Towards a support system for simulation aided-design in the development phase of automotive industry

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Towards a Support System for Simulation-Aided Design in the Development Phase of Automotive Industry

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Titre : Vers un système de soutien à la conception assistée par la simulation dans la phase de développement de l'industrie automobile

Mots clés : conception technique, conception assistée par la simulation, développement d'ontologies, processus à forte intensité de connaissances, gestion des connaissances, extraction de connaissances, industrie automobile

Résumé : Cette recherche vise à soutenir le processus de conception assistée par la simulation dans la phase de développement des véhicules. La phase de développement est soutenue par la modélisation et la simulation et consiste à affiner itérativement les spécifications de conception, à évaluer les performances du véhicule et à résoudre les problèmes de conception rencontrés. Nous sommes dans un contexte de conception assistée par la simulation puisque la décision concernant la conception du véhicule s'appuie principalement sur la simulation. Nous nous concentrons principalement sur le processus d'analyse de la simulation en crash. La conception assistée par la simulation est une activité à forte intensité de connaissances car elle dépend principalement des connaissances des analystes et des experts.

Tout d'abord, nous identifions les difficultés et les défis rencontrés dans le processus de résolution des problèmes de conception. Nous menons une étude empirique pour mieux comprendre le processus de conception implémenté dans l'entreprise. Les défis industriels ont été identifiés sur la base d'une analyse à deux niveaux, celui de l'équipe d'analystes et celui du projet. Les défis comprennent l'accès et le partage des connaissances, la cohérence des données et la formalisation des approches et du processus. L'étude empirique confirme que la connaissance est un facteur clé pour l'amélioration du processus de conception assistée par la simulation.

De plus, nous proposons une ontologie pour formaliser les connaissances cruciales pour la simulation en crash. Nous l'appelons ontologie de post-traitement de la simulation en crash. Cette ontologie formalise les connaissances relatives aux phases de post-traitement et d'interprétation des résultats de la simulation en crash automobile. L'objectif est de formaliser les connaissances relatives à la résolution des problèmes et à la proposition de modifications de conception du véhicule.

Par ailleurs, la nature multidisciplinaire, hautement collaborative et contextuelle de la conception technique a soulevé le besoin de soutenir le développement de produits intégrés et collaboratifs. La réussite de la conception technique collaborative dépend de la capacité à gérer et à partager les connaissances techniques. Par conséquent, la gestion des connaissances joue un rôle crucial dans la compétitivité des entreprises, d'où notre proposition d'une approche, intégrée et collaborative, de la gestion des connaissances basée sur l'ontologie. Nous développons ainsi un système de management des connaissances basé sur l'ontologie, pour soutenir le processus de conception, en mettant l'accent sur l'extraction des connaissances. Nous proposons une architecture pour le système de soutien et une implémentation pour son évaluation. Nous avons démontré l'efficacité du système de soutien pour saisir les connaissances techniques, faciliter la résolution des problèmes de conception et faire gagner du temps aux analystes.

Title : Towards a Support System for Simulation Aided-Design in the Development Phase of Automotive Industry

Keywords : engineering design, simulation-aided design, ontology development, knowledge intensive process, knowledge management, knowledge retrieval, automotive industry

Abstract : This research aims to support the simulation-aided design process in the development phase of vehicles. The development phase is supported by modelling and simulation and consists of iteratively refining the design specifications, evaluating the vehicle's performance and solving design issues encountered. We are in a context of simulation-aided design since the decision about the vehicle design is mainly based on simulation. In this thesis research, our focus is mainly on the crash simulation analysis process. The simulation-aided design is knowledge-intensive; it depends heavily on the knowledge of analysts and experts.

First, we identify the difficulties and challenges encountered in the design issue resolution process. Therefore, we conduct an empirical study to understand better the simulation-aided design process in use in the company. The industrial challenges have been identified based on a two-level analysis, the analysts' team level and the project level. The challenges include the access and share of knowledge, data consistency, and the formalisation of approaches and the process. The empirical study confirms that knowledge is a key factor for the improvement of the simulation-aided design process.

Moreover, we propose an ontology to formalise crucial knowledge for car crash simulation. The ontology we have developed is called the Crash Simulation Post-Processing Ontology. This ontology formalises knowledge related to the post-processing phase of car crash simulation and the interpretation of simulation results. The aim is to formalise knowledge related to the resolution of design issues and the proposal of design changes.

Furthermore, the multidisciplinary, highly collaborative and contextual nature of engineering design has raised the need to support integrated and collaborative product development. Successful collaborative engineering design depends on the ability to manage and share engineering knowledge. Therefore, nowadays, knowledge management plays a crucial role in business competitiveness, hence our proposal of an integrated and collaborative ontology-based approach to knowledge management. We develop an ontology-based knowledge management support system with a focus on knowledge retrieval. The architecture of the support system is proposed, and implementation for its evaluation is undertaken. The support-system proposed is proven effective for capturing engineering knowledge, facilitating design-issue resolution and saving analysts' time.

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Abstract

In today's competitive and challenging market for the automotive industry, it is crucial to maintain an edge by reducing development time and costs and ensuring a high level of quality. To this end, the automotive industry is constantly embracing new tools, technologies and processes allowing to improve the effectiveness of development, where simulation has proven efficient and important. Car safety is a crucial concern for car manufacturers. Thus, crash simulation is an important step in vehicle development. The research for this thesis is conducted in a French multinational automotive company. At the end of the development phase, the vehicle model must be at the right level of performance and the right manufacturing cost. The development phase consists of iteratively refining the design specifications, evaluating the vehicle's performance and solving design issues encountered. This phase is supported by modelling and simulation. Thus, we are in a context of simulation-aided design since decision about the vehicle design is mainly based on simulation. The simulation process evaluates the vehicle’s performance and solves the design issues revealed.

In this thesis research, our focus is mainly on the crash simulation analysis process. In fact, the simulation-aided design is knowledge-intensive; it depends heavily on the knowledge of analysts and experts. Car crash simulation is expensive, time consuming and requires considerable effort. Therefore, in such a complex context, we aim to improve the simulation-aided design process, by reducing time, while producing more robust vehicles. Hence, our research objective is to support the simulation-aided design process.

First, in order to identify the difficulties and challenges encountered in the design issue resolution process, we conduct an empirical study that also provides a better understanding of the simulation-aided design process in use in the company. A comprehensive descriptive study has been conducted. Based on a two-level analysis, at the analysts’ team level and at the project level, industrial challenges have been identified, such as access and share of knowledge and expertise, data consistency, lack of expertise of novice analysts and the formalisation of approaches and the process. The empirical study confirms that knowledge is key factor for the improvement of the simulation-aided design process.

Moreover, Finite Element Analysis (FEA) is used for the car crash simulation. The FEA process includes a pre-processing, computation and post-processing phase, and is supported by algorithmic and non-algorithmic tasks. The literature review reveals a lack of approaches supporting the post-processing phase and its related non-algorithmic tasks. Besides, to support FEA, different FEA techniques are used, including ontologies. However, ontologies are mainly used for the development of knowledge-based engineering systems to automate the pre-processing phase. Therefore, we propose an ontology to formalise key knowledge for car crash simulation. The ontology we have developed is called the Crash Simulation Post-Processing Ontology (CSPP). This ontology formalises knowledge related to the post-processing phase of car crash simulation and the interpretation of simulation results. The aim is to formalise knowledge related to the resolution of design issues and the proposal of design changes.

Furthermore, the multidisciplinary, highly collaborative and contextual nature of engineering design has raised the need to support integrated and collaborative product development. Successful collaborative engineering design depends on the ability to manage and share engineering knowledge. Therefore, nowadays, knowledge management is playing a crucial role for companies’ competitiveness.

In engineering design, knowledge management approaches focus on either the personalisation approach or the codification approach. To our knowledge, no ontology-based knowledge management approach has been developed to support simulation-aided design, and more specifically, the car crash simulation process. Therefore, we propose an integrated and collaborative ontology-based knowledge management approach. The aim is to support analysts in their activities and ensure collaboration with the different stakeholders. Therefore, we develop an ontology-based knowledge management support system with a focus on knowledge retrieval. The architecture of the support system is proposed and an implementation for its evaluation is undertaken. The support-system proposed is proven effective for capturing engineering knowledge, facilitating design-issue resolution and saving analysts' time.

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Merci à tous,

Naouress

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List of Abbreviations

CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
FEA	Finite Element Analysis
CM	Countermeasure
DESLOOP	Design Loop Acceleration by Simulation
RQ	Research Question
KM	Knowledge Management
KBE	Knowledge-Based Engineering
KMS	Knowledge Management System
DRM	Design Research Methodology
PAR	Participation Action Research
CSPP	Crash Simulation Post Processing ontology
S&D	Strength and Durability

PART I: Thesis Compilation

This thesis is based on academic publications resulting from doctoral research work. The thesis consists of two parts. The first part, " Thesis Compilation ", includes summaries of the contributions that form the doctoral thesis. The second part, "List of Academic Publications", provides the list of academic papers, detailing each contribution.

The first part consists of five chapters. Chapter 1 presents the background, the industrial context and the research questions. Chapter 2 presents an overall literature review with a gap analysis. Chapter 3 details the proposed research approach and methodology. Chapter 4 summarises the academic papers while presenting the objective, approach and results of each, and studies the generalisability of the findings. Finally, Chapter 5 discusses the thesis research, answering the research questions and verifying the quality of the research, and outlines the conclusions and perspectives of the thesis.

PART 1 Short Summary

1 Introduction

The aim of this research is to propose a support system for simulation-aided design. We have conducted our research in a French multinational automotive company. This chapter introduces the background of this research and the industrial context. Then, it discusses the research objectives and underlines the research questions.

1.1 Background

In today's competitive and challenging market for the automotive industry, it is crucial to maintain an edge by reducing development time and costs and ensuring a high level of quality. Thus, automotive development seeks out flexible and powerful tools while continuously adopting new technologies and processes to improve development effectiveness (Mario et al., 2013; Spethmann et al., 2009). Stagnating sales volumes and intense competition lead to increasing product diversification, driven by complex requirements for vehicle variants and functionalities, and decreasing time-to-market processes (Mario et al., 2013).

Automotive development is integrated, virtual and supported by CAD-CAE processes (Mario et al., 2013). A virtual car is a representation of the parts of a vehicle in a shared workspace that allows its concurrent development. This workspace also enables the simulation and evaluation of vehicle performance (Weber, 2009).

Road traffic incidents ranked ninth in the global disease burden in 2016 (Ritchie and Roser, 2018) and are projected to rank third by 2020 (Patane et al., 2015). Therefore, vehicle safety is a critical factor for vehicle manufacturers. Vehicle safety includes both the ability of the vehicle to reduce accident risk, i.e active safety, and, in the event of an accident, the ability to avoid injury and damage to passengers and the car, i.e passive safety (Weber, 2009). Since crash tests consist of destroying the vehicle, physical crash tests to examine passive safety are highly expensive. Therefore, crash simulation is an essential step in vehicle development; the automotive industry has the most extensive application of crash simulation (Yadav and Pradhan, 2014). Crash simulation is a virtual reconstruction of a vehicle crash test, used to analyse and examine the crashworthiness of the vehicle. It is also used to examine the safety of the vehicle and its occupants (Patane et al., 2015; Yadav and Pradhan, 2014).

Specific simulation tools are used to analyse the performance of a virtual car, and Finite Element Analysis (FEA) is used to calculate, for example, structural dynamics, strain and stress (Mario et al., 2013). FEA is a major approach used for car crash simulation. However, FEA is expensive and time-consuming, due to software and hardware costs, and the extensive representation of mechanisms in the crash (Pawlus et al., 2013).

1.2 Industrial Context

This research is conducted within a French multinational automotive company (Renault Group). Within this company, the vehicle project is divided into 3 phases: upstream, development and industrialisation. The upstream phase involves establishing the concepts, requirements, style and trade-offs of the vehicle. In the development phase, the vehicle design specifications are progressively refined through several digital loops marked by milestones, starting with the Vehicle Pre-Contract (VPC) milestone and ending with the Tooling Go Ahead (TGA) milestone. During this phase, the vehicle only exists as a digital model. At the end of the development phase, at the TGA milestone, the vehicle model must be at the right level of performance and the right manufacturing cost. The digital vehicle goes into the industrialisation phase, where the physical prototypes are assembled and tested. The vehicle will then be mass produced. Our focus is mainly on the development phase.

A vehicle model is a variation on a reference vehicle model in a specific segment. A vehicle is composed of a platform, a powertrain and an upper body; they are developed in different projects simultaneously and synchronised. In this research, we focus on the development of the upper body, which will be called the vehicle project.

Within the company, engineers are organised into teams and vehicle projects. The teams are organisationally independent of each other and are geographically decentralised. Each team has its own objectives, skills, expertise and resources. However, they have different levels of involvement in the projects. A vehicle project is a transversal environment that brings together different teams and entities working together to achieve a common goal. The main industrial stakeholder in this research is the vehicle projects digital simulation team, which is a part of the customer performance engineering, digital simulation and testing, integrated CAE & PLM department. This team, during the development phase, is responsible for the evaluation of the vehicle's performance with respect to requirements, such as crash performance and noise and vibration performance, by conducting digital simulation tests. Simulation allows the detection of design issues when vehicle performance does not meet specifications. Performance is extracted from simulation results interpreted by experts and simulation analysts. Thus, throughout digital loops, when a design issue arises, the simulation analysts fix it by making design changes. Therefore, a digital loop will be considered as a design analysis loop, because during a loop, the vehicle design is refined and evaluated with the aid of simulation.

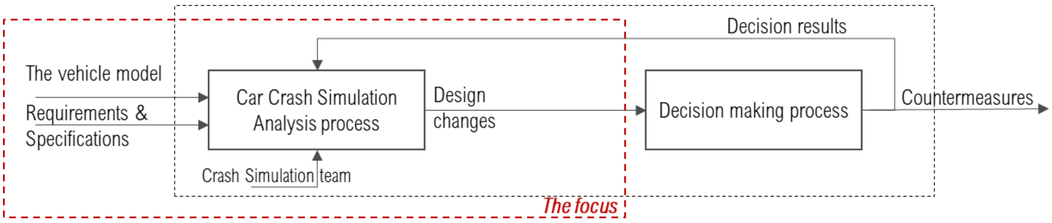

Figure 1.1 The overall Countermeasure design process for car crash simulation

This PhD focuses on car crash simulation enabling the analysis of the crashworthiness of the vehicle and examining the level of safety of the car and its occupants, according to crash requirements. Figure 1.1 describes the overall Countermeasure design process. A Countermeasure (CM) is a design change that solves one or more design issues, which is validated and implemented within the vehicle project. At the beginning of each design analysis loop, the crash simulation team obtains the vehicle model to be evaluated and design requirements and specifications to be achieved. The result of the analysis process is the proposal of design changes to solve the design issues detected by the simulation. The decision-making process regarding whether or not to incorporate the design change is not considered in this research; only the resulting decisions about CMs are taken into account.

This thesis research is also a part of an improvement plan for Renault engineering processes, methods and tools. This plan is called *Design Loop Acceleration by Simulation (DESLOOP)*. The aim is to set up processes and tools for data sharing and analysis allowing the simulation to improve its relevance and speed. DESLOOP aims to accelerate the design loop, mainly by reducing its time, for the different simulation performances involved within the vehicle projects.

1.3 Research Objective

We formulate the research objective based on preliminary research works (Fatfouta et al., 2016) in the company. As the vehicle development and decisions about the vehicle design are mostly based on simulation, the context is simulation-aided design. Simulation analysts are geographically decentralised, and there are only a few crash simulation experts and one digital simulation expert in the company. The analysts' mission is to deliver a vehicle model compliant with various requirements. They rely on simulation to verify vehicle performance, and they propose design changes to improve the vehicle model. Simulation experts have the most significant expertise within the company, and strong collaboration exists between the analysts and experts. Analysts require comprehensive knowledge and expertise related to modelling and simulation. The simulation-aided design is knowledge-intensive; it depends heavily on the knowledge of analysts and experts. Car crash simulation is expensive and time-consuming and requires considerable effort. Therefore, in such a complex context, we aim to improve the simulation-aided design process, by reducing time and number of iterations, while producing more robust vehicles.

Our research objective is to support the simulation-aided design process, taking into account the specificities of the industrial context; the most important ones being the fact that the process is knowledge intensive and heavily dependent on analysts and experts, the geographical decentralisation of stakeholders and the omnipresence of collaboration between them.

1.4 Research Questions

Given the research objective, this doctoral research must answer the following research question RQ:

- *RQ*: How can we support the simulation-aided design process?

Considering that the simulation-aided design is knowledge intensive, our research is based on the following hypothesis:

- *Hypothesis*: Knowledge is a key factor for improving the process of simulation-aided design, in use in the company.

Thus, any support system must address and integrate knowledge. RQ is therefore divided into two sub-questions:

- *RQ1*: What knowledge is needed for simulation-aided design and how can it be formulated?
- *RQ2*: How can we support the simulation-aided design process while integrating the pre-identified knowledge?

1.5 Outline of the Thesis

In Chapter 1, the research is justified and details about the industrial context, research objectives, hypothesis and research questions are given. In Chapter 2, a literature review on the research areas concerning our thesis research is explained. In Chapter 3, the research approach is presented. In Chapter 4, summaries of papers and contributions of this research are presented. A global protocol and the generalisability of the research findings are also discussed. In Chapter 5, the research questions are answered, and results and contributions are discussed. Conclusion, limitations and perspectives are also outlined. Finally, the academic publications, containing the core contributions of this research, are presented in the end of the thesis.

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2 Literature Review

Chapter 2 presents the positioning of the thesis. It presents a literature review on the different research areas concerning our subject. A specific literature review is presented in each academic paper.

2.1 Engineering Design is Knowledge Intensive and Collaborative

Engineering design takes place in the development phase of the overall product development process and is of central importance to the company. Engineering design is a task in which engineers apply their scientific and engineering knowledge to solve technical problems and to optimise the solution in compliance with the requirements and constraints under consideration (Pahl et al., 2007). With rapid technological development and international competition, time and costs are fixed, leading companies, including automotive companies, to design better products faster and more efficiently, and to address product diversification (Eckert and Clarkson, 2005; Mario et al., 2013; Verhagen et al., 2012).

Engineering design reflects the essential influence of Computer-Aided Design (CAD), originating in the processing of data on computers (Pahl et al., 2007). With many specialised software applications, CAD supports the development of designs and enables extensive virtual and physical testing (Eckert and Clarkson, 2005). CAD is used to create a geometric representation of the product in a virtual environment, and Computer-Aided Engineering (CAE) allows simulation and optimisation of the product in several disciplines that are carried out in parallel with the creation of the geometry (Mario et al., 2013). Virtual models have become the central communication platform for cooperation, and virtual engineering, like in the automotive industry, encourages worldwide collaboration (Mario et al., 2013; Weber, 2009).

The engineering design process is knowledge-intensive and collaborative (Chen et al., 2008; Peng et al., 2019; Wallace et al., 2005; Zha and Du, 2006). Design of modern products, such as cars, requires the collaboration of multidisciplinary teams, with the appropriate expertise, to conduct multiple tasks involving different areas of knowledge and expertise (Eckert and Clarkson, 2005; Sun et al., 2010; Wallace et al., 2005). Moreover, design tasks in all industries, including the automotive industry, are now more complex, with increasing timescales and geographically distributed teams (Mcmahon et al., 2004). Cooperative communication among teams is complicated (Chen et al., 2008). Collaborative engineering design is mainly concerned with problem-solving (Chen et al., 2008) and embodies a significant level of complexity; more than that which is required for a single engineer to work on such problems (Zha and Du, 2006). Engineering design is heavily informational (Peng et al., 2017), given that engineering designers spend considerable time locating information in human and nonhuman sources (Peng et al., 2017; Sun et al., 2010; Wallace et al., 2005); they engage 55.75% of their time in informational behaviour, such as processing, communicating and disseminating information (Robinson, 2010). They spend less time locating the source when it is a human source than when it is a non-human source, and so it is more efficient to use people as sources of information (Robinson, 2010). However, due to the current transient nature of modern industrial organisations, experienced designers and experts are not going to be available to consult in the future (Wallace et al., 2005); companies suffer significant setbacks from staff loss, such as the deterioration of their relationships with customers or suppliers and the loss of revenue (Alavi and Leidner, 2001).

Given the current market context and the complexity of the design, companies need to improve the effectiveness of their design processes by leveraging their available knowledge base and planning more effectively (Eckert and Clarkson, 2005). Moreover, given the central position of the engineering design process in the overall product development process, and that even sales and marketing depend on specialised engineering knowledge, it is crucial to make full use of the engineering knowledge and product experiences of designers (Pahl et al., 2007). In (Quintana-Amate et al., 2017), the authors also argued that each step in the engineering design process requires technical knowledge and experience that must be effectively captured, formalised and reused, thereby improving the quality of product development while reducing time and costs. Thus, this thesis addresses the knowledge capitalisation strategy of companies with a focus on engineering knowledge. We, therefore, explain what we mean by engineering knowledge, and how to capitalise on engineering knowledge and support designers.

2.2 Engineering Knowledge

Many ways of defining knowledge exist in the literature. Table 2.1 presents most knowledge taxonomies revealed through the literature review.

Table 2.1 Knowledge definition and taxonomies

Definition of knowledge	**References**
A value chain or hierarchical relationship with data and information: • data is in the form of symbols and words, • information is structured data that forms a pattern, • knowledge is processed information, facts and rules of thumb acquired through experience.	(Heisig, 2009; Liebowitz, 2001; Mcmahon et al., 2004; Peng et al., 2017; Shin et al., 2001; Sun et al., 2010)
The capability of knowing: • The “know-about”: a state of knowing, • The “know-how”: a capacity for action, • The “body of knowledge”: articulated and captured facts, methods and so on.	(Alavi and Leidner, 2001; Apurva and M.D., 2011)
The stage of accessibility: explicit, implicit and tacit • Explicit knowledge, or formal knowledge, is knowledge that can be expressed, codified and documented. • Implicit knowledge is knowledge that can be implied by or inferred from observable behaviour or performance. • Tacit knowledge is subconscious and cannot be expressed.	(Apurva and M.D., 2011; Beesley and Cooper, 2008; Heisig, 2009; Liebowitz, 2001; Mcmahon et al., 2004; Peng et al., 2017; Shin et al., 2001; Sun et al., 2010)

In the context of engineering design, engineering knowledge can be defined as formal knowledge and tacit knowledge. Formal knowledge can be codified in different sources, including 3D geometric models and simulation models and refers to the know-about and know-how embedded in codified information resources. Tacit knowledge, on the other hand, refers to personal knowledge and experience, such as developing a problem-solving strategy and reasoning on the possible decision (Peng et al., 2017). Design knowledge is also classified as product knowledge and process knowledge (Peng et al., 2019; Wallace et al., 2005; Zha and Du, 2006). The authors in (Wallace et al., 2005) explain that information refers to what is stored and transferred outside the human mind, and that knowledge only exists when information is interpreted. They then classify engineering design knowledge into product and process knowledge. Thus, when stored externally, information can either describe the design process or the product itself. However, knowledge, which is embedded in human memory, can be either explicit or implicit or tacit. First, explicit knowledge is an explanation of both the process and the product and can be articulated in the form of information. Second, implicit knowledge is the understanding that engineers have of both the process and the product and cannot be expressed by themselves engineers; methods of knowledge elicitation can articulate it. Finally, tacit knowledge is more about intuition and cannot be articulated.

2.3 Knowledge Approaches in Engineering Design

As the thesis research focuses on the capitalisation of engineering knowledge and the support of designers, we conduct a literature review on the different approaches to knowledge used in engineering design. In (La Rocca, 2012), the author explains a complementary coexistence between different research fields, as shown in Figure 2.1, that aims at identifying, codifying and managing engineering knowledge: knowledge engineering, knowledge-based engineering and knowledge management. Knowledge engineering is the field that focuses on the acquisition and codification/representation of knowledge. Knowledge-based engineering focuses on the technical development of the application to retain knowledge and support its reuse. Knowledge Management is the domain that deals with the use of knowledge assets in organisations.

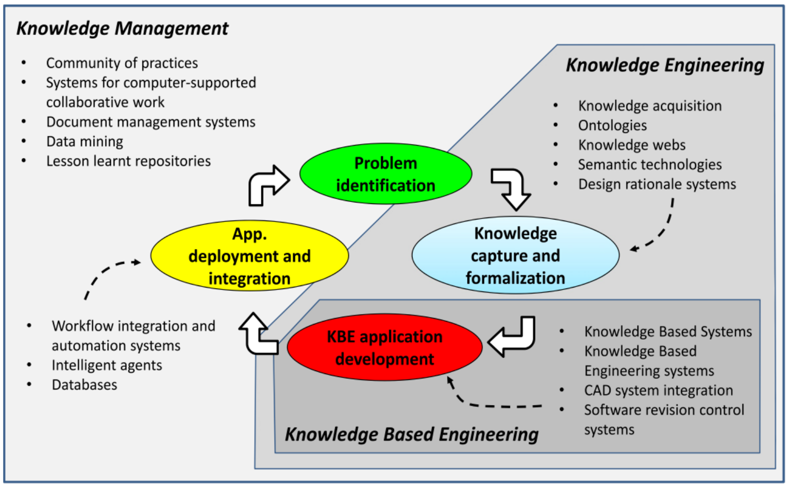

Figure 2.1 The explanation of the complementarity between knowledge management, knowledge engineering and knowledge-based engineering, from (La Rocca, 2012).

We therefore present an overview of the different areas of research that our research addresses, namely: knowledge management, knowledge acquisition, knowledge representation and knowledge-based engineering.

2.3.1 Engineering Knowledge Management

Nowadays, knowledge Management (KM) plays a crucial role in the global economy and is important for the competitiveness of companies (Barão et al., 2017). KM has multiple definitions and perspectives. Knowledge management refers to identifying and leveraging collective knowledge (Alavi and Leidner, 2001; Barão et al., 2017; Liebowitz, 2001) and it is usually defined as a process involving multiple sub-processes including knowledge capture, storing, retrieval and transfer (Al-Emran et al., 2018; Alavi and Leidner, 2001; Girard et al., 2015; Heisig, 2009). KM is also defined as the ability of an organisation to manage, store, value and distribute knowledge (Girard et al., 2015); an organisation is defined as a social unit of people structured and managed to meet a need or to achieve collective goals (Barão et al., 2017). KM is an essential asset in modern institutions; it enables learning from corporate memory, growth, success and innovation (Al-Emran et al., 2018). The multidisciplinary, highly collaborative and contextual nature of engineering design has raised the need to support integrated and collaborative product development (Peng et al., 2017). Successful collaborative engineering design depends on the ability to manage and share engineering knowledge (Chen et al., 2008). In engineering design, knowledge can either present itself as tangible objects that can be modified, copied and transferred, or experience accumulated through a community of expertise; this results in two approaches to KM, the codification and the personalisation approach (Peng et al., 2017). The most common approaches are technology-oriented, called the codification approach; the explicit nature of knowledge is underlined, and knowledge needs to be formalised and stored in knowledge repositories and transferred via Information and Communication Technologies (Peng et al., 2017). On the other hand, people-oriented, or personalisation approaches, underline the tacit and context-dependent nature of knowledge; it requires informal human communication to transfer knowledge (Liebowitz, 2001; Saito et al., 2007). It is argued that a trade-off between the two approaches, known as an integrated approach, is more effective (Mcmahon et al., 2004; Ng et al., 2012; Peng et al., 2017; Saito et al., 2007). An integrated approach to KM can improve the quality and efficiency of design through the capture and reuse of informal and contextual knowledge.

Table 2.2 Knowledge Management System Definitions

Definition of Knowledge Management System	**References**
A KMS is commonly considered as an information system which supports different phases of the KM process.	(Dehghani and Ramsin, 2015)
KMS refer to a class of information systems applied to managing organisational knowledge. That is, they are IT-based systems developed to support and enhance the organisational processes of knowledge creation, storage/retrieval, transfer and application.	(Alavi and Leidner, 2001)
KMS has to fulfil three functions: acquiring knowledge, storing it and reusing it.	(Zhang et al., 2011)
KMS refer to a class of information systems applied to managing organisational knowledge and are developed to support and enhance the organisational processes of knowledge creation, storage, retrieval, transfer, and application, mainly at organisational (corporate) work- places.	(Barão et al., 2017)

Information systems play a key role in the development of KM as it enables automation, production and sharing of knowledge (Al-Emran et al., 2018). These systems are called Knowledge Management Systems (KMS) and they support KM processes (Alavi and Leidner, 2001). The literature is rich with definitions of KMS, as presented in Table 2.2, however, it is usually defined as an Information System (through Information Technologies (IT)) to support KM processes. The essential function of KMS is the sharing and reuse of knowledge. Therefore, to achieve this function, the acquisition of knowledge is fundamental. Thus, KMS has to fulfil three functions: acquiring knowledge, storing it and reusing it (Zhang et al., 2011).

Table 2.3 Applied Information Technologies to support Knowledge Management processes

KM processes	**Applied Information Technologies**	**References**
Generation, creation, capture	Data mining tools, knowledge discovery tools, knowledge content generation tools, authoring tools, data capturing tools	(Antonova et al. , 2006; Kestel et al., 2019)
Codification, representation Storing	Ontology, maps, rule-based reasoning system, CBR, semantic nets, frames, concept maps Data/ knowledge warehouses, databases, knowledge bases, document management applications, digital library	(Antonova et al., 2006; Blondet et al., 2018; Kestel et al., 2019; Liu & Lim, 2011; Peng et al., 2017; Wriggers, Siplivaya, Joukova, & Slivin, 2007; Y. Zhang, Luo, Zhao, & Zhang, 2015)
Transformation, retrieval	Expert systems, DSS, visualisation tools, Case based reasoning, Trace-based reasoning,	(Antonova et al., 2006; Bonjour et al., 2014; Peng et al., 2019; Wriggers et al., 2007)
Transfer, sharing	Information portal, intelligent agents, multi-agent system,	(Antonova et al., 2006; Girodon et al., 2015; Peng et al., 2017)

Different frameworks to develop KMS exists in the literature, however, no one way of building a KMS is proved. Therefore, we studied the literature to identify IT used to support the different KM processes, presented in Table 2.3. This proves that there is no single Information System that can provide clear-cut support to all processes of KM.

2.3.2 Knowledge Acquisition and Knowledge Elicitation

Knowledge acquisition is the primary activity of knowledge engineering and consists of acquiring knowledge from a variety of sources, such as documents, computer files and human experts. Knowledge can be domain-specific or problem-solving process specific; it can also be general or meta-knowledge (knowledge about knowledge) (Turban et al., 2005). Knowledge acquisition is the core activity of knowledge-based systems management, as well as any critical system step and bottleneck (Do Rosário et al., 2015). Knowledge elicitation is the acquisition of knowledge from human sources. Various techniques for knowledge elicitation have been discussed in (Do Rosário et al., 2015) including structured and unstructured interviews, observation, protocol analysis and verbal reporting. In (Gavrilova and Andreeva, 2012), the authors proposed a taxonomy of knowledge elicitation techniques based on the relationship between the analyst, i.e., the person responsible for eliciting the knowledge, and the expert, i.e., the person who possesses the knowledge. They also mapped knowledge elicitation techniques, such as interviews, questionnaires and observations, to the types of knowledge elicited, such as tacit, explicit, individual and group knowledge. For example, interviews are very suitable for eliciting explicit and individual knowledge.

2.3.3 Knowledge Representation

Knowledge representation is a major activity of knowledge engineering that involves encoding acquired and organised knowledge into a knowledge base (Turban et al., 2005). Moreover, it aims to develop enabling technologies for KM tools (Peng et al., 2017). Knowledge representation is also considered as part of Artificial Intelligence, which consists of using a symbolic representation to set up propositions to be executed by the agent. It is involved in the construction of knowledge-based systems, where the symbolic representation concerns their knowledge bases (Brachman and Levesque, 2004). Knowledge representation, also called knowledge formalisation, aims to structure knowledge in a machine-readable form and to store it. Thus, it allows processing the knowledge by an engineering support system automatically (Kestel et al., 2019). Various knowledge models have been developed, such as function-based knowledge models, frames, object-oriented representation models, rule-based representation, and ontology-based representation models (Kestel et al., 2019; Peng et al., 2017, 2019).

The interest in developing ontologies is growing in engineering design because it involves knowledge sharing and the development of a common standard language (Saeema et al., 2007). According to (Iaksch and Borsato, 2019; Kestel et al., 2019), Gruber (1993) defines ontology as an explicit specification of shared conceptualisation, and confirms that any knowledge base or knowledge-based system is, implicitly or explicitly, related to conceptualisation. Ontologies are usually used for the formalisation of domain knowledge (Premkumar et al., 2014). An ontology represents, through a shared vocabulary, a set of domain concepts, attributes, relationships, instances and functions (Khanbabaei et al., 2018; Premkumar et al., 2014). It provides a common format that is machine readable (France-Mensah and O'Brien, 2019; Kestel et al., 2019). An ontology needs to be understandable, editable and generalisable (Blondet et al., 2018; Khanbabaei et al., 2018).

2.3.4 Knowledge-Based Engineering

Knowledge-based engineering (KBE) has been applied and successfully deployed to wide range of industries such as aerospace, automotive and shipbuilding (Quintana-Amate et al., 2015; Reddy Esanakula et al., 2015), and it is positioned in the group of knowledge technologies. In (Chapman and Pinfold, 2001), the authors define KBE as: "KBE represents an evolutionary step in CAE and is an engineering method that represents a merging of object oriented programming, artificial intelligence techniques and CAD technologies, giving benefit to customised or variant design automation solutions".

Table 2.4 Knowledge-Based Engineering definitions in the Literature

Definitions of Knowledge Based Engineering	**References**
Knowledge-based engineering (KBE) has been applied and successfully deployed to wide range of industries such as aerospace, automotive and shipbuilding and it is positioned in the group of knowledge technologies	(Quintana-Amate et al., 2015; Reddy Esanakula et al., 2015)
"KBE represents an evolutionary step in CAE and is an engineering method that represents a merging of object-oriented programming, artificial intelligence techniques and CAD technologies, giving benefit to customised or variant design automation solutions"	(Chapman & Pinfold, 2001)
KBE is considered as both an area and a technology, based on the use of KBE systems, which are able to capture, retain and systematically reuse product and process engineering knowledge	(La Rocca, 2012)
KBE offers the possibility of engineering automation while retaining relevant knowledge, which can improve the quality of design decisions and results, as well as significantly reduce design time	(Bermell-Garcia et al., 2012; Verhagen, Bermell-garcia, et al., 2012)
KBE is evolving towards data management and collaboration systems, with the goal of sharing information in real time to make the collaborative design process more effective	(Reddy Esanakula et al., 2015)

There are multiple perceptions and definitions of KBE across different research and industrial communities, as presented in Table 2.4. For example, KBE is seen as a technology solution to retain company knowledge and support its reuse from a knowledge management perspective, and it is seen as technologies that support design work by increasing the level of automation and intelligence of the conventional CAD system from the perspective of designers and engineers (La Rocca, 2012). However, a global definition is proposed in (La Rocca, 2012): KBE is considered as both an area and a technology, based on the use of KBE systems, which are able to capture, retain and systematically reuse product and process engineering knowledge. The objectives of KBE are reducing the time and costs of product development through automation of repetitive and non-creative design tasks. KBE offers the possibility of engineering automation while retaining relevant knowledge, which can improve the quality of design decisions and results, as well as significantly reduce design time (Bermell-Garcia et al., 2012; Verhagen et al., 2012). In (Reddy Esanakula et al., 2015), the authors argued that KBE is evolving towards data management and collaboration systems, with the goal of sharing information in real time to make the collaborative design process more effective.

2.4 Thesis Positioning

A detailed analysis of the literature is presented in the academic papers. In this section, we explain only the positioning of the thesis and highlight the various gaps in the research. Paper 1 and 2 present the empirical study and verify that knowledge is a key factor for the improvement of the design process. The objective of the research is to support simulation-aided design, with a focus on the analysis of car crash simulation, and to reduce time. In our context, Finite Element Analysis (FEA) is used for the car crash simulation.

FEA process includes a pre-processing, computation and post-processing phase, and is supported by algorithmic and non-algorithmic tasks. Although the existing literature deals, in detail, with the pre-processing stage of FEA, less attention is paid to the post-processing phase and its non-algorithmic tasks, in particular. Besides, to support FEA, different FEA techniques are used, including ontologies. However, the ontologies for the development of KBE are mainly used to automate the pre-processing phase. To our knowledge, there is no ontology to support non-algorithmic tasks in the post-processing phase of FEA, in particular for car crash simulation.

Moreover, in engineering design, knowledge management approaches focus on either the personalisation approach or the codification approach. To our knowledge, no ontology-based knowledge management approach is developed to support simulation-aided design, and more specifically, the car crash simulation process.

To address the previously highlighted gaps, Paper 3 proposes an ontology to formalise the engineering knowledge related to the post-processing phase and the interpretation of crash simulation results. This ontology presents the first steps towards the development of a KBE system that incorporates the design rules and engineering knowledge related to crash simulation, with the integration of intelligence that supports the resolution of design issues. Furthermore, in Papers 4 and 5, we propose an integrated and collaborative knowledge management approach that integrates the proposed ontology and proposed reasoning for the support system. Paper 5 details the proposal for an ontology-based knowledge management system and the reasoning used for knowledge retrieval.

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3 Research Approach

This chapter details the approach used in this thesis to conduct research and validate results. We use qualitative approaches as well as Participation Action Research (PAR). This chapter maps out the research methodology and presents quality validation. The research progress is also detailed based on the Design Research Methodology (DRM).

Research approaches are research plans and procedures that cover steps ranging from general assumptions to detailed methods of data collection, analysis and interpretation (Creswell, 2014). Research approaches can be qualitative, quantitative or mixed. The research in this thesis tends to be qualitative. In qualitative research, specific strategies called research designs are employed, such as case studies, narrative research and action research (Creswell, 2014). In this thesis, research designs are mainly cases studies and action research.

Action research has mainly been used in social studies since the second half of the 20th century. Action research is commonly defined as “a process of joint learning”, where the object of research is a social system involving human interaction. The researcher integrates himself/ herself within this complex organisation and its culture, and the goal is not only to solve a problem for the others in the organisation but with the others, in joint learning, and to contribute to science (Ottosson, 2003). Participatory action research takes place when the researcher is in close and active contact with practitioners and is defined as a social research method and process. Participation Action Research (PAR) is a research method to improve management methods and concepts and where the researcher is either a team member or a manager/ project leader (Ottosson et al., 2006).

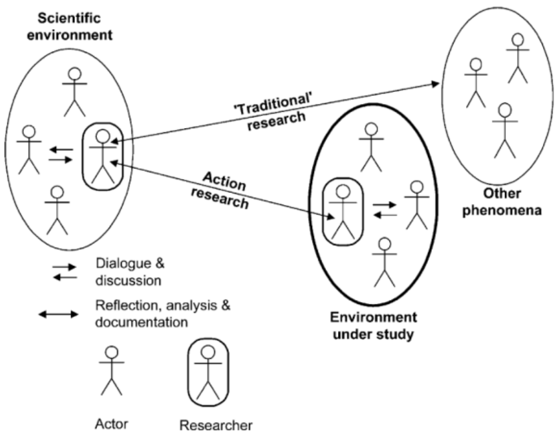

Figure 3.1 Illustration from (Ottosson, 2003) describing the optimal research situation when performing participation action research.

Ottosson (Ottosson, 2003) also details an optimal research situation for PAR, as presented in Figure 3.1. The researcher needs to be inside the object of research, “environment under study”, as a manager or team member, and at the same time, a member of a “scientific environment”. For further research, the researcher needs to apply traditional research methods, as it is not possible to be inside competing companies. In this thesis, the researcher is a team member of a multinational automotive company (Renault Group), within the Vehicle Projects Digital Simulation Team and a part of the industrial engineering department (LGI) as a scientific environment. Within the company, the researcher is also an active member of a transversal project, the improvement plan DESLOOP, aiming to improve the design analysis loop with a focus on digital simulation. For further research, historical information and the literature are analysed.

Design as a topic of research has become interesting as design became more complex and its economics became more important. The overall aim of design research is to improve the effectiveness and efficiency of design to develop more successful products. Blessing and Chakrabarti (Blessing and Chakrabarti, 2009) integrate two objectives while defining design research: (1) the development of understanding through both the formulation and the validation of models and theories relating to the design phenomenon, and (2) the development and validation of support, based on these theories, to improve design practice. This thesis focuses on the development of support to engineering design based on the proposal of an ontology-based knowledge management approach.

3.1 The Design Research Methodology

Design Research Methodology (DRM) is a methodology developed by Blessing and Chakrabarti (Blessing and Chakrabarti, 2009) with the aim of supporting engineering design research. The overall objectives are those already defined for design research. DRM consists of four main stages: Research Clarification (RC), Descriptive Study I (DS I), Prescriptive Study (PS) and Descriptive Study II (DS II).

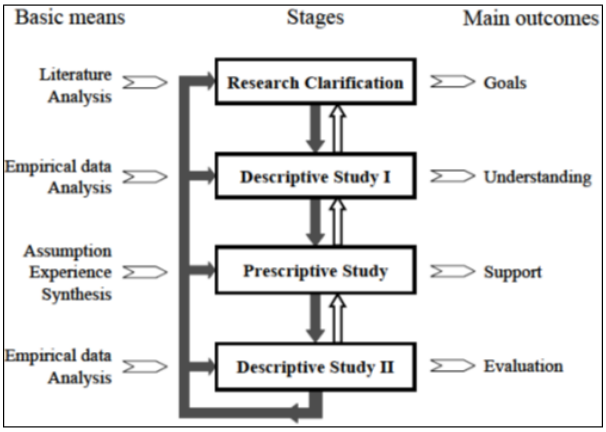

Figure 3.2 DRM framework with its stages, means and outcomes, from (Blessing and Chakrabarti, 2009).

These stages, their means and their outcomes are represented in Figure 3.2. Iterations are allowed between the different stages. RC aims to clarify the current situation, the overall research goal and the desired situation. It seeks to set the goals and define the research plan. It is mainly ensured by literature review. DS I aims to increase the understanding of the existing situation through empirical studies and may include a literature review. Based on the results of DS I, PS aims to develop the support or suggestions towards creating the desired situation. It also ensures the implementation of the support and outlines the evaluation plan. The support can have any form, including guidelines, a framework and methods. DS II aims to evaluate the impact of the proposed support. Empirical studies are used to evaluate whether the support is improving the current situation.

Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1. Review-based	Comprehensive		
2. Review-based	Comprehensive	Initial	
3. Review-based	Review-based	Comprehensive	Initial
4. Review-based	Review-based	Review-based Initial/ Comprehensive	Comprehensive
5. Review-based	Comprehensive	Comprehensive	Initial
6. Review-based	Review-based	Comprehensive	Comprehensive
7. Review-based	Comprehensive	Comprehensive	Comprehensive

Figure 3.3 Types of research defined by DRM, from (Blessing and Chakrabarti, 2009).

For each research project, not all stages will be undertaken in equal depth. Thus, DRM identifies seven types of design research, as mentioned in Figure 3.3. The review-based study is based only on literature. A comprehensive study includes a literature review as well as a study with results produced by the researcher, such as an empirical study or a support development. An initial study involves the first steps of any of the stages. This thesis is Type 5 research as will be detailed in section 3.2.

3.2 Research Quality

In qualitative PAR, the objective is to contribute to increasing the knowledge that can be used by the practitioner and to contribute to science. Thus, in order to verify the quality of research, we need to judge its authenticity and trustworthiness, while taking into account the validity, reliability and credibility of academic research and ease of use for practitioners (Björk and Ottosson, 2007; Sargeant, 2012). As detailed in (Björk and Ottosson, 2007), validity is the accuracy of the research and its results in assessing the research questions. Reliability refers to the quality of the research results. Credibility is verified by the existence of the results. However, in qualitative research, researchers approach qualitative validity by examining the trustworthiness, truthfulness and credibility of the research, and different strategies are used, such as data triangulation, method triangulation and participant checking (Creswell, 2014; Twining et al., 2017). Data triangulation involves using data from different sources, and method triangulation involves using different methods to collect data. Participant checking consists of verifying the accuracy of the results from the participants. The generalisation is also referred to by some qualitative researchers (Twining et al., 2017) and can be considered as external validity of the qualitative research (Blessing and Chakrabarti, 2009). Qualitative reliability can be addressed through intensive documentation of procedures and steps and detailed case studies and protocols (Creswell, 2014). Finally, usability is also discussed in (Björk and Ottosson, 2007) and refers to user satisfaction and the achievement of industrial objectives.

The research quality will be discussed in Chapter 5. Details on strategies used to ensure validity, including data and method triangulation, participant checking, and generalisation, will be presented. Reliability and usability of the research will also be discussed.

3.3 The Proposed Research Approach in this Thesis

In this research, we perform PAR. Being inside the organisation gives us access to the subjective reality of daily life, which is important in qualitative research (Björk and Ottosson, 2007). Thus, our research is mainly qualitative. The environment under study of our research is the car crash simulation team within the multinational automotive company Renault Group, during the development phase of vehicles. We use the DRM as guidelines for our research, the adaptation of which is detailed in Figure 3.4. As mentioned in section 3.1, we are conducting Type 5 research, as the evaluation of the support is preliminary.

As shown in Figure 3.4, the research methodology is not sequential; multiple iterations between the different stages are established. Each stage is supported by an in-depth literature review. For example, the prescriptive study is supported by a literature review and a re-examination of the industrial context. New data is collected and analysed. As a result, our understanding of the current situation evolves. Thus, throughout the prescriptive study, iterations with different stages are undertaken.

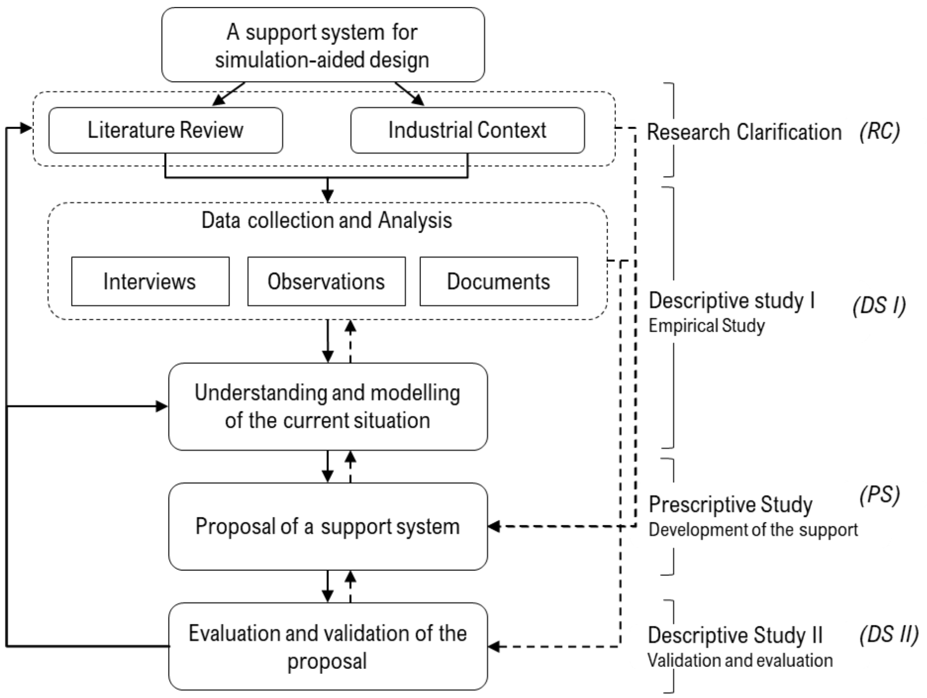

Figure 3.4 The adapted research methodology inspired by DRM (whose main steps are shown on the right side of the figure).

During this research, several work-packages (WP) were carried out through the DRM stages. We have summarised the WPs in Table 3.1. Each WP has a corresponding DRM stage, a name and details about the tasks performed. The aim of the WP or its tasks is also explained. Finally, there is a description of the deliverables obtained. The literature review that started in the Research Clarification (RC) stage continues through the whole stages. The five main WPs are distinguished from each other. These are:

“Empirical Study”, “Knowledge Capture”, “Continuous Improvement”, “Ontology Development” and “Knowledge Management Framework".

Table 3.1 The Work-packages carried out during the thesis research

DRM	*Workpackage*		*Aim*	*Delivrables*
	Name	*Details*		
RC	Literature review on research areas		Better understanding of the research problem	- Industrial deliverable: a description of the current situation - A Conference Paper in design18 (paper 1) - A conference paper in ICED19 (Paper 2)
RC, DS I	Empirical Study	Company's documentataion analysis: State of the existence on crash simulation and design-issue resolution	Better understanding of the design process, the developement phase and crash simulation analysis	
DS I		An overview of design issue resolution from observations	Better understanding of the industrial context	
DS I		Interviews with different actors about their daily acitivities	Better understanding of the role of each actor and the design resolution process	
DS I		Workshops facilitation to analyse specific design-issues and their resolution	Better understanding of resolution of a design issue	
DS I	Knowledge Capture	Company's documentataion analysis: Extraction of existing design-issues and their Coutermeassures	Extraction and analysis of existing and ongoing design-issues and their Coutermeassures in order to build a knowledge base for later proposals	Industrial deliverable: building a knowledge base about design-issue resolution
DS I		Workshops facilitation for brainstorming about ongoing and most frequent design issues		
DS I		Weekely meeting for update about ongoing design-issue resolution		
DS I, PS		Meetings for raising awarness about DESLOOP	- Inform about DESLOOP - Elicit the needs and expectataion of simulation analysts from the project	Industrial deliverable: integration of the analysts's needs and expectations
PS		Proposal of files for knowledge capture	- Capture knowledge in a formal format - Get analysts to think about all the steps for design-issue resolution (design issue, root cause, CM) - A shared vocabulary	Industrial deliverable: the file was adopted for documenting ongoing design-issues and their resolution
PS	Continuous Improvement	Process modelling	A proposal of a design-issue resolution process as there is no details in the developement process	Industrial deliverable & Integration within academic papers
PS		Crash scenario formalisation (focus on frontal crash)	- Formalise knwoledge - Integrate within ontology - Identify all necessary elements for a good post processing - Identify crucial knwoledge for results interpretation - Formalise scenario to share with analysts - Better structure requirements	Industrial deliverable: a definition of a crash scenario and a proposal of guidlines for a scenario desciption Integration within the developed ontology
PS	Ontology Developement	Iterative conceptualisation & fromalisation	The developement of an ontology to formalise the knowledge related to the post-processing and results' interpretation of car crash simultion: starting from the simulation ressults, to the identification of the design issue and its resolution	- Industrial deliverable: implementation of the onotlogy within DESLOOP - A journal paper submitted in the international journal "Advanced Engineering informatics" (Paper 3)
PS		Workshops for discussing and building the ontology		
PS		Interviews for validation		
DS II		Evaluation and testing of the ontology		
PS	Knowledge Management Framework	Proposal of a framework for knwoledge management	The developement of a virtual collaborative knowledge management system, based on the devloped onotlogy, and integrating all necessary elements to support the car crash simulation. The developement of the knowledge retrieval block based on a probabalistic reasoning. generalisation of the proposal to another simualtion discilpine.	- Industrial deliverable: discussion with DESLOOP - A conference paper in Design20 (Paper 4) - A journal paper submitted in the international journal "Computers in Industry" (Paper 5)
PS, DS II		Developement of the knowledge retrieval block		
DS II		Implementatation og the KM support system		
DS II		Generalisation of the proposal		

We started the RC with the literature review and the analysis of existing documentation within the company on the global design process, the development phase and the crash simulation. In the beginning of the thesis research, the research problem was formalised as a support for analysis and diagnosis of car crash simulation results. Therefore, the purpose was to have a better understanding of the research context.

During the Descriptive Study I (DS I), both the “Empirical Study” and the “Knowledge Capture” WPs were carried out. The purpose was to analyse in detail the industrial situation and the knowledge related to the current design-issue resolution process. A description of the research and industrial challenges were then identified.

The Prescriptive Study (PS) covered parts of the “Knowledge Capture” WP, and all of the “Continuous Improvement”, “Ontology Development” and “Knowledge Management Framework” WPs. As we lacked existing data and knowledge related to solving design issues, we proposed files and facilitated workshops within the “Knowledge Capture” WP, to extract knowledge for further analysis. The “Continuous Improvement” WP consists of tasks that we carried out to improve the current situation, which allowed us to develop stronger contributions. Both the “Ontology Development” and “Knowledge Management Framework” WPs are the PS's main contributions to the formulation of our support system proposal.

Finally, the Descriptive Study II (DS II), was iterated with the PS during both the “Ontology Development” and “Knowledge Management Framework” WPs for the evaluation and validation of the proposal. The first steps of the evaluation were carried out and the implementation of the proposal is still to come.

3.4 Thesis Research Progress

In Table 3.2, we detail the progress of the research in terms of academic publications and their respective DRM stages. The academic publications and their role in validating the hypothesis and answering the RQs are also detailed.

Table 3.2 Research progress in terms of Hypothesis, RQ and academic publications, at all stages of DRM. The dots highlight publications with their respective stages of DRM. A dark dot indicates that the publication fully covers the DRM stage. A light dot indicates that it is partially covered.

					RQ2: How to support simulation-aided design?	
			RQ1: What knowledge? How to formalise it?			
		Hypo validation: knowledge is key factor for the improvement of the process				
		Paper 1: empirical study	**Paper 2:** empirical study	**Paper 3:** Ontology development	**Paper 4:** Support-system development	**Paper 5:** Support-system development
DRM stages	RC	●	○	●	●	●
	DS I	○	●			
	PS		○	●	●	●
	DS II			○	○	●

First, we conduct an empirical study to better understand the simulation-aided design process in use at the company and to identify the difficulties and challenges encountered. This study verifies the hypothesis that knowledge is a factor for the improvement of the simulation-aided design process. This study results in both academic publications: Paper 1 presents the early stages of RC and DS I, and Paper 2 presents mainly DS I and initiation of the SP stage.

Second, we propose an ontology to formalise the key knowledge for crash simulation and necessary for the simulation-aided design process. This ontology formalises the knowledge related to the post-processing phase of the crash simulation and the interpretation of the simulation results. The objective is to formalise the knowledge related to the resolution of design issues and the proposal of design changes. This work answers RQ1. It results in Paper 3, covering mainly the PS phase.

Finally, to support simulation-aided design, we develop an ontology-based knowledge management approach. Its objective is to support analysts in their activities and to ensure collaboration with the various stakeholders. Its purpose is to address RQ2, which results in two academic publications, Paper 4 and Paper 5, covering the PS and DS II stages. Paper 5 is an extension of Paper 4.

The academic publications, which will be presented at the end of this thesis, are:

- *Paper 1*: N. R. Fatfouta, J. Stal-Le Cardinal, and C. Royer, “A Proposition of a Knowledge Elicitation Methodology for Crash Simulation Diagnosis Support System,” in Proceedings of International Design Conference, DESIGN, 2018, vol. 4, pp. 1663–1672.
- *Paper 2*: N. Fatfouta, J. Stal-Le Cardinal, and C. Royer, “Empirical Study of Car Crash Simulation Analysis within the Development Phase,” in 22nd International Conference on Engineering Design ICED, 2019, pp. 2843–2852.
- *Paper 3:* N. Fatfouta, A.-M. Hein, J. Stal Le-Cardinal, and E. Delacou, “An Ontology Towards a Knowledge-Based Support of the Post-Processing Phase of Car Crash Simulation,” Adv. Eng. Informatics, under revision, 2019.
- *Paper 4:* N. Fatfouta, J. Stal-Le Cardinal, “Towards a Framework for Integrated and Collaborative Knowledge Management for Engineering Design- a Case Study,” in Proceedings of International Design Conference, DESIGN, 2020, accepted.
- *Paper 5:* N. Fatfouta, J. Stal-Le Cardinal, “An Application of an Ontology-Based Knowledge Management Approach to Support Simulation-Aided Design to Car Crash Simulation in the Development Phase,” Computer in Industry, submitted 2020.

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4 Academic Publications Summaries and Research Results

In this chapter, we present a summary of the academic publications resulting from our research. This chapter aims to provide a global understanding of our doctoral Thesis. Each academic publication is outlined through its objective, approach and findings. Further details are available, at the end of this thesis, in the List of Academic Publications, where all the papers are presented. The global protocol followed is described, and the generalisability of the research findings is also discussed.

To have a better understanding of the content of this Chapter, we explain the objects that are manipulated in this research. As explained in Table 3.1 of Chapter 3, we propose a file for knowledge capture to help capture and structure knowledge related to design issues resolution. Hence, Figure 4.1 presents a documented design issue and its resolution. This design issue resolution is documented by a crash simulation analyst. The design issue is described in Box 1 (clarify the issue). Box 2 (set the target) represents the non-satisfied requirement. In Box 3 (diagnosis: analyse the root cause), the analyst diagnoses the root cause of the design issue. Then, in Boxes 4 (develop countermeasure) and 5 (implement countermeasure), the analyst proposes the design change. The new vehicle performance (simulation results) are described in Box 6 (results). Then, other information, such as lessons learnt and feasibility, is also documented, in Boxes 7 and 9.

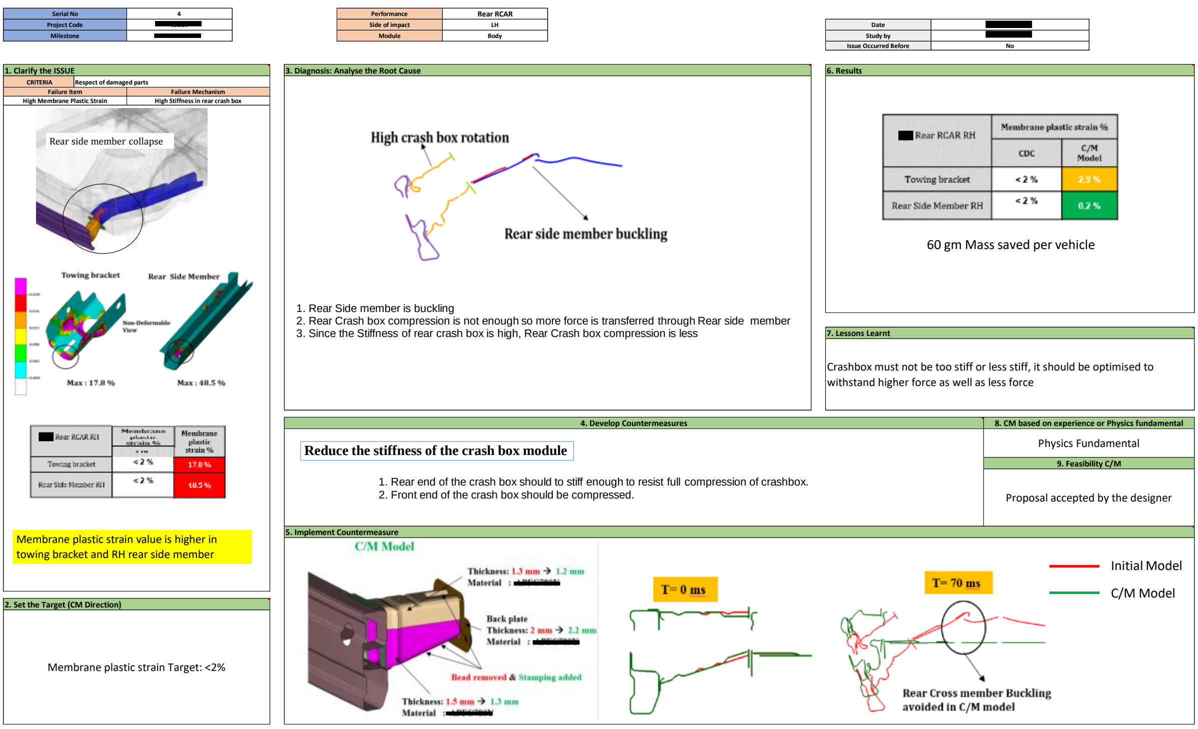

Figure 4.1 A knowledge capture file of a design issue resolution for car crash simulation. An example of a documentation of a crash design issue with a focus on knowledge related to the design issue, the root cause and the design change

4.1 The Empirical Study

Paper 1: A Proposition of a Knowledge Elicitation Methodology for Crash Simulation Diagnosis Support System

Paper 1 presents the early stages of Research Clarification and Descriptive Study I (See Figure 3.4).

Objective

At the beginning of the research, the thesis subject was "Analysis and diagnosis support for car crash simulation results". We conducted a research clarification to formulate a better understanding, by analysing subjacent research areas. Paper 1 is the first steps in the research. The aim of Paper 1 is to better understand the industrial context and to propose a knowledge elicitation methodology.

Approach

Some insights on the related research areas are presented in Paper 1. Based on first interpretation of the research objective, and on preliminary works, we study the literature on diagnosis, diagnosis systems and knowledge-based system. Assuming knowledge is an issue, we also study the literature related to implicit knowledge and knowledge elicitation methods. The literature review provided us with a better understanding and some methods and techniques to elicit and acquire key knowledge.

In Paper 1, we propose the first steps of the empirical study, staring from formalising the industrial needs and reviewing the literature. Then, we conduct a descriptive study, by acquiring data from observations, interviews and company documentation. Finally, we propose a knowledge elicitation tool for analysts, to elicit and acquire project information and knowledge throughout the project.

Findings

In Paper 1, tentative wordings were used:

- A design issue is referred to as simulation issue
- A design change is referred to as a redesign alternative

Three important results are identified. First, we characterise the design-issue resolution process, that is called the process of Countermeasure (CM) development in Paper 1. The purpose of this characterisation is to explain the activities ensured by analysts within crash simulation. They start from obtaining the vehicle model and the specification, to launch the simulation, post treat the results, identify a design issue and diagnose it, propose a design change, and verify the new vehicle performance. If the design change is satisfactory, they go on to the next design issue, if not, they attempt another iteration.

Second, we illustrate the cognitive process and a resulting mental map for solving design issues. It is an attempt to interpret the implicit cognitive process of the analysts, their behaviour facing a design issue to solve. Figure 4.2 shows both the cognitive process and the mental map. For each activity of the process, the corresponding elements from the metal map are presented.

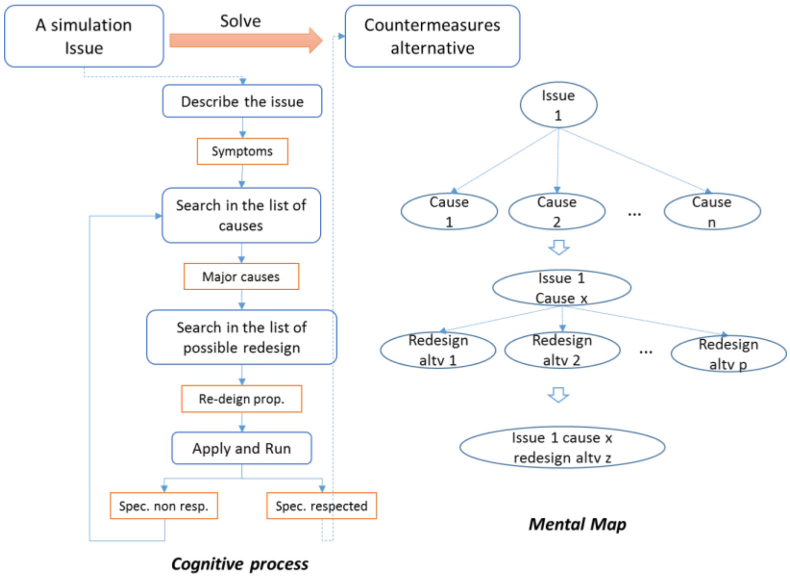

Figure 4.2 The developed cognitive process and its resulting mental map presented in Paper 1. The cognitive process describes the activities that analysts execute when facing a design issue. The mental map describe how issues are related to their causes and then to the design changes. Each design issue has a limited list of root causes, and for each root cause, a limited list of possible design changes is considered.

Finally, we propose a knowledge elicitation tool which is an elicitation file, which the sections are presented in Figure 4.3. As there is no satisfactory capitalisation on the resolved design issue, this file will help capture knowledge and information in real time, throughout the vehicle project. The purpose is to capture enough information and knowledge to be analysed later towards proposing a support system for the simulation-aided design process.

	Definition of the issue				Diagnosis			Countermeasures (CM)		Results
Id	Description	Crash test	Affected Zone	Criticality	Symptoms	Probable causes	Major causes	Possible redesign	Chosen CM	Result after CM

Figure 4.3 The sections of the elicitation file presented in Paper 1. These sections evolved to better accommodate the analysts in their day-to-day work. A CM, as explained in Chapter 1, is a design change that solves one or more design issues, which is validated and implemented within the vehicle project

Based on these first results, we conduct a comprehensive empirical study to identify the industrial difficulties and challenges (Presented in Paper 2).

Paper 2: Empirical Study of Car Crash Simulation Analysis within the Development Phase

Paper 2 presents mainly the Descriptive Study I and initiation of the Prescriptive Study stage (See Table 3.2).

Objective

The aim of Paper 2 is to better understand the simulation-aided design process in use in the company and to identify the difficulties and challenges encountered. It also aims to verify the research hypothesis that knowledge is a factor for the improvement of the simulation-aided design process. Industrial challenges and difficulties are also drawn.

Approach

In Paper 2, we conduct a descriptive study. Based on the literature review and preliminary understanding of the industrial context, we collect data from different sources and then analyse it. The most important results are the modelling of the crash simulation analysis process and the industrial challenges and difficulties. The validation of the results was done by the company's experts.

In order to identify the industrial challenges, we conduct a two-level analysis. First, we propose a team-level analysis with the aim of characterising the team's activities, resources and objectives and identifying the dysfunctions that lie within. We define a dysfunction as a problem in the team's functioning. Second, we propose a project level analysis, with the aim of linking the team-level dysfunctions with the project risks. The purpose is to identify the most impacting dysfunctions on the project.

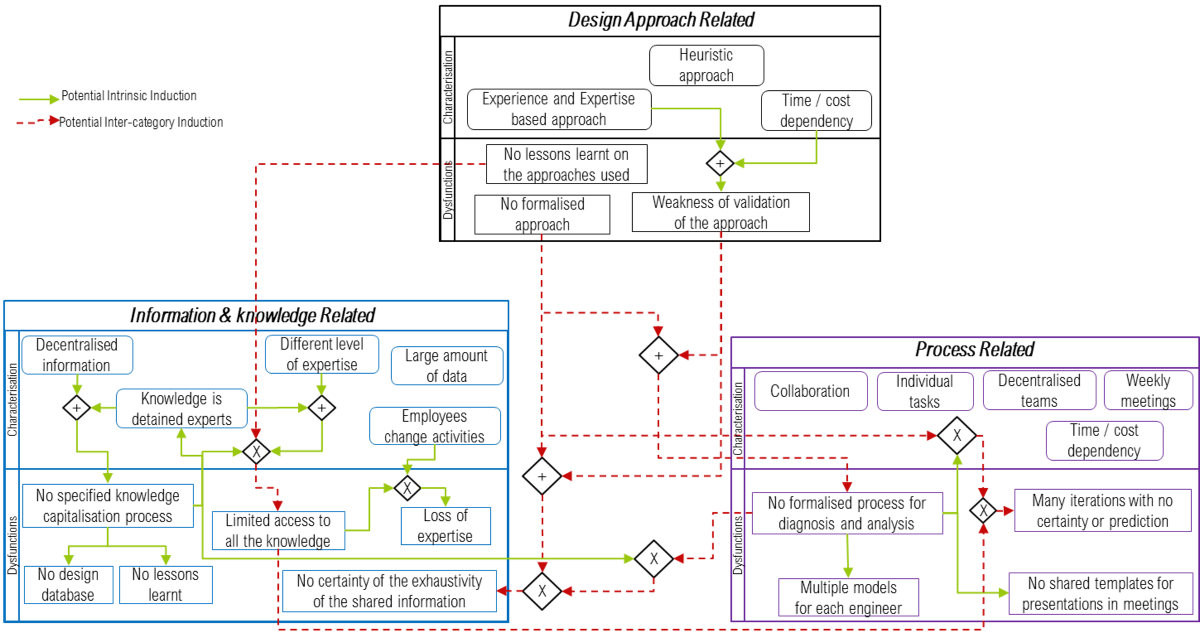

Figure 4.4 Mapping of the observations (elements) categories and the induced dysfunctions.

For the team-level analysis, as presented in Figure 4.4, we start by characterising the context into three categories: process related, information-and-knowledge related, and design-approach related observations. Moreover, each categories' observations are sorted in characteristics and dysfunctions. Afterwards, we study the relations between characteristics and dysfunctions, with emphasis on the induction relationship. Induction happens when one (or more) element(s) induce another (see mapping in Figure 4.4). Thus, we introduce the notion of an induced dysfunction, which is a dysfunction that is induced by one or more elements. Then, we focus on the most induced dysfunctions (as explained in Paper 2, the dysfunctions with the highest probability of occurrence), since they appear simultaneously to an inducing element.

Dangerous Situation (Project-Level)	Contact Causes (Team-level)	Feared Event (Project-Level)	Initiating Causes
Difficulties in the decision-making process	No certainty of the exhaustivity of the shared information	No respect of QCTW	Missing information about QCTW
Difficulties in the decision-making process	No certainty of the exhaustivity of the shared information	Missing some important information for QCTW evaluation	No shared templates for presentations in meetings
Non-Feasibility of the proposed design action (CM)	No certainty of the exhaustivity of the shared information	Loss of time	Approving a non-feasible CM
Non-Feasibility of the proposed design action (CM)	No certainty of the exhaustivity of the shared information	Making a wrong decision about a CM	No lessons learnt about the manufacturing process
Loss of time	Many iterations with no certainty or prediction	An Issue is standing throughout the project	No CM is proposed
Loss of time	Many iterations with no certainty or prediction	An Issue is standing throughout the project	Limited access to knowledge
No efficiency of the results	No formalised process or approach	Making a wrong decision about a CM	Non-valid approach when searching for CM

Figure 4.5 Preliminary Hazard Analysis at the project level. For each dangerous situation, we identify a possible contact cause (dysfunctions at the team level). The feared event is an event that could cause the dangerous situation. The initiating cause is a trigger, at the team-level, of the feared event.

After identifying the induced dysfunctions, we analyse their impact on the progress of the project, i.e the project-level analysis. Since the smooth progress of the vehicle project is our priority, we aim to identify team-level dysfunctions with a highly undesirable impact on the project. For this analysis, we used the Preliminary Hazard Analysis PHA method, as explained in Figure 4.5. PHA aims to identify a hazardous element, how it could lead to an incident, leading to an event that could cause a hazardous situation. However, the cause/consequence relations linking the hazardous events can be explored via inductive or deductive reasoning. Since our preliminary knowledge is more about the consequences on the project, we proceed by deduction to identify the causes from the team-level.

Findings

As first results of the empirical study, we model the crash simulation analysis process (As-Is). It helps identify where we need to focus while supporting it.

As a synthesis for both analyses, we conclude that most impacting dysfunctions are related to the non-formalisation of both the process and the design approach and the limited access to corporate knowledge. As a result of the empirical study, we detail the industrial challenges, such as access and share of knowledge and expertise, data consistency, lack of expertise of novice analysts and the formalisation of approaches and the process. We can deduce that knowledge is a key factor for improving the design process. Experts also prove that simulation results with more certainty can allow us to gain at least one iteration per design issue and so we save about nine hours of computation and about one hour of analyst effort.

Henceforth, we focus on the post-processing phase and the interpretation of crash simulation results. Since simulation-aided design is knowledge intensive, we focus on knowledge in the proposal of the support system. Paper 3 aims to identify key knowledge and to formalise it.

4.2 The Ontology Development

Paper 3: An Ontology Towards a Knowledge-Based Support of the Post-Processing Phase of Car Crash Simulation

Paper 3 covers mainly the Prescriptive Study stage, with insight from Research Clarification and initiation of Descriptive Study II (See Table 3.2).

Objective

Facing a knowledge-intensive context that requires comprehensive expert intervention, we propose to formalise necessary knowledge using ontologies. The interest in developing ontologies is growing in engineering design because it involves knowledge sharing and the development of a common standard language (Saeema et al., 2007). Gruber (1993) in (Iaksch and Borsato, 2019; Kestel et al., 2019), defines ontology as an explicit specification of shared conceptualisation, and confirms that any knowledge base or knowledge-based system is, implicitly or explicitly, related to conceptualisation. Paper 3 proposes an ontology to formalise knowledge related to the post-processing phase and the interpretation of car crash simulation results.

Approach

The methodology used in Paper 3 is the 5 stage- ontology development life cycle proposed by Pinto and Martins (Pinto and Martins, 2004). It goes through the stages of specification, conceptualisation and formalisation using a formal language, implementation, and finally maintenance. Other activities need to be performed during the ontology development process, such as knowledge acquisition, evaluation and documentation. We focus on the conceptualisation and formalisation stages of the ontology, with insights on the knowledge acquisition and the evaluation activities. Firstly, we define the scope and the purpose of the ontology specification. Secondly, the knowledge is captured, and the conceptualisation is ensured by the identification of relevant concepts and relationships. The evaluation of the ontology consists of an expert validation and a use-case validation.

Findings

The “Crash Simulation Post-Processing” Ontology (CSPP) formalises knowledge related to the post-processing phase of car crash simulation and the interpretation of simulation results. The aim is to formalise knowledge related to the resolution of design issues and the proposal of design changes.

To represent the concepts more accurately, we suggest separating the ontology into three levels, as presented in Figure 4.6:

- The context level describes information about the context in which the digital test happens such as the requirements to be met and the impact configuration, such as a frontal and a rear crash. It contains existing standardised information that is independent from the vehicle project under development, for example, the regulations and the requirements.
- The project level can be considered as an instantiation of the reasoning level for a specific vehicle. It formalises engineering knowledge related to the vehicle project. We considered all

necessary elements to ensure an accurate interpretation of simulation results and resolution of design issues.

- The reasoning level formalises the resolution of design issues. It is a proposal to support design issue-solving and design change proposals. The reasoning level is project independent.

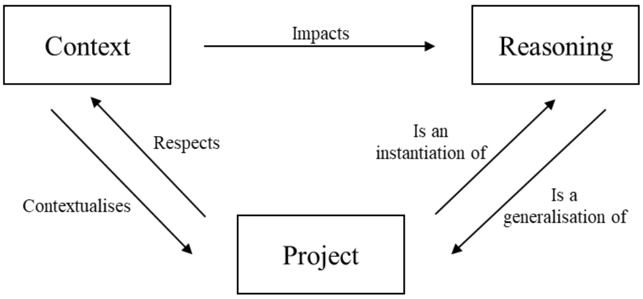

Figure 4.6 The relations between the three levels. The context situates the vehicle project development. Similarly, the vehicle project should respect the context. Moreover, the context impacts the reasoning level by delimiting the reasoning space. While the reasoning level is the generalisation of the resolution within the project level, the project is an instantiation of the reasoning proposals.

Some of the ontology's concepts are presented to ensure the coherence and understanding of this chapter. Therefore, we discuss most important concepts at both the context and the project levels, and we present the whole reasoning level.

The context level formalises the technical requirements to be met. A *Technical Requirement* is defined as a *Target* on a *Criterion* for a certain *Impact Configuration* and a certain *Performance Reference*. An example of a *Technical Requirement* is expressed as "For a damageability (*Performance Reference*), frontal at 16km/h impact (*Impact Configuration*), the minimum of the energy absorbed by the frontal Crash Box is 6000J (*Target* on a *Criterion*)".

The purpose of the crash simulation is to evaluate and validate the performances of a specific vehicle model. Therefore, the project level presents the concepts related to such evaluation. This evaluation is ensured by the *Assessment* of the *Simulation Results* according to the specifications of the project. Two types of *Assessment* are considered for two types of specifications. The *Requirement Assessment* evaluates the considered *Project Requirement* (an instantiation of a Technical Requirement), and the *Scenario Assessment* evaluates the expected *Crash Scenario* (the impact propagation within connected vehicle parts during a crash test). Although the design issues are identified at the project level, their analysis and resolution happen at the reasoning level.

The reasoning level, shown in Figure 4.7, consists of defining in a generic way a design issue, a root cause and a design change. A design issue occurs when a vehicle simulation results violates the requirements. A vehicle model consists of vehicle parts, and each vehicle part has a role to play in the vehicle structure during the crash test and adopts an expected behaviour to ensure this role. Thus, we define a *Generic Issue* as a behaviour *Gap* between the expected *Behaviour* and a defect *Behaviour* of a *Generic Vehicle Part*. A design issue has root causes. A *Generic Root Cause* is also defined as a behaviour *Gap* of a *Generic Vehicle Part*. A design change is one or more *Generic Corrective Action*s applied to a vehicle part.

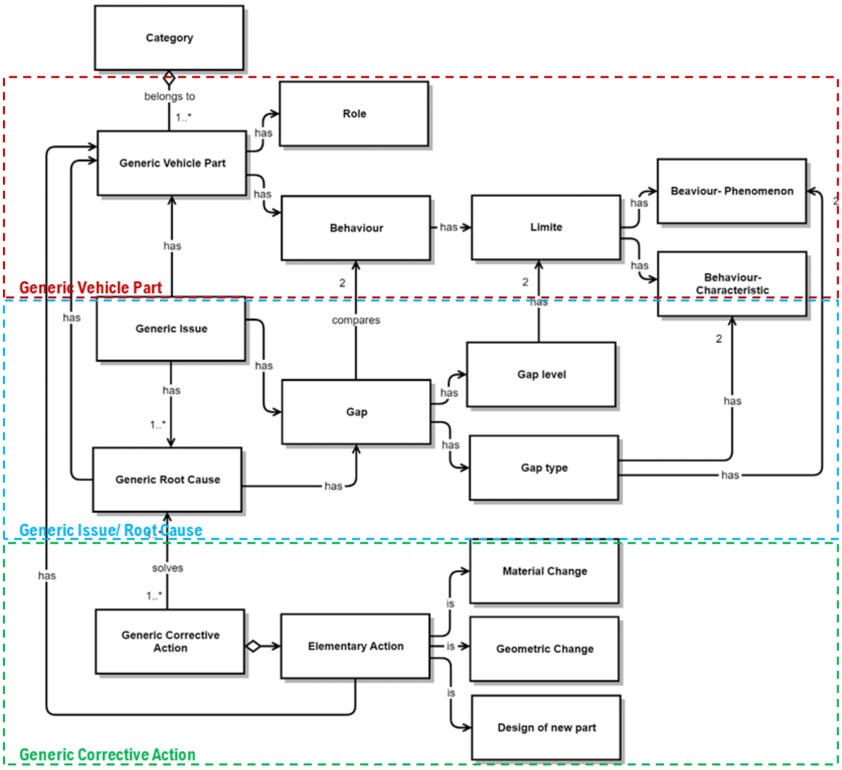

Figure 4.7 The reasoning level of the CSPP ontology

The reasoning level also suggests to categories design issues based on the vehicle part involved. This reasoning is based on two hypotheses: 1) crash simulation is related to physical and mechanical phenomena, therefore, the behaviour of vehicle parts has limited possibilities of deformation and can be predictable, 2) vehicle parts sharing the same role and behaviour are generally exposed to similar issues and belong, therefore, to the same *Category*. Then, issues with similar diagnosis and root causes share similar corrective actions.

Paper 3 also focuses on describing the implementation of the reasoning level and, in particular, its role in design issues resolution.

Following the formalisation of the ontology, we study its integration within a simulation-aided design support system, which is the subject of Paper 4.

4.3 The Ontology-Based Knowledge Management Approach

Paper 4: Towards a Framework for Integrated and Collaborative Knowledge Management for Engineering Design- a Case Study

Paper 4 covers the Prescriptive Study stage and initiation of Descriptive Study II (See Table 3.2).

Objective

The analysis of car crash simulation is both knowledge intensive in nature and characterised by human interactions. Specifically, it relies heavily on experts and expertise. These characteristics can be a source of inefficiency in the overall engineering process due to the unavailability of experts and the time required to search for information. To address these issues, we propose an ontology-based knowledge management approach, in Paper 4, to support simulation-aided design, with a focus on crash simulation.

Approach

In Paper 4, to propose the Knowledge Management System (KMS) architecture, we perform an extensive literature review on knowledge management frameworks and KMS architectures, mainly in engineering design. We also focus on the use of ontologies for such systems. To our knowledge, there is no ontology-based knowledge management approach to support simulation-aided design. Moreover, since we perform PAR, the proposal is formalised and discussed with practitioners. We also present a use case scenario to explain the application of the proposed KMS.

Findings

The most important results in Paper 4 are the KM framework and the KMS architecture. This proposal considers the different stakeholders involved in simulation-aided design. It will support them in their activities and it will facilitate their collaboration and communication.

Figure 4.8 briefly explains the proposed ontology-based KMS architecture. The KMS integrates the KM processes including, knowledge capture, knowledge storing, knowledge retrieval and knowledge sharing. The KMS captures and retains engineering knowledge, including knowledge related to the evaluation of simulation results, assessment of design issues and design change proposals. The CSPP ontology is the knowledge model that formalises the captured knowledge in order to store it in knowledge repositories. The knowledge needs then to be retrieved, using the retrieval model, and shared with users.

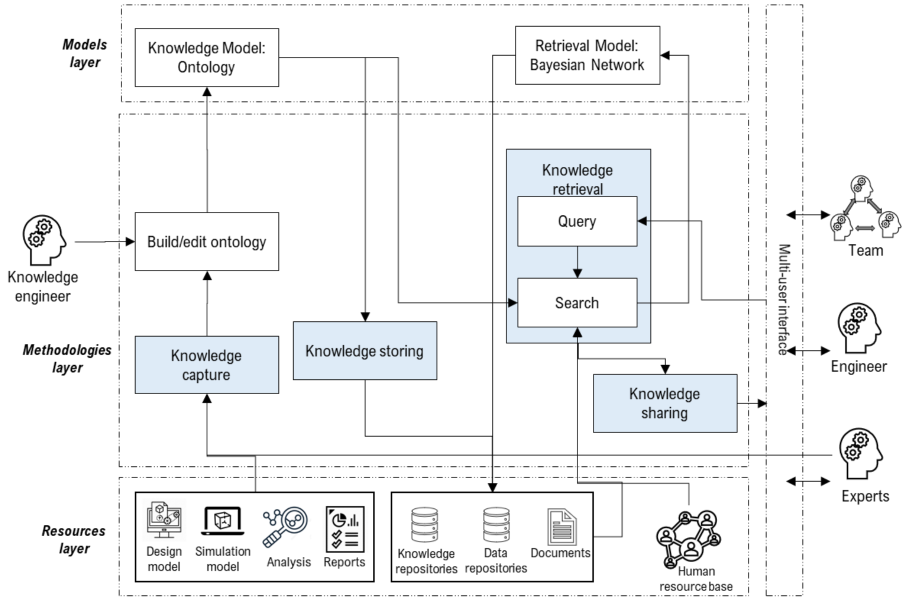

Figure 4.8 A proposal, in Paper 4, of an ontology-based knowledge management system architecture to support simulation-aided design. The support system consists of 3 layers and a multi-user interface (MUI). The resources layer refers to the repositories of different types of knowledge and the human resource base. The methodologies layer represents the methodologies used to carry out KM activities. The models layer consists of the models developed to ensure the implementation of the system.

The knowledge management support system should help reduce the time spent on crash simulation by reducing the time spent solving design issues and proposing design changes, as well as the time spent searching for a human source of information, such as experts. It should also increase the accuracy of proposals for more effective design changes.

Then, Paper 5 is an extension of Paper 4 that aims to detail the KM support system architecture.

Paper 5: An Application of an Ontology-Based Knowledge Management Approach to Support Simulation-Aided Design to Car Crash Simulation in the Development Phase

Paper 5 presents the Prescriptive Study and Descriptive Study II stages. Paper 5 is an extension of Paper 4 (See Table 3.2), with a focus on the development of the KM support system and its application.

Objective

The engineering design process is a knowledge-intensive and collaborative task (Chen et al., 2008; Wallace et al., 2005; Zha and Du, 2006). Successful collaborative engineering design depends on the ability to manage and share engineering knowledge (Chen et al., 2008). Nowadays, knowledge management plays a crucial role in the global economy and is important for the competitiveness of companies (Barão et al., 2017). Hence, Paper 5 aims to develop an integrated and collaborative ontology-based knowledge management system to support simulation-aided design based on the initial ideas developed in Paper 4. Paper 5 details the capabilities of the KM support system, and develops the different blocks and models needed to achieve these capabilities. An application to car crash simulation is also presented. An implementation for the evaluation of the support system is also undertaken using different use case scenarios and a time saving of 20% is justified.

Approach

In Paper 5, as a follow-up to Paper 4, we focus mainly on the development of the virtual knowledge management support system, with some improvements to the first proposal. To develop the knowledge management support system, we first define its capabilities. Next, we present its architecture, including the different layers and building blocks. The description of the building blocks in terms of models and implementations is further carried out.

Findings

The result of Paper 5 consists of a proposal for a virtual KMS to support simulation-aided design, with an application to car crash simulation. Knowledge capture and retrieval building blocks are developed. A proof of concept implementation is also presented with the aim of evaluating the proposed support system, using different use case scenarios.

Paper 5 presents an improved version of the KM support system, as shown is Figure 4.9, starting from the architecture proposed in Paper 4. The KM support system is integrated and collaborative. The integrated aspect is represented by the CSPP ontology, which combines formal knowledge, such as requirements and models, and tacit knowledge, such as design issue resolution. The KM support system also ensures the codification of knowledge and the capture of in-context and tacit knowledge through communication. The collaborative aspect is considered to ensure stakeholder collaboration and communication. This KMS architecture, described in Figure 4.9, ensures the pre-identified capabilities, that are collaboration, knowledge capture and knowledge retrieval. The collaboration is mainly ensured by the multi-user interface.

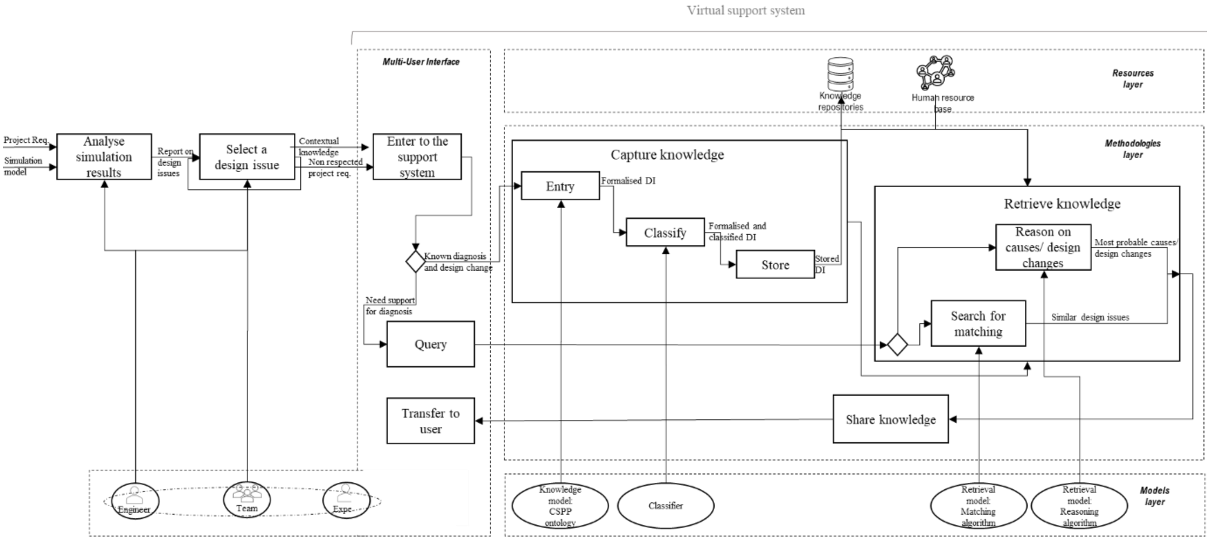

Figure 4.9 The proposal of the knowledge management support system in Paper 5. The integrated and collaborative KM support system consists of three layers and multi-user interface. A representation of the activities performed before interacting with the KM support system is also given (on the right), to identify the inputs required.

The knowledge capture block ensures the capture of engineering knowledge and its classification. Three sub-blocks are developed, the “Entry”, the “Classify” and the “Store” blocks. We also develop the classifier model. According to the knowledge capture block, the knowledge repositories would consist of several clusters representing the categories and containing engineering knowledge, the associated design issues and their resolution. The knowledge retrieval block ensures the retrieval of engineering knowledge based on users’ query. Within the retrieval block, two sub-blocks and two models are developed. Figure 4.10 describe the results of both models. The first is the matching algorithm, a filter, that ensures the “search for matching” sub-block. The second is the probabilistic reasoning algorithm, that ensures the “reason on causes/ design changes” sub-block. The knowledge retrieval models are developed with respect to the reasoning level of the CSPP ontology.

I- Matching

category	*context*	*design issue*	*cause*	*design change*
1	C1	DI 1	Cause 1	DC 1
1	C2	DI 2	Cause 2	DC 2
1	C3	DI 3	Cause 3	DC 3
1	C4	DI 4	Cause 4	DC 4
1	C5	DI 5	Cause 5	DC 5
1	C6	DI 6	Cause 6	DC 6
1	C7	DI 7	Cause 1	DC 7
1	C8	DI 8	Cause 2	DC 8
1	C9	DI 9	Cause 3	DC 2
1	C5	DI 10	Cause 6	DC 3
1	C6	DI 11	Cause 7	DC 7
1	C7	DI 3	Cause 8	DC 1
1	C2	DI 4	Cause 4	DC 3
1	C3	DI 5	Cause 2	DC 6
1	C1	DI 9	Cause 3	DC 4
1	C4	DI 10	Cause 6	DC 5
1	C5	DI 11	Cause 8	DC 6

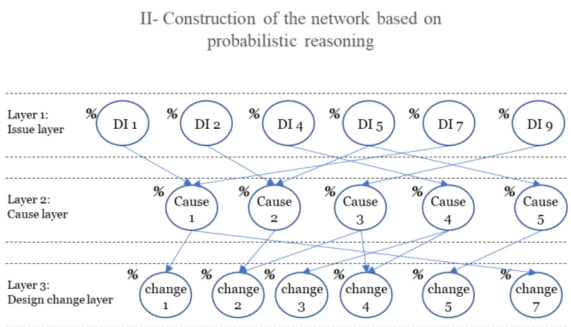

Figure 4.10 (I) presents the list of design issues and their resolution that results from the matching algorithm. (II) explains the construction of the network, where design issues (DIs) are presented with their respective causes and design changes, and the % represents the probability of each node.

The empirical study, in Paper 2, highlights that simulation with more certainty about the results can allow us to gain at least one iteration per issue and so we save about nine hours of computation and about one hour of analyst effort. In practice, analysts encounter two or three significant design issues concerning fifteen impact configurations, per project and design loop. Thus, by saving one iteration per design issue, we can save about thirty-five hours or one week of the design loop, out of the five weeks it usually lasts, which corresponds to 20% the analyst's time saved.

Further improvements on the developed ontology-based KMS can be introduced. First of all, it is necessary to integrate the different simulation disciplines, such as noise and vibration and stress. Secondly, a web-based prototype needs to be developed to facilitate communication between users and the system. Third, users, who have different roles, need to work in their virtual spaces and create knowledge as the project progresses, which will enrich the knowledge base and improve the models.

4.4 Global Protocol and Generalisability of the Ontology-Based Knowledge Management System

This section provides an overview of the global protocol used for our proposal for an ontology-based knowledge management system to support simulation-aided design. The generalisability of this proposal is also discussed, extending the research findings from crash simulation to other simulation disciplines, still in the automotive industry.

4.4.1 Global Protocol of the Ontology-Based Knowledge Management System

To summarise the results of the thesis research, we present, in Figure 4.11, a global protocol that describes the steps followed, the methodologies used, and the findings obtained. In order to achieve the research objective of supporting simulation-aided design, we followed several steps, presented in Figure 4.11, starting with the assessment of the current situation. This step is based on an empirical study that identified the specificities of the industrial context and the industrial challenges. This research focuses on the challenge that the knowledge factor is essential to improve the industrial context. Therefore, the second step consists in developing a knowledge model that formalises crucial engineering knowledge. Thus, the development of an ontology is undertaken.

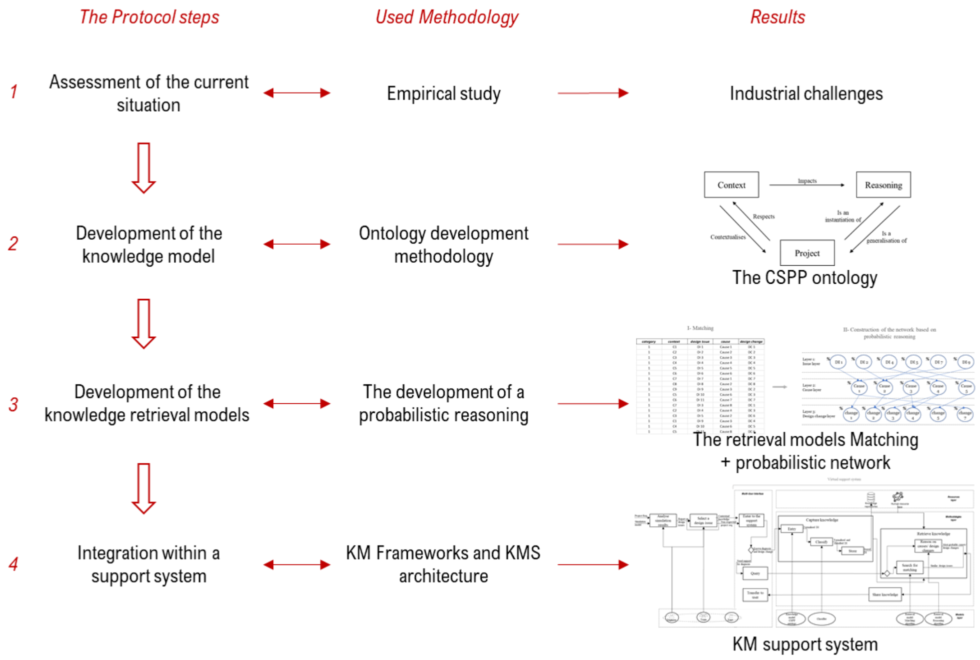

Figure 4.11 Explanation of the global protocol steps, with the associated used methodology and the findings of each step.

Moreover, in order to develop the knowledge management system to support simulation-aided design, we have conducted extensive research on the development of knowledge retrieval models and the development of knowledge management systems. Therefore, we develop knowledge retrieval models that consist of a filter-based matching algorithm and a probabilistic reasoning algorithm. Finally, the integration of the knowledge model and the knowledge retrieval models within the support system is carried out, resulting in the ontology-based knowledge management support system.

4.4.2 Generalisability

Generalisation is not widely used in qualitative research, and is even considered problematic (Twining et al., 2017), as the value of qualitative research lies in the particularity of a specific context, not in the generalisation of results outside the scope of the study (Creswell, 2014). However, some researchers discuss the generalisability of qualitative research when they study additional cases. Nevertheless, repeating the results of a case study in a new case requires thorough documentation of qualitative procedures, such as protocols (Creswell, 2014). Twining et al. (Twining et al., 2017) discuss two ways to apply the findings of qualitative research to different contexts. First, if a research setting is similar to another, the findings can help to illustrate and explain phenomena in the other setting. Second, theoretical development can extend the relevance of qualitative research beyond the current scope. In this research, we explore the generalisability of our findings by extending them to similar contexts. Two aspects of generalisability are considered: inter-contextual generalisability and interdisciplinary generalisability. The inter-contextual generalisability consists in extending the results to the car crash simulation in similar companies. Furthermore, the interdisciplinary generalisability consists in extending the results to different simulation disciplines, such as strength and durability, in the same company.

This research is applied within the Renault group, and more specifically for the Renault company. However, other automotive companies are part of the group, such as Nissan and Mitsubishi; the models and architectures of the vehicles are similar. Thus, the discipline of crash simulation is similar, and similar design issues are encountered. The two companies, Renault and Nissan, are working together on DESLOOP, the improvement plan for engineering processes (presented in Chapter 1). Thus, inter-contextual generalisability is addressed, since the models were developed to take into account the constraints of the two companies' contexts.

To address interdisciplinary generalisability, we study the resolution of different design issues from other simulation disciplines, hence the focus on Strength and Durability (S&D) simulation. To investigate the generalisability of the findings, we first present the applicability of the results to S&D simulation, following the global protocol presented in Figure 4.11. Next, we discuss interdisciplinary generalisability. As this research is part of DESLOOP, whose objective is to accelerate the design loop for all simulation disciplines involved in vehicle development, the industrial challenges can be generalised. The different simulation disciplines are subject to the acceleration of the design loop and are highly dependent on comprehensive knowledge. Thus, the first step of the global protocol is generalisable to the different disciplines, including S&D simulation.

The applicability of the findings, including the ontology, the knowledge retrieval models and the KMS, is illustrated in Figure 4.12, following the global protocol, explained in Figure 4.11. Figure 4.12 outlines the extent of applicability of the models developed for crash simulation to S&D simulation and highlights the changes required. For the applicability of the ontology to S&D simulation, the first step is to gather and analyse documentation on S&D requirements and some reports on the resolution of S&D design issues. The information and knowledge related to the resolution of S&D design issues is structured using the proposed file for capturing engineering knowledge related to crash simulation (Figure 4.1). Figure 4.13 shows an example of a documented resolution of S&D design issue using the knowledge capture file. The same design issue resolution process is undertaken, and the same vocabulary is used to define design issues, causes, and design changes. As the CSPP ontology is developed from these files, we verify its applicability to the S&D discipline. As shown in Figure 4.12, all three levels of the ontology are verified. The context level formalises the technical requirement. Only concepts representing the impact configuration are modified into concepts representing the S&D configuration. Concepts related to the performance reference and the target on criterion stay unchanged.

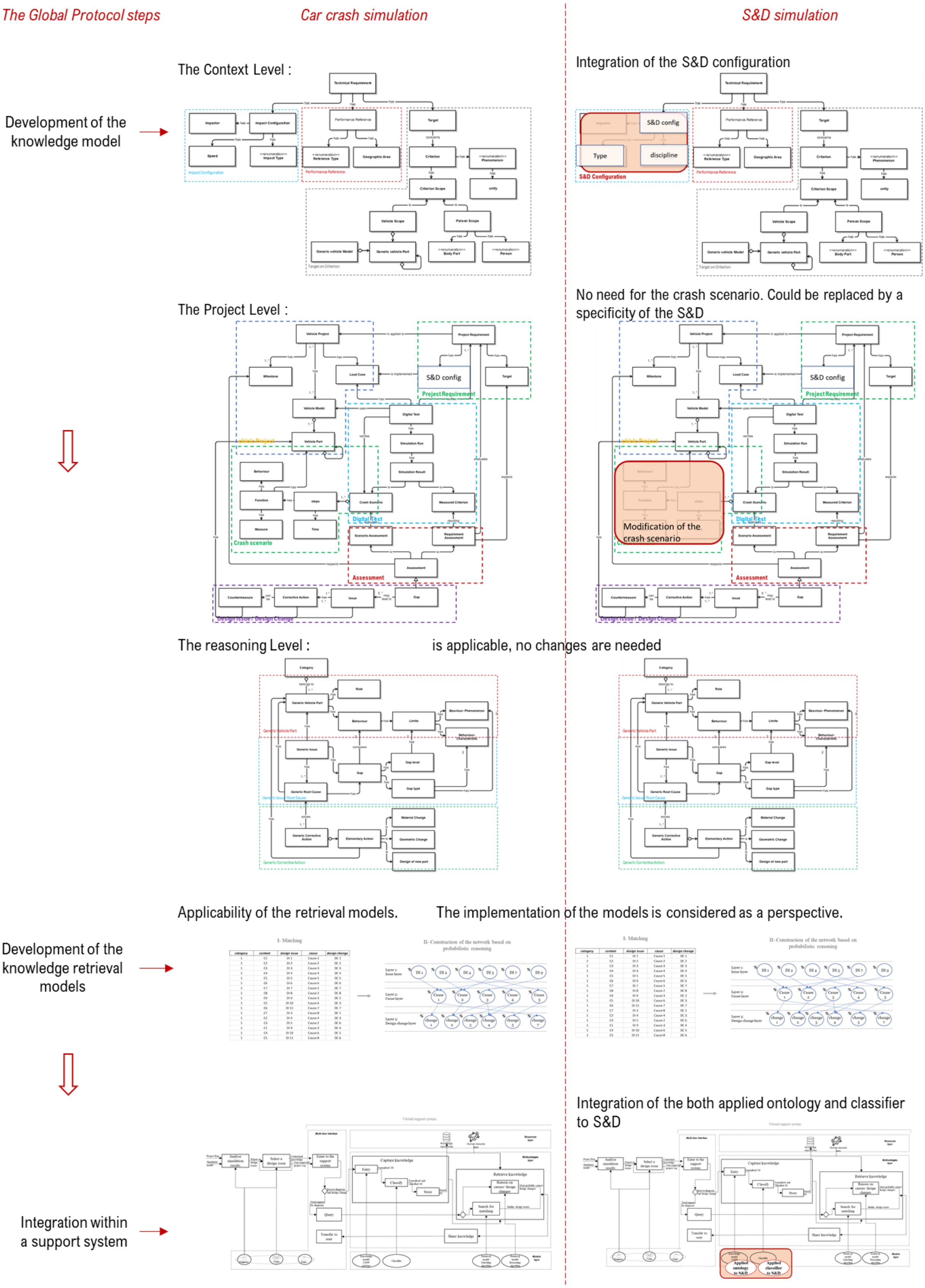

Figure 4.12 Applicability of the thesis research findings to the Strength and Durability simulation. The extent of the findings is analysed and the changes to be made are highlighted (orange zones).

For the project level, only the concepts related to the crash scenario are not relevant in the S&D context. It could be modified with the S&D scenario if necessary. Since design issues, root causes and design changes are described the same way in both simulation disciplines, the reasoning level can be applicable in S&D simulation. Since S&D itself focuses on distinct vehicle parts and scope, the categorisation can also be respected. The ontology is then applicable and generalisable to the S&D discipline.

The knowledge retrieval models, as mentioned in section 4.3.2, refer mainly to the level of reasoning of the CSPP ontology. Since the reasoning level remains unchanged, the retrieval models should apply to S&D simulation.

Finally, concerning the knowledge management system, only the models layer needs an adaptation to become applicable to S&D simulation. The ontology-based knowledge management system should integrate the ontology applied to S&D simulation. The classifier should also include categories that are specific to S&D simulation that may be different from the categories for crash simulation. For example, the classifier should assign a category to a vehicle part, from different perspectives, such as the crash simulation perspective and the S&D simulation perspective.

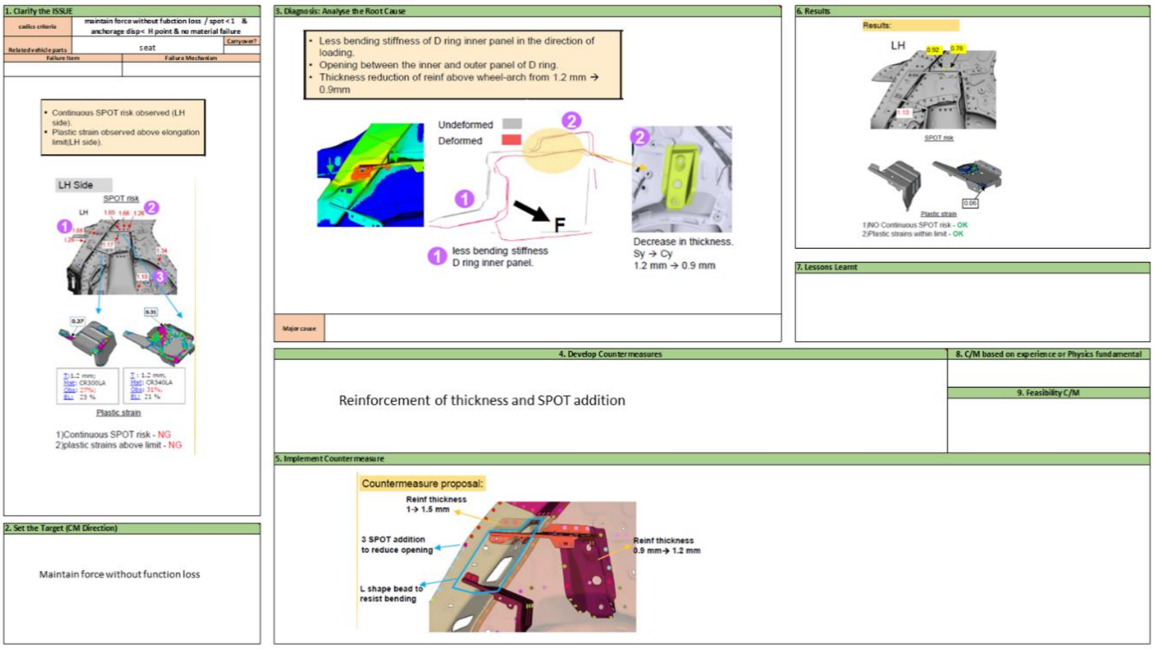

Figure 4.13 Applicability of the knowledge capture file to the S&D simulation. An example of a documentation of an S&D design issue using the knowledge capture file with a focus on knowledge related to the design issue, the root cause and the design change. (To be compared with Figure 4.1)

Based on a first analysis of the existing documentation on the different disciplines, such as noise and vibration, it appears that the generalisation of ontology is possible since the same laws of physics apply to the different disciplines. Therefore, a generic ontology, including the different simulation disciplines of vehicle development, could be framed. Only the changing concepts from the different disciplines should be duplicated. For example, at the context level, since only the configuration is discipline dependent, a "Discipline Configuration" concept should be added that includes the configurations of the different disciplines.

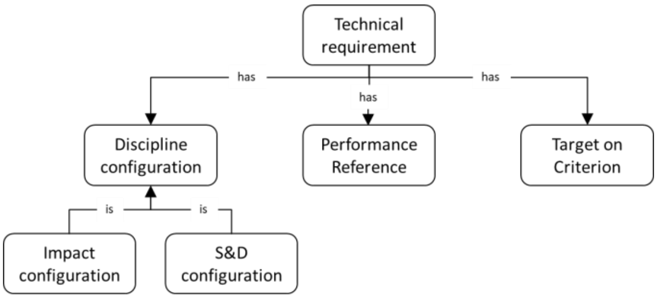

Figure 4.14 Simplification of the context level of a generic ontology. Since configuration concepts depend on the simulation discipline, the concept "Discipline Configuration" would group different configurations such as the impact configuration for crash simulation and the S&D configuration for S&D simulation. The configuration could be multiplied according to the disciplines considered in the vehicle development.

Figure 4.14 simplifies the context level of the generic ontology, showing both impact and S&D configuration as examples. It shows that only the discipline configuration needs to be duplicated for the different disciplines considered in vehicle development. Concepts representing the Performance reference and the Target on Criterion remain the same. The project level of the generic ontology should reproduce, as with the context level, the specificities of the disciplines, such as the crash scenario for crash simulation. The reasoning level of the generic ontology remains the same as that of the CSPP ontology. Therefore, the knowledge management system should be based on the generic ontology. For the categorisation of engineering knowledge, a generic classifier can integrate different categories for different disciplines.

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5 Discussion, Conclusions and Perspectives

Chapter 5 discusses the research hypothesis verification and the answer to the research questions. It also discusses the research quality. Then, it presents concluding remarks and outlines the perspectives of the research.

5.1 Discussion

We can conclude here that our principal hypothesis is verified; in fact, knowledge is a key factor for the improvement of simulation-aided design. The knowledge considered here is formalised thanks to an ontology, the CSPP ontology, that separates knowledge into context, project and reasoning. Then, to support simulation-aided design, we propose a virtual knowledge management system that integrates the CSPP ontology at different levels. Finally, research quality is addressed.

5.1.1 Hypothesis Verification and Response to the Research Questions

5.1.1.1 Hypothesis Verification:

Knowledge is a key factor for improving the process of simulation-aided design, in use in the company.

The empirical study verifies that multiple challenges are linked to knowledge, such as the lack of access to it, the need to share it and the non-formalisation of approaches since they depend on comprehensive knowledge. As explained in Chapter 1, our research objective stems from the need to improve simulation-aided design, by reducing time, and producing more robust vehicles. Therefore, to achieve this objective, we aim to support simulation-aided design. Based on the empirical study, we have identified that simulation takes time and relies heavily on expert knowledge. Therefore, we can reduce the simulation time by reducing the number of iterations to solve design issues by providing knowledge to the analyst. Reducing the time would reduce the cost of simulation. In addition, producing a more robust vehicle requires more accurate simulation results. This can also be possible by enhancing the company's knowledge of simulation. In short, the hypothesis that knowledge is a factor in improving simulation-aided design is verified with the results of the empirical study.

5.1.1.2 Response to RQ1:

What knowledge is needed for simulation-aided design and how can it be formulated?

We focus on the post-processing phase and the interpretation of crash simulation results, since the resolution of design issues is done in this phase of the simulation. Optimising an iteration of the resolution of a design issue should save an average of nine hours of computation and at least one hour of analyst effort for average issues. In addition, the pre-processing phase and the solver are well covered in the literature. Therefore, in our case, we identify the knowledge needed to solve the design issues in the post-processing phase and the interpretation of crash simulation results, formalising it then in the form of an ontology. We propose an ontology, called CSPP ontology, since we need a shared conceptualisation and vocabulary between the different stakeholders that is machine-readable and easy to implement afterwards. The resolution of design issues depends on the context, such as the configuration of the impact, the project vehicle and the requirement to be met. Then, resolution and proposals for design changes depend on analysts and experts' knowledge. Thus, to capture and formalise all the necessary knowledge, we start by formalising the context, which structures the overall background on crash simulation, independently of the project vehicle. The context is made up of all the information and knowledge related to the impact configuration, the performance to be achieved and the requirements to be met; the context is usually regulated. Then, the project also demarcates the resolution of design issues, such as project-specific requirements, the vehicle model itself, the simulation environment and the simulation results. Then, once the design issue is identified, analysts and experts get involved. Therefore, we propose a formalisation of their reasoning that is independent of the project but is mainly acquired through experience.

5.1.1.3 Response to RQ2:

How can we support the simulation-aided design process while integrating the pre-identified knowledge?

Taking into account the specificities of our context, and since engineering design is collaborative and knowledge-intensive, we propose a knowledge management approach to support the simulation-aided design process. Considering that engineering knowledge is already formalised using an ontology, the CSPP ontology, our approach to developing the knowledge management system is based on this ontology. Hence, the pre-identified knowledge is integrated into our support system proposal. The proposed knowledge management approach is integrated and collaborative. Collaboration is ensured while guaranteeing communication and collaborative working spaces. The integrated aspect is ensured by the integrated knowledge model, the CSPP ontology, and the integration of both the codification and the personalisation of knowledge.

The identified capabilities of the support system are collaboration, knowledge capture and knowledge retrieval. The proposed architecture of the knowledge management support system consists of a Multi-User Interface (MUI) and three layers: resources, methodologies and models. The MUI ensures collaboration. We have developed the knowledge capture block and the knowledge retrieval block. The models supporting knowledge capture are the knowledge model, i.e. the CSPP ontology, and the classifier, which classifies engineering knowledge according to the categories defined in the CSPP ontology. Knowledge retrieval follows the reasoning introduced in the CSPP ontology reasoning level, which is implemented as probabilistic reasoning.

In brief, to support simulation-aided design, we propose a virtual knowledge management system that integrates the CSPP ontology at different levels. First, as a knowledge model, the ontology formalises and captures engineering knowledge. Second, the classifier implements the categories of engineering knowledge specified in the reasoning level of the ontology. Finally, the retrieval models respect the reasoning level of the ontology by delimiting the search space using categories.

5.1.2 Research Quality

Different strategies are implemented to address the quality of research. For research validity, the credibility and reliability of the research are ensured through data triangulation, method triangulation and participant checking. Data triangulation and method triangulation are primarily carried out through the empirical study. Different data sources are considered, such as company documentation and experts. Furthermore, multiple data collection methods are used, such as interviews, workshops and document analysis. Participant checking is applied in this research for the different findings. Follow-up interviews and workshops were conducted to allow participants to comment on the findings. Comments on the transcripts were also taken into account. The generalisation of the research findings is also undertaken, thus enhancing external validity.

The research reliability is also considered through the proposal of the global protocol and the documentation of each step. The assessment of the current situation is thoroughly documented in Papers 1 and 2. Paper 2 details each step of the empirical study and explains the methods of analysis used. Paper 3 presents rich documentation of the methodology used to develop the CSPP ontology. Documents 4 and 5 detail methodologies used for the development of the knowledge retrieval models and the knowledge management system framework.

Finally, the usability of the research is also ensured. The user is integrated at each step of the research. Their validation of the industrial findings is always carried out. The achievement of industrial objectives can also be assessed since the significant findings are integrated into the DESLOOP tools and are implemented on a larger scale.

5.2 Conclusions

The work carried out during this thesis has contributed to the scientific and industrial understanding and application of knowledge approaches in engineering design. From a scientific point of view, this thesis highlights the research gaps concerning the representation of knowledge related to the post-processing phase of simulation, car crash simulation in particular, and the support of simulation-aided design using an ontology-based knowledge management system. From an industrial point of view, this thesis proposes solutions regarding the simulation process, the capture and formalisation of engineering knowledge and support of the simulation-aided design process.

The scientific contributions of this thesis are summarised as follows:

- A comprehensive empirical study using an adaptation of methods from safety and risk analysis, such as Preliminary Hazard Analysis and risk propagation.
- The development of an ontology to formalise knowledge related to the post-processing phase and the interpretation of simulation results, for car crash simulation.
- The proposal of a virtual, integrated and collaborative, ontology-based knowledge management system, to support simulation-aided design.
- The development of knowledge retrieval models, using probabilistic reasoning to support design issues resolution.
- Demonstration of the applicability and the generalisability of the research findings, including the ontology, the knowledge retrieval models and the knowledge-management support system

The industrial contributions of this thesis are summarised as follows:

- The capture of knowledge related design issues resolution using the proposed knowledge capture files.
- The formalisation of knowledge related to design issues resolution using the proposed ontology and its integration within the objectives of DESLOOP.

- The formalisation of car crash scenario and its integration within the ontology, to ensure better analysis of the simulation results.
- The proposal of more accurate design changes with more certainty about the simulation results.
- The improvement of the design process by saving simulation time and improving decision making about design changes.

5.3 Limitations

As discussed previously in section 5.2, the findings of this thesis contribute to both the state of the art in the knowledge management domain, and the improvement of simulation-aided design within the vehicle development process. However, this research has some limitations that prevent the direct industrial application of results.

A significant limitation is that knowledge capture has been done retrospectively, given that engineers and analysts consider knowledge capture tools to be intrusive. Simulation analysts have a heavy workload, hence so little time is spent documenting the resolution of design issues encountered. Therefore, the captured knowledge is biased, since not all the iterations are documented and only the retained design change is captured. This can result in a lack of useful design context and can be improved by capturing knowledge throughout the process.

Another limitation is the specificity of the industrial context in which the ontology has been developed. Even though the generalisability has been proven, further work is needed to enrich the context and improve the proposed ontology.

Regarding the knowledge management support system, only the most important activities have been developed and implemented. More details on the multi-user interface and additional KMS activities should be discussed. The knowledge retrieval model used in the proof of concept implementation is also simplified due to the lack of time and insufficient knowledge base. Further models' investigation for knowledge retrieval purposes should be done. Moreover, a sufficiently rich knowledge base should also be made available.

The findings of this research have been discussed in workshops concerning the DESLOOP project. In particular, the CSPP ontology played a role in the progress of the project. However, the implementation of our proposals in the wider context of DESLOOP could not take place simultaneously during the thesis progression due to scheduling offsets.

5.4 Perspectives

Further improvements can be done to widely implement the research findings within design activities in other vehicle development projects, or even across companies.

Since the findings are generalisable, further work on their implementation to other disciplines and contexts can also be undertaken. The ontology can be improved by introducing concepts related to the different simulation disciplines involved in vehicle development and by enriching it with more contextual concepts.

Further models' investigation for knowledge retrieval purposes should be done. Knowledge retrieval using Bayesian networks seem adequate while respecting the layers defined in our proposal. Bayesian network layers should integrate contextual elements. Further work could also focus on the relationships between the different nodes of a layer that could be represented as a network.

The knowledge management support system needs to be improved. A web-based prototype should be developed to facilitate users and system interaction. Moreover, an improved system interaction should allow users, with different roles, to work in their virtual spaces and create knowledge as the project progresses. System interaction should enable the knowledge base enrichment and models' improvement.

Large-scale implementation of the support system in the company is considered a necessary next step. The proposed solution should also be integrated within the design process to ensure knowledge capture throughout the process. The knowledge management support system could go beyond simple collaboration to become real-time concurrent engineering where each participant in each discipline could access the same vehicle model at the same time.

Finally, solving design issues through simulation is not limited to the automotive industry. The proposals of this thesis could be applied to other companies developing other means of transportation, such as buses, trucks and even planes.

PART II: List of Academic Publications

The second part of the thesis consists of the five academic papers resulting from the doctoral research work which have been introduced and summarised in Chapter 4. Paper 1 constitutes the first steps of the research and aims at a better understanding of the industrial context. Paper 2 details the empirical study. Paper 3 develops the CSPP ontology. Paper 4 presents the first steps towards the Knowledge Management System framework. Finally, Paper 5 develops the ontology-based knowledge management system to support simulation-aided design.

PART 1 Short Summary

Paper 1

A Proposition of a Knowledge Elicitation Methodology for Crash Simulation Diagnosis Support System

Published and presented in: The International Design Conference, DESIGN, 2018

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Abstract:

Crash simulation analysis process is a complex task because of the enormous data to analyse and the integration of different disciplines. This paper is integrated within a research about developing a diagnosis support system of car crash simulation. The overall purpose is, based on organisational and individual knowledge, to provide diagnostic support for experts. This paper only focuses on early difficulties encountered within this research. The knowledge about car crash simulation process is implicit. The objective is to build a methodology for eliciting implicit knowledge from experts.

Key words:

knowledge elicitation, design knowledge, knowledge-based engineering (KBE), design analysis

Reference: N. R. Fatfouta, J. Stal-Le Cardinal, and C. Royer, “A proposition of a knowledge elicitation methodology for crash simulation diagnosis support system,” in Proceedings of International Design Conference, DESIGN, 2018, vol. 4, pp. 1663–1672.

1. Introduction

Crash simulation analysis process is a complex task because of the enormous data to analyse (Kondo and Makino, 2008) and the integration of different disciplines. It solves crash simulation issues. This paper is integrated within a research about developing a diagnosis support system of car crash simulation. The overall purpose is, based on organisational and individual knowledge, to provide diagnostic support for experts. This would ensure proposing the most adaptable solutions to the simulation issues. The diagnosis support is a system capable of analysing symptoms, identifying root causes of the issue and proposing possible solutions.

This paper only focuses on early difficulties encountered within this research. The knowledge about car crash simulation process is implicit. Simulation issues solving is mainly based on the experience and expertise of the experts. The need of the elicitation of this knowledge from the experts is defined.

The state of the art made on Knowledge Acquisition and Knowledge Elicitation (Do Rosário et al., 2015; Wang and Min, 2007; Ya, Chervinskaya and Wasserman, 2000; Ford and Sterman, 1998; Cooke, 1994; Dhaliwal and Benbasat, 1990; Boose, 1989) done while preparing this research shows that it is a "bottleneck" in Knowledge Engineering and developing Knowledge Based Systems. Eliciting knowledge from experts is delicate because they cannot express all the knowledge they have.

The objective of this paper to build a methodology for eliciting implicit knowledge from experts. This methodology is based on a detailed description of the industrial context. A proposition of an issues solving process and cognitive process is made. Then a method for Knowledge Elicitation is proposed.

The structure of this paper is as follow. In section 2, the industrial background of the car crash simulation is described. In section 3, a state of the art on related research areas is developed. The last section represents the proposed methodology for Knowledge Elicitation.

2. Industrial background: Car crash simulation analysis

The case study focuses on the process of analysis of the crash behaviour of the vehicle: car crash simulation analysis. The inputs are the vehicle model and the requirements and specifications to be achieved. The output is the list of proposed Counter-Measures (CMs) to be applied. The CM is a corrective action (design action on the vehicle model) to solve one or various issues encountered in car crash analysis. An issue is defined as a failure to meet one or multiple specifications.

The team of car crash simulation analysis is international and decentralised. They are working daily on building CMs. The sample of the team studied is in France and is composed of eleven engineers. The coordination and collaboration with the rest of team is not considered in this study. They are also collaborating with engineers from other disciplines working on the same vehicle construction projects. This collaboration is also not considered.

In the Philosophy of Models in Engineering Design Workshop, Sissoko. T presented the simulation based issue resolution process (Sissoko, 2017). It describes the global process for all performances. Starting from the Design Reference, the Model Factory creates a model for simulation. Design References contains all the product specifications and knowledge about the evolution of the vehicle under development. The Model Factory is responsible for the development of the digital model. Then he runs a simulation to evaluate the performances. If the performance reach target, there is an update of the Design reference. If the performance does not meet the specifications, an issue is created to be solved. This is when the crash simulation team is involved. So, they work on CMs development to solve simulation issues within the crash performance in order to update the Design Reference.

The most critical phase in the crash simulation analysis is the diagnosis of the issue to find the most adapted CM. To reduce the number of iterations and the analysis time, the proposition of an automated diagnosis support is made. One the main problems is that, today, the analysis is mainly carried out by the simulation engineers (they can be described as the experts). There is no real capitalisation on the various issues and their CMs during the projects.

3. Theoretical foundation

The purpose of the research is to develop a diagnosis support system for car crash simulation. One of the first difficulties encountered is that knowledge about the CM development process is not explicit. The question is how to elicit knowledge from experts about the process to be implemented in the diagnosis support system. One of the alternatives is to build a Knowledge Based System to ensure the diagnosis support. And to do so, knowledge elicitation from experts is needed.

In this section, the state of the art on the different research areas is done to ensure a better understanding of the research problem. First, an understanding of the diagnosis is described. Then, a state of the art about Knowledge Based System, Knowledge Elicitation and implicit Knowledge is developed to identify the methods, advantages, difficulties and limitations of developing such systems.

3.1. Diagnosis

Diagnosis is the process of identifying the root cause of an issue / a problem from symptoms resulting from measurements or tests (Lamperti and Zanella, 2003). The problem could be a disease, a failure or a malfunction. The task of diagnosis can be seen as a classification problem of failures and so the diagnostic system as a diagnostic classifier (Rychener, 1985). Diagnosis is defined as the task of classifying an object to a desirable degree since observations about it and potential actions to be applied are available. As usually it is not possible to describe the true state of the object with certainty, the result of the diagnosis is a set of possible solutions (Puppe and Frank, 1999).

In the context of Artificial Intelligence, (Wagner, 2017) defined in their work that, diagnosis is the task of finding what is wrong with the physical system: based on observation about the system behaviour, a diagnostic reasoning has to find what is abnormal and responsible for such behaviour. In early work of (Liao, 2005), he defined diagnosis in expert systems as weighting and classifying complex patterns to evaluate a situation: abnormal or developable in a new way. It is also defined as inferring system malfunctions from observables (Liebowitz, 1997).

3.2. Knowledge Based System/ Expert System

Expert System (ES) or Knowledge Based System (KBS) (as a phase 2 of ES) is an application of AI. Knowledge Based System includes all the organizational information technology applications which are helpful to the management of knowledge assets (Wagner, 2017). (Do Rosário *et al.*, 2015) represented a brief history on expert system from the beginning in 1950s. A more recent work of (Liebowitz, 1997), the trends and utility of expert systems from 1984 to 2016 and proved the evolution of those systems in multiple domains. They are being developed in multiple application areas like diagnosis, perception, learning, design, planning etc.

Expert system is an AI application to solve problem in certain domain, based on the knowledge elicited from the experts of the field (Bowman, 2007). The components of an expert system are: the dialogue structure (user interface), the inference engine (control structure) and the knowledge base. The knowledge base is the most important component, it includes domain facts and rules of thumb based on experience (Liebowitz, 1997). Modelling knowledge is the most difficult aspect of developing knowledge based system (Cooke, 1994). The approach of building an expert system is “build a little, test a little” until the knowledge base is refined. Starting with defined the problem, the goal and the knowledge sources then the criteria. The next step is the acquisition and elicitation of knowledge. More details about this procedure is well described in (Gavrilova and Andreeva, 2012).

The most important concepts in KBS configuration are: rule-based systems, case-based configuration, constraint-based system, etc. (Günter and Kühn, 1999).

3.3. Knowledge Elicitation

Knowledge Elicitation is the process of collecting relevant information to the knowledge from human source. It is a part of knowledge acquisition which includes the explication and formalisation of this knowledge. And this later is a "front-end" of knowledge engineering, which is the process of building knowledge based systems or expert systems (Gavrilova and Andreeva, 2012). The purpose of knowledge elicitation is described by (Gavrilova and Andreeva, 2012) as developing methods and tools to ensure the efficiency and effectiveness of the task of "capturing and validating an expert's knowledge". Extracting and formalising the expert knowledge is considered as a critical 'bottleneck' in the development of knowledge based systems (Cooke, 1994; (Gavrilova and Andreeva, 2012); (Gavrilova and Andreeva, 2012).

In the literature, two roles are identified: the expert and the analyst or the engineer. The expert is the individual who possesses the knowledge to be elicited and the analyst/engineer is the person who is responsible for eliciting knowledge from the expert (Gavrilova and Andreeva, 2012).

Different methods and techniques of knowledge elicitation are described in multiples work like: interview either unstructured or structured, observation, card sorting, twenty questions … (Schweickert et al., 1987; Cooke, 1994(Ford and Sterman, 1998); (Wang and Min, 2007). Until this stage of work, interviews and observation are used as techniques for eliciting knowledge. (Ford and Sterman, 1998) developed a method for eliciting knowledge , which was employed by (Do Rosário *et al.*, 2015) in his case. The approach is described on three phases: position phase, description phase and discussion phase. And for each phase different techniques can be employed.

3.4. Implicit Knowledge

The knowledge is usually implicit or tacit, not explicit. Implicit knowledge is subjective and context-specific, which makes it "difficult to describe, examine and reuse" (Ribeiro, 2013). Based on the work of Nonaka and Takeushi, (Holste and Fields, 2010) resumed the conversion of knowledge between its two dimensions, implicit and explicit, in order to create knowledge in an organization. Tacit knowledge is the kind of knowledge that a human develop through the experience over the years, and can be transferred by a set of instructions (Sissoko, 2017). (Kondo and Makino, 2008) proposed in his work a comparison table of explicit and tacit knowledge based on the literature: explicit knowledge is impersonal, easily reduced to writing and tacit knowledge is personal, difficult to reduce to writing and ingrained by the experience and values.

3.5. Synthesis

A literature review on diagnosis process helps determine the nature and type of information needed to successfully diagnose a problem and propose robust solutions. The results of the diagnosis process are different alternatives of solution (CM), based on the analysis of the issue symptoms and causes.

In our case, the work is mainly carried out by humans. Most of the knowledge about the diagnosis process is implicit and based on heuristics. In order to develop a knowledge-based diagnosis system, knowledge elicitation from experts has to be done. The techniques of knowledge elicitation to be used in the methodology will be interviews and observations. A thinking about maintaining the knowledge base dynamic is important in order to ensure the evolution of the knowledge within the knowledge-based system.

4. Methodology

The research project is evaluated as a type 5 of research within the Design Research Methodology Framework “Development of Support Based on a Comprehensive Study of the Existing Situation” (Blessing and Chakrabarti, 2009). And in this paper, only initial proposition for the perspective study is proposed (could be seen as a type 2).

This paper presents a methodology for extracting and acquiring knowledge. The purpose is to analyse the industrial context and to propose an alternative for eliciting the knowledge about simulation issues solving process. After the identification of the industrial needs presented in section 2 and the literature review, a descriptive study is done. It supports a better understanding of the industrial context. Based on the analysis results of this phase, a proposition of a knowledge elicitation file is made.

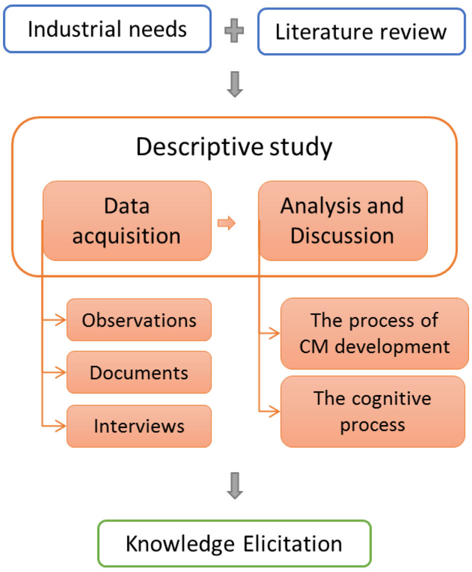


Figure 1. The Methodology for Knowledge Elicitation

4.1. Descriptive study:

Based on qualitative methods and KA techniques, a descriptive study is made. Data acquisition is supported by three different techniques: observations, documents and interviews. Then a discussion based on the collected data is made to better define the case study. Some propositions are developed.

4.1.1. Data acquisition

Different stakeholders are involved with the crash simulation activity, only the close team is considered in this case study. The focus of interviews and observations is within the team composed of eleven engineers working on the development of CMs and the simulation expert (on a managerial level) who’s involved with this study. More details about the methods used is described below:

- Interviews: unstructured interviews are chosen to get a better understanding of the situation. First, one of the engineers (considered as domain experts) was the interest of iterative unstructured interviews. The goal was to describe how the work was done. For each interview, notes are made. Then the notes are analysed and combined with the previous ones. New questions arise. Another interview is conducted to validate previous comprehension and provide more knowledge.

- Observations: organised meetings to discuss current issues were proposed to observe discussions about different experts. Assessing to meetings to note the CM development suggestions. Two tutorials about building CM were proposed by one of the experts.
- Documents analysis: documents about the global process, different configurations of crash tests, list of the specifications and feedbacks from different meetings were analysed.

Based on interviews and observations, no formal description of the symptoms is communicated, and no root/major cause is discussed. Once this issue is identified, the search for CMs is done in a heuristic way, no diagnosis is done. A rethinking about the process of CM development will be discussed in section 4.1.2.

Based on the documents' analysis, some needed documents were not available: capitalisation on diagnosis process, documents on lessons learned or experience feedbacks, documentation on all current issues to be treated etc.

The deduced dysfunctions can be divided into three axes, which are interconnected and dependent:

- Knowledge and expertise related: there is no specified knowledge capitalisation process for the different projects (the existent capitalisation process is more at the decision-making level than the daily tasks level). The information is decentralised, everyone has their share of it, and nowhere to find all necessary information on certain needs. There is also a risk of loss in expertise, as employees would frequently change activities.

- Process related: iterations without any certainty or prediction of the results. The engineers treat daily a large amount of data. There are regular evolutions in the software used, which requires a big storage of the projects.

- Team related: the work is decentralised at the international level, different levels of experience, different perceptions on the tasks. Some small meetings (between two or three persons) with no reports (knowledge and expertise axis) because of the multiple meetings per day. Some neglected information can be so important for the rest of the project.

4.1.2. Analysis and discussion

In this section, results and propositions to be adopted for the rest of the study. As stated above, a proposition of a process for CM development is built to highlight the diagnosis phase. Experts are asked to follow it and to provide knowledge about the diagnosis. In the second part, an issue-solving cognitive process is presented. The purpose is to build a causal model relating issues to causes and then to CMs, then to automate it. In this paper, the focus is on building of the model.

4.1.2.1. The process of CM development

A rethinking about the CM development process is descried. The diagnosis phase needs to be explicated, and the experts needs to adopt this updated way for building CMs. Figure 4 presents the proposed CM development process. The diagnosis task will be explicitly done by the experts while thinking about the solution for a certain issue, they need to consecrate time to answer it and put words into it.

All simulation issues are reported into the file containing the list of specifications of the project (Excel file to ensure traceability). The process starts with expert choosing an issue represented by a specification not met. The CM development process is composed of 5 main phases:

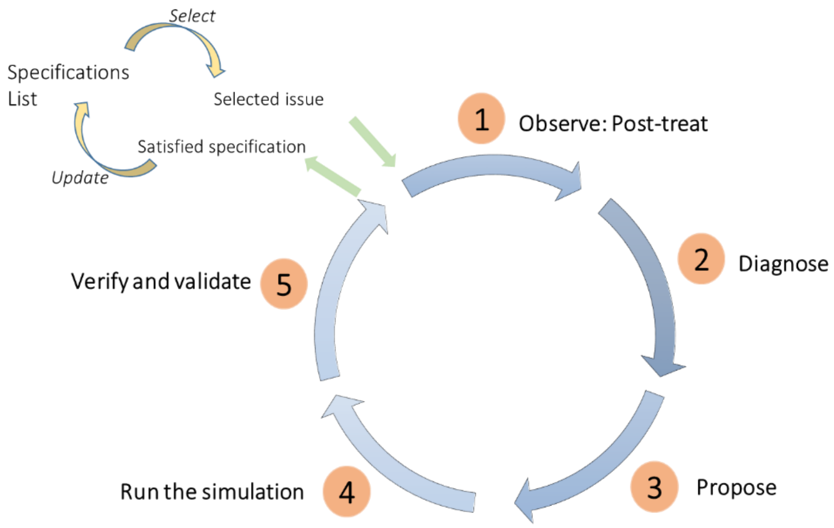


Figure 2. The process of CM development

1. Observe / post-treat: The post-treatment phase of the crash simulation results, the model animation, values.
2. Diagnose: Based on his experience, the engineer analyses the symptoms, identifies possible causes and selects the major causes.
3. Propose a possible re-design: Based on observation and analysis, the engineer determines the most appropriate re-design (possible CM) to solve the simulation issue and modify the design.
4. Run the simulation: This phase is automatically done by the software, to test the new behaviour of the vehicle model again.
5. Verify and validate: Based on the new results, the engineer checks whether they meet the specifications. If so, he validates the CM (a retained re-design proposition), updates the specifications list and goes to a next no ok case. If the specifications are not met, a further iteration on the process is requested, starting by the observation phase.

The validation step is simplified in this modelling process. To validate a re-design as a CM, constraints related to the project (besides the crash specifications) needs to be respected, such as the budget value of the re-design, weight, respect all performances, etc.

4.1.2.2. Deduced cognitive process and resulting Mental map

The focus is on the cognitive process of solving the simulation issues. To solve it means to propose CMs alternatives to help meet the specifications. Today, this process is no explicit. The considered alternative in this paper is to translate the solving process into a causal model. It would relate an issue to its causes, and then the CMs to the causes. The mental map results from the cognitive process to solve simulation issues. The process is based on experience and expertise. The cognitive simulation issue-solving process and the resulting mental map are represented in Figure 3.

For each issue (for example issue 1), an identification of symptoms is made. Then, the major causes related to these symptoms, is selected from a mental causes list (Cause x is selected from the list [cause1, cause 2, …, cause n]). This list is referred to as mental because it is based on the experience, in previous projects, knowledge about mechanics and physics and the heuristic engineering reasoning. It links symptoms to their possible causes. The major causes are identified, then, based on a CMs mental list, the identification of the most appropriate redesign is done (Redesign alternative z is selected from the list [redesign altv1, redesign altv2, …, redesign altv p]). The second list is the same as the first one, but links causes with redesigns to solve the issues (redesign alternative z is the most appropriate to the cause x identified as a major cause of the issue1).

The validation of the proposed redesign will be ensured by the simulation. The global list is a relationship between symptoms, their related causes, and the corresponding CMs. It represents the knowledge of each person. The more experienced they are, the longer the list will be. The goal is therefore to extract knowledge from this list.

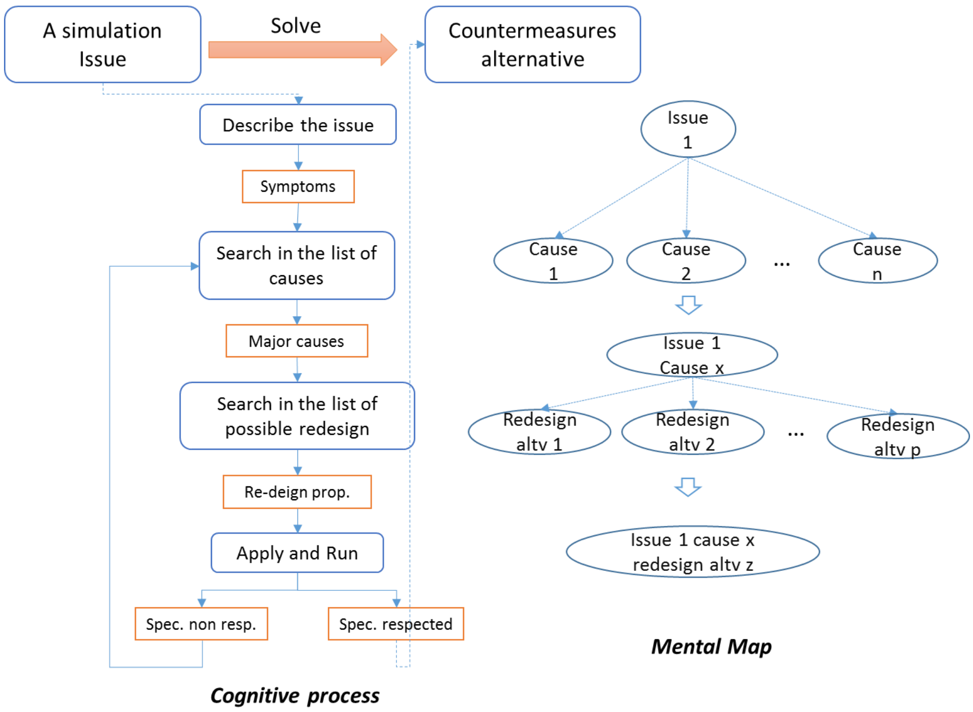


Figure 3. Cognitive Process and resulting Mental Map

4.2. Knowledge Elicitation

Based on the results of the analysis and discussion phase, a knowledge elicitation method is proposed. The experts are asked to work on filling an elicitation file and hebdomadary meetings are set to discuss the elicited knowledge and formalise it. The elicitation file is created based on the different phases of the CM development process (section 4.1.2.1). And it will be filled according to the cognitive process section 4.1.2.2). The purpose is to elicit knowledge about building CMs within current projects. Each expert work on the file during the week. The discussion between the different experts on the filled information ensures the robustness and the formalisation of the knowledge.

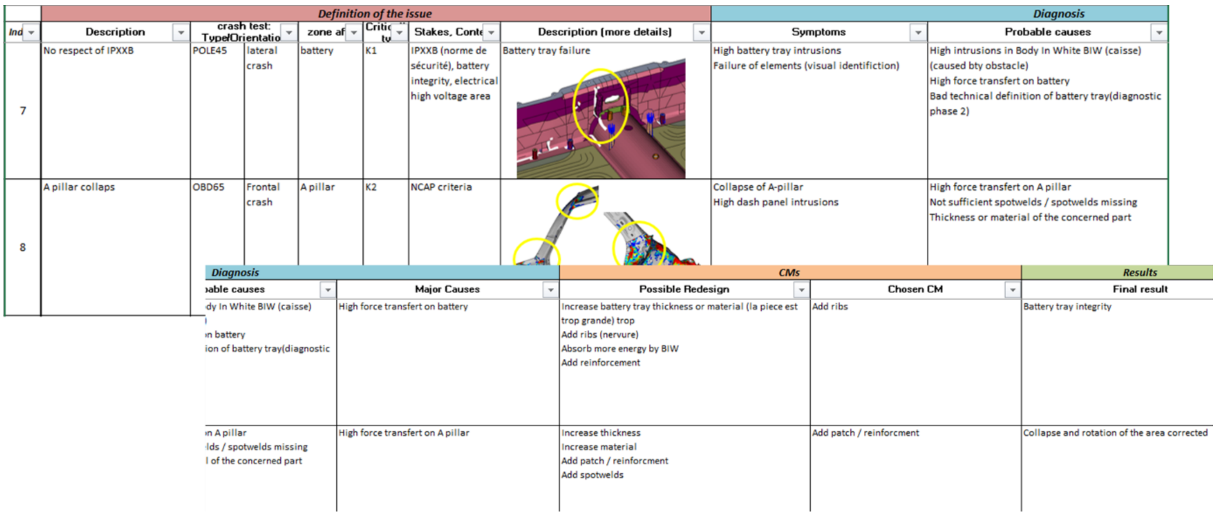
The different sections of the elicitation file are represented in Table 1.

Table 1. Sections of the elicitation File

	Definition of the issue				Diagnosis			CMs		Result
Id	Description	Crash test	Aff. zone	C	Symptoms	Prob. Causes	Major Causes	Poss. Redesign	Chosen CM	Result after CM

- Id: Index column for each case studied.
- Definition of the issue: A description of the crash simulation issue, type and configuration of the crash test, the effected zone or module of the digital model and C the criticality of the issue.
- Diagnosis: According on the cognitive process, a detailed description of symptoms is made (unusual behaviour). The list of all the probable causes related to the issue is listed. Finally, the major cause(s) is selected. Getting all the possible causes would help categorise some of them.
- CMs: Counter-Measures: The experts would write down the list of the possible redesigns useful to solve the issue considering its related major cause. The chosen CM is the validated one within the project. Another table is designed to gather information on the different iterations on the possible redesign tested as well as the decision and its reasons for each one.
- Result: In this section the results after integrating the CM is described to validate that the issue is solved.

At this stage, the table is being filled by the experts in an intuitive way. The work on the ontology to use would be iterative and discussed within the meetings. Figure 4 shows an extract from the elicitation file. More sections exist in the real file to help get a better definition of the issue: The details description section can contain a picture to locate the issue. Stakes and context are additional information to judge criticality and context of the issue.



	Definition of the issue							Diagnosis	
Ind	Description	crash test: Type/Orientatio		zone af	Criticity	Stakes, Conte	Description (more details)	Symptoms	Probable causes
7	No respect of IPXXB	POLE45	lateral crash	battery	K1	IPXXB (norme de sécurité), battery integrity, electrical high voltage area	Battery tray failure	High battery tray intrusions Failure of elements (visual identifiction)	High intrusions in Body In White BIW (caisse) (caused bty obstacle) High force transfert on battery Bad technical definition of battery tray(diagnostic phase 2)
8	A pillar collaps	OBD65	Frontal crash	A pillar	K2	NCAP criteria		Collapse of A-pillar High dash panel intrusions	High force transfert on A pillar Not sufficient spotwelds / spotwelds missing Thickness or material of the concerned part

Diagnosis		CMs		Results
able causes	Major Causes	Possible Redesign	Chosen CM	Final result
dy In White BIW (caisse) n battery ion of battery tray(diagnostic	High force transfert on battery	Increase battery tray thickness or material (la piece est trop grande) trop Add ribs (nervure) Absorb more energy by BIW Add reinforcement	Add ribs	Battery tray integrity
n A pillar lds / spotwelds missing l of the concerned part	High force transfert on A pillar	Increase thickness Increase material Add patch / reinforcment Add spotwelds	Add patch / reinforcment	Collapse and rotation of the area corrected

Figure 4. Screen shot of the elicitation file

The file ensures the creation of knowledge about the CM development process based on the diagnosis. The goal is to create enough formalised knowledge and start automating the diagnosis phase.

From analysing feedbacks of the hebdomadary meetings, improvements on the file has been conducted. The purpose is to ensure flexible filling and that all necessary knowledge is explicit and available.

5. Conclusion and Outlook

The methodology, in this paper, ensured a better understanding and formalisation of the CM development process. The diagnosis phase is now explicit, and experts need to formalise their knowledge. Issues solving is not deterministic. This problem needs to be taken into consideration.

Experts have some difficulties explaining their knowledge because it is based on heuristic and contextual language. Hence, workshops on issues diagnosis will be organised. In these workshops, the most frequent issues will be described, and the related CM development process will be discussed. The goal is to identify whether the process is based on experience (for some issues) or on physics and mechanics (analysis of the simulation results).

Based on the first results from these workshops and daily work, the file will be improved. It would be easier and faster to complete and would cover all the necessary information. The improvement will be iterative and based on feedbacks from weekly discussions and workshops.

Further work is conducted to ensure the robustness of the methodology.

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Paper 2

Empirical Study of Car Crash Simulation Analysis within the Development Phase

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Abstract:

Car crash simulation analysis is an important phase within the vehicle development. It intends to analyse the crashworthiness of the vehicle model and examine the level of passive security. However, this activity is not trivial because of the considerable collaboration within the project, the large amount of analysed and exchanged data and a high exigency. Consequently, a solution to assist, ease and reduce the time of the process is desired.To study the current practices followed in the car crash simulation analysis an empirical study has been conducted. This study has been applied within the simulation analysis team, in the development phase, within an automotive company. This paper describes a qualitative analysis of the industrial context and diagnoses the dysfunctions in the current practices. This paper also highlights the current challenges encountered in the car crash simulation analysis.

Key words:

Knowledge management, Case study, Process modelling

Reference: N. Fatfouta, J. Stal-Le Cardinal, and C. Royer, “Empirical Study of Car Crash Simulation Analysis within the Development Phase,” in 22nd International Conference on Engineering Design ICED, 2019, pp. 2843–2852.

1. Introduction

Car crash simulation is used to analyse the crashworthiness of the vehicle and examine the level of safety of the car and its occupants. The crash simulation analysis process is a complex task due to the enormous amount of data to be analysed and the involvement of different disciplines.

This paper presents the first steps of a research work which aims to develop an approach to support and optimise the crash simulation analysis process. This process is time-consuming, and the required effort is considerable. This paper presents an empirical study that has been conducted within a French automotive company. The aim of this study is to capture the difficulties encountered within the development phase of a vehicle, and more especially during the simulation process.

Within this company, engineers are organised in teams and projects. Teams are organisationally independent of each other. Each team has its own objectives, skills, competencies, expertise and resources. However, they have different levels of involvement in projects. A project is a transversal environment that brings together different teams and entities collaborating to achieve a common objective. Thus, to better understand and analyse the situation, it is necessary to study both the team and project.

In our context, the simulation analysis is knowledge and expertise based (knowledge intensive activity). The simulation analysts possess the tacit knowledge about analysing the simulation. Understanding the simulation results and solutions provided as countermeasures for identified issues is possible due to knowledge possessed by experts. Knowledge capitalisation is essential because it allows engineers, with different levels of experience, to have access to the required information.

This paper aims at a better understanding of the context and an identification of problems in the team's functioning called dysfunctions. It also aims at identifying the team dysfunctions that have the highest impact on the project.

The rest of this paper will be organised as follow: Section 2 reviews the related literature. In section 3 we describe the methodology. In section 4, we detail and analyse the case study of car crash simulation analysis. Section 5 discusses the challenges encountered. Finally, section 6 draws conclusions and gives insights into future work.

2. Related work

"Numerical simulation techniques are essential in today's engineering design practices." (Kestel et al. 2019). The Finite Element Method (FEM) is the most successful method of numerical simulation and engineering analysis: stress analysis, structure deformation and mechanical vibration. Wriggers et al. state that the tasks within the FEM analysis process can be divided into tasks with algorithmic nature and non-algorithmic tasks involving a knowledge-based approach (Wriggers et al. 2007). The algorithmic tasks are the meshing, the FEM computation itself and the visualisation of results. The non-algorithmic tasks are problem classification, decision making about parameters, evaluation and interpretation of the result. These tasks influence the accuracy, the quality and reliability of the results and require considerable comprehensive knowledge and a high level of expertise from the specialist (Kestel et al. 2019; Wriggers et al. 2007). The algorithmic tasks can be considered as the phases of the FEM analysis process: pre-processing (setup), computation (analysis solver) itself and post-processing of results. The non-algorithmic tasks can be seen as enabling or support tasks to ensure the efficiency and the quality of the process. The focus will be on the non-algorithmic (knowledge-based) tasks. To our knowledge, most of the studies focus on both pre-processing and computation phases. We focus on post-processing knowledge.

"Engineering design is a knowledge-intensive process" (Peng et al. 2017). A knowledge-intensive process is knowledge and data-centric process. The conduct of a knowledge-intensive process depends heavily on "knowledge workers performing interconnected knowledge intensive decision-making tasks" (Di Ciccio et al. 2015). Brandt et al. affirm that knowledge about the engineering design process is the most valuable asset for modem companies. This knowledge is implicit and relies on the personal experience backgrounds of designers. And to exploit this knowledge, it must be explicit and shared across the company (Brandt et al. 2008).

Post-processing of simulation results is heavily depending on the knowledge and expertise of analysts. Therefore, knowledge capitalisation is essential because it allows engineers, with different levels of experience, to have access to the required information.

3. Research methodology

To have a better understanding of the industrial context, we conducted a descriptive study. It consists of observing the analysts' team and their simulation analysis activity within vehicle project context, interviewing the analysts and analysing the relevant company documentation (Figure 1). The descriptive study has allowed us to model the current car simulation process and analyse the context to identify the industrial challenges. The results of this study have been discussed and validated by analysts, experts and the simulation department head. Section 3.1 and section 3.2 detail the methodology used.

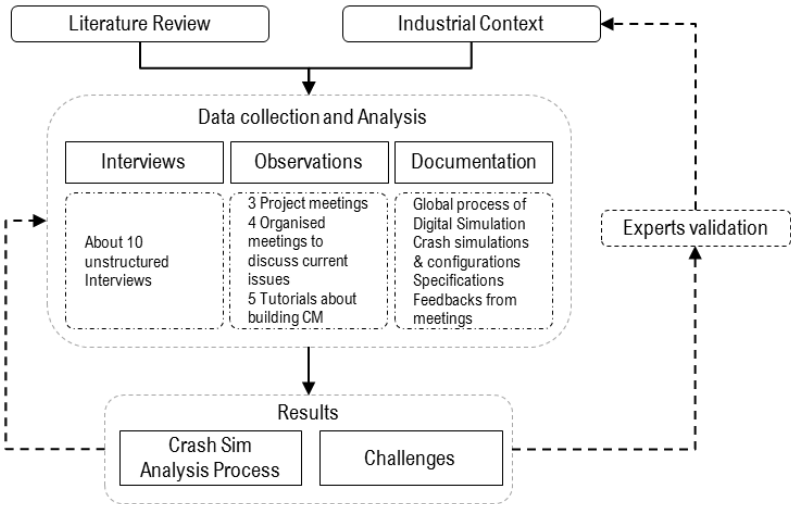

Figure 1. Research Methodology

3.1. Data collection

We have started the data collection with direct observations. This included observations of analysts while conducting their activities and during 3 project meetings. As a result, we built the simulation analysis process. Moreover, we have organised and participated in 3 meetings dealing with specific cases. We concluded that even within different vehicle projects, the simulation issues encountered can be similar, and hence they can be compared and overlapped to adapt the solution of one problem to the other. Interviews and documentation were conducted to assist and control the observations. Interviews with analysts were mainly unstructured and iterative. The interview included questions about the daily work, the existing process. Interviews have also helped us to validate our understanding and modelling. Interviews with experts and department head support the validation and decision about the risks to avoid on the project. Company documentation was also analysed to better understand the activities, the specifications and the different requirements.

3.2. Data analysis

Given the constraints imposed by the industrial organisation and the development process, two levels can be identified within the vehicle project: First, the Team-level (simulation analysis team); they form an independent entity within the organisation. They have their own objectives and participate in the development of the project. Second, the Project-level (vehicle development project) which is a transversal environment. It brings together multiple teams collaborating to achieve a common goal. Based on this distinction, two analyses are carried out for identifying the dysfunctions within the team that could disturb and impact the project.

3.2.1. Team-level analysis:

The purpose of the team-level analysis is to illustrate the team's activity, resources and objectives and to identify dysfunctions within the team. Dysfunction is a problem in the team's functioning. A qualitative analysis of dysfunctions and their propagation is carried out. First, we describe the characteristics of the team and their context. Then, we distinguish dysfunctions. Second, we introduce the notion of Induced Dysfunction: An induced dysfunction is a dysfunction that could be induced by another element. An element could be a dysfunction, a characteristic, or a combination of both. This analysis would determine the most inducting dysfunctions, the most induced ones or both elements.

3.2.2. Project level analysis

At the project level, inspired by the Preliminary Hazard Analysis (PHA), we will link team-level dysfunctions to project risks. The aim is to identify the team-level dysfunctions with high impact on the project. PHA is used to reveal and identify potential hazards, threats and hazardous events early in the system development process (Rausand 2011). PHA aims at identifying a hazardous element, how it could lead to an incident, leading to an event that could cause a hazardous situation. But, the cause/consequence relations linking the hazardous events can be explored via inductive or deductive reasoning. If preliminary knowledge is more about the consequences, we proceed by deduction to identify the causes. On the opposite, if preliminary knowledge is related to the causes, we proceed by inductive approach (Mazouni et al. 2007). In our case, we will proceed by the deductive approach.

The aim is to identify the risks to avoid at the project, and then, to search, at the team-level, for the dysfunctions that could lead to those risks. Later, the focus will be on these dysfunctions because of their high impact on the project progress. The primary interest is to ensure the successful completion of the project.

4. Case study: car crash simulation

4.1. Industrial Context

The empirical study is conducted in the context a vehicle project, during the development phase, within a French automotive Industry. This study focuses on the car crash simulation analysis process and the involved team within the process (simulation analysts). More details about the vehicle projects and the decision process are discussed in the work of Sissoko et al. (Sissoko et al. 2018).

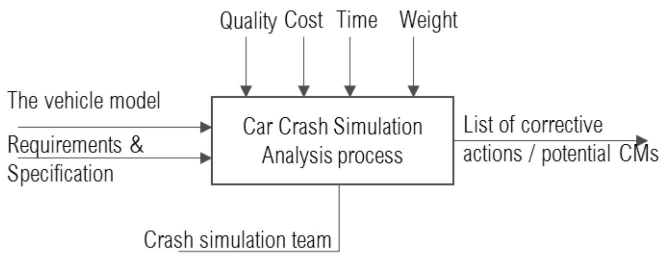

Figure 2. Structured Analysis and Design Technique (SADT): Car Crash Simulation process

For each milestone, the team receives the project vehicle model and the list of requirements and specifications to be satisfied. A specific vehicle model is extracted from the basic vehicle model that is customised based upon the required specifications to get the target model. Vehicle models are deduced from a generic model. The crash simulation analysis process (SADT representation in Figure 2) consists of identifying issues (where requirements are not satisfied) and proposing a corrective action for each one. A corrective action (CA) is a demand for a design modification to be applied to the vehicle model in order to satisfy the requirements. The CA could be multiple complementary small actions. A countermeasure (CM) is a validated CA within the project (since it verifies the different project constraints).

Table 1. The Context of the Case study

Collaboration	Complexity	High Exigencies
• Collaboration: international teams & teams from other disciplines • A collaboration with the analysts in India is taken into consideration	• The team is international and decentralised • The sample of the team studied is in France and is composed of eleven engineers • Each analyst is working on a vehicle project (sometimes more than one) • A vehicle project considers: one vehicle range, targeted market • Large amount of data treated daily	• Daily work on multiple issues. • Deliver potential Countermeasures CM (solutions) daily • Ensure the activity at a lower cost • Robustness of the proposed CMs

The decision-making process about CMs is not considered in this study; only the result (decision to validate or not a CA as a CM) is considered. Our focus is mostly on the analysis activity (identification of issues and proposal of CAs). The decision depends on the project specific constraints. Sissoko et al. focus on the decision-making process (Sissoko et al. 2018). In Table 1, the context of the case study is characterised. We propose this categorisation in order to respect the vehicle project development as much as possible.

As the Simulation analysis activity is based on tacit knowledge, experience and expertise of the analysts, we propose to capitalise on this know-how. The aim is to explain their reasoning and know-how. We proposed a file, with instructions, for analysts to fill-in. One file will contain one issue, its analysis and the proposal of CAs and CMs. These files will form the first knowledge base. Figure 3 illustrates an example of an issue and the related CAs and CMs. The focus is on the diagnosis of the issue and the proposal of CAs. The clarification of the issue (step 1) describes the issue. Setting the target (step 2) helps the analyst define his objectives. The diagnosis (step 3) clarifies the analysis of root causes. The development of CAs (step 4) proposes different CAs to solve the issue. After decision making, the analysts implement the decided CM that solves the issue and satisfies the project requirements (step 5).

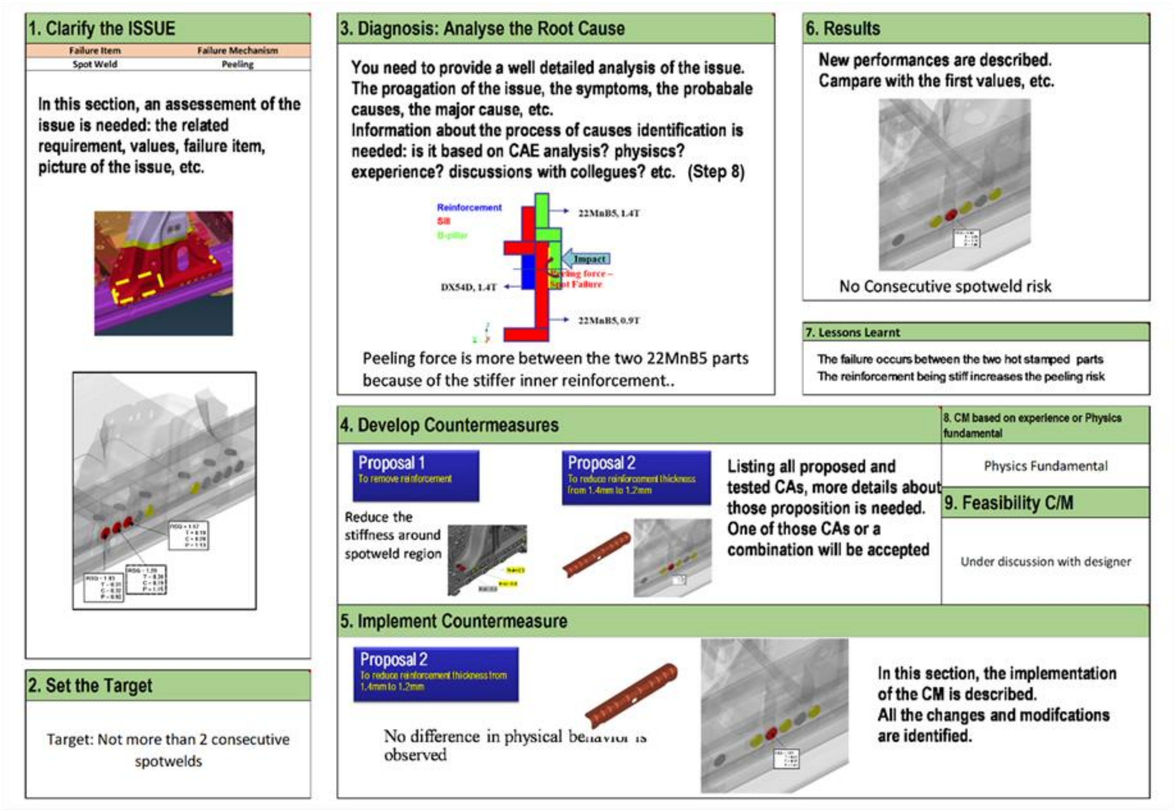

Figure 3. An example of capitalisation on an Issue solving and CM proposition (in 9 steps)

Finally, the analyst draws the results of the implementation of the considered CM (step 6). Lessons learnt are reported (step 7). We added a step for information about the feasibility of the Countermeasures (step 8). And we tried to capitalise on whether the CA is proposed based on experience (seen before) or physics and mechanics fundamentals (step 9).

4.2. Car Crash Simulation Analysis Process (As-Is)

Figure 4 represents the modelling of the current process of crash simulation analysis. When performance does not reach the requirements target, an issue is created. The simulation analyst, in collaboration with other engineers from the project, works on proposing CAs. Then they wait for the decision (while working on other issues). Sometimes, several iterations are necessary. If the CA is rejected (not satisfying the context of a specific project), the analyst needs to refine his proposal. If the CA is validated as a CM, the resolution process is closed.

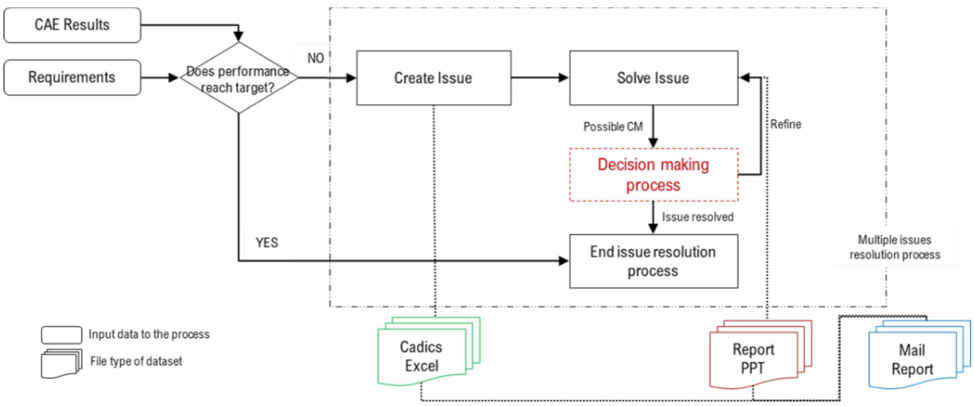

Figure 4. Crash Simulation Analysis Process and data/ information transfer (As-Is)

4.3. Analysis at the team level: Induced Dysfunctions

In Table 2, we propose to classify the observations at the team level into three categories: Process related (all processes considering tasks and activities of analysts), Information & Knowledge related (flows of information and knowledge, sources, detention, etc.), and Design approach related (the how to do their work, how to think) observations category. This categorisation describes at best the functioning of the team. The team must adjust to the development process of vehicles. An important amount of information and knowledge is involved.

Table 2. Observations at the team-level: Characterisation and Dysfunctions

Categories	Characteristics	Dysfunctions
Process Related Observations	Collaboration Individual tasks Decentralised international teams Weekly meetings (discussion and decision making) Time / cost dependency …	No formalised process for diagnosis and analysis Many iterations with no certainty or prediction of the results Multiple models for each analyst No shared templates for presentations in meetings …
Information and Knowledge Related Observations	Decentralised information Different level of expertise Employees would frequently change activities Knowledge is detained by analysts and experts Large amount of data treated daily …	No specified knowledge capitalisation process Limited access to all the knowledge Loss of expertise No certainty of the exhaustivity of the shared information No lessons learnt/ No design database …
Design Approach Related Observations	Experience and Expertise based approach Heuristic approach (no search for optimal solutions) Time / cost dependent …	No lessons learnt on the approaches used No formalised approach Weakness of validation of the approach …

As the simulation analysis is based on expertise, we propose to separate the design approach to emphasise its importance. Within each category, a distinction is proposed between the characteristics (elements describing the category) and the dysfunctions (elements pointing to the problem within the category). For example, for the Information & Knowledge related observations category, "decentralised information" and "different level of expertise" is only a characterisation of the context. But, the "no specification of a knowledge capitalisation process" is seen as a dysfunction. Then, the three categories were mapped with respect to their characteristics and dysfunctions (Figure 5), to explicit the relation between potential dysfunctions from the different categories. Each category is represented by a table. Each table has two columns, one for the characteristics and another for the dysfunctions. The Induced Dysfunctions, highlighted in the mapping of figure5, are analysed. To do so, we introduce the notion of induction.

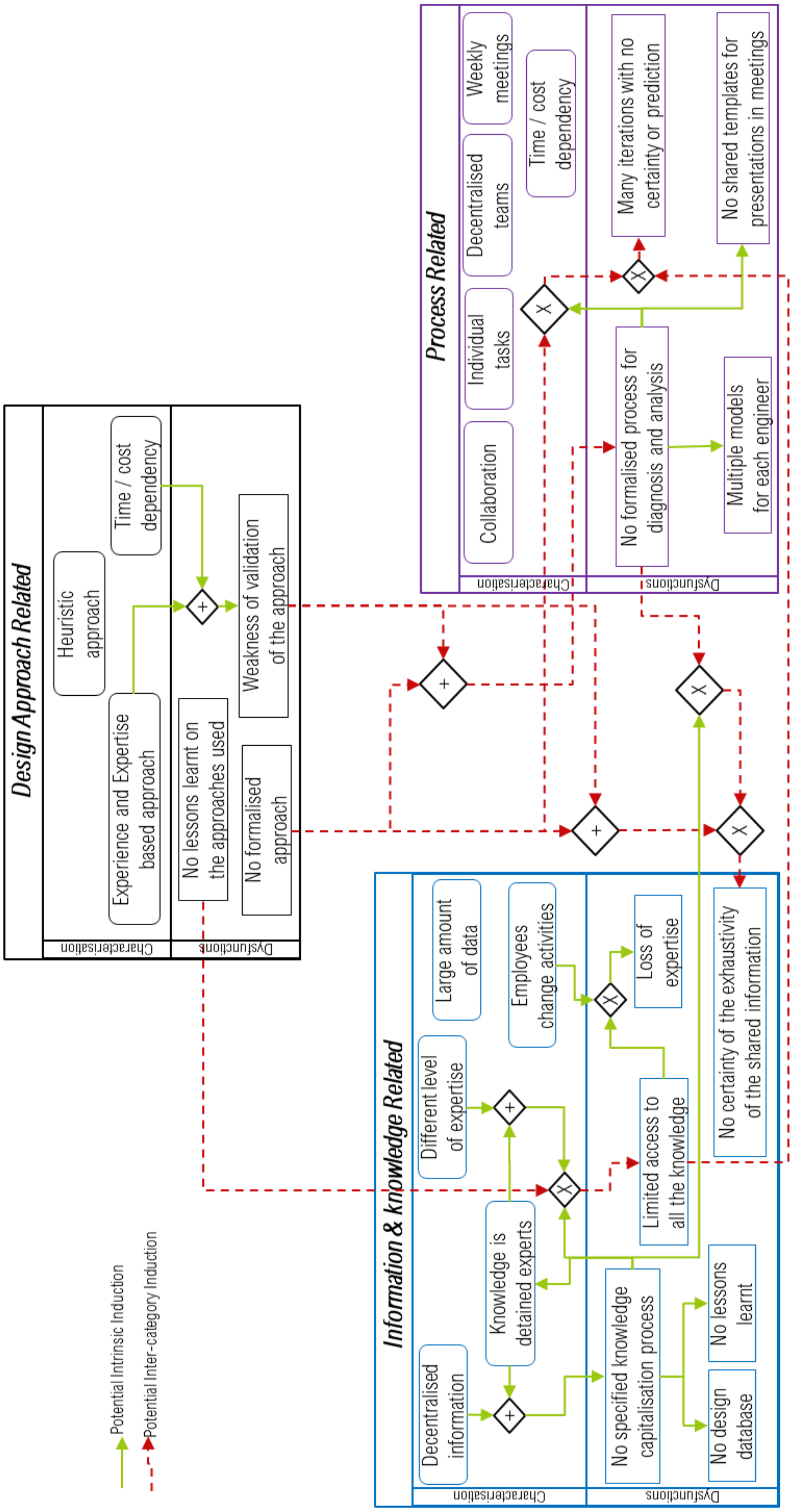

Figure 5. Mapping: Observations Categories and Induced Dysfunctions

Induction happens when one or more element induces another. In this analysis, we look for the elements that induce a dysfunction. Those elements, which we call inductors, could be either characteristics or dysfunctions. As we conduct a qualitative analysis, all identified inductions are potential inductions. We propose two levels of induction. The intrinsic induction (green arrows) is the induction of dysfunction by a characteristic or dysfunction of the same category. The inter-category induction (red arrows) is the induction of dysfunction by a characteristic or dysfunction of another category.

As represented in Figure 5, for each dysfunction, we look for intrinsic and inter-category inductions. We represent an induction by oriented arrows from the inductors to the induced dysfunction. When there is more than one inductor, their combination is represented by (+) if all are necessary to induce the dysfunction, and by (x) if some of them are enough (Figure 5). To analyse the propagation of dysfunctions, we assume that the probabilities of inductions are equal. Therefore, we choose to identify and focus on dysfunctions with the highest probability of occurrence. As the probabilities of inductions are equal and inductions are independent, the probability of occurrence of a dysfunction is the sum of probabilities of its inductions. For this qualitative analysis, the probability of occurrence of a dysfunction is first measured by the number of inductions. Furthermore, we assume that inter-category inductions exist. This means that dysfunctions can be induced by at least two categories: its own category and a different one. These dysfunctions are important because they illustrate the interdependency of categories. Therefore, in the case of dysfunctions with the same number of inductions, the one with an inter-category induction has the highest probability of occurrence. Thus, dysfunctions with high probability of occurrence would have a high number of inductions and at least one inter-category induction. The number of inductions is indicated by the number of arrows entering a dysfunction. The existence of red arrows among induction arrows verifies the existence of inter-category induction. According to this reasoning, the dysfunctions with the highest probability of occurrence are: "Many iterations with no certainty or prediction" and "No certainty of the exhaustivity of the shared information".

4.4. Analysis at the project level: inspired from Process Hazard Analysis (PHA)

In our case, the impact on the project is our priority. The purpose is to identify the team-level dysfunctions with high impact on the project. The progress of the project must be ensured, so team-level dysfunctions with a negative impact on the project must be identified and addressed later.

To determine undesirable situations (risks) to avoid at the project level, we interviewed the experts and the department head. Thanks to their expertise and experience within decision making about projects, they have a better visualisation of the project development and decisions impacting the project. The question that we were interested in is: "What are the most impacting risks on the project?"

The risks expressed by the interviewees are (in no specific order):

- Loss of time
- Difficulties in decision-making (deciding whether the CA could be a CM in the context of a project)
- Having a standing issue through the project
- No respect of QCTW (Quality, Cost, Time, Weight)
- Non-feasibility of the decided CM because of manufacturing constraints

Table 3. PHA analysis at the project level

Dangerous Situation (Project-Level)	Contact Causes (Team-level)	Feared Event (Project-Level)	Initiating Causes
Difficulties in the decision-making process	No certainty of the exhaustivity of the shared information	No respect of QCTW	Missing information about QCTW
Difficulties in the decision-making process	No certainty of the exhaustivity of the shared information	Missing some important information for QCTW evaluation	No shared templates for presentations in meetings
Non-Feasibility of the proposed design action (CM)	No certainty of the exhaustivity of the shared information	Loss of time	Approving a non-feasible CM
Non-Feasibility of the proposed design action (CM)	No certainty of the exhaustivity of the shared information	Making a wrong decision about a CM	No lessons learnt about the manufacturing process
Loss of time	Many iterations with no certainty or prediction	An Issue is standing throughout the project	No CM is proposed
Loss of time	Many iterations with no certainty or prediction	An Issue is standing throughout the project	Limited access to knowledge
No efficiency of the results	No formalised process or approach	Making a wrong decision about a CM	Non-valid approach when searching for CM

In Table 2, inspired from the PHA methodology, we tried to understand the main causes of these risks. For each dangerous situation (risk), we identify a possible contact cause (dysfunctions at the team level). The feared event is an event that could cause the dangerous situation. And the initiating cause is a team-level cause that could trigger the feared event. The focus will be mostly on team-level dysfunctions appearing as contact cause for the project risks. The feared event and its initiating causes are event dependent, they can be considered as an instantiation of risk (dangerous situation) and its contact cause.

"Many iterations with no certainty or prediction" and "No certainty of the exhaustivity of the shared information" are the most recurrent team-level dysfunctions appearing as contact causes. Because they cause multiple risks, they can be seen as the most impacting on the project progress among the other risks taken into account. Overcoming those dysfunctions could ensure better development of the vehicle project.

4.5. Synthesis

Both analyses at the team level and project level explain that the two dysfunctions, "Many iterations with no certainty or prediction" and "No certainty of the exhaustivity of the shared information" have the highest probabilities of appearance and the most significant impact on the project. Two hypotheses are proposed. The first is: what if one of these dysfunctions is overcome? We follow the induction arrows backwards and suppress the first level of induction. For example, if we suppose to overcome "Many iterations with no certainty or prediction", the first level of induction is: "no formalised approach", "no formalised process for diagnosis and analysis" and "limited access to knowledge". The second hypothesis is: what if we overcome the first level of induction? This implies that if we overcome a dysfunction, we would overcome its inducing elements. Then we break the induction arrows linking those elements. Therefore, dysfunctions induced by the first level of induction will be overcome. We notice that we overcome the second important dysfunction. The same reasoning was done starting with "No certainty of the exhaustivity of the shared information" and we got the same result: the second dysfunction was overcome. We conclude that the two dysfunctions are interdependent. So, the focus should be on the dysfunctions of the first level of induction. First, we will focus on “limited access to knowledge” and “non-formalization of the process”. We consider that the environment has a strong interdependence and it will change. So, if we address these two dysfunctions, it would improve the design approach.

5. Challenges and Discussion

In this paper, we conducted a two-level empirical study, at the team and project levels. We identified the team-level dysfunctions with high impact on the project. As the analysis was qualitative, internal and external validities need to be addressed. Internal validity of the proposed methodology is ensured by the triangulation and convergence of the different sources of information, as well as by an iterative verification and validation of the qualitative results. External validity can be achieved by the possibility of generalising the methodology. The notion of induced dysfunction, its propagation and projection at the project can be generalised. The generalisation needs a similar organisation in teams and projects. The collaboration, the objectives and resources should be considered. This methodology could be improved by introducing risk propagation and multi-domain risk analysis. Quantitative indicators could provide a complementary analysis: ratios of the importance of dysfunctions or risks at the project. Further work on a proposal for guidelines for generalisation could be carried out.

The case study presents different constraints linked to the company organisation and the development process of vehicles. Time is one of the most important constraints in project development. Then, reducing the number of iterations would help reduce the time. According to our interviews with the experts, simulation with more certainty about the results would allow us to gain at least one iteration per issue. With the assumption of saving one iteration per issue, we save about 9 hours of computation and about 1h of analyst effort. On the other hand, simulation analysis is based on tacit knowledge and expertise of analysts. As the simulation analysis process is not formalised, feedback on how to solve the issue, the feasibility of countermeasures and costs, etc. are not shared. Following this analysis, some of the challenges identified can be summarised as follow: access and share knowledge and expertise, formalise the simulation analysis process, the consistency and the effectiveness of data and information, the feasibility of manufacturing CMs, etc. Collaboration within the team and with other project stakeholders needs to be improved. We also need to locate and access the necessary knowledge, improve the learning process, develop the competencies and skills of novice simulation analysts and reduce simulation time. The integration of the results of physical tests into the simulation process would increase confidence in the results obtained: feedback on the difficulties encountered in the manufacture of prototypes will increase knowledge on the feasibility of CMs. Feedback for and from modelling could avoid the design of parts that could cause problems in the simulation. Today, the necessary information on feasibility and modelling may exist, but it is neither centralised nor accessible.

6. Conclusion

In this article, we have investigated the simulation analysis process and its challenges in the vehicle development phase of an automotive company. We focused on the post-processing phase, the analysis of the simulation results and the proposal of Countermeasures to the encountered issues. The process is based on knowledge and expertise. The accuracy of the analysis depends heavily on the experience and expertise of the analysts. We have described the simulation analysis process. We conducted a two-level analysis, at the team and project level. We have identified various dysfunctions at the team-level. Then, we identified the dysfunctions with high impact on the project. It led us to identify the difficulties encountered in the simulation analysis process such as access and sharing of knowledge and expertise, formalisation of the simulation analysis process, data consistency, feasibility of CMs, lack of expertise of novice analysts, etc.

The objective of the research is to develop an approach to support and optimise the car crash simulation analysis process. Therefore, the next steps will include a prescriptive study to develop a support system for the simulation analysis process. The integration of case studies of Noise, Vibration and Harshness (NVH) simulation department is also discussed to give a generic dimension to our proposal.

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Paper 3

An Ontology Towards a Knowledge-Based Support of the Post-Processing Phase of Car Crash Simulation

Submitted to: The international journal, Advanced Engineering Informatics, Under revision

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Abstract:

In the automotive industry, the design process is both expensive and time-consuming. This research considers procedural improvements to design by reducing time and cost while producing more robust vehicles. In the development phase, the vehicle model is ensured to be at the right level of performance and at the right cost for manufacturing. This development is supported by modelling and simulation. The focus of this research is on engineering analysis, with specific regard to car crash simulation. The post-processing phase and interpretation of simulation results require comprehensive expert knowledge.

An ontological approach is used towards supporting simulation analysts in post-processing and interpreting the results of the crash simulation. This paper presents a three-level ontology that formalises the necessary engineering knowledge. This ontology is a first step towards the development of a knowledge-based engineering system.

Key words:

ontology, knowledge-based engineering KBE, car crash simulation, engineering analysis, FEA

Reference: N. Fatfouta, A.-M. Hein, J. Stal Le-Cardinal, and E. Delacou, “An ontology towards a knowledge-based support of the post-processing phase of car crash simulation,” Adv. Eng. Informatics, under revision, 2019.

1. Introduction

In automotive engineering, the development of vehicles requires collaboration and the integration of diverse knowledge of different stakeholders and disciplines. Within the development phase of vehicles, Engineering analysis is an important process. Finite Element analysis (FEA) is the commonly used method for engineering analysis. The FEA process can be classified with regard to its different phases or the tasks performed within it. FEA is divided into three phases: pre-processing phase of analysis, matrix calculation, post-processing phase of analysis [1]. Wriggers et al. [2] state that the tasks within the FEM analysis process can be divided into tasks with algorithmic nature and non-algorithmic tasks involving a knowledge-based approach. The algorithmic tasks are the meshing, the FEA computation itself and the visualisation of results. The non-algorithmic tasks are problem classification, decision making about parameters, evaluation and interpretation of the results. The non-algorithmic tasks influence the accuracy, the quality and reliability of the results, requiring comprehensive knowledge and expertise [2], [3]. Non-algorithmic tasks can be considered as a support to algorithmic tasks as they ensure the efficiency and the effectiveness of the FEA process.

There are different types of engineering analysis such as crash, thermodynamics, and stress. The focus of this paper is on car crash engineering analysis. Crash simulation is a virtual recreation of a crash test of a vehicle to analyse and examine the crashworthiness of the vehicle and examine the level of safety of the vehicle and its occupants [4], [5]. The crash simulation analysis process requires the analysis of large amounts of data and interdisciplinary contributions.

FEA, and in particular, post-processing phase of simulation results, demands comprehensive knowledge and expertise of analysts. These simulation analysts apply their tacit knowledge towards interpreting results and finding countermeasures for design issues. Therefore, a knowledge-based approach is essential, as it allows engineers, with different levels of experience, to have access to the required information. Knowledge-Based Engineering (KBE) has been applied to a variety of industries including the automotive industry, to support and automate the engineering process. KBE offers the possibility of engineering automation while retaining relevant engineering knowledge. In addition to significantly reducing design duration, KBE improves the quality of design decisions and results [6]. Different techniques such as knowledge bases and ontologies are developed to support KBE systems in engineering analysis. Ontologies are used because they are one of the most promising ways to separate and represent domain knowledge from operational knowledge [7].

Dolšak and Novak [1] outlined a list of problems and bottlenecks within FEA. These bottlenecks are mainly encountered during the pre-processing and post-processing phases of the analysis process. The bottlenecks can be summarized according to several categories, selection issues (i.e. the selection of simulation tools, finite elements, mesh model, and design action), interpretation of results, and coordination and collaborative exchanges.

The existing literature has treated the pre-processing phase of FEA in detail. However, less attention has been paid generally to the post-processing phase- its non-algorithmic tasks in particular. In the post-processing phase, different techniques have been used; although, ontology development is yet to be addressed.

This paper proposes an ontology-based approach towards the development of a knowledge-based system to support the post-processing phase of car crash simulation. The novelty of this approach lies in the representation of the domain knowledge required to interpret simulation results and propose design changes. A three-level ontology is proposed consisting of the context level, the project level and the reasoning level. The context level describes the information related to the car crash simulation and the requirements to be fulfilled. The project level formalises the post-processing phase and the interpretation of simulation results from the implementation of the digital test to the design changes proposals. Finally, the reasoning level attempts to formalise the process to solve design issues and propose appropriate design changes.

The article is organised as follows. Section 2 provides the background to this research. It presents a state of the art of Knowledge Based-Engineering and its application to engineering analysis, with a focus on the use of ontologies. The industrial context is also detailed. Section 3 presents the development of the ontology. Then, section 4 outlines the two-step validation based on expert feedbacks and use-case explanation. A brief discussion follows in section 5. Finally, a conclusion and outlook are given.

2. Research background:

This section presents a literature review on the use of Knowledge Based-Engineering and ontologies development in engineering analysis. An explanation of the industrial context will also be detailed.

2.1. Related work:

Knowledge-Based Engineering has been applied to wide range of industries such as aerospace, automotive and shipbuilding [8]. There are multiple perceptions of KBE across different research and industrial communities. For example, KBE is seen as a technological solution to retain company knowledge and to support its reuse from a Knowledge Management point of view [9]. However, a global definition is introduced [9], [10]: KBE is considered as both an area and a technology, based on the use of KBE systems, which are able to capture, retain and systematically reuse product and process engineering knowledge. The objectives of KBE are reducing the time and costs of product development through automation of repetitive and non-creative design tasks. KBE offers the possibility of engineering automation while retaining relevant knowledge, which can improve the quality of design decisions and results, as well as significantly reduce design time [6]. Usually, KBE is associated with Knowledge Engineering and Knowledge Management. A complementary coexistence can be described [9]. KE is the area that focuses on the acquisition and formalisation of knowledge, which is an essential step before KBE development. KM is the area that is engaged in the use of knowledge assets in organisations.

Engineering analysis such as FEA is important in today's design process. However, the knowledge intensive nature of this process requires comprehensive knowledge and experience [3]. KBE is an evolutionary step in computer aided engineering CAE [11], [12], for which multiple approaches are studied [1], [3], [9], [11]–[13].

Some research papers present efforts, based on KBE techniques, to support and improve finite element analysis. Most of the research papers focus on the pre-processing stage of FEA [1]. Today's commercial software proves thoroughly inadequate in supporting the post processing phase, thus needing expert knowledge in the interpretation of results [11]. Concurrent research efforts demonstrate the use of KBE techniques supporting the post-processing phase of FEA. In [14], the authors focus on the post-processing phase; proposing a prototype of an intelligent system to support design decision for stress / stain and thermal analysis. They then direct their research towards studying the design improvement process. First, in [11], the authors propose an intelligent advisory system for design improvement. The system objective is to provide design support and help with the decision-making process. Then, in [1], they develop a framework for intelligent decision support to improve the FEA-structural design analysis process. The prototype is composed of four intelligent knowledge-based modules: to support initial decisions, select finite elements, design finite element mesh, and finally the interpretation process for results. In the automotive industry, inexperienced design engineers need intelligent advice to adequately interpret the results. So, in [12], [15], the authors develop KBE to automate design changes based on FEA results for structure and engine analyses.

Grosse et al. [7] present a literature review on the development of ontologies for supporting knowledge-based systems in engineering, with a focus on FEA. They confirm that separating domain knowledge from problem-solving knowledge is one of the most promising ways to develop ontologies. Ontologies for supporting KBE are mostly used in the pre-processing phase. Kestel et al. [3], develop an ontology-based approach to support less experienced analysts with the setup of reliable FEA. They apply ontologies to automatically formalise and provide necessary knowledge from experts, simulation models and documentation, acquired in automated text and data mining. Wriggers et al. [16] develop a concept of intelligent knowledge-based support of engineering analysis of contact mechanism using FEA. They use ontologies for the representation of knowledge related to physical systems and engineering analysis cases, and they use case-based reasoning for reasoning mechanisms. And in [17], they focus only on the pre-processing stage. Sun et al. [18] propose an automation of the FEA setup using a design ontology and FEA ontologies. The FEA ontology gives FEA methods to solve the engineering problems presented in the design domain ontology.

KBE is used to support and automate FEA. Ontologies for KBE development were mostly used to automate the pre-processing stage. To our knowledge, there is no ontology for supporting non-algorithmic tasks in the post-processing phase.

2.2. Industrial background: Car Crash Simulation:

Road incidents are ranked ninth among the world's disease burdens in 2016 [19] and they are projected to rank third by 2020 [5]. Therefore, car safety is a crucial factor for car manufacturers. Crash simulation is an important step in vehicle development; automotive industry has the widest application of such simulation [4]. Crash simulation is a virtual recreation of a crash test of a vehicle, used to analyse and examine the crashworthiness of the vehicle. It is also used to examine safety level of the vehicle and its occupants [4], [5]. FEA is a major approach used for car crash simulation [20]. However, FEA is expensive and time-consuming, due to the costly software and hardware required, and the extensive representation of the mechanisms in the crash event [20].

This research is conducted within a French multinational automotive company. To have a better understanding of the industrial context and the simulation crash simulation process challenges, the authors have conducted an empirical study [21]. A second empirical study has also been conducted by Sissoko et al. [22], in the same company, from a decision-making point of view. The results of the empirical studies show that car crash simulation is expensive, time-consuming, and there is considerable effort required. Simulation analysts are geographically decentralised, and there is only one crash simulation expert and one digital simulation expert in the company. The analysts' mission is to deliver a vehicle model compliant with multiple requirements. They rely on simulation to verify vehicle performance. If the model fails to meet a requirement (analysts encounter design issues), they propose design changes to improve the vehicle model. The post-processing phase and the simulation results interpretation require comprehensive knowledge. Analysts need knowledge of modelling and simulation. They also need to make decisions about paths of design issue investigation and design change proposals.

Car crash simulation validates and evaluates the performance of the vehicle according to the crash requirements. If the requirements are not reached, a design change on the vehicle model must be considered in order to improve performance and meet the necessary requirements. In the development phase, the analysts receive the requirements and the vehicle model to evaluate, for each project milestone. The goal is to deliver a vehicle model that reaches those requirements. Crash simulation analysis is an iterative process, starting from the pre-processing of the simulation, the simulation run, and finally the post-processing phase and the interpretation of results. When the vehicle performance does not reach the requirement, the analyst creates and clarifies the design issue, analyses and diagnoses it, then proposes a design change to fix the issue. The design change can be one or more design actions to improve the vehicle design and reach the requirement. The analyst then tests if the design change proposal is good enough. If not, he investigates a new path for another design change. This process is highly relying upon the analysts' knowledge and experience. This process involves decisions about the design issue investigation paths and design change proposals. These decisions are mainly done by the analyst. The decision whether to integrate the proposed design changes within the vehicle model depends on the project, as factors, such as the cost and the weight must be considered. Only the resulting decision is considered in this research, not the decision-making process. At the end of each stage within the development phase, all approved design changes by the different disciplines, such as crash, stress and acoustic, are integrated within the vehicle model, ready for the next stage.

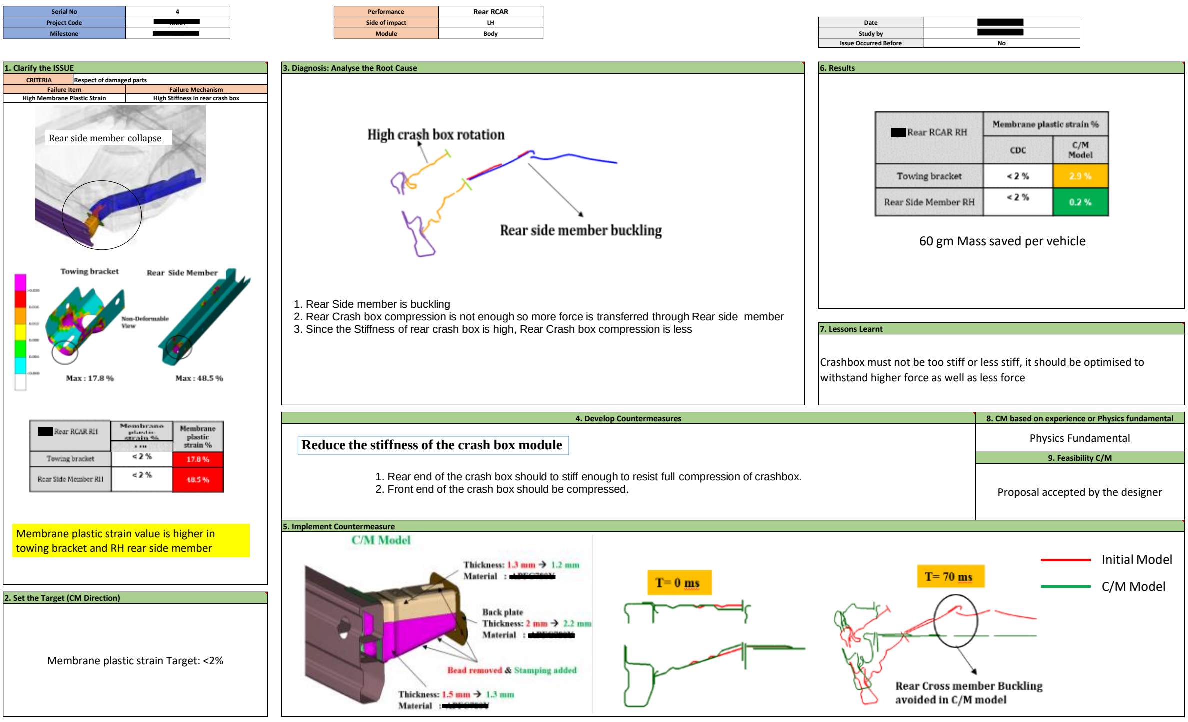

Figure 1: An example to document a process to solve a design issue and a proposal of a design change

Figure 1 presents an example of a process to solve a design issue and a proposal of a design change. This is an attempt to document the post-processing phase and the analysts' interpretation of results. Information about the vehicle project, including the crash test configuration, is documented. First, the analyst clarifies the design issue and the related requirement. Then, he sets the target of the design change investigation. The diagnosis and the search for the root cause is then detailed. A proposal of the adequate design change is proposed then implemented. An accepted design change within the vehicle project is called a countermeasure. Results and lessons learnt are discussed. And finally, information about the feasibility and prior knowledge are provided.

Within the previously described process, and based on the empirical study [21], analysts encounter several challenges within the post-processing phase of crash simulation. They immediately need to locate all relevant data and knowledge, from different sources, spending as little time as possible. In order to improve the crash simulation analysis process, time needs to be reduced, decisions about investigation paths and design change proposals must be substantiated, repetitive tasks can be automated such as launching the simulation and extracting adequate information. The post-processing phase and interpretation of results needs to be supported when it comes to issue analysis and design change proposal formulation, in order to reduce time, and reduce of less experienced analysts' bias when interpreting results

We are addressing challenges in the post-processing phase and the interpretation of the simulation results, due to the industrial challenges and the current literature gap. As the existent literature does not present an ontology to support the post-processing phase of car crash simulation, the authors of this paper propose an ontology formalising the knowledge of non-algorithmic tasks in the post-processing phase. The ontology is a first step towards the development of a knowledge-based support system to overcome most of the FEA bottlenecks previously mentioned, such as the interpretation of results and the selection of design actions.

3. Research Methodology

The interest in developing ontologies is growing in engineering design because it involves knowledge sharing and the development of a common standard language [23]. According to [3], [24], Gruber (1993) defines ontology as an explicit specification of shared conceptualisation, and confirms that any knowledge base or knowledge-based system is, implicitly or explicitly, related to conceptualisation. Ontologies are usually used for the formalisation of domain knowledge [25]. An ontology represents, through a shared vocabulary, a set of domain concepts, attributes, relationships, instances and functions [25], [26]. It provides a common format that is machine readable [3], [27]. An ontology needs to be understandable, editable and generalisable [26], [28].

An ontology development involves, usually, domain knowledge acquisition to identify concepts and relations and their organisation into a hierarchy [23]. Various generic methodologies to build ontologies have been developed in the literature [23], [24], [27], [29]–[31]. The methodology used in this paper is the 5 stage- ontology development life cycle proposed by Pinto and Martins [29]. It goes through the stages of specification, conceptualisation and formalisation using a formal language, implementation, and finally maintenance. They also identify activities to be performed during the development process such as knowledge acquisition, evaluation and documentation. This paper focuses on the conceptualisation and formalisation stages of the ontology, with insights in the knowledge acquisition and the evaluation activities. Implementation and maintenance are taken into account when formalising the ontology, with the assistance of an IT team to be certain that the needs and constraints of implementation are considered.

The methodology developed within this paper will be as follows. Firstly, the scope and the purpose of the ontology spec must be defined. Secondly, the knowledge is captured, and the conceptualisation is ensured by the identification of relevant concepts and relationships. The evaluation of the ontology consists of an expert validation and a use-case validation.

3.1. Ontology Specification:

The aim of the ontology specification is to produce a formal description of the purpose of the ontology development. In this specification stage, some questions are proposed to determine the domain of the ontology and its purpose of use [24], [27], [29]. The domain knowledge is identified based on the industrial diagnosis. This is the knowledge from the post-processing phase of crash simulation analysis.

What is the purpose? The developed ontology provides a representation that can be used to support the post-processing phase and the interpretation of results of the car crash simulation. It ensures the formalisation and reuse of crash simulation knowledge.

What is the scope? The ontology will include information on vehicle projects, safety requirements, crash simulation, simulation results and their interpretation, simulation issues and the design changes.

Who are the intended end users? The users include the analysts (different countries) and the experts. Other stakeholders of the vehicle development could be considered.

What is the intended use? The ontology intends to support the analysts in the interpretation of simulation results, the issue-solving process and the proposal of design changes. It will also help document the vehicle projects.

3.2. Ontology Conceptualisation and Formalisation

After defining the ontology specification, the next step is to describe how the knowledge was acquired and formalised. Most of the acquired knowledge is unstructured and needs to be organised and formalised [31]. The conceptualisation stage aims to describe the ontology in a conceptual model that meets the ontology specification. The conceptual model contains concepts that describe the domain and the relationships between these concepts [29]. The Formalisation stage seeks to transform the conceptual model into a formal model [29].

For this stage, we collaborated with an architect and an “CAE support” expert. Acquiring domain knowledge is crucial to identifying the concepts and relations of the ontology discussed later in this paper. As the crash simulation analysis is mainly based on comprehensive knowledge, knowledge is elicited from experts and analysts via interviews and workshops. Five interviews with the numerical simulation expert were organised. Two workshops with the crash simulation expert and analysts took place. The knowledge acquisition was also supported by a literature review. Ten workshops were organised to discuss and develop the ontology while making ensuring the compatibility with IT. The company’s existing documentation and universal standard documentation about crash simulation were analysed. The current process of vehicle development was analysed in depth to locate important knowledge. The focus of this paper is the post-processing phase of crash simulation, beginning with launching the digital test, finishing with the interpretation of the results and a redesign if necessary.

The development process is an iterative process: the first step, analyse the current process of crash simulation analysis in depth. Then, the crucial tacit knowledge that needs to be considered and make explicit is identified.

3.3. Evaluation of the ontology

The evaluation is important to guarantee the quality of the ontology for its users. A technical evaluation consists of two parts. The two parts are the verification of the ontology correctness and the validation of the ontology’s adherence to its specifications [29]. In this paper, an evaluation by experts will be presented. An explanation of some use cases will be given to assess how the ontology can be used within the support system of the post-processing phase of crash simulation analysis.

4. Crash Simulation Post-Processing (CSPP) Ontology

To represent the concepts more accurately, we suggest separating the CSPP Ontology into three levels. The aim of the CSPP to better represent the concepts, the authors suggest separating the CSPP Ontology into three levels. The aim of the CSPP Ontology is to ensure knowledge sharing and reuse in the post-processing phase of crash simulation. Main concepts are extracted from the industrial context, and specifically, from the current process of crash simulation analysis. The three levels are the context level, the project level and the reasoning level. First, the context level contains existing and standardised information that is independent from the vehicle project under development, for example, the regulations and the requirements. Second, the project level can be considered as an instantiation of the reasoning level for a specific vehicle. The project level captures knowledge about the vehicle project and provides the knowledge needed for the issue-solving process. Finally, the reasoning level is the authors' proposal to support issue-solving and design changes proposals. Fig 1 shows the relations between the three levels. The context contextualises the vehicle project development. Similarly, the vehicle project should respect the context. Moreover, the context impacts the reasoning level by delimiting the reasoning space. While the reasoning level is the generalisation of the issue-solving within the project level, the project is an instantiation of the reasoning proposals. An UML class diagram is used to represent the concepts and relations that constitute the CSPP Ontology.

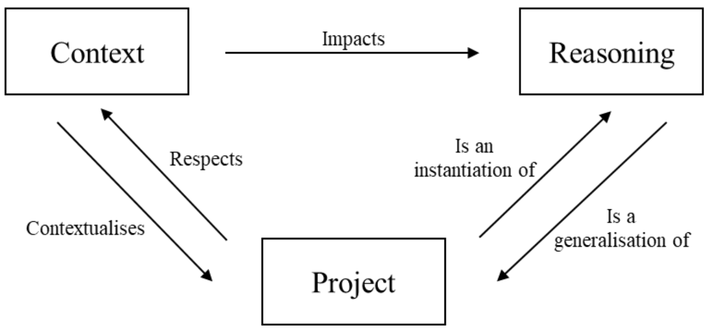

Figure 2: The three levels of the ontology and their relationships

4.1. CSPP Ontology: The Context Level

Within the context level, the main concepts which were extracted from the company's documentation and overall process are the *Technical Requirement* and *Impact Configuration*. The identification of the other concepts has been done by analysing the data scattered in the documentation. Fig 2 represents the context level of the CSPP Ontology.

A *Technical Requirement* is the interpretation of the customer's needs through a technical specification. A *Technical Requirement* is defined as a *Target* on a *Criterion* for a certain *Impact Configuration* and a certain *Performance Reference*. An example of a *Technical Requirement* is expressed as "For a damageability, frontal at 16km/h impact, the minimum of the energy absorbed by the frontal Crash Box is 6000J". This example will be used to illustrate the rest of the concepts of the ontology.

In order to verify the crashworthiness of the vehicle, the simulation engineer needs to perform a crash test. The *Impact Configuration* represents this crash test by illustrating the context of the simulation. Most of the crash tests are standardised. However, there are crash tests that are specific to the company. *Impact Configuration* has different *Impact* T*ype*s: frontal, rear, side and pedestrian. *Impact Configuration* has different levels of *Speed*. It has also different types of *Impactor*s such as Deformable Barriers *Technical Requirement* has also different *Performance Level*s that need to be ensured according to ratings and regulation. A *Performance Reference* has a *Performance Type* as NCAP and a *Geographic Area* where it is applied as Europe. And so that gives the EuroNCAP *Performance*

Reference. In the developed example, the *Impact Configuration* is a frontal Impact at 16km/h for a *Performance Level* called damageability performance.

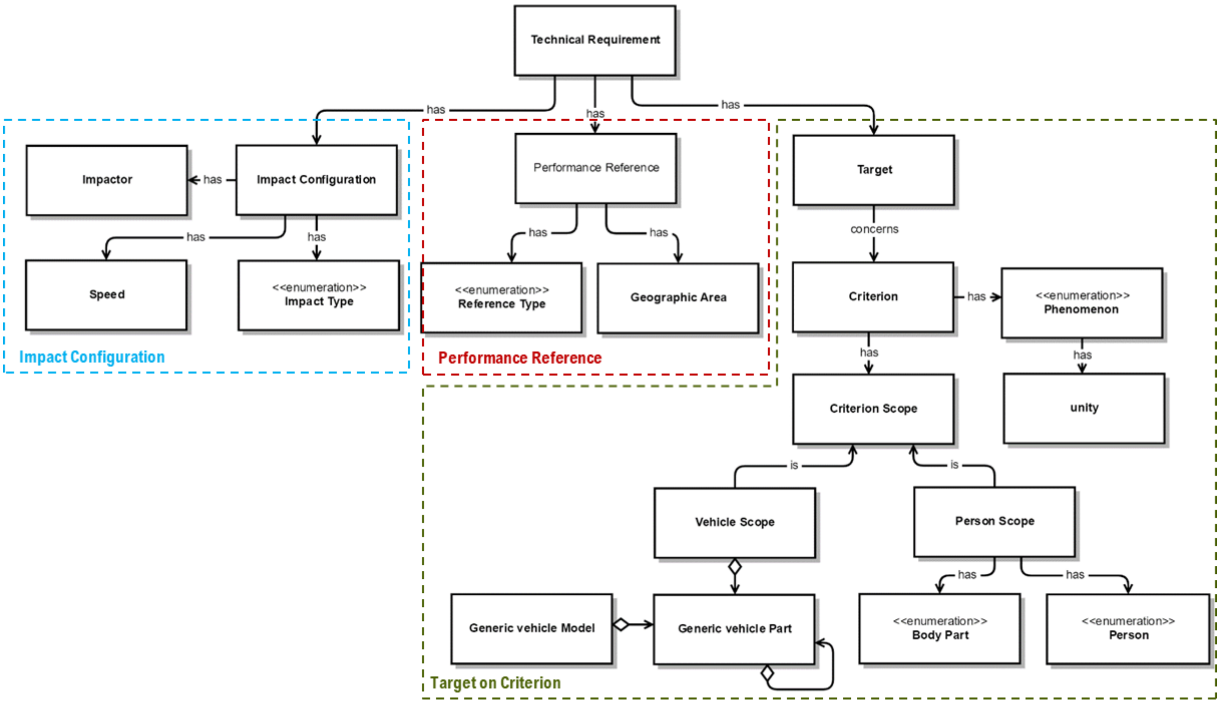

Figure 3: The context level of the CSPP Ontology

The *Technical Requirement* has one or more *Target*s which a crash test should respect. The *Criterion* gives the parameters that need to be verified within a simulation test. The *Target* gives the value (logical or mathematical equation) which the *Criterion* needs to respect. For the developed example, the *Criterion* is the absorbed energy by the Crash Box and the *Target* value should be greater than or equal to 6000J. A *Criterion* is the description of the *Phenomenon* to observe within a specific *Criterion Scope*. The *Phenomenon* has a *Unity*. In this example the *Phenomenon* of the *Criterion* is the absorption of energy and the *Unity* is Joule. The *Criterion Scope* is where the analyst can perceive and evaluate the criterion. The *Criterion Scope* can be *Person Scope* and *Vehicle Scope*. For the *Person Scope* there is the type of *Person* which can be, for example, an occupant or a pedestrian. It can also define *Body Part*s involved in the requirement, such as the head or the thorax. The *Vehicle Scope* describes the related *Generic Vehicle Part*. In this example, the scope is a *Vehicle Scope* and it is the Crash Box. The *Generic Vehicle Part* constitutes a *Generic Vehicle Model* of a standard vehicle. A model of a specific vehicle is an instantiation of the generic model.

4.2. CSPP Ontology: The Project level

The project level represents the context of a specific vehicle development. A *Vehicle Project* is a succession of *Milestone*s for the development of a particular vehicle. A *Vehicle Model* is an instantiation of the *Generic Vehicle Model* from the context level. Each *Vehicle Model* is composed of *Vehicle Part*s. A *Vehicle Part* is constituted of other *Vehicle Part*s.

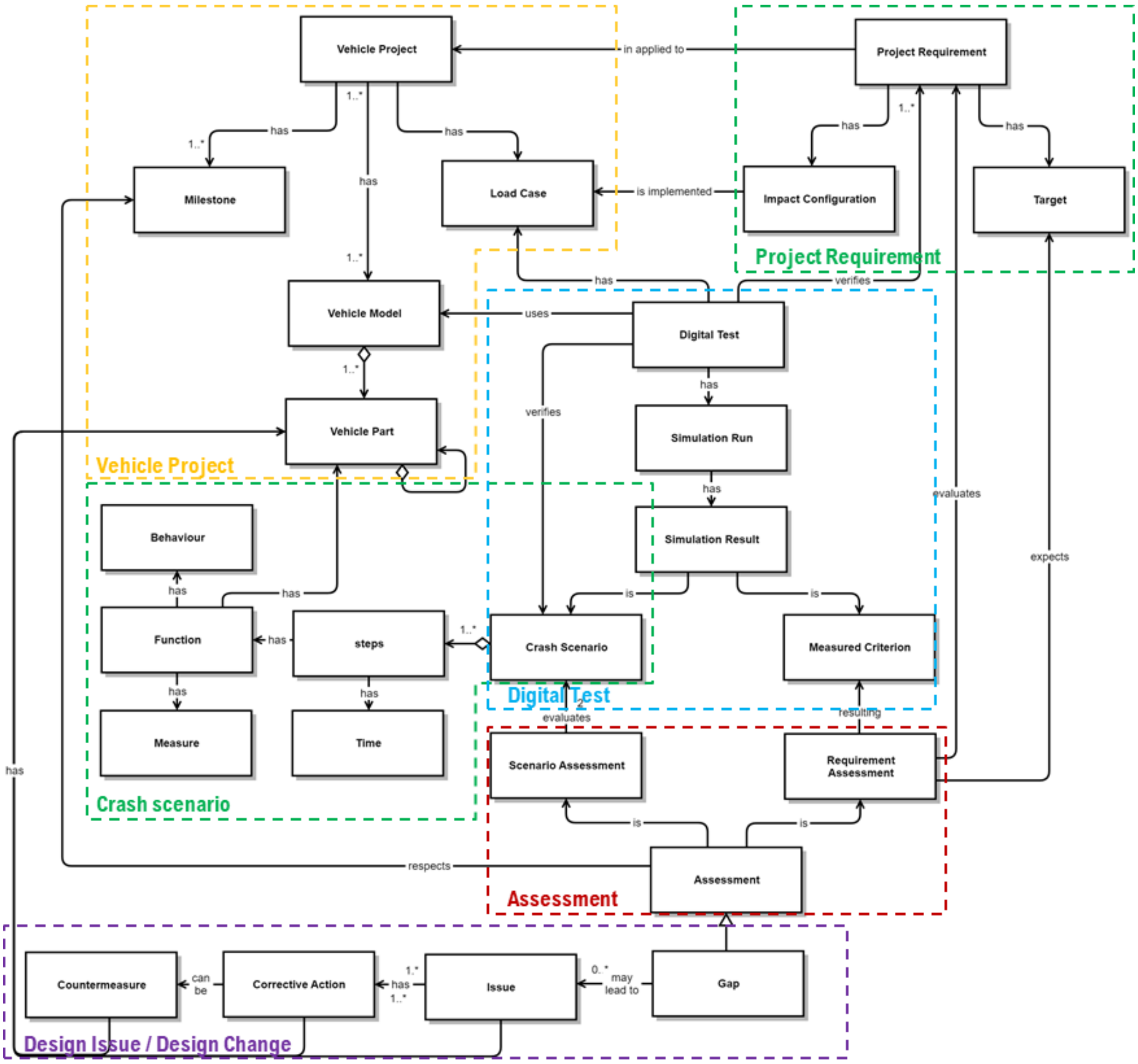

Figure 4: The Project level of the CSPP Ontology

The purpose of the crash simulation is to evaluate and validate the performances of a specific vehicle model. This evaluation is ensured by the *Assessment* of the *Simulation Result*s according to the specifications of the project. Two types of *Assessment* are considered for two types of specifications. The *Requirement Assessment* evaluates the considered *Project Requirement*, and the *Scenario Assessment* evaluates the expected *Crash Scenario*. Compliance with the *Crash Scenario* precedes the evaluation of the *Project Requirement*.

The Project Requirement is an instantiation of a *Technical Requirement* from the context level, and within a *Vehicle Project*, the objective is to satisfy a set of *Project Requirement*s. The *Crash Scenario* describes the impact propagation within connected vehicle parts during a crash test. Currently, the *Crash Scenario* is not formalised, but experienced analysts tend to check the smoothness of the impact propagation. First definition of a Crash Scenario is proposed within this ontology. A *Crash Scenario* is a succession of *Step*s over Time. A *Step* is defined by a *Role* played by a *Vehicle Part* over *Time* during the impact propagation. For example, at 5 ms the crash box compresses to absorb the crash energy. The *Role* has then a *Behaviour* (compression) of a certain *Vehicle Part* (Crash Box) and a *Measure* (Joule for the absorption of energy).

Both assessments evaluate both specifications according to the *Simulation Result*s coming from *Simulation Test*. A *Simulation Test intends to verify one or several Project Requirements within a specific Milestone and an expected Crash Scenario. A Simulation Test* uses a *Vehicle Model* to be evaluated. *A Simulation Test* has a *Load case* which is the implementation of an *Impact Configuration* (from the context level) within the simulation environment. *The Load case* is also defined by the *Vehicle Project*. The *Simulation Run* is the solver analysis for *a Simulation Test. Simulation Result*s are the results of the *Simulation Run*. *The Simulation Results* to be assessed are the resulting *Crash Scenario* and the *Measured Criterion. The Measured Criterion* is the evaluation of the *criterion* of the considered *Project Requirement.* In short, the *Scenario Assessment* allows for evaluating the resulting *Crash Scenario* regarding the expected *Crash Scenario*. And the *Requirement Assessment* aims at evaluating the *Measured Criterion* with respect to the *Target* set at the *Project Requirement*.

If the *Crash Scenario* is not respected or the *Measured Criterion* does not respect the *Project Requirement*, a *Gap* from the Assessment will contain the difference between the expected and resulting values. If the *Gap* exists, an *Issue* is created and clarified. Once the *Issue* is identified, the role of the analyst is to propose a *Corrective Action*. A *Corrective Action* is a design change on the *Vehicle Model* that aims to solve the *Issue*. A *Countermeasure* is the chosen *Corrective Action* for an *Issue* within a specific *Vehicle Project*. The *Corrective Action* is the result of reasoning activities which will be explained in the reasoning level of the CSA ontology (section 4.3).

To illustrate the concepts of the project level, the example of the project issue (Figure 1) provided in section 2.2. will be used. To keep the example anonymous, the details about the project are masked. In this example, the project code in Figure 1, represents the *Vehicle Project*. Moreover, details about the milestone (*Milestone*) and the module (*Vehicle Part*) are given in the top of the figure. The performance Rear RCAR represents the (*Load case)* of the simulation test. The *Project Requirement*s which a simulation test should respect is "Membrane plastic strain (MPS) for both Towing bracket and rear side member RH is less than 2%". In this example, there is no verification of the crash scenario, the only assessment done is the *Requirement Assessment.* After the *Simulation Run*, the *Simulation Result*s are extracted. The first *Measured Criterion* is "MPS in towing bracket = 17.8%" and the second one is "MPS in Rear side member RE = 48.5%". In our example, the expected *Target* (less than 2%) is not respected (*Requirement Assessment*). And so, a *Gap* exists and contains the difference between the expected MPA and the actual one. Hence, the *Issue "*MPS is too high" is created. In this case, the proposed *Corrective Action* is to reduce the stiffness of the Crash Box by reducing the thickness of the Crash Box, increasing the thickness of the back plate, removing Bead and adding stamping. The results of the simulation test, with these modifications, respect the requirement.

4.3. CSPP Ontology: The Reasoning level

Currently, analysts solve issues and propose design changes based on their tacit knowledge and expertise. The reasoning level intends to formalise the reasoning behind issue-solving with the objective to improve the vehicle design and meet the project and context requirements. It would also help classifying the separate cases into overall categories. This level would help improve the simulation analysis process and reduce its time as it increases certainty on the analysis results and design actions proposal.

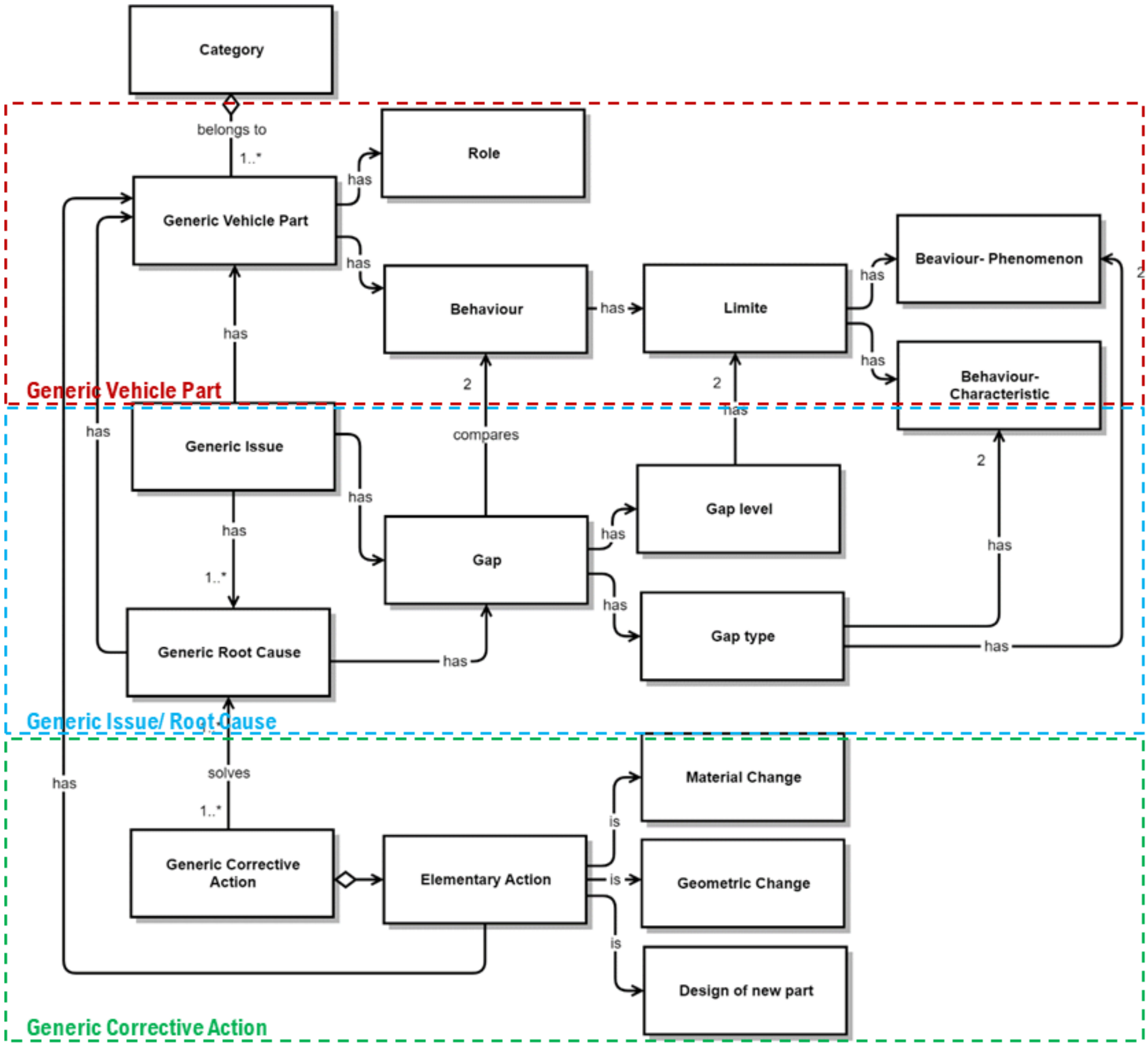

Figure 5: The reasoning level of the CSPP Ontology

Each *Generic Vehicle Part* has a *Role* to play within the structure of the vehicle during a crash test. The *Role* respects the *Technical Requirement* and the *Crash Scenario*. To ensure this *Role*, the *Generic Vehicle Part* adopts a certain expected *Behaviour*. For example, in order to absorb the energy, the Crash Box compresses. A *Behaviour* has a Limit on a *Behaviour Phenomenon* and a *Behaviour Characteristic*. The *Limit* is the optimal boundary of the *Behaviour*. A *Behaviour- Phenomenon* is the needed phenomenon to ensure the Role, such as the compression. A *Behaviour- Characteristic* is a physical characteristic such as stiffness and plastic strain.

If the *Generic Vehicle Part* has a defect *Behaviour* and it does not play its role well, it will lead to a *Generic Issue*. A *Generic Issue* is the generalisation of *Issue* from the project level. A *Generic Issue* is defined as the *Behaviour-Gap* between the expected *Behaviour* and the defect *Behaviour* of the considered *Generic Vehicle Part*. The *Behaviour-Gap* has a *Gap-Type* where it indicates if the expected *Behaviour* and the defect *Behaviour* have the same *Behaviour-Phenomenon* or *Behaviour - Characteristic*. And it has also a *Gap-Level* that indicates the difference of the *Limit*s of both behaviours. For example, for the compression of the Crash Box, either it does not compress or ruptures (*Gap-Type*) or it compresses but not enough or too much (*Gap-Level*).

A *Generic Issue* has a *Generic Root Cause*. A *Generic Root Cause* is also defined as a *Behaviour-Gap* for a *Generic Vehicle Part.* Once the *Generic Root Cause* is identified, a proposal of a *Generic Corrective Action* is done. The *Generic Corrective Action* can be a *Material Change*, a *Geometric Change* or a *Design of new Part*. The *Generic Corrective Action* has also a *Generic Vehicle Part* where to be applied. A *Corrective Action* within the project level is an instantiation of the associated *Generic Corrective Action*.

In this example, the side member buckling is not an elementary root cause. Hence a second iteration is necessary. In the second-level analysis, the side member is now the *Generic Vehicle Part*, and it has the buckling behaviour as a *Gap* and more specifically a *Gap-Type*. Now, the G*eneric Root cause* is the new *Generic Issue*. The second-level analysis gives the failure in crash box compression as a G*eneric Root cause*. In this case, the crash box is the *Generic Vehicle Part* and the failure of compression is the *Gap-Level*. Again, the failure in crash box compression is not an elementary root cause; consequently, a third iteration is necessary. In this example, the elementary G*eneric Root cause* is related to the stiffness of the crash box. The stiffness was found to be very high, which impacts the crash box compression. For this elementary G*eneric Root cause*, the *Generic Corrective Action* is to reduce the stiffness by *Geometric Change* on different parts of the crash box which corresponds to our *Design change scope*.

Table 1: An example of application of the reasoning level

	Part: Generic vehicle Part	**Expected Behaviour: Behaviour**	**Defect Behaviour: Behaviour**	**Gap: Gap**		**Elementary Action**
				Gap- Type	**Gap-Level**	
1st Level Issue: Generic Issue	Rear Side Member	MPS	MPS		High MPS	
1st Level Issue: Generic Root Cause	Rear Side Member	Compression	Buckling	Buckling instead of compression		
2nd level Cause: Generic Root Cause	Rear Crash Box	Compression	Compression		Not enough compression	
3rd Level cause: Generic Root Cause	Rear Crash Box	Stiffness	Stiffness		High stiffness	
Generic Corrective Action	Rear Crash Box					Reduce thickness

The abstraction of the reasoning level is based on two hypotheses. The first hypothesis is that crash simulation is based on physical and mechanical phenomena, consequently, vehicle parts' behaviour has limited deformation possibilities and can be predictable. For example, the side member, in order to absorb energy (*Role*), it compresses or deflects (*Behaviour*). The second hypothesis is that vehicle parts sharing the same role and behaviour would be exposed to similar issues. *Generic Vehicle Part*s with similar *Role*s and *Behaviour*s would share similar *Generic Issue*s and could belong to the same *Category*. For example, both the Crash Box and Add On have the *Role* of absorbing energy by compression (*Behaviour*) during the frontal crash. Thus, those parts would be subjected to similar *Generic Issue*s, such as low energy absorption. Issues with similar diagnosis and root causes would share similar Corrective actions. For example, for any issue, if the root cause will be related to the stiffness of some vehicle part, the corrective action would be to reduce or to increase the stiffness depending on the context.

5. Ontology Evaluation:

The ontology was evaluated, at first, by the domain experts who helped with the knowledge elicitation. They were asked to assess if the concepts and their relations describe at best their knowledge. Iterative interviews were conducted, confirming the concepts. Second, the ontology was evaluated by the software engineering department. The completeness was appreciated. Finally, the ontology was verified and validated by the crash simulation analysts as the end user.

For further validation, some case studies are studied. We selected four additional cases of issues and their resolution based on the examples. These cases come from different projects and were not used for the ontology development. The aim is to assess how the support system for the post-processing phase of crash simulation can use the ontology.

The case studies will be explained in relation to the example presented in section 2.2, shown in example 1 of Table 1. This table summarises the most important information for the evaluation. Example 2 to 5 are the cases to be tested.

For example 2, which has the same context as example 1 but within a different project, the non-respected requirement is “Membrane Plastic Strain of Towing Bracket < 2%”. It shares the same Issue as example 1, as it is a known Issue for the knowledge base. The support system would propose to verify the compression of the Rear crash Box. For this case, the Rear Crash Box was highly compressed and did not absorb the necessary energy. As a consequence, the same Root Cause would be selected by the analyst, which is failure of compression. As this root cause is not elementary, the support system will propose to check the stiffness of the Rear Crash Box. In this case, the stiffness is low and that is why it was compressing fast. In this case, the proposal of the Generic Corrective Action will be to increase the stiffness unlike in the first example. Based on this proposal, the analyst would instantiate the Generic Corrective Action within the current project.

Example 3 and 4 share the same Generic Issue but in different projects and different context. The non-respected requirements are: Membrane Plastic Strain of Rear Left Side Member < 2% and Membrane Plastic Strain of Rear Floor Panel are < 2%. Both cases share the Generic Vehicle Part with the example 2.2. Whether it is the Left or the Right Side Member, as a generalisation they are both represented by the same Generic Vehicle Part which is the Side Member. As explained before, the support system will propose to check its known root causes and the analyst will verify if is the same as in these cases. For both cases, the root cause was the high stiffness of the Rear Crash Box and so the Generic Corrective Action proposal is to reduce the stiffness whether by changing the material or reducing the thickness for a geometric change.

Another presented example, example 5, is for a frontal crash test concerning the Requirement “Partner Protection: standard deviation < 100”. The issue was that the deformation was high. Post-Analysis, the analyst identified the Root cause as the failure in compression of the frontal Crash Box. At the Reasoning Level, the frontal Crash Box and the Rear Crash box are generalised in the Generic vehicle Part Crash Box. So, the support system would propose to verify the stiffness of the Crash Box. In the example 5 the stiffness of the frontal crash Box was too high, and so reducing the stiffness would be the Generic Corrective Action to propose.

Table 2: Case studies for the evaluation of the CSPP ontology

Case study	Project Level					Reasoning Level	Reasoning Level		Project Level		Reasoning Level	Project Level
	Impact Configuration	*Project Requirement*			*Measured Criterion*	*Generic Issue*	Elementary *Generic Root Cause*		Elementary *Root Cause*		*Generic Corrective Action*	*Corrective Action to implement*
		Criterion	*Criterion scope*	*Target*			*Gap*	*Generic Vehicle Part*	*Gap*	*Vehicle Part*	Proposal	
1	Rear Rcar Right Side	Membrane plastic strain	Towing Bracket	<2%	17,80%	MPS is high	High stiffness	Crash Box	High stiffness	Rear Right Crash Box	Reduce Stiffness	Increase thickness
			Rear Right Side Member	<2%	48,50%							
2	Rear Rcar Right Side	Membrane plastic strain	Towing Bracket	<2%	10,80%	MPS is high	Low stiffness	Crash Box	Low stiffness	Rear Right Crash Box	Increase Stiffness	Increase width
3	Rear Rcar Left Side	Membrane plastic strain	Rear Left Side Member	<2%	19%	MPS is high	High stiffness	Crash Box	High stiffness	Rear Left Crash Box	Reduce Stiffness	change material to a lower one
			Rear Floor Panel	<2%	3%							
4	Rear Rcar Left Side	Membrane plastic strain	Rear Left Side Member	<2%	11,10%	MPS is high	High stiffness	Crash Box	High stiffness	Rear Left Crash Box	Reduce Stiffness	Increase thickness
			Rear Floor Panel	<2%	2,97%							
5	Frontal Ncap Rating	Standard deviation	Partner Protection	<100	110%	SD is high	High stiffness	Crash Box	High stiffness	Frontal Crash Box	Reduce Stiffness	Add crash initiator

For this case study, starting from a known case, the knowledge-based support system would be able to assist the diagnosis of the issue and propose corrective actions. Case 1 to 4 share similar contexts and similar project issues. And so, the generic root causes were similar and so were the generic corrective actions. Case 5 have a different context and a different project issue. But once the generic root cause is similar to the other cases, the generic corrective action will be also similar. The use case validates the reasoning that different issues with similar generic root causes will have similar generic corrective actions. The use case helped also validating the completeness of the ontology. The authors were able to describe the use case based on the developed concepts and relations.

6. Discussion

The Crash Simulation Post-Processing Ontology aims to formalise knowledge used in the post-processing phase and the interpretation of simulation results. This ontology supports the analysis and the diagnosis of design issues when the vehicle performance does not meet specifications. It also facilitates the proposal of design changes to improve vehicle design. This ontology is developed based on observations, several use cases and interviews with experts and crash simulation analysts.

The focus of this contribution is on the post-processing phase and the interpretation of car crash simulation results. The pre-processing phase is not supported by this approach. The formalisation in three levels better structures engineering knowledge. The context level describes information about the context in which the digital test happens. The project level formalises engineering knowledge of the vehicle project, including digital tests, assessment and interpretation of simulation results. The formalisation of a crash scenario and its assessment improves the interpretation of results. The purpose is to consider all necessary elements to enable an accurate interpretation of simulation results. The reasoning level is a proposal to formalise the resolution of design issues and the formulation of design change proposals. The reasoning level is independent of the project.

This ontology is a first step towards the development of a knowledge-based support system. The knowledge-based system will capture and retain engineering knowledge, including knowledge related to digital tests, assessment of simulation results, solutions of design issues and design changes proposals. The support system would significantly reduce the crash simulation time by reducing the time spent on design issue resolution and design change proposal. It would also increase the accuracy and reliability of proposals for more effective design changes, possibly leading to more effective vehicle models. The support system could also be a learning tool for novice analysts, as they would have access to engineering knowledge that has been retained by the system. There are also some limitations to the ontology. For example, it was developed within a specific industrial context. We encountered difficulties in acquiring knowledge, and it would have been helpful to have had access to more cases to analyse. The reasoning level could be improved with the integration of new cases.

7. Conclusions and outlook

Vehicle development is costly and time consuming. The objective of this research is to improve the robustness of vehicles, while minimising cost and time. This paper's results have a crucial impact on the vehicle development phase due to its focus on improving car crash simulation analysis. The literature reveals a lack of approaches supporting the post-processing phase and the attendant interpretation of crash simulation results.

In the post-processing phase and the attendant interpretation of crash simulation results, an ontological approach formalises and structures engineering knowledge. This ontology is developed based on observations, analyses of several use cases and interviews with car crash simulation experts and analysts. The ontology is a first step towards the development of a knowledge-based support system to overcome difficulties within the interpretation of results, the resolution of design issues the selection of design actions.

Continuing work focuses on implementing a knowledge base which throws up design issues and their related countermeasures. Future work should also investigate the existing algorithms to build a knowledge-based support system. Algorithms based on Bayesian networks and case-based reasoning are promising solutions for reasoning mechanisms.

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Paper 4

Towards a Framework for Integrated and Collaborative Knowledge Management for Engineering Design- a Case Study

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Abstract:

In automotive industry, the design process is costly and time-consuming. Car safety is a crucial factor in the development of a vehicle, which is why crash simulation is an essential step in the design process. To improve car crash simulation analysis, it is necessary to reduce the time required and support the resolution of encountered design issues. We propose a knowledge management approach to support car crash simulation analysis and ensure the collaboration of different stakeholders. In a knowledge-intensive context, we used an ontology-based approach to formalise and capture knowledge.

Key words:

knowledge management, collaborative design, car crash simulation, ontology, engineering design

Reference: N. Fatfouta, J. Stal-Le Cardinal, "Towards a Framework for Integrated and Collaborative Knowledge Management for Engineering Design- a Case Study", in Proceedings of International Design Conference, DESIGN, 2020, accepted.

1. Introduction

In the automotive industry, the design process is both expensive and time-consuming. This research focuses on improving the design process by reducing time and costs while producing more robust vehicles. At the end of the development phase, the vehicle model must be at the right level of performance and the right manufacturing cost. Vehicle development requires collaboration and integration of the diverse knowledge of different stakeholders and disciplines. Vehicle development is based on modelling and simulation.

Road incidents are ranked ninth among the world's disease burdens in 2016 (Ritchie and Roser, 2018), and they are predicted to rank third by 2020 (Patane et al., 2015). Hence, car safety is a crucial factor for car manufacturers. Crash simulation is an essential step in vehicle development. Therefore, the automotive industry has the widest application of such simulation (Yadav and Pradhan, 2014). Crash simulation and more generally engineering analysis is knowledge intensive; it requires comprehensive expert knowledge. Within nowadays organisations, engineers and experts change missions and teams very often. Knowledge is usually transferred via communication. Thus, knowledge management is playing a crucial role in today's industry. Knowledge management refers to identifying and leveraging collective knowledge (Alavi and Leidner, 2001; Barão et al., 2017). It aims to reuse knowledge through transferring it into information and between participants (Peng et al., 2017).

Therefore, this paper aims to propose a knowledge management approach to support the development phase of vehicles, mainly car crash simulation.

This article is organised as follows. Section 2 presents a literature review on knowledge management in engineering design. Then, section 3 explains the case study. Section 4 proposes an integrated and collaborative knowledge management framework with a focus on the knowledge model and knowledge retrieval model. Finally, conclusions and outlook are given in section 5.

2. Literature review: Knowledge management in engineering design

Design involves people with the appropriate expertise undertaking a process to develop a product; This takes place within an organisation that provides necessary infrastructure and resources (Wallace et al., 2005). Design tasks, including within the automotive industry, are now more complex, their timescales are increasing and their teams are geographically distributed (Mcmahon et al., 2004). Engineering design process is knowledge-intensive and collaborative (Peng et al., 2017). It requires multiple designers and experts to conduct multiple tasks involving different areas of knowledge and expertise (Sun et al., 2010). Collaborative engineering design is evolving towards a problem-solving task (Chen et al., 2008) that embodies a significant level of complexity. Engineering design is heavily informational; engineering designers spend considerable time locating information in human and nonhuman sources (Peng et al., 2017; Sun et al., 2010); they engage 55.75% of their time in informational behaviour, such as processing, communicating and disseminating information (Robinson, 2010). Human sources are more solicited than non-human ones (Robinson, 2010). However, due to the current transient nature of industrial organisations, experienced designers and experts are not going to be available to consult in the future (Wallace et al., 2005). The multidisciplinary, highly collaborative and contextual nature of engineering design has raised the need to support integrated and collaborative product development (Peng et al., 2017). Successful collaborative engineering design depends on the ability to manage and share engineering knowledge (Chen et al., 2008). Therefore, nowadays, knowledge management is playing a crucial role for companies' competitiveness (Barão et al., 2017).

There are multiple definitions of knowledge management (KM) in literature (Girard et al., 2015). It is usually defined by its relationship with knowledge. Therefore, we start by defining knowledge.

Many ways of defining knowledge exist in literature. Knowledge is usually defined using a hierarchical relationship with data and information (Alavi and Leidner, 2001; Peng et al., 2017; Sun et al., 2010): where (1) data is in the form of symbols and words, (2) information is structured data that forms a pattern, and (3) knowledge is processed information and rules of thumb acquired through experience. Knowledge can also refer to a state of knowing, the “know-about”, a capacity for action, the “know-how”, and to articulated and captured facts and methods, the “body of knowledge” (Apurva and M.D., 2011). Another frequent dichotomy of knowledge is based on its stage of accessibility: explicit, implicit and tacit (Apurva and M.D., 2011; Mcmahon et al., 2004; Sun et al., 2010). Explicit knowledge, also identified as formal knowledge (Peng et al., 2017), is knowledge that can be codified and documented. Implicit knowledge can be implied by or inferred from observable behaviour or performance. Tacit knowledge is subconscious and cannot be expressed. In the context of engineering knowledge, Wallace et al. (Wallace et al., 2005) classify engineering design knowledge into product and process knowledge. When it is stored externally, it is considered as information and can either describe the design process or the product itself. When it is sored un human memory, knowledge can be explicit, implicit and tacit. Explicit knowledge is an explanation of both the process and the product and can be articulated. Implicit knowledge is the understanding the engineers have of both process and product and cannot be expressed by engineers themselves; it can be articulated through knowledge elicitation. Tacit knowledge is more a matter of intuition and cannot be articulated.

Given the different definitions and perspectives of knowledge, knowledge management (KM) has multiples definitions. KM refers to identifying and leveraging collective knowledge (Alavi and Leidner, 2001; Barão et al., 2017) and it is usually defined by its processes including knowledge capture, storing, retrieval and transfer (Al-Emran et al., 2018; Alavi and Leidner, 2001; Girard et al., 2015). KM is an essential asset in modern institutions; it enables learning from corporate memory, growth, success and innovation (Al-Emran et al., 2018). In engineering design, knowledge can be in form of tangible objects or experience learnt and accumulated through a community of expertise; this constitute both approaches of KM, the codification and the personalisation view (Peng et al., 2017). Most common approaches are technology-oriented, called codification approach; it underlines the explicit nature of knowledge that can be formalised and stored in knowledge repositories and transferred via information and communication technologies. Then, people-oriented also called personalisation approach underlines the tacit and context-dependent nature of knowledge; it requires informal human communication to transfer knowledge (Peng et al., 2017; Saito et al., 2007). It is argued that a trade-off between the two approaches, called integrated approach, is more effective (Ng et al., 2012; Peng et al., 2017; Saito et al., 2007). An integrated approach to KM can improve the quality and efficiency of design through the capture and reuse of informal and contextual knowledge.

3. Case study: car crash simulation

This research is conducted within a French multinational automotive company. Within this company, the development phase is a succession of design analysis loops, terminating in milestones. At the end of the development phase, the vehicle model must be at the right level of performance and the right manufacturing cost. The development phase consists of iteratively refining the design specifications, evaluating the vehicle's performance and solving design issues encountered. This phase is supported by modelling and simulation. We are in a context of simulation-aided design as decision about the vehicle design is mainly based on simulation. Several variations on a vehicle model exist at the same time, as there are several markets with different expectations.

The development phase consists of different processes. The design process consists of creating and updating the design reference representing the knowledge gathered about the vehicle under development. The customer performance specification process provides the specification of the vehicle. The simulation model generation process consists of creating and updating the digital vehicle models required for the simulation. The simulation process evaluates the vehicle's performance and solves the design issues revealed; a design issue occurs when the performance does not meet the specification. Finally, the decision-making process determines which design changes to incorporate. A design change is a solution to the design issue. Different stakeholders are involved in these processes.

According to an empirical study we conducted within the company (Fatfouta, Stal-Le Cardinal, et al., 2019), car crash simulation is expensive, time-consuming, and there is considerable effort required. Therefore, we focus on crash simulation and mainly on the analysts involved. The analysts' mission is to deliver a vehicle model compliant with multiple requirements. They rely on simulation to evaluate vehicle performance. Figure 1 presents a formalisation of the simulation process including design issue resolution and design change proposals. During the development phase, for a design analysis loop, crash simulation analysts receive the specification and the vehicle model to evaluate. Following the simulation results, they proceed with the interpretation of these results. If the model fails to meet specification, a design issue is identified. The analysts assess and diagnose the design issue, then propose design changes to fix it. If the design change is not good enough, they consider a new path for another design change. If the design change satisfies the requirement, the project decision-makers decide whether to implement it in the model. This decision depends on project factors including cost and weight. The decision-making process is not considered in this research; only the resulting decision is considered. At the end of each design analysis loop, all design changes that have been approved by the different disciplines, such as crash and stress, are incorporated into the vehicle model, ready for the next loop.

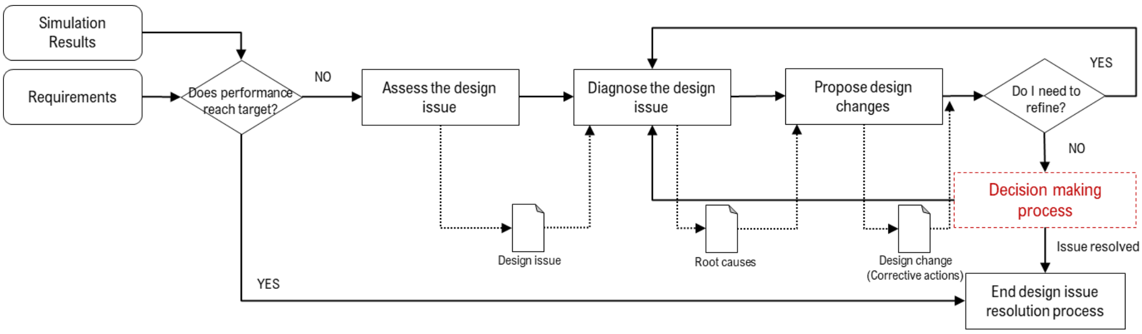

Figure 1. Design-issue resolution and design-change proposal formulation

Analysts are required to have knowledge of modelling and simulation. They are also required to make decisions on paths for addressing design issues and proposing design changes. Car crash simulation analysts are geographically decentralised, and there are only one crash simulation expert and one digital simulation expert in the company (Fatfouta, Hein, et al., 2019). Car crash simulation analysts collaborate with different stakeholders. They collaborate with other crash simulation analysts from other work sites and with simulation analysts from different disciplines such as stress simulation analysts. A strong collaboration exists with the simulation experts as they have the most significant expertise within the company. Analysts, designers and customer-performance specialists exchange information on the statues of the resolution of design issues. Finally, decision-makers are involved in decision-making process regarding the design changes to be incorporated into models.

Simulation analysts encounter several challenges within car crash simulation (Fatfouta, Stal-Le Cardinal, et al., 2019). They need to quickly locate all relevant data and knowledge, from different sources, spending as little time as possible. Design-issue analysis and design-change proposal formulation need to be supported, in order to reduce the time spent on simulation and reduce bias of less experienced analysts when interpreting simulation results.

4. Framework of integrated and collaborative knowledge management

In this research, we perform participation action research (PAR). Being part of the organisation under study allows us to contribute to increasing the knowledge that can be used by the practitioner, and being part of a scientific environment enables us to contribute to science (Björk and Ottosson, 2007).

The aim of this paper is to improve simulation-aided design; time needs to be reduced and decisions about investigation paths and design change proposals must be substantiated. Crash simulation is knowledge intensive and depends heavily on expertise. Since there is only one crash simulation expert, it is important to capture the knowledge and expertise, knowing the risk that the expert may not be available. Collaboration between the different participants is very important for the successful running of the design process. Taking these characteristics into consideration, we propose a knowledge management approach to improve simulation-aided design through the support of analysts and collaboration with the different stakeholders involved.

To develop our proposal, we conducted an extensive literature review on existent knowledge management frameworks (Alavi and Leidner, 2001; Chen et al., 2008, 2012; Li et al., 2009; Pawlowski and Bick, 2012; Peng et al., 2017), while considering the specifics of our industrial context mentioned above. In previous work (Fatfouta, Hein, et al., 2019), we proposed formalising knowledge related to car crash simulation using an ontology. The interest in developing ontologies is growing in engineering design as it involves knowledge sharing and the development of a common standard language for the formalisation of domain knowledge (Premkumar et al., 2014). An ontology is an explicit specification of a shared conceptualisation, and any knowledge base or knowledge-based system is, implicitly or explicitly, linked to conceptualisation (Iaksch and Borsato, 2019; Kestel et al., 2019). Thus, the literature review was performed in light of this ontology. To our knowledge, there is no ontology-based knowledge management approach to support simulation-aided design, for the development phase of vehicles. Moreover, since we perform PAR, the proposal is formalised and discussed with practitioners, including engineers responsible for the development of this support, experts and end-users.

4.1. Ontology-based knowledge management

The ontology we have developed in previous work is called the Crash Simulation Post-Processing Ontology (Fatfouta, Hein, et al., 2019). This ontology formalises knowledge related the post-processing phase of car crash simulation and the interpretation of simulation results. The aim is to formalise knowledge related to the resolution of design issues and the proposal of design changes. To better structure engineering knowledge, the ontology is formalised in three levels: the context level, the project level and the reasoning level:

- The context level describes information about the context in which the digital test happens such as the requirements to meet and the impact configuration, such as a frontal and a rear crash.
- The project level formalises engineering knowledge related to the vehicle project. We considered all necessary elements to ensure an accurate interpretation of simulation results.
- The reasoning level formalises the resolution of design issues and the formulation of design change proposals. The reasoning level is independent of the project.

In this paper, for brevity, we focus on the reasoning level of the ontology as it represents the engineering knowledge related to the resolution of design issues. Currently, analysts solve design issues and propose design changes based on their implicit and tacit knowledge and expertise. The reasoning level intends to capture and formalise the reasoning behind the resolution of design issues. It would also help to classify the separate cases into overall categories.

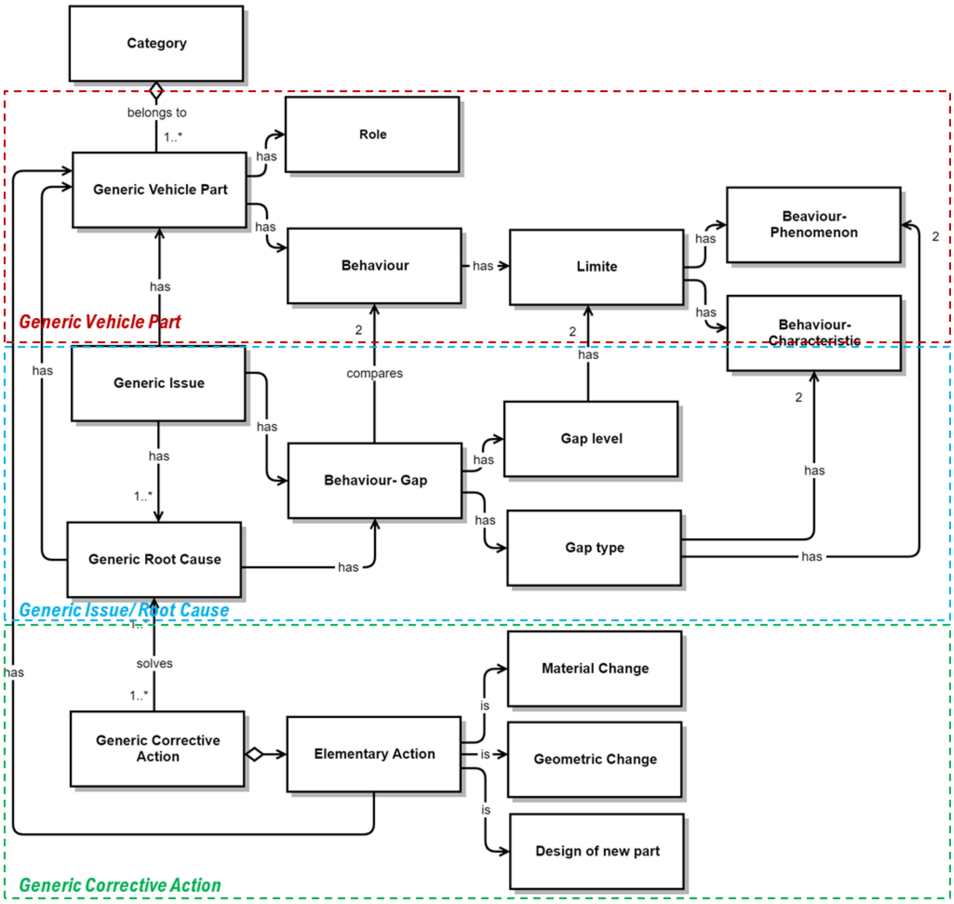

Figure 2. The reasoning level of the ontology: focus on the design-issue resolution

As the reasoning level is independent of the project, we deal with a generic vehicle model. The instantiation of the generic vehicle model is a project vehicle model for a specific context. A generic vehicle model is composed of generic vehicle parts, just as a project vehicle model is composed of vehicle parts. Each vehicle part has a specific role to play, within the vehicle structure, during the crash, to ensure the safety of the occupants. As explained in Figure 2, A *Generic Vehicle Part* is defined by its *Role* to play and an expected *Behaviour* to ensure that role. Then, a *Generic Issue* exists if the *Generic Vehicle Part* does not play well its *Role*, and it engages a defect *Behaviour*. Thus, a *Generic Issue* is defined as a *Behaviour-Gap* between the expected *Behaviour* and the defect *Behaviour* of the considered *Generic Vehicle Part*. A *Generic Issue* has a *Generic Root Cause*. Once the *Generic Root Cause* is identified, a proposal of a *Generic Corrective Action* is done. A *Generic Corrective Action* is composed of *Elementary Action*s, such as *Material Change*, *Geometric Change* and *Design of a new part*. A design change is one or multiple corrective actions.

The abstraction of the reasoning level is based on two hypotheses. First, crash simulation is based on physical and mechanical phenomena, so the behaviour of vehicle parts has limited deformation possibilities and can be predicted. Second, vehicle parts sharing the same role and behaviour would be exposed to similar issues. Generic vehicle parts with similar roles and behaviours would share similar generic issue and could belong to the same *Category*. Therefore, design issues with similar diagnoses (root causes) would require similar design changes.

4.2. A framework of a collaborative and integrated knowledge management

In this paper, we propose a framework of an integrated and collaborative knowledge management frameworks which integrate the developed ontology as a knowledge model. This framework aims to support simulation-aided design. Figure 3 shows the proposal of the KM framework. KM processes are presented, starting from knowledge capture. Engineering knowledge will be captured as the project proceeds. Three type of engineering knowledge are identified. First, there is information about vehicle projects, such as vehicle models and digital tests. Then there is explicit knowledge, including knowledge related to the assessment of design issues, root causes and design changes. Finally, implicit knowledge relates to the paths of investigation and the know-how associated with proposed design changes.

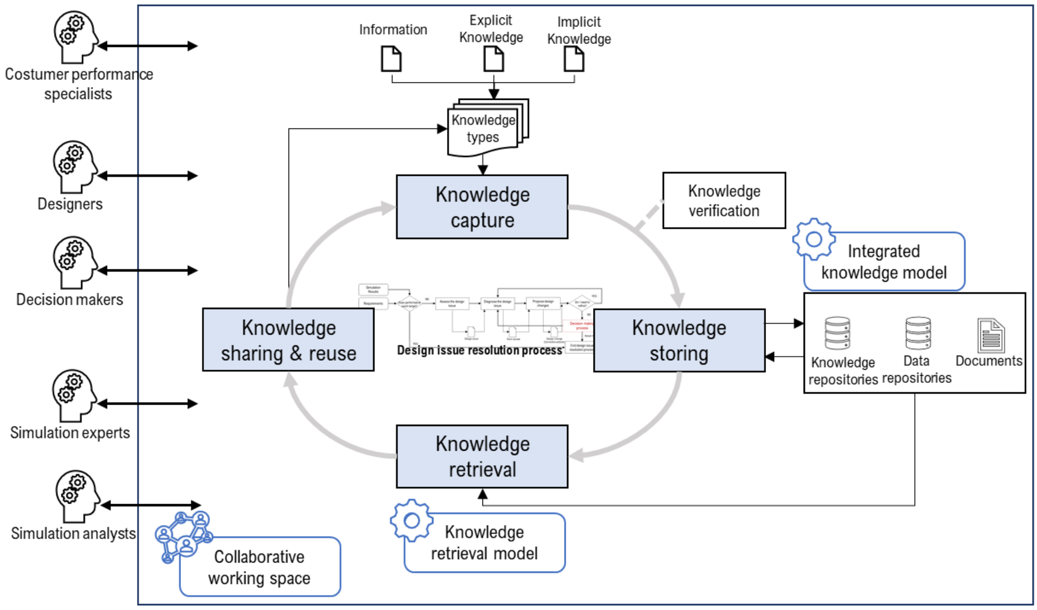

Figure 3. A proposal of a framework of a virtual integrated and collaborative knowledge management

Before storing captured knowledge, it must be verified and validated. This could be done by knowledge workers, such as experts. Knowledge is stored according to the ontology, an integrated knowledge model. The repositories retain engineering knowledge including evaluation of simulation results, design issues and design changes. They also store contextual information, such as vehicle models, and specifications. Documents and discussions between participants can also be stored, as they may contain comprehensive information that could help other participants better understand. The KM framework is then integrated since it is based on an integrated knowledge model that captures both information and formal knowledge and considers the implicit and context-dependent nature of knowledge. In addition, the knowledge is retrieved by a search engine based on a knowledge search model. When retrieved, the knowledge is shared and reused. Hence, knowledge is enhanced, created and re-captured.

Supporting collaborative design is important for this framework and it ensured by the collaborative working space. Collaboration and communication can take place between different participants such as analysts, designers and experts. Communication has an important role to play in KM to facilitate knowledge sharing and reuse (Peng et al., 2017). It is therefore necessary to ensure it throughout the project. Identifying the experience and expertise of participants is also important, as it would make it easy to identify the contact person if needed. Decision-makers are also considered; this would give more visibility on the decision-making process.

4.3. Knowledge management system architecture

A knowledge management system (KMS) is an information system applied to manage corporate knowledge and is developed to support and improve KM processes in organisational workplaces (Barão et al., 2017). The KMS aims to support engineering collaborative activities. It would supply engineers with contextual and accurate knowledge, and it would also ensure knowledge capture and reuse throughout the collaborative process. The KM support system is expected to significantly reduce the crash simulation time by reducing the time spent on design-issue resolution and design-change proposal. It would also increase the accuracy of proposals for more efficient design changes. Our proposal is based on an extended literature review of the KMS architecture (Desta et al., 2014; Li et al., 2009; Peng et al., 2017; Sun et al., 2009; Zhang et al., 2011). The main requirements of the proposed KMS are to support knowledge workers in their activities within the collaborative process and to enable the transfer and sharing of knowledge between individuals and teams.

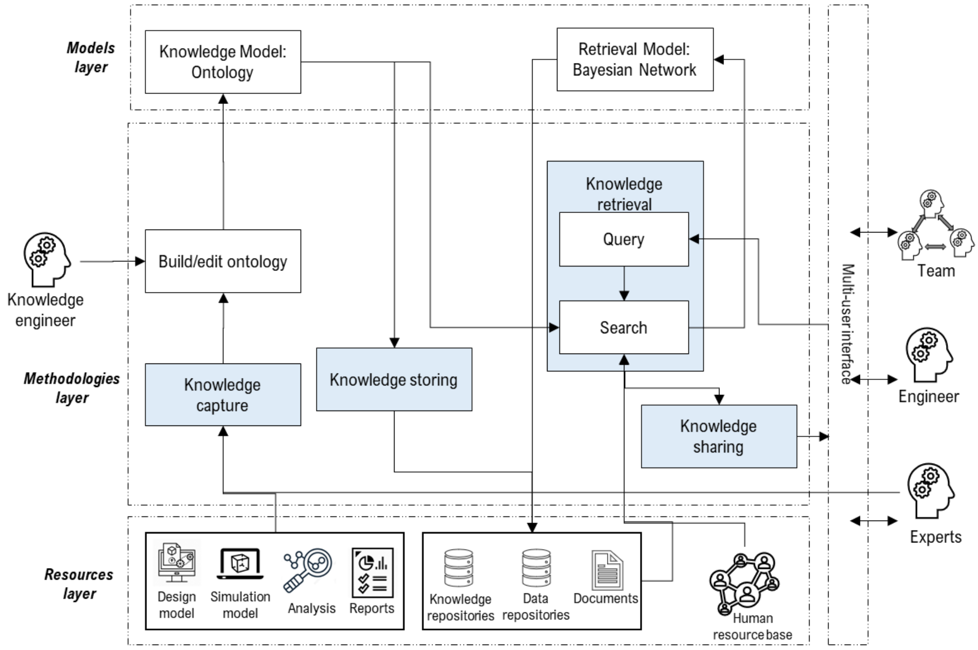

Figure 4. A proposal of a knowledge management System architecture

The system architecture is explained in Figure 4 and consists of four main parts: three layers and a multi-user interface (MUI). The MUI ensures the performance of KM activities and interaction between the users within the integrated working environment. KM is also distributed as it offers the users or a group of them distributed working spaces for individual and collaborative tasks within the teams. The three layers consists of resources layer, methodologies layer and models layer.

- The resources layer refers to knowledge repositories in various data and knowledge formats. The repositories include captured information and knowledge as explained above. Implicit and tacit knowledge embedded in the human mind could be shared through communication. Therefore, the human resource base of each employee's roles, skills and abilities, is available.
- The models layer consists of models developed to support the implementation of the system including the integrated knowledge model and the knowledge retrieval model. The integrated knowledge model is the Crash Simulation Post-Processing Ontology. The retrieval model will be based on a Bayesian network and will be subject to future work.
- The methodologies layer represents the methodologies used to carry out KM activities. Some of the main connections are explicated (in the Figure 4). For example, knowledge can be

captured from experts and from formal knowledge elements. To store knowledge, the knowledge engineer must build/edit the ontology. Knowledge retrieval is usually accessible via the MUI. The user expresses his query, then the search uses the retrieval model. Depending on the query, the search accesses the ontology, the knowledge repositories and the human source base. Finally, knowledge is shared and transferred via the MUI.

4.4. Use case scenario

As an application of the proposed KMS, we propose to explain a use case scenario based on 3 cases detailed in Figure 5. These cases represent 3 different design issues and their design changes, encountered in different projects, for different vehicle models, solved and documented by different analysts, but occurred for the same impact configuration (Rear RCAR).

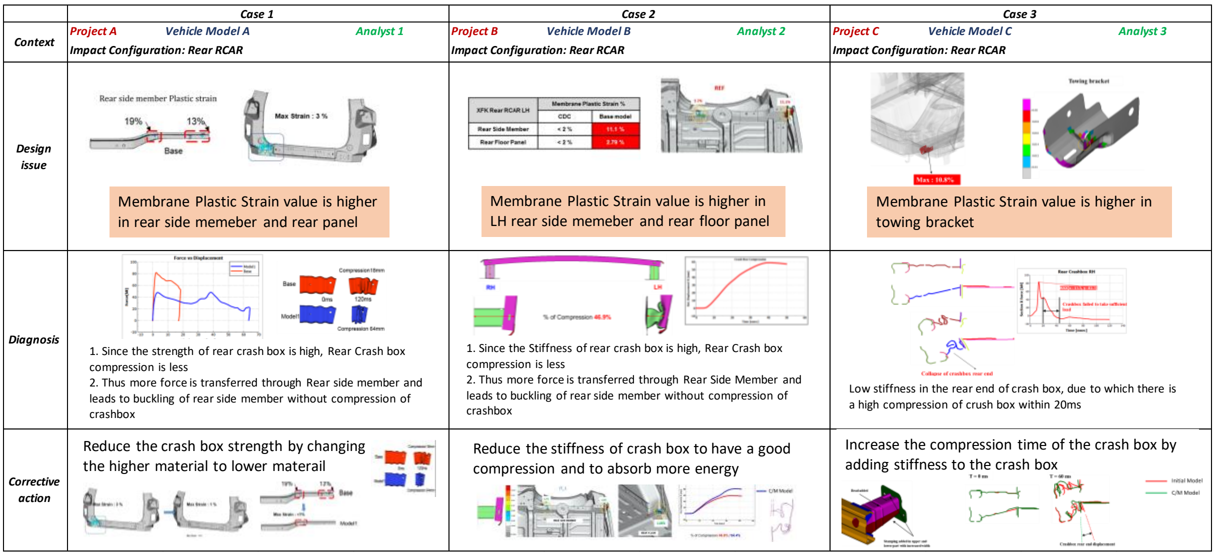

Figure 5. Three cases of actual design-issue resolution used for the use case scenario

To better understand the KMS use case scenario, we begin by explaining the role of ontology and the reasoning that will be used in the knowledge retrieval. Figure 6 presents a brief instantiation of the reasoning level ontology for case 1. In case 1, the encountered design issue is that membrane plastic strain (MPS) of the side member and the rear panel is too high. The objective is to identify the elementary root cause. An elementary root cause is a cause for which analysts can propose corrective actions. Thus, for the first iteration, the root cause identified is the low compression of the crash box. This cause is not elementary because the analyst cannot propose a design change to address it. Thus, for the second iteration, the root cause of the crash box's low compression is its high stiffness. High stiffness is elementary. Therefore, the corrective action is to reduce stiffness. In this case, the analyst proposes to reduce it by changing materials.

Iteration	Vehicle part	Role	Expected Behaviour	Issue			Root Cause				Corrective action
				Defect behaviour	Behaviour Gap		Defect behaviour	Behaviour Gap		Elementary	
					Gap level	Gap Type		Gap level	Gap Type		
	Side memeber	Absorb energy	MPS within a limit L	MPS > L	X						
Iteration 1	Crash Box	Absorb energy	compress within a limit L1	Compression < L1	X		Compression < L1	X			
iteration 2	Crash Box	Absorb energy	stiffness S				Stiffness > S	X		X	reduce stiffness

Figure 6. Instantiation of the ontology's reasoning level for case 1

In a scenario where the KMS described above is implemented, users interact with it via the MUI. They formulate the query. Based on the query, the search engine will look for similar cases and get the matching results. This is where the Bayesian network intervenes. The network is supposed to link an issue, knowing the context, to its probable causes in a hierarchical way, like the iterations presented in Figure 6. Then, the elementary root cause will be linked to possible corrective actions. Thereby, the KMS will support analysts throughout the design issue resolution process. Finally, the knowledge will be transferred to the user via the MUI and re-captured to improve the existing knowledge in the repositories.

Based on the assumption that case 1 is already captured via the ontology and stored within knowledge repositories, we explain briefly use case scenario of the support provided by the KMS for cases 2 and 3 (from Figure 5). In case 2, the analyst faces a similar design issue in a context with some similarities. Thus, the knowledge retrieval will most probably make it possible to extract case 1 and propose to check the stiffness of the crash box. For case 2, according to the analysis, the stiffness of the crash box was also high, and the corrective action will then be to reduce it. The corrective action is evaluated and approved, so the analyst can formulate the design change proposal. In case 3, for a similar design issue, the root cause is also related to the stiffness of the crash box but in this case, it is rather low. In this case, based on the implicit knowledge captured, the system would propose to increase stiffness. If the search does not find a match to the design issue, or if the request is to identify an expert or engineer, the search will be conducted in the human source base. It would suggest the most appropriate expert/ engineer to meet the request. Communication would be provided by the MUI. The interaction would be recorded. Then, if necessary, analysts would have access to it to formulate their own judgements and draw lessons.

5. Conclusions and outlook

Car crash simulation analysis is characterised by its knowledge intensive nature and human-based interactions. More precisely, it relies heavily on experts. These characteristics can be a source of inefficiency in the overall engineering process due to the unavailability of experts and the long time needed for information retrieval. To address these issues, we propose, in this paper, an ontology-based KM framework and a KMS architecture to support simulation-aided design, with a focus on crash simulation.

The KMS will capture and retain engineering knowledge, including knowledge related to the evaluation of simulation results, assessment of design issues and design change proposals. It will also ensure collaboration. The knowledge management support system would help reduce crash simulation time by reducing the time spent solving design issues and proposing design changes, as well as the time spent searching for a human source of information. This would also increase the accuracy of proposals for more effective design changes, since the proposals will be based on corporate knowledge. This could lead to the development of more robust vehicle models. Novice analysts would have access to the engineering knowledge retained by the KMS, making it a learning tool.

Future work will focus on exploring knowledge retrieval and the applicability of Bayesian networks. The framework could be extended to the simulation of all performances, such as noise and vibration. It could also include the design process, thus avoiding that certain design issues arise during the simulation and avoiding proposing design changes that cannot be included in the vehicle model (design). The framework could also go beyond simple collaboration to real-time concurrent engineering where each participant in each discipline could access the same vehicle model at the same time.

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Paper 5

An Application of an Ontology-Based Knowledge Management Approach to Support Simulation-Aided Design to Car Crash Simulation in the Development Phase

Submitted to: The international journal, Computers in Industry

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Abstract :

In the automotive industry, the design process is both costly and time-consuming. This research focuses on improving the design process by mainly reducing time while producing more robust vehicles. Vehicle development is based on simulation; thus, the design process is referred to as simulation-aided design. Engineering design is highly collaborative and knowledge-intensive. Therefore, knowledge management plays a crucial role in today's global economy and is essential for the competitiveness of companies. However, current research on engineering knowledge management focuses on either the codification or the personalisation approaches of knowledge management. Thus, this paper addresses an integrated and collaborative approach. This paper aims to develop an ontology-based knowledge management system to support simulation-aided design, specifically car crash simulation. The knowledge management support system is designed to ensure the capture and retrieval of engineering knowledge and to enable collaboration between different stakeholders. An evaluation of the models and technologies used is also undertaken, based on use case scenarios.

Key words:

knowledge management, ontology, knowledge model, knowledge retrieval, collaboration, engineering design, crash simulation

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1. Introduction

Design involves people with the appropriate expertise undertaking a process to develop a product. This activity takes place within a specific organisation that provides the necessary infrastructure and resources [1]. Moreover, design tasks in all industries, including the automotive industry, are now more complex, with increasing timescales and geographically distributed teams [2]. This research focuses on the development phase of the vehicle design process. At the end of the development phase, the vehicle model is guaranteed to be at the right level of performance and the right manufacturing cost. Development is based both on modelling and simulation, and decision-making is mainly based on simulation. We are, therefore, in the context of simulation-aided design. This research focuses on improving the vehicle design process by mainly reducing time while producing more robust vehicles. The objective is, therefore, to support simulation-aided design. We focus on car crash simulation as it is an essential step in vehicle development [3]. Car safety is a crucial factor for car manufacturers since road accidents were the ninth leading cause of disease in the world in 2016 [4] and are expected to be the third by 2020 [5]. The car crash simulation is expensive, time-consuming and requires considerable effort.

Engineering design process is a knowledge-intensive and collaborative task [1], [6], [7]. It requires multiple designers and experts to conduct multiple tasks involving different areas of knowledge and expertise [8]. Cooperative communication among teams is complicated [7]. Collaborative engineering design is evolving towards a problem-solving task [7] that embodies a significant level of complexity; more than that which is required for a single engineer to work on such problems [6]. Engineering design is heavily informational [9], given that engineering designers spend considerable time locating information in human and nonhuman sources [1], [8], [9]; they engage 55.75% of their time in informational behaviour, such as processing, communicating and disseminating information [10]. They spend less time locating the source when it is a human source than when it is a non-human source, and so it is more efficient to use people as sources of information [10]. However, due to the current transient nature of modern industrial organisations, experienced designers and experts are not going to be available to consult in the future [1]; companies suffer significant setbacks from staff loss, such as the deterioration of their relationships with customers or suppliers and the loss of revenue [11].

The multidisciplinary, highly collaborative and contextual nature of engineering design has raised the need to support integrated and collaborative product development [9]. Successful collaborative engineering design depends on the ability to manage and share engineering knowledge [7]. Therefore, nowadays, knowledge management plays a crucial role in the global economy and it is important for the competitiveness of companies [12]; knowledge management is recognised in both academic and industrial studies [2].

In this paper, we propose an ontology-based approach for integrated and collaborative knowledge management. Specifically, we develop a knowledge management system to support simulation-aided design with an application to car crash simulation. Current research focuses on either codification or personalisation of knowledge [9]. However, an integrated approach combines both the codification of knowledge objects and the transfer of contextual and tacit knowledge via communication. Collaboration also facilitates the sharing of knowledge between different actors. In this paper, the KM support system is based on an integrated knowledge model, an ontology, which captures formal, contextual and problem-solving knowledge. Knowledge retrieval models mimic the reasoning of simulation analysts and experts.

This paper is organised as follows. Section 2 presents a literature review on knowledge management in engineering design. Section 3 presents the industrial context describing car crash simulation in vehicle development. Section 4 explains the ontology-based approach to knowledge management and details the knowledge management support system by explaining its activities, blocks and sub-blocks. We propose an evaluation of the knowledge management support system using three use case scenarios that will be detailed in Section 5. A brief discussion is presented in Section 6 and conclusions are outlined in Section 7.

2. Literature review: knowledge management in engineering design

There are multiple definitions of knowledge management (KM) in literature [13], [14]. However, it is usually defined by its relationship with knowledge. Therefore, we start by defining knowledge.

Many ways of defining knowledge exist in literature. Knowledge is usually defined using a value chain or hierarchical relationship with data and information [2], [8], [9], [15]–[17]: where (1) data is in the form of symbols and words, (2) information is structured data that forms a pattern, finally (3) knowledge is processed information, facts and rules of thumb acquired through experience. Knowledge is difficult to assimilate and has a personal aspect that demonstrates the crucial difference between knowledge and information, a "notion of competence" and not a tangible object [9]. Knowledge can refer, from different perspectives, to an object, a cognitive state or a capability and it may reside in individuals, social groups, documents, processes, or computer applications and databases [11]. Knowledge can also refer to a state of knowing, the "know-about", a capacity for action, the "know-how", and finally to articulated and captured facts, methods and so on, the "body of knowledge" [18]. Another frequent dichotomy of knowledge is based on its stage of accessibility: explicit, implicit and tacit [2], [8], [9], [15]–[19]. Explicit knowledge, also identified as formal knowledge [9], is knowledge that can be expressed, codified and documented. Implicit knowledge is also knowledge that can be implied by or inferred from observable behaviour or performance. Tacit knowledge is subconscious and cannot be expressed.

In the context of engineering knowledge, formal knowledge can be codified in different sources, such as a 3D geometric model and a simulation model, and tacit knowledge refers to personal knowledge and experience, such as developing a problem-solving strategy and reasoning on possible decision. In [1], the authors explain that information is what is stored and transferred outside the human mind and knowledge only exists when information is interpreted. They classify engineering design knowledge into product knowledge and process knowledge. Thus, when it is stored externally, information can either describe the design process or the product itself. When it is sored un human memory, knowledge can be explicit, implicit and tacit. Explicit knowledge is an explanation of both the process and the product and can be articulated in the form of information. Implicit knowledge is the understanding the engineers have of both process and product and cannot be expressed by engineers themselves; it can be articulated through knowledge elicitation methods. Finally, tacit knowledge is more a matter of intuition and cannot be articulated.

Given the different definitions and perspectives of knowledge, knowledge management (KM) has multiples definitions. Knowledge management refers to identifying and leveraging collective knowledge [11], [12], [16] and it is usually defined as a process involving multiple sub-processes including knowledge capture, storing, retrieval and transfer [11], [14], [17], [20]. KM is defined as the ability of an organisation to manage, store, value and distribute knowledge [14]; an organisation is defined as a social unit of people structured and managed to meet a need or to achieve collective goals [12]. KM is an essential asset in modern institutions; it enables learning from corporate memory, growth, success and innovation [20]. In projects, KM enables communication improvement, best practice gathering while providing informal knowledge sharing, and productive collaboration [13]. Information systems plays a key role in the development of KM as it enables the automation, production and sharing of knowledge [20]. These systems are called knowledge management systems and they support KM processes [11]. The essential function of KMS is the sharing and reuse of knowledge. Therefore, to achieve this function, the acquisition of knowledge is fundamental. Thus, KMS has to fulfil three functions: acquiring knowledge, storing it and reusing it [21].

In engineering design, knowledge can be whether in form of tangible objects that can be modified, copied and transferred, or experience learnt and accumulated through a community of expertise; this constitute both approaches of KM, the codification and the personalisation view [9]. Most common approaches are technology-oriented, called codification approach; the explicit nature of knowledge is underlined, and knowledge need to be formalised and stored in knowledge repositories and transferred via Information and Communication Technologies [9]. On the other hand, people-oriented, also called personalisation approaches underlines the tacit and context-dependent nature of knowledge; it requires informal human communication to transfer knowledge [16], [22]. It is argued that a trade-off between the two approaches, called integrated approach, is more effective [2], [9], [22], [23]. An integrated approach to KM can improve the quality and efficiency of design through the capture and reuse of informal and contextual knowledge.

Knowledge representation and retrieval research areas aim to develop enabling technologies for knowledge management systems [9]. Ontology-based approaches to knowledge management have been developed for different application in design engineering. Sun et al. [24] propose a knowledge management approach to support knowledge intensive product design; they develop an ontology-based product knowledge model including different types of knowledge and propose methodologies for retrieving explicit and tacit knowledge. A prototype of the knowledge support system and an implementation at a paper currency binding' company are also carried out. Zhang et al. [21] construct a framework for an ontology-based knowledge management system. They also propose an implementation using a mechatronics case and develop part of the ontology-based knowledge retrieval modules. Premkumar et al. [25] develop an ontology-based semantic knowledge management system to support the design, analysis and manufacturing of laminated composite materials. The system includes an ontological framework for laminated composite materials and their design for manufacturing, and an integrated engineering design framework to facilitate collaboration among domain experts. To our knowledge, no ontology-based knowledge management approach has been developed to support simulation-aided design, and specifically car crash simulation process.

3. Industrial context: Car crash simulation in vehicle development

This research is conducted within a French multinational automotive company. Two empirical studies have been conducted with the aim of having a better understanding of the development phase of a vehicle development project [26], [27]. The results of these studies explain that simulation is expensive and time consuming, and that there is considerable effort required.

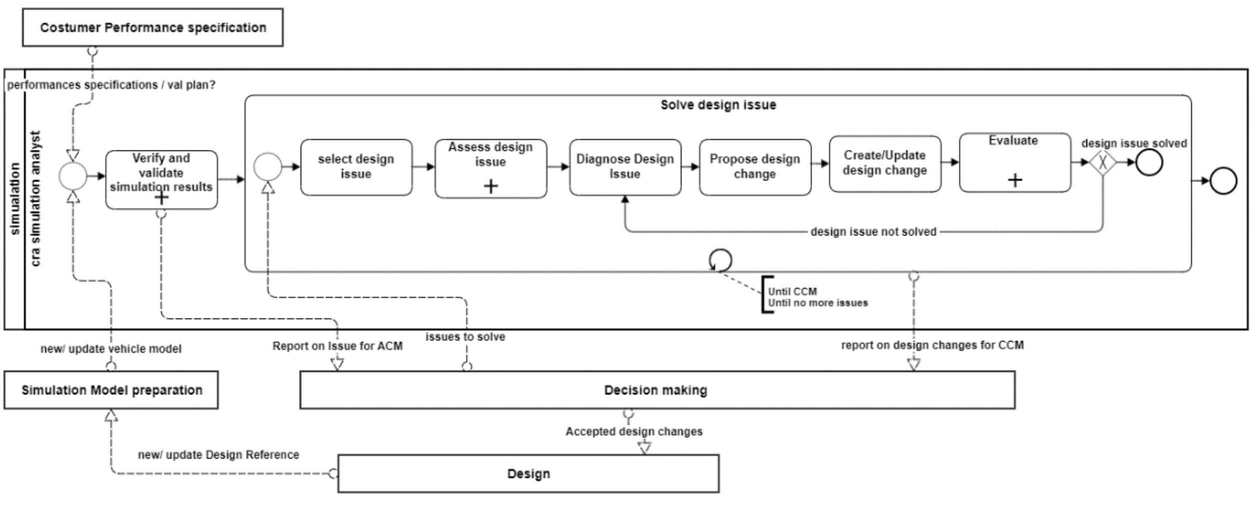


Figure 1. Simulation analyst's activities, focussing on the design issue resolution process, with a glance into the collaboration with other stakeholders

The development phase is a succession of digital loops, called design analysis loops, terminating in milestones. These loops involve design and simulation activities and are referred to as digital since the vehicle exists only in the form of numerical models, and both design and simulation activities are numerical. At the end of the development phase, the vehicle model must be at the right level of performance and the right manufacturing cost. The development phase consists of iteratively refining the design specifications, evaluating and validating the vehicle's performance and solving any design issues encountered. This phase is supported by modelling and simulation (M&S); the vehicle is represented by a digital model and the engineering activities are digital. Several variations on a vehicle model exist at the same time, as there are several markets with different expectations. The design reference (DR) represents the knowledge gathered about the vehicle under development and its specifications. The design activity aims to define and adjust the DR. Simulation aims to evaluate the vehicle performance. If a design issue is revealed by the simulation, it must be solved. We focus on solving the design issues encountered during the car crash simulation.

Figure 1 shows the different processes in the development phase with a focus on the car crash simulation. The design process consists of creating and updating the DR. The simulation model generation process consists of creating and updating the digital vehicle models required for the simulation. The customer performance specification process provides the specification of the vehicle to be met. The simulation process evaluates the performance of the vehicle and solves the design issues; a design issue occurs when the performance does not meet the specification. Finally, the decision-making process determines which design changes to incorporate. A design change is a solution to the design issue. Different stakeholders are involved in the different processes, as explained in Table 1.

Table 1: Stakeholders of each process within the development phase

Process	***Stakeholders***
Simulation	Simulation analyst, synthesis engineer CAE
Design	Designer, synthesis architect
Simulation model generation	Model factory engineers
Costumer Performance specification	PPC, costumer performance leader
Decision making	Designer, synthesis architect, project manager

Our focus is on the crash simulation process and mainly on the analysts involved within this process. The analysts' missions are to evaluate and validate vehicle performances and to deliver a vehicle model compliant with multiple requirements. They rely on simulation to evaluate vehicle performance. During the development phase, for a design analysis loop, crash simulation analysts receive the specification and the vehicle model to be evaluated. Once they have obtained the simulation results, they proceed with the interpretation of these results. If the model does not meet one or more requirements, a design issue is identified. The analysts assess and diagnose the design issue, then propose a design change to fix the design issue. If the design change is not satisfactory (unresolved design issue), they consider a new path for another design change. If the design change satisfies the requirement, the project decision-makers decide whether to implement it in the vehicle model. This decision depends on project factors including cost and weight. The decision-making process is not considered in this research; only the resulting decision is considered.

Analysts are required to have knowledge of modelling and simulation. They are also expected to make decisions on paths relating to investigation of design issues and on proposals for design changes. At the end of each design analysis loop, all design changes that have been approved by the different disciplines, such as crash, stress and noise and vibration, are incorporated into the vehicle model, ready for the next loop.

Crash simulation analysts are geographically distributed, and there is only one crash simulation expert and one digital simulation expert in the company [28]. Car crash simulation analysts collaborate with different stakeholders. They collaborate with other crash simulation analysts from other work sites and with simulation analysts from different disciplines, such as noise and vibration simulation analysts. There is a strong collaboration between simulation analysts and simulation experts, as the latter have the most significant expertise within the company. Analysts, designers and customer performance specialists exchange information on the status of the resolution of design issues. Finally, decision-makers participate in the decision-making process regarding the design change to be incorporated into vehicle models.

According to the empirical study [27], analysts encounter several challenges within car crash simulation. They need to quickly locate all relevant data and knowledge, from different sources, in as little time as possible. Design-issue analysis and design-change proposal formulation need to be improved, in order to reduce the time spent on simulation and reduce bias of less experienced analysts when interpreting simulation results.

This paper addresses these issues by proposing an ontology-based knowledge management approach to support simulation-aided design. The knowledge management support system is based on a knowledge model that formalises formal knowledge and knowledge related to the resolution of design issues. Knowledge retrieval models will support the analysis of design issues and design change proposals. Section 4 details the architecture of the KM support system with a focus on engineering knowledge capture and retrieval.

4. An ontology-based approach for an integrated and collaborative knowledge management

To improve the crash simulation analysis process, time should be reduced and decisions concerning investigation paths and design-change proposals should be substantiated. The crash simulation analysis process is knowledge intensive and highly dependent on expertise. Since there is only one crash simulation expert, it is important to capture the knowledge and expertise and share it with analysts. Collaboration between the different people involved is very important for the process to run smoothly. With these characteristics taken into consideration, we propose an integrated and collaborative knowledge management approach to support analysis and to ensure collaboration with the different stakeholders involved in the design issue resolution process.

In previous work [28], we proposed formalising the knowledge related to car crash simulation using an ontology. The interest in developing ontologies is growing in engineering design as it involves knowledge sharing and the development of a common standard language [29], usually used for the formalisation of domain knowledge [25]. The proposed ontology is called Crash Simulation Post-Processing CSPP ontology, and an overview of this ontology will be given in section 4.1. We also presented the first steps towards the development of the knowledge management support system in later work [30], based on an in-depth literature review of knowledge management frameworks and knowledge management systems architecture while taking into account the specificities of our industrial context, in light of the ontology.

Hence, in this paper, as an extension of the research presented in [30], we focus mainly on the development of the virtual KM support system. First, we define its capabilities, then we present the architecture and specify the blocks and sub-blocks.

4.1. The Crash Simulation Post-Processing (CSPP) Ontology

In this section, we briefly explain the Crash Simulation Post-Processing Ontology that we have developed in previous work [28]. The purpose of crash simulation is to evaluate the performance of a specific vehicle model. The ontology, therefore, formalises the knowledge related to design issue resolution, mainly the knowledge related to the post-processing phase of the crash simulation and the interpretation of the simulation results. The ontology is formalised according to three levels to better structure the engineering knowledge. Firstly, the context level contains information on the context in which the digital test takes place, such as the requirements to be met and the impact configuration, including frontal and rear crashes. Second, the project level formalises the engineering knowledge related to a specific vehicle project, including the vehicle model, the assessment of simulation results, and the resolution of design issues. Finally, the reasoning level formalises the reasoning behind the resolution of design issues. For brevity, we explain only the concepts, mainly at the level of reasoning, that are necessary to understand this paper.

A design issue occurs when requirements are not met by the vehicle. A vehicle model consists of vehicle parts, and each vehicle part has a role to play in the vehicle structure during the crash test and adopts an expected behaviour to ensure this role. Thus, we define a design issue as a behaviour gap between the expected behaviour and a defect behaviour of a vehicle part. A design issue has root causes. A root cause is also defined as a behaviour gap of a vehicle part. An elementary root cause is a root cause to which the analyst can propose a design change. A design change is one or more corrective actions applied to a vehicle part. This reasoning is based on the hypothesis that, first of all, crash simulation is based on physical and mechanical phenomena. Therefore, the behaviour of vehicle parts has limited possibilities of deformation and can be predictable. Secondly, vehicle parts sharing the same role and behaviour would be exposed to similar issues and could, therefore, belong to the same category. Then, issues with similar diagnosis and root causes would share similar corrective actions.

4.2. Capabilities of the knowledge management support system

Engineering knowledge related to design-issue resolution includes the design issue, its root causes, and associated design changes, as formalised in the CSPP ontology. We now refer to it as engineering knowledge.

The capabilities of the KM support system can be characterised into three overall capabilities:

- Collaboration: The support system must ensure collaboration between the various stakeholders within vehicle projects. Virtual collaboration is considered in this context.
- Capturing engineering knowledge: the support system must be able to capture engineering knowledge based on the CSPP ontology, classify it, and store it in knowledge repositories.
- Retrieval of engineering knowledge: the support system must be able to retrieve knowledge based on user queries and share it with users.

This paper aims to develop an integrated and collaborative knowledge management system. It is integrated since the CSPP ontology combines formal knowledge, such as requirements and models, and tacit knowledge, such as design issue resolution. The integrated aspect is also present in the combination of both methodologies for codification and personalisation of KM. The KM support system ensures the codification of knowledge and the capture of in-context and tacit knowledge through communication. The collaborative aspect is undertaken by ensuring stakeholder collaboration within vehicle projects and enabling communication.

4.3. A virtual KM support system for simulation-aided design

Based on pre-defined capabilities, we propose a virtual system to support simulation-aided design within vehicle projects. As shown in Figure 1, the support system consists of four main parts: three layers and a multi-user interface.

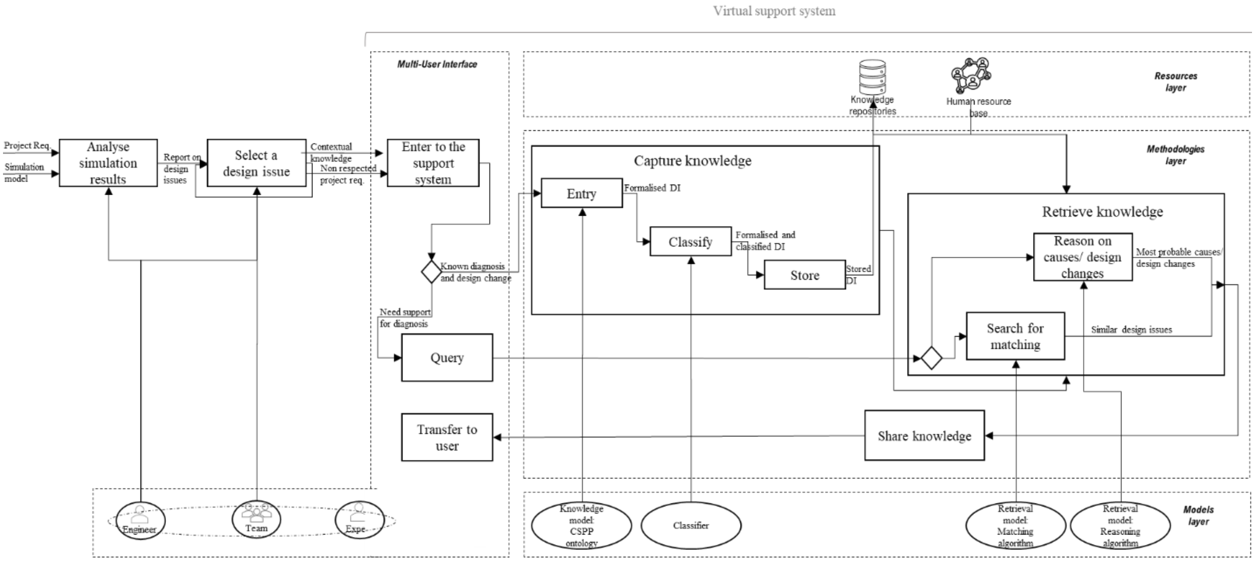


Figure 2: The description of the Virtual KM support system, with its three layers and multi-user interface. A representation of the activities performed before interacting with the KM support system is also given (on the right), to identify the inputs required.

The three layers constituting the support system are the resources, methodologies, and models layers:

- The resources layer refers to knowledge repositories in various data and knowledge formats. Repositories may include data and information such as simulation models and reports used and transferred as part of the process. Other explicit and implicit knowledge is stored in knowledge repositories. Implicit and tacit knowledge embedded in the human mind could be shared through communication. Therefore, the KM support system includes a human resource base of employees, detailing their roles, skills, and capabilities.
- The models layer consists of models developed to support the implementation of the system, including an integrated knowledge model, a classifier, and two knowledge retrieval models. The integrated knowledge model is the CSPP ontology. The classifier and the two retrieval models will be explained later in Section 4.4.1.
- The methodologies layer represents the methodologies used to conduct KM activities. Based on the capabilities detailed in section 4.2, two principal methodologies are required: "capture knowledge," leading from raw information to knowledge stored in repositories, and " retrieve knowledge," leading from knowledge in repositories to specific knowledge required by the user. We then added " share knowledge" to ensure the continuity of the information flow from the knowledge retrieval to the user. More details on "capture knowledge" and "retrieve knowledge" will be presented in section 4.4.

Finally, the multi-user interface (MUI) ensures interaction between users and the virtual system and collaboration between users within the integrated work environment. Users, including engineers, experts, and teams, can have distributed workspaces for individual tasks and project environments for collaboration if required. The support system must ensure collaboration between stakeholders working on the same project via a virtual environment where they can communicate, interact, and update the current project. The MUI provides multiple activities to ensure user interaction with the system, such as "enter support system," "query," and "transfer to the user." These activities ensure, firstly, the input of input data into the system, secondly, the choice of entering new engineering knowledge or retrieving knowledge, and thirdly, the transfer of the retrieved knowledge to the user. All MUI activities are accessible to the various users. For reasons of clarity, the links between users and MUI activities are not presented in the Figure 2.

4.4. The KM support system architecture

In this section, we focus on both the methodologies and models layers of the KM support system. As explained in Section 4.3, and based on the capabilities previously described, the KM support system must have two blocks realizing both "capture knowledge" and "retrieve knowledge" activities. Each block consists of sub-blocks and calls for a specific model to perform each function.

4.4.1. The knowledge capture block:

The KM support system must be capable of capturing engineering knowledge from different resources, such as extracting knowledge from formal knowledge records (such as simulation models, reports) and obtaining knowledge from the user. We focus on capturing the user's engineering knowledge.

The knowledge capture block carries out the "knowledge capture" activity presented in Figure 2. It should allow the user to document new design issues and their resolution. Accordingly, engineering knowledge is entered into the system based on the CSPP ontology. Each design issue is classified into its category via a classifier and then stored in knowledge repositories. Thus, three different sub-blocks are identified to perform three different functions.

Firstly, the *Entry* sub-block, shown in Figure 2, allows formalising the data and information entered into the system using the knowledge model. Information about the design issue and its resolution will be entered in the fields proposed by the CSPP ontology. The output of this sub-block is the formalised engineering knowledge.

Second, the *Classify* sub-block, shown in Figure 2, allows the system to classify formalised design issues. This sub-block relies on the classifier. The classifier can be based on a statistical or deterministic classification that identifies a set of categories to which the design issues belong. The result of this sub-block is a formalised design issue with its corresponding category.

In this paper, to exemplify, we propose a deterministic classifier based on the categories explained at the reasoning level of the CSPP ontology. Vehicle parts sharing similar roles and behaviours would be subject to similar design issues and then to similar design changes. Therefore, vehicle parts sharing similar roles and behaviours would belong to the same category. In this case, the classifier will sort the design issue according to the vehicle part affected. Based on this reasoning, we propose a classifier based on matrix multiplication, as explained in Figure 3. The first matrix P defines the vehicle parts (vp) by their roles (r) and their behaviours (b) using a pair (r, b). The second matrix C defines the categories (cat) according to the pair (r, b). Finally, the matrix PC classifies the vehicle parts into their respective categories by matrix multiplication of P and C, while maximising $pc_i > 0$ to 1.

In order to classify a new vehicle part, the designer must be involved. The designer must assign the pair (r,b). If (r,b) exists, the classifier will classify the new vehicle part. If not, the designer shall fill in the matrix C.

The matrix of the vehicle parts and their (r,b)

$$\boldsymbol{P = (p_{ij}), p_{ij} = 1}, \text{if } \boldsymbol{vp_i \text{ adopts } (r,b)_j}$$

P	(r,b)1	(r,b)2	(r,b)3
vp1	1	0	1
vp2	1	0	0
vp3	0	1	1
vp4	0	1	0

The categories based on (r,b)

$$\boldsymbol{C = (c_{ij}), c_{ij} = 1}, \text{if } \boldsymbol{(r,b)_i \text{ exists in } cat_j}$$

C	cat1	cat2
(r,b)1	1	0
(r,b)2	0	1
(r,b)3	1	1

The categorisation of vehicle parts

$$\boldsymbol{PC = P * C}$$

P\C	cat1	cat2
vp1	1	1
vp2	1	0
vp3	0	1
vp4	0	1

Figure 3: The classifier is described, which is based on the multiplication of matrices. An example is drawn for a better understanding. The equations representing each matrix are presented in detail. The matrix PC is the result of the product of the matrix and a normalization at 1 for all matrix elements >1.

Finally, the *Store* sub-block (see Figure 2) allows the system to store the formalised and classified design issue in knowledge repositories, ready to be retrieved later. The knowledge repository space would consist of several clusters representing the categories and containing the associated design issues and their resolution. It would facilitate later retrieval as it would limit the search space.

4.4.2. The knowledge retrieval block:

The knowledge retrieval block realises the “retrieve knowledge” activity presented in Figure 2. Based on the user's query, the knowledge retrieval block must call the appropriate retrieval model. Two queries are possible. First, the user may request a list of design issues that are similar to the design issue under study along with their resolution. For this purpose, the support system accesses the sub-block *Search for matching*, involving the matching algorithm. The user can also request the most probable design diagnosis (causes) and design change for the design issue under study. For this purpose, the support system accesses the *Reasoning on causes / design change* sub-block (referred to as Reasoning), involving the reasoning algorithm. The knowledge retrieval block automatically calls the knowledge capture block so that the support system captures the studied design issues. If the knowledge retrieval block does not find an answer to the query, it is supposed to search for the most apt stakeholder to answer the query. This option is not detailed in this paper.

To exemplify the two retrieval models, we propose a filter for the matching algorithm and a probabilistic reasoning for the reasoning algorithm.

For the matching algorithm, we propose a two-step filter, shown in Figure 4. As explained above, the knowledge repository space is divided into clusters of categories of design issues and their resolution. Therefore, similarity means that the design issues belong to the same categories. Thus, the first step will select the categories related to the vehicle part affected by the design issue, and thereby obtain all design issues from these categories. The second step is optional. If necessary, the user can define filter criteria in the query, according to which design issues resulting from the first step will be filtered. The filter criteria will address one or more elements of the definition of the design issue, such as the criterion to be respected and the impact configuration.

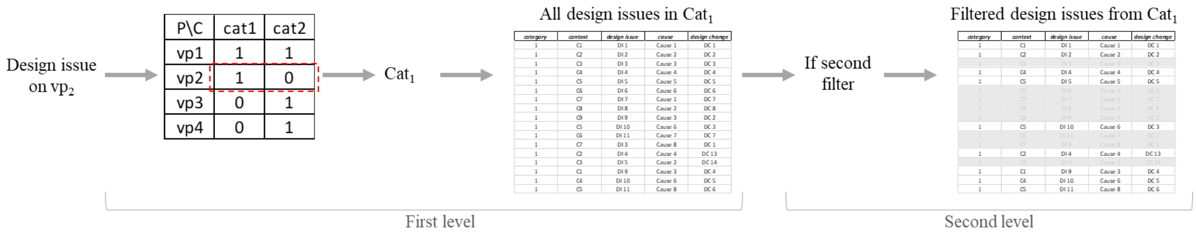
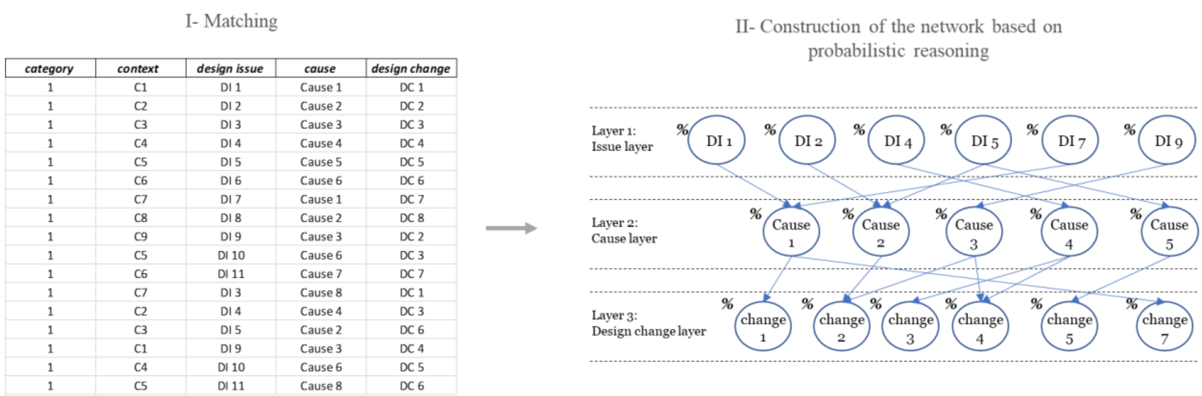


Figure 4: The two-step filter for the matching algorithm, with an example for explanation. Knowing the vehicle part affected by the design issue under study, the first step of the matching algorithm would identify the corresponding categories (Cat_1) to the vehicle part (vp_2) and then list all the respective design issues and their resolution. Then, for the second step, based on the filter criteria, it would retain only the design issues that meet those criteria. The hidden lines are the eliminated design issues.

More explicitly, for the first step, the matching algorithm will go into the PC matrix and extract the categories related to the vehicle part. Then, we will obtain a database containing all the design issues related to the selected categories. Then, for the second step, based on the filter criteria identified by the user, the matching algorithm will filter the new set of design issues, merely keeping the ones that satisfy these criteria.



category	context	design issue	cause	design change
1	C1	DI 1	Cause 1	DC 1
1	C2	DI 2	Cause 2	DC 2
1	C3	DI 3	Cause 3	DC 3
1	C4	DI 4	Cause 4	DC 4
1	C5	DI 5	Cause 5	DC 5
1	C6	DI 6	Cause 6	DC 6
1	C7	DI 7	Cause 1	DC 7
1	C8	DI 8	Cause 2	DC 8
1	C9	DI 9	Cause 3	DC 2
1	C5	DI 10	Cause 6	DC 3
1	C6	DI 11	Cause 7	DC 7
1	C7	DI 3	Cause 8	DC 1
1	C2	DI 4	Cause 4	DC 3
1	C3	DI 5	Cause 2	DC 6
1	C1	DI 9	Cause 3	DC 4
1	C4	DI 10	Cause 6	DC 5
1	C5	DI 11	Cause 8	DC 6

Figure 5: (I) presents the list of design issues and their resolution that is the result of the matching algorithm for the design issue under study. (II) explains the construction of the network, where some design issues (DIs) are presented with their respective causes and design changes. The % represents the probability of each node, which is calculated based on a statistical calculation of occurrence from part (I).

The reasoning algorithm must propose the most probable cause of the design issue and the most probable design change. As explained in Figure 5, it starts by calling the matching algorithm, which will identify the categories to be addressed, and thereby all design issues, from these categories, and their resolution. Then, based on probabilistic reasoning, it would establish a network of three layers, including design issues, causes, and design changes, while assigning their probability of occurrence. Hence, the reasoning algorithm will present the most probable causes and the most probable design changes for the design issue under study.

5. Knowledge management support system, application and evaluation

In this section, for the evaluation of our proposal, we present three use case scenarios with a proof of concept implementation for each model. Each use case scenario will take into account a methodology (capture and retrieval) and the models that will be applied. For the three scenarios, we have built a knowledge base of several design issues and their resolution. This base is built based on real information documented by simulation analysts, and we have duplicated some information in order to have more cases and to be able to calculate probabilities. As shown in Figure 6, the columns represent the fields proposed by the CSPP ontology; not all of them are presented, since we chose some of them to have a complete picture without getting into all details.

vehicule_seg	impact_config	performance	criterion	target	scope_crtierion	appreciation	category	cause_scope	expected_behaviour	behaviour_gap	elementary_cause	corrective_action
A	front	EuroNCAP	MPS	<2	Side_member	High	C1	CB	Compression	High compression	Low stiffness	Material change
A	front	EuroNCAP	MPS	<2	Floor_panel	High	C1	CB	Compression	High compression	Low stiffness	increase thickness
B	front	EuroNCAP	MPS	<2	Side_member	High	C1	CB	Compression	Break	Low stiffness	increase thickness
A	front	EuroNCAP	MPS	<2	Side_member	High	C1	CB	Compression	No compression	High stiffness	Material change
B	front	EuroNCAP	MPS	<2	Floor_panel	High	C1	CB	Compression	High compression	Low stiffness	increase thickness
A	rear	EuroNCAP	MPS	<2	Floor_panel	High	C1	Side_member	Compression	High compression	Wrong geometry	add rainure
A	rear	EuroNCAP	MPS	<2	Floor_panel	High	C1	CB	Compression	Low compression	High stiffness	decrease thickness
A	rear	EuroNCAP	MPS	<2	Side_member	High	C1	Side_member	Rotule	No rotule	Wrong geometry	design of new part
C	rear	EuroNCAP	MPS	<2	Side_member	High	C1	Side_member	Rotule	No rotule	High stiffness	decrease thickness
A	front	EuroNCAP	MPS	<2	Towing_bracket	High	C1	CB	Compression	Low compression	High stiffness	increase thickness
A	front	EuroNCAP	MPS	<2	Side_member	High	C1	Side_member	Compression	Low compression	Wrong geometry	design of new part
C	Pedestrian	NCAP	HIC	<1000	Hood	High	C2	Hood	contact force	High force	High stiffness	design change
B	front	EuroNCAP	MPS	<2	Side_member	High	The example of the use case scenario					

Figure 6: The knowledge base used for the use case scenarios. The last line represents the example that will be used for the use case scenarios 2 & 3.

For each use case scenario, we will document the interaction between the user and the system and present the inputs and outputs of each scenario. Figure 7 shows the main part of the algorithm that interacts with the user to obtain the query and then call the appropriate block or sub-block to answer the query. We used Python 3 for programming.

```
if __name__ == "__main__":

    txt = input("What do you want to do? (add design issue, find solutions, find causes,
find similar inputs)")
```

Query

```
    if txt == "design issue" or "add design issue":
        capture_desing_issue('database.xlsx')
```

If the query is to add a new design issue and its resolution, call for the knowledge capture block

```
    else:
        db, levels_of_db, test_scenario = capture_test_scenario('database.xlsx')
```

If the query is to retrieve knowledge, start by calling the knowledge capture block

```
        if txt == "solutions" or "find solutions":
            find_solutions(levels_of_db, test_scenario, "solutions")

        elif txt == "causes" or "find causes":
            find_solutions(levels_of_db, test_scenario, "causes")
```

If the query is to search for most probable cause/ design change, call for the reasoning sub-block

```
        elif txt == "similar inputs" or "find similar inputs":
            category = test_scenario['category'][0]
            filter_similar(db, category)
```

If the query is to search for similar design issues, call for the matching sub-block

```
        exit("closing app")
```

Figure 7: Presentation of the main part of the algorithm with a detailed description. The main part allows the user to enter the query. Then, depending on the query, it calls the appropriate functions.

5.1. Use case scenario 1: Capture engineering knowledge

The user must enter a new design issue with its resolution to the KM support system. The KM support system will then access the *Knowledge Capture* block and call the CSPP ontology and classifier as models.

Figure 8 shows the function “capture_design_issue” responsible for capturing engineering knowledge, classifying it and storing it.

```
def capture_desing_issue(name):

    table = pd.read_excel(name)
    print("input needed are {}".format(table.columns))

    input_line = {}
    for col in table.columns:
        if col != 'category':
            data = input('What is the value for {}?'.format(col))
            input_line[col] = data or None

    input_line = find_category(input_line)

    validation_and_add_to_db(input_line, name, table)

    return input_line
```

Propose the ontology fields for the user to fill

Entry of the knowledge documented by the user

Classification of the design issue

Storing

Figure 8: The knowledge capture block, starting with entry, through to classification and finally storing the design issue and its resolution.

Figure 9 describes the interaction between the user and the KM support system while capturing a new design issue and its resolution. The user must enter the various fields provided by the KM support system. The user is then requested to validate the new design issue and its resolution before storing it. As it is shown, the category is automatically generated by the classifier.

```
What do you want to do? (add design issue, find solutions, find causes, find similar inputs)
add design issue

input needed are ['vehicule_seg', 'impact_config', 'performance', 'criterion', 'target',
'scope_crtierion', 'appreciation', 'cause_scope', 'expected_behaviour', 'behaviour_gap',
'elementary_cause', 'corrective_action']


What is the value for vehicule_seg? A
What is the value for impact_config? rear
What is the value for performance? NCAP
What is the value for criterion? MPS
What is the value for target? <2
What is the value for scope_crtierion? Side_member
What is the value for appreciation? High
What is the value for cause_scope? CB
What is the value for expected_behaviour? Compression
What is the value for behaviour_gap? High compression
What is the value for elementary_cause? Low stiffness
What is the value for corrective_action? Material change


FYI, the part is in the category : C1
this line will be added to the database, do you validate ? (yes/no) : {'vehicule_seg': 'A',
'impact_config': 'rear', 'performance': 'NCAP', 'criterion': 'MPS', 'target': '<2',
'scope_crtierion': 'Side_member', 'appreciation': 'High', 'cause_scope': 'CB',
'expected_behaviour': 'Compression', 'behaviour_gap': 'High compression', 'elementary_cause':
'Low stiffness', 'corrective_action': 'Material change', 'category': 'C1'}yes
```

Figure 9: The knowledge capture block, with its inputs and outputs. Queries are in green. The result of this block is the creation and storage of a new design issue. The system does not ask the user to enter the category. However, it is assigned later when the system requests validation of the information entered.

5.2. Use case scenario 2: retrieval of similar design issues

The user will search for design issues similar to the one under study (last line of Figure 6). Therefore, during the query, the user will ask for "search for matching". The user will also use filter criteria to narrow the search result. The KM support system will then access the *Search for matching* sub-block and the matching algorithm as a model. Figure 10 presents the function “filter similar” in the algorithm, representing the *Search for matching* sub-block, with the two steps filter.

```
def filter_similar(table, category ):

    res = table.loc[category == table.category]

    other_filter = input("do you want to add another filter ?")
    while other_filter == "yes":
        print("the possible columns to filter are {}".format(list(table.columns)))
        precise_filter = input("write the filter like this :  'columns : value'").split(" : ")
        res = res.loc[precise_filter[1] == res[precise_filter[0]]]
        other_filter = input("do you want to add another filter ?")

    print(res)
    return res
```

First step filter based on the category

Second step filter based on filter criteria chosen by the user

Figure 10: The search for matching sub-block, with the matching algorithm represented by the function *loc [rows [column = value]]*. This function filters the rows of the knowledge base, based on a specified column. For the first step filter, the *[column=category]*, and the second step filter, the value of the column will be entered by the user.

As mentioned above, for use case scenario 2, the user requests design issues similar to the one under study (represented in the last line of the knowledge base). Figure 11 represents the interaction between the user and the support system and the results of the support system. First, the user selects "similar inputs" in the query and then requests a second step filter based on "impact_config=front." The support system then lists seven design issues and their resolution, similar to the one understudy.

```
What do you want to do? (add design issue, find solutions, find causes, find similar inputs)similar inputs
New study case found, we will try to find possible solutions
do you want to add another filter ?yes
the possible columns to filter are ['vehicule_seg', 'impact_config', 'performance', 'criterion', 'target', 'scope_crtierion',
'appreciation', 'category', 'cause_scope', 'expected_behaviour', 'behaviour_gap', 'elementary_cause', 'corrective_action']
write the filter like this :  'columns : value'impact_config : front
do you want to add another filter ?no

   vehicule_seg impact_config performance criterion target scope_crtierion  \
0             A         front     EuroNCAP       MPS     <2     Side_member
1             A         front     EuroNCAP       MPS     <2     Floor_panel
2             A         front     EuroNCAP       MPS     <2     Side_member
3             A         front     EuroNCAP       MPS     <2     Side_member
4             B         front     EuroNCAP       MPS     <2     Floor_panel
9             A         front     EuroNCAP       MPS     <2  Towing_bracket
10            A         front     EuroNCAP       MPS     <2     Side_member

   appreciation category  cause_scope expected_behaviour     behaviour_gap  \
0          High       C1           CB        Compression  High compression
1          High       C1           CB        Compression  High compression
2          High       C1           CB        Compression             Break
3          High       C1           CB        Compression    No compression
4          High       C1           CB        Compression  High compression
9          High       C1           CB        Compression   Low compression
10         High       C1  Side_member        Compression   Low compression

   elementary_cause   corrective_action
0     Low stiffness     Material change
1     Low stiffness  increase thickness
2     Low stiffness  increase thickness
3    High stiffness     Material change
4     Low stiffness  increase thickness
9    High stiffness  increase thickness
10   Wrong geometry  design of new part
```

Figure 11: The interaction between the user and the support system and the outputs. Queries are in green. The result is an extraction from the knowledge base. The user has requested design issues similar to the one he has documented and has requested a second step filter using the "impact_config: front" criterion. Seven design issues respond to the query.

5.3. Use case scenario 3: Retrieval of most probable causes and design changes

The user is looking for the most likely cause and design change for a design issue they are addressing. Therefore, when querying, the user will request "reason for the cause or design change". The KM support system then accesses the sub-block " *Reasoning on causes/ design change"* and the reasoning algorithm as a model whose representative function "find_solutions" is shown in Figure 12. To have a better understanding of the construction of the network, we present an example in Figure 13. The network layers in this use case scenario are consistent with the concepts used for the CSPP ontology. Starting by the design issue layer, the layers are: “cause scope”, “behaviour gap”, elementary cause” and “design change”.

```
def find_solutions(levels_of_db, test_case_scenario, last_layer):

    final_solutions = {}

    cause_scope_layer = search_children(levels_of_db["cause_scope"], test_case_scenario, "cause_scope")

    network_layers = ["behaviour_gap", "elementary_cause", "corrective_action"]
    if last_layer == "solutions" else ["behaviour_gap", "elementary_cause"]

    for studied_cause_scope, cause_scope_weight in cause_scope_layer.items():
        parent_layer = {studied_cause_scope: cause_scope_weight}

        for layer in network_layers:
            children_layer = {}
            for parent_node, parent_node_weight in parent_layer.items():
                children_nodes = search_children(levels_of_db[layer], parent_node, layer)
                children_layer = build_children_layer(children_nodes, children_layer, parent_node_weight)
            parent_layer = {k: v for k, v in sorted(children_layer.items(), key=lambda item: item[1],
          reverse=True)}

        final_layer = {key: round(value, 2) for key, value in parent_layer.items()}
        final_solutions[studied_cause_scope] = final_layer
        print("solutions for cause {} are : {}".format(studied_cause_scope, parent_layer))

    print(final_solutions)
    return final_solutions
```

Identify the children nodes (from the cause scope layer) of the design issue under study

Identify the layers involved, if the search focuses on causes or for design changes

for each node from the cause scope layer, construct the network

Construct the network: starting from a node of the cause scope layer, identify the children nodes (from the next layer) and calculate their probabilities

Print results for each cause scope node

Figure 12: The sub-block of the *Reasoning on causes/design change* represented by the "find solutions" function. In the "test_case _senario," the first step of the matching is performed. Starting from the cause scope layer, its nodes, and their probabilities, the construction of the network consists of identifying, for each layer, the children nodes, and their probabilities, up to the layer of elementary causes or design changes.

As shown in Figure 13, focusing on the first two layers, we begin by identifying the child nodes, from the cause scope layer, of each parent node, from the issue layer. Next, the probability of a child node is the probability of the parent node multiplied by the probability of the arrow (the probability of the cause scope knowing the design issue). If several arrows are pointing at a child node, then the probability is the sum of all the probabilities of the parent nodes multiplied by the probability of their arrows.

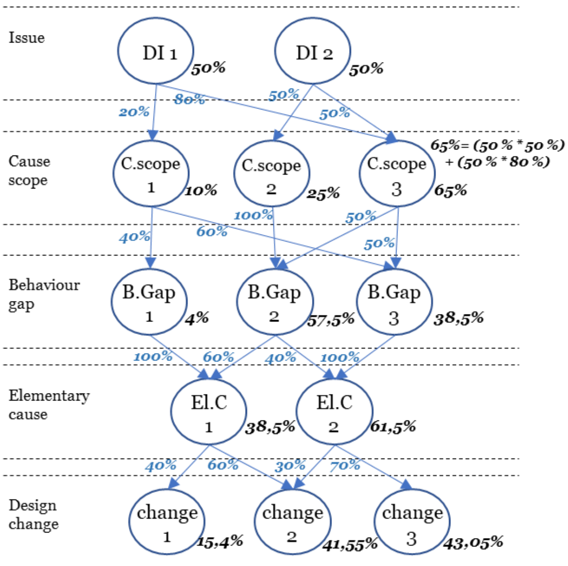


Figure 13: A detailed explanation of the proposed network, with its layers, and the calculation of probabilities for each node. The probability of each node is the probability of the parent node multiplied by the probability of the arrow.

For this use case, we present two scenarios: first, the user requests the causes, and second, the user requests the design changes. Figure 14 shows the interaction between the user and the support system when requesting causes and Figure 15 when requesting design changes. Both queries are for the same design issue with the same inputs.

```
What do you want to do? (add design issue, find solutions, find causes, find similar inputs)causes
New study case found, we will try to find possible solutions

solutions for cause CB are : {'Low stiffness': 29.55, 'High stiffness': 21.22, 'Wrong geometry': 12.88}

We need more info about the behaviour of the possible problematic piece : Side_member
Behaviours can be ['Compression', 'Rotule']
what value do you have as expected_behaviour ? Compression

solutions for cause Side_member are : {'Low stiffness': 13.63, 'High stiffness': 12.12, 'Wrong geometry': 10.6}

{'CB': {'Low stiffness': 29.55, 'High stiffness': 21.22, 'Wrong geometry': 12.88}, 'Side_member': {'Low stiffness': 13.63,
'High stiffness': 12.12, 'Wrong geometry': 10.6}}

closing app
```

Figure 14: The results of the KM support system for reasoning on causes. Queries are in green. In the end, we can read that two scopes of causes are possible, the CB and the Side_member, with their respective elementary causes and probabilities, in decreasing order.

For the design issue under study, the cause scope can be either the "Crash Box" or the "Side member." For the reasoning on causes (Figure 14), the algorithm stops at the elementary cause layer. It gives, as a result, each cause scope with its respective elementary causes and their probabilities, in descending order. Moreover, for the reasoning on design changes (Figure 15), the algorithm stops at the design change layer. It gives as output the same cause scope (since we are studying the same design issue), with their respective design changes and their probabilities, in descending order.

```
What do you want to do? (add design issue, find solutions, find causes, find similar inputs)solutions
New study case found, we will try to find possible solutions

solutions for cause CB are : {'increase thickness': 27.47, 'Material change': 12.69, 'decrease thickness': 10.61,
'design of new part': 8.59, 'add rainure': 4.29}

We need more info about the behaviour of the possible problematic piece : Side_member
Behaviours can be ['Compression', 'Rotule']
what value do you have as expected_behaviour ? Compression

solutions for cause Side_member are : {'increase thickness': 13.26, 'design of new part': 7.07, 'Material change': 6.44,
'decrease thickness': 6.06, 'add rainure': 3.53}

{'CB': {'increase thickness': 27.47, 'Material change': 12.69, 'decrease thickness': 10.61, 'design of new part': 8.59,
'add rainure': 4.29}, 'Side_member': {'increase thickness': 13.26, 'design of new part': 7.07, 'Material change': 6.44,
'decrease thickness': 6.06, 'add rainure': 3.53}}

closing app
```

Figure 15: The results of the KM support system for reasoning on design changes. Queries are in green. In the end, it indicates the same cause scopes, with their respective design changes and probabilities, in decreasing order.

6. Discussion

The integrated and collaborative knowledge management system aims to support simulation-aided design, based on the different models and technologies used. The KM support system captures engineering knowledge using the CSPP ontology, which is characterised as integrated since it combines formal and tacit knowledge. It also ensures the retrieval of engineering knowledge, based on user queries, using different retrieval models. The retrieval models are developed based on the reasoning already developed in the CSPP ontology, which formalises the resolution of design issues and is independent of the specificities of the vehicle project. This reasoning imitates the tacit knowledge of analysts and experts. The collaborative KM support system not only facilitates the resolution of design issues but also provides contextual and tacit knowledge captured during communication between the different stakeholders of vehicle projects.

The different models, which ensure the capture and retrieval of engineering knowledge, are developed and evaluated using use case scenarios of car crash simulation. The models and technologies used are effective in capturing and retrieving knowledge since the outcomes meet the expected results communicated by analysts and experts.

Time is one of the most important constraints in project development. The KM support system would help reduce crash simulation time by reducing the time spent solving design issues and proposing design changes. During the empirical study conducted within the company, we proved that simulation with more certainty about the results would allow us to gain at least one iteration per issue and so we save about nine hours of computation and about one hour of analysis [27]. Based on interviews with analysts, they encounter two or three significant design issues for about fifteen impact configurations, per project and design loop. Thus, by saving one iteration per design issue, we would save about thirty-five hours or one week of the design loop, out of the five weeks it usually lasts. Hence, we would save 20% of the analyst's time.

The KM support system would also contribute to more accurate proposals for more effective design changes since proposals are made based on in-depth knowledge of the company. It could lead to the development of more robust vehicle models. The KM support system is also considered a learning tool, where novice analysts would have access to the engineering knowledge retained.

The main functionalities of the system have been developed and applied, although it is still considered a prototype which can be further enhanced. First, there is a need to integrate the different simulation disciplines, such as noise and vibration and stress. Second, a web-based prototype must be developed to facilitate communication between users and the system. Third, users, with different roles, need to work in their virtual spaces and create knowledge as the project progresses, which will enrich the knowledge base and improve the models.

In this paper, the KM support system is applied to the car crash simulation. Although, it can be generalised to different simulation disciplines, such as strength and noise and vibration. The same laws of physics apply to the different disciplines. Based on the analysis of documented design issues from different simulation disciplines, the design issues are mainly described in the same way as for crash simulation as well as the design changes. Only the context level of the ontology should integrate the concepts formalising the requirements of the discipline. The project level of the ontology could also integrate some specificities of the discipline if needed. However, the reasoning level of the ontology would remain the same. Hence, the models implemented within the KMS support system would remain unchanged. Future work on the generalisation of the ontology-based knowledge management approach will be undertaken.

7. Conclusion

In this paper, we present an ontology-based knowledge management system to support simulation-aided design, specifically car crash simulation. The KM support system includes an integrated ontology-based knowledge model that structures and formalises the formal knowledge and tacit knowledge related to design issue resolution. It also includes various knowledge retrieval methods to satisfy user needs. Moreover, a multi-user interface facilitates and enhances collaboration on vehicle projects.

A prototype and parts of knowledge retrieval methods are implemented. However, the next steps in this research need to focus on large-scale implementation of the support system and the generalisation to different simulation disciplines. The KM support system has been demonstrated to save simulation time. Further research could investigate the autonomy of such a system, whether we should continue to support analysts to analyse and solve design issues, or whether only expert validation would be sufficient.

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APPENDIX

```python
# -*- coding : utf-8 -*-
import os
import xlrd
import numpy as np
import pandas as pd


def search_children(data, raw_val, name):
    """   Compute the bayesian table and extract only the line matching our input case.
    The algorithm will do :
        - filter data to match input case
        - search all solutions  in the filtered data
        - compute statistical weight of this solutions to extract bayesian table
        - propose the table to the user
        - save user's choice into the table to have dynamic/learning beyesian table
    :param data: Table containing the data of the level
    :param raw_val: test scenario input or parent node name
    :param name: name of the children layer as stated in the database
    :return: solutions with wieghts for the level considered    """
    cols = list(data.columns)
    parameter_cols = get_parameters_cols(data, name)
    filter_cols = ['category'] if name == 'cause_scope' else parameter_cols
    tmp_data, input_scenario = filter_data_with_case(data, raw_val, cols, filter_cols,
parameter_cols)

    # compute dummies to transform categorical values into binary columns that we will use to
compute bayesian table.
    tmp_data = pd.get_dummies(tmp_data, columns=[name])

    # Compute the occurence of each solution against all the time similar cases appear
    group_poids = tmp_data.groupby(filter_cols).sum()
    group_count = tmp_data.groupby(filter_cols).count()
    bayesian_table = group_poids.div(group_count, level=parameter_cols) * 100

    # technical line (groupby messes the index)
    bayesian_table = bayesian_table.reset_index()
    # post-treating to get the result in the desired format
    if bayesian_table.empty:
        # This means we have no data matching the case scenario
        result = input_scenario.to_dict()
        print("This is a new case, we have no data to help you, contact your team expert for
support")
        return result, None
    # Combine bayesian table to the data to predict to add solutoins + weights in the scenario
    join = pd.merge(bayesian_table, input_scenario, on=filter_cols).drop([name], axis=1)
    # Technical : cleaning for easier manipulation and readability
    result = join.to_dict()

    childrens = {key[len(name)+1:]: round(value[0], 2) for key, value in result.items()
                 if key[0:len(name)] == name}
    return childrens


def add_new_test_scenario(name):
    table = pd.read_excel('database.xlsx')
    print("input needed are {}".format(table.columns))
    input_line = {}
    cols = get_parameters_cols(table, name)
    cols.remove('category')
    for col in cols:
        data = input('What is the value for {}?'.format(col))
        input_line[col] = data or None
    return input_line


def capture_desing_issue(name):
    """   ask for values to put in the Db    """
    table = pd.read_excel(name)
    print("input needed are {}".format(table.columns))
    input_line = {}
    for col in table.columns:
        if col != 'category':
            data = input('What is the value for {}?'.format(col))
            input_line[col] = data or None
    input_line = find_category(input_line)
    validation_and_add_to_db(input_line, name, table)
    return input_line
```

```
def cut_database_into_levels(database, category):
    database = database.loc[database.category == category]
    cause_scope = database[["impact_config","performance","criterion","target","scope_crtierion",
                            "appreciation","category","cause_scope"]]
    behaviour_gap = database[["cause_scope", "expected_behaviour", "behaviour_gap"]]
    elementary_cause = database[["behaviour_gap", "elementary_cause" ]]
    corrective_action = database[["elementary_cause", "corrective_action"]]
    return {"cause_scope": cause_scope, "behaviour_gap": behaviour_gap,"elementary_cause":
elementary_cause,
            "corrective_action":corrective_action}


def get_parameters_cols(df, name):
    """ quickly filter the input columns based on list order. Can be specified for each table"""
    for i, val in enumerate(df.columns):
        if val == name:
            return list(df.columns[:i])


def filter_data_with_case(data, raw_val,cols, filter_cols, parameter_cols):
    # filter on cases with the same scenario (inputs = values in index columns)
    if type(raw_val) == str:
        # Technical for iterations over
        tmp_data = data[data[cols[0]] == raw_val]
        input_scenario = pd.DataFrame([[raw_val]+[None]*(len(cols)-1)], columns=cols)
        if 'expected_behaviour' in cols:
            input_scenario = find_behaviour(input_scenario)
        elif len(parameter_cols) > 1:
            # other case not possible in our databases but we ask the user if it happens
            print('it seems that we are missing context data')
            print(input_scenario)
            for col in parameter_cols[1:]:
                txt = input("what value do you want for {} ? ".format(col))
                input_scenario[col][0] = txt
    else:
        tmp_data = data.copy()
        # first table scenario
        input_scenario = raw_val
        for col in filter_cols:
            val = input_scenario[col][0]
            # Filter over all the columns that have the same parameters as the case scenario input
            tmp_data = tmp_data[tmp_data[col]==val]
    return tmp_data, input_scenario


def get_test_scenario(data):
    """     getter of the test scenario.
    we let 2 possibilities to the user :
        - one case is already open (so you can re-use it without manually entering values
        - manual insertion of the values of the case
    the open cased is modelled as the last line of the db with only the "issue" / input parameters
filled and empty out
    :param data: full database
    :return: database without the open case, case as df of one line     """
    if not type(data["cause_scope"][len(data)-1]) == str:
        print("New study case found, we will try to find possible solutions")
        data.loc[len(data)-1, "cause_scope"] = None
        input_scenario = data.iloc[len(data)-1].to_dict()
        data.drop(data.tail(1).index, inplace=True)
    else:
        print("No new scenario waiting in db adding new scenario")
        input_scenario = add_new_test_scenario("cause_scope")
    if "category" in input_scenario and type(input_scenario["category"]) not in [str, list]:
        input_scenario = find_category(input_scenario)
    input_scenario = pd.DataFrame(input_scenario, index=[0])
    return data, input_scenario


def find_category(input_scenario):
    """ use the classifier to add category to the input scenario"""
    classifier = pd.read_excel("parts" + ".xlsx")
    classes = list(classifier.loc[classifier.parts == input_scenario['scope_crtierion'],
"category"])
    if classes :
        classes = classes[0]
    else :
        print("You are trying to insert a new part, caontact the expert to add this part in the
parts datbase.")
    input_scenario["category"] = classes
```

```
    return input_scenario


def find_behaviour(input_scenario):
    """ use the classifier to add behaviour to the input scenario if not filled    let the user 
defined which one is applied if there can be multiple behaviours for one part """
    classifier = pd.read_excel("parts" + ".xlsx")
    behaviours = list(classifier.loc[classifier.parts == input_scenario['cause_scope'][0], 
"behaviours"])
    behaviours = behaviours[0].split(', ')
    if len(behaviours) > 1:
        print('We need more info about the behaviour of the possible problematic piece : 
{}'.format(input_scenario['cause_scope'][0]))
        print('Behaviours can be {}'.format(behaviours))
        txt = input("what value do you have as expected_behaviour ? ")
        input_scenario['expected_behaviour'][0] = txt
    else:
        input_scenario["expected_behaviour"][0] = behaviours[0]
    return input_scenario



def build_children_layer(children_nodes, children_layer, parent_node_weight):
    if children_nodes is not None:
        for key, val in children_nodes.items():
            try:
                children_layer[key] += val * parent_node_weight / 100
            except KeyError:
                children_layer[key] = val * parent_node_weight / 100
    return children_layer


def validation_and_add_to_db(result, name, data):
    validation = input("this line will be added to the database, do you validate ? (yes/no) : 
{}".format(result))
    if validation == "yes":
        final_data = pd.concat([data, pd.DataFrame(result, 
index=[0])]).reset_index()[list(data.columns)]
        final_data.to_excel(name, index=False)
        return final_data
    else:
        return None


def find_solutions(levels_of_db, test_case_scenario, last_layer):
    # get all possible cause_scope for level 0
    final_solutions = {}
    cause_scope_layer = search_children(levels_of_db["cause_scope"], test_case_scenario, 
"cause_scope")

    network_layers = ["behaviour_gap", "elementary_cause", "corrective_action"] if last_layer == 
"solutions" else ["behaviour_gap", "elementary_cause"]
    for studied_cause_scope, cause_scope_weight in cause_scope_layer.items():
        parent_layer = {studied_cause_scope: cause_scope_weight}
        for layer in network_layers:
            children_layer = {}
            for parent_node, parent_node_weight in parent_layer.items():
                children_nodes = search_children(levels_of_db[layer], parent_node, layer)
                children_layer = build_children_layer(children_nodes, children_layer, 
parent_node_weight)
            # sort to have most probable
            parent_layer = {k: v for k, v in sorted(children_layer.items(), key=lambda item: 
item[1], reverse=True)}
        final_layer = {key: round(value, 2) for key, value in parent_layer.items()}
        final_solutions[studied_cause_scope] = final_layer
        print("solutions for cause {} are : {}".format(studied_cause_scope, parent_layer))
    print(final_solutions)
    return final_solutions


def filter_similar(table, category):
    res = table.loc[category == table.category]
    other_filter = input("do you want to add another filter ?")
    while other_filter == "yes":
        print("the possible columns to filter are {}".format(list(table.columns)))
        precise_filter = input("write the filter like this :  'columns : value'").split(" : ")
        res = res.loc[precise_filter[1] == res[precise_filter[0]]]
        other_filter = input("do you want to add another filter ?")
    # res = pd.merge(table, test_case_scenario, on="category", how='inner')
    print(res)
    return res
```

```
def capture_test_scenario(database):
        data = pd.read_excel(database)
        db, test_case_scenario = get_test_scenario(data)
        levels_of_db = cut_database_into_levels(db, test_case_scenario['category'][0])
        return db, levels_of_db, test_case_scenario


if __name__ == "__main__":
    txt = input("What do you want to do? (add design issue, find solutions, find causes, find
similar inputs)")
    if txt == "design issue" or "add design issue":
        capture_desing_issue('database.xlsx')
    else:
        db, levels_of_db, test_scenario = capture_test_scenario('database.xlsx')
        if txt == "solutions" or "find solutions":
            find_solutions(levels_of_db, test_scenario, "solutions")
        elif txt == "causes" or "find causes":
            find_solutions(levels_of_db, test_scenario, "causes")
        elif txt == "similar inputs" or "find similar inputs":
            category = test_scenario['category'][0]
            filter_similar(db, category)
        exit("closing app")
```

Appendix: Résumé en Français

Pour ce résumé en français, on commencera par présenter le contexte et l'objectif de recherche de la thèse. Ensuite, on présentera la méthodologie de recherche et on fera un résumé des contributions. Enfin, on présentera la conclusion et nos recommandations pour les recherches futures.

Concernant le contexte industriel, au sein de Renault, le projet de véhicule est divisé en 3 phases. La phase en amont consiste à établir les concepts et les exigences. La phase de développement consiste à affiner les spécifications de conception du véhicule. A la fin de la phase de développement, le modèle de véhicule doit être au bon niveau de performance et au bon coût de fabrication. Dans la phase d'industrialisation, les prototypes physiques sont assemblés et testés. Un véhicule est composé d'une plate-forme, d'un groupe motopropulseur et d'une caisse supérieure ; ils sont développés simultanément dans le cadre de différents projets. Nous nous concentrons sur le développement de la partie supérieure du corps. Nous nous concentrons sur la phase de développement où l'affinement des spécifications se fait par le biais de plusieurs boucles numériques, appelées boucle d'analyse de la conception. Durant cette phase, le véhicule n'existe que sous forme de modèle numérique et les activités d'ingénierie sont numériques. Dans la phase de développement, les deux activités principales sont la conception et la simulation, où nous affinons, évaluons et validons les modèles de véhicules. La simulation permet de détecter les problèmes de conception lorsque les performances du véhicule ne sont pas conformes aux spécifications. Lorsqu'un problème de conception se pose, les analystes de simulation le résolvent en apportant des modifications à la conception. Un CM est un changement de conception mis en œuvre avec le projet de véhicule. Le développement de véhicules est également un travail de collaboration. La collaboration a lieu tous les jours même si les équipes sont géographiquement décentralisées.

Dans cette recherche, nous nous concentrons sur le processus de simulation et principalement sur la simulation en crash, car elle est une étape essentielle étant donné que la sécurité du véhicule est un facteur critique. La simulation en crash est coûteuse et prend du temps.

Chez Renault, nous utilisons la méthode des éléments finis (MEF) pour la simulation en crash. Le processus la méthode des éléments finis comprend 3 phases : le pré-traitement, le calcul et le post-traitement. Il comprend également des tâches algorithmiques telles que le maillage et des tâches non algorithmiques telles que la classification des problèmes et l'interprétation des résultats. Les tâches non algorithmiques nécessitent des connaissances et une expertise approfondie et influencent la qualité et la fiabilité des résultats. L'MEF est une activité à forte intensité de connaissances, coûteuse et longue. Nous nous concentrons sur la phase de post-traitement et ses tâches non algorithmiques puisque la résolution du problème de conception se fait à l'intérieur.

Quant au contexte académique, nous avons utilisé l'approche de « Participation Action Research » car elle donne l'opportunité de faire partie d'un environnement scientifique et l'environnement étudié étant l'environnement industriel. La PAT est généralement liée à la recherche qualitative car le fait d'être au sein de l'organisation nous donne accès à la réalité subjective de la vie quotidienne, ce qui est important dans la recherche qualitative. La conception en tant que sujet de recherche est devenu intéressant à mesure que le design devenait plus complexe. L'objectif de la recherche sur le design est d'améliorer l'efficacité et l'efficience du design afin de développer des produits plus performants, soit par le développement de la compréhension du phénomène du design, soit par le développement d'un soutien pour améliorer la pratique du design. Le DRM est une méthodologie qui guide la recherche en matière de design de forme. Cette méthodologie constitue un pont entre les deux mondes, industriel et universitaire.

Ce travail de recherche fait également partie d'un plan d'amélioration au sein de Renault, qui vise à améliorer la pertinence et la rapidité des simulations. Nous sommes également dans un contexte de conception assistée par la simulation puisque les décisions sont principalement basées sur la simulation. Le processus de conception assistée par la simulation est un processus à forte intensité de connaissances, collaboratif et long. Par conséquent, nous visons à améliorer le processus en réduisant le temps tout en produisant un véhicule plus robuste. Notre objectif de recherche est donc de soutenir la conception assistée par la simulation, en tenant compte des spécifications industrielles qu'on a introduite ci-dessus. La question de recherche est donc la suivante : comment soutenir un tel processus ?

En a conduit un état de l'art sur différents domaines de recherche. Pour ce résumé, nous allons simplement mettre en évidence les gaps de la recherche. Nous avons constaté que l'on accorde moins d'attention à la phase de post-traitement de la MEF et à ses tâches non algorithmiques, en particulier. Il n'existe pas de représentation formelle des connaissances liées aux tâches non algorithmiques dans la phase de post-traitement de l'MEF pour la simulation d'accidents de voiture (telles que les ontologies). Nous avons aussi remarqué que dans la conception technique, les approches de gestion des connaissances sont axées soit sur l'approche de la personnalisation, soit sur l'approche de la codification. Enfin, aucune approche de gestion des connaissances basée sur l'ontologie n'est développée pour soutenir la conception assistée par la simulation, et plus particulièrement le processus de simulation d'accident de voiture.

Dès notre première compréhension, et étant donné que la conception assistée par la simulation est intensive en connaissances, nous avons fait l'hypothèse que la connaissance est un facteur clé pour améliorer le processus de conception assistée par la simulation, en usage dans l'entreprise. Nous avons mené étude empirique et nous avons validé l'hypothèse. Par conséquent, nous avons divisé notre question de recherche en deux questions : la première est, puisque la connaissance est un facteur clé, Quelles connaissances sont nécessaires pour la conception assistée par la simulation et comment les formuler ? Et le seconde est : Comment pouvons-nous soutenir le processus de conception assistée par la simulation tout en intégrant les connaissances pré-identifiées ?

Ensuite, nous avons mené trois work-packages (WP) différents : le WP de capture des connaissances qui vise à extraire et à capturer les connaissances d'ingénierie et les WP de développement de l'ontologie et du Framework de management des connaissances (KM) qui sont les principales contributions à la formulation de notre proposition de système de soutien (KMS). D'où nos contributions dans ce travail de recherche : l'étude empirique qui vérifie l'hypothèse, le développement de l'ontologie qui répond à la première question de recherche et le Framework KM et KMS et le système de support KM qui répondent à la deuxième question de recherche.

Nous allons expliquer brièvement chaque contribution.

L'objectif de l'étude empirique est de mieux comprendre le processus de conception assistée par la simulation en usage dans l'entreprise et d'identifier les difficultés et les défis rencontrés. Pour cette étude empirique, nous avons procédé à la collecte et à l'analyse des données ; nous avons mené plusieurs entretiens, nous avons fait de multiples observations et étudié la documentation de l'entreprise. Nous avons également effectué une analyse à deux niveaux, un niveau d'équipe et un niveau de projet. L'objectif de l'analyse au niveau de l'équipe est de caractériser l'équipe en identifiant les activités, les ressources et les objectifs, puis d'identifier les dysfonctionnements. Un dysfonctionnement est un problème dans le fonctionnement de l'équipe. L'analyse au niveau du projet permet d'identifier les dysfonctionnements ayant un impact sur l'avancement du projet et de les hiérarchiser. La validité de l'étude empirique a également été vérifiée en interne par la triangulation de différentes sources de données et méthodes d'analyse et la vérification itérative avec les acteurs impliqués, et en externe, par la possibilité de généralisation de cette méthodologie.

Les résultats de l'étude empirique sont les suivants : la modélisation du processus de résolution des problèmes de conception As-Is, l'identification des dysfonctionnements les plus importants liés à la non-formalisation du processus et de l'approche de conception et à l'accès limité aux connaissances de l'entreprise. Nous avons donc identifié les défis industriels et nous nous concentrons sur les défis liés à la phase de post-traitement et aux connaissances d'ingénierie, tels que la réduction du temps, l'accès et le partage des connaissances et de l'expertise. Les limites de l'étude sont le manque d'indicateurs quantitatifs et les lignes directrices pour la généralisation.

L'objectif du développement de l'ontologie est de formaliser les connaissances liées à la phase de post-traitement et à l'interprétation des résultats de simulation, c'est-à-dire les connaissances liées à la résolution des problèmes de conception et à la proposition de changements de conception. Une ontologie est une spécification explicite de la conceptualisation partagée, et toute base de connaissances ou système basé sur la connaissance est, implicitement ou explicitement, lié à la conceptualisation. Pour le développement de l'ontologie, nous avons utilisé le cycle de vie en 5 étapes du développement de l'ontologie proposé par Pinto et Martins, qui propose des techniques, des lignes directrices et des méthodes pour construire des ontologies à partir de zéro. Nous avons commencé par la spécification de l'objectif et de la portée de l'ontologie, la conceptualisation et la formalisation des différents concepts et de la relation, à l'évaluation par la validation des experts, l'évaluation des utilisateurs et la validation basée sur des scénarios. Nous avons également procédé à l'acquisition de connaissances par le biais d'entretiens, d'ateliers et de documentation.

Cela a permis à l'ontologie du CSPP de formaliser les connaissances liées à la phase de post-traitement de la simulation d'accident de voiture et à l'interprétation des résultats de la simulation. Nous proposons trois niveaux, pour améliorer les connaissances en ingénierie des structures, pour séparer les connaissances du domaine des connaissances en résolution de problèmes et pour assurer la couverture de la totalité du processus de résolution des problèmes de conception. Le niveau contexte donne le contexte dans lequel se déroule le test numérique, le niveau projet formalise les connaissances d'ingénierie liées à un projet spécifique et le niveau raisonnement formalise le raisonnement suivi lors de la résolution des problèmes de conception. Cette ontologie présente aussi quelques limites. L'ontologie ne décrit que les concepts et les relations, qu'aucune interaction n'est prise en compte, et qu'elle a été développée dans un contexte industriel spécifique. La saisie des connaissances a été faite rétrospectivement, d'où l'absence de contexte de conception utile. Le niveau de raisonnement pourrait être amélioré avec l'intégration de nouveaux cas.

Une fois que nous avons eu notre modèle de connaissances, nous avons proposé une approche de gestion des connaissances pour soutenir la conception assistée par la simulation dans la phase de développement des véhicules, en mettant l'accent sur la simulation en crash de voiture. Nous avons fait cette proposition sur la base d'une analyse documentaire approfondie sur les Framework de gestion des connaissances et les architectures KMS, principalement dans la conception technique, en mettant l'accent sur l'utilisation d'ontologies pour ces systèmes. Nous avons également discuté de la proposition avec des praticiens, notamment des ingénieurs responsables du développement de ce support, des experts et des utilisateurs finaux. Enfin, nous avons discuté d'un scénario de cas d'utilisation expliquant l'application du KMS proposé.

En conséquence, nous avons développé une approche de KM intégrée et collaborative et le cadre de KMS qui inclut les différents acteurs impliqués dans la conception assistée par la simulation. Il intègre les processus de management de connaissances, notamment la saisie, le stockage, la récupération et le partage des connaissances. Le système de support se compose de 3 couches : ressources, modèles et méthodologies et une interface multi-utilisateur. La limitation est qu'à ce niveau, le Framework décrit les exigences du KMS mais ne va pas au-delà avec le développement de la technologie.

Pour répondre à cette limitation, nous avons proposé l'architecture du système de support KM, dans le but de développer un système de management des connaissances intégré et collaboratif basé sur une ontologie pour soutenir la conception assistée par la simulation, avec une application à la simulation d'accidents de voiture. Pour développer un tel système, nous avons commencé par définir les capacités, nous avons détaillé l'architecture, y compris les différentes couches et les éléments de construction et enfin, nous avons décrit les blocs de construction en termes de modèles et nous avons proposé une mise en œuvre. La proposition est évaluée par le département SI. Nous avons également travaillé sur trois scénarios de cas d'utilisation avec une comparaison à des cas réels et une implémentation de preuve de concept pour chaque modèle. Enfin, nous avons étudié la généralité de la proposition.

En conséquence, nous disposons d'un KMS virtuel basé sur une ontologie pour soutenir la conception assistée par la simulation, avec une application à la simulation en crash. Le système de support KMS est intégré et collaboratif. Il assure les capacités pré-identifiées qui sont la collaboration, la saisie et la récupération des connaissances. Comme avantage attendu, nous pourrions faire gagner jusqu'à 20 % du temps des analystes. Quant aux limites de ce travail, plus de détails sur l'interface multi-utilisateurs et des activités supplémentaires de KMS devraient être développés. Nous devons aussi étudier des modèles de récupération des connaissances.

Pour conclure sur ce travail de recherche, nous avons tracé notre protocole et les étapes que nous avons suivies pour proposer le système de soutien à la conception assistée par la simulation, avec une application à la simulation en crash. Nous avons commencé par l'évaluation de la situation actuelle qui a abouti aux défis industriels. Comme nous nous concentrons sur la composante de la connaissance, nous avons mis l'accent sur le développement du modèle de connaissance qu'est l'ontologie, puis nous avons développé les modèles de récupération de la connaissance et enfin nous avons intégré tous les modèles développés dans un système de gestion de la connaissance. Si nous revenons à notre objectif de recherche, nous l'avons rempli en proposant un système de soutien à la conception assistée par la simulation, en répondant aux différentes questions de recherche. Les contributions scientifiques sont donc l'étude empirique, l'ontologie, les Framework KM et KMS et l'architecture du système de soutien KMS, et enfin la démonstration de l'applicabilité et de la généralisation de tous ces résultats. Nous pouvons également résumer nos contributions industrielles par les fichiers de saisie des connaissances qui ont permis de saisir les problèmes de conception et leur résolution, même de la part des analystes de simulation en Inde, l'intégration de l'ontologie avec le projet desloop et sa mise en œuvre au sein de Renault et nous avons également démontré l'avantage attendu en termes de gain de temps et d'amélioration du processus de résolution des problèmes de conception.

Quant à nos recommandations pour les travaux futurs, nous pouvons commencer par l'amélioration des résultats. Pour l'ontologie, nous pouvons l'enrichir par des concepts contextuels. Le modèle de raisonnement peut être amélioré en vue de la modélisation des réseaux bayésiens et le KMS peut être amélioré par le développement d'un prototype basé sur le web et d'un système d'interaction amélioré. Nous recommandons également l'application du système de support dans l'entreprise afin qu'il puisse être intégré dans le processus et contribuer à enrichir la base de connaissances et à améliorer les modèles. Nos propositions peuvent également être appliquées à d'autres entreprises, car la résolution des problèmes de conception par la simulation ne se limite pas à l'industrie automobile.