECTRE), Multi-Group Hierarchical Discrimination (MHDIS), Method for Enrichment Evaluations (PROMETHEE) and Utilities Additives Discriminants (UTADIS). The increased use of MCDM tools in research reflects their significance in dealing with complex decisions. Eighteen out of 256 papers used AHP as a multi-criteria decision tool in the field of finance between 1955 and 2001 (Steuer & Na, 2003). The authors also reported that AHP is used for predicting bankruptcy and forecasting the foreign exchange rate.

Furthermore, several MCDM methods were reviewed by Velasquez & Hester (2013), who summarised the strengths and weaknesses of each method. Some methods such as MAUT and AHP consider the uncertainty and risk which are the focus of this research and hence they be reviewed in the following paragraphs.

The MAUT method has been applied in several fields due to its usefulness in addressing various real-world scenarios. For example, it is used to assess the different evacuation options in emergencies (Kailiponi, 2010). MAUT's advantages lie in its ability to take uncertainty into account, and its high levels of accuracy are convenient. However, it is characterised as extremely data-intensive, due to the amount of data required to capture DMs' preferences.

The AHP method can also be applied to assess, prioritise and rank risks and uncertainties in different areas. For example, Dong (2016) applied orders-of-magnitude AHP (OM-AHP) to prioritise and rank supply chain risk management according to the severity of their impact on different criteria. Such methods gain their popularity from their ease of use, in addition to their acceptable accuracy. However, the interdependence between criteria and alternatives might raise some problems.

These methods are constructed based on the DMs' experiences, such as assigning weights to the expected utility of each outcome or the importance of each alternative. However, the role of the DMs' attitudes is overlooked, though it may influence the final decision.

DMs are influenced by several psychological characteristics under risk and uncertainty, such as (1) reference dependence, (2) loss aversion, (3) diminishing sensitivity and (4) probability weighting (Gonzalez & Wu, 1999; Abdellaoui, 2000; Bruhin et al., 2010). Therefore, it is important to take such characteristics into account when evaluating risk. Although some MCDM methods consider the DMs' preferences in evaluating different kinds of risk, they are unable to capture the aforementioned DMs' psychological characteristics. Therefore, the cumulative prospect theory (CPT) will be adapted to address these disadvantages of MCDM methods.

Several behavioural decision-making methods have been developed since the prospect theory was developed by (Kahneman, 1979). These include regret theory (Bell, 1982; Loomes & Sugden, 1982), disappointment theory (Bell, 1985), third-generation theory (Schmidt et al., 2008) and CPT (Tversky & Kahneman, 1992). CPT demonstrated its superiority by accurately describing the aforementioned DMs' attitudes and providing the formulas required to calculate values and weights in a clear, logical and simple computation process. For this reason, it has been widely applied to address risk decision problems in consideration of behavioural characteristics.

The application of CPT is seen in various areas, including finance (Barberis & Huang, 2008; Gurevich et al., 2009) and insurance markets (Cicchetti & Dubin, 1994; Barberis & Huang, 2008). In marketing, prospect theory has attracted attention, as it is applied to the analysis of buyers' decisions to purchase extended warranties under risk (Voss & Ahmed, 1992; Huysentruyt & Read, 2010; Jindal, 2014).

2.7 Cumulative prospect theory (CPT)

In prospect theory, decisions under risk and uncertainty are processed in two phases: framing and valuation. During the framing phase, DMs construct a representation of potential outcomes, contingencies and acts, which are relevant to the decision. In the valuation phase, the value of each prospect is assessed and then the decision is made (Tversky & Kahneman, 1992).

Prospect theory was originally developed by Kahneman (1979). There were some limitations to that version; for example, it is applied to gambles with a maximum of two nonzero outcomes and predicted that people sometimes choose the dominant gambles. Tversky & Kahneman (1992) have therefore amended this version and developed a new version, called "cumulative prospect theory" to address such limitations and other disadvantages existing in the original version.

CPT is a descriptive model that has shown its effectiveness in capturing DMs' behaviour under risk, towards forming and evaluating the risks' consequences, called *outcomes* in CPT (Gonzalez & Wu, 1999; Abdellaoui, 2000; Bruhin et al., 2010). It is a generalised method of the expected utility, in that the choices under risk are prospects that are defined as gains or losses with respect to a specific reference point, rather than the final asset, as is the case with the expected utility. Based on the reference point, the value function of CPT captures the fact that people are generally risk-averse for gains and risk-seeking for losses. Additionally, the pain of loss is greater than the pleasure of gain, and this observation is known as loss aversion. This function is concave in the gains region and convex in the losses region. This creates the effect of diminishing sensitivity, whereby it is high for the outcomes close to the reference point and low for those further from it. CPT also holds that people tend to overweight lower probabilities and underweight middle-to-high probabilities.

CPT is widely applied and showed its robustness. It is used to investigate how insurance contracts are chosen based on consumer risk preferences when quality is the decision variable (Kairies-Schwarz et al., 2017). CPT is used in the transport field to examine travellers' dynamic mode choice behaviour under travel time variability (Yang et al., 2017). In the field of energy, a novel grey CPT combining with multi-criteria decision making (MCDM) model, the best-worst method (BWM) and the entropy weighting approach is developed for optimum selection of micro-grid planning programs (Zhao et al., 2018). In finance, the choice of the portfolio is examined under CPT (Consigli et al., 2019).

2.8 Warranty price optimisation

Numerous approaches have been proposed to optimise the warranty price. For example, Matis et al. (2008) developed a model to optimise a warranty price for a product under a non-renewable combined warranty policy and pro-rata warranty duration. Lin et al. (2009) proposed a dynamic decision model to optimise the warranty price, duration and production rate for defective items under a dynamic demand and free-replacement warranty policy. Aggrawal et al. (2014) optimised warranty price using a two-dimensional innovation diffusion model to represent the product life cycle. Yazdian et al. (2016) optimised multiple decisions concerning the warranty, remanufacturing and pricing of end-of-life products under linear and nonlinear demand functions. Xie (2017) proposed a model to seek the maximum profit by investigating the impact of the price and the two-dimensional warranty on marketing for a new product. Luo & Wu (2018a) have recently proposed a model for collectively optimising the producer's total profit using a mean-variance optimisation method. The authors used the warranty price and duration as decision variables. Luo & Wu (2018b) also optimised warranty policy considering the dependency of faults for a set of products produced by the same manufacturers.

The above-mentioned studies have investigated the optimisation of the warranty policy away from the DMs' risk preferences, which may influence the final decision in determining the warranty's price and its duration. In other words, the risk preferences of the DMs in optimising the warranty policy have received little attention. For example, Ritchken & Tapiero (1986) proposed a framework that aims to evaluate warranty policies according to the risk preferences for both the warrantor and the buyer. Padmanabhan & Rao (1993) characterised the producer's warranty policy and its effect on the consumer's consideration of different risk attitudes. Chun & Tang (1995) developed a warranty model to determine the optimal warranty price for producers and buyers under the free-replacement, non-renewable warranty policy. They used the exponential utility function and the gamma failure rate distribution to determine the producer's certainty profit equivalent. Jindal

(2014) investigated the drivers of buyers' choices under risk, particularly the risk preferences and demand for the extended warranty.

The above publications, however, have not considered the risk attitudes of warrantors and buyers, in terms of their behavioural aspects, such as risk aversion, risk-seeking and loss aversion, which may have a significant impact on final pricing decisions. For example, the warrantor seeks high profits and may have a risk-averse attitude to the losses raised from the claims costs exceeding the warranty price. Additionally, the buyer may evaluate the offered warranty price with respect to the value of expected repair cost. Based on perceived failure rate, he or she may then decide whether to purchase the extended warranty or to pay the warranty repair cost individually, once it has occurred. If the buyer has decided to purchase the extended warranty, the losses may arise when the total amount spent on the warranty repair costs is lower than the warranty price that they bought at the time of purchase.

In this study, the maximum profit will be sought by determining the optimal warranty price. The warrantor's risk attitude towards the profit and the buyers' risk attitudes towards warranty cost will be considered. A warranty decision model will be developed based on CPT, and the sensitivity of the profit to the aforementioned behavioural aspects will subsequently be examined. In the paragraphs that follow, different types of warranty policy.

2.8.1 Warranty policies

Based on the decision variables, warranty policies can generally be categorised into two groups: warranty price and warranty duration. The warranty price refers to the warranty repair cost and the revenue gained from the buyers' payments. In this case, the warranty policy can be classified mainly into two categories:

1) Free-replacement warranty (FRW), which implies that the warrantor is obliged to provide the required repairs or replacements free of charge during the warranty period (Yeh et al., 2015).
2) Pro-rata warranty (PRW), which implies that faulty items will be replaced or repaired, and the cost is prorated to the age at which the product's failure has occurred (Park et al., 2018).

The warranty policy based on the warranty duration can be classified as fixed-period or renewable. In the case of the fixed warranty period, the expiry date is not extended by the number of warranty claims that occur during the warranty period, and this type of policy is the most common in the marketplace (Ye & Murthy, 2016; Zhang et al., 2018). In the case of the renewable warranty policy, the expiry date is extended when a repair or replacement of the failed product has been necessary within the warranty period (Jung et al., 2015; Tian et al., 2016).

Warranty policy also can be categorised based on the eligibility of the product to receive warranty services. The usual method for this is the implementation of a single-diminution warranty policy, which is designed based on the warranty duration. Another method is to design the warranty policy based on two dimensions: the product's age at the time of failure and the warranty duration. The warranty policy can also be classified based on the purpose of its provision: promotional or protective (Yeh et al., 2015). In this thesis, a single-dimension, fixed (non-renewable), FRW is considered. Accordingly, a warranty decision model is developed based on CPT in order to better capture the decision of the buyers and warrantor under uncertainty towards the warranty costs and profits, respectively.

2.9 Summary

The objective of this chapter is to analyse WaRM literature comprehensively.

Findings: based on the analysis of the above literature, the following knowledge gaps are identified.

1) The existing literature has paid very little attention to WaRM. The reason for this may be the interplay between warranty management and almost all departments within an organisation. For example, some contributing factors (e.g., the products' reliability and quality) to warranty incidents have been discussed from an engineering perspective, while other publications have discussed some warranty risks from the marketing perspective. Others are concerned with financial planning, such as the estimation of warranty costs, the number of warranty claims or warranty prices. Additionally, the existing work mainly discusses WaRM from the buyer's

point of view. However, from the manufacturer’s perspective, it has received little attention. Moreover, the existing warranty hazard identification tools rely mainly on analysing warranty claim data which needs time to be collected and analysed. In warranty literature, the use of advanced technologies which help in collecting and analysing steaming warranty-related data posted by buyers on the internet has received very little attention. Thus, there is a necessity to analyse WaRM comprehensively and to develop a generic WaRM framework which can integrate a sort of advanced technology as an early warning tool. The warrantor can then be prepared for undesired warranty-related risks.

2) In addition to the need for developing a generic WaRM framework, warrantors need to identify the existing contributions to warranty incidents and cost. Although this point is very important, warranty literature has not comprehensively studied the top contributors to warranty incidents from the product life cycle perspective. Thus, decision makers or warranty managers who work in manufacturing companies need to be surveyed. This survey should include suppliers, OEMs and WSPs.
3) Warranty risk mitigation is one of the main steps in the WaRM framework. Obviously, it is overlooked in the literature as a part of WaRM. Since it is a decision problem, it is important to analyse the criteria that can be influenced when a mitigation plan is chosen. Additionally, the voice of the decision makers from different departments such as engineering, marketing, etc. needs to be taken to account.
4) In the literature, there is a vast number of publications discussing the design of warranty policy. The role of DMs’ risk preferences, such as risk aversion, risk-seeking and loss aversion, in optimising warranty price has, however, received little attention.

Based on the above analysis of the existing literature, this research aims to address various issues in WaRM, including the following aspects:

1) the development of a new WaRM framework and the use of social media data and other forums data as a source of streaming data to identify warranty hazards at the early stage;

2) the determination of the top contributors to warranty incidents and costs in the automotive industry from different aspects: the product life cycle and warranty chain, and then designing generic warrant hazard taxonomies;
3) the development of a warranty risk mitigation model to aid DMs in selecting the optimal mitigation plan; and
4) the development of a warranty decision model based on CPT to optimise warranty price.

CHAPTER 3: WARRANTY RISK MANAGEMENT

3.1 Introduction

Manufacturers aim to offer competitive warranty policies to their customers to ensure that they maintain or increase their market shares. This often entails lengthy warranty periods or generous compensation. Furthermore, revenue from extended warranties motivates those manufacturers to expand this complementary business. It has been stated that warranty may contribute more than sales to firms' profits (Murthy et al., 2004).

However, offering warranties is also associated with various risks that can significantly impact manufacturers' profits and reputations. For example, Ford and GM usually spend $3 and $4 billion per year, respectively, on warranty claims (WarrantyWeek, 2015). Between 2003 and 2017, Toyota and Honda paid 605 billion yen[10] and 341 billion yen, respectively, in warranty claims (WarrantyWeek, 2017).

Although warranties are becoming increasingly important, the management of warranty risk remains ineffective. As such, it is essential to develop an effective WaRM framework, in view of two challenges in particular: the complexity of new products (innovation) and market pressure (e.g., to offer long warranty periods).

The WaRM process mainly consists of warranty risk planning, warranty hazard identification, risk assessment, risk mitigation, risk monitoring and review. In this chapter, the focus is on WaRM tools. Warranty hazard identification and warranty risk assessment and mitigation will be thoroughly discussed in Chapters 4 and 5, respectively.

This research aims to better understand the current practice of WaRM from the manufacturer's perspective, by answering the following questions:

1) Which tools are used to identify warranty hazards? And what are their limitations?

[10] The yen-to-dollar exchange rate has fluctuated between 82 and 120 yen to the dollar over the past fifteen years.

2) Which tools are used to assess warranty risk? And what are their limitations?
3) What are the most criteria may be influenced if warranty risk has occurred?
4) How the streaming data collected from social media can help in identifying warranty hazards at the early stage of the product life cycle?

Based on the above questions, the research objectives can be identified as follows:

1) To analyse the existing work pertaining to WaRM comprehensively.
2) To develop a generic WaRM framework.
3) To investigate the importance of advanced technology in identifying warranty hazards and offer an example from social media.

The literature review of this chapter was discussed earlier in this thesis, in Section 2.4.

3.1.1 Novelty and contribution

To the best of my knowledge, there is no literature has comprehensively addressed WaRM. As such, the novelty of this research is listed as follows:

1) It is the first study that is comprehensively analysed WaRM and developed a generic WaRM framework.
2) It is the first study to apply social media data as an early warning tool for the identification of warranty hazards.

The study's potential contributions are as follows:

1) This framework can contribute to scientific research as the first work to improve WaRM, by opening avenues for further research in WaRM.
2) A questionnaire was designed and circulated to the decision makers who work in the automotive industry in the UK to gain a better understanding of the tools used to manage warranty risks.
3) To overcome the limitation of these tools, a new hazard identification tool which is used streaming data (social network and forums) has been integrated into the WaRM framework. This streaming data is fused with warranty claim data by data fusion technique to improve the data accuracy.

4) In practice, this framework will help warranty DMs to reform their thinking regarding the importance of adopting new technologies (e.g., big data analytics) to identify warranty hazards. Consequently, the warranty risk identification process will become more efficient and DMs will be better enabled to allocate required resources, efforts and funding to manage warranty risk.

3.1.2 Overview

In the rest of this chapter, WaRM tools will be discussed from different perspectives in Section 3.2, followed by a brief discussion about social media data in Section 3.3. The development of the WaRM framework will then be discussed in Section 3.4. Data fusion technique and adaption to the WaRM framework will be discussed in Section 3.5 followed by an illustration of this framework in Section 3.6. Then the summary of this chapter is provided in Section 3.7.

3.2 WaRM tools

Risk is defined as "the effect of uncertainty on objectives"[11]. This effect can be a positive or negative deviation from what was planned. Generally, known risks can be planned in advance, in contrast to the unknown risks, which are difficult to predict due to the lack of information about future events. ISO 31000 also defines risk management as a set of activities and methods employed to direct and control an organisation risks that can affect the ability to achieve its objectives. These activities can be categorised into five stages, namely: (1) risk planning; (2) hazards identification; (3) risk assessment; (4) risk evaluation, (5) risk controlling and monitoring.

Based on the above definitions of risk management, WaRM can be defined as the process that identifies potential warranty hazards associated with warranty programmes across the products' life cycles, assesses the associated risks that occur during warranty periods, and mitigates, monitors and reviews those risks (Figure 3-1). As such, the main role of WaRM is to

[11] Available at: https://www.iso.org/news/ref2263.html. Accessed date: 02 Oct. 2019.

maximise acceptable events and to reduce the impact of unacceptable events, or to prevent their occurrence during the warranty period.

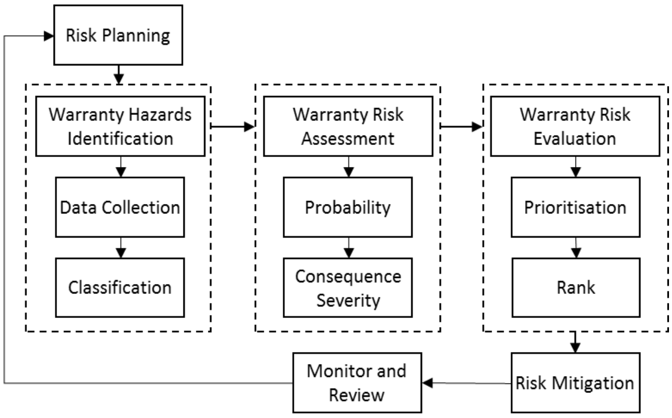

Figure 3-1: Warranty risk management process

WaRM deals with uncertain events which, if they occur, can have a negative impact on the achievement of warranty objectives, see Table 3-1. Therefore, the importance of analysing risks, whether before or after their occurrence, is linked to the improvement of product reliability and quality, in addition to the improvement of warranty risk mitigation strategies.

Table 3-1: Examples of warranty objectives

Warranty objectives	Financial aspects	Strategic aspects	Marketing aspects	After-sale aspects (Servicing)
To increase	Profits	• Maintain customers' loyalty • Understanding of customers' demands to develop warranty strategies	• Sales rate • Understanding of customers' demands • Customers' satisfaction	• The accuracy of repair scheduling • Servicing quality • The efficiency of resources' allocation
To reduce	Warranty cost		Threats from competitors	• Waste of expenses and efforts • Customers' defection • Assistance time

The WaRM's stages and the existing tools that can be adapted will be discussed as follows.

Warranty Risk Planning

Warranty management should generally be managed through the concurrent engineering philosophy, due to the fact that warranty management touches on almost all departments within an organisation. As such, the exchange of information relating to product design between stakeholders will result in a quick overall understanding of the product and process under development. Owing to the clear image obtained from this information, planning for future product issues can be more precise.

To build a robust warranty risk system, first, a sound plan that is consistent with the overall business strategy is required. Accordingly, the tools, methods and data required to build such a model should be determined. Other steps in the planning process should be considered, such as assigning roles and liabilities to avoid contradictory decisions in respect of emerging risks and allocating the required funding, efforts and resources. Unifying the procedures of managerial works once risks have actualised is also necessary, in terms of reporting them to interested departments, and ensuring that such risks are documented so that a new warranty risk strategy may be developed.

The planning for WaRM includes, but is not limited to, planning for risks associated with product reliability and quality, warranty policy, warranty logistics, warranty servicing, customers' usage, required equipment and stakeholders' involvement.

As such, it is essential to identify what tools will be used and what source of data is needed, as it will play a vital role in providing useful information. The determination of the appropriate tool relies on the product life cycle stage (i.e., pre-launch, launch or post-launch) and the availability of data. Some tools used in project management can be adapted to warranty risk planning, including the following tools:

- Project network diagrams: This is a graphic technique used to present project tasks and precedence relationships (Tavares, 2002). It can be adapted to warranty programmes in addition to the critical path method (CPM), for the purpose of planning and identifying critical tasks.

- Precedence diagrams method: This is concerned with representing the overlapping tasks between two dependent activities (Badiru, 1996). Adapting this method to warranty risk planning allows warranty DMs to focus more on prioritising tasks and their required time.
- Generalised activity networks (GAN): This approach gives a graphic illustration of the probabilistic branching of the project activities (Dawson & Dawson, 1998). It gives all possible paths or scenarios that may arise in the project. As the average warranty period is three years (or more), it is essential to envisage different scenarios for uncertain outcomes and to plan for such scenarios.
- Root cause analysis: It is a proactive tool used to identify the root cause of potential hazards by analysing the causes that lead to problems (Okes, 2019).
- Design structure matrices (DSM): This method uses a square matrix of equal numbers of rows and columns representing the precedence relationships of project tasks. This tool also helps to identify which task should be performed first, or whether it is dependent or independent in relation to other tasks.

Additionally, it is essential to assign roles and liabilities for each action and stage. Leaders and WaRM members must be determined to avoid conflict between tasks or hesitation with regard to actions during emergency situations. Furthermore, in terms of the financial aspects, budget and time should be established at this stage. As WaRM is a continuous process of observation during the warranty programme, warranty cost analysis should be periodically reviewed.

The threshold for the level of acceptable risk is particularly important to be determined as it will be used by DMs as a reference point. In the risk planning stage, it is essential to standardised reports such as determining the method of analysis, reports, and documents and then determine which department the report should send to.

Warranty Hazard Identification

Warranty risk identification is a crucial step in WaRM. It addresses the question of what could go wrong with the product design, development process and the supervision of warranty and its associated services at any time of warranty period. To record and identify warranty risk, general tools can be adopted as a broad perspective on the project's hazards such as Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis. This analysis refers to identifying the strengths and weaknesses of the organisation and identifying the opportunities and threats in the external environment (Phadermrod et al., 2019).

However, to ensure that they are identified in detail, further tools/approaches are utilised as follows:

- *Failure mode and effect analysis (FMEA)*: This is a systematic and highly structured method for failure analysis. It determines causes, effects and their interrelationships. It is also used to determine the consequences of component or systems failures. As such, the potential hazards can be identified through the visualisation of such problems (Stamatis, 2003; Ben-Daya, 2009a).
- *Interviews*: Once the project hazards have generally been identified, it is essential to interview experts regarding such hazards and their potential outcomes.
- *Assumption analysis*: This technique is used as a means of risk reduction and hazard identification. This analysis is concerned with the set of assumptions made during the risk planning stage and validates their accuracy.
- *Document reviews*: The review of warranty hypotheses, assumptions and other data aids to improve warranty hazard identification.
- *Delphi technique*: This is an important technique due to its ability to combine DMs' different views. In particular, warranty hazards must be identified by DMs in different departments. Therefore, this technique will be useful to gather and combine their views.

- *Brainstorming*: This technique can be used to encourage all participants in warranty chains (suppliers, OEMs, dealers and customers) to contribute their ideas regarding warranty-related issues.
- *Checklist analysis*: This simple method of hazards identification is used to list the critical points in the project for the purpose of determining potential risk situations (Institute, 2016). It is a useful tool for comparing the existing warranty programme with its previous iteration, based on historical records.
- *Influence diagrams*: This is a graphical representation method concerned with decisions, uncertain events, potential outcomes and their interrelationships (Clemen & Reilly, 2013). This method can be adapted to warranty decisions taken at the early stage of product design and manufacturing in order to present warranty hazards.
- *Cause and effect diagrams*: These are commonly called fishbone diagrams and are graphical representations presenting the root causes of a specific problem. Such causes are broken down into different categories based on the potential source of this problem (Ahmed & Ahmad, 2011).
- *Fault tree analysis*: This is a visual method used to break down faults to determine their sources and to present the relationships between causes and effects (Khare et al., 2019). It is particularly useful for identifying warranty hazards at the design and manufacturing stages. However, it is quite challenging to apply to complex systems which typically have large numbers of events.
- *Event tree analysis*: This visual method can be used within a simple system to identify the potential consequences of failures (Henley & Kumamoto, 1996).
- There are other tools that can help in the warranty identification process such as process flowchart and cause-effect diagram.

As the warranty management interacts with different departments, the identification of warranty hazards is a challenge for warranty DMs. The interdependence between warranty and other departments can be briefly discussed as follows:

a) *Warranty and materials*: Murthy & Djamaludin (2002) observed that product design plays a vital role in product reliability, which, in turn, is essential for managing warranty cost. Another issue relating to the warranty and materials is the product quality, which is classified by engineers into “nonconforming” if the design specification is not met, and “conforming” otherwise.
b) *Warranty and marketing:* Warranties function as a promotional mechanism that influences buyers’ purchase decisions since a long warranty period implies better product reliability. This assumption is consistent with signalling theory, as proven by (Liao et al., 2015).
c) *Warranty and logistics:* The relationship between warranty and logistics is strongly correlated (Díaz et al., 2012a). Warranty logistics can be observed at both the pre-sale and post-sale stages; however, they are more evident in the post-sales, particularly in activities related to warranty services, such as the provision of spare parts and inventory control.

Analysis of the above relationships is crucial for identifying warranty hazards, including product design, manufacturing, logistics, servicing and development. One of the main sources used to identify warranty hazards is warranty data, which is divided into claim data and supplementary data. Claim data are collected from warranty service providers, and include product-related data, owner-related data, failure-related data, engineer’s diagnosis and the required equipment, whereas the data collected from designing departments, manufacturing departments, marketing department and others constitute the supplementary data.

These data are highly valuable for identifying warranty hazards. They are also vital in the improvement of products’ reliability because they include the field test data. Additionally, they can be used to determine customers’ demands. Although such data are important, they also have some disadvantages, such as the process of aggregating warranty data, data lags and incompletely censored data (Wu, 2012).

Other sources of data can be used to identify warranty hazards, such as the CRM system. This involves important data, including customers’ feedback and complaints, repetitive failures and hidden defects. It is a module of the enterprise resources plan system (ERP), which provides a useful qualitative and quantitative analysis based on data generated by both customers and engineers (Lawless, 1998).

With the development of data warehousing and big data techniques, it is possible to collect large amounts of data from various sources. In relation to the warranty-related data, it can be collected from structured datasets (e.g., CRM, ERP, etc.) and unstructured datasets (e.g., social networks, specialised forums, blogs, etc.). Analysis of both types of dataset using big data analytics tools can provide useful information, which is difficult to acquire with the traditional tools of data analysis. The application of these advanced techniques will be the optimal means of capturing warranty hazards at the early stage of the product life cycle.

Warranty Risk Assessment

The identification of warranty hazards is meaningless if they are not analysed for the purpose of measuring the associated warranty risk and their impacts on the accomplishment of warranty objectives. To assess warranty risk, two types of analysis are required: qualitative and quantitative. The first type is concerned with the identification of repetitive trends and the determination of actions that should be taken to address them, whereas quantitative analysis is mainly based on numerical measurement of the probabilities and consequences of the identified warranty hazards. The probability of warranty risk is the likelihood of the actualisation of such risks during the warranty period, whereas the consequences severity is the expected loss if such events have occurred. Such losses can be determined by experts or through comparison with similar events that have occurred in the past.

To quantitatively measure warranty risk, several methods are used, including decision tree analysis, sensitivity analysis, failure mode and effect analysis (FMEA) and failure mode and effect criticality analysis (FMECA). The probabilities of such risks and their potential impacts can be measured by these tools. In the follows, several risk assessment methods are discussed in terms of their adaption to warranty risk assessment:

- *Estimation of system reliability*: This technique is used to determine how long the product will perform its intended function over a specific period without failure (Henley & Kumamoto, 1991; Krishnamurthy & Mathur, 1997). As such, the overall system reliability can be computed by calculating the reliability of integrated components, either serial or parallel, based on the relationships between them.
- *Fault tree analysis*: This method is used to determine the potential occurrence of faults caused by events in the lower levels of the tree, which passed through logical gates (Stewart & Melchers, 1998). This technique can be adapted to assess warranty risk for simple products by visualising the overall risks from the top level to the lower level.
- *Event tree analysis*: This is an analytical technique used to identify the outcomes of a given event (Stewart & Melchers, 1998). Such outcomes are presented in branches which initially began with an event. Since warranty incidents mainly occur due to reliability issues, the adoption of such a technique can help engineers and warranty DMs at the design stage to identify future warranty risks and their outcomes.
- *Sensitivity analysis*: This technique refers to what-if analysis aimed at identifying the impact of changes in an independent variable on a specific dependent variable (Clemen & Reilly, 2013). This technique can be adapted to warranty risk assessment: for example, to determine the impact of changes in warranty terms on future warranty incidents and customers' satisfaction.
- *Failure and effect analysis (FMEA)*: This tool, already discussed above, can be used to assess risks. For example, it is applied to assess the risks associated with supplier selection decisions (Li & Zeng, 2016).
- *Failure mode effect and criticality analysis (FMECA)*: This method is used to analyse the product design or system for the purpose of determining the effects of failure mode on operation, and subsequently to categorise such failures according to the severity of their consequences, failure occurrence and risk priority number (RPN), which is the value summarising the impact of severity, occurrence and deductibility (Gullo, 2012). This technique is the most widely used tool for assessing warranty risk.

Warranty Risk Evaluation

Once warranty risk has been assessed, it can then be prioritised and ranked accordingly. At this stage, warranty risks are evaluated to determine the magnitude of each risk based on the severity of its impact on different criteria, such as warranty cost, the manufacturer's reputation, human safety and the environmental damage. Accordingly, the overall rank for all risks can be obtained, and, hence, the plan that was defined at the first step of the warranty risk process for mitigating such risks will be applied. As such, warranty DMs can allocate the required funds, resources and efforts to reduce the unacceptable risks and take the acceptable ones in balance with the potential rewards (opportunities) that might be gained.

Some methods can be adapted to evaluate warranty risk as follows:

- *Decision tree analysis*: This technique is used to structure decisions and determine the ranking of potential outcomes from uncertain events (Clemen & Reilly, 2013).
- *Portfolio management*: This method is used to compare multiple projects based upon risk in investment and return (Dickinson et al., 2001).
- *MCDM methods*: These methods can be used to evaluate risks based on tangible and intangible criteria, such as the AHP method (Dong & Cooper, 2016).

Warranty Risk Mitigation

At the first step of the WaRM process, planning for warranty risk mitigation strategies is crucial (proactive plans) to effectively respond to warranty risks once they have actualised. As such, the function of warranty risk mitigation is to evaluate such strategic planning and select the optimal solution. Nevertheless, warranty programming involves a degree of uncertainty which is difficult to plan for in advance. As such, this step's role is reactive to emerging risks. A combination of the aforementioned approaches can be applied to follow one of the mitigation strategies, such as risk avoidance, mitigation of risk occurrence, mitigation of the impact of risk, transference of risk or retention of risk.

During such processes, it is important to ensure that risks are properly responded to. Certain factors are essential to consider during the selection of the appropriate response, namely, (1) severity of consequence, (2) cost needed to deal with the event, (3) required time, (4) warranty programme context and (5) the impact of each involved component.

Warranty Risk Monitoring and Review

This stage is also essential to managing the identified warranty risk. Consequently, such risks are periodically evaluated to assess whether they are within control or require further action. In addition, the warranty risk plan should be periodically checked to ascertain whether it needs to be updated. If it is found to be inadequate, it should be updated to ensure that such risks are decreased if not thoroughly addressed. WaRM is thus a continuous process, and the plan for such risks must be established at the early stage of the product's life cycle.

As such, it is essential to track the identified risks to assess whether they are within control or require further action. Several mitigation plans can be applied, such as:

a) Contingency plans.
b) Utilisation of corrective actions.
c) Reconstruction of a new plan for overall WaRM.

3.2.1 Potential criteria influenced by warranty risk

Once the warranty risk has actualised, the possible criteria that can be affected vary from one manufacturer to another. However, the following criteria are most likely to be influenced by warranty risk:

- Warranty costs: Warranty costs may be direct expenses that result from warranty incidents (discussed later in this chapter), such as product design-related problems, or indirect expenses as a result of various activities associated with warranty services, such as logistics, different exchange rates, warranty administration, etc.

- Customers' dissatisfaction: This may arise for various reasons, such as increasing product failure rates, long service times, and mistreatment of customers or poor service quality.

Other criteria may be prone to such risks, such as human safety and environmental impacts.

3.2.2 Questionnaire design and analysis

The questionnaire is attached to this thesis, see Appendix B.

Questionnaire objectives and target group

- The objectives of the questionnaire are listed below:
    - To obtain a better understanding of the existing WaRM tools in practice.
    - To investigate the top contributors to warranty incidents and costs.
    - To investigate the level of communication between the
    - To know the top drivers leading to human error.
- Since this thesis provides the automotive industry as an example of the consumer durables, the target group of the questionnaire is the automotive industry in the United Kingdom, which includes suppliers, OEMs and dealers.

Design questionnaire questions

The questionnaire questions were designed as follows:

- The first block is general information about the respondents including their positions, experience, organisations, and organisation size. *(Q1 in the questionnaire)*
- The second block is concerned with the top contributors to warranty incidents and costs. The questions were designed based on the Global Automotive Warranty Survey Report (2007) and (Kallstrom, 2015). *(Q2 in the questionnaire)*
- The third block is about outsourcing activities and the level of collaboration between parties (suppliers, OEMs, and dealers). *(Q3 in the questionnaire).*

- The fourth block is concerned with the offered warranty duration and expected price. *(Q4 in the questionnaire)*
- The fifth block is about the existing tools used to manage warranty risks (Ericson, 2005; Ben-Daya, 2009b; Ahmed & Ahmad, 2011; Gullo, 2012; Clemen & Reilly, 2013; Li & Zeng, 2016). *(Q5 in the questionnaire)*
- The sixth block is related to human errors (Estrada et al., 2007). *(Q6 in the questionnaire)*

Pilot and re-adjusting the questionnaire

The questionnaire was initially designed to include 31 questions and 7 blocks. After discussing the questionnaire with researcher and professionals, the questions were reduced to 22 questions and 6 blocks which can be mainly grouped to answer this chapter's questions and chapter 4' questions.

Respondents and data collection

This questionnaire was distributed by Qualtrics[12] platform to different organisations (suppliers, OEMs and dealers) in the UK automotive industry. The data was also collected by Qulatrics in March 2018. Out of the 110 surveyed decision makers, 40 respondents met the data quality validation conditions.

Questionnaire data analysis

The first question concerns the respondents' current management levels, whether high-, middle- or low-level management. Generally, the majority (60%) of respondents are in middle-level management (Figure 3-3). Their experiences are grouped into four categories, and a large proportion (51%) have over ten years' experience (Figure 3-4). It is important in this research to survey those with considerable experience as, generally, the hazards identification process relies heavily on the DMs' experiences.

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[12]Qualtrics platform is an iconic platform that makes it simple for any organisation to collect, understand, and take action on experience data. Available at: https://www.qualtrics.com/ Accessed date: 08 Oct. 2019.

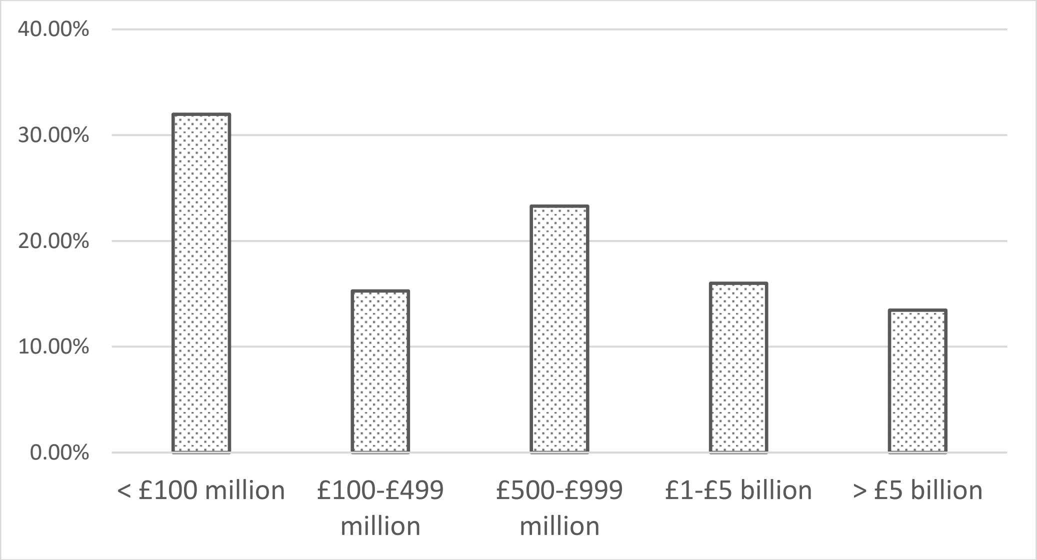

Figure 3-2: Organisations sizes

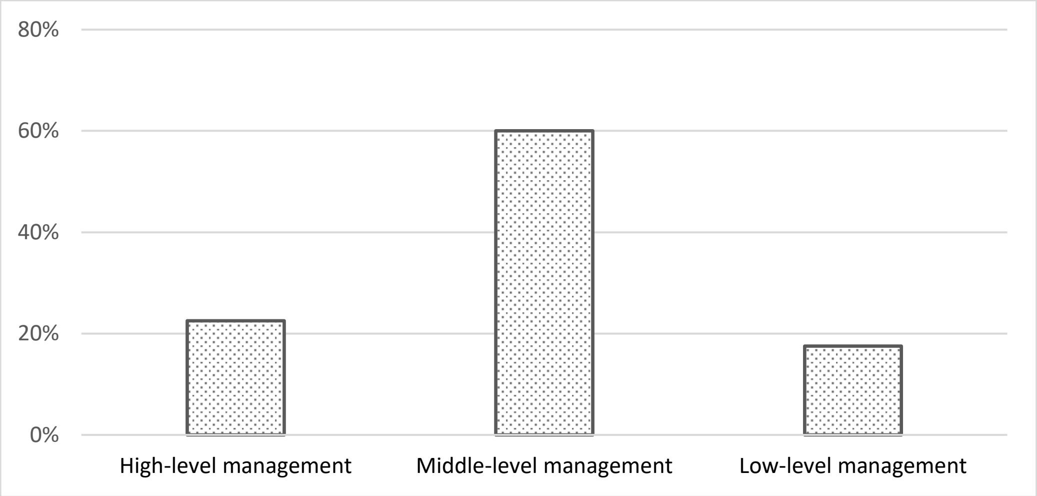

Figure 3-3: The management level of respondent

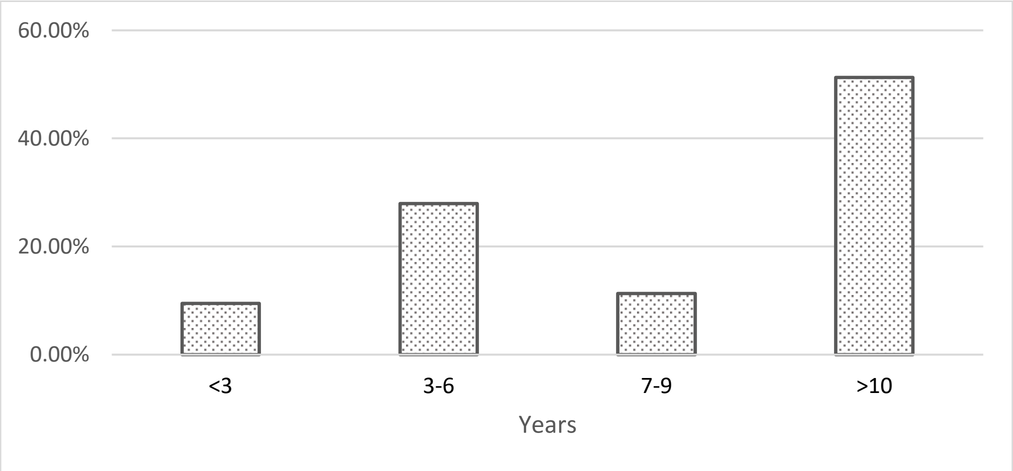

Figure 3-4: The respondents' experiences

This questionnaire aims to obtain a better understanding of the existing tools as the better we can understand methods for analysing warranty risk, the more accurate the developed models will be. Therefore, the respondents were asked, *"Which tools are used by your organisation to identify warranty hazards?"*, and they each selected the appropriate answers.

As may be seen in Figure 3-5, the tool most frequently used (16%) by the respondents' organisations is the root cause analysis technique, followed by checklist analysis (15%) and information gathering (15%). By contrast, the assumption technique is rarely adopted (4%).

The efficacy of these tools in identifying warranty hazards relies on timely access to the requisite data. For example, root cause analysis requires time to identify the cause of the product's failure and to find the resolution. This technique requires detailed information from the warranty services provider (the dealer in this research) regarding product failure (e.g., failure symptoms, usage status, etc.). However, as discussed above, the collaboration between parties is often insufficient (i.e., the required information will take time to aggregate and disseminate to the manufacturer or to suppliers).

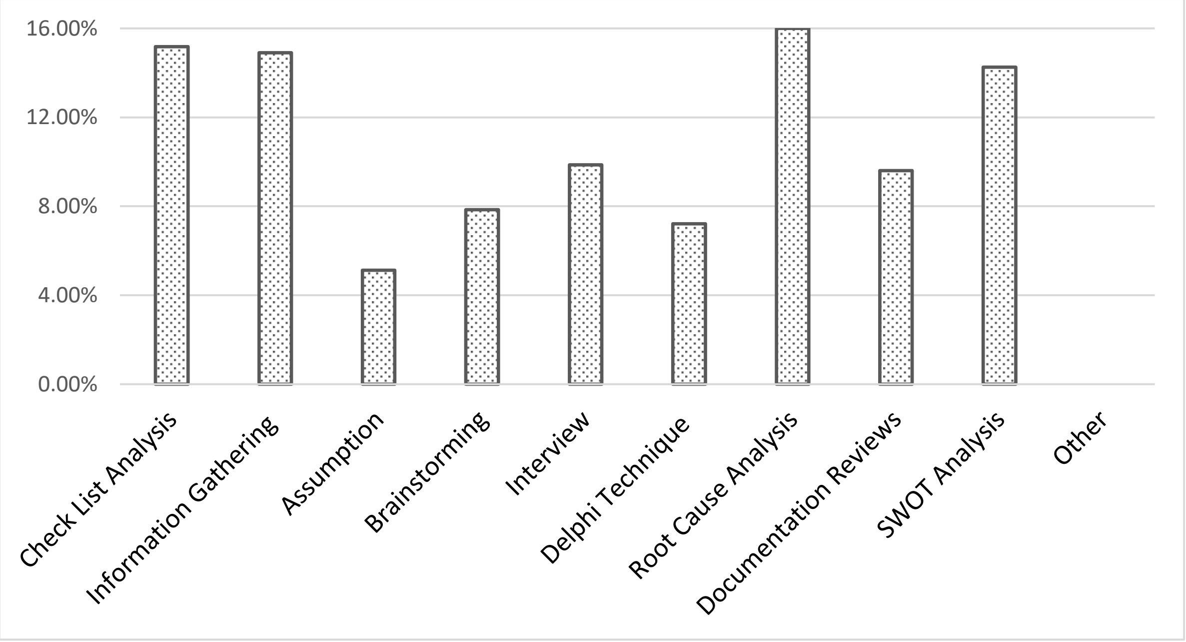

Figure 3-5: The existing hazards identification tools

With regard to the warranty risk assessment tools, the respondents were asked about the existing tool(s) used to assess warranty risk. Figure 3-6 indicates that the most common (40%) technique used to assess warranty risk is the FMECA, followed by FMEA (29%).

Respondents were also asked *“What are the limitations of the existing tool(s) used to assess warranty risk?”* in order to determine the weaknesses. They listed various limitations but mainly focused on the importance of updating the existing tools by taking advanced vehicle technology into consideration. Furthermore, the time required for processing and accessing such tools is another challenge to the use of such tools to assess warranty risk (i.e., these tools are unable to detect warranty hazards at the early stage of the product’s life cycle).

For example, some of their answers regarding the limitations of such tools include “requires human interaction” and “risks tend to remain unknown until an incident has happened on a recurring basis, and the tools do not always identify this as a risk”. These responses imply that such tools must be improved to identify hazards systematically, although some said: “there are no limitations”.

Once a warranty risk has actualised, its impact can affect different criteria and might affect the whole business. Therefore, the respondents were asked *“Once a warranty incident has occurred, what are the top criteria that can be severely influenced?”* and they were asked to select the impact severity level on a scale from *“None”* to *“Catastrophic”* for each criterion.

In Figure 3-7, it can be seen that warranty risks have a medium-to-severe impact on warranty costs and manufacturers’ reputations. However, the impact of such risks on human safety and the environment is minor to medium.

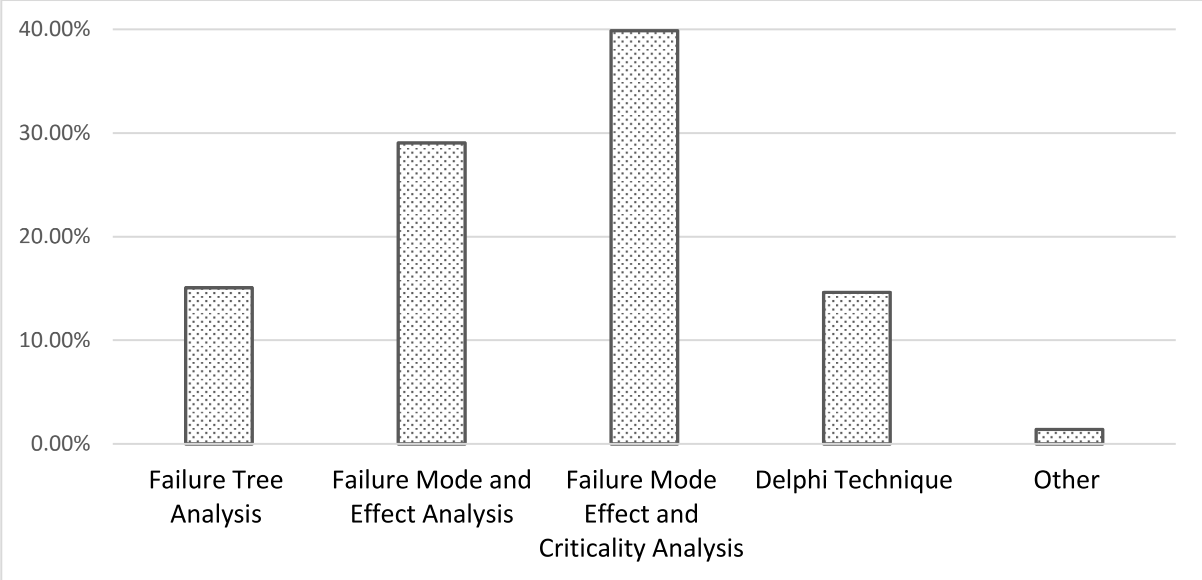

Figure 3-6: Warranty risk assessment tools

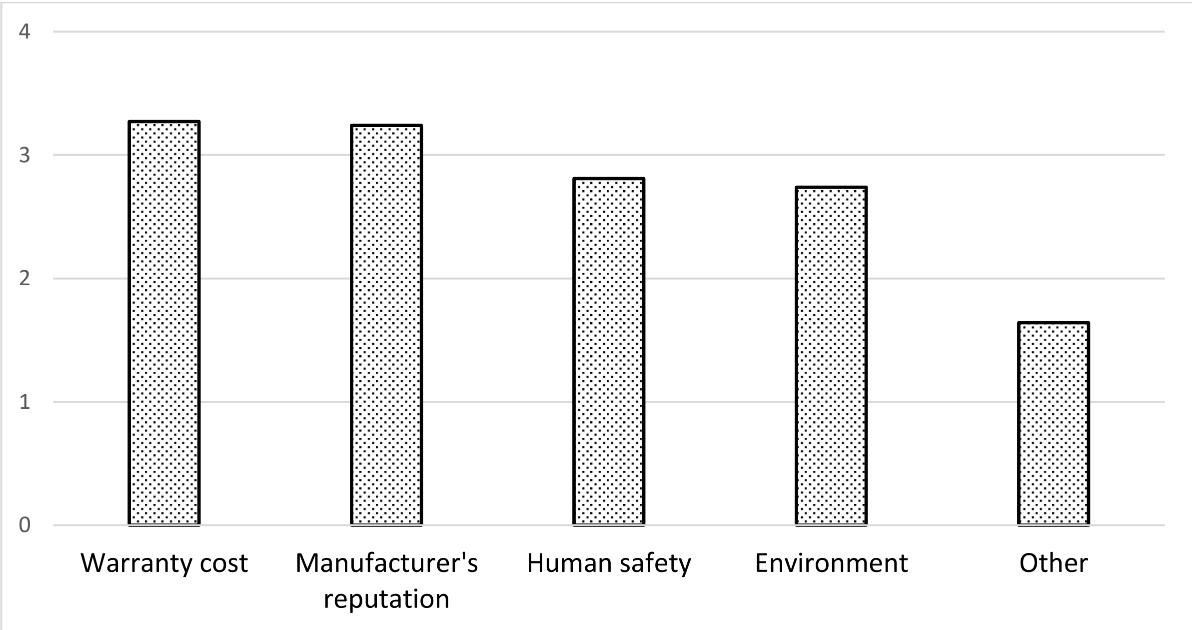

Figure 3-7: Criteria influenced by warranty risk

Respondents were also asked about the existing warranty risk mitigation plans. Generally, they use different techniques, which can be grouped into (1) mitigation plans such as recall, insurance, manufacturer support, problem diagnosis, (2) software such as CRM and Omef and (3) methods such as Delphi, historical data collection and experience.

3.3 Social network data

Nowadays, a large volume of information is generated over the Internet. Many people share their interests and opinions about various aspects of life through different platforms on the Internet. This information can reflect on their experiences or complaints regarding products and services. Therefore, such information is particularly important and useful to various stakeholders, such as manufacturers or warranty services providers (if the warranty services assigned to a third party). As such, analysis of such data can yield useful information that will aid in the development of products and organisations' strategies.

The sources of such information vary between structured data, semi-structured data and unstructured data (Barbier & Liu, 2011). The latter can be derived from various sources, such as Twitter, Facebook, Instagram, YouTube, blogs and forums, etc. These social network platforms are often used to post reviews, feedback or suggestions from customers regarding products or services that have been experienced. However, such data are messy and noisy and must be cleansed and prepared before they will yield useful information. The structured data, however, are comparatively easy to analyse and interpret. They are known as "relational data", and include warranty data, CRM data, vendors' data and logistics data, among others (Blischke et al., 2011).

In the literature, the use of social network data as a source of information can be seen in different areas such as health, business and governmental sectors. One of its uses is to provide governments with useful information for use in emergency systems. For example, in disaster management, some systems have been developed based on data collected from social network data, because of their usefulness as a source of streaming data. "Emergency 2.0 Australia" in Australia employs social network data as a source of real-time data and relies heavily on Twitter and Facebook streaming data. The aim of this system is to detect the signs of disaster before its occurrence, to allow time to prepare the required equipment, efforts and apply the proper evacuation plan (Sim et al., 2014). In the US, an earthquake detection system called TED was developed by the United States Geological Survey (USGS) and it is fed with streaming data harvested from Twitter. This system relies on the analysis of tweets that have just been posted with regard to a specific location to assess the potential earthquake risk associated with this location. It was proven that earthquake detection using tweets was faster than that using conventional tools.

Conventionally, manufacturers conduct surveys to obtain customers' feedbacks and opinions on their products using manual methods, such as well-designed questionnaires. Although such methods provide quality estimation, they are often costly and time-consuming, particularly if the population size is large. Today, however, social network data, as mentioned above, provides valuable information that can be used and analysed instead of the traditional methods used to engage with customer feedback, demands and complaints. To obtain such information, sentiment analysis is the technique most frequently used to extract information from data generated by customers or potential customers. It combines artificial intelligence, natural language processing and text mining.

Several tools are used to perform sentiment analysis. For example, Support Vector Machine (SVM) and Naïve Bayes (NB) are the most common machine learning algorithms used in sentiment analysis for the extracted tweets (Singh et al., 2014). The former technique has been widely used for sentiment analysis of movie reviews (Pang et al., 2002; Pang & Lee, 2004; Whitelaw et al., 2005), whereas the NB technique is commonly used for web discourse (Pang et al., 2002; Pang & Lee, 2004). Mullen & Collier (2004) claimed that SVM's performance is superior to that of NB. The accuracy of sentiment analysis is also important to be measured. Singh et al. (2014) compared the accuracy of different techniques and found that probabilistic models (Celikyilmaz et al., 2010) and machine learning techniques (Go et al., 2009) showed higher accuracy than others.

As such, in this research, social network data will be used as a source of streaming data, which can help to detect warranty hazards (e.g., product failure, service quality, etc.) at the early stage of the product's life cycle. Therefore, Twitter and specialised forums data will be used to develop an early warning tool to identify warranty hazards. Twitter is a microblogging service that allows users to publicly and promptly write a tweet using 280 characters. It yields large amounts of data, with active users[13] totalled 326 million as of the third quarter of 2018, and over 500 million tweets are generated every two days (Jianqiang & Xiaolin, 2017).

3.4 The WaRM framework

The WaRM framework is developed based on the general risk management framework guided by ISO_Guide (2009) and interpreted as follows, see Figure 3-8:

1) The internal and external stakeholders who should be communicated with or consulted to gain inputs for each step of the framework are identified. The engineering, marketing, finance, legal and accounting departments are examples of the internal stakeholders, while suppliers, dealers and distributors are examples of the external stakeholders affecting decisions pertaining to the management of warranty risk. Communication and consultation is a continuous process throughout all WaRM steps and is the key to understanding the objectives of the stakeholders. Accordingly, such objectives can be considered when establishing the warranty risk plan.
2) The warranty risk plan is established by determining warranty programme objectives and the factors that influence the achievement of such objectives. It is also important to determine the mitigation plans for each potential hazard by consulting experts or learning from similar cases that have occurred with competitors.
3) Warranty hazards are identified. This is the cornerstone of the WaRM framework and will be discussed in the section that follows.
4) Warranty risks associated with the identified hazards are assessed based on the likelihood (e.g. frequency rate) and the severity of the consequences of such risks for some criteria.
5) These risks are evaluated. This includes prioritising and ranking them based on their severity in terms of warranty cost and the organisation's

[13] Available at: https://investor.twitterinc.com/home/default.aspx. Accessed date: 02 Oct. 2019.

reputation. Then, warranty DMs can evaluate these risks and distinguish between those that are acceptable and those that are unacceptable.

6) The risk is mitigated based on the outcomes of the above steps 3) and 4) and based on the mitigation plans established in step 2).
7) Risks are visualised to ensure the effectiveness of the mitigation plan. The monitoring and review process is continuous throughout all stages of WaRM. For example, warranty risk plans, including procedures, liabilities, documentation and others must be updated in response to changes. Likewise, the approaches used to identify, assess, evaluate and mitigate warranty risk will be updated, if necessary, according to such changes.

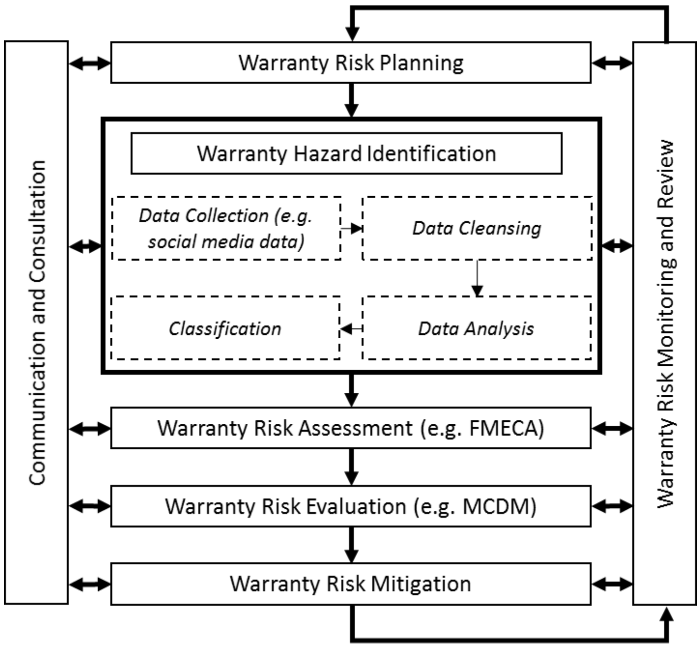

Figure 3-8: The WaRM framework

3.5 Data fusion

Since multiple data sources will be collected to identify warranty hazards, data fusion techniques will be adapted to the WaRM framework. This section, therefore, will succinctly highlight the data fusion technique.

In the broad definition of data fusion, data from multiple sources are synthesised to generate (e.g., predict or estimate) more accurate and consistent information, compared to that provided by a single source (Haghighat et al., 2016; Steinberg & Bowman, 2017). Data fusion has been applied in various commercial areas, such as robotics (Sossai et al., 2001), manufacturing (Bray, 1995) and medicine (Baum et al., 2008; King et al., 2017). In the case of WaRM, the data will be mainly collected from different sources: warranty claim data (claim data and supplementary data) and customers' feedback data. Efficient management of such data using the data fusion technique may provide the manufacturer with useful and more accurate real-time information, compared to sole reliance on warranty data.

3.5.1 Data fusion models

The Joint Directors of Laboratory (JDL) model, which was developed to improve communication among military researchers and system developers, is among the most widely used data fusion models (Hall & Llinas, 1997; Haghighat et al., 2016). Luo & Kay (1990) proposed a four-level hierarchical architecture on which fusion can be performed: signal-level fusion, pixel-level fusion, feature-level fusion and symbol-level fusion. These levels have been expanded by Dasarathy (1997) to process input-output modes, such as data-in, feature-out fusion. Other data fusion models are disparate, from one area to another, and, thus, it is difficult to construct a universal model that will suit all purposes (Esteban et al., 2005).

3.5.2 Integrating data fusion technique to the WaRM framework

In the absence of a universal data fusion model, a generic hierarchical data fusion architecture for WaRM is proposed based on three levels, namely, low-level fusion, high-level fusion and decision-level fusion (see Figure 3-9). The JDL data fusion model will be adapted to the WaRM framework to group and merge activities and processes that may have the same output into an appropriate phase. Then, each group will be processed into the accordance data fusion level to obtain higher quality data for further analysis. The data from heterogeneous sources are fused in the JDL model to obtain a low false alarm rate along with a high hazard detection rate (Hall & McMullen, 2004).

The WaRM framework can be reconstructed based on the data fusion model as the following process: (1) planning, (2) analysing warranty risk in different levels of fusion, (3) decision-making (evaluating risks and selecting the optimal mitigation plan) and (4) monitoring and reporting the identified risk (see Figure 3-9). These process will be discussed in detail below.

Determining the data sources: Typically, warranty data is deemed to be the main data source for identifying warranty hazards. Since this source is not sufficient, as has been stated by experts (in the questionnaire data), other sources must be sought. The customers' comments (feedback) posted on social network platforms, such as Twitter (Kim & Hastak, 2018) and other sources (e.g. specialised forums) are therefore collected and pre-processed by replacing blank spaces, removing punctuation, removing links, removing tabs and blank spaces at the beginning and end. Subsequently, the data mining technique is applied to remove irrelevant information by specifying stop words in the search query. Once these datasets (Twitter and forums) have been processed, interpretable and understandable terms and phrases will be stored in the entities database, which may include warranty hazards.

Low-level fusion: At this level, the stored datasets will be converted to structured data. To this end, the named-entity extraction technique (or neutral language processing technique) will be used to convert unstructured warranty claims data to structured data (Blischke et al., 2011). Prominent examples of the entities in warranty claims data include faulty vehicle parts, actions undertaken by technicians, the location of the fault and its cause and any actions on the part of the customer that may have led to the fault (Sureka et al., 2008). These entities can be determined based on pre-specified rules, terms or phrases. This fusion level then allows the reduction of the volume of such datasets and improves the data analysis by making it more feasible and time-efficient.

High-level fusion: Patterns underlying the stored entities (terms, words, phrases, etc.) and the relationships between them can be identified. To this end, data mining techniques, such as classification and clustering, can be used. In WaRM, the data stored in the entities database can be fused with the unstructured data provided by the warranty claim data (e.g., failure symptoms provided by customers, technicians' comments, etc.) to yield better quality data, and then the identified hazard can be more reliably assessed, see Figure 3-10.

Decision-level fusion: The current situation will be analysed to evaluate the identified risks and rank them according to the probability and the potential consequence severity of each risk. Accordingly, DMs may evaluate different mitigation plans to respond to such risks. The risk is then monitored to ensure that the mitigation plan is effective. Subsequently, such risks are reported and filed to improve the current WaRM plan.

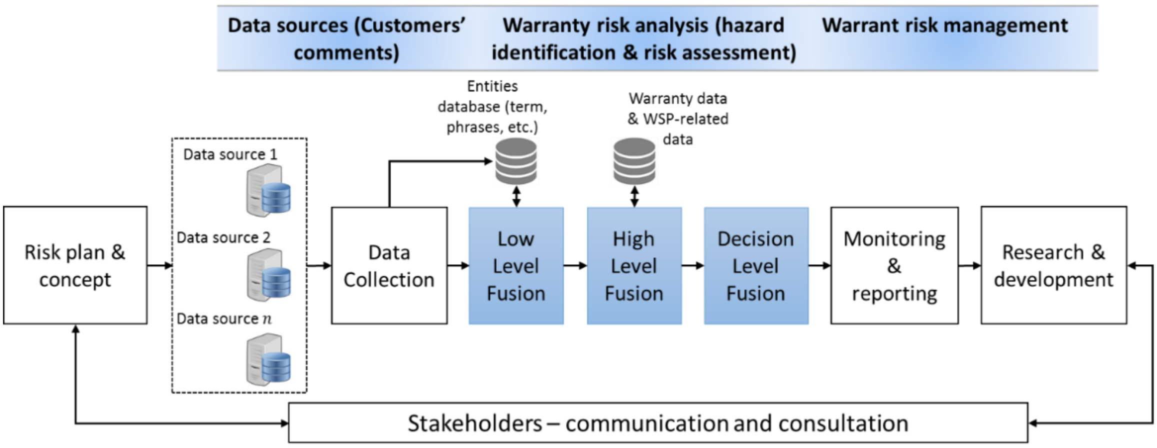

Figure 3-9: Fusion-based WaRM

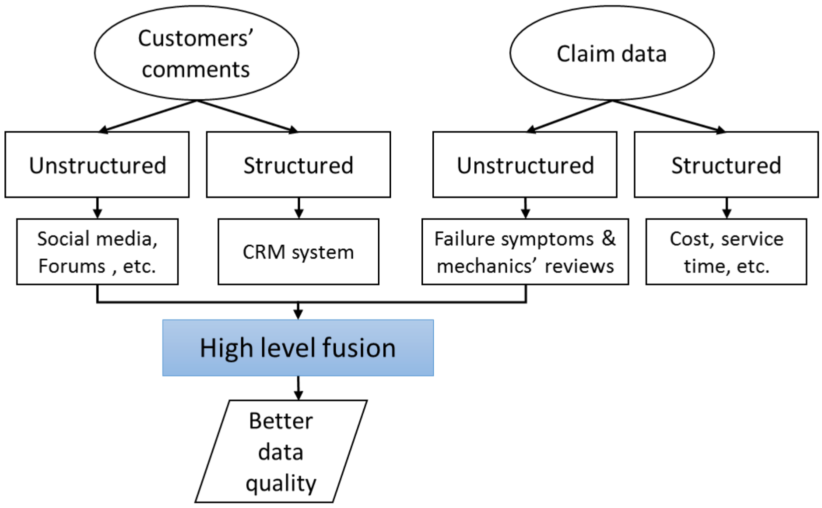

Figure 3-10: High-level fusion of customers' comments and claim data

3.6 An illustration of the WaRM framework

3.6.1 Research design and data collection

This chapter mainly concerns the design of a generic WaRM framework and proposes a new warranty hazard identification tool, based on the use of big data as an early warning tool. As such, a large-scale text analytics study was performed to identify warranty hazards based on customers' comments posted on different social network platforms. These comments are about three models of car (denoted as C1, C2 and C3) produced by one of the largest automakers in the United States and denoted as C. For ethical and legal reasons, neither the names of the models nor the manufacturer- and customer-related information will be disclosed in this research.

Since the aim of this study is to demonstrate the utility of big data in identifying warranty hazards, a limited number of forums' data, in addition to Twitter data, are used as sources of customers' comments posted on different social network platforms on the Internet. That is, these comments were collected from several forums, including consumeraffairs.com, uk.trustpilot.com, carcomplaints.com, parkers.co.uk, edmunds.com, honestjohn.co.uk/owner-reviews, autotrader.co.uk/car-reviews and carbuyer.co.uk. Unlike other forums that contain significant amounts of advertising content, these forums are more related to complaints indicating warranty issues. The users of these forums may be required to provide detailed information about their complaints, including the vehicle identification number (VIN), for verification by the manufacturers, and a unique problem in each comment. Additionally, customers post comments on Twitter. Along with customers' comments, further information is available, such as the tweet location, date and time, review rating (in the case of forums), and can also be used for further analysis (Figure 3-11 and Figure 3-12).

Figure 3-11: An example of a customer's comment posted in a forum

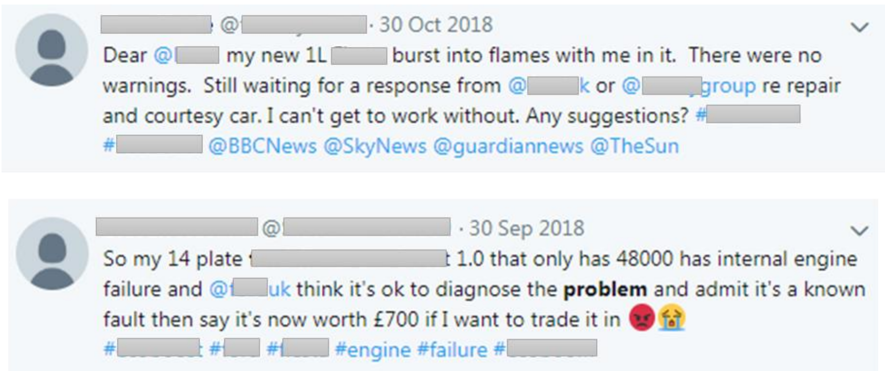

Figure 3-12: An example of customers' tweets posted on Twitter

Warranty data is deemed to be the main source of the field reliability data, which is then used to assess potential risks and improve the product. In the WaRM framework, however, customers' comments expressing their experiences regarding different car models will be used as a source of streaming data and warning of potential warranty hazards. Comments on Twitter and forums were therefore collected as follows.

There are differences between forums and Twitter, in terms of the data collection processes and tools. For forums, the data were collected between 18 June 2018 and 20 Dec 2018. The ParseHub[14] scraping tool was used to collect these data, including the customers' comments about cars, customers' IDs, the dates and times of the comments and the review ratings. This

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[14] It is a web scraping tool used to extract data. For more information, please refer to: https://www.parsehub.com/. Accessed date: 02 Oct. 2018

scraping process ultimately resulted in the collection of 1,762 comments, complete with the reviewers' names, review ratings, dates and times of the comments and the car model name. This dataset was stored in an Excel sheet for later use with the Twitter dataset to improve data quality and accuracy.

For Twitter, the use of appropriate keywords helped to increase the efficiency and precision levels of the search process. Since, to our knowledge, there was no vehicle-customers' complaint-related dictionary, the identification of such keywords was conducted manually. To this end, 300 comments were randomly selected from the above forums' data and then analysed to find the most common words used to indicate the various warranty hazards of the cars in question and related services. The preliminary analysis of the collected comments yielded 3,211 terms and 781 unique terms. The terms formed a high frequency, and those relevant to the focus of this research were used to harvest Twitter data, see Table 3-2.

Once the keywords had been determined, the RapidMiner[15] platform was used to harvest and process customers' tweets. To gain access to Twitter data, one needs to have an account on Twitter and create a New App through https://apps.twitter.com/. Once the terms have been agreed, the shown application programming interface (API) keys (API Key and API Key Secret) and access tokens (Access Token and Access Token Secret) will be used to connect RapidMiner with Twitter API. The data collected from Twitter include customer IDs, locations, dates and times and retweet counts[16].

[15] RabidMiner is a platform for data science, which showed its superurity in the easy use of the data prepration, machiene learning and predictive models. Avaliable at: https://rapidminer.com/ Accessed date: 02 Oct. 2019
[16] Available at: https://developer.twitter.com/en/docs/tweets/data-dictionary/overview/intro-to-tweet-json, Accessed date: 15 Jan. 2020

Figure 3-13: Word cloud to present the keywords

In the period between 18 June 2018 and 20 Dec 2018, the tweets (customers' comments) were collected on a weekly basis as the Twitter API provides tweets from the last seven days. The determined keywords were used along with the brand name of the car. This process was repeated for the three car models (C1, C2 and C3), resulting in the harvesting of 170,592 tweets, with an average of 6,571 tweets per week for the three cars. This dataset is stored within another dataset in Excel sheet.

Table 3-2: Identified keywords used to harvest Twitter data

Word	Frequency	Word	Frequency
problem	23	failure	18
replaced	17	faulty	17
recall	11	leak	14
recalled	14	quality	9
broken	8	dealership	23
recalls	7	dealer	16
reliable	5	fixed	19
repaired	13	service	16
component	8	warranty	9
damage	13	fix	8
defect	8	complaints	9

fail	12	complaint	11
failed	11	scratch	8
defective	6	schedule	7
warrant	6	waiting	21
mechanic	11		
mechanically	7		
damaged	22		

Since the datasets were collected from different sources, the data fusion technique was used to improve the data quality and, hence, to improve the warranty risk analysis process, as described below.

3.6.2 Low-level fusion

Since the warranty risk analysis in the WaRM framework relies on data collected from different sources, the low-level fusion of data can improve data quality and relevant information. It typically includes data pre-processing to determine the themes (Fan et al., 2006), which is essential to establishing content validity by extracting the relevant linguistic entities (terms) from the corpus (Bauer, 2007). The data pre-processing involves several steps, including the removal of punctuation, URLs, extra spaces, general English stop words (such as it, the, I'm, as, via, just, etc.) and special stop words (such as the manufacturer's name, bought, drive, cars, vehicle, etc.). After processing such data and obtaining understandable and interpretable terms or phrases, they are stored in the entities database.

Accordingly, the initial preparation of the data collected from forums and Twitter resulted in 319,201 total terms and 26,922 unique terms. The special stop words, such as the vehicles' brand names (C1:22015, C2: 29620 and C3: 36488), *driving* (15871), *vehicle* (34219), *car* (65811), etc., were then removed, and irrelevant terms such as *feel* (31,004), *come* (16,423), *home* (9007), *told* (29,309), etc. were also removed (Figure 3-13 depicts a word cloud of such terms). The result of the data preparation was a bank of 321 relevant words used by customers to express their experiences of using a vehicle and its related warranty services.

In dealing with big data and wishing to conduct statistical analysis, the effect sizes and variation should be the focus rather than the p-value, to explain the relationships at play (George et al., 2014). In addition, Boyd & Crawford (2012) stated that with regard to big data analytics, it is not necessarily the case that more data is always better. As such, the focus of the analysis will be on identifying the warranty hazard-related words that have the highest explanatory power regarding the customer's dissatisfaction. After filtering out the terms of low explanatory power and the variation of the words (e.g. failure, failed and faulty), the new number was 89 words, which were then stored in the entities database (Table 3-3). Factor analysis is then conducted to identify the underlying pattern to the customers' comments.

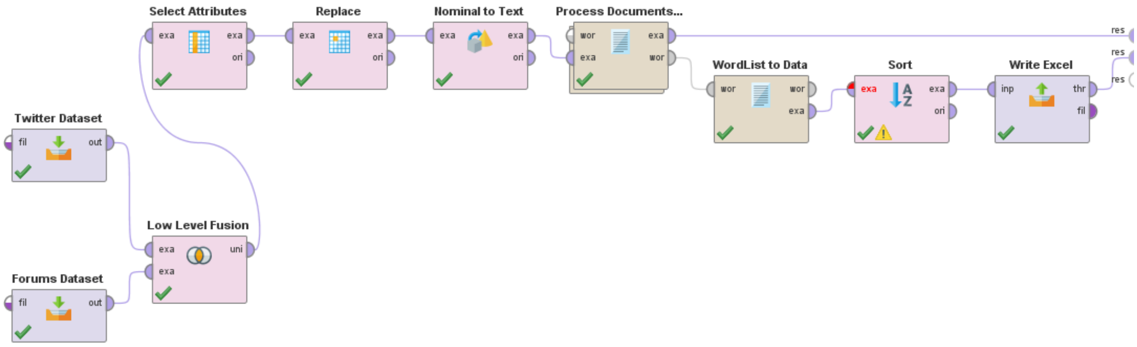

Figure 3-14: Data collection and the fusion process

Table 3-3: The top and relevant 89 words indicating warranty hazards

word	freq.	word/ C	word	freq.	word /C	word	freq.	word/ C
clutch	1952	650.7	managers	254	84.7	wait	115	38.3
replaced	1892	630.7	staff	248	82.7	upset	114	38.0
recall	1613	537.7	burned	248	82.7	gearbox	113	37.7
radiator	1183	394.3	failure	247	82.3	engine	110	36.7
caught fire	1102	367.3	email	231	77.0	parts	109	36.3
ignition	1025	341.7	leak	223	74.3	acceleration	109	36.3
reliable	986	328.7	coolant	218	72.7	shuddering	108	36.0
repaired	956	318.7	quality	211	70.3	jerking	108	36.0
sensor	903	301.0	dealership	207	69.0	downshifts	103	34.3
unsafe	895	298.3	unreliable	201	67.0	inability	101	33.7
fire	866	288.7	fixed	201	67.0	wrong	100	33.3

damage	825	275.0	schedule	192	64.0	useless	99	33.0
defect	634	211.3	service	182	60.7	horrible	98	32.7
Steering	629	209.7	vehicle	177	59.0	overheating	95	31.7
poor	623	207.7	claim	169	56.3	ability	89	29.7
call	618	206.0	complaints	141	47.0	angry	88	29.3
hurt	613	204.3	noise	135	45.0	agent	87	29.0
working	586	195.3	scratch	135	45.0	countless	86	28.7
Transmission	562	187.3	schedule	132	44.0	issue	83	27.7
clutch	550	183.3	accident	128	42.7	delay	78	26.0
charge	492	164.0	safety	128	42.7	disappointed	78	26.0
performance	422	140.7	mechanic	128	42.7	depressing	78	26.0
cost	421	140.3	price	127	42.3	distance	77	25.7
attitude	401	133.7	damaged	127	42.3	airbag	74	24.7
repair	365	121.7	coil	125	41.7	electric	69	23.0
warranty	359	119.7	contact	124	41.3	experience	63	21.0
expensive	324	108.0	Day	122	40.7	item	58	19.3
broke	306	102.0	week	121	40.3	late	55	18.3
write	287	95.7	worse	121	40.3	care	49	16.3
Fraud	261	87.0	waste	116	38.7			

3.6.3 High-level fusion

At the high level, the data stored in the entities database will be fused with the warranty data, as presented in Figure 3-10. Several data mining techniques were then used to extract the underlying patterns, which can be examined to determine their impacts on customer satisfaction as a dependent variable (i.e., review ratings stored in the forums dataset can be treated as a customer dissatisfaction measure).

Identifying patterns

In Figure 3-15, the identical process of the warranty claim is presented, which was used to ensure the validity and reliability of the pattern exploration process formed through a group of the warranty hazard-related terms that had been extracted in the previous step. This process mainly involves two parties: customers and WSPs. Customers may claim warranty service due to product failure. The WSP is obliged to respond to such claims. The WSP will check the validity of the warranty and, if it is valid, the preliminary diagnosis will be carried out. The technician may then estimate the required service time and cost (if the required parts are not covered in the warranty policy). The WSP may also communicate with the customer to inform them of the new collection date. Based on the quality, time and cost invested on the part of the WSP, the customer can evaluate these services and may decide whether to recommend using the product or to consider another competitive product.

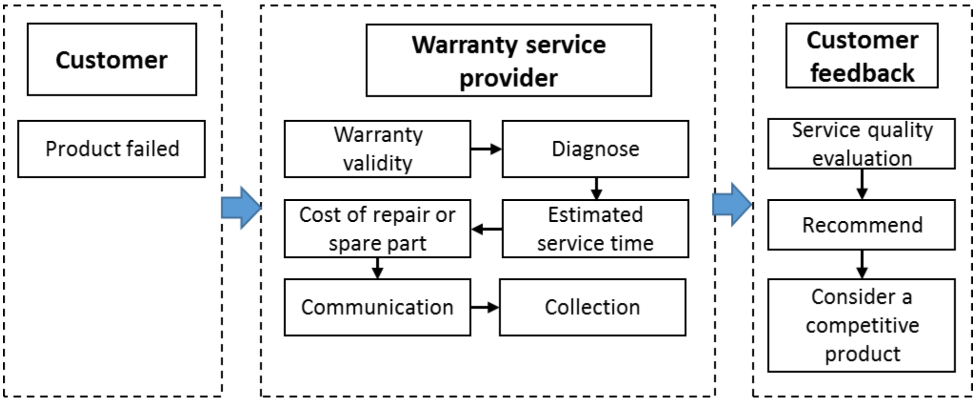

Figure 3-15: Warranty claim process was used to identify the main pattern

The coding of the first step includes the identification of the fault as stated by the customer, in comments such as "Our [C1] has an issue with the anti-lock braking system activating on sharp turns.", "[C2] with power shift gearboxes have got serious problems with juddering and other faults" and "We've had the car in twice for transmission work and it still vibrates and drags". The second step is the coding of other issues related to the provision of warranty services, such as "… was very unimpressed with the general customer service and the cost of service from [C1]", "turned up they didn't tell him it was booked in.. no email, no call no txt NOTHING", "1 Star is too kind to describe the absolute waste of time that is [C] customer service" and "…truly the worst possible garage in the country they will lie to your face". The third step is the feedback (action) given by the customer as stated in their comment, such as "I'd advise everyone to stay away from purchasing [C]", "Won't be going again, that effectively makes the warranty useless" and "Most useless company I've ever used, won't be using [C] again". Finally, the relevance of the extracted terms to each step of the warranty claim process was verified, from the high-frequency to the low-frequency terms.

With large amounts of data, however, the identification of patterns can be challenging, considering the high number of entities (derived terms). Therefore, factor analysis techniques may be applied to reduce such terms and, hence, determine the pattern underlying the customers' comments.

Table 3-4: Pattern identification based on factor analysis

Pattern Matrix[a]

	Component	
	1	2
clutch	.836	-.280
transmission	.811	-.261
fire	.735	
recall	.501	.234
hours	.492	
caught_fire	.449	
insurance	.364	
mechanic	.279	
called	.262	
door	.218	
engine		
dealer		.581
replaced		.518
warranty		.507
service		.471
problem		.415
cost		.412
damage		.358
customer_service		.357
waste		.340
months		.297
part		.270
quality		.269
radiator		.203
response		
times		

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.

a. Rotation converged in 5 iterations.

Table 3-4 presents the two main factors, which can be termed reliability-related complaints and warranty servicing-related complaints, for factors 1 and 2, respectively. The terms presented in factor 1, such as 'clutch', 'transmission', 'fire', 'recall' and 'caught fire' seem to be dominated by reliability-related hazards. In factor 2, the terms such as 'dealer', 'replaced', 'warranty', 'problem', 'cost', 'damage', 'customer service' and 'waste' seem to represent warranty servicing-related hazards.

At this level of data fusion, the Twitter dataset and the forum dataset were therefore classified into the above categories. Each row presents a customer's comment and, hence, the target attribute is labelled as "1" for the reliability-related comments and "2" for warranty servicing-related comments. To this end, different classification techniques, such as the Naïve Bayes model, the Generalized Linear model, Fast Large-Margin, Decision Tree, Random Forest, Gradient Boosted Trees and SVM were utilised and validated to obtain the optimal classification model, see Figure 3-16.

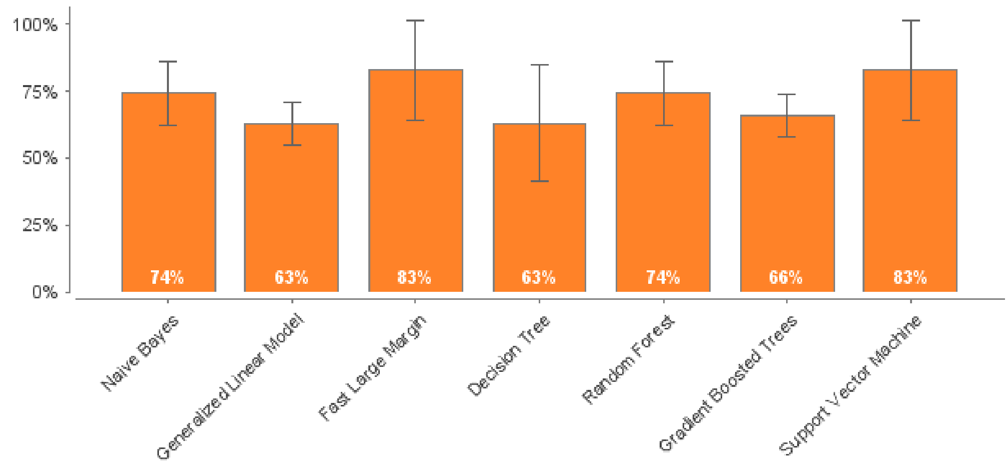

Figure 3-16: Accuracy of different classifiers

It can be seen that the SVM and Fast Large-Margin techniques relatively outperformed other techniques. As such, SVM was selected for classifying the customers' comments posted on Twitter and forums.

After identifying the main pattern underlying the customers' comments, the impact of the identified hazards may be analysed. As mentioned, warranty is offered as a strong marketing tool signalling product reliability and quality, and to retain customers' loyalty to manufacturers' products. Failure to achieve this goal may result in customers' dissatisfaction, which can be indicated by the review ratings selected, along with the comments posted on the forums, as indicated above. Table 3-5 presents the customers' review ratings for the three car models (C1, C2 and C3). Unsurprisingly, the majority of ratings for the three cars were between one and two stars, as the related customers' comments mainly concerned the cars' problems. For example, the percentage of customers rating the car brand C1 as one star, two stars, three stars, 4 stars and five stars were 62%, 24%, 2%, 5% and 7%, respectively.

Table 3-5: The three brands review ratings

	C1		C2		C3	
Review rating	Freq.	%	Freq.	%	Freq.	%
1	305	62	314	58	422	58
2	118	24	169	31	146	20
3	11	2	30	6	75	10
4	23	5	18	3	47	6
5	32	7	13	2	39	5
Total	489	100%	544	100%	729	100%

Based on the classification of the forums dataset into the identified patterns, it was found that the majority (76%) of the customers' complaints concern the warranty servicing-related issues, such as cost, repair and time. Additionally, 89% of customers who complained about warranty service selected star rating "1", whereas 61% of the reliability-related comments were associated with the review rating "1". As such, this result indicates that warranty servicing-related hazards have a greater impact on customer dissatisfaction than reliability-related hazards do.

3.6.4 Decision-level fusion

At this level, the DMs may assess the current situation and estimate the potential consequences. Accordingly, the pre-specified risk mitigation plans can be evaluated to respond to such risks. Such risks can be evaluated by adapting, for example, MCDM methods to identify where the risk ranks in relation to others and then selecting the optimal mitigation plan.

Additionally, other datasets can be fused with the above datasets (Twitter and forums) to respond to the emerging risks in a timely and efficient manner. For example, the locations of the customers who complained about warranty-related issues can be determined based on the locations (latitude and longitude attributes) in the Twitter dataset. The manufacturer therefore may use the existing data (structured data), such as inventory status, customers' records, sold products, etc., to prepare the required spare parts, labours, communications, etc., in advance so that they can respond swiftly to such occurrences.

The identified risks in the previous steps must be tracked and monitored to ensure that the applied mitigation plan is performing well. To this end, the monitoring process requires determination of how often such risks are reviewed, which risk should be focused on and how to report it. As such, the manufacturer may set periodic check-ups, which may involve identifying new hazards and, hence, the existing risks may need to be reprioritised. Meanwhile, the identified risk is reported as standard and filed for later use in designing a new WaRM strategy.

3.7 Summary

WaRM is an important area that must be thoroughly investigated. Warranty risks are not limited to financial problems but may involve other impacts on customers' dissatisfaction and manufacturers' reputations. This chapter has developed a WaRM framework that provides warranty managers with a useful tool for managing warranty risk.

This chapter has achieved the following outcomes:

- Analysed the warranty literature comprehensively. Accordingly, the concept of WaRM is established.
- Carried out a questionnaire survey to better understand the tools currently used by manufacturers to manage warranty risk and to identify their limitations.
- Developed a generic WaRM framework.
- Collected and analysed various data posted on social network platforms and forums as a means of identifying warranty hazards and to overcome the limitation in the existing tools. The data fusion technique is then used to fuse different types of data and increase the accuracy of the predictions. As part of the data fusion process, data mining and factor analysis were used to identify the hidden hazards among the users' comment.

The main objective of this chapter is to obtain an in-depth understanding of the existing practices of WaRM in the automotive industry in the UK, specifically focusing on procedures and tools used to manage warranty risk.

Findings: The following findings have answered this chapter questions as follows:

Q1: Which tools are used to identify warranty hazards? And what are their limitations?

- The most common tool used to identify warranty hazards is the root cause analysis technique (Figure 3-5).
- The limitations of the existing tools used to identify warranty hazards are the time required to process such tools and the capability to detect such hazards at the early stage.

Q2: Which tools are used to assess warranty risk? And what are their limitations?

- The most common tool used to assess warranty risk is the FMECA (Figure 3-6).

Q3: What are the most criteria may be influenced if warranty risk has occurred?

- Warranty costs and manufacturers' reputation are the criteria most susceptible to warranty risk (Figure 3-7).

Q4: How the streaming data collected from social media can help in identifying warranty hazards at the early stage of the product life cycle?

- Based on the analysis of the users' complaints posted on social media platforms and forums, two main hazard categories were identified: reliability-related issues and warranty servicing-related issues. The latter accounts for the majority (76%) of the users' complaints, which may indicate that the warranty servicing hazards can have a greater impact on the customers' satisfaction than reliability-related hazards do.

Table 3-6 provides the tools and warranty hazards mentioned in the existing literature, obtained from analysing the questionnaire data and the role of social media as an early warning tool to detect warranty hazards.

Table 3-6: WaRM tools and hazard in the literature and practice

	Existing literature	**Questionnaire**	**Social media data**
Warranty hazard identification and risk assessment tools	• SWOT • Analogy • *FMEA* • *Interviews* • *Assumption analysis* • *Document reviews* • *Delphi technique* • *Brainstorming* • *Checklist analysis* • *Influence diagrams* • *Cause and effect diagrams* • *Fault tree analysis* • *Event tree analysis* • *FMECA*	• The most tool used to identify warranty hazard is *Root Cause Analysis.* • The most tool used to assess warranty risk is *FMECA*	Analysis of the customers' feedback posted on the internet (Twitter and forums)
Top contributors	• Design-related	• Human error	WSP-related issues account for

to warranty hazards	• Manufacturing-related • Distributing-related • Operating-related • WSP-related	• Miscommunication between parties	the majority of customers' complaints compared to the design or manufacturing-related issue

This research has also reviewed and analysed the literature to present the main tools that can be used at different stages of the WaRM process. As such, this research is the first work to open avenues for future research in WaRM.

In practice, this framework will help warranty DMs to reform their thinking regarding the importance of adopting new technologies to identify warranty hazards, and the analysis of social media data is an example of such an adaption. Consequently, the warranty hazard identification process will become more efficient and DMs will be better able to allocate required resources, efforts and funding to manage warranty risk.

CHAPTER 4: WARRANTY HAZARD IDENTIFICATION

4.1 Introduction

Warranty plays a significant role in the marketplace and is an essential aspect of most commercial products. Its importance is evident from various perspectives. The first is the fact that manufacturers use it as a protective and marketing tool: they aim to compete with one another by offering a competitive warranty policy. From the customer's perspective, meanwhile, warranty is considered to be an insurance tool.

The importance of warranty goes beyond manufacturers and customers, as is evident from the fact that government bodies impose several regulations for the resolution of any potential disputes. For example, in the United States, the Magnusson-Moss Warranty Act (1975) was passed by Congress. In the European Union, the legislation was imposed on manufacturers to offer a two-year warranty on all new products (Murthy & Djamaludin, 2002).

Manufacturers pay more attention to the sale of extended warranties as a revenue source, since they may contribute more to profits than product sales do (Murthy et al., 2004). Nevertheless, they may also carry various risks, which may affect the manufacturer's profits and reputation. For example, warranty claims in the automotive industry in the United States cost between $10 and $15 billion, with a global cost of around $40 billion per year (MSX-International, 2010). Ford and GM, for example, usually spend $3 and $4 billion on warranty incidents per year, respectively (WarrantyWeek, 2015). Between 2003 and 2017, Toyota and Honda paid 605 billion yen[17] and 341 billion yen in warranty claims, respectively (WarrantyWeek, 2017).

To mitigate (or, if possible, resolve) the aforementioned problems, it is crucial to identify the potential contributors to warranty incidents and costs, on the strategic and tactical levels, on the basis of which DMs will be better enabled

[17] The yen-to-dollar exchange rate has fluctuated between 82 and 120 yen to the dollar over the past fifteen years.

to tailor warranty policy as well as establishing better plans for potential future warranty claims.

Unfortunately, the traditional approach to managing warranty risk is mostly reactive, including techniques such as root cause analysis when the product has failed. This traditional approach can incur huge losses for companies as a result of improper management of warranty risk. Decisions regarding warranty policy must be in line with product design specifications, manufacturing process capabilities, quality control standards, distribution strategy and after-sales planning to protect manufacturers from adverse events.

Additionally, based on the survey conducted as part of this study, human error plays a vital role in warranty incidents. As such, this research aims to address the following questions:

1) What are the top contributors to warranty incidents from the suppliers', OEMs' and WSPs' perspectives?
2) What is the role of human error in warranty incidents on the part of suppliers, OEMs, dealers and customers?

As such, the objectives of this study can be derived from the above questions as follows:

1) To analyse the literature to identify warranty hazards from two different angles: from the product life cycle and the warranty chain perspectives
2) To analyse the role of human error which contributes to warranty incidents across the various product life cycle stages.
3) To design taxonomies of the top contributors to warranty hazards from the two angles: product life cycle and warranty chain.

The literature review of this chapter was discussed earlier in this thesis, in Section 2.5.

4.1.1 Novelty and contribution

To the best of my knowledge, there is no literature has comprehensively discussed warranty hazards. As such, the novelty of this research is listed as follows:

1) The literature is comprehensively analysed from two perspectives to determine the top contributors to warranty incidents and warranty costs, namely: (1) product life cycle, and (2) warranty chain.
2) A questionnaire is designed and circulated to the decision makers who work in the automotive industry in the UK to determine the top contributors to warranty incidents and costs.
3) Two warranty hazards taxonomy are designed from the two perspectives: product life cycle and warranty chain.

These taxonomies are presented to assist DMs in identifying the main contributors to warranty incidents and costs across product life cycles, mainly at the stages of design, manufacturing, distribution and after-sale support. Moreover, warranty hazards will be investigated from the warranty chain perspective for the purpose of exploring those hazards resulting from the movement of material, finding the hidden costs and the main role of information exchange between parties (suppliers, OEM, WSPs and customers).

4.1.2 Overview

In the rest of this chapter, the design of the questionnaire is discussed in Section 4.2 and the questionnaire analysis in Section 4.3. Then a general discussion regarding warranty hazards is given in Section 4.4 followed by the design of the warranty hazards taxonomies in Section 4.5. The summary is then provided in Section 4.6.

4.2 Questionnaire design

A questionnaire of 22 questions was designed and circulated using the Qualtrics platform for the purpose of better understanding the main contributors to warranty incidents, warranty costs, human error on the part of various parties and the main contributors to customers' dissatisfaction in relation to warranty activities. The questionnaire was divided into several blocks, including (1) warranty-related information, (2) warranty hazards and (3) human error. The questionnaire was designed to survey the warranty DMs working in the UK automotive industry. The Qualtrics platform was utilised to distribute the survey to the main stakeholders, including suppliers, OEMs and

WSPs. Of the 110 questionnaires distributed, 40 respondents met the validation conditions aimed at ensuring the data's quality.

4.3 Questionnaire analysis

The questionnaire's reliability was tested to enhance its accuracy. Cronbach's alpha coefficient was therefore used to test internal consistency (Gliem & Gliem, 2003). The internal consistency represents the extent to which a test consisting of multiple items measures the same concept. This consistency should be determined prior to carrying out the survey to ensure its validity (Tavakol & Dennick, 2011).

This reliability coefficient of a questionnaire based on Cronbach's alpha usually ranged from 0 to 1. The greater the coefficient for the items in the test, the greater the internal consistency will be. Furthermore, it must be greater than 0.65 for the questionnaire to be considered reliable. Cronbach's α is computed as

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{K}\sigma_{Y_i}^2}{\sigma_X^2}\right)$$

where K is the number of items Y in the test $X = \sum_{i=1}^{K} Y_i$, of the σ_X^2 is the variance of the total scores in the test, and $\sigma_{Y_i}^2$ is the variance of the ith item for the current sample.

Since the questionnaire was designed to measure different issues related to WaRM, the Cronbach's alpha coefficient is computed for each issue (Table 4-1).

Table 4-1: Cronbach's alpha coefficient - reliability test

Blocks	Cronbach's Alpha	N of items
Measure: the top contributors to warranty incidents and cost.	0.835	18
Measure: which organisations contribute more to warranty incidents?	0.756	5
Measure: the effect of warranty incidents on customers' dissatisfaction	0.703	3
Measure: the top contributors to human error	0.768	5

The above table indicates that Cronbach's alpha coefficient is greater than 0.7, which indicates a high level of internal consistency for our scale with this specific sample. (Gliem & Gliem, 2003).

4.3.1 Warranty-related information

The first question concerns the current management level of the respondent, whether high-, middle- or low-level management. Generally, the majority (60%) of respondents are in middle-level management, and their average overall experience is over ten years[18]. It was considered important in this research to survey those with considerable experience as, generally, the hazards identification process relies heavily on the DMs' experiences.

Respondents were asked about the average warranty period being offered by their organisations. Figure 4-1 presents various warranty periods ranging from one year to over five years. The average warranty periods are two and three years, accounting for 31% and 30%, respectively.

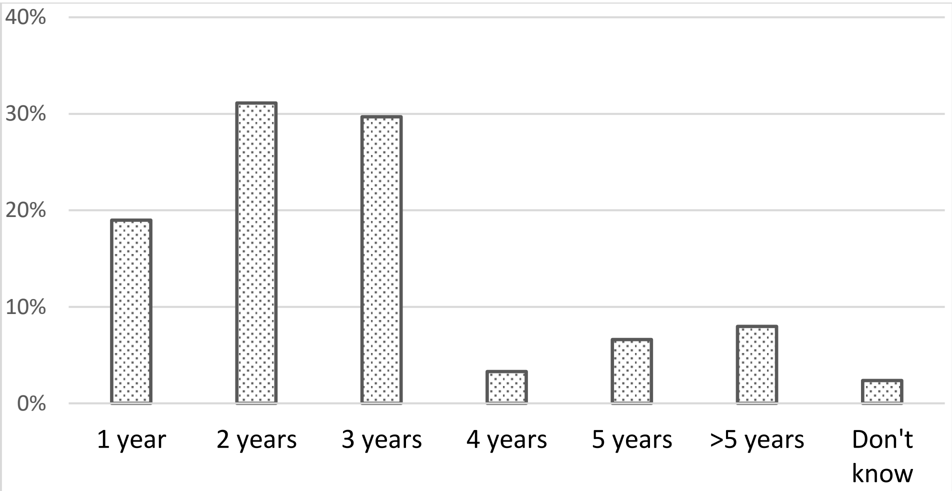

Figure 4-1: Average warranty period

Respondents were also asked about the average warranty cost and the average reserve fund for future warranty claims. The answers to both questions were grouped into different categories, as shown in Figure 4-2. The

[18] Page 71.

group with an average warranty cost £401–£500 was chosen by most respondents.

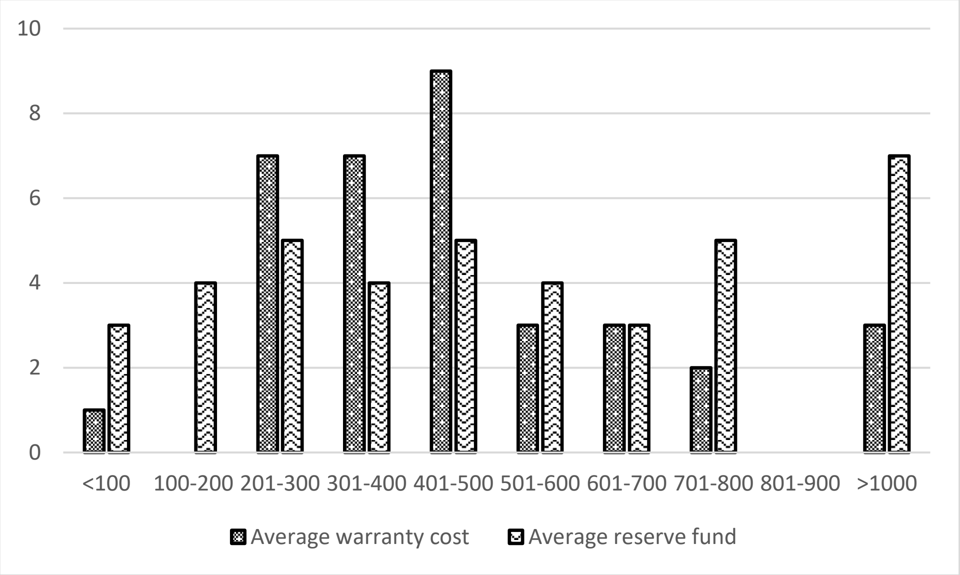

Figure 4-2: Average warranty costs and reserve fund

4.3.2 Top contributors to warranty incidents and warranty costs

The contributors to warranty incidents are mainly divided into two groups: (1) internal contributors, within the warranty chain including suppliers, OEMs and dealers and (2) external contributors, which mainly involve customers' errors.

The internal parties were asked "*what are the top contributors to warranty incidents?"*, on a scale ranging from "Very unlikely (1)" to "Very likely (5)". Figure 4-3 presents the top contributors to warranty incidents triggered by the parties. The respondents from dealers' organisations answered that the manufacturing process capability is the highest contributor to warranty incidents, followed by human error on the part of OEMs. They also said that customers' errors and suppliers' assembly processes account for a high proportion of contributions to warranty incidents, whereas distribution-related issues showed a medium impact.

The respondents from the suppliers' organisations answered that the assembly process capability at suppliers is the highest contributor to warranty incidents, followed by customers' errors. Other contributors, such as distribution-related issues, faulty product design and diagnostics errors, are considered to be slightly high contributors from the dealers' perspective, while human error on the part of dealers also has an impact on warranty incidents.

From the OEMs' perspective, the manufacturing process capability is the highest contributor to warranty incidents, followed by human error on the part of OEMs. Remarkably, these two contributors are the same top two issues reported by dealers in relation to warranty incidents. OEMs' respondents claimed that faulty product design and diagnosis-related issues account for the least impact on warranty incidents.

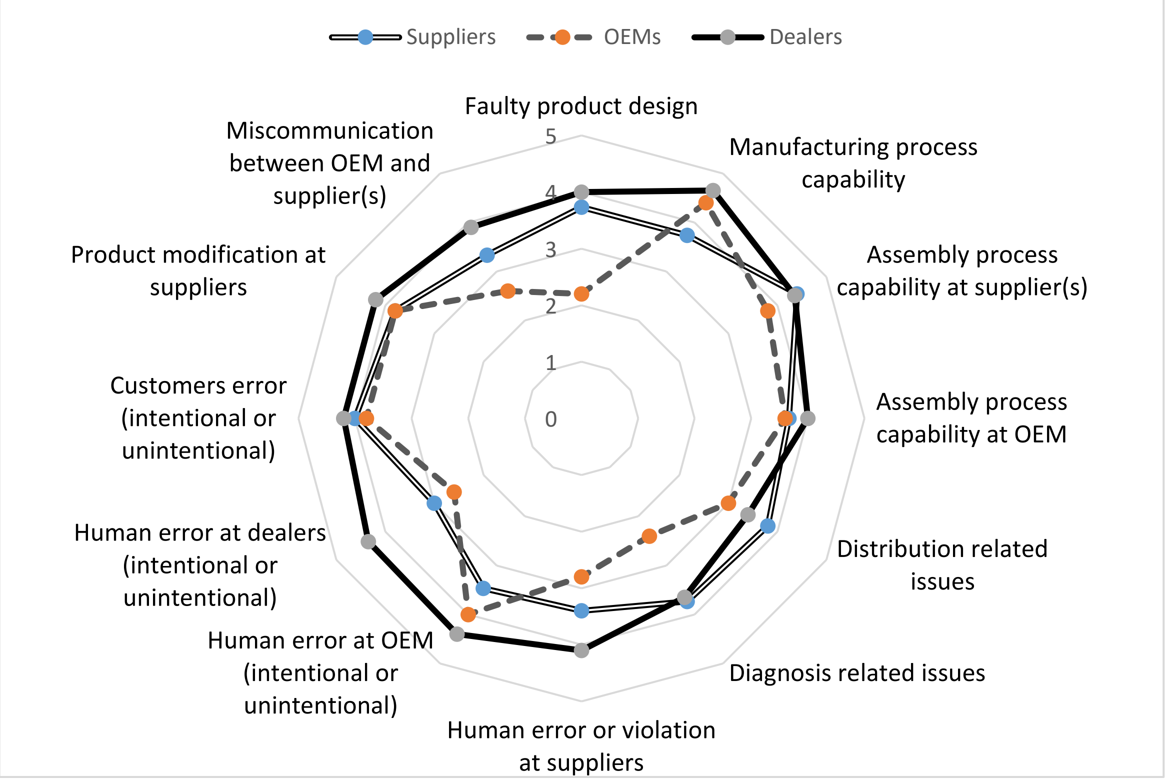

Figure 4-3: Top warranty incidents contributors

Those parties all responded differently to this question. However, their responses overlapped regarding some contributors. For example, all parties agreed that customers' errors, followed by product modification by suppliers, are two of the highest contributors to warranty incidents. Furthermore, as stated before, dealers and OEMs complained about the manufacturing process capability and human error on the part of OEMs. The assembly process at suppliers is a serious issue for both dealers and suppliers, in relation to warranty incidents.

It is evident that the main contributor to warranty costs is the aforementioned warranty incidents. However, other hidden costs lead to increases in such costs even when the warranty incidents remain constant. Therefore, the respondents were asked, *“In addition to the aforementioned warranty incidents, what the other contributors to warranty costs?”*

In Figure 4-4, these contributors to warranty costs are presented. From all parties’ perspectives, the provision of warranty services is considered to be the highest contributor to warranty costs, followed by the movement of material and storage expenses. Remarkably, customers’ fraud has a greater impact than dealers’ fraud on the warranty cost, whereas it is stated that the highest number of fraudulent claims are the result of warranty service agents’ fraud (Kurvinen et al., 2016).

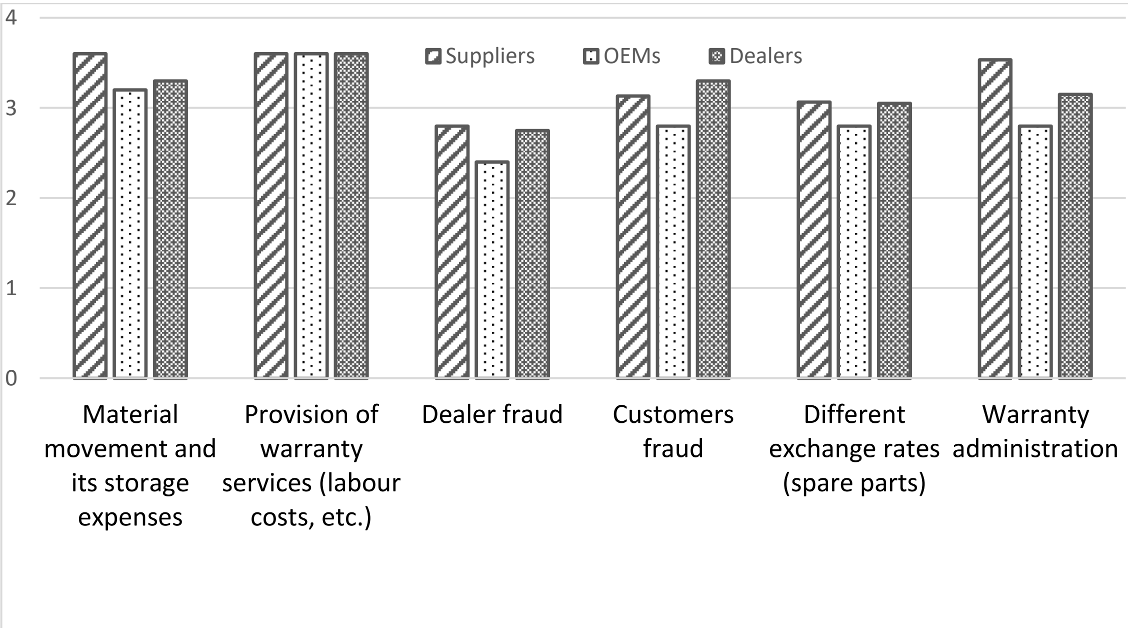

Figure 4-4: Other contributors to warranty cost

The provision of warranty services involves different kinds of risk, one of which is customers’ dissatisfaction. Hence, the questionnaire includes the following question: “*In relation to warranty services provision, what are the top contributors to customers’ dissatisfaction?*”. The respondents answered that service quality is the most prominent problem leading to customers' dissatisfaction (Figure 4-5).

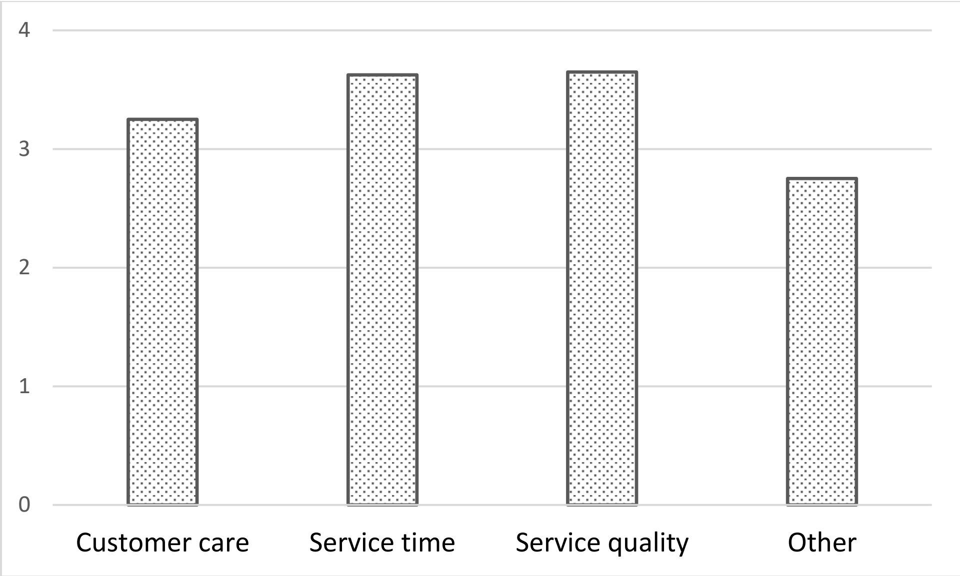

Figure 4-5: The top contributors to customers' dissatisfaction

4.3.3 Warranty hazards from a warranty chain perspective

To better understand the role of chain flow in warranty, the survey participants were asked, *"Which of the following activities (or part of) are outsourced?"* and instructed to tick all answers that applied. Figure 4-6 shows that distribution services account for the highest percentage (30%) of the stated services that are expected to be outsourced. Warranty services are the second-highest outsourced service (25%). Product design is the lowest (15%) service being outsourced as, possibly, manufacturers wish to ensure that the product design is thoroughly tested. Therefore, the in-house design allows them to test and improve the product design until the target reliability level is achieved, and then other tasks, such as manufacturing systems or sub-systems, can be outsourced.

The outsourcing of various activities can provide organisations with greater flexibility and allow them to focus on improving existing products and developing new ones. However, improper management of such activities can increase warranty costs, and this impact has been seen earlier in Figure 4-4.

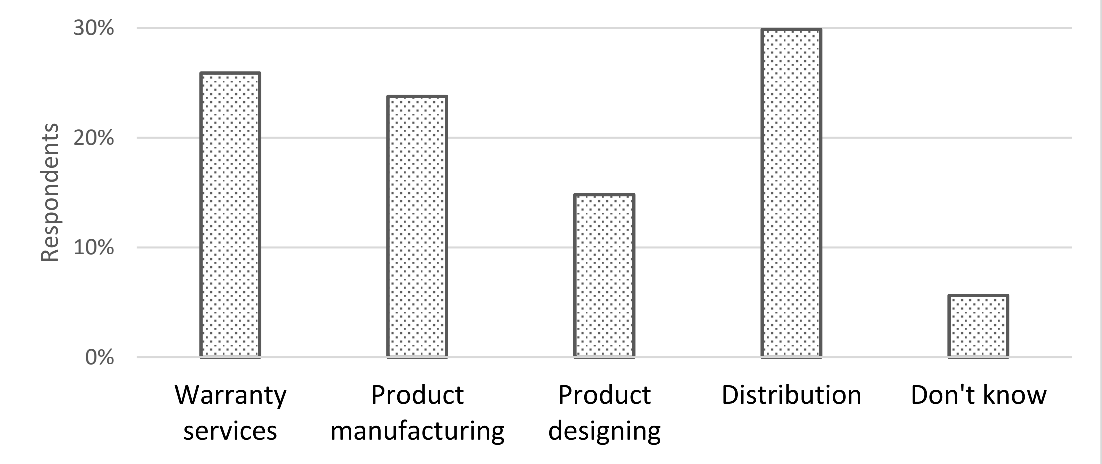

Figure 4-6: Outsourced activities

Another difficulty that may result from outsourcing activities relates to the collaboration between those parties, particularly regarding the exchange of warranty-related data. Undoubtedly, access to the required information at the proper time allows warranty DMs or engineers to take timely, correct action. Therefore, the respondents were asked, *"To what extent would/will you be able to access warranty-related data (in real-time or almost)?"* and each respondent could choose the appropriate answer among five different options, ranging from *"Not at all"* to *"To a great extent"*.

Their answers are presented in Figure 4-7, Figure 4-8 and Figure 4-9, based on their organisation's types. Dealers and OEMs can access suppliers' warranty-related data, but suppliers have less permission to access dealers' and OEMs' warranty-related data.

Generally, the collaboration between those parties is limited or insufficient to improve the warranty hazard identification process. These figures present a serious problem, which must be addressed if these parties seek to reduce warranty costs and to retain customers' satisfaction. The role of information flow was discussed in section 4.5.2.

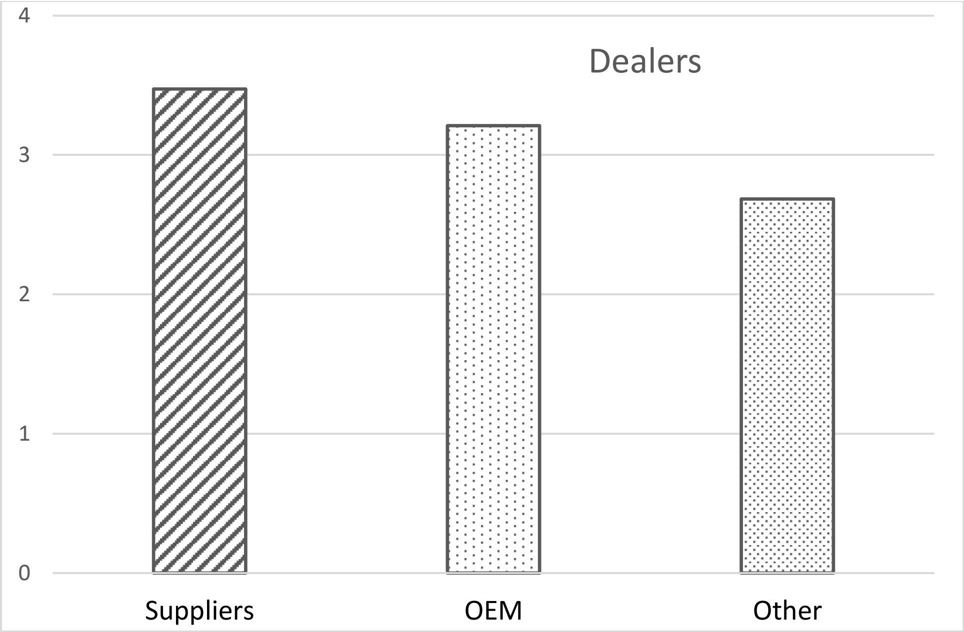

Figure 4-7: To what extent can dealers access warranty-related data from other parties?

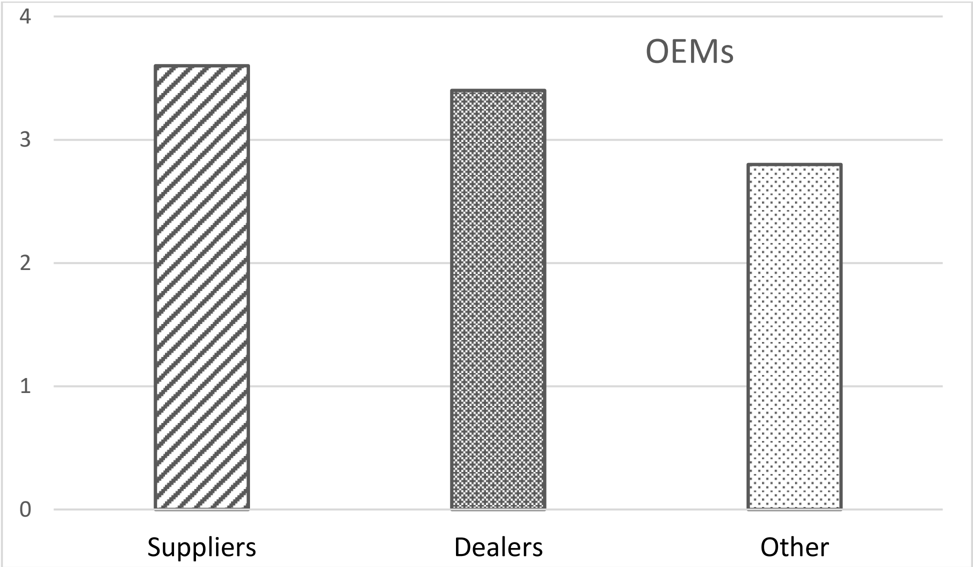

Figure 4-8: To what extent can OEMs access warranty-related data from other parties?

Figure 4-9: To what extent can suppliers access warranty-related data from other parties?

To determine which is the greatest contributor to products' failures among those parties and customers, the respondents were asked to *"Rate the following parties according to their contributions to the products' failures".* Figure 4-10 shows the contribution of each party to products' failures. Customers are the highest contributor, followed by OEMs, which confirms the aforementioned result shown in Figure 4-3.

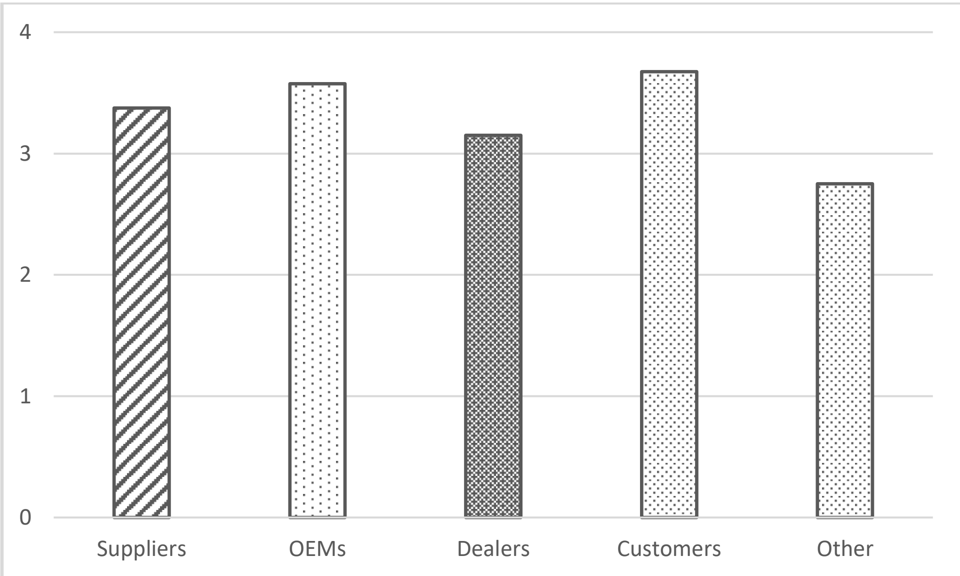

Figure 4-10: The contribution of different parties and customers to the products' failures

Addressing human error can significantly reduce warranty incidents and costs, as a significant portion of warranty incidents are caused by it. Respondents were asked, *"What are the top contributors to human error caused warranty incidents?"*. It is evident that lack of training is the highest contributor to human error (Figure 4-11). This implies that technicians have not received adequate training, particularly with regard to new and complex innovations. This also illustrates the importance of planning carefully for future warranty services at the design stage. Employing experienced labour can mitigate diagnostic errors and, hence, the problem of NFF can be reduced.

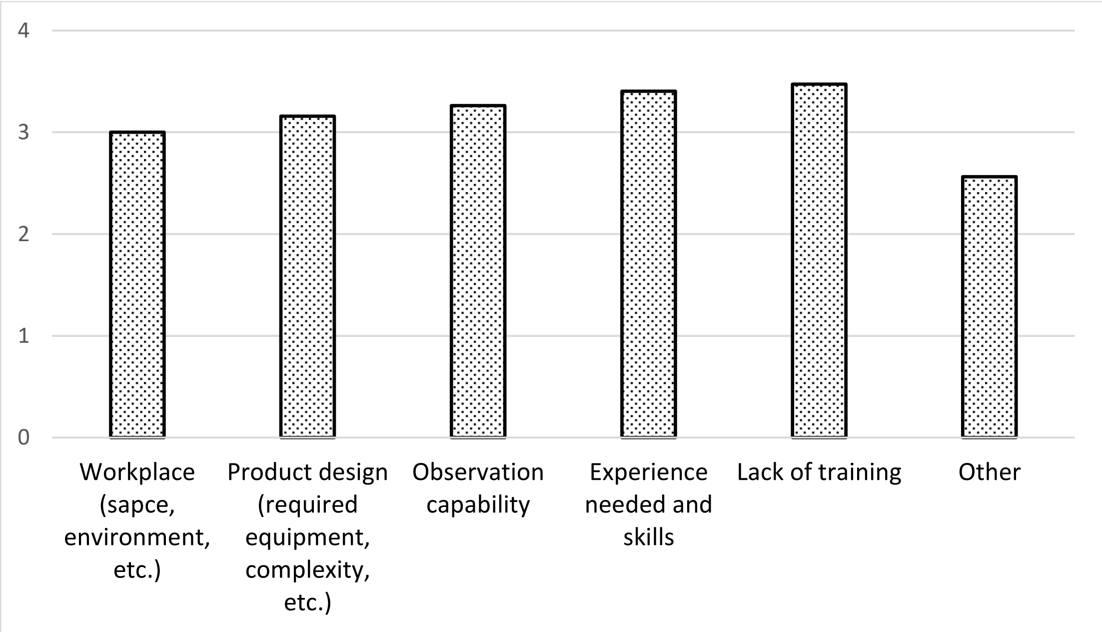

Figure 4-11: Top contributors to human error

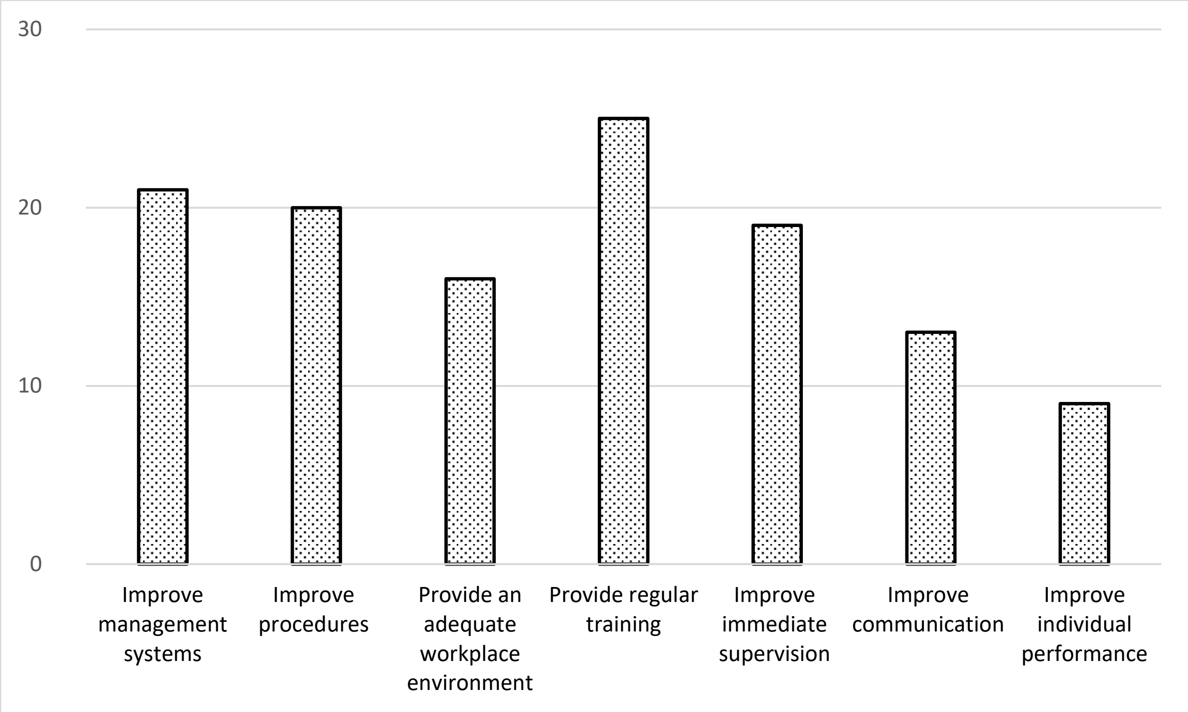

Figure 4-12: Potential solutions to reduce human error

Since human error is a critical problem, respondents were asked to choose between the different potential solutions. As such, Figure 4-12 indicates that the provision of regular training is the most important of these. This finding suggests that labour training is the first issue that should be addressed.

4.3.4 Findings

Before presenting the most important findings, the correlations between some measures were assessed. While this questionnaire's design was mainly based on a Likert-type model, Kendall's tau coefficient is used to measure the ordinal association between two measures. It is defined as (Nelsen, 2001)

$$\tau = \frac{\text{number of concordant pairs } - \text{number of discordant pair}}{n(n-1)/2}$$

, where the concordant pairs are any pairs of observations (x_i, y_i) and (x_j, y_j), where the rank of both elements either $x_i > x_j$ and $y_i > y_j$, or $x_i < x_j$ and $y_i < y_j$. In contrast, if both pairs $x_i > x_j$ and $y_i < y_j$, or $x_i < x_j$ and $y_i > y_j$, then the pairs are discordant. In the case of $x_i = x_j$ or $y_i = y_j$, there is neither concordant nor discordant pairs.

In this questionnaire, some correlations were found based on the above test, as follows:

- There is a medium correlation (0.438) between the organisation size and the manufacturing process capability, which is one of the top contributors to warranty incidents. Larger manufacturers may face more challenges during the manufacturing process than smaller ones, as a result high-volume manufacturing over a short period of time, in addition to the products' complexity.
- Human error on the part of suppliers and human error on the part of dealers are positively correlated (0.637). This indicates that the warranty incidents caused by human error on the parts of suppliers and dealers may have the same characteristics.
- The movement and availability of material are positively correlated (0.520) with the provision of the warranty services cost. This relationship may be due to the expenses invested in the provision of warranty services onsite or the logistics-related cost incurred due to the demand for spare parts.
- There is a positive correlation (0.450) between the warranty cost, caused by the provision of warranty services, and the service quality. The provision of high-level warranty service quality requires both well-trained personnel and adequate equipment, which may involve high costs. By contrast, one may reduce the warranty cost, but this may be at the expense of the service quality level.
- Dealer's fraud and customer's fraud are positively correlated (0.585). This may imply that the dealer and customer are conspiring to cheat. For example, the customer may get out-of-warranty service and the dealer accepts this in order to resell the spare parts, inflate the price of existing claims, etc.
- Warranty service time and service quality are positively correlated (0.541). This may imply that better service quality may require appropriate time. The WSPs therefore need to ensure a trade-off between both these important criteria that influence customers' satisfaction.
- The suppliers and dealers are positively correlated (0.516) in relation to their contribution to warranty incidents.

- With regard to the contributors to human error, observation capability is positively correlated (0.493) with the experience and skills required.

Analysis of the questionnaire data yields several interesting findings, which will be discussed as follows:

- Manufacturing process capability and human error on the part of OEMs are the top contributors to warranty incidents from the OEMs' and dealers' perspectives (Figure 4-3).
- Customers' errors and the modification of products by suppliers are the top contributors to warranty incidents from all parties' perspectives (Figure 4-3).
- Customers' fraud contributes more to warranty costs than WSPs' fraud, which contradicts the statement that most fraudulent claims are attributable to warranty service agents (Kurvinen et al., 2016) (see Figure 4-4).
- Collaboration among parties is limited, particularly in terms of access to warranty-related data between suppliers, OEMs and dealers (Figures: Figure 4-7, Figure 4-8 and Figure 4-9).
- Customers are the highest contributor to product failure, compared to other parties (Figure 4-10).
- Lack of training is the top contributor to human error (Figure 4-11).

4.4 Warranty hazard

In this section, a brief discussion about the warranty hazard is given and then the warranty hazards taxonomies will be designed based on the analysis of both the literature and the questionnaire data.

Business Dictionary[19] defines insurance hazards as a

"condition or situation that creates or increases the chance of loss in insured risk, separated into two kinds (1) Physical hazard: a physical environment which could increase or decrease the probability or severity of a loss. It can

[19] Available at: http://www.businessdictionary.com/definition/hazard.html. Accessed date: 02 Oct. 2019.

be managed through risk-improvement, insurance policy terms, and premium rates. (2) Moral hazard: attitude and ethical conduct of the insured. It cannot be managed but can be avoided by declining to insure the risk".

As such, warranty hazards can be defined as the source of a condition or situation that creates or increases the chances of loss of business profits and/or customers' satisfaction.

ISO 31000 also defines risk management as a set of activities and methods employed to direct and control the risks that can affect an organisation's ability to achieve its objectives. These activities can be categorised into five stages: (1) risk planning, (2) hazards identification, (3) risk assessment, (4) risk evaluation and (5) risk control and monitoring.

The focus of this chapter, however, is on the determination of the top warranty contributors to warranty hazards (incidents) and warranty costs.

Generally, the identification of hazards depends entirely on the context of the organisation and the attitude of DMs towards emerging risks (knowledge, understanding, risk preferences, etc.). In warranty management, the hazards identification process is challenging, as it interacts with different areas within the organisation and with external organisations. For example, the relationship between warranty and other areas can be summarised in the following points:

a) *Warranty and materials*: Product design plays a vital role in the reliability of products, which is in turn essential for managing warranty cost. Another issue relating to warranty and materials is product quality, which is classified by engineers as "nonconforming" if it fails to meet the design specification, and "conforming" otherwise.
b) *Warranty and marketing:* Warranty works as a promotional mechanism that influences purchase decisions since a long warranty period implies better product reliability. This assumption is consistent with signalling theory, as proven by (Liao et al., 2015).
c) *Warranty and logistics:* The relationship between warranty and logistics is strongly correlated (Díaz et al., 2012a). Warranty logistics can be observed at both the pre-sale and post-sale stages; however, it is more evident in

post-sales departments, particularly in activities related to warranty services, such as the provision of spare parts and inventory control.

Therefore, understanding the interdependences and relationships between warranty management and other disciplines is crucial to identifying warranty hazards and hence assessing the associated risk to improve the overall efficiency of the warranty programme.

The warranty identification process therefore includes thorough examinations for all technical and commercial activities at different stages of the product's life cycle. Such examinations require productive collaboration between different departments within the organisation, as mentioned above, and with the external partners, such as suppliers, WSPs and customers. The collaboration is then deemed the cornerstone of the warranty hazard identification process' success, particularly collaboration in exchanging warranty data on a real-time basis. Consequently, root causes analysis can be rapidly conducted and the required improvement decisions can be made at the proper time.

One of the primary sources for identifying warranty hazards is warranty data. It is classified into two main groups: claim data and supplementary data. Claim data are data recorded by warranty service providers during the warranty period, including data related to products, owners, fault details, engineers' suggestions and maintenance or replacement requirements. Supplementary data include data derived from other related departments, such as design, manufacturing and marketing. Undoubtedly, analysis of those datasets can yield useful information obtained from field tests. Such datasets aid in the detection of faults in the early stages of the product life cycle. They also yield information that helps engineers to improve the performance of products to meet customers' expectations and reduce warranty costs by improving the products' reliability and warranty terms. Although warranty data are considered to be the primary source of field testing for product performance, they account for some disadvantages, such as the aggregation process, data lags and incomplete, censored data (Wu, 2012). These issues will be discussed later in this chapter.

Other sources of data are also essential in identifying warranty hazards. For example, manufacturers generally depend on the CRM system because it includes useful information for identifying potential warranty hazards, such as customers' complaints, hidden defects and repetitive failures. In addition, CRM, as a module of the ERP system provides an interesting quantitative and qualitative analytical tool, based on data generated by customers' and technicians' statistical results (Lawless, 1998). Advanced technology can be applied, such as big data analytics tools, which can analyse both internal (warranty data, CRM, ERP, etc.) and external data (e.g. customers' complaints on the social media, forums), and give a holistic impression of the hazards associated with the warranty programme.

Once those datasets have been collected, they should be documented to determine their characteristics and identify warranty hazards. Hence, several methods are recommended for identifying warranty hazards, such as SWOT analysis, analogy, interviews, assumption, documents reviews, the Delphi technique, brainstorming, checklist analysis, etc. These tools have been discussed in detail in Chapter 3.

4.5 Warranty hazards taxonomies

Since the warranty hazard identification is the first step of warranty risk analysis, it is essential to process it from the strategic perspective, including the overall business strategy and the product life cycle plan. As such, warranty strategy should be consistent and linked with other departments' strategies within the organisation. This strategy is generally limited by the type of product, targeted customers and the overall business strategy. Technical and commercial aspects are also important factors that should be considered during the construction of warranty strategies. The former might affect warranty costs, whereas the latter can have an impact on products' prices. Hence, it is essential to establish the strategy at an early stage in the product's life cycle.

The main focus of warranty management is generally on two objectives: the reduction of warranty cost and the retention of customers' satisfaction. Although there are other objectives, these two objectives are the most important from the manufacturers' perspective. Achievement of these objectives requires an in-depth understanding of the potential warranty hazards.

The traditional approach to achieving such objectives relies mainly on analysing products' failures once they have occurred. This approach is one of the main reasons for increasing warranty costs. Another reason is the different perceptions of warranty that may co-exist within the same organisation. For example, engineering departments may consider warranty to be a material issue, whereas marketing departments regard warranty as a promotional tool. Therefore, to improve warranty management, the strategic view of warranty-related problems must be taken into account. As such, warranty management will be discussed from two angles: from the product life cycle perspective and from the warranty chain perspective as follows.

4.5.1 Warranty life cycle

The general framework of the product life cycle consists of different stages: product design, manufacturing, distribution and after-sales support (Figure 4-13). The top contributors to warranty incidents at each stage is presented in Figure 4-16 and will be discussed as follows.

Design Stage

The product design stage involves several steps, including product design specification (PDS), concept design (concept generation and evaluation) and detail design. The PDS phase involves a document in which manufacturers can record their current or potential customers' demands. Accordingly, they can generate a list of the intended product's requirements to ensure its success in the marketplace. The second phase is the concept design, whereby the output of the PDS constitutes the input for this phase. It outlines the general design and the main components of the product. This phase is processed via two steps: concept generation (e.g., brainstorming) to produce different models and concepts and evaluate them to refine and choose the most suitable one. The last phase is to draw the chosen model and write up its specifications to produce a prototype to test the idea. Designers usually work closely with the manufacturing unit to ensure that the selected model is applicable or determine whether it needs some improvements.

- *Design specification*: Prior to the design stage, product features are determined in response to market demands. The cost per product item and the desired sale price are also estimated. Accordingly, the decision regarding the design specifications is made based on those factors. As such, it is crucial to consider the serviceability and its estimated repair costs at this phase. For example, the complexity of the product design increases the uncertainty of the field performance, and, hence, the estimation of future warranty claims becomes more challenging. To provide services for complex systems or sub-systems, certain levels of labour skills and equipment are required, which poses another challenge to future warranty services.
- *Failure to consider warranty policy*: Warranty claims are significantly influenced by products' reliability. Despite the difficulties encountered during the product design process (e.g., market demands, product complexity, manufacturing costs and the desired sale price), the design of warranty policy must be in alignment with the expected product reliability and customers' expectations.
- *Modification by OEMs or suppliers*: Due to the challenge facing OEMs or suppliers caused by two factors, target value and the launch date, OEMs or suppliers may modify the product design accordingly. These two factors, in addition to those mentioned above, can have a direct impact on the product's reliability. For example, if the competitors plan to release their products on a specific date, then the entire pre-launch processes must be in alignment with them (if not before) if they are to retain their market share. Future warranty claims, however, will be based on the efficiency of the processes being managed. Hence, DMs must consider whether they should change the launch date or alter the warranty terms.
- *Human error in design:* According to BearingPoint, problems created during the product design stage are regarded as the most significant warranty hazard (page 16 in BearingPoint, 2007). These problems may be regarded as mainly due to human error, which can be defined as the way

in which humans deal either intentionally or unintentionally with products, physically or psychologically, in relation to product design, manufacturing, distribution, servicing and use. There is a paucity of literature concerning the role of human error in warranty risk. The role of human error in warranty incidents exists in the conflict of interests among DMs prior to the design stage (Insua et al., 2018). These decisions involve two or more groups with different interests. As such, their views on reliability issues will differ with regard to issues such as acceptance sampling, testing, warranty and insurance. Furthermore, unauthorised changes made by suppliers are a prominent example of human error.

Figure 4-13: Product life cycle stages

To respond to the large demand and achieve the target value and launch date, OEMs often outsource various tasks, such as the product design and manufacturing of some systems/sub-systems (Collins et al., 1997; Pandremenos et al., 2009). It is now the norm among most of the automotive and other industries to outsource some aspects, systems or sub-systems of their complex systems due to various factors, such as lower labour costs and improvement of efficiency and flexibility at the manufacturing stage.

Product reliability and warranty terms are considered the core contributors to warranty incidents and warranty costs. Thus, an in-depth understanding of warranty-associated hazards at the design stage can significantly reduce future warranty costs. This can be achieved by considering the design of warranty policy alongside the early phase of PDS. Figure 4-14 represents the role of product reliability and warranty terms in the entire business process. Hence, paying greater attention to the potential warranty hazards during the product design stage can reduce the total warranty costs in addition to retaining customers' satisfaction.

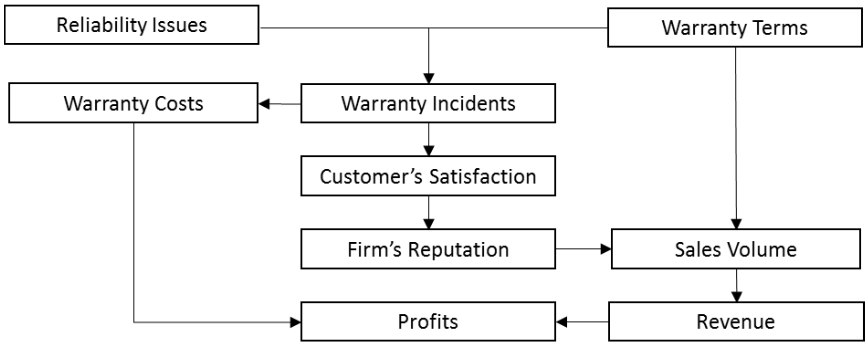

Figure 4-14: The role of reliability and warranty terms in the whole business

To improve products' reliability, two approaches are commonly used: redundancy and reliability growth by development programme (Blischke & Murthy, 2011). The second approach requires more development through the R&D phase, as the products are tested for a certain period of time or until a fault has occurred. Failure to properly test products leads to negative consequences in the products' performances, which, in turn, increase warranty claims and dissatisfy customers.

Manufacturing Stage

At this stage, there are several issues relating to warranty hazards.

- *Manufacturing process capability*: At the manufacturing stage, the approved design is processed through two main steps: manufacturability and quality. The first step involves checking the capability to produce the product on a large scale. The decision between "go" and "no-go" in manufacturing plays a crucial role in terms of the product's quality. Due to market pressure, such a decision can be made recklessly, without regard for the preservation of the required level of quality. Consequently, the result will be at the expense of product quality. In fact, these problems account for a large percentage of the main contributors to warranty incidents, in addition to the problems associated with inferior raw materials (BearingPoint, 2007). Manufacturing process capability issues may occur as a result of failure to respond to changes, particularly during the early stage of the product life cycle. To effectively manage and respond to such changes, the production capacity (technologies and personnel skills) should be designed at the required level.

- Variability in the manufacturing process leads to the production of nonconforming items that fail to meet the quality standard. Murthy & Djamaludin (2002) termed this type of product's quality "nonconforming" while the other products were termed "conforming". They suggest several tools, including both on-line (e.g., inspection or Burn-in) and off-line approaches (e.g., environmental stress screening (ESS)) as a means of managing nonconforming quality.
- *Quality control*: The second step of the manufacturing stage is the test of product quality. Random products are tested to ensure the quality of manufacturing as well as the product's reliability. A root cause analysis is carried out to analyse the inferior products. If the problem is related to the product's design, then another design should be considered or the existing one should be improved, see Figure 4-15. Otherwise, the problem may reside in the manufacturing process capability. The quality procedure itself might pose a further challenge for manufacturers as, due to mass production and the complexity of products' designs, the quality control process has become more challenging. Therefore, quality control can play a significant role in detecting inferior products which can, in turn, reduce the potential for warranty incidents and enhance the likelihood that customer satisfaction will be retained. Thus, consideration of warranty hazards during both steps of the manufacturing stage is crucial to protecting manufacturers against huge losses caused by eventualities such as product recall.
- *Warranty terms in manufacturing stage*: The quality standard must consider warranty terms and assess whether or not the product conforms to the product specifications and warranty terms. If not, further actions should be taken, including the adjustment of warranty terms so as to align with the expected results of a quality inspection or to improve the existing product design.
- *Assembly process capability at suppliers and OEMs*: This process can contribute significantly to warranty incidents, and depends mainly on the product design, workers' skills and equipment used. Assembly problems may arise as a result of human or machine error, such as improper

fastening of parts or incorrect assembly. As such, it is crucial to select suppliers judiciously and to understand the capability of the manufacturing process and standard of the systems validity process to ensure the integrity and compatibility of different systems after they have been assembled.

- *Human error in manufacturing*: At the manufacturing stage, human error may contribute to warranty incidents, though most modern products are built/assembled by robots. For example, human error at this stage may include mishandling, poor installation, and incorrect assessment. Other examples of human error can be found in the observation capability and batch inspection that continue to be challenges for OEM workers. These issues will have an impact on future warranty incidents.

Another issue, as mentioned earlier, is that OEMs often outsource some manufacturing tasks, such the manufacturing of systems, sub-systems or parts, to improve efficiency and flexibility, as well as seeking lower labour costs. However, the outsourcing of manufacturing can trigger undesirable events. It is then essential to select suppliers of spare parts and understand the capability of the manufacturing process and the systems validity process of each supplier. Additionally, it is important to ensure that the design specification is applied and that no unauthorised change has been made by the suppliers. For the OEMs, it is also essential that there are at least two suppliers, in case one ceases working for any reason, in which case the second could cover the demand or the minimum required quantity. For example, Ericsson faced a crisis as a result of relying on a single supplier which experienced a fire accident (Christopher & Peck, 2003). In fact, suppliers' issues are numerous. However, this chapter focuses on those that affect warranty costs and customers' satisfaction.

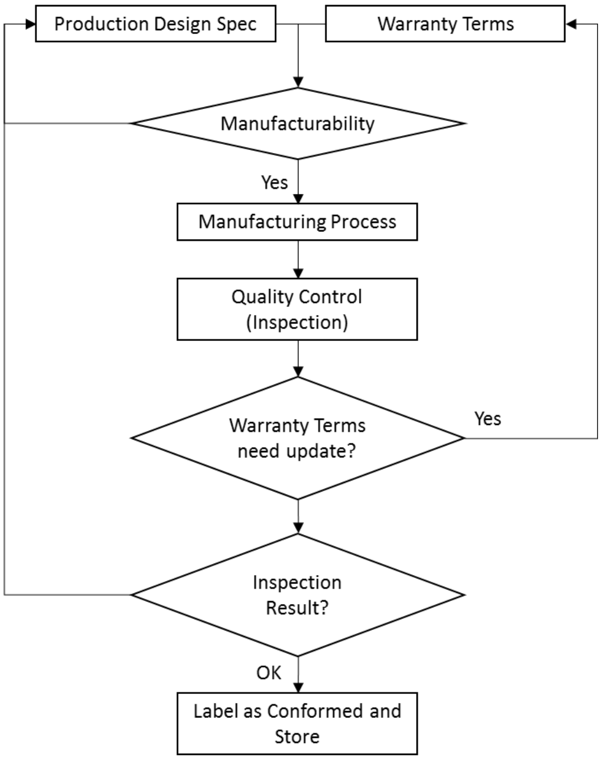

Figure 4-15: The role of the warranty in the manufacturing stage

Although outsourcing can improve the efficiency of the manufacturing process, it is also associated with some problems that cannot be detected through laboratory tests carried out by the OEM to ensure the integrity and compatibility of different systems, after they have been assembled in the final manufacturing line. Such problems often emerge during field testing and can bring huge warranty costs.

Based on the above, the quality standard must take the warranty terms into account and assess whether or not the product conforms to the product specifications and warranty terms. If not, further actions should be taken, such as the adjustment of warranty terms with the quality results or the improvement of the current product design (Balachander, 2001).

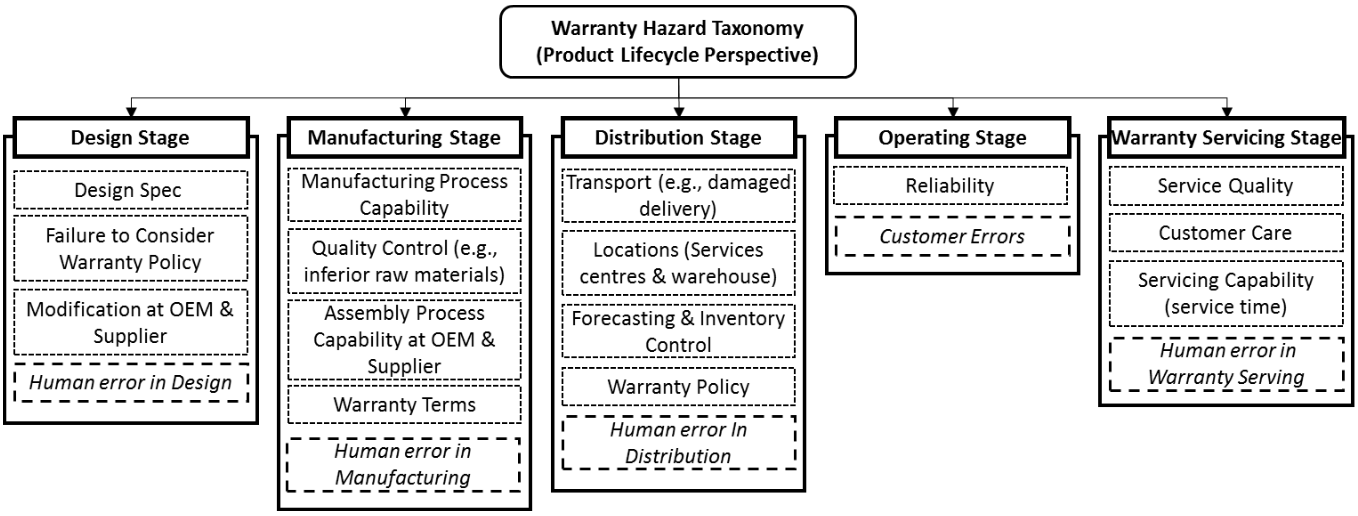

Figure 4-16: Warranty hazard taxonomy (product life cycle perspective)

Distribution Stage

When the products have been labelled as conforming and moved to the warehouses, the market strategy will then be applied in order to sell them. One of the primary tools used in such strategies is the warranty services.

- *Warranty policy (prior to the product distribution)*: As mentioned above, warranty terms can affect sales volume. Hence, the warranty terms should be evaluated based on the information provided by the marketing department, and its applicability should be verified or another warranty policy considered if it does not meet the criteria. Selection of the optimal policy is the first step towards protecting manufacturers from warranty consequences. For example, the FRW policy can be offered with higher reliability products, whereas a PRW policy may be optimal with lower reliability products. Offering a longer warranty period must be considered in the context of the business as a whole.
- *Locations of services centres and warehouses*: Determining the location of warranty services centres is crucial, as it can have a significant impact on customers' satisfaction and sales revenue. Warehouse locations are also important as they can have an indirect impact on warranty costs, due to the expenses associated with their management and the costs spent on travelling between them and warranty service centres. As such, superior

warranty service logistics can lower warranty costs and retain customers' satisfaction.

- *Forecasting and inventory control*: For example, if there is any shortage of spare parts, WSPs will not be able to give customers an accurate estimate of the replacement or maintenance time. As such, this problem can result in customers' dissatisfaction and damage the manufacturer's reputation. Therefore, the logistics department is responsible for planning for the spare parts and the repair capacity. For example, repairing a complex product requires advance planning in respect of the required spare parts and equipment. Therefore, the timely provision of spare parts requires strategic control of the warehouses and inventory in order to provide an adequate warranty programme at the lowest cost. In addition, warranty activities, in particular those related to logistics, are often outsourced to a third party; therefore, their efficiency can impact warranty costs and quality perception (Díaz et al., 2012a).
- *Transport*: Various warranty hazards can emerge as a result of the distribution process. For example, items may be damaged in transit. The movement of products also involves hidden costs, based on the distance between warranty service centres and warehouses, or the provision of warranty services on site.
- *Human error in distribution*: Key examples of human error at the distribution stage are errors in packing and handling activities.

It is also important to pay attention to the costs required to operate such centres, in terms of equipment, personnel and so on. Such costs can be estimated based on the reliability of the product and the geographical distribution of sales. Therefore, determining the optimal location of warehouses or service centres can protect firms from extra expenses. Firms can also save time (i.e., the time required to deal with warranty claims), which is positively reflected in customers' satisfaction.

Operating Stage

At this stage, the two main contributors to warranty incidents and costs are product reliability and customers' errors.

Reliability: Field reliability is determined at the operating stage, which differs from the laboratory testing performed at the pre-sale stage. Field reliability involves a high level of uncertainty that then accounts for the most contributions to warranty incidents.

Customers' errors: These account for the most contributions to warranty incidents that occur as a result of unintentional or intentional errors. Unintentional errors can happen for several reasons, such as failure to follow the installation instructions. As such, the product parts may be incorrectly assembled, which, at worst, may cause serious injury to the user when they start using the product. Intentional errors, on the other hand, may occur due to fraudulent activities.

It is reported that consumer fraud contributes more to warranty cost, compared to WSPs fraud. Hence, manufacturers attempt to protect themselves against such activities or misuse by clearly stating the following points in the warranty policy:

- Proof of purchase.
- Usage limitation.
- Parts covered by warranty, spare parts, labour and logistics.
- Warranty provider's right to review the item within the warranty period.

Warranty Servicing Stage

Products are often sold by agents or sales channels (e.g. dealer in the automotive industry). These are also responsible for carrying out the obligations of repairing or replacing faulty products under warranty terms. Warranty policy generally states several conditions that must be verified before the maintenance or replacement actions are fulfilled. Once these conditions are met, WSPs must perform the entitled warranty services.

- *Service quality:* Warranty services quality is a crucial factor that directly affects customers' satisfaction. Poor quality of warranty services might result from lack of knowledge or inadequate equipment. To achieve a good level of quality, one needs to recruit skilful technicians in addition to providing them with the necessary training and equipment. Warranty services can be outsourced, so the OEM must monitor the service quality, as some WSPs may recruit unskilled technicians to reduce labour costs at the expense of quality. If the warranty services are provided by the OEM, then the service quality can be better controlled. However, the cost of labour remains one of the main contributors to warranty cost, as warranty services should retain a reasonable level of quality.

- *Servicing capability:* To perform warranty services within a reasonable time, it is crucial to ensure the availability of spare parts, suitable warranty terms, knowledge and accessibility to product details. Service time is one of the top contributors to customer dissatisfaction. Therefore, planning for spare parts, job scheduling, labour training and availability of the required equipment is crucial to shortening the required service time.
- *Customer care:* Product performance, service quality and service time all influence customers' satisfaction. As such, it is essential to have a customer care programme in place to deal with customer complaints and respond to them efficiently. Otherwise, the inappropriate provision of warranty services might affect customers' satisfaction and cause further negative consequences. As such, analysis of customers' complaints in a very short time aids in protecting manufacturers from losses.
- *Human error in warranty servicing:* Products are often damaged by technicians, resulting in improper fitting and scratches, as observed on a daily basis in warranty services centres (BearingPoint, 2007). Analysing the drivers of such activities is crucial to mitigate (if not resolve) them. Some such drivers may be due to a lack of training, the complexity of the product design or inadequate resources or work environment.

4.5.2 Warranty chain management

Warranty chain management is concerned with the movement of material and information and the associated financial issues across suppliers, OEMs, WSPs and customers. Such flows can have a direct impact on warranty costs and customers' satisfaction. Tang & Musa (2011) reviewed the existing publications and then categorised supply chain risks into three categories: material flow risk, financial flow risk and information flow risk. In this section, we investigate warranty risk under these three types of risk from a warranty chain perspective, as shown in Figure 4-17.

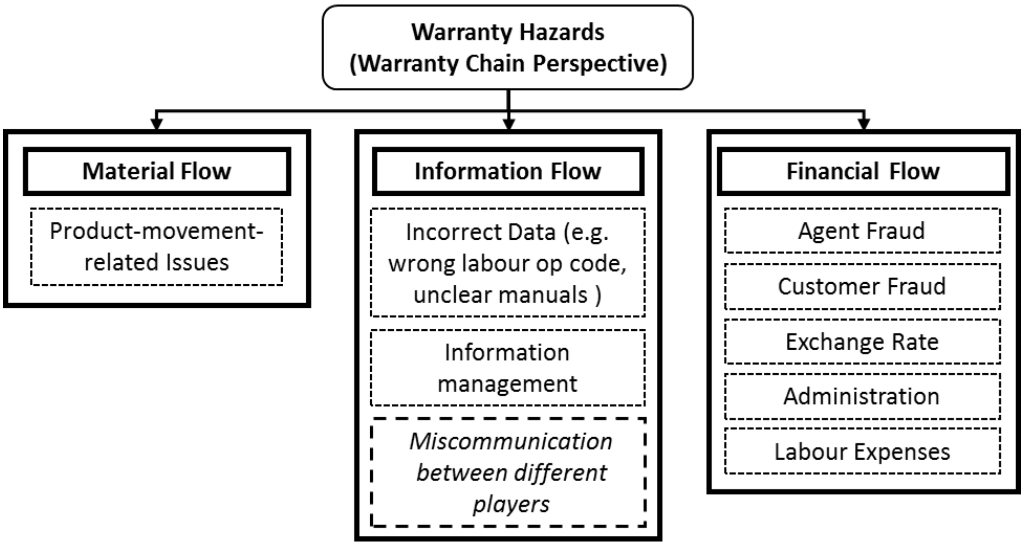

Figure 4-17: Warranty hazard taxonomy (warranty chain perspective)

Material flow

Material flow risk refers to all warranty incidents resulting from material movement (e.g. spare parts, sub-systems, etc.) from one party to another. Material flow risks begin during the product design and manufacturing stages in the first part of the warranty chain (suppliers). At the suppliers, several serious issues can affect the reliability of the product. It is stated that one of the main contributors to warranty incidents are unauthorised changes made by suppliers, inferior material and the assembly capability process at suppliers (BearingPoint, 2007). These examples can present as material-related problems at the first tier (supplier) of the material flow. In this context, the warranty policy (with regard to the duration and compensation approach) must be carefully designed, considering the aforementioned problems.

Once the parts, systems or sub-systems have been manufactured and tested by the suppliers, they are shipped to the OEM, to the final assembly line and tests. Some inferior items can be detected through the quality control process. However, inferior raw materials remain among the main contributors to warranty incidents, as mentioned above. Failure to detect inferior materials implies that there is a problem in the systems validations and tests at the OEM.

Accordingly, the quality control process at the OEM must be reviewed and updated. Otherwise, such validations can add more hazards that contribute to warranty incidents. Several statistics indicate that inferior raw material is one of the main contributors to warranty incidents (BearingPoint, 2007).

Once the material has been determined as conforming to the quality control standard, it is shipped again to the warehouses or directly to the market. Generally, the movement of materials, from the suppliers (Tiers 1 or 2) to the OEM to the final destination (the customer), involves a different kind of hazard, resulting from the packing, shipping, handling processes and excessive storage. Shipping may be executed in two ways: the first is, as mentioned above, from the supplier to the customer, including all parties in the chain. The second is the reverse, beginning with customers to various higher levels, including (if necessary) the suppliers. For example, if the purchased product has failed during the warranty period, it must be brought to the warranty service centre or the required diagnosis must be performed on site. If the product cannot be repaired at the local warranty centre, then it must be shipped to a higher level. When the necessary maintenance has been completed, it is shipped again to the customer. Consequently, the financial impact of such activities on warranty costs cannot be neglected, particularly in cases of a product recall. Another impact is on the customers' satisfaction as a result of lengthy waiting times for repair (Batur et al., 2018).

As mentioned previously, warranty services are often provided by agents, such as dealers in the automotive industry. Those agents have a direct impact on the material, including carrying out improper failure diagnoses. The technicians' experiences are therefore the backbone of the warranty service quality (i.e. if they fail to diagnose the failure, it might be replaced rather than repaired). Furthermore, some technicians' interventions can affect other, non-faulty parts, causing additional warranty costs. The proper diagnosis of failures can improve the process of root cause analysis and mitigate the NFF problem.

Information flow

In warranty management, information and data can be gathered internally or externally. External sources may include warranty service agent systems and retailers systems, while internal sources may include marketing, production and engineering units, in addition to the information collected during the feasibility stage of the product life cycle (Blischke et al., 2011). Such data and information are highly valuable and play a vital role in protecting firms from undesired events. Warranty claim data, service quality, customers' demands, inventory status, customers' feedback and competitors' news are examples of such information, which must be thoroughly analysed. As long as this information is updated and approaches streaming data, the decision can be more accurate. However, such information involves some risks, such as information security and disruption, information accuracy, information accessibility and information efficiency.

One of the key tasks of warranty management is to update each department within the organisation with the relevant information obtained from warranty data. For example, design or manufacturing departments should be informed about technical issues caused by warranty incidents, to improve product reliability and quality, which, in turn, reduce the occurrence of warranty incidents.

Warranty data (claims data and supplementary data) contains useful information regarding product quality and reliability (Wu, 2012). It is considered to be the main source of failed-test data, in terms of product performance. Therefore, data of this nature should be updated on a daily basis, particularly in the presence of advanced technologies that permit the immediate sharing of information with partners (WSPs, OEMs and suppliers). Such datasets include product-, customer-, agent-, and market-related data.

Therefore, failure to obtain such information at the proper time might lead to inappropriate decisions affecting warranty costs or might affect the entire business. Although warranty data is the most important source of products' field testing information, it requires time for collection and analysis. The warranty-related data, termed ‘coarse data’, were grouped by Wu (2012) into the following issues:

- Aggregated data: For example, claims grouped based on age (e.g. 0–30 days) and then sent to the analysts.
- Data lag: Such delays may result from sales or reporting processes that need time for verification before submission.
- Incomplete censored data: It is caused by the expiration of the warranty period.

The aggregation of warranty data might cause major problems, as a result of the delay in detecting the failure at the early stage. In some cases, the failed item has to be sent to the OEM to carry out root cause analysis. If the item was manufactured by the suppliers, then it must be sent again to be further analysed by the supplier responsible. It has been stated that this process may take up to two months or longer (BearingPoint, 2007). This impedes the detection of product failures at the early stage of the product life cycle that protects manufacturers from extra costs resulting from further warranty claims.

Another issue can emerge during the validation process of warranty claims. It includes two undesirable scenarios: the first is the processing of such validation quickly in order to accommodate large numbers of warranty claims. However, it is possible that WSPs’ fraud will go undetected. The second issue is that if warranty claims are thoroughly validated to protect manufacturers from the agents’ fraud, it might delay the response to warranty claims which, in turn, raises dispute between the manufacturers and the WSP. Therefore, both these issues should be efficiently managed to obtain a trade-off between a quick validation and fraudulent activity checking.

The information flow hazards mentioned in the taxonomy are discussed below:

- *Incorrect data:* This refers to incorrect qualitative data, such as the failure symptoms reported by the customer and the technician’s comments. Technicians may also use incorrect failure codes, and this can hinder the identification of the failure’s cause and increase the NFF problem.

- *Information management:* The information obtained from warranty data is highly valuable. Hence, such information must be well managed in relation to risks resulting from, but not limited to, information interruption, information security, information privacy, compatibility and integration of systems between WSPs and other parties (OEMs and suppliers), information delays and lack of information transparency between the former parties.
- *Miscommunication between parties*: Managing warranty-related data efficiently can yield useful information. If such data are available, the question concerns to what extent it can be adequately shared between parties. Increasing collaboration between parties should result in a reduction in warranty incidents and costs and meanwhile retain customers' satisfaction. Figure 4-18 presents an example of data that can be exchanged between parties to improve the efficiency of the warranty hazard identification process. For example, design-product-related data and manufacturing-related data, which should be exchanged between suppliers and OEMs to improve the reliability of the product and reduce the use of inferior raw material and unauthorised changes made by suppliers. Furthermore, the collaboration between WSPs and OEMs will allow the latter to monitor the WSPs activities, while WSPs will be able to access the product details to ensure a high level of service quality, particularly in the maintenance of complex products. It is essential to exchange warranty data between parties, as a collaboration between OEM and WSPs will ensure swifter improvement of products' reliability. WSPs may swiftly receive technical support from suppliers if the faulty component was manufactured by the later. Furthermore, warranty data obtained from WSPs can help suppliers to identify product failures at the early stage. Customers are the main players in the information chain, as their collaborations with the other parties can yield several benefits. They may receive online technical support from the OEM, as well as sending useful information about product usage-related data to help manufacturers to determine their demands.

The information obtained from warranty data is highly valuable for the reasons mentioned above. Therefore, such information must be well managed in relation to risks resulting from, but not limited to, information interruption, information security, information privacy, compatibility and integration of systems between warranty services providers and other parties (OEMs and suppliers), information delays and lack of information transparency between the former parties.

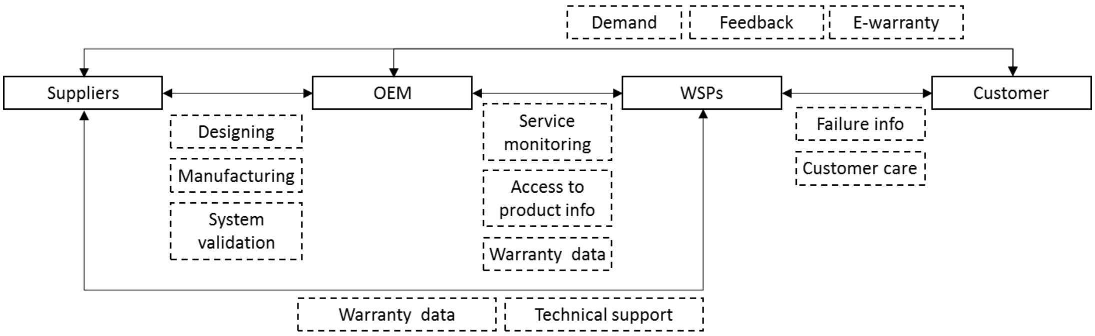

Figure 4-18: Example of collaboration between parties

Financial flow

Financial flow hazards associated with warranty refers to those activities that cause an increase in warranty costs. These activities may be one or more of the follows.

- *WSP fraud:* WSPs may deceive the OEM in different ways, and some consider fraud to be their main source of revenue (Ratley, 2014; Kurvinen et al., 2016). For example, they might replace or repair products without entitlement to increase claims numbers.
- *Customer fraud:* Fraud is higher among customers than among WSPs. A prominent example of customer fraud is the NFBR issue (Wu, 2011; 2012).
- *Currency exchange rate:* The provision of warranty service can last for five years or more. During this period, the prices of spare parts may increase[20] (WarrantyWeek, 2015).
- *Administration:* This includes expenses spent on managerial, legal and accounting work, among others (Murthy & Djamaludin, 2002).

[20] Retrieved from: http://www.warrantyweek.com/archive/ww20151022.html (October 22, 2015)

- *Labour expenses:* Such expenses include salaries, compensations and training, among others. It is found that although warranty incidents have decreased, warranty costs have not changed, due to the labour expenses (BearingPoint, 2007).

To simplify the identification of warranty hazards contributing to warranty incidents and warranty costs, Table 4-2 presents the main hazards from both perspectives: life cycle and warranty chain.

Table 4-2: A summary of the top warranty hazards contributors

	Pre-launch				Post-launch	
	Suppliers		OEM			
Warranty LC	Design	Manufacturing	Design	Manufacturing	Distribution	After-sale supports
Warranty Chain						
Material hazards (product/ spare parts)	• Unauthorised changes • Assembly process capability	• Shortage in manufacturing process capability • Assembly process capability • Inadequate quality control • Human error	• Improper design of warranty policy • Over/underestimate the future warranty services requirements	• Failure to update the expected warranty costs • Assembly process capability • Inadequate quality control • Human error	• Under/overestimate the required spare parts (forecasting) • Vibration, packing and handling during transports • Capacity and location of warranty service centres • Products damaged during transit	• Dealer error • Customers error
Financial hazards	• Increasing warranty incidents and hence increasing warranty costs		• Increasing warranty incidents and hence increasing warranty costs		• Material movement expenses (from/to supplier, OEM, dealer or customers) • Different exchange rate • Storage expenses	• Warranty services-related costs (labour, equipment, etc.) • Dealer fraud • Customer fraud • Warranty administration expenses
Information hazards	• Shortage of diagnostic data entered by warranty services providers • Difficulties to collect warranty-related data from OEM or WSPs systems on a real-time basis • Information security		• Lack of collaboration with suppliers in relation to warranty data • Information security • Limited access to manufacturing-related data at suppliers		• Diagnostic errors (e.g. incorrect data or) • Lack of failure-related data (e.g. failure symptom) • Information security	

4.6 Summary

Although offering a long warranty period can increase sales volume, it carries various risks that may affect manufacturers' profits and customers' satisfaction. Therefore, this research attempts to improve WaRM through a systematic analysis of the top contributors to warranty incidents and warranty costs.

This research has achieved the following outcomes:

- Analysed the literature comprehensively to determine the top contributors to warranty incidents and warranty costs from two perspectives, the product life cycle and warranty chain. Accordingly, the human error at different stages of the product life cycle has received little attention in the warranty area, whereas it is considered one of the critical hazards in other areas such as nuclear and aviation industries.
- A questionnaire survey has been designed, circulated and analysed to better understand the top contributors to warranty incidents and costs.
- Two warranty hazards taxonomy have been designed.

The key objective of this chapter is to identify the top contributors to warranty incidents and cost.

Findings: the following results have been achieved:

- Manufacturing process capability followed by human error on the part of OEMs are the top contributors to warranty incidents from the OEMs' and dealers' perspectives.
- Customers' errors and the modification of products by suppliers are the top contributors to warranty incidents from all parties' perspectives.
- Collaboration among parties is limited, particularly regarding access to warranty-related data between suppliers, OEMs and dealers.
- Customers' fraudulent activity contributes more to warranty costs than WSPs' fraud.
- The criteria most influenced by warranty risk are warranty costs and manufacturers' reputation.

- The tools currently used to analyse warranty risk are unable to detect warranty risk at the early stage.

CHAPTER 5: WARRANTY RISK MITIGATION

5.1 Introduction

Warranty increasingly plays a vital role in marketing strategy. As such, manufacturers aim to offer competitive warranty policies to maintain or increase their market shares. As a result, they may offer longer warranty periods to mitigate customers' concerns during the purchase decision process, which also provides a degree of assurance that faulty products under warranty will be repaired or replaced. Moreover, manufacturers employ warranties to signal products' quality (Chu & Chintagunta, 2011).

Although the provision of warranty has advantages, it may also have severe implications for manufacturers. For example, due to the complexity of new innovations, product reliability and quality can involve a high level of uncertainty, particularly for those with longer warranty periods. Therefore, manufacturers may face unexpected costs, which may vary from 1 to 10% of the product's sale price (Blischke et al., 2011). In addition, the provision of warranty (base or extended) involves uncertain and risky activities as a result of different contributors, such as product failure (reliability and quality) or human error (intentional or unintentional) at different stages. As such, it is crucial that manufacturers identify top contributors to warranty incidents and costs and subsequently prepare mitigation plans corresponding to each potential risk. This proactive approach must be implemented at the risk planning stage.

Although WaRM is an important topic, it received little attention in the literature, such as Díaz & Márquez (2011) and Costantino et al. (2012). Despite the rarity of studies investigating warranty risk, the DMs' behaviour under risk and uncertainty has not been considered in warranty literature. In warranty practice, DMs may be influenced by the degree of uncertainty associated with the decisions that deal with emerging warranty risk. Consequently, it is important to develop a method that can address risk decision problems and that is capable of capturing the DMs' behaviour, which is the aim of this chapter.

In relation to the mitigation of warranty risk, selection of the optimal warranty mitigation plan can face several challenges, due to the following reasons:

1) Warranty-related issues may affect all departments in the organisation, such as engineering, marketing, finance, after-sale, logistics, etc. As such, the decision of selecting the optimal mitigation plan must consider such departments' perspectives.
2) The length of the warranty period may influence the behaviour of the DMs, which can affect the final decision. As such, the time variable should be considered.

For the above reasons, the AHP method is used to gather the DMs' perspectives and then the CPT is adapted for the following reasons:

1) the reference point changes based on the decision made immediately previously. That is, the reference points are time-dependent, and
2) the DM's attitude may change from one time to another, based on the severity of the risk they experienced.

As such, we can draw the following research objectives for this chapter:

1) To investigate the conventional methods used to mitigate warranty risk.
2) To develop a CPT-based warranty risk management model to determine the optimal risk mitigation plans.
3) To develop a dynamic CPT-WaRM considering the change in the reference point and DMs' behaviour (warranty risk mitigation policy).

The literature review of this chapter was discussed earlier in this thesis, in Section 2.6 and 2.7.

5.1.1 Overview

In the remainder of this chapter, Section 5.1.2 outlines the novelty and contribution of this chapter. Then in Section 5.2, the influencing criteria from the warranty risk will be discussed. Notation table is then presented in Section 5.3 and the main elements of CPT are presented in Section 5.4 followed by AHP in Section 5.5. The development of the CPT-WaRM model will subsequently be presented in Section 5.6, and the dynamic CPT-WaRM will be discussed in Section 5.7. Then, a numerical example is given in Section

5.8**Error! Reference source not found.**, followed by the summary in Section 5.9.

5.1.2 Novelty and contribution

To the best of my knowledge, there is no literature has comprehensively addressed warranty risk mitigation. As such, the novelty of this research is listed as follows:

1) This is the first attempt to analyse warranty risk mitigation plans from the manufacturer's point of view.
2) Different methods are proposed for determining the reference point of the CPT-WaRM model, as it is the key to deriving utility gains and losses.
3) AHP is merged with the CPT to ensure the consistency of the initial judgements given by different DMs in various departments.
4) CPT is adapted to determine the local and global optimal mitigation plan by considering the reference point and the parameters capturing DMs' behaviour as time-dependent variables.

The impact of this research on the industry is another practical novelty. The proposed model will allow warranty DMs from different departments to determine the optimal warranty risk mitigation plan considering their behavioural aspects towards different qualitative and quantitative criteria, which can affect the final decision. They will be able to determine the optimal mitigation plan to deal with the emerging risk, as well as determining the optimal mitigation policy across the warranty period.

5.2 Influencing criteria

Several criteria can be affected by warranty risks, such as warranty cost, manufacturer reputation, human safety and the environment.

- *Manufacturer reputation*: One of the principal purposes of providing warranty services is to satisfy customers by providing a competitive warranty. Therefore, customers' satisfaction depends on the extent to which the manufacturer provides satisfactory warranty service. The outcome of this will impact the manufacturer's reputation. For example, with the existence of social media, customers can post their views regarding such services: if several people agree with a negative comment, the manufacturer's reputation can be significantly impacted.

- *Environmental damage*: This is a major global concern and environment-related law has become increasingly strict. As a result of the disposal of faulty parts, the environment can be damaged. For example, vehicle disposal can cause the release of fluids etc. and pollution.[21]
- *Human Safety*: This is an important criterion that may be considered by the DMs in responding quickly to emerging warranty risk. For example, the manufacturer may recall faulty products if the fault poses a threat to human safety.[22]

5.3 Notations

The notations used in the CPT-WaRM model are presented in the following table:

Notation	Explanation
x_i	Outcome
π_i	Decision weight of the ith outcome
$v(\cdot)$	Value function
$d_i\ (i = 1, \dots, m)$	Set of the mitigation plans.
$c_i\ (i = 1, \dots, m)$	Cost incurred due to using the ith mitigation plan.
c^{ref}	Reference point for the costs $c_i, \dots, c_m$ of the mitigation plans.
$s_j\ (j = 1, \dots, n)$	States of the emerged warranty risk.
$p_j\ (j = 1, \dots, n)$	Probability of the jth state of the emerged warranty risk, where $\sum_{j=1}^{n} p_j = 1$.
$h_k\ (k = 1, \dots, q)$	Criteria that may be influenced if the jth state has occurred.
z_{ik} $(i = 1, \dots, m)$ $(k = 1, \dots, q)$	Initial judgements of the decision makers, when applying the ith mitigation plan to mitigate the impact of the warranty risk on the kth criterion.

[21] Environment Australia, Department of the Environment and Heritage. Available at: http://www.environment.gov.au/protection/ozone/publications/environmental-impacts-refrigerant-gas-end-life-vehicles-australia. Accessed date: 02 Oct. 2019.

[22] For example: Due to a Takata airbag problem, tens of millions of vehicles were recalled. Available at:https://www.nhtsa.gov/equipment/takata-recall-spotlight. Accessed date: 02 Oct. 2019.

z_k^{ref} $(k = 1, \dots, q)$	Reference point for the kth criterion values. In this research, the average of the z_k values are used as a reference point (Terzi et al., 2016).
I^{c}, I^{r}	Importance degree of the cost (I^{c}) compared to the result (I^{r}) with respect to each mitigation plan, where $I^{\text{c}} + I^{\text{r}} = 1$ and $0 \leq I^{\text{c}}, I^{\text{r}} \leq 1$.
G_i	Prospect value of the mitigation plans results.
V_i	Value of the costs of the mitigation plans.
Y_i	Overall prospect value of the mitigation plans.

5.4 Cumulative prospect theory (CPT)

Although some MCDM methods consider the DMs' preferences in evaluating different kinds of risks, they are unable to capture the aforementioned DMs' behavioural characteristics. Therefore, CPT will be adapted to address these shortcomings in the above-mentioned MCDM methods.

CPT is a descriptive model that has shown its effectiveness in capturing DMs' behaviour under risks towards forming and evaluating the risks' consequences, called *outcomes* in CPT (Gonzalez & Wu, 1999; Abdellaoui, 2000; Bruhin et al., 2010). In the follows, a brief review of CPT is presented.

Assume that a gamble has the following outcomes:

$$(x_{-m}, p_{-m}; x_{-m+1}, p_{-m+1}; \dots; x_0, p_0; \dots; x_{n-1}, p_{n-1}; x_n, p_n),$$

where the notations are read as an outcome x_i with probability p_i for $i = -m, -m+1, \dots., n-1, n$. These outcomes are arranged in increasing order, presented as $x_i > x_j$ if $i > j$ and $x_0 = 0$. The CPT model evaluates the prospect of the above gamble, with

$$\sum_{i=-m}^{n} \pi_i v(x_i),$$

where $v(\cdot)$ is the *value function,* which is an increasing function with $v(0) = 0$, and π_i $(i = -m, \dots, -1,0,1, \dots, n)$ are the *decision weights*.

The core principle of CPT assumes that DMs are influenced by four behavioural aspects under risk and uncertainty: (1) reference dependence, (2) loss aversion, (3) diminishing sensitivity and (4) probability weighting. These four concepts are explained below.

- *Reference dependence*. In prospect theory, as mentioned above, individuals evaluate utility from gains and losses perspectives based on reference points rather than current wealth. Hence, in CPT, the argument of $v(\cdot)$ is x_i and this assumption is termed "reference dependence". To select a warranty risk mitigation plan, the DM may consider the estimated warranty cost as a reference point.
- *Loss aversion* is another element that can be captured by the value function of $v(\cdot)$, as individuals are much more sensitive to losses than gains, even with the same magnitude of change. In the case of warranty risk mitigation, DM may consider the probabilities of the outcomes of reducing the emerging risk when a mitigation plan is applied. For example, the DM will think about the cost of the mitigation plan and the outcome of applying such a plan to reduce the warranty risk. If the expected outcome is (reduced by 30%, 0.5; reduced by 70%, 0.5), then it may be attractive to the natural-risk DM due to the positive outcome. However, the loss-averse DM may consider another plan, because the result of reducing only 30% of the risk has a greater impact than the pleasure of reducing the warranty risk by 70%. The perception of the difference between DM can be informally presented as steeper in the domain of loss $v(x_i) = -\lambda(-x_i)^{\delta_2}, x_i < 0$ and λ>1, compared to the domain of gain $v(x_i) = x_i^{\delta_1}, x_i \geq 0$, as shown in Figure 5-1.

$$v(x_i) = \begin{cases} x_i^{\delta_1} & x_i \geq 0 \\ -\lambda(-x_i)^{\delta_2}, & x_i < 0 \end{cases} \tag{1}$$

  The parameters δ_1, δ_2 and λ are estimated based on experimental data, where $0 < \delta_1, \delta_2 \leq 1$. In the expected utility theory, it is difficult to explain this fact in relation to current wealth.

- *Diminishing sensitivity*. Diminishing sensitivity represents the impact of the change on the outcomes, with the same magnitude of change for loss and gain. For example, replacing £100 (loss or gain) with £150 (loss or gain) has a significant utility impact, while replacing £1000 with £1050 has a smaller utility impact. The curve of the value function (Figure 5-1) shows that this value is concave in the area of gains and convex in the area of losses. This S-shape represents the concept of "diminishing sensitivity" as one of the four elements of CPT. Moreover, the curve on the gains domain exhibits the preference of risk-averse people for moderate probability gains: they prefer £100 for sure than a 50% chance of gaining £200, whereas the convex curve exhibits the risk-seeking people over losses: they prefer a 50% chance of losing £200 than a 100% chance of losing £100.

- *Probability weighting*. The last element of the CPT is the decision weight π_i. According to this theory, outcomes are not weighted by their objective probabilities p_i. However, individuals tend to use transformed probabilities or decision weights π_i for each outcome. To calculate the decision weight, the weighting function is required for each outcome as its argument is an objective probability. The weighting function is presented as

$$w(p_j, \mu) = \frac{p_j^{\mu}}{\left(p_j^{\mu} + (1 - p_j)^{\mu}\right)^{\frac{1}{\mu}}}, \qquad (2)$$

where p_j is the objective probabilities and μ is a parameter determined based on experimental data ($0.27 < \mu < 1$). It is a monotonic function depicting the inverse S-shaped (Tversky & Kahneman, 1992). The μ parameter reflects the behaviour of DMs, such as overweighting the outcomes with low probabilities and underweighting the outcomes with moderate and high probabilities. This is determined through experiments (Tversky & Kahneman, 1992). This function overweights low probabilities and underweights moderate and high probabilities. In CPT, this function has been applied to cumulative probabilities. The overweighting of unlikely extreme outcomes has been inferred from the fact that individuals may like both lotteries and insurance. For example, they may prefer a 0.001 chance of £5000 gain to £5 for sure, while also preferring to lose £5 for sure to a 0.001 chance of £5000 loss.

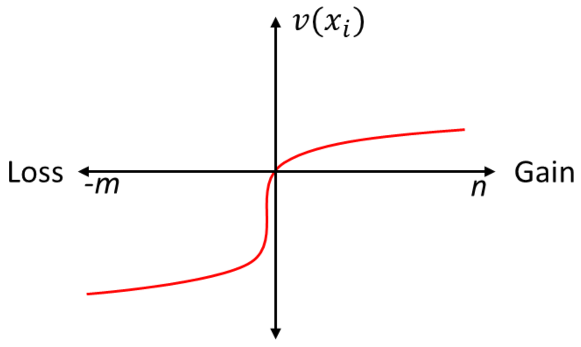

Figure 5-1: The S-shape of CPT representing graph plots of the value function

In the literature, several different behavioural decision-making methods have been developed since the prospect theory was developed by (Kahneman, 1979). For example, regret theory (Bell, 1982; Loomes & Sugden, 1982), disappointment theory (Bell, 1985), third-generation theory (Schmidt et al., 2008) and CPT (Tversky & Kahneman, 1992). CPT has demonstrated its superiority by accurately describing the aforementioned DMs' behaviours and providing the formulas required to calculate values and weights in a clear, logical and simple computation process. For this reason, CPT has been widely applied to addressing risk decision problems in consideration of behavioural characteristics.

5.5 Analytic hierarchy process (AHP)

First, the AHP method will be used to obtain the initial values of z_{ik} for the following reasons:

1) Assigning a ratio scale allows different groups of DMs to compare several criteria that are difficult to quantify, such as the manufacturers' reputations or environmental damage (Stevens, 1946).
2) The use of different criteria with different measurements poses another challenge, so the AHP method can unify them within a single scale (Saaty, 1990).

The first step of the AHP approach is to deconstruct the problem into a hierarchical structure where the highest level is the goal (e.g., a set of states s_j of an emergent warranty risk), followed by the criteria ($h_1, h_2, \dots, h_q$). The last level is the alternatives (level 3: e.g., a set of warranty mitigation plans: $d_1, d_2, \dots, d_m$). It is important to treat each state by AHP separately as each has its objective probability which will be weighted later by the weighting function of CPT (Figure 5-2).

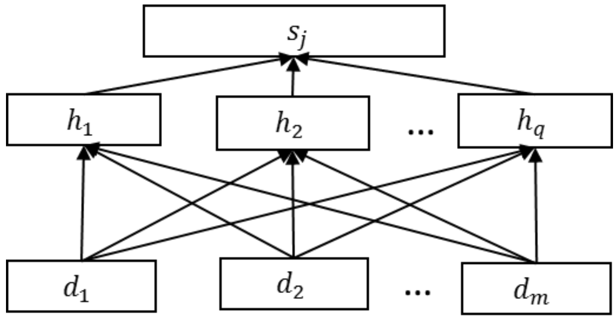

Figure 5-2: The hierarchy of warranty risk mitigation

Once the warranty risk has been deconstructed, each level will be evaluated in respect of its parents. In the warranty risk case, the criteria (manufacturer reputation, environmental damage and human safety) will be evaluated based on the expected magnitude of the observed failure, which depends on the preliminary diagnosis of the product. This diagnosis may reveal different states ($s_1, s_2, \ldots, s_n$) of the emerging risk.

To this end, a pairwise comparison matrix is implemented. This comparison has been widely utilised to overcome the subjective and objective judgements regarding different criteria (qualitative or quantitative). It is particularly used in the AHP and analytic network process (ANP). Saaty (2008) proposed the creation of a matrix O wherein the DM can evaluate criteria. This matrix is a $m \times m$ real number, where m is the number of the elements considered. The entries of such a matrix are o_{ab}, where each entry is the preference of the ath element compared to the bth element, with respect to the level immediately above. The ath element is more preferred if $o_{ab} > 1$ and less preferred if $o_{ba} < 1$, and both elements are equally preferred if $o_{ab} = o_{ba} = 1$. Matrix O can be presented as:

$$O = \begin{pmatrix} o_{11} & o_{12} \ \cdots & o_{1m} \\ \vdots & \vdots & \vdots \\ o_{m1} & o_{m2} \ \cdots & o_{mm} \end{pmatrix}, \qquad a, b = 1,2, \ldots, m$$

The DM can then evaluate the elements by assigning the relative preference using a numerical scale proposed by Saaty (2008), which contains numerical options from 1 to 9 to interpret the relative preferences for alternatives (Table

5-1). This table represents the scale and the suggestive expression represents the qualitative view of the DM.

When the matrix O is constructed, then the normalisation of the pairwise comparison matrix can be derived. Let O_{norm} be the normalised pairwise comparison matrix of O. O_{norm} is derived by dividing each entry o_{ab} by the sum of the entries of each column, which can be presented as:

$$\bar{o}_{ab} = \frac{o_{ab}}{\sum_{e=1}^{m} o_{eb}}$$

By averaging the entries of each row in O_{norm}, the criteria weight vector[23] W is computed as

$$W_o = \frac{\sum_{e=1}^{m} \bar{o}_{ae}}{m} \tag{3}$$

Table 5-1: Saaty's scale (Saaty, 2008)

Numerical scale	Verbal scale
1	Both elements are equally preferred
3	The ath element is moderately preferred over the bth element.
5	The ath element is strongly preferred over the bth element.
7	The ath element is very strongly preferred over the bth element.
9	The ath element is extremely preferred over the bth element.
2,4,6,8	Intermediate values between two adjacent judgements

To compute the scores of the alternatives with respect to the criteria, a matrix Z of a $n \times m$ real number must be created, where its entry z_{ik} denotes the preference score of the ith alternative, with respect to the kth criterion. To derive the z_{ik} scores, we need to create a matrix $R^{(s)}$ for each criterion, where $s = 1,2, \dots, q$. The $R^{(s)}$ is a $n \times n$ real matrix and n is the number of the

[23] It is an q-dimensional column vector, where q is the number of the criteria considered in the O matrix.

alternatives with respect to the sth criterion. i.e. the pairwise comparison of the alternative with respect to criterion 1 is represented as:

$$R^{(1)} = \begin{pmatrix} r_{11} & r_{12} \cdots & r_{1\mathrm{n}} \\ \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} \cdots & r_{nn} \end{pmatrix} \quad (4)$$

The same steps must be repeated with the matrix O to derive the weighting vector $W^{(s)}$ for each $R^{(s)}$ matrix. Thus, the score vector derived from $W^{(s)}$ is the score vector $z^{(s)}$, $s = 1,2, \ldots, q$. The vector $z^{(s)}$ contains the weighting vector of the alternatives with respect to the sth criterion. Now, the matrix Z is created as follows:

$$Z = \left[z^{(1)} \ldots z^{(q)}\right] \quad (5)$$

In the above step, the local weight of the alternatives with respect to each criterion is determined. Let g be the scores of the global weight vector of the alternatives, resulting from the multiplication of the matrix Z (Eq. (5)) by the weight vector W_o of the criteria (Eq. (3)). It is represented as:

$$g = Z * W_o \quad (6)$$

where the ith entry g_i of g is the global score of the ith alternative assigned by AHP.

As mentioned above, one of the main reasons for using the AHP method is to ensure the consistency of the experts' judgements presented in the comparison matrix. To this end, the main condition is the transitivity: if the element e_1 is more preferred than e_2, and e_2 is more preferred than e_3, then the element e_1 is more preferred than e_3. This consistency depends on the consistency index (CI) proposed by Saaty, which is given by $CI = \frac{u-m}{m-1}$, where scalar u is the average of the components of the vector that its bth element is the ratio of the bth element of the vector $O.W$ to the corresponding component of the vector W(Wind & Saaty, 1980). The perfect consistency index should be $= o$, in an ideal scenario. This value, however, is difficult in practice. As such, Saaty proposed a random index (RI) (see Table 5-2) to assess the acceptable consistency index, where $\frac{CI}{RI} < 0.1$. The consistency must be carried out for O matrix and $R^{(s)}$ matrices.

Table 5-2: Random index (Saaty)

q	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

5.6 CPT- WaRM model

In this section, CPT will be used to prioritise warranty risk mitigation plans. As the warranty risk mitigation plan is a decision problem, the mitigation plans must be ranked from greatest to smallest, based on the value of the overall prospect value score, which considers $p_j, c_i, z_{ik}, c^{\mathrm{ref}}, z_k^{\mathrm{ref}}$ and I^{c}, I^{r}. To develop the CPT-WaRM model, the following steps are required:

(1) The AHP method will be utilised to derive the preference weight of applying the ith mitigation plan compared to another ith mitigation plan in respect of reducing the impact of the emerging warranty risk on the kth criterion derived from Eq.(5).

(2) The value function of CPT will then be utilised to address the irrationality of DMs' judgements given in (1).

(3) The global weight vector of the mitigation plans will be determined by multiplying the weight vector of the criteria W by the matrix derived from (2).

(4) The above steps will be repeated with each jth state to derive the value of applying the ith warranty mitigation plan on the jth state.

(5) The weighting function of CPT will be used to weigh the objective probability p_j of each jth state. The objective probability can be estimated from historical warranty claims data, see Wu (2012). In the case of the new product, such probabilities can be estimated by other tools, such as fault tree analysis (FTA) and FMEA. Readers interested in determining p_j may consult (Tim & Roger, 2001; O'Hagan et al., 2006).

(6) Based on (4) and (5), the prospect value of each mitigation plan can be calculated.

(7) The overall prospect value of each mitigation plan is then calculated by considering the prospect value obtained from (6), the actual cost of the ith plan and the importance degree of the cost and result.

(8) Based on the above steps, the rank of warranty risk mitigation plans can be achieved based on the overall prospect value derived from (7).

(9) The global warranty mitigation ranks are determined by the dynamic CPT-WaRM (warranty mitigation policy).

Based on the above steps, the CPT-WaRM model will be constructed below.

Although the AHP is used to allow DMs from different departments to evaluate the proposed mitigation plans, it does not capture the DMs' irrationality under risk and uncertainty. As such, the CPT is adapted to address the irrationality of the judgements obtained by AHP, and, hence, the optimal mitigation plan can be determined. Based on the matrix in Eq. (5), the local weight vector of the mitigation plans with respect to the kth criterion is derived.

Once all local weight values have been computed, the DMs' irrationality (reference dependence, loss aversion and diminishing sensitivity) for the Z matrix will be addressed by the value function of the CPT. Let V_z matrix be the value function of matrix Z, based on Eq. (1) as follows:

$$V_Z = \begin{pmatrix} v(z_{11}) & v(z_{12}) \dots & v(z_{1q}) \\ \vdots & \vdots & \vdots \\ v(z_{m1}) & v(z_{m2}) \dots & v(z_{mq}) \end{pmatrix} \tag{7}$$

where, z_{ik} is the local weight of the ith mitigation plan with respect to the kth criterion and the reference point z_k^{ref} is the average of the values in the kth criterion.

That is, each entry in V_z is presented by the function value in Eq.(1) as:

$$v(z_{ik}) = \begin{cases} \left(z_{ik} - z_k^{\text{ref}}\right)^{\delta_{1_k}}, & z_{ik} - z_k^{\text{ref}} \geq 0 \\ -\lambda\left(z_k^{\text{ref}} - z_{ik}\right)^{\delta_{2_k}}, & z_{ik} - z_k^{\text{ref}} < 0 \end{cases}$$

The values derived by Eq. (7) will be multiplied by the weight vector of the criteria obtained by Eq. (3) to determine the global weight of each mitigation plan on the jth state. According to Eq. (6), let g_j denote the global weight vector of the mitigation plans d_i with respect to the jth state.

$$g_j = V_z \,. W_o \tag{8}$$

Let G denote a $m \times n$ real matrix where its entry is g_{ij} derived from Eq. (8), $i = 1,2,\dots,m;\ j = 1,2,\dots,n$. Based on Eq.(8), the G matrix can be presented as

$$G = \begin{pmatrix} g_{11} & \cdots & g_{1n} \\ \vdots & \ddots & \vdots \\ g_{m1} & \cdots & g_{mn} \end{pmatrix} \tag{9}$$

that is, the entries g_i of G is the global weight vector of the alternative with respect to the jth state.

The prospect value of each mitigation plan can then be calculated based on the result values obtained by Eq. (9). To this end, these values are ranked in ascending order for each row in the G matrix. The rank should be presented as $g_{i(-m)} \le g_{i(1-m)} \le \cdots \le 0 \le \cdots \le g_{i(n-1)}, g_{i(n)}$ and the probabilities of the states p_j are accordingly re-indexed. Let G_i denote the prospect value of the ith mitigation plan. It is computed as:

$$G_i = \sum_{k=0}^{n} g_{i,k}\, \pi_{i,k}^{+} + \sum_{k=-m}^{0} g_{i,k}\, \pi_{i,k}^{-}\,, \quad i = 1,2,\dots,m\,, \tag{10}$$

The decision weight $\pi^{+/-}\,(\cdot)$ is weighted based on the Eq. (2) and presented as

$$\pi_{i,k}^{+} = w\left(\sum_{k=l}^{n} p_{i,k}\,, \mu\right) - \ w\left(\sum_{k=l+1}^{n} p_{i,k}, \mu\right), \quad 0 \le l \le n-1 \tag{11}$$

$$\pi_{i,k}^{-} = w\left(\sum_{k=-m}^{l} p_{i,k}, \mu\right) - \ w\left(\sum_{k=-m}^{l-1} p_{i,k}\,, \mu\right), \quad 1-m \le l < 0 \tag{12}$$

The cost of the mitigation plans c_i may increase as a result of repairing faulty items, personnel expenses, spare parts, logistics expenses, etc. This cost can be measured; however, determining the reference point is the main challenge in modelling real-world issues with CPT, as it has its basis in deriving utility gain or loss (Barberis, 2013). In warranty practice, this reference point can be estimated based on:

(1) The industrial warranty claim statistics. For example, warrantyweek.com publishes warranty claim statistics for reference.
(2) The manufacturer's own historical warranty claims data, which is especially relevant for old products, for which the manufacturer should have retained historical data. The reference point may be the average cost of an existing product.
(3) Experts' opinions. For new products, there may not be historical data to be used as reference points. In such scenarios, expert opinions may be sought (O'Hagan et al., 2006).
(4) Data fusion techniques that aggregate all three sources of data to obtain reference points.

Once the reference point has been determined, the costs of mitigation plans can be assessed. Since the mitigation plan cost is given as a quantitative measure, it can be used as the prospect value of the cost. Let V_i denote the value of the mitigation plans costs. According to Eq. (1), V_i can be computed as:

$$V_i = \begin{cases} \left(c_i - c^{\mathrm{ref}}\right)^{\delta_1}, & c_i \geq c^{\mathrm{ref}} \\ -\lambda\left(c^{\mathrm{ref}} - c_i\right)^{\delta_2}, & c_i < c^{\mathrm{ref}} \end{cases} \quad (13)$$

The overall prospect value Y_i of each mitigation plan can then be computed by considering the importance degree of the result, compared to the cost:

$$Y_i = I^{\mathrm{r}}.G_i + I^{\mathrm{c}}.V_i \quad , i = 1,2,\ldots,m \quad (14)$$

Based on the result of Y_i, the greater the overall prospect value is, the better the mitigation plan will be. Accordingly, the mitigation plans will be ranked according to their overall prospect values and the greatest will be selected to mitigate the emerging warranty hazard.

5.7 The dynamic CPT-WaRM model

The overall ranking of the mitigation plans was determined based on the reference point set at the planning stage of WaRM. In warranty practice, however, the case is different, as manufacturers may schedule several check-ups to review the warranty claims-related issues and respond to the emerging risk by selecting the optimal mitigation plan, as discussed above. The plan selected at one check-up, however, may affect future decisions concerning the determination of the optimal mitigation plan at future check-ups. Accordingly, the reference point of the mitigation plans c^{ref} and the values of the parameters α, β and λ may vary over time. For example, loss aversion λ can be greater at t_{i+1} than at t_i, due to losses experienced in the recent past.

New reference points

To determine the new reference point c_t^{ref}, the DM may assess the expected value S_i of the aggregated warranty cost for the interval $[T_{t-1}, T_t)$. The reference point of the mitigation plan at the time T_t may be determined based on the expected aggregate warranty cost S_i and the expected impact of the selected mitigation plan at T_{t-1} on the reference point and the time T_t. This can be computed as (Luo & Wu, 2018a):

$$E[S_i(T_t)] = N(T_t)Z_i \tag{15}$$

where $N(T_t)$ is the number of warranty claims assumed to follow the non-homogenous Poisson process and Z is the warranty unit cost. It may be assumed that the reference points at different check-up times follow a function, such as

$$c^{\text{ref}}(T_t) = f(S_i), \tag{16}$$

where $f()$ can represent the impact of the DMs' behaviour on the incurred warranty cost.

DMs' behaviour

We assume that the DMs' behaviour may change, based on the impact of the warranty risk that they have just experienced. To capture such behaviour, let $V_{z(t)}$ denote the value of applying the ith mitigation plan to the kth criterion at time t. Thus, based on the Eq.(1) and Eq. (7), $V_{z(t)}$ is presented as:

$$V_{z(t)} = \begin{pmatrix} v_t(z_{11}) & v_t(z_{12}) \ldots & v_t(z_{1q}) \\ \vdots & \vdots & \vdots \\ v_t(z_{m1}) & v_t(z_{m2}) \ldots & v_t(z_{mq}) \end{pmatrix} \qquad (17)$$

where the parameters of the value function v_t are $\delta_{1_k}(t)$, $\delta_{2_k}(t)$ and $\lambda_k(t)$ denoting time-varying parameters to represent the time-varying levels of risk aversion of DM over the *gain*, risk-seeking over the *loss* and the loss aversion with respect to the kth criterion, respectively, where $0 < \delta_{1_k}(t), \delta_{2_k}(t) \leq 1$; $\lambda_k(t) > 1$.

Overall prospect value

The new variables—the reference point in Eq. (15) and the DMs' behaviour parameters in Eq. (16)—will be used to compute the Y_i for the warranty mitigation plans at different T_t times. To determine the global prospect value at each t time, the score of the Y_i for each mitigation plan will be aggregated for all possible roots (mitigation policy score; see Figure 5-3). For example, it is assumed that the manufacturer offered a three-year warranty for a new product and set six check-ups (every six months) to review the warranty claims, as shown in Figure 5-3. To determine the optimal mitigation policy from the first check-up, all root possibilities are generated. Then, based on Eqs. (15) and (16), the reference point is amended to respond to changes in time and the decision made at the immediately preceding check-up. Furthermore, based on Eq. (14), the parameters of the value function are set to be a function of the time. The Y_i for each mitigation plan in each root is then aggregated to determine the score of the root. Subsequently, the optimal warranty mitigation policy can be determined, whereby the greatest root score indicates the best mitigation plan policy.

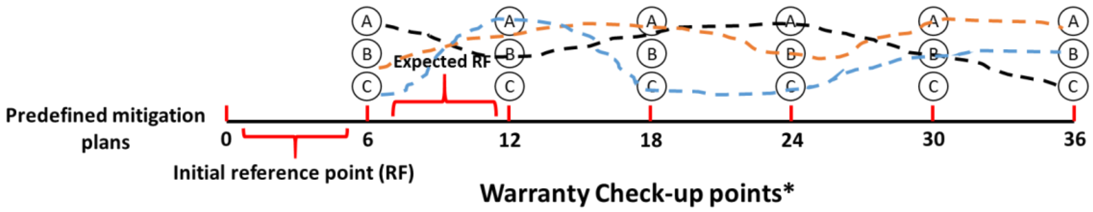

Figure 5-3: The root of the warranty risk mitigation plan policy

The time-varying property of this model is represented by the change in the reference point of the cost of the mitigation plans c^{ref} and the time-varying parameters related to the DM's behaviour under risk and uncertainty.

5.8 Numerical example

5.8.1 The design and analysis of the AHP questionnaire

In this section, a questionnaire was carried out in October 2018 to collect experts' judgments towards mitigating warranty incidents in the automotive industry in the UK.

In order to collect data from different experts working in different departments in an automaker firm, a questionnaire was designed and distributed manually to experts working in different departments mainly: engineering, marketing and logistics. Out of the 21 questionnaires were distributed, 11 were returned.

In the questionnaire, it is assumed that there are three warranty incidents ($n = 3$, Ignition switch, Faulty brake lights and Defective steering components) in which each can have different impacts on four criteria (q=4, warranty cost, manufacturer's reputation, environmental damage and human safety). Also, we propose three mitigation plans ($m = 3$, Recall all products, Partial recall and refund, Partial recall). In addition, the experts can use "Do Nothing" as a reference point. In other words, they can evaluate the impact of the warranty incident on the criteria in case they Don't Do anything and then use the local weight of this decision as a reference point for the three proposed mitigation plans.

Based on the AHP structure presented in Figure 5-2, the questionnaire was designed to collect the experts' preferences about selecting the preferred mitigation plan over others to reduce each warranty incident. As such, five pairwise comparison matrices were designed as follows.

- One matrix for evaluating the decision criteria with respect to the jth warranty incident.
- Four matrices for evaluating the m mitigation plans with respect to each decision criterion.

- Since we proposed 3 incidents, the questionnaire consists of fifteen pairwise comparison matrices.

There are tools can be used to ease constructing and analysing AHP such as Super decision among others. While the group of the experts is relatively small, each returned questionnaire was analysed individually.

For each questionnaire, the local weights vector derived from each pairwise comparison matrix will be obtained by the following steps:

(I) The consistency of each pairwise comparison matrix will be assessed, if it is not consistent, the expert may be asked to re-evaluate the elements.

(II) If it is consistent, then the vector of the local weights is obtained by Eq. (3).

(III) As the judgments were assigned by a group of the experts, one needs to aggregate the local weights vectors collected from the different questionnaires and then compute the geometric mean (Xu, 2000) for each ith mitigation plan. Let L denote the number of the experts, and k denote the local weights of the ith mitigation plan provided by different experts, then the geometric mean is obtained as

$$\left(\prod_{l=1}^{L} k_l\right)^{1/L} = \sqrt[L]{k_1 \times k_2 \times \ldots \times k_l}$$

(I) For each local weight, the geometric mean will be calculated as discussed in the above step.

(II) The scores derived from the above steps will be used as inputs to the Eq.(13) the value function of the CPT-WaRM model.

Assume that the warranty claim is increasing rapidly caused by the above warranty incidents (Ignition switch, Faulty brake lights and Defective steering components). Since the increasing complaints about such incidents, the decision makers may respond to them by one of the following mitigation plans:

(d_1) Recall all product: manufacturer are required to may recall defective products which already claimed or expected to claim due to reliability-related issues or safety-related issues.

(d_2) Partial recall and refund: The manufacturer may recall products manufactured in a certain period due to safety or reliability-related defect and provide the customer with a refund for the repair costs they already have spent.

(d_3) Partial recall: The manufacturer may recall products manufactured in a certain period due to a safety or reliability related defect

(d_4) Do nothing: It means that the manufacturer will not recall defective products and will only perform the routinely scheduled warranty services.

Table 5-3 provides the value of the local weight for each mitigation plan, which obtained by the same way in Eq. (3).

Table 5-3: The aggregated outcomes

Switch ignition ($\boldsymbol{j_1}$)	Warranty cost	Manufacturer reputation	Environmental damage	Human Safety
d_1	0.052	0.112	0.089	0.535
d_2	0.105	0.288	0.175	0.189
d_3	0.202	0.284	0.220	0.189
d_4 (do nothing)	0.630	0.236	0.387	0.078
Faulty brake lights ($\boldsymbol{j_2}$)				
d_1	0.062	0.067	0.047	0.309
d_2	0.136	0.467	0.125	0.271
d_3	0.191	0.178	0.174	0.278
d_4 (do nothing)	0.603	0.211	0.647	0.054
Defective steering components ($\boldsymbol{j_3}$)				
d_1	0.057	0.090	0.061	0.503
d_2	0.107	0.315	0.170	0.216

d_3	0.238	0.207	0.190	0.210
d_4 (do nothing)	0.595	0.185	0.554	0.056

Firstly, in order to determine the reference point, the mitigation plan d_4 is treated as a reference point for the m mitigation plans, i.e. $d_4 = z^*_{jr,\theta}$. As such, it is compared with the remaining mitigation plans in each pairwise comparison matrix. Its local weight score with respect to the rth criterion will therefore be used as a reference point for this criterion. I.e. when the m mitigation plans are evaluated with respect to the warranty cost criterion, the local weight score of the mitigation plan d_4 will be used as a reference point for this criterion. Since we have three warranty incidents, one may need to calculate the mean of the scores of each reference point (d_4) at different warranty incidents. I.e. the reference points for the warranty cost criterion at different warranty incidents can be computed as $\frac{(z^*_{11,\theta}+z^*_{21,\theta}+z^*_{31,\theta})}{n} = \frac{(0.630+0.603+0.595)}{3} = 0.609$. Likewise, the reference points of the remaining decision criteria (manufacturer's reputation, environmental damage, and human safety) are obtained by the same way and the results are 0.210, 0.530 and 0.062, respectively.

Secondly, the scores obtained by the AHP in Table 5-3 need to be assessed by the value function of the CPT to address the irrationality of the decision makers, see Table 5-4. In this table, one can notice that the reference points' scores are omitted as they were used as reference points for the rest mitigation plans s in the value function.

Table 5-4: The value function of the local weights

Switch ignition ($\boldsymbol{j_1}$)	Warranty cost	Manufacturer reputation	Environmental damage	Human Safety
d_1	-1.345	-0.290	-1.095	0.517
d_2	-1.231	0.106	-0.905	0.163
d_3	-1.020	0.101	-0.802	0.163
Faulty brake lights ($\boldsymbol{j_2}$)				
d_1	-1.324	-0.405	-1.185	0.292

d_2	-1.164	0.303	-1.015	0.253
d_3	-1.044	-0.110	-0.907	0.260
Defective steering components ($\boldsymbol{j_3}$)				
d_1	-1.334	-0.348	-1.156	0.486
d_2	-1.226	0.138	-0.915	0.193
d_3	-0.940	-0.013	-0.870	0.187

Thirdly, the vector of the global weights for the m mitigation plans with respect the jth incident will be determined based on Eq. (8). I.e. the global weights for the m mitigation plans used to reduce the impact of the j_1 warranty incident are given as,

$$g_1 = V_z \,.\, W_1 = \begin{pmatrix} -1.345 & -0.290 & -1.095 & 0.517 \\ -1.231 & 0.106 & -0.905 & 0.163 \\ -1.020 & 0.101 & -0.802 & 0.163 \end{pmatrix} . \begin{pmatrix} 0.120 \\ 0.110 \\ 0.085 \\ 0.652 \end{pmatrix} = \begin{pmatrix} 0.051 \\ -0.107 \\ -0.073 \end{pmatrix}$$

Similarly, the global weights vectors for the m mitigation plans (g_2 and g_3) are obtained and presented all together as,

$g_2 = \begin{pmatrix} 0.130 \\ 0.141 \\ 0.080 \end{pmatrix}$ and $g_3 = \begin{pmatrix} 0.143 \\ 0.124 \\ 0.058 \end{pmatrix}$, respectively, see Table 5-5.

Table 5-5: The global weight

Incidents	p_j	d_1	d_2	d_3
j_1	0.10	0.051	-0.107	-0.073
j_2	0.15	-0.146	-0.036	-0.065
j_3	0.75	0.021	-0.083	-0.063

These scores will be assessed by the prospect value to find G_i based on Eq. (10). To this end, each column scores will be ordered from the smallest to the greatest and the incidents' probabilities will be re-indexed to follow such order in each column, see Table 5-6. Then Eqs. (11) and (12) will be used to calculate the decision weight $\pi_{i,k}$ of each score. It is assumed that the initial objective probabilities of the warranty incidents $p_j = (p_1,\ p_2\ ,\ p_3)$ are (0.10, 0.15, 0.75). The parameters of the weighting function μ are estimated (Tversky & Kahneman, 1992) as 0.61 and 0.69 for gains and losses, respectively (Tversky & Kahneman, 1992).

Table 5-6: The increasing order of values and re-index of their probabilities

Incidents	p_j	d_1	p_j	d_2	p_j	d_3
j_1	0.15	-0.146	0.10	-0.107	0.10	-0.073
j_2	0.75	0.021	0.75	-0.083	0.15	-0.065
j_3	0.10	0.051	0.15	-0.036	0.75	-0.063
Prospect value ($\boldsymbol{G_i}$)	-0.013		-0.110		-0.094	

Finally, once the decision weight is determined for each $g_{i,k}$ score will be determined based on Eqs. (11) and (12). Then Eq. (10) will be used to obtain the prospect value of each mitigation plan. As such, the G_i results are $d_1 = -0.013$, $d_2 = -0.110$ and $d_3 = -0.094$. Based on these results the optimal mitigation plan is d_1 (Recall all products) considering the impact of the three incidents on different criteria. Since the identified warranty incidents are more related to human safety and their probabilities are relatively high (e.g. $p_3 = 0.75$), the experts may consider the Recall all products as a the optimal mitigation plan. Although the expected failed products may not all products, the experts assigned more weight to human safety criterion (see, Table 5-3) to ensure the potential injuries or death will be kept with the minimum level and to avoid potential fines.

5.9 Summary

Although warranty plays a significant role as a marketing tool, it can also cause substantial financial and reputational losses for warrantors. A well-planned method for mitigating warranty hazards is therefore extremely important. As such, warranty DMs should consider proactive plans for the mitigation of warranty risks when they have actualised.

The objective of this chapter is to develop a decision tool which can assist warranty DMs in selecting suitable mitigation plans based on different criteria. Results: The following points therefore have been achieved:

1) Analysed the literature comprehensively. Accordingly, this research found that the decision regarding the selection of the warranty risk mitigation plan faces two challenges: the conflict among the decision makers representing different departments and the uncertainty of the outcome of the mitigation plan.
2) Developed a decision model which has merged analytic hierarchy process (AHP) method and the cumulative prospect theory (CPT) to overcome, respectively, two issues: (1) the conflict among the decision makers, and (2) the uncertainty of the outcomes of the mitigation plan and its impact on the decision makers attitudes.
3) Various methods have been proposed to determine the reference point of the CPT-WaRM model, as this is the key to deriving utility gains and losses.
4) Since the reference point for mitigation plans costs are subject to change over the warranty period, the time dependence is integrated into the CPT-WaRM model to respond to such changes. Likewise, the DMs' behaviour may change over time, depending on the magnitude of the emerging risk and their previous experiences. As such, such behaviour is considered and treated as time-dependent parameters.

This model will assist warranty DMs in evaluating and ranking different mitigation plans by considering those behavioural aspects that affect the final decision, including reference dependence, loss aversion, diminishing sensitivity, and probability weighting.

CHAPTER 6: WARRANTY PRICE OPTIMISATION

6.1 Introduction

Warranty is defined as a contractual obligation provided by a warrantor (e.g. a manufacturer) to a client (e.g. a buyer) for a period of time after the product has been sold (Murthy & Djamaludin, 2002). It is provided as part of the sold product and is called the "base warranty", which is imposed by the law such as two-years warranty for the new products in the European countries (Wu, 2014). For some purposes, the warrantor may extend the base warranty for a period of time, known as an extended warranty, which is used as an insurance and promotional tool. For instance, the duration of the warranty may be used by the buyer to indicate the quality of the product and hence it is promoting the purchase decision.

Although the provision of warranty provides some benefits, it may involve a high degree of risk due to the complexity of the new innovations and the associated uncertain performance. Such a risk can be a direct risk such as the warranty expenses or indirect risk such as the reputational damage. As an example of the financial risk, General Motors spent $4.1 billion[24] to recall 30.4 million vehicles in 2014 due to a serious issue with the ignition switch.

From the perspectives of both the warrantor and the buyer, the number of warranty claims is uncertain and the estimate of the warranty cost is therefore uncertain. Additionally, the provision of the long warranty duration requires more resources to handle warranty claims, which implies more expenses from the warrantor. As such, there is a necessity to develop models to optimise the warranty price while the risk attitudes of both the warrantor and the buyer are taken into consideration.

The literature review of this chapter was discussed earlier in this thesis, in Section 2.8.

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[24]Available at: https://money.cnn.com/2015/02/04/news/companies/gm-earnings-recall-costs/index.html. Accessed date: 02 Oct. 2019.

6.1.1 Novelty and contribution

To the best of my knowledge, there is no literature has optimised warranty price where different behavioural characteristics under risk are considered for a warrantor and buyers.

It makes the following contribution:

- The perception of the buyers' and warrantor's towards the product failure rate are considered in optimising warranty price.
- The effect of the warranty repair cost on the profit is analysed.
- Warranty decision models are developed to determine the optimal warranty price.

6.1.2 Overview

The rest of this chapter is structured as follows. In Section 6.2, the problem's assumptions and notations are provided. Then the warranty models are developed in Section 6.3 to determine the optimal warranty policy satisfying the maximum total profit. In Section 6.4, a numerical example is provided to illustrate the proposed methods. Finally, the summary of this chapter is given in Section 6.5.

6.2 Assumptions and notations

In this chapter, we make the following assumptions.

A1. The maximum number of warranty claims within time period $(0, t)$ is assumed to be $K(t)$.

A2. Buyer i assumes that the product item may have $N_i(t)$ failures within time period t, where $N_i(t)$ is a random number. Denote $p_i(n, t) = P(N_i(t) = n)$ as the probability that there are exactly n claims.

A3. Denote $M(t)$ as the number of warranty claims per product item within time period t, where $M(t)$ is a random number. Based on historical claim data, the warrantor may estimate the probability distribution: $p_w(n, t) = P(M(t) = n)$.

A4. Assume $P(N_i(t) = n) = \frac{e^{-\lambda t}(\lambda t)^n}{n!}$, where λ is the expected number of failures and it is estimated by buyer i. λ is a random variable with a gamma distribution, whose probability density distribution is $f(\lambda) = \frac{\beta^\alpha}{\Gamma(\alpha)}\lambda^{\alpha-1}e^{-\beta\lambda}$ and cumulative distribution function is $F(\lambda) = \frac{\gamma(\alpha,\lambda\beta)}{\Gamma(\alpha)}$.

This paper uses the following notations.

- Denote c_r as the cost of repairing a failure from a buyer's perspective, c_w as the cost of handling a warranty claim from a warrantor's perspective, and $c_p(t)$ as the price per product item of selling extended warranty with period t.
- Denote $r_p(t) = \sum_{n=0}^{K(t)} np_w(n,t)$, which is the expected number of warranty claims and the reference number of warranty claims.

Remarks.

R1. Assumption A1 is a reasonable assumption: within $(0,t)$, the actual number of warranty claims should not exceed a given number $K(t)$. For example, if the warranty duration is 36 months or 1095 days, then $K(t)$ should be smaller than 1095 as handling each warranty claim takes time.

R2. We make Assumption A4 because different buyers may have different estimates of the numbers of failures of the product they will purchase.

R3. $c_w r_p(t)$ is the reference point from the warrantor's perspective.

R4. From a buyer's perspective, the reference number of failures is $r_b(t) = \frac{c_p(t)}{c_r}$.

R5. $c_r r_b(t)$ is the reference point from the buyer i's perspective. That is, the offered warranty price $c_p(t)$ is the reference point for the buyers.

6.3 Model development

The objective of this chapter is to develop warranty models to find the optimal warranty price that maximises the final profit, which is analysed in this section.

6.3.1 Warrantor's and buyer's utilities

On the one hand, the buyer's willingness to buy the extended warranty will be first modelled by treating the offered warranty price as a reference point and the expected number of claims is assumed to follow the Poisson distribution with the perceived failure rate by the buyer. If the buyer expected value of the repair cost is greater than the offered warranty price, he will be willing to buy warranty as the cost covered beyond the warranty price is deemed as a gain in the buyer's utility. Otherwise, the extended warranty is undesired since such a cost is less than the offered warranty price and hence it is considered as a loss, as shown in Figure 6-1.

On the other hand, the warrantor estimates the warranty claims costs. This cost is the product of two variables: (1) the expected claims number for each product estimated based on the warrantor's perceived failure rate, and (2) the repair cost for the warrantor. As such, if the value of the expected warranty claims costs is lower or equal to the offered warranty price, it is deemed as a gain. Otherwise, it is a loss, see Figure 6-2.

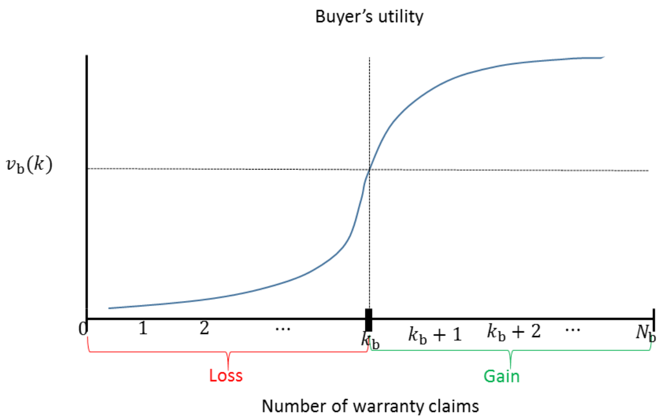

Figure 6-1: A representation of the buyer utility by the value function of the prospect theory

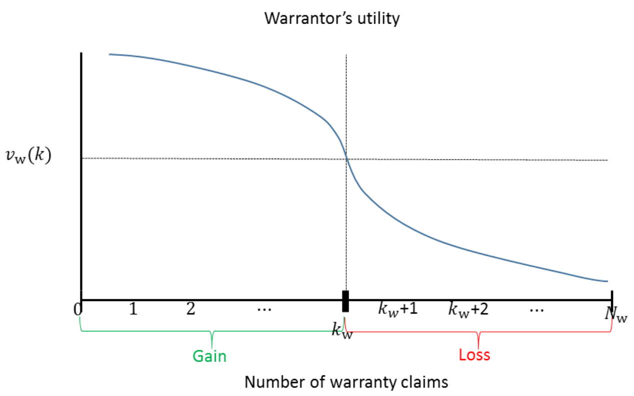

Figure 6-2: A representation of the warrantor utility by the value function of the prospect theory

Based on the Assumptions in Section 6.2, warranty policy is optimised through determining the optimal warranty price that the buyer should pay at the time of purchasing the product to cover repairing or replacing the failed items during the warranty period t.

6.3.2 Buyers' willingness to buy the extended warranty

From a buyer's perspective, for a given warranty period t, if the product item has n_b failures, then the cost of repairing is $c_{\mathrm{r}}n_{\mathrm{b}}$. If $c_{\mathrm{r}}n_{\mathrm{b}}$ is greater than $c_r r_b(t)$, then the buyer may purchase the extended warranty and consider as a gain. Following the cumulative prospect theory (Tversky & Kahneman (1992)), the gain can be expressed as $(c_{\mathrm{r}}n_i - c_r r_b(t))^{g_{\mathrm{b}}}$, where $0 < g_{\mathrm{b}} \le 1$ is a parameter representing the risk aversion attitude in the gain region. Conversely, if $c_{\mathrm{r}}n_{\mathrm{b}}$ is less than $c_r r_b(t)$, the buyer might be unwilling to buy the extended warranty as it is deemed as a loss, which can be expressed as $-\xi_{\mathrm{b}}(c_r r_b(t) - c_r n_i)^{l_{\mathrm{b}}}$, where $0 < l_{\mathrm{b}} \le 1$ is a parameter representing the risk-seeking attitude, and $\xi_{\mathrm{b}} > 1$ is the loss aversion.

Many authors estimated those parameters based on experiments to analyse subjects' choices under risk and uncertainty. For example, Tversky & Kahneman (1992) estimated $g_{\mathrm{b}} = l_{\mathrm{b}} = 0.88$ and $\xi_{\mathrm{b}} = 2.25$. Another study by Tu (2005) estimated $g_{\mathrm{b}} = 0.68, l_{\mathrm{b}} = 0.74$ and $\xi_{\mathrm{b}} = 3.18$. Abdellaoui et al. (2007) estimated $g_{\mathrm{b}} = 0.72, l_{\mathrm{b}} = 0.73$ and $\xi_{\mathrm{b}} = 2.54$. These parameters were also estimated by Booij et al. (2010) as $g_{\mathrm{b}} = 0.86, l_{\mathrm{b}} = 0.83$ and $\xi_{\mathrm{b}} = 1.58$. From those publications, one can see that $g_{\mathrm{b}} \in (0.6,0.9)$, $l_{\mathrm{b}} \in (0.5,0.9)$, and $\xi_{\mathrm{b}} \in (1,4)$.

The utility of buyer i can then be expressed by the value function of CPT as follows:

$$v_{b_i}(c_{\mathrm{r}}, n, t) = \begin{cases} (c_{\mathrm{r}}n - c_r r_b(t))^{g_{\mathrm{b}}}, & n \ge r_b(t) \\ -\xi_{\mathrm{b}}(c_r r_b(t) - c_{\mathrm{r}}n)^{l_{\mathrm{b}}}, & n < r_b(t) \end{cases}, \quad (1)$$

The values of outcomes obtained from Eq. (1) will be weighted by the decision weight, which is computed based on the gain and loss outcomes, respectively. The outcomes $c_{\mathrm{r}}n_i$ depend on the number of warranty claims, which is assumed to follow the Poisson distribution. Since the buyer is irrational in the decision under risk and uncertainty (Tversky & Kahneman, 1992), the decision weight is used to transform the objective probability $p(n_i)$ as follows:

$$\pi^{-}_{b_i,n}(t) = w^{-}\left(\sum_{j=0}^{n} p_i(j,t)\right) - w^{-}\left(\sum_{j=0}^{n-1} p_i(j,t)\right), 0 \le n \le r_b(t) - 1, \quad (2)$$

and

$$\pi^{+}_{b_i,n}(t) = w^{+}\left(\sum_{j=n}^{K(t)} p_i(j,t)\right) - w^{+}\left(\sum_{j=n+1}^{K(t)} p_i(j,t)\right), r_b(t) + 1 \le n \le K(t), \quad (3)$$

respectively, where $p_i(j,t) = P(N_i(t) = j)$ (see assumption A2 for the definition of $p_i(j,t)$), both $w^{-}(\cdot,t)$ and $w^{+}(\cdot,t)$ denote weighting functions and are assumed to be strictly increasing and satisfying $w^{-}(0,t) = w^{+}(0,t) = 0$ and $w^{-}(1,t) = w^{+}(1,t) = 1$, and expressed as follows:

$$w^{-}(p) = \frac{p^{\delta_{\mathrm{b}}^{-}}}{\left(p^{\delta_{\mathrm{b}}^{-}} + (1-p)^{\delta_{\mathrm{b}}^{-}}\right)^{\frac{1}{\delta_{\mathrm{b}}^{-}}}}, \quad (4)$$

and

$$w^{+}(p) = \frac{p^{\delta_{\mathrm{b}}^{+}}}{\left(p^{\delta_{\mathrm{b}}^{+}} + (1-p)^{\delta_{\mathrm{b}}^{+}}\right)^{\frac{1}{\delta_{\mathrm{b}}^{+}}}}, \quad (5)$$

respectively, where both δ_{b}^{-} and δ_{b}^{+} are the shape parameters. δ_{b}^{-} overweighs low probabilities and δ_{b}^{+} underweighs middle and high probabilities. Abdellaoui (2000) estimated such parameters as $\delta_{\mathrm{b}}^{-} = 0.65$ and $\delta_{\mathrm{b}}^{+} = 0.60$. Booij et al. (2010) estimated $\delta_{\mathrm{b}}^{-} = 0.59$ and $\delta_{\mathrm{b}}^{+} = 0.62$, and Abdellaoui et al. (2005) estimated $\delta_{\mathrm{b}}^{-} = 0.84$ and $\delta_{\mathrm{b}}^{+} = 0.83$. That is, $\delta_{\mathrm{b}}^{-}, \delta_{\mathrm{b}}^{+} \in (0,1)$.

Then the prospect value of a buyer i's expected repair cost can be expressed as follows:

$$V_{b_i}(c_{\mathrm{r}}, t) = \sum_{n=0}^{\lfloor r_b(t) \rfloor} v_{b_i}(c_{\mathrm{r}}, n, t)\pi^{-}_{b_i,n}(t) + \sum_{n=\lfloor r_b(t) \rfloor}^{K(t)} v_{b_i}(c_{\mathrm{r}}, n, t)\pi^{+}_{b_i,n}(t), \quad (6)$$

where $\lfloor x \rfloor$ represents the greatest integer less than or equal to x.

The decision maker will be indifferent between two choices (one is certain and another one is uncertain (gamble)) when the utility of the certain choice is equivalent to the expected utility of the uncertain once. This point is known as the certainty equivalent in the standard expected utility (Keeney & Raiffa, 1993). In the prospect value, however, the utility is determined based on a reference point, where the decision maker is indifferent between the two choices. In other words, a certain point determined by the decision maker is treated as a reference point to evaluate the gains outcomes and the losses. For example, in Remarks R3, R4 and R5 in Section 6.2, we discuss reference points from perspectives of both the warrantor and the buyer, respectively.

Based on assumption A2, the prospect value of the uncertain prospect $c_r n$ is determined based on n, where the probability of n is determined based on the buyer failure rate λ, see assumption A4 in Section 6.2. For a large number of buyers, the failure rates the buyers estimate are distributed as a continuous density $f(\lambda_i)$. To determine the proportion of buyers who are willing to buy the extended warranty, we assume that the ith buyer whose failure rate λ_i^* is indifferent between the prospect value of the risky prospect $c_r n$ and the utility of the reference point $c_r r_b(t)$. i.e. $v_{\mathrm{b}}(c_r r_b(t)) = V_{b_i}(c_{\mathrm{r}}, t) = 0$. Hence, the buyer's willingness to buy the extended warranty is $q = V_{b_i}(c_{\mathrm{r}}, t) > 0$.

Based on Assumption A4, the higher the buyer estimates the product failure rate λ, the more likely he will be willing to purchase the extended warranty. In other words, if $\lambda_i > \lambda_i^*$, the buyer would buy the extended warranty because he estimates$V_{b_i}(c_{\mathrm{r}}, t) > v_{\mathrm{b}}(c_r r_b(t))$. As such, denote $q(\lambda)$ as the proportion of buyers who are willing to buy the extended warranty, which is given as follows:

$$q(\lambda) = 1 - F(\lambda_i^*). \tag{7}$$

Obviously, $q(\lambda)$ is a continuous and strictly decreasing function.

Remark: The proportion $q(\lambda)$ is decreasing in λ if t is held constant. $0 \leq q(t) \leq 1$ where 0 means no buyer purchases warranty and 1 means all buyers buy warranty at the product purchase time.

6.3.2.1 The value of λ

Now we consider the scenario where λ is a random variable, which follows the gamma distribution with probability density function $f(\lambda) = \frac{1}{\Gamma(\alpha)} \beta^{\alpha} \lambda^{\alpha-1} e^{-\beta\lambda}$.

Hence,

$$
\begin{aligned}
&P(N_i(t)=n)\\
&=\int_0^\infty P(N_i(t)=n|\lambda)f(\lambda)d\lambda\\
&=\int_0^\infty \frac{e^{-\lambda t}(\lambda t)^n}{n!}\frac{1}{\Gamma(\alpha)}\beta^\alpha\lambda^{\alpha-1}e^{-\beta\lambda}d\lambda\\
&=\frac{\beta^\alpha t^n}{n!\,\Gamma(\alpha)}\int_0^\infty \lambda^{n+\alpha-1}e^{-(\beta+t)\lambda}d\lambda\\
&=\frac{\beta^\alpha t^n}{(\beta+t)n!\,\Gamma(\alpha)(\beta+t)^{n+\alpha-1}}\int_0^\infty [(\beta+t)\lambda]^{n+\alpha-1}e^{-(\beta+t)\lambda}d((\beta+t)\lambda)\\
&=\frac{\beta^\alpha t^n}{n!\,\Gamma(\alpha)(\beta+t)^{n+\alpha}}\int_0^\infty z^{n+\alpha-1}e^{-z}dz\\
&=\frac{\beta^\alpha t^n\Gamma(n+a)}{n!\,\Gamma(\alpha)(\beta+t)^{n+\alpha}}. \qquad (8)
\end{aligned}
$$

Assume $r_b(t)$ is a deterministic function of t. For example, one may assume $r_b(t)=rt$. Since different buyers may have different values of failure rate λ, then prospect value of the outcomes to all buyers making the decision is given by $V_{B_1}(c_{\mathrm{r}},t)$, where $p_i(j,t)$ in Eqs. (2) and (3) with the above quantity in Eq. (8) $p_i(j,t)=P(N_i(t)=j)$.

6.3.2.2 The value of $r_b(t)$

As assumed by Remark R4, $r_b(t)$ is the reference number of failures. Different buyers may have different reference numbers. It is therefore reasonable to assume that $r_b(t)$ is a random variable. For example, we may assume that $P(r_b(t)=k)=\binom{K(t)}{k}p_r^k(1-p_r)^{K(t)-k}$. If this is the case, then Eq. (6) becomes

$$V_{B_2}(c_\mathrm{r},t) = \sum_{k=1}^{K(t)} \binom{K(t)}{k} p_r^k (1-p_r)^{K(t)-k} \left(\sum_{n=0}^{k} v_{b_i}(c_\mathrm{r},n,t)\pi_{b_i,n}^{-}(t) + \sum_{n=k}^{K(t)} v_{b_i}(c_\mathrm{r},n,t)\pi_{b_i,n}^{+}(t) \right). \quad (9)$$

If we also consider the randomness of the parameter λ, then we have

$$V_{B_3}(c_\mathrm{r},t) = \sum_{k=1}^{K(t)} \binom{K(t)}{k} p_r^k (1-p_r)^{K(t)-k} \left(\sum_{n=0}^{k} v_{b_i}(c_\mathrm{r},n,t)\pi_{b_i,n}^{-}(t) + \sum_{n=k}^{K(t)} v_{b_i}(c_\mathrm{r},n,t)\pi_{b_i,n}^{+}(t) \right), \quad (10)$$

where $P(N_i(t) = n)$ in Eq. (10) is replaced with the one shown in Eq. (8).

6.3.2.3 Random cost c_r

The above discussion assumes that the cost of repairing a failure, from a buyer's perspective, is fixed for every buyer. However, this may not be the case in reality. One may therefore assume c_r is a random variable following a lognormal distribution, for example. Similar to the method used in Sections 6.3.2.1 and 6.3.2.2, $V_{b_i}(c_r t)$ in Eq. (6) will then be updated accordingly.

6.3.3 Warrantor's profit

Denote $\psi(h,t)$ as the warrantor's profit earned from the extended warranty. Denote h as the number of the sold product items, then the number of purchases of the extended warranty is $hq(t)$. Denote $r_p(t)$ as the expected number of warranty claims per product item. It should be noted that $r_p(t)$ may not be the same as the number of failures. This profit can be expressed as follows:

$$\psi(h,t) = hq(t)\left(c_p(t) - c_\mathrm{w} r_p(t)\right). \quad (11)$$

The warrantor's sales price $hq(t)c_p(t)$ is gained from the buyers who decided to purchase the extended warranty at the purchase time and $hq(t)r_p(t)c_\mathrm{w}$ is the cost of handling warranty claims from the warrantor's perspective.

From a warrantor's perspective, denote $V_w(c_w, t)$ as the prospect value of the uncertain claims costs $c_\mathrm{w} r_p(t)$. Based on the historical warranty claim data, the warrantor should be able to estimate the expected number, $r_p(t)$, of warranty claims during the period of extended warranty. The warrantor can of course use $r_p(t)$ as the reference point. The certainty profit equivalent can be expressed based on the prospect value of the uncertain prospect $c_\mathrm{w} n$ as:

$$\psi(h, t) = hq(t)\left(c_p(t) + V_W(c_\mathrm{w}, t)\right). \tag{12}$$

Based on the reference point $r_p(t)$, the prospect value of the uncertain prospect $c_\mathrm{w} r_p(t)$ can then be expressed as follows:

$$V_w(c_\mathrm{w}, t) = \sum_{n=0}^{r_p(t)} v_w(c_\mathrm{w}, n, t)\pi_{w,n}^{-}(t) + \sum_{n=r_p(t)}^{K(t)} v_w(c_\mathrm{w}, n, t)\pi_{w,n}^{+}(t), \tag{13}$$

where

$$v_w(c_\mathrm{w}, n, t) = \begin{cases} \left(c_r r_p(t) - c_\mathrm{w} n\right)^{g_w}, & n < r_p(t) \\ -\xi_w\left(c_\mathrm{w} n - c_w r_p(t)\right)^{l_\mathrm{w}}, & n \geq r_p(t) \end{cases}. \tag{14}$$

The group of buyers

Assume $r_b(t)$ is a deterministic function of t. For example, one may assume $r_b(t) = rt$. Since different buyers may have different values of failure rate λ, then expected utility of the outcomes to all buyers making the decision is given by

$$V_{w_1}(c_w, t) = \int_0^\infty \left(\sum_{n=0}^{r_p(t)} v_w(c_\mathrm{w}, n, t)\pi_{w,n}^{-}(t) + \sum_{n=r_p(t)}^{K(t)} v_w(c_\mathrm{w}, n, t)\pi_{w,n}^{+}(t) \right) \frac{\beta^\alpha}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\beta\lambda} d\lambda. \tag{15}$$

The warrantor then would determine the maximum of ψ by seeking the optimal $c_p(t)$ as follows:

$$\max_{\{c_p(t)\}} \psi = qhc_p(t) + V_{w_1}(c_w, t) \tag{16}$$

6.4 Numerical examples

In this section, we will first illustrate the impact of the warranty duration on the buyer's willingness to buy the extended warranty. Then buyers' risk attitudes towards the offered warranty price will be analysed. Once the proportion of the buyers has been estimated, the warrantor's total profit can be computed. Then the sensitivity of the total profit to the warrantor's risk attitude will be analysed. Additionally, the impact of the repair cost c_r to the total profit will be investigated.

The values of the variables and parameters in Table 6-1 are used in the numerical example.

Table 6-1: Notations and values for the numerical example

Variable	Value	Variable	Value
t	12, 24, 36	l_b , l_w	0.88
$c_p(t)$	£3, £5, £7	ξ_b	2.25
c_r	£2	δ_b^- , δ_w^-	0.62
$r_b(t)$	$\lambda_p(t)$, where λ_p is the product failure rate	δ_b^+ , δ_w^+	0.61
$K(t)$	$t/2$ *	c_w	1.5
h	500		
g_b ,g_w	0.88		

*Although in reality, the maximum number of failures won't reach $t/2$, it is assumed as the worst case.

6.4.1 Buyers' perspective

According to Assumption A2, the probability of $N_b = n$ is estimated based on the Poisson distribution, where the buyer's failure rate λ is distributed as a gamma distribution with $\alpha = t$ and $\beta = 1/9$. Accordingly, we generate 500 buyers' failure rates in order to estimate later the proportion of buyers who are willing to buy an extended warranty. Once the value and probability of each outcome $c_r n$ are estimated, the prospect value for the repair cost estimated by the ith buyer can be calculated based on Eq. (6).

6.4.1.1 *The effect of the warranty duration on the buyers' willingness towards the extended warranty*

Generally, the extended warranty is offered as a discrete number (e.g. number of months such as 6 months, 12 months, etc.). Since the buyer is assumed to determine the reference point of the number of failures based on the given warranty price $c_p(t)$, the utility of each prospect $c_r n$ is computed according to the value function Eq. (1), and its probability is then weighted based Eqs. (2) to (5). The product of the value function and the decision weight for each prospect is illustrated in Figure 6-3 (from the left to the right,$\boldsymbol{t} = \{\mathbf{12}, \mathbf{24}, \mathbf{36}\}$) with respect to different warranty durations. It can be seen that the maximum prospect value V_{b_i} will be around the reference point of *n* claims.

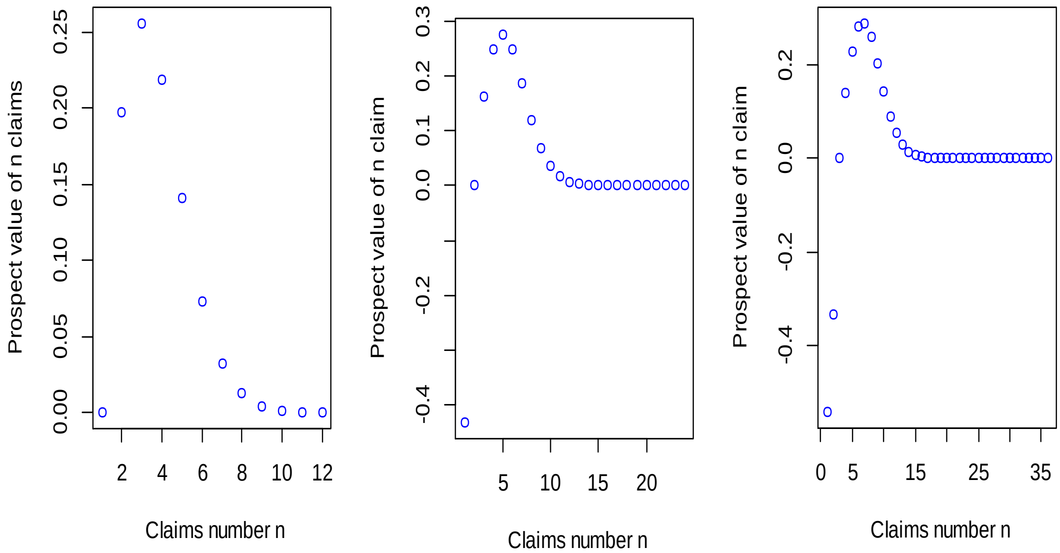

Figure 6-3: n claims with respect to different warranty duration

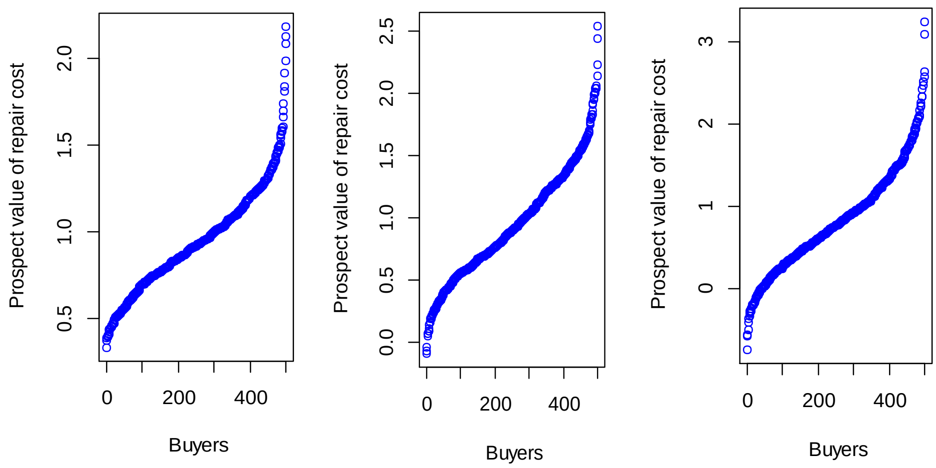

Figure 6-4: Warranty duration effect on the buyer's decision

Figure 6-4 (from the left to the right, $t = \{12, 24, 36\}$) illustrates the prospect value of the total cost of repair, which is estimated by buyers for different warranty durations. When the warranty duration is 12 months and $c_p(12) =$ £3, the prospect values of the total repair cost for all buyers are greater than 0. It implies that all buyers will buy the extended warranty since the prospect value $V_{b_i}(c_{\mathrm{r}}, t) \geq 0$. In other words, the estimated failure number is 1 (based on Remark R4) and hence its total cost of repair is estimated at £2. Accordingly, from the failure number $n = 2$ until $n = K(t) = \frac{t}{2} = \frac{12}{2} = 6$, the repair cost will exceed the offered warranty price $c_p(t) =$ £3 and hence the extended warranty will be appealing since it will cover the remaining 5 failures.

We assume that the longer warranty period implies the higher warranty price. As such, for the warranty period $t = 24$ and $t = 36$, we assume the warranty prices are $c_p(24) =$ £5 and $c_p(36) =$ £7. When the warranty duration is 24, there are 3 buyers who are unwilling to buy the extended warranty and this number has increased to 49 buyers when the warranty duration is 36, see Figure 6-4.

6.4.1.2 The effect of the buyers' risk preferences on the proportion $q(\lambda)$

The proportion of the buyers is estimated based on the buyers' failure rate λ and their attitudes under risk and uncertainty. The prospect value of the uncertain outcome $V_{b_i}(c_{\mathrm{r}}, t)$ is computed based on Eq. (6), considering the reference point as a function of the warranty price provided by the warrantor. In this numerical example, the risk aversion, risk-seeking and loss aversion attitudes will be analysed.

Firstly, the risk-aversion attitude of the buyers g_{b} , in Eq. (1), is varied from 0.1 to 0.8, where the offered warranty price is fixed at $c_p(t)$ =£7 and warranty duration is fixed at $t = 36$. The lower value of the risk aversion parameter implies a high degree of risk-aversion attitude, whereas the value 1 means the decision maker is neutral-risk. Figure 6-5 represents that the more the buyer risk-averse towards the offered warranty price, the less he is willing to buy the extended warranty. For example, at the risk aversion degree $g_{\mathrm{b}} = 0.10$, the proportion of the buyers who want to buy warranty is nearly zero. This proportion is increasing when the risk aversion degree is decreasing. When the degree of the risk aversion is low $g_b = 0.80$, the proportion of buyers has increased to 0.25.

Secondly, Figure 6-6 presents the risk-seeking attitude of the buyer towards the warranty price. The parameter l_b in Eq.(1) is therefore varied from 0.1 to 0.8 and the warranty price is set to $c_p(t) = £7$. It can be seen that when the buyers are extremely risk-seeking ($l_b = 0.1$), they all would buy the extended warranty $q(h) = 1$, whereas this proportion has decreased to nearly zero when the buyers less risk-seeking $l_b = 0.8$.

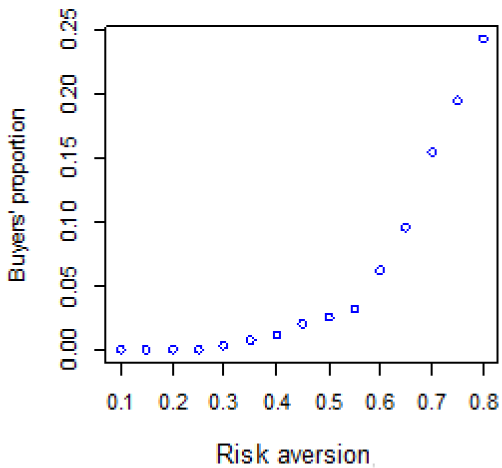

Figure 6-5: Effect of risk aversion attitude on the buyers' decision

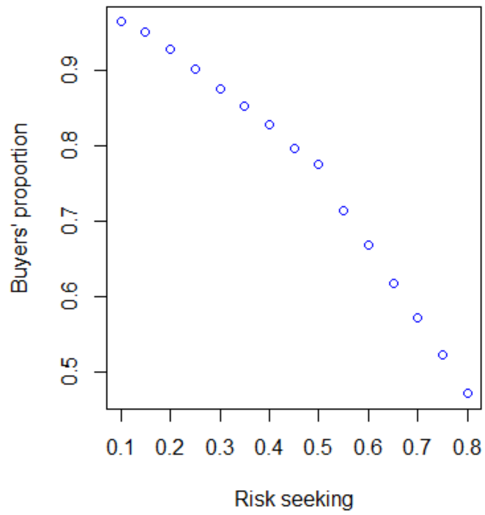

Figure 6-6: Effect of risk-seeking attitude on the buyers' decision

The buyer's loss aversion behaviour has also a great impact on the purchase decision of the extended warranty (Jindal, 2014). To examine that, ξ_b in Eq.(1) is varied from 1.1 to 3.8. Figure 6-7 shows that the proportion of the buyers is decreasing when the loss aversion impact towards the warranty price is increasing. For example, when the influence of the loss aversion behaviour is very low (1.1), almost all buyers are willing to buy an extended warranty for £7. When the loss aversion degree is 3.5, around11% of buyers are willing to buy the extended warranty.

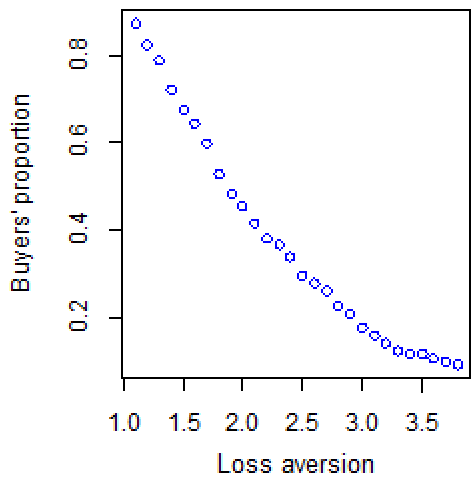

Figure 6-7: Effect of loss aversion attitude on the buyers' decision

6.4.2 The warrantor's perspective

In this section, the sensitivity of the profit to the warranty price and risk attitudes of both buyers and the warrantor will be analysed from two perspectives: from the commercial view and from the technical view. The former mainly analyses the impact of the warranty price and repair cost c_r on the final profit. The latter analyses the impact of the buyers' perceptions of the product failure rate.

6.4.2.1 Commercial view

In this subsection, the warranty price and repair cost for the buyer will be analysed.

The sensitivity of the profit to the offered warranty price $c_p(t)$

The profit is computed based on Eqs. (11) to (16), where it is estimated according to the prospect value of the warranty claims costs from the warrantor's perspective. The warrantor seeks the maximum profit by offering the optimal warranty price. To set warranty price, the warrantor may consider different factors such as the expected failure number, the length of warranty and other measures. In this numerical example, the reference point is determined based on the proportion of the buyers who purchased the extended warranty $q(t)$, product failure rate denoted as λ_p, and repair cost for the warrantor c_{w}.

To analyse the sensitivity of the profit to the change in warranty price, $c_p(t)$ is varied from £1 to £15 and t is fixed to 36 months. It is assumed that the warrantor is risk-averse towards warranty cost. Figure 6-8 shows that the maximum profit (£2145.37) can be reached when the warrantor offers the warranty price at £4.1.

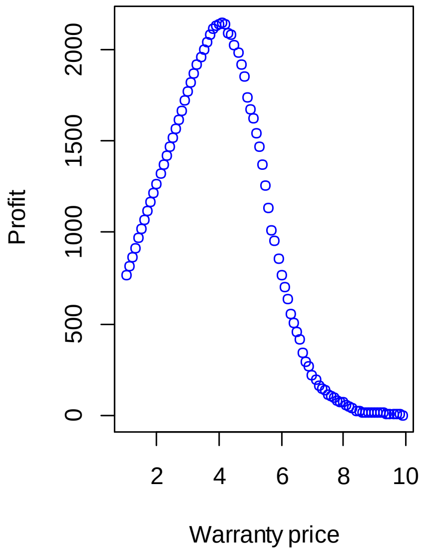

Figure 6-8: The sensitivity of the warrantor profit to the change in warranty price

In order to examine the sensitivity of the profit to the warrantor and buyers risk preferences, the risk aversion attitude of buyers g_b is set to the degrees: 0.20, 0.50 and 0.88, respectively, whereas the risk aversion degree of the warrantor g_w, in Eq.(14), is fixed on 0.88. Based on Eq.(16), the maximum profit is computed and achieved £2453.68 when the risk aversion degree of the buyers g_b is 0.88 and the warranty price is £5, see Figure 6-9 ($\boldsymbol{g_b}$=0.88; #Buyers=500). The more the buyer is risk-averse, the less the maximum profit will be. For example, the maximum profit has increased from £1626.52 to £2453.68 in response to the decrease in the buyer's risk aversion degree from 0.20 to 0.88, see Table 6-2.

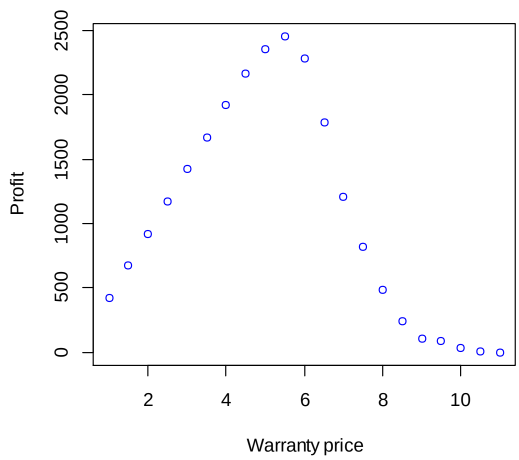

Figure 6-9: Profit sensitivity to the risk aversion attitude of the buyers

Table 6-2: The impact of the risk aversion of buyers on the warrantor's profit

Buyers risk aversion g_b	Max profit ψ (£)	Optimal warranty price $c_p(t)$ (£)
0.20 (high risk-averse)	1626.53	3.5
0.50	1881.82	4.0
0.88 (low risk-averse)	2453.68	5.5

The warrantor's risk-aversion attitude may also influence the final profit. To examine the buyer's risk-aversion attitude, g_b is set to 0.88 and the warrantor's risk-aversion attitude g_w takes these values 0.20, 0.50 and 0.88, respectively. Table 6-3 shows that the maximum profit, which is computed based on Eq.(16), is increasing when the warrantor becomes less risk-averse towards the expected warranty claims costs. That is, the more the warrantor is risk-averse, the more the warranty cost is expected and thus the profit is decreased. The optimal warranty price remains constant since the change is only on the prospect value of the expected warranty claims costs $V_{w_1}(c_w, t)$. Based on the results obtained from Table 6-2 and Table 6-3, it can be said that the buyer's risk-aversion attitude has more impact on the profit than the warrantor. For example, when the degree of the buyers' risk aversion attitudes is changed from 0.20 to 0.50, it leads to an increase in the warrantor maximum profit value by £255.29. With the same magnitude of change in the degree of the warrantor's risk aversion, a slight increase in the maximum profit value (£5.28) has been observed.

Table 6-3: The impact of the risk aversion of the warrantor on the profit

Warrantor's risk aversion g_w	Max profit ψ (£)	Optimal warranty price $c_p(t)$ (£)
0.20 (high risk-averse)	2387.37	5.5
0.50	2392.65	5.5
0.88	2453.68	5.5

The sensitivity of the profit to the loss aversion attitude of both the warrantor and buyers is examined as follows. Firstly, the buyer's loss aversion attitude ξ_b is varied from 1.25 to 3.25 and the warrantor's loss aversion ξ_w is fixed on 2.25, where the higher value of ξ indicates a high risk-averse attitude. Then, the warrantor's loss aversion attitude will be varied from 1.25 to 3.25 and the buyer's loss aversion attitude is fixed on 2.25. Table 6-4 shows that the more the buyer is loss-averse towards the offered warranty price, the less the maximum profit value will be. In other words, the magnitude of the pain of the buyer in the loss case (when the incurred warranty cost is lower than the price of the extended warranty) is greater than the pleasure from the gain (the incurred warranty cost exceeds the warranty price). Thus the increase in the degree of the loss-aversion attitude leads to a decrease in the proportion of the buyers and thus reducing the maximum profit value.

Table 6-4: The sensitivity of the profit to the loss aversion attitude of the buyers

Buyers' loss aversion ξ_b	**Max profit ψ (£)**	**Optimal warranty price $c_p(t)$ (£)**
1.25	2984.49	6.5
2.25	2453.68	5.5
3.25	2120.15	5.0

Likewise, in Table 6-5, the more the warrantor is loss-averse towards the expected warranty claims costs, the greater the prospect value of the expected claims costs $V_{w_1}(c_w, t)$ and thus the lower profit will be. It can also be noticed that the loss aversion attitude of the buyers has more effect on the profit then the warrantor.

Table 6-5: The sensitivity of the profit to the loss aversion attitude of the warrantor

Warrantor's loss aversion ξ_w	**Max profit ψ (£)**	**Optimal warranty price $c_p(t)$ (£)**
1.25	2517.52	5.5
2.25	2453.68	5.5
3.25	2398.84	5.5

The effect of the warranty repair cost c_r on the profit

The repair cost per claim c_r can affect the final profit. Obviously, it will increase the profit, but it may lead buyers to consider other warranty services providers if the warranty service of the product is not monopolised. To examine the sensitivity of profit to the repair cost c_r, this cost is examined at £1.5, £2.5 and £3.5 and the number of buyers is set to 50 in order to reduce the simulation time. For each repair cost c_r , the warranty price $c_r(t)$ is also varied from £3 to £13 and then the maximum profit is opted to present the effect of c_r.

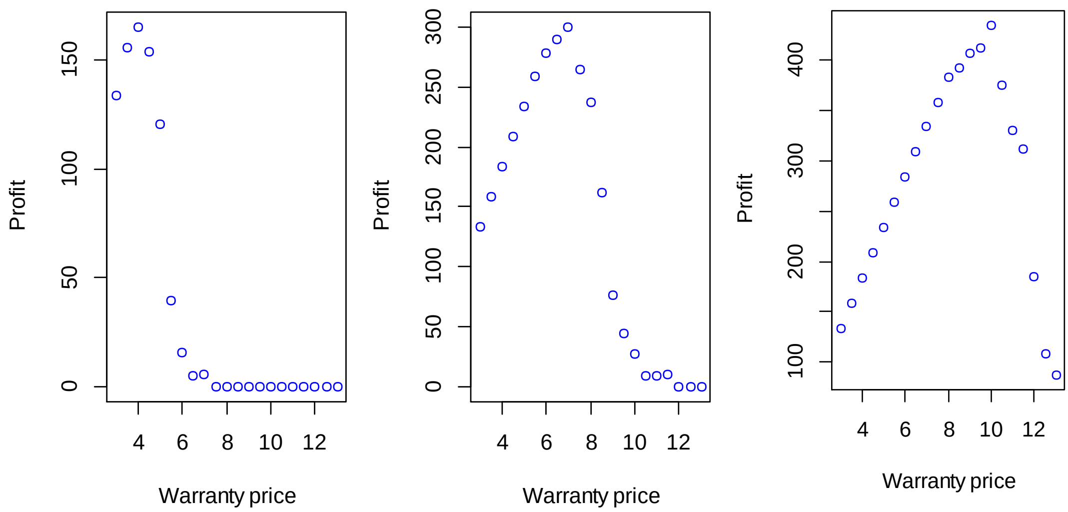

Figure 6-10: Buyers' repair cost effect on the profit

Based on Eqs. (6) and (16), it can be seen from Figure 6-10 that the maximum profit increases when the repair cost c_r increases ($\boldsymbol{c_r} = £\mathbf{1.5}, £\mathbf{2.5}, £\mathbf{3.5}$). For example, when the repair cost $c_r = £1.5$, the maximum profit is £165.05 and the optimal warranty price is £4, while the change in the warranty cost to £3.5 leads to increasing the maximum profit 435.05 and the optimal warranty price to £10, see Table 6-6. The buyers may therefore prefer to buy a high warranty price if they expect a high repair cost.

Table 6-6: The effect of the repair cost on the profit

c_r	Max profit ψ (£)	Warranty price R (£)
1.5	165.05	4.0
2.5	300.05	7.0
3.5	435.05	10.0

6.4.2.2 Technical view

Both the warrantor and buyers may have different knowledge towards the product failure rate λ_p. The warrantor, however, may have more experience and knowledge due to the performance and reliability test performed in the warrantor's laboratory. The warrantor therefore can estimate the product failure more accurately compared to the buyers. As such, we focus on examining the effect of the buyers' failure rates λ on the profit. To this end, the mean of f in Assumption A4 varies from 2 to 6 by varying α from 0.8 to 7.2 and β from 2.5 to 0.83. Table 6-7 illustrates that the more the buyers perceived, the higher the failure rate, the more they are willing to buy the extended warranty and accept a high warranty price. The higher the profit will therefore be gained.

Table 6-7: The effect of the buyers' perceived failure rates on the profit

$\lambda(t)$	Max profit ψ (£)	Warranty price R (£)
2	1509.49	3.5
4	2453.68	5.5
6	3516.33	8.0

6.5 Summary

Warranty policy is mainly designed based on two main factors: the technical-related and commercial-related aspects. In order to set the warranty price, both factors need to be considered. On the one hand, the warrantor mainly provides an extended warranty as a promotional tool to increase the total profit. He may be concerned with the loss resulting from the claims costs exceeding the warranty price. On the other hand, the buyers may seek protection from the unexpected repair costs, but they may also fear the loss resulting from the unused warranty.

The objective of this chapter therefore is to optimise warranty policy by considering the risk preferences of the warrantor and buyers.

Results: this research has achieved the following points:

- Reviewed the literature and found that the design of a warranty policy that captures the risk preferences of a warrantor and buyers simultaneously has received little attention.
- Developed a warranty decision model to capture risk preferences of the warrantor and buyers and then determine the optimal warranty price that maximises the total warrantor's profit. In this model, the risk preferences such as risk aversion and loss aversion for both parties were considered. Then the sensitivity of the total profit to the warranty price and risk preferences for both the warrantor and buyers was analysed.

From the numerical example, the following findings can be made:

- When the buyers are extremely risk-averse or loss aversion to the warranty price, the warrantor may consider less warranty price to increase the proportion of buyers willing to buy the extended warranty and hence to increase the total profit.
- The warrantor's risk attitude has less impact on the profit compared to the buyers' risk attitudes.
- The increase in the repair cost may lead buyers to accept higher warranty price.
- The higher the buyers perceive the product failure rate, the more likely they will be willing to buy the extended warranty.

CHAPTER 7: CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

Warranty has been provided as an insurance mechanism to buyers and as a strong promotional and protection tool to manufacturers to boost their sales volume. As such, the manufacturers offer a long warranty period and/or the use of warranty as a promotional tool can bring benefits such as increasing the sales volume, it can bring various types of risks which may lead to huge losses including the manufacturer's profitability and customers' satisfaction.

Since the provision of warranty is unavoidable due to the marketing purposes, a systematic analysis of WaRM is imperative. WaRM has, however, received very little attention in the literature. This thesis, therefore, has established the concept of WaRM, surveyed the consumer durable manufacturers, developed a WaRM framework, developed a method of warranty risk mitigation, and developed a method to optimise warranty policy, as concluded in the following subsections.

7.1.1 WaRM concept and framework

The literature pertaining to WaRM is comprehensively analysed. This research therefore found that this area has received little attention. Accordingly, it is essential to understanding the real practice of WaRM in the manufacturing companies, for which this thesis answered main questions regarding the used tools to manage warranty risk, the challenges and the top contributors to warranty incidents and costs. A questionnaire of 22 questions was then designed and circulated to the warranty decision makers who represent different organisations in the field of the automotive industry in the UK, which can be generalised to other durable manufacturers.

Based on the analysis of the questionnaire data, It is found that the most widely used tool for identifying warranty risk is the root cause analysis and that conventional tools are unable to identify warranty hazards at the early stage of their emergence. A typical process of identifying warranty hazards relies on analysing warranty claim data, which requires between 30 to 60 days to collect and analyse.

Since time is crucial in managing warranty risk, the WaRM framework was developed to overcome this problem by integrating a new identification tool that can use streaming data as a source of the information. Such data is collected from the buyers' comments posted on the internet, such as social network platforms and specialised forums. To improve the accuracy of this data, the fusion technique was utilised. The analysis of the users' complaints posted on social network platforms and forums, two main hazard categories were uncovered: reliability-related issues and warranty servicing-related issues. The latter accounts for the majority (76%) of the users' complaints, which may indicate that the warranty servicing hazards can have a greater impact on the customers' satisfaction than reliability-related hazards do.

7.1.2 The identification of warranty hazards

On the one hand, the warranty hazard identification tools were integrated into the WaRM framework to detect the unexpected hazards, as mentioned above. On the other hand, the expected warranty hazards or the top contributors to warranty incidents and costs in manufacturing companies need to be identified in order to help the decision makers (DMs) to prepare suitable mitigations plans once they have occurred. To this end, this thesis has comprehensively analysed relevant literature and identified the potential contributors to warranty hazards from two perspectives: the product life cycle perspective and the warranty chain perspective. Additionally, the warranty DMs were surveyed (as part of the aforementioned questionnaire) in order to obtain a better understanding of the top contributors to warranty incidents and cost in the automotive industry in the UK, which can be generalised to other manufacturing companies.

Based on the analysis of the questionnaire data, the top contributors to warranty incidents and costs were identified. Then, two warranty hazard taxonomies were designed to represent the warranty hazard from the two perspectives: product life cycle and warranty chain perspectives. There are some contributors to warranty incidents and costs that have been overlooked in warranty literature, namely:

- human error at different stages of the product life cycle,

- the miscommunication between parties (suppliers, OEM and WSPs),
- manufacturing process capability,
- customers' errors and product modification by suppliers are the top contributors to warranty incidents from all parties' views, and
- customers' fraudulent activity contributes more to warranty costs than WSPs' fraud.

The main findings obtained derived from the existing literature, the analysis of questionnaire data and social network data are provided in the following table:

	Existing literature	Questionnaire	Social media data
Warranty hazard identification and risk assessment **tools**	• SWOT • Analogy • *FMEA* • *Interviews* • *Assumption analysis* • *Document reviews* • *Delphi technique* • *Brainstorming* • *Checklist analysis* • *Influence diagrams* • *Cause and effect diagrams* • *Fault tree analysis* • *Event tree analysis* • *FMECA*	Warranty hazard identification tool: • *Root cause analysis* Warranty risk assessment tool: • *FMECA*	Analysis of the customers' feedback posted on the internet (Twitter and forums)
Top contributors to warranty hazards	• Design-related • Manufacturing-related • Distributing-related • Operating-related • WSP-related	• Human error • Miscommunication between parties	WSP-related issues account for the majority of customers' complaints compared to the design or manufacturing-related issue

7.1.3 Warranty risk mitigation

The preparation of the mitigation plans for the above warranty hazards is crucial to protect warrantors from huge losses and or reputation damage. As such, warranty DMs should consider proactive plans for the mitigation of warranty risks when they have actualised. To this end, this thesis has comprehensively analysed the literature and determines two main challenges in selecting the mitigation plan: the conflict among the decision makers representing different departments and the uncertainty of the outcomes of the mitigation plans. Additionally, the main criteria that can be influenced when a mitigation plan is applied are determined, namely: warranty cost, manufacturer reputation, health and safety and the environmental damage. These criteria, or some, can be influenced if the warranty risk has occurred.

Additionally, a warranty decision tool was developed as a tool to assist warranty DMs in selecting suitable mitigation plans based on different criteria. This model has merged analytic hierarchy process (AHP) method and the cumulative prospect theory (CPT) to overcome, respectively, two issues: (1) the conflict among the decision makers, who represent different departments (e.g. engineering and marketing departments), towards the mitigation plan; (2) the decision makers' attitudes under risk and uncertainty which can affect the final decision.

Since the reference points for mitigation plans costs are subject to change over the warranty period, the time dependence is integrated into the CPT-WaRM model to respond to such changes. Likewise, the DMs' behaviour may change over time, depending on the magnitude of the emerging risk and their previous experiences, which are captured by the time-dependent reference point.

7.1.4 Optimisation of warranty policy

This thesis also developed a warranty policy considering views of warrantor and buyers. In other words, to set the warranty price, the warrantor concerns with the excessive warranty cost, whereas the buyer concerns with the excessive repair cost.

Accordingly, a warranty decision model was developed to capture the risk preferences from both warrantor and buyers and then determine the optimal warranty price that maximises the total warrantor's profit. In this model, the risk preferences such as risk aversion and loss aversion for both parties were considered. Then the sensitivity of the total profit to the warranty price and risk preferences for both the warrantor and buyers was analysed.

From the numerical example, the following findings can be made:

- When the buyers are extremely risk-averse or loss aversion to the warranty price, the warrantor may consider less warranty price, which may increase the proportion of buyers who are willing to buy the extended warranty and hence to increase the total profit.
- The warrantor's risk attitude has less impact on the profit compared to the buyers' risk attitudes.
- The increase in the repair cost may lead buyers to accept higher warranty price.
- The higher the buyers perceive the product failure rate, the more likely they will be willing to buy the extended warranty.

7.2 Objectives and findings

In this section, the objectives of this thesis and findings will be provided.

Objective1: To analyse WaRM literature comprehensively.

> ***Findings***: It has been found that the warranty related issues are scattered in different research areas such as reliability, quality, logistics, marketing, manufacturing and financial planning. Additionally, WaRM is rarely mentioned in the literature and just discussed as a side topic in two papers.

Objective 2: To obtain an in-depth understanding of the existing practices of WaRM in the automotive industry in the UK, specifically focusing on procedures and tools used to manage warranty risk.

> ***Findings:*** Based on the analysis of the questionnaire data, it has been found the following: 1) there is no a specific system to manage warranty risk; 2) organisations are varied in terms of the department that is

responsible for managing warranty. Some organisations assign warranty related issues to the quality department while others assign warranty management to the after-sale department; 3) the most tool used to identify warranty hazard is Root Cause Analysis approach; 4) the most tool used to assess warranty risk is FMECA approach; 5) the prominent limitation of those approaches is a long time required to identify warranty hazard.

Objective 3: To develop a generic WaRM framework.

Findings: Since the existing tools are unable to detect warranty hazards at the early stage of the product life cycle, WaRM is developed to overcome this issue by integrating the analysis of the streaming data posted by customers on different social network platforms and forums. As such, it has been found that the majority of warranty related issues are caused by WSPs activities.

Objective 4: To design a taxonomy for the top contributors to warranty incidents from two perspectives: product life cycle perspective and warranty chain perspective.

Findings: 1) Manufacturing process capability and human error on the part of OEMs are the top contributors to warranty incidents from the OEMs' and dealers' perspectives; 2) customers' errors and the modification of products by suppliers are the top contributors to warranty incidents from all parties' perspectives; 3) customers' fraud contributes more to warranty costs than WSPs' fraud, which contradicts the statement that most fraudulent claims are attributable to warranty-service agents (Kurvinen et al., 2016); 4) collaboration among parties is limited, particularly in terms of access to warranty-related data between suppliers, OEMs and dealers; 5) customers are the highest contributor to product failure, compared to other parties; 6) lack of training is the top contributor to human error. Based on the findings, two taxonomies were designed from two perspectives: product life cycle and warranty chain perspectives. The main finding from the first perspective is the role of the human error at different stages of the product life cycle, while the main finding from the second perspective is the lake of collaboration between parties (suppliers, OEM and dealers).

Objective 5: To develop a warranty decision model to aid warranty decision makers (DMs) in assessing and mitigating warranty risk.

Achievement: 1) Developed a decision model which has merged analytic hierarchy process (AHP) method and the cumulative prospect theory (CPT) to overcome, respectively, two issues: (a) the conflict among the decision makers, and (b) the uncertainty of the outcomes of the mitigation plan and its impact on the decision makers attitudes; 2) Various methods have been proposed to determine the reference point of the CPT-WaRM model, as this is the key to deriving utility gains and losses; 3) since the reference point for mitigation plans costs are subject to change over the warranty period, the time dependence is integrated into the CPT-WaRM model to respond to such changes. Likewise, the DMs' behaviour may change over time, depending on the magnitude of the emerging risk and their previous experiences. As such, such behaviour is considered and treated as time-dependent parameters.

Objective 6: To develop a model that optimises warranty policy by considering the warrantor's and buyers' risk attitudes towards the profit and repair cost, respectively.

Achievement: Developed a warranty decision model to capture risk preferences of the warrantor and buyers and then determine the optimal warranty price that maximises the total warrantor's profit. In this model, the risk preferences such as risk aversion and loss aversion for both parties were considered. Then the sensitivity of the total profit to the warranty price and risk preferences for both the warrantor and buyers was analysed.

7.3 Theoretical and practical implications

The theoretical implications of this thesis are listed as follows:

- Develop a framework for WaRM.

- Determine the top contributors to warranty hazards and hence two taxonomies were developed.
- Develop a decision model to select the optimal mitigation plan to respond to the emergent warranty risk.
- Develop a mathematical model to optimise warranty price considering the buyer and warrantor point of views towards the expected repair cost and claims cost, respectively.

The practical implications of this thesis are listed as follows:

- The WaRM framework will provide warranty practitioners with the required guidelines to manage warranty risks.
- The result of using the streaming data as an early warning tool has shown its efficiency in highlighting the warranty issues.
- The warranty hazards taxonomies might help warranty practitioners in improving the process, procedures or technologies which are required to reduce the occurrence of warranty risks.
- The development of WaRM-CPT model may aid the decision makers in selecting the optimal mitigation plan to respond to an emergent warranty risk.
- The determination of the optimal warranty price can be achieved when the warrantor and buyers views are considered. To this end, a mathematical model is provided.

7.4 Future work

The following future work can be investigated:

- The use of advanced technology such as big data may help not only in identifying hazards at the early stage of the product life cycle but in assessing the associated risks and suggesting a suitable mitigation plan. This can be achieved when different data sources are linked. For example, analysing the stream data and visualise it may provide an early warning tool as mentioned in this thesis. One may improve this step by linking the streaming data with other systems to respond to the emerged risk. For example, when a hazard has been identified and assessed, the system may evaluate different mitigation plans based on the available resources listed in the ERP system. Additionally, the mitigation plan can be visualised and tracked to ensure its efficiency.

- Based on the questionnaire analysis, one of the top warranty hazards is the miscommunication between the main agents in the automotive industry, mainly: suppliers, OEM, distributors, dealers and customers. This problem can have an impact on both the OEM and suppliers. No failure found (NFF), for example, is one of the top contributors to warranty cost which mainly affected by such a hazard. To obtain a better understanding of the communication problem and consequences on all parties, one may simulate the behaviour of those agents regarding some factors of concern. The impact of these factors on NFF can be seen from two points of view: OEMs' and suppliers' points of view.
- A warranty model that was developed in this thesis to optimise warranty price has considered one dimension (warranty age t) as a base to determine the reference point from buyers' and a manufacturer's perspectives. One may consider the two-dimensional warranty (age and usage) which is widely provided by consumer durable manufacturers. For example, automotive manufacturers may offer three-years warranty or 60k mile, whichever comes first. The buyers may have different views regarding the offered warranty policy, where some may concern about the usage limit more than the age limit and vice versa. Taxi driver, for example, may focus more on the usage limit rather than the age.

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Appendix A: Data collection from the social media

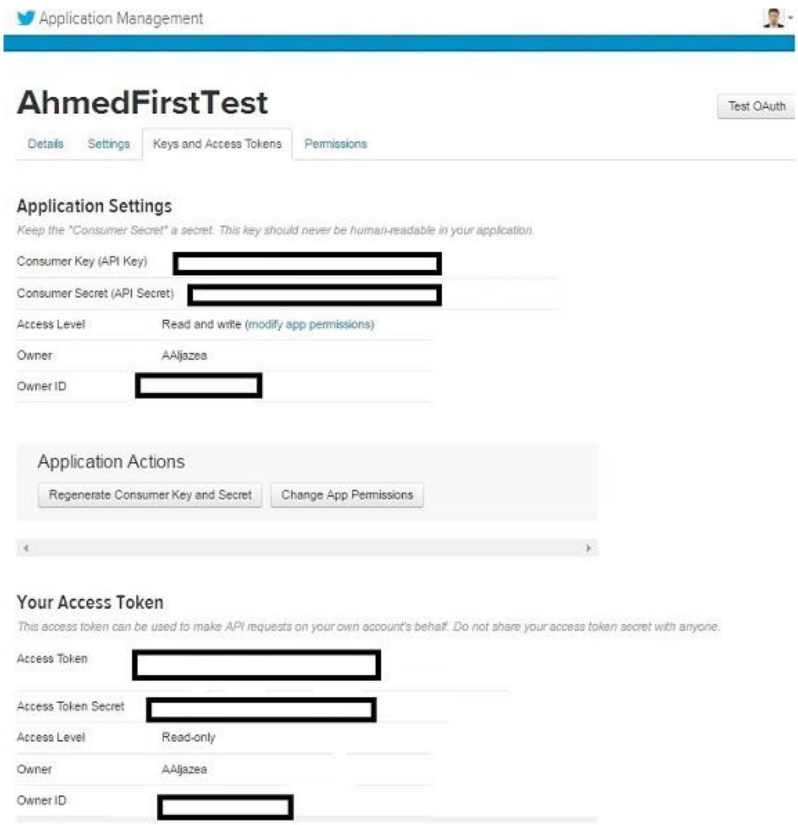

Figure A-1: API account on Twitter

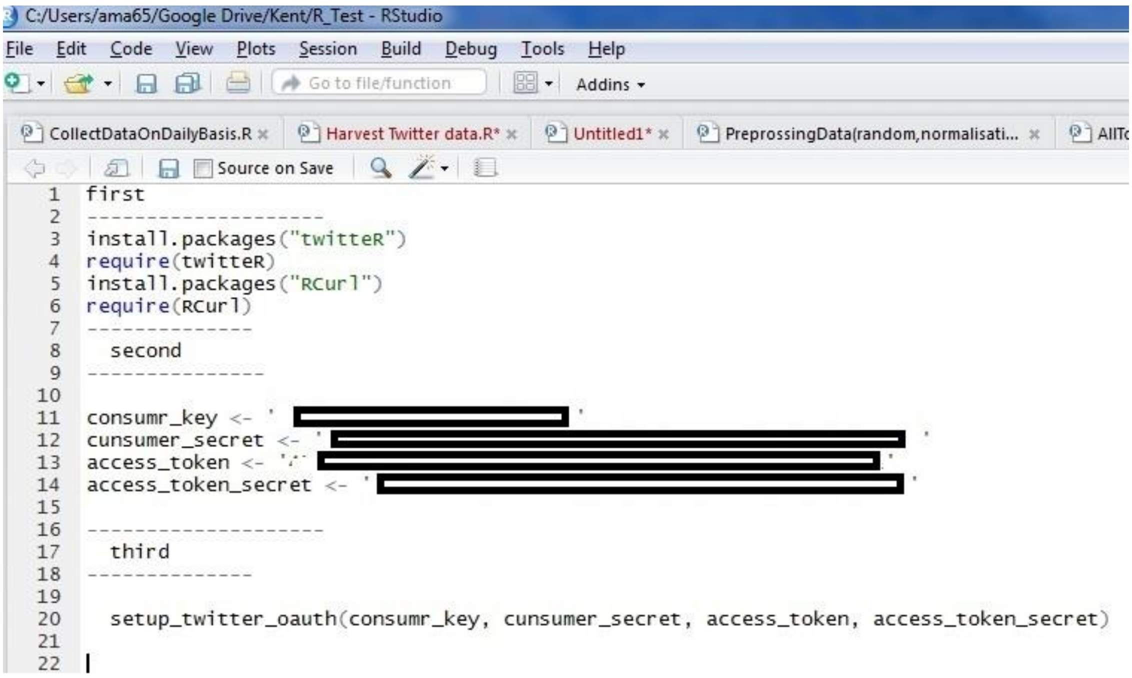

Figure A-2: Authentication code

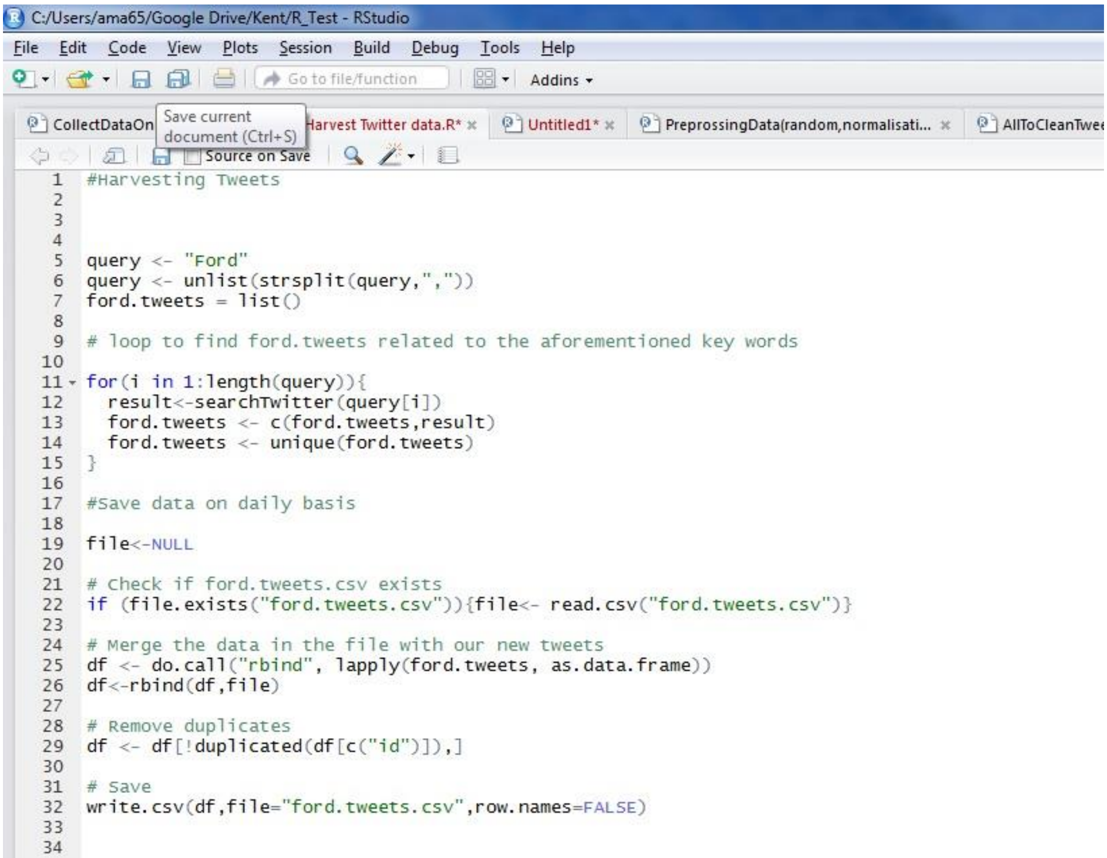

Figure A-3: Gathering Twitter data and update the existing file

Appendix B: Survey (Chapter 3&4)

Welcome to the research study!

Dear Participant,

May I invite you to participate in a research study entitled: “Warranty Management”. I am currently a PhD student, studying at the University of Kent. The purpose of the research is to improve warranty management in relation to risk management. The enclosed questionnaire has been designed to collect information on warranty-associated issues in the automotive industry in the United Kingdom.

Your participation in this research project is voluntary. Please be assured that your responses will be kept completely confidential. If you agree to participate in this project, please click the button below and answer the questions on the questionnaire as best you can. It should take approximately 12 minutes to complete.

Please note that this survey will be best displayed on a laptop or desktop computer. Some features may be less compatible for use on a mobile device.

Should you have any questions about this survey, please feel free to contact me, Mr Ahmed Aljazea, ama65@kent.ac.uk.

Thank you very much for your participation in this research.

Kind Regards,
Ahmed Aljazea

- ○ I consent, begin the study
- ○ I do not consent, I do not wish to participate

Q1.1 What is your current management level?

- ○ High-level management (1)
- ○ Middle-level management (2)
- ○ Low-level management (3)
- ○ Other (4) ____

Q1.2 How many years of experience do you have in this role?

- ○ <3 (1)
- ○ 3-6 (2)
- ○ 7-10 (3)
- ○ >10 (4)

Q1.3 What organisation are you and your team a part of?

- ○ Supplier (1)
- ○ Original equipment manufacturer (OEM) (2)
- ○ Dealer (3)
- ○ Other (4) ____

Q1.4 What is the size of your parent organisation?

- ○ > £5 billion (1)
- ○ £1-£5 billion (2)
- ○ £500-£999 million (3)
- ○ £100-£499 million (4)
- ○ < £100 million (5)

Q2.1 What are the top contributors to warranty incidents?

	Very unlikely	Unlikely	Equally likely	Likely	Very likely
Faulty product design	◯	◯	◯	◯	◯
Manufacturing process capability	◯	◯	◯	◯	◯
Assembly process capability at supplier(s)	◯	◯	◯	◯	◯
Assembly process capability at OEM	◯	◯	◯	◯	◯
Distribution related issues	◯	◯	◯	◯	◯
Diagnosis related issues	◯	◯	◯	◯	◯
Human error or violation at suppliers	◯	◯	◯	◯	◯
Human error at OEM (intentional or unintentional) (7)	◯	◯	◯	◯	◯
Human error at dealers (intentional or unintentional)	◯	◯	◯	◯	◯
Customers error (intentional or unintentional)	◯	◯	◯	◯	◯
Product modification at suppliers	◯	◯	◯	◯	◯
Miscommunication between OEM and supplier(s)	◯	◯	◯	◯	◯
Other	◯	◯	◯	◯	◯

Q2.2 In addition to the above listed contributors, what are the other top contributors to warranty costs?

	Very unlikely	Unlikely	Equally likely	Likely	Very likely
Material movement and its storage expenses	○	○	○	○	○
Provision of warranty services (labour costs, etc.)	○	○	○	○	○
Dealer fraud	○	○	○	○	○
Customers fraud	○	○	○	○	○
Different exchange rates (spare parts)	○	○	○	○	○
Warranty administration	○	○	○	○	○
Other	○	○	○	○	○

Q2.3 In relation to warranty services provision, what are the top contributors to customers' dissatisfaction?

	Very unlikely	Unlikely	Equally likely	Likely	Very likely
Customer care)	○	○	○	○	○
Service time	○	○	○	○	○
Service quality	○	○	○	○	○
Other	○	○	○	○	○

Q3.1 Which of the following activities (or part of) are outsourced?

- ☐ Product designing
- ☐ Product manufacturing
- ☐ Distribution
- ☐ Warranty services
- ☐ Don't know

Q3.2 Rate the following parties according to their contributions to the product failures.

Suppliers	☆	☆	☆	☆	☆
Original equipment manufacturer (OEM)	☆	☆	☆	☆	☆
Dealers	☆	☆	☆	☆	☆
Customers	☆	☆	☆	☆	☆
Others	☆	☆	☆	☆	☆

Q3.3 To what extent would/will you be able to access warranty-related data (in real-time or almost)?

	Not at all	To a very little extent	To some extent	To a great extent	To a very great extent
Suppliers	○	○	○	○	○
OEM	○	○	○	○	○
Dealers	○	○	○	○	○

Q4.1 What is the current average warranty period offered by your organisation?

- ◯ 1 year
- ◯ 2 years
- ◯ 3 years
- ◯ 4 years
- ◯ 5 years
- ◯ >5 years
- ◯ Don't know

Q4.2 Please choose the appropriate value range in British Pound (£)

	<100	100 - 200	201 - 300	301 - 400	401 - 500	501 - 600	601 - 700	701 - 800	801 - 900	>1000
The average WARRANTY COST/vehicle	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
The average RESERVE FUND/vehicle for the forthcoming warranty claims	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Q4.3 What is the procedure used to determine WARRANTY PRICES? and who makes the final decision?

____

Q4.4 What is the procedure used to determine WARRANTY DURATION? and who makes the final decision?

____

Q5.1 Which tools are used by your organisation to identify warranty hazards? (Tick all that apply)

- ☐ Check List Analysis
- ☐ Information Gathering Technique
- ☐ Assumption
- ☐ Brainstorming
- ☐ Interview
- ☐ Delphi Technique
- ☐ Root Cause Analysis
- ☐ Documentation Reviews
- ☐ SWOT Analysis (Strengths, Weaknesses, Opportunities and Threats)
- ☐ Other (please list them below)

____

Q5.2 Which model/approach/technique is used to assess warranty risks, e.g., to assess the probability of the occurrence of a hazard? (Please tick all that apply)

- ☐ Failure Tree Analysis (FTA)
- ☐ Failure Mode and Effect Analysis (FMEA)
- ☐ Failure Mode Effect and Criticality Analysis (FMECA)
- ☐ Delphi Technique
- ☐ Other (please list them below)

____

Q5.3 Once a warranty incident has occurred, what are the top criteria that can be severely influenced?

	Non	Minor	Medium	Serious	Catastrophic
Warranty costs (1)	○	○	○	○	○
Manufacturer's reputation (2)	○	○	○	○	○
Human safety (3)	○	○	○	○	○
Environment (4)	○	○	○	○	○
Other (5)	○	○	○	○	○

Q5.4 What are the limitations of the existing tool(s) used to assess warranty risks?

____

Q5.5 What is/are the existing tool(s) used to mitigate warranty risks?

____

Q6.1 At your organisation, what are the top contributors to warranty incidents as result of human error?

____

Q6.2 What are the top contributors to human errors caused warranty incidents?

	Very unlikely	Unlikely	Equally likely	Likely	Very likely
Workplace (space, environment, etc.) (1)	○	○	○	○	○
Product design (required equipment, complexity, etc.) (2)	○	○	○	○	○
Observation capability (3)	○	○	○	○	○
Experience needed and skills (4)	○	○	○	○	○
Lack of training (5)	○	○	○	○	○
Other (6)	○	○	○	○	○

Q6.3 What approaches can be used to reduce human error? (Please tick all that apply)

☐ Improve management systems (documentation control, investigation management,..)

☐ Improve procedures (accuracy, human-engineered, available and enforceable)

☐ Provide an adequate workplace environment

☐ Provide regular training

☐ Improve immediate supervision (need to have supervisors on the floor, not in the office)

☐ Improve communication (e.g. need to be informed what should be achieve daily,..)

☐ Improve individual performance (evaluate conditions that might influence them,..)

☐ Other ____

Appendix C: AHP Survey and global utility scores

C.1: AHP Survey

Dear Participant,

May I invite you to participate in a research study, entitled: “Warranty Risk Management”? I am currently a PhD student, studying at the University of Kent. The purpose of the research is to improve warranty risk management. The enclosed questionnaire aims to collect information on warranty-associated issues in the automotive industry. Your participation in this research project is voluntary and highly appreciated. Please be assured that your responses will be kept completely confidential. If you agree to participate in this project, please answer the questions. It should take approximately 7 minutes to complete.

Should you have any questions about this survey, please feel free to contact me, Mr Ahmed Aljazea, ama65@kent.ac.uk.

Thank you very much for your participation.

Kind Regards,

Ahmed Aljazea

Introduction

This questionnaire is designed to gain a better understanding of the response of experts, in the automotive industry, to different warranty incidents (e.g. responding to unexpected products' failures). They may consider different criteria and then choose one of the multiple mitigation plans to deal with warranty claim incidents.

This questionnaire therefore uses a pairwise comparison matrix, which is widely used to compare alternatives (mitigation plans, in this questionnaire) in pairs, to judge which entry is preferred over others.

In this questionnaire, we need to rank different warranty risk mitigation plans, considering the impact of different warranty incidents on different decision criteria.

The warranty claims are considered as an example of warranty incidents. In this questionnaire, we use a case study of General Motors (GM) recall in 2014. GM recalled vehicles (Chevrolet Cobalt, Pontiac G5, Saturn Ion, Chevrolet HHR, Pontiac Solstice and Saturn Sky) model year between 2005 and 2010 due to the following failures:

1) Ignition switch: The switch can accidentally be switched off which leads to the engine shut off and prevent the airbag working in the case of a crash.
2) Faulty brake lights.
3) Defective steering components: A problem in the software that controls the power steering which can lead to losing control.

The criteria that may be influenced by the above warranty incidents are:

1) Warranty cost: The cost incurred directly (repair cost) and indirectly (fines and civil settlements, etc.). In this questionnaire, however, the direct cost is only considered.
2) Manufacturer's reputation and image: Due to the occurrence of one or more of such incidents, the manufacturer's reputation may be influenced.
3) Environmental damage: The decision to replace the failed part may consider the negative impact on the environment.
4) Health and safety: The effect on the health of the public or the drivers' and passengers' safety.

We assumed that there are prescheduled three mitigation plans, namely:

1) Recall all products: manufacturer are required to may recall defective products which already claimed or expected to claim due to reliability-related issues or safety-related issues. This recall is for 30 million vehicles and the cost is around $4.1 billion.
2) Partial recall with a refund: The manufacturer may recall products manufactured in a certain period due to a safety or reliability related defect

and provide customer with a refund for the repair costs they already have spent. The estimated cost for this mitigation plan is $159,900,000.

3) Partial recall: A manufacturer may recall products manufactured in a certain period due to a safety or reliability related defect. This recall is for 780,000 vehicles and the cost is around $106,600,000.
4) Do nothing: It means that the manufacturer will not recall defective products and will only perform the routinely scheduled warranty services. The cost of this plan is only the expected warranty cost ($300 per vehicle). Note, this cost is for the whole warranty incidents occurred in warranty period, whereas the above costs in mitigation plans 1) and 2) are the cost incurred due to rectifying the unexpected warranty incidents (Ignition switch, Faulty brake lights and steering).

How to assign your preference?

The following pairwise matrices allow you to assign your preference of one element (on the first column of the matrix) over the corresponding one (on the last column of the matrix). You can choose only one option for each comparison between the two elements based on a scale ranged from 1 to 9, where 1 is equally preferred and 9 is absolutely preferred. If you prefer the element on the lift side (i.e., the first column) over the one on the right (i.e., the last column), please choose the answer from the scale ranged from **9** to **1** on the left side, or if you prefer the element on the right, please choose the answer from the scale ranged from **1** to **9** on the right. Otherwise, you can choose **1** if both elements are equally preferred.

1) Pairwise comparison of the criteria with respect to the goal (Ignition switch),

Warranty incident: Ignition switch.																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Warranty cost																		Manufacturer's reputation & image
Warranty cost																		Environmental damage
Warranty cost																		Health & safety
Manufacturer's reputation & image																		Environmental damage
Manufacturer's reputation & image																		Health & safety
Environmental damage																		Health & safety

1.1) Pairwise comparison of the mitigation plans with respect to the criterion (Warranty Cost).

Warranty incident: Ignition switch. Criterion: Warranty cost.																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

1.2) Pairwise comparison of the mitigation plans with respect to the criterion (Manufacturer's reputation & image).

Warranty incident: Ignition switch. Criterion: *Manufacturer's reputation & image*.																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

1.3) *Pairwise comparison of the mitigation plans with respect to the criterion (Environmental damage),*

Warranty incident: Ignition switch. Criterion: *Environmental damage*.																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

1.4) Pairwise comparison of the mitigation plans with respect to the criterion (Health & safety).

Warranty incident: Ignition switch. Criterion: *Health & safety*.																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

2) Pairwise comparison of the criteria with respect to the goal (Faulty brake lights)**.**

Warranty incident: Faulty brake lights.																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Warranty cost																		Manufacturer's reputation & image
Warranty cost																		Environmental damage
Warranty cost																		Health & safety
Manufacturer's reputation & image																		Environmental damage
Manufacturer's reputation & image																		Health & safety
Environmental damage																		Health & safety

2.1) Pairwise comparison of the mitigation plans with respect to the criterion (Cost).

Warranty incident: Faulty brake lights. Criterion: ***Warranty cost.***																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

2.2) Pairwise comparison of the mitigation plans with respect to the criterion (Manufacturer's reputation & image).

Warranty incident: Faulty brake lights. Criterion: ***Manufacturer's reputation & image.***																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

2.3) Pairwise comparison of the mitigation plans with respect to the criterion (Environmental damage).

Warranty incident: Faulty brake lights. Criterion: ***Environmental damage.***																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

2.4) Pairwise comparison of the mitigation plans with respect to the criterion (Health & safety).

Warranty incident: Faulty brake lights. Criterion: *Health & safety.*																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

3) Pairwise comparison of the criteria with respect to the goal (Defective steering components).

Warranty incident: Defective steering components.																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Warranty cost																		Manufacturer's reputation & image
Warranty cost																		Environmental damage
Warranty cost																		Health & safety
Manufacturer's reputation & image																		Environmental damage
Manufacturer's reputation & image																		Health & safety
Environmental damage																		Health & safety

3.1) Pairwise comparison of the mitigation plans with respect to the criterion (Warranty cost).

Warranty incident: Defective steering components. Criterion: ***Warranty cost.***																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

3.2) Pairwise comparison of the mitigation plans with respect to the criterion (Manufacturer's reputation & image).

Warranty incident: Faulty brake lights. Criterion: ***Manufacturer's reputation & image.***																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

3.3) Pairwise comparison of the mitigation plans with respect to the criterion (Environmental damage).

Warranty incident: Defective steering components. Criterion: *Environmental damage.*																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

3.4) Pairwise comparison of the mitigation plans with respect to the criterion (Health & safety).

Warranty incident: Defective steering components. Criterion: *Health & safety.*																		
Raw	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Column**
Recall																		Partial recall with a refund
Recall																		Partial recall
Recall																		Do nothing
Partial recall with a refund																		Partial recall
Partial recall with a refund																		Do nothing
Partial recall																		Do nothing

C.2: Global Score

Table C-7-1: The potential roots and their GLOBAL score

# Possibilities	t_1	t_2	t_3	t_4	t_5	t_6	G. Score
1	C	C	B	B	B	A	-10.011
2	B	A	A	A	C	C	-8.367
3	A	A	B	A	C	B	-9.045
4	C	C	B	B	B	A	-10.011
5	C	B	C	A	C	C	-9.025
6	B	C	C	B	B	B	-10.180
7	C	C	C	A	B	C	-9.417
8	C	C	B	C	C	B	-9.986
9	C	A	B	A	B	A	-8.938
10	A	C	B	C	C	B	-9.931
11	B	C	B	C	B	A	-9.926
12	B	B	C	B	C	B	-9.569
13	A	B	A	B	B	B	-9.192
14	C	C	B	B	C	B	-9.586
15	A	C	C	B	A	B	-10.314
16	A	B	B	C	B	C	-9.049
17	B	B	C	C	C	A	-10.430
18	B	B	A	A	C	B	-8.969
19	A	A	B	B	C	A	-9.042
20	B	C	C	C	A	B	-10.524
21	A	B	A	B	B	A	-9.414
22	B	C	C	C	C	B	-10.801
23	B	B	C	A	C	B	-9.441
24	A	B	A	B	B	C	-8.641
25	B	B	A	B	C	B	-8.964
26	C	A	A	B	B	A	-8.608
27	C	C	C	B	A	C	-9.999

28	A	C	B	B	B	A	-9.956
29	B	B	B	C	A	A	-9.650
30	C	C	C	A	B	B	-9.968
31	B	A	C	B	B	C	-8.839
32	C	A	C	B	B	C	-8.483
33	C	B	C	B	A	B	-9.660
34	B	C	B	B	C	A	-9.560
35	A	B	B	C	A	B	-9.541
36	B	A	B	A	A	B	-9.138
37	B	C	B	A	B	B	-9.619
38	C	B	B	A	B	B	-9.250
39	C	A	A	C	B	B	-8.466
40	A	A	B	B	A	C	-8.966
41	C	A	B	C	B	B	-8.802
42	A	B	C	B	B	C	-9.247
43	C	B	A	C	B	B	-9.007
44	B	B	B	A	A	B	-9.556
45	B	B	C	A	B	A	-9.720
46	C	C	A	A	B	A	-9.351
47	B	A	C	B	B	B	-9.389
48	B	B	B	B	A	B	-9.723
49	C	B	C	B	B	A	-9.755
50	B	C	B	C	C	B	-9.923
51	C	B	B	B	C	B	-9.154
52	B	B	B	B	B	B	-9.597
53	B	A	A	B	B	C	-8.191
54	C	C	B	B	A	B	-9.916
55	A	B	B	A	B	B	-9.514
56	B	A	A	B	B	A	-8.963
57	A	B	B	B	B	A	-9.844
58	B	B	B	C	A	B	-9.516

59	A	C	B	B	A	B	-9.861
60	B	A	B	C	A	B	-9.099
61	B	A	C	B	B	B	-9.389
62	B	A	C	B	C	B	-9.186
63	B	B	C	C	B	B	-10.175
64	A	C	B	C	C	A	-9.967
65	A	A	C	A	C	C	-8.911
66	C	B	C	A	B	B	-9.259
67	A	A	A	C	A	B	-8.792
68	B	B	A	B	B	C	-8.616
69	B	B	C	B	C	A	-9.605
70	A	B	B	C	B	B	-9.600
71	B	B	B	B	C	A	-9.430
72	B	C	B	B	C	C	-9.346
73	C	B	A	A	B	B	-8.787
74	B	B	B	B	A	B	-9.723
75	B	B	B	A	B	B	-9.489
76	B	A	B	A	B	B	-9.072
77	B	B	B	C	C	C	-9.616
78	C	B	B	A	B	B	-9.250
79	B	B	C	A	B	C	-8.947
80	A	B	B	B	B	B	-9.622
81	A	A	B	B	C	A	-9.042
82	B	C	B	B	C	B	-9.524
83	B	A	C	B	B	C	-8.839
84	B	C	A	C	A	A	-9.362
85	B	B	B	B	A	A	-9.857
86	B	B	C	B	B	B	-9.772
87	A	B	B	B	B	C	-9.071
88	B	B	B	A	B	B	-9.489
89	C	B	B	C	A	C	-8.907

90	B	B	B	B	B	B	-9.597
91	B	B	C	B	C	B	-9.569
92	B	A	A	B	A	A	-9.002
93	B	A	A	C	B	C	-8.270
94	B	C	B	B	B	B	-9.727
95	A	B	C	C	C	A	-10.455
96	C	C	C	A	B	C	-9.417
97	B	A	A	C	B	A	-9.042
98	A	A	A	B	B	B	-8.772
99	C	C	B	C	B	A	-9.989
100	C	B	B	B	B	C	-8.807
101	A	B	B	B	A	B	-9.748
102	B	B	A	B	A	B	-9.293
103	B	B	B	C	A	B	-9.516
104	B	B	C	A	A	C	-9.195
105	B	B	C	B	A	A	-10.032
106	B	C	B	C	C	B	-9.923
107	B	A	C	A	A	B	-9.182
108	A	C	C	C	C	C	-10.632
109	A	B	C	A	C	B	-9.467
110	B	B	A	B	B	C	-8.616
111	B	A	C	A	C	B	-9.058
112	C	B	A	C	B	B	-9.007
113	C	B	B	B	B	B	-9.358
114	C	A	B	C	A	B	-8.744
115	B	B	A	C	B	B	-9.246
116	A	A	A	B	B	B	-8.772
117	A	A	B	A	B	A	-9.323
118	B	B	C	B	A	B	-9.899
119	B	A	B	B	A	B	-9.306
120	B	B	B	B	A	A	-9.857

121	B	B	C	A	C	B	-9.441
122	B	C	C	C	B	C	-10.032
123	C	C	A	A	C	C	-8.895
124	B	C	A	C	B	B	-9.287
125	B	A	C	C	B	B	-9.792
126	B	B	B	B	C	B	-9.394
127	C	B	B	B	A	B	-9.484
128	B	A	A	B	B	B	-8.742
129	C	C	A	B	B	B	-9.271
130	B	B	C	A	A	B	-9.565
131	B	C	C	B	B	A	-10.401
132	B	B	C	B	B	C	-9.222
133	C	B	B	A	B	A	-9.471
134	B	B	A	C	B	C	-8.695
135	A	A	C	C	C	B	-10.041
136	B	B	B	C	B	B	-9.575
137	B	B	A	B	C	B	-8.964
138	B	C	A	A	B	C	-8.516
139	B	B	C	B	B	B	-9.772
140	B	B	C	B	B	A	-9.994
141	B	B	C	A	B	C	-8.947
142	C	A	B	B	A	B	-8.951
143	B	B	B	B	B	B	-9.597
144	B	B	B	C	B	C	-9.024
145	A	A	B	C	A	B	-9.129
146	C	B	B	C	A	A	-9.411
147	A	C	C	C	B	B	-10.590
148	C	B	A	B	B	A	-9.149
149	C	C	C	A	C	A	-9.947
150	C	B	C	C	C	B	-10.155
151	C	B	B	B	A	B	-9.484

152	B	B	C	B	A	C	-9.529
153	A	B	B	A	B	A	-9.736
154	B	B	C	C	C	A	-10.430
155	B	C	A	C	C	B	-9.505
156	B	B	B	B	C	B	-9.394
157	C	C	A	B	B	B	-9.271
158	C	A	A	C	B	B	-8.466
159	B	B	B	B	B	B	-9.597
160	B	C	C	B	C	C	-9.799
161	A	B	B	B	C	B	-9.419
162	C	B	A	B	B	A	-9.149
163	B	C	C	B	C	C	-9.799
164	B	A	A	B	C	C	-8.361
165	A	A	C	B	B	C	-8.869
166	B	C	B	A	B	B	-9.619
167	B	A	A	B	B	B	-8.742
168	A	A	B	B	A	A	-9.470
169	C	A	C	B	C	A	-8.867
170	B	A	C	B	B	A	-9.611
171	C	B	B	B	B	A	-9.579
172	B	B	B	B	A	C	-9.353
173	C	B	A	A	A	B	-8.853
174	B	A	B	A	A	B	-9.138
175	C	B	A	C	C	B	-9.225
176	B	C	B	B	B	C	-9.176
177	B	B	C	A	C	C	-9.264
178	A	C	B	B	A	A	-9.995
179	C	B	B	C	B	B	-9.336
180	B	B	B	A	C	C	-9.255
181	B	A	B	B	B	B	-9.179
182	C	B	B	B	B	A	-9.579

183	B	C	B	B	B	B	-9.727
184	B	C	B	C	B	C	-9.154
185	C	B	B	A	B	C	-8.699
186	B	B	C	C	B	B	-10.175
187	C	C	B	B	A	B	-9.916
188	B	B	B	B	B	B	-9.597
189	A	B	B	B	B	C	-9.071
190	A	B	A	B	A	A	-9.452
191	A	B	A	B	B	A	-9.414
192	A	B	C	B	A	C	-9.554
193	A	C	C	C	C	C	-10.632
194	C	B	A	B	A	A	-9.188
195	A	B	A	B	B	C	-8.641
196	B	A	B	B	A	B	-9.306
197	B	A	B	C	A	B	-9.099
198	C	C	B	B	C	B	-9.586
199	C	B	C	B	B	A	-9.755
200	C	B	C	B	B	C	-8.982
201	B	A	C	A	B	A	-9.337
202	A	C	B	C	A	A	-9.788
203	A	B	A	C	A	C	-8.842
204	C	B	A	B	A	C	-8.684
205	C	A	B	B	B	A	-9.046
206	B	C	B	A	B	B	-9.619
207	B	B	C	C	C	A	-10.430
208	B	C	C	A	B	B	-9.905
209	A	B	B	B	C	A	-9.455
210	C	B	C	B	B	C	-8.982
211	B	B	B	A	B	C	-8.938
212	B	B	B	B	A	B	-9.723
213	C	B	A	B	B	B	-8.928

214	B	B	B	A	B	C	-8.938
215	C	C	C	B	A	B	-10.369
216	C	B	B	C	C	B	-9.554
217	C	B	B	B	C	B	-9.154
218	B	C	C	B	B	B	-10.180
219	A	B	A	A	B	A	-9.272
220	B	B	B	B	A	C	-9.353
221	B	A	A	C	B	A	-9.042
222	B	C	B	B	B	B	-9.727
223	B	B	B	B	A	C	-9.353
224	B	A	C	B	C	B	-9.186
225	A	C	B	B	A	B	-9.861
226	B	B	B	B	C	C	-9.216
227	B	B	A	A	B	B	-9.026
228	C	C	B	B	A	C	-9.546
229	B	B	A	B	C	B	-8.964
230	B	C	A	B	C	A	-9.041
231	A	B	B	C	C	A	-9.855
232	A	B	A	C	B	B	-9.271
233	A	B	B	B	B	B	-9.622
234	B	B	C	B	B	B	-9.772
235	B	B	B	B	B	A	-9.818
236	B	B	C	B	B	A	-9.994
237	B	C	B	B	B	B	-9.727
238	B	A	B	A	B	B	-9.072
239	C	B	A	A	B	B	-8.787
240	C	A	B	B	B	A	-9.046
241	A	B	B	C	C	B	-9.818
242	B	B	C	A	A	B	-9.565
243	A	B	C	B	C	A	-9.631