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.

Keywords: Knowledge management, Case study, Process modelling

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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.

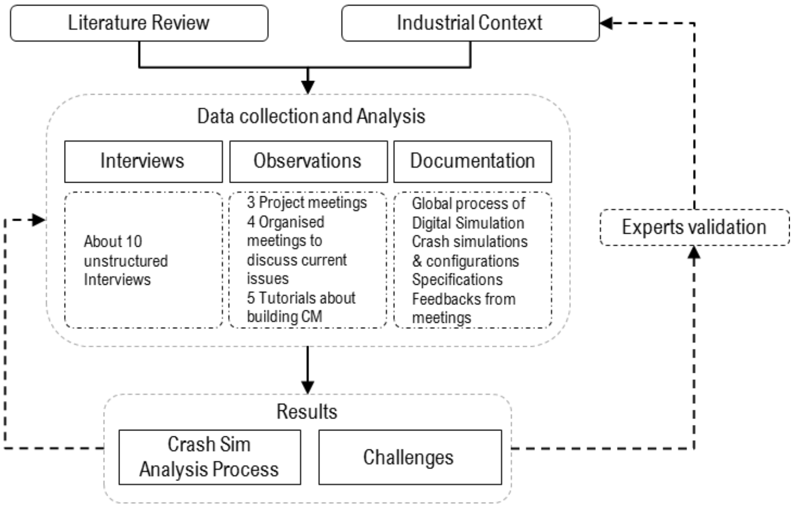

Figure 1. Research Methodology

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.

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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).

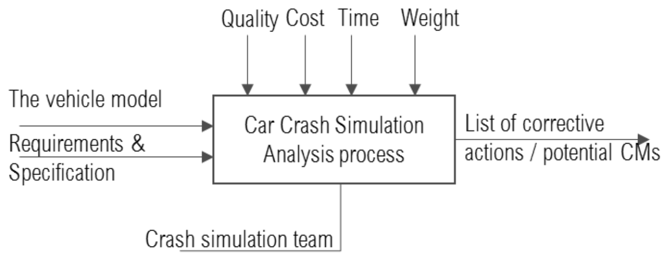

Figure 2. Structured Analysis and Design Technique (SADT): Car Crash Simulation process

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

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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).

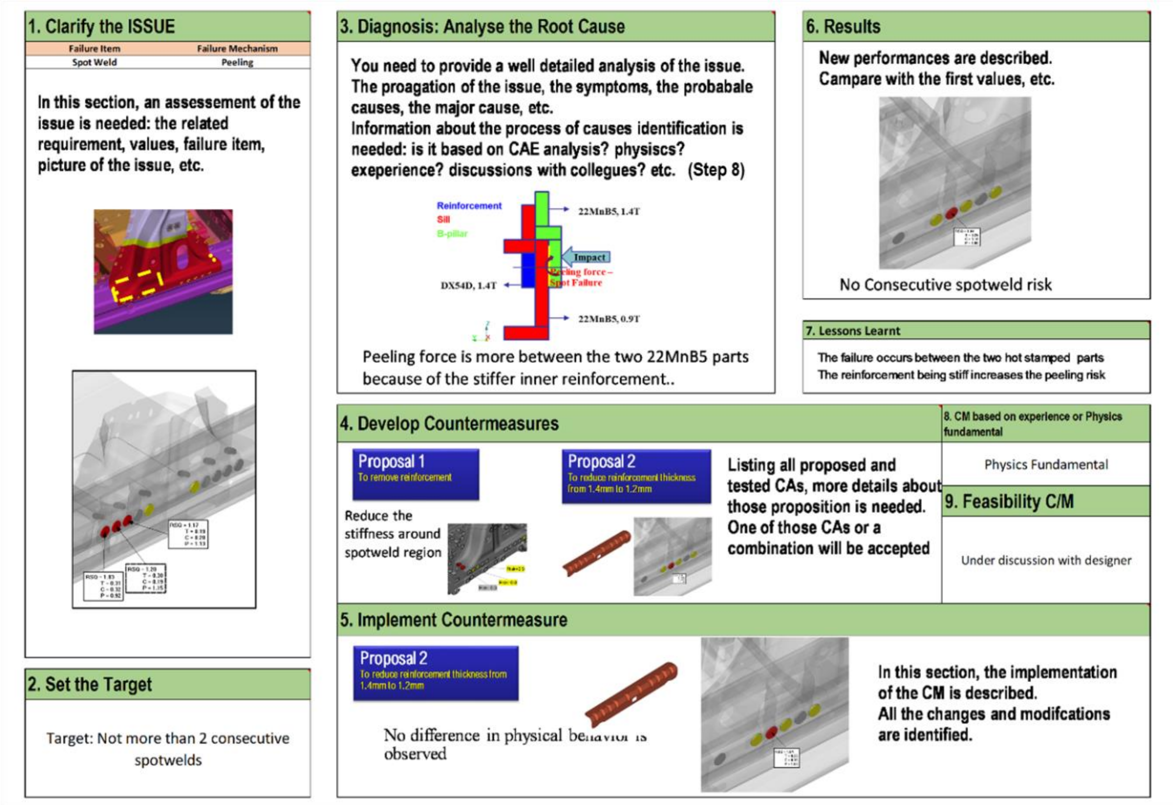

Figure 3. An example of capitalisation on an Issue solving and CM proposition (in 9 steps)

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.

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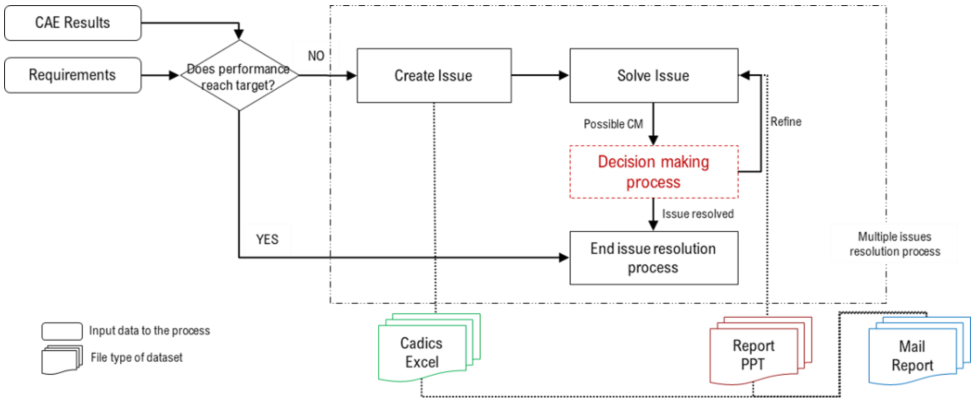

Figure 4. Crash Simulation Analysis Process and data/ information transfer (As-Is)

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.

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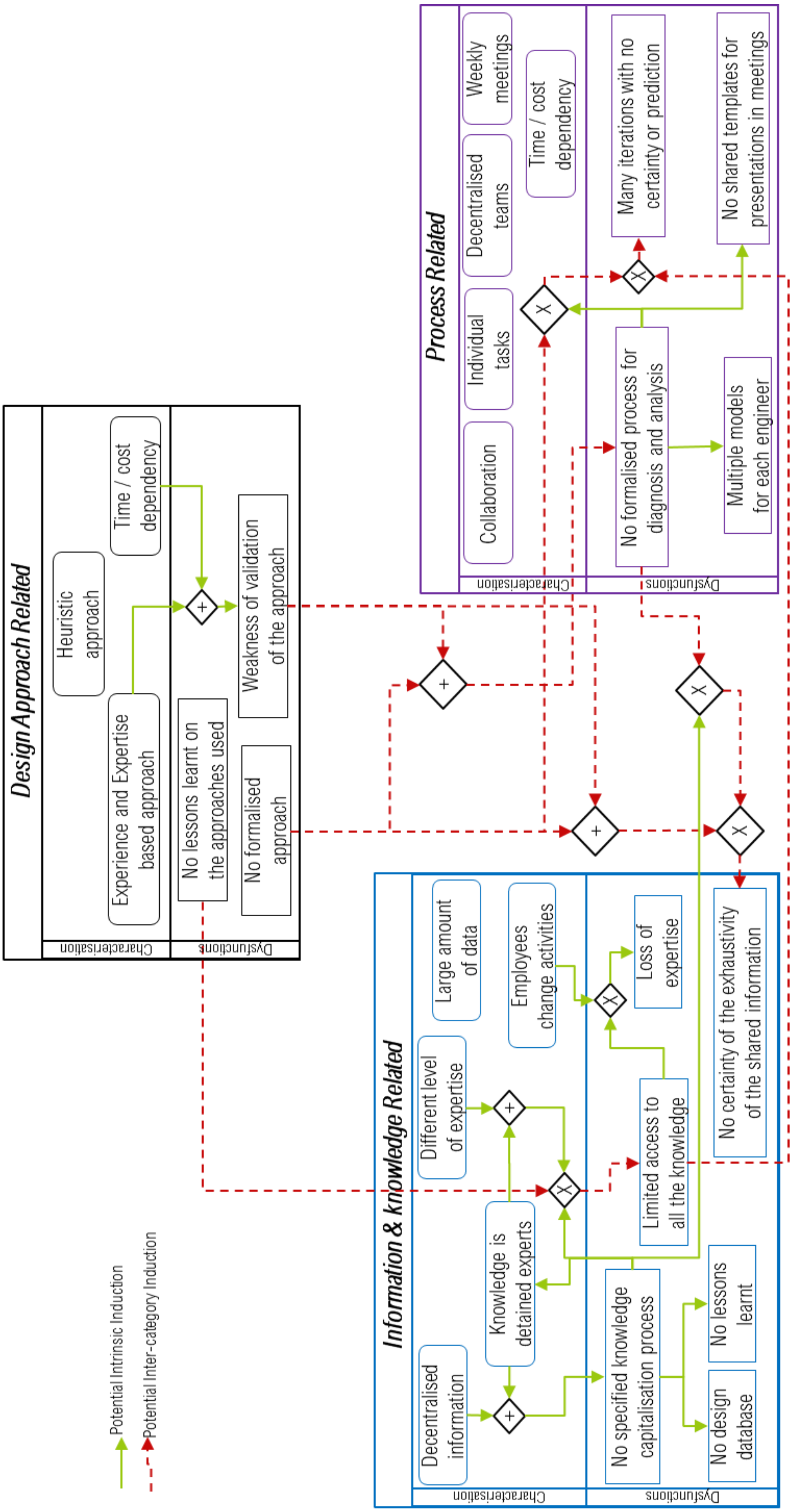

Figure 5. Mapping: Observations Categories and Induced Dysfunctions

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?”

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

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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

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

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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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