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TOWARD DESIGN FOR SAFETY PART 1: FUNCTIONAL REVERSE ENGINEERING DRIVEN BY AXIOMATIC DESIGN

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ABSTRACT

The design process of product development is the earliest opportunity to integrate safety into products. The term 'design for safety' captures this effort to integrate safety knowledge in the design process. Whereas, reverse engineering (RE) has been a common method to obtain design feedback and knowledge of the existing system, this paper presents a method for functional reverse engineering (FRE). Axiomatic Design (AD) is an attractive support for the concept of FRE because of its criteria for evaluating designs, its standard format for recording design decisions, and its ability to present design requirements and associated design parameters. The power take-off (PTO) system is used as a case study to illustrate and examine the proposed method.

Keywords: design for safety, IRAD method, functional reverse engineering, Axiomatic Design.

1 INTRODUCTION

The main accountability for making a product safe lies in the design process. The term 'design for safety' captures this effort to integrate the knowledge on safety in the design process. Hazards should be eliminated and risk reduced during early design phases of the product. Furthermore, safeguards and safety sheets should be used to mitigate any residual risk. General principles for safe design of machinery are stated in safety standards type A [ISO 12100, 2010; ISO/TR 14121-2, 2008]. These two standards show that an unacceptable risk may be reduced by the designer based on a four-step safety improvement strategy in this order of priority: 1. Elimination of hazards by design; 2. Risk reduction by design. This can be obtained by reducing energy, using more reliable components and etc; 3. Safeguarding by using barriers, as well as implementing protective measures through engineering controls and specific safety functions; 4. Adopt administrative measures to inform and warn users about residual risks.

Furthermore, many standards (type B and type C) have been issued to detail the design requirements, typical applications, and mode of utilization of various types of safeguards. In parallel, much research has been conducted to integrate safety objectives, constraints and requirements in the design processes [Hasan *et al.,* 2003; Fadier and De la Garza, 2006; Houssin *et al.*, 2011]. Although there is much research on safety considerations in the design process, we are not aware of any full general accounts. In this context, Ghemraoui *et al.* [2009a; 2009b; 2011] attempted to define safety objectives early in the product design process by proposing the innovative risk assessment design (IRAD) method. This method offers the mechanism for generating non-technical design objectives when preparing the requirements and constraints list based on AD.

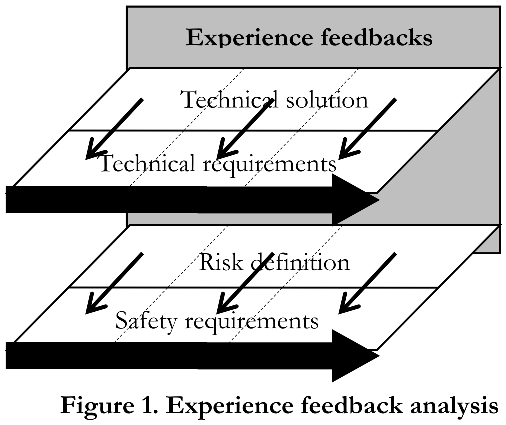

Figure 1. Experience feedback analysis

For successful safety integration in design, design experiences to answer what-how and then know-how play a crucial role. On the other hand, to make an effective design, designers would like to reuse existing design knowledge along meaning, reasons, arguments, choices, consequences, etc. Indeed, it is important to extract design information to use in the design process. However, IRAD does not yet guide the designers how to achieve these aims.

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Chikofsky and Cross [1990] present a taxonomy of engineering terminology: "Forward engineering is the traditional process of moving from high-level abstractions and logical, implementation-independent designs to the physical implementation of a system". "Reverse engineering is the process of analyzing a subject system to identify the system's components and their interrelationships and create representations of the system in another form or at a higher level of abstraction". "Re-engineering is the examination and alteration of a subject system to reconstitute it in a new form and the subsequent implementation of the new form." In this context, in the research work toward design for safety, reverse engineering and re-engineering are investigated.

RE has been a common method to obtain the design feedback and knowledge of the existing system [Urbanic, 2008; Tang *et al.*, 2010]. In the aim of safety integration in design, it needs to obtain the original intrinsic knowledge which is located in the function model of the existing system. However, up to date, the majority of research on RE is focused on the geometric and structured design rather than the functional aspects of the design. Therefore, there is a need to expand upon reverse engineering as a FRE. Little research has been conducted in form to function mapping [Otto and Wood, 1998; Gietka *et al.*, 2002; Tang *et al.*, 2010] which is important for FRE. However, the process of FRE is commonly informal. FRE does not consider either the reason why the concepts were introduced into the system, nor the functions and solution principles. Furthermore, FRE does not consider specific mechanisms to facilitate the identification of functions and solution principles, both important to the design process. Therefore, it is necessary to propose a formal method for FRE. The function analysis system technique (FAST) develops the system function tree. This technique highlights the order function(s) [Adams and Lenzr, 1997] but not clearly their interrelation with the solution. Whereas, AD [Suh, 1990; 2001] is a design methodology that guides the designer to find suitable design parameters (DPs) to meet the needs of the functional requirements (FRs). Therefore, the idea is to use this method in order to assess the original intrinsic knowledge of the design and to highlight areas of its improvement to enhance safety. Therefore, the objective of this paper is to propose a method for functional reverse engineering driven by AD. This method will be used to determine how the system works, and what the DPs and FRs are, but also the safety hazards and which DP and FR can be responsible for causing an accident. It is necessary to note that FRE does not involve changing the system objective or creating a new solution based on the reverse engineered system. Hence, the next step of design for safety will be to propose a functional re-engineering method based on the result of this paper to propose the safe design solutions.

The remainder of this paper is organized as follows. Section 2 explains briefly the AD principles and structure. This section also describes the motivation of our research work in terms of using AD as a base for proposing one method for FRE. Section 3 explains the proposed method for FRE. In Section 4, the PTO system is used as a case study to illustrate and examine the various steps of the proposed method. Finally, Section 5 includes the results, a brief discussion and conclusion.

2 AXIOMATIC DESIGN AND FUNCTIONAL REVERSE ENGIEERING

AD is an attractive support for the concept of FRE due to its criteria for evaluating designs, the standard format for recording design decisions, and the ability to present design requirements and associated design parameters. This method consists of four fundamental concepts. In the context of our objective to propose one method for FRE, we use all these concepts. In the following, we list [Suh, 1990] these four concepts and their link with our objective:

2.1 Design as a Mapping Process

In FRE, for each component of the system, the DP and FR have to be defined. We have to well describe the mapping between functional domain and physical domain.

2.2 Design Top-Down Hierarchical Structure

In the framework of FRE objective, the design top-down hierarchical decomposition proposed by AD is used for hierarchies of the DPs defined for system components and then hierarchies of the FRs defined for DPs.

2.3 Design Axioms

The results of FRE have to respect two axioms of AD. Based on these axioms, our aim is to design a reliable safe system.

2.4 Design Matrix

In our research work, we need to use design matrix after DPs and FRs identification of system to analyze their relationships for technical and safety solutions.

3 PROPOSED METHOD

The objective of this section is to propose a FRE method as a convenient way to express and represent the design history by describing how and why it proposed. As it is explained in previous sections, AD is basic. In this paper, the product's structure and architecture is called the 'system'. This paper addresses the following questions: What is the intended context of use of the system? What are the system elements and their interactions and associated accidents and hazards? What is the function of the system component? (It must focus on the accidental component). In order to answer these questions, we suggest a FRE method of four steps and two sub-steps:

3.1 System Technical Evaluation

3.1.1 Identify System Evolution

The first step is to study the previous systems in order to identify system evolution. In fact, the term 'evolution' represents the value of the new system under study which is the result of meticulous work in the last years that has evolved into the new. The resources needed to investigate system evolution are: standards, patents, instruction for use, safety data sheets, accident reports and other applicable resources related to the system.

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3.1.2 IDENTIFY SYSTEM COMPONENTS AND THEIR INTERACTION

The system components not only contain the physical components in the system, but also performance requirements (behavior), which are important in determining the relationship with DPs. The purpose of this paper is to present a 'component to function' mapping framework to determine the function structure of the existing system. At first, the abstraction schema of the system has to delineate to find the units. In the second step, the product breakdown structure (PBS) [Ho Kon Tiat, 2006] is used to represent the system components by the structural decomposition (Figure 3). To illustrate the interaction between this system component decomposition [Ho Kon Tiat, 2006], we propose to use the functional block diagram (FBD). This diagram (Figure 4) highlights the fluxes existing between the elements of the product (contact, energy, matter, regard), and the external environments. This step involves the identification of the component defined based on the technical objective and the component based on the safety objective. The safety components will be grayed in the PBS and FBD.

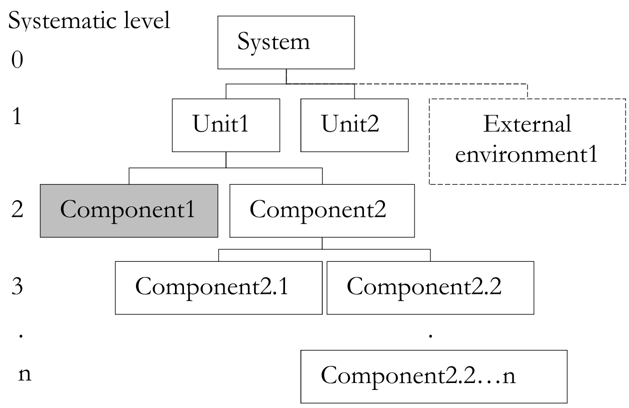

Figure 2. The product breakdown structure.

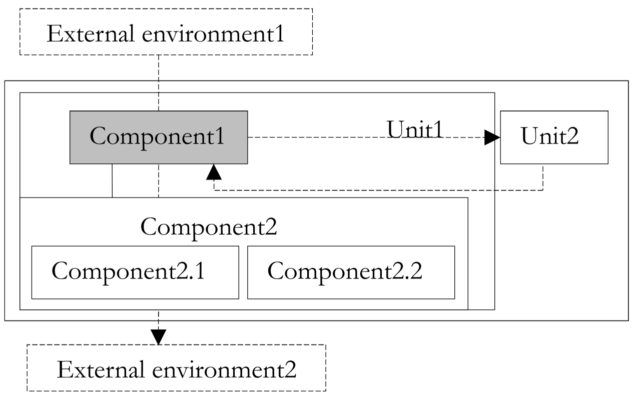

Figure 3. The functional block diagram.

3.2 SYSTEM ACCIDENT EVALUATION

3.2.1 INVESTIGATE ON ACCIDENT REPORTS

The goal of this section is to determine the hazardous conditions of the system. Understanding the cause of accidents in the work place is an essential step toward design to safety. Accident scenario definitions help to describe the reason accidents occur. One of the documents for describing the accident scenario is called the 'accident report'. The important question is how do we define, understand and describe accidents? Accident reports provide details on factors that can cause an injury, but it is difficult to predict the location, the time and the reason the accident occurred.

For accident evaluation, the cause tree analysis (CTA) suggested to use. As a result, for accidents, the following information is listed: phase of machine usage, task identification, state of the machine, unintended behavior of the operator, harm, hazard zone, hazardous situation, hazardous event and hazard.

3.2.2 IDENTIFY SYSTEM COMPONENT THAT GENERATES THE HAZARD

After the system hazards are identified, the specific system component related to these hazards needs to be determined. In step 2, the system and its components have been defined, and in step 3, the accident causes are listed. Therefore, by comparing these two steps, it is possible to connect each accident cause in its system component.

3.3 SAFETY DESIGN IDENTIFICATION

3.3.1 DEFINE DPS AND FRS HIERARCHY AND DESIGN MATRIX

As explained in Section 2, from the AD point of view, product design begins in the customer domain, where various kinds of design constraints are considered to arrive at a final design solution after an iterative mapping process. This step is based on a design with a top-down hierarchical structure concept proposed by AD, but it starts from the system component, and after searching the design solutions, it defines the design goals. It means we do AD in the reverse way.

Table 1. Guide to formulate the DPs, FRS based on AD

	DPs: Solutions	**FRs: Goals**
Answer	what does it look like?	what is its function?
Start	with nouns	with verbs
Present	design solutions	design goals
Describe	-principal solution: working means - mechanical motion components: rotating, reciprocating and transverse elements - mechanical action component: cutting, fitting, jointing, locking, accelerating, decelerating, elements	- working principle: efficiency - layout design: space requirements, weight, arrangement, fits, etc. - form design: material utilization, durability, deformation, strength, wear, shock resistance, stability, resonance, etc. - safety design: protection, etc.

The schema of defining DPs and FRs as shown includes two steps (Figure 4). Table 1 is proposed as a guide to formulate the DPs and FRs. For each system component, two sequential questions have to be answered: what does it look like? and what is its function?. The PBS and FBD have to integrate in this step to make DPs and FRs decomposition in a hierarchical way. After formulating the DPs and FRs hierarchy, the aim is use AD matrix to evaluate the design.

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3.3.2 DEFINE THE LINK BETWEEN FR-DP- HAZARD

This section aims to establish a link between the hazard identified in Section 3.2 and the DP and FR. In Section 3.2, following accident evaluation, the system component that generates the hazard is defined. As stated in the previous section, the DP and FR for each component are determined. Therefore, the two section results combined together will define the FR and DP related to the mechanical hazard.

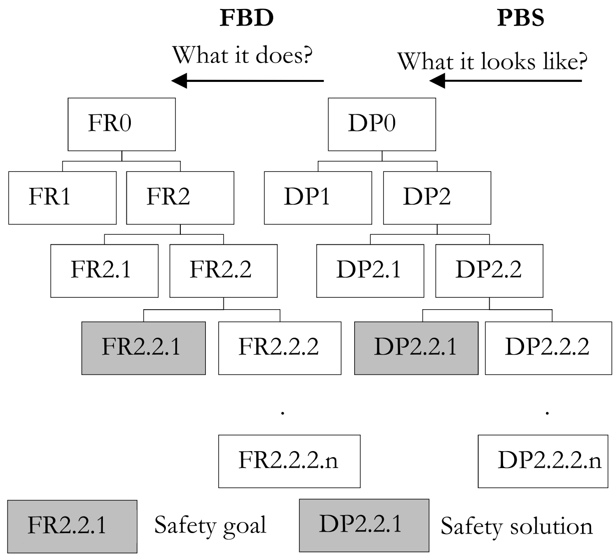

Figure 4. DPs and FRs hierarchy definition.

3.4 SAFETY RISK MEASUREMENT

3.4.1 RATE THE PROBABILITY FOR EACH HAZARD

According to NF EN ISO 12100, the risk associated with a particular hazardous situation (H) depends on the severity of harm and the probability of occurrence of that harm. Based on this definition, the Probability of hazard (P_h) is defined as:

$$P_h = \frac{\text{Number of Hazards happened}}{\text{Number of utilisation of system}} \quad (3)$$

And the severity of harm is identified as impact factor for hazard (IF_h), in Figure 5:

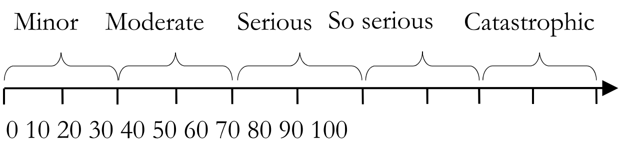

Figure 5. IF_h identification.

3.4.2 DEFINE THE JUDGMENT CRITERIA TO BE USED IN RISK LEVEL IDENTIFICATION

Based on the risk definition presented in Section 3.4.1, we defined the decision factor for hazard (DF_H), as the following equation, to measure the level of safety risk. A safer design solution is a solution with low DF_H.

$$DF_H = \sum_{h=H1}^{Hn} (P_h \times IF_h) = P_{H1} \times IF_{H1} + \cdots + P_{Hn} \times IF_{Hn} \quad (4)$$

$0 \leq IF_h \leq 100;\ 0 \leq P_h \leq 1$

3.5 SYNTHESIS

In the framework of ongoing research in 'design for safety', a FRE method driven by AD is proposed. Table 2 lists the objective, input and output of each step of proposed FRE method.

Table 2. FRE method steps.

Step	Summary
1: System technical identification	**Objective1:** identify system evolution **Input:** information on standards, patents, instruction for use, safety sheets, other applicable resources **Output:** the value of the new system form technical and safety points of view **Objective2:** identify system components and their interaction based on schema abstraction of system, PBS and FBD **Input:** information about a typical system **Output:** list of system components and their interaction
2: System accident identification	**Objective1:** evaluate system accident through CTA **Input:** information in accident reports **Output:** accident causes **Objective2:** identify system components that generate hazard **Input:** list of accident causes **Output:** hazard related each system component
3: Safety design identification	**Objective1:** define DPs and FRs hierarchy and design matrix **Input:** system components and their interaction **Output:** DPs and FRs hierarchy and their mapping evaluation with AD matrix **Objective2:** define the link between DP-FR-hazard **Input:** component and the hazards generated with that , component and related DPs, FRs, **Output:** component-DP-FR-hazard
4: Safety risk measurement	**Objective1:** rate the probability for each hazard **Input:** information in accident reports **Output:** for each mechanical hazard, its P_h and IF_h **Objective2:** define the judgment criteria to be use in risk level identification **Input:** for each mechanical hazard, its P_h and IF_h **Output:** component-DP-FR- hazard- DF_H

4 CASE STUDY: PTO SYSTEM

Currently, the farming sector constitutes a serious problem in the domain of human safety. In this sector, the main source of safety risks is related to PTO systems. In agricultural tractors, the power of the engine is transmitted to a PTO drive shaft through a clutch and a mechanical reduction gear. It is further transmitted through a PTO clutch and a PTO shaft to a work machine provided at the rear of a tractor body. Figure 6 shows a PTO system.

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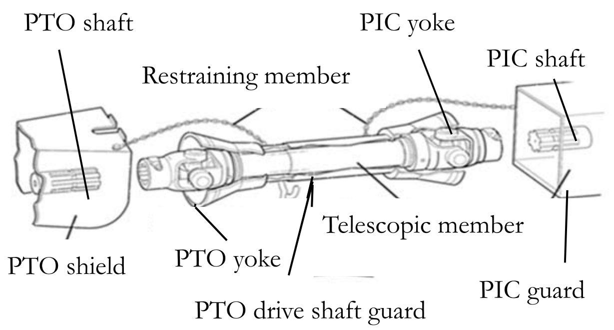

Figure 6. A PTO system.

4.1 IDENTIFY PTO SYSTEM EVOLUTION

The existing PTO is the result of almost one century of technical evolution and more than 80 years of safety evolution. Nevertheless, along with the extensive work done to improve the safety of PTO, this system is one of the oldest and most persistent hazards associated with agricultural machinery, and it is extremely dangerous even with safeguards [Klancher, 2008]. At first, we look at the PTO standards and patents evolution to find the gaps during its development.

Agricultural PTOs are standardized [ISO 5673-1, 2005; ISO 5673-2, 2005; NF EN ISO 5674, 2009; NF EN 12965+A2, 2009] in dimensions and rotation speed and the guards, shields and coupling have been introduced to eliminate or minimize the risk of entanglement. Current United States and Australian standards allow for the safety cover to rotate with the shaft. However, the safety cover must stop rotating when it comes into contact with an object. This requirement is normally achieved by the use of a safety guard bearing between the safety guard and the PTO shaft. European standards specify that safety guards must not rotate with the PTO shaft. PTO shafts typically incorporate the restraining member in the outer surface. Most current safety guard bearings have a flange or projection that rests in the groove in the PTO.

The patent evolution analysis covers a period of 88 years, from 1924 to 2012. We gathered and analyzed more than 50 patents as the solutions correspond to improving the PTO from a technical aspect or a safety aspect. This analysis confirms the first concept (using the rotating element to transform tractor energy to implement) has not changed and thus, more patents have been investigated to improve the PTO system from the safety point of view. To improve the safety of the PTO system, the researchers proposed to use guards to cover the rotating elements or they propose protective devices to shut the PTO systems down.

4.2 IDENTIFY PTO SYSTEM COMPONENTS AND THEIR INTERACTION

A typical PTO system is selected to identify its components and their interaction. Figure 7 represents the abstraction schema of this system. This figure uses 0 for the PTO shaft, 1 and 2 for universal joints by the side of tractor, T1 for the telescopic member, 3 and 4 universal joints by the side of the implement, and 5 for the PIC shaft. This schema helps to determine the system units to analyze.

Based on abstraction schema of PTO system, the PBS is used to represent the PTO system components by structural decomposition (Figure 8). Figure 9 represents the PTO system component interaction based on a FBD.

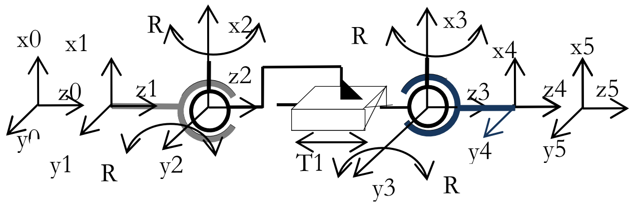

Figure 7. Abstraction schema of the PTO system.

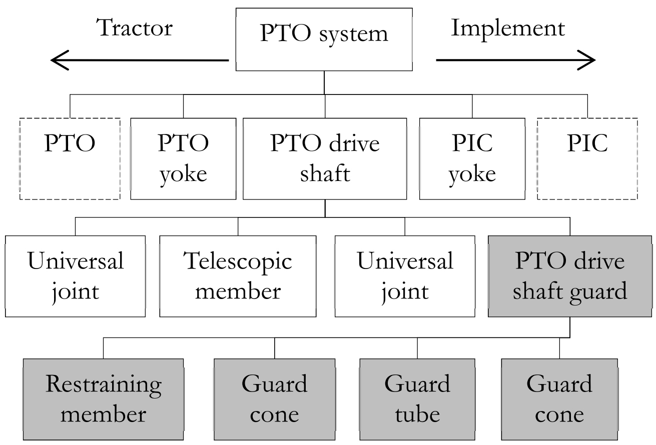

Figure 8. Decomposition of PTO system components.

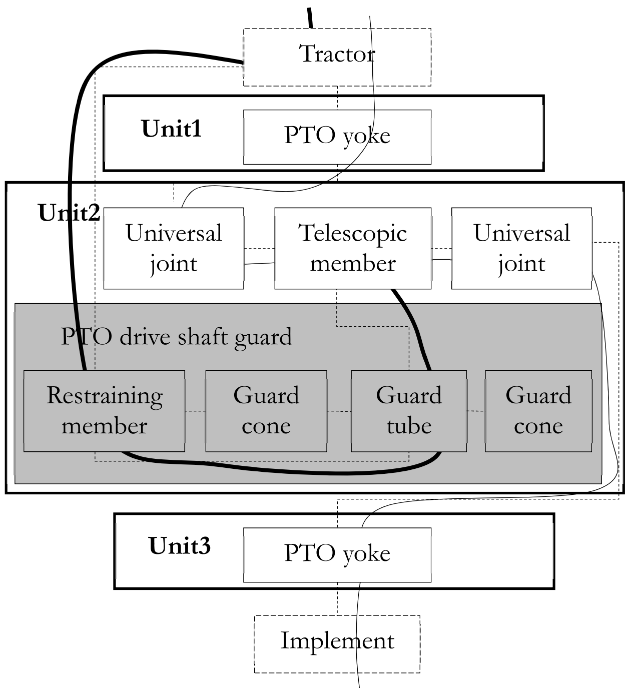

Figure 9. PTO system component interaction.

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4.3 Evaluate PTO System Accidents

The aim of this step is to evaluate the accidents that occur as a result of the power take-off system through cause tree analysis (CTA). In France, from 2000 to 2011, there were 1915 accidents related to PTO systems. Table 3 shows the results of two selected accident report evaluations related to this system. Figure 10 shows that a person is at an increased risk of having an accident if they are in the vicinity of a PTO system with a missing, broken, damaged or poor fitting safeguard. The figure also correlates the number of accidents with the body part that is injured.

Table 3. The results of two PTO accident analyses.

Results	Accident1	Accident2
Phase of its usage	Use	Use
Task identification	removal of product from the system	preventive maintenance
State of machine	operates normally but without guard	operates normally but with broken guard
Unintended behavior of the operator	lack of carelessness	lack of concentration
Harm	death	death
Hazardous situation	possibility to get closer to system	possibility to get closer to system
Hazardous event	get closer to system	get closer to system
Hazardous zone	space around of system	space around of system
Hazard	entanglement with rotating element without guard	entanglement with rotating element with broken guard

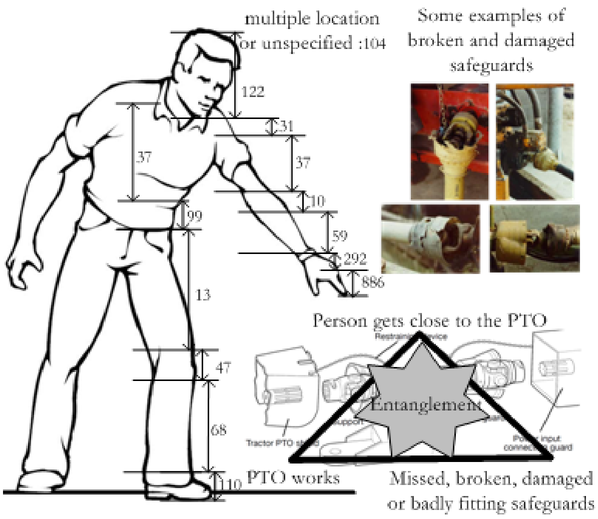

Figure 10. PTO system accident evaluation.

4.4 Identify PTO System Components that Generate Hazards

The accident evaluation confirms that PTO drive shaft safe guards still don't ensure human safety. In fact, in the case of missing, broken, damaged or badly fitting safeguards of the PTO system, this system will be very dangerous. As a consequence, to improve the safety of the PTO system, we will investigate the safeguards and define their DPs and FRs.

4.5 Define DPs and FRs Hierarchy and Design Matrix of a PTO System

Using the Figure 7, Figure 8 and Figure 9, and based on the design top-down hierarchical structure concept proposed by AD, we identified the hierarchy for the DPs and the FRs of the PTO system (Figure 11). Each DP presents what does component look like; for example, telescopic members like the shaft (DP1.2) or safe guarding (DP2.2) presents PTO shaft guard. The FRs describe the functions of the DPs; for example, allow a translation along the PTO shaft (FR1.4) describes T1. Figure 11 shows in PTO system, there is no design solution to carry out the alignment between universal joint and PTO. That is because DP13 does not satisfy any of the FRs.

After formulating the FRs and DPs hierarchy, the AD matrix is used to evaluate the PTO system design (Figure 12). This matrix illustrates the coupling related to FRs for the PTO system itself and also for its safeguarding. These couplings have to be evaluated from mechanical and safety points of view. The evaluation shows that, from a mechanical point of view, the PTO system and its safeguarding are coupled designs. One DP has to satisfy several FRs. Moreover, the accidents are not introduced by the coupling. Indeed, from the safety point of view the safeguard designing is not a robust design and Axiom 2 of AD is not verified. The aim of this research is not to eliminate the coupling.

4.6 Define the Link Between DP-FR-Hazard

Based on results of previous steps, the aim of this step is to define the link between DP-FR-Hazard related to PTO system. Table 4 shows the link for two the PTO accidents presented in Table 3.

Table 4. Hazard- DP-FR.

Hazard	DP	FR
Entanglement with rotating element without guard	Enclosing guard	Make the system rotating safe
Entanglement with rotating element with broken guard	Enclosing guard	Make the system rotating safe

4.7 Rate the Probability of Hazard

In this step based on the available accident reports, the P_h and the IF_h for the PTO system are defined as following. In this case, 'h' is defined as 'entanglement by PTO drive shaft with a missing, broken, damaged or a badly fitting safeguard'.

$P_h = 0.7$ $80 \leq IF_h \leq 100$

4.8 Define Judgment Criteria for PTO System Risk Level Identification

After defining the P_h and IF_h related to the PTO system accident, the decision factor for hazard as a judgment criterion for risk measurement is determined:

$56 \leq DF_H \leq 70$

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- DP0: system with rotating element
  - DP1: positioning system
    - DP1.1: universal jointing by side of implement
    - DP1.2: universal jointing by side of tractor
    - DP1.3: -
    - DP1.4: telescopic shaft
    - DP1.5: fixed jointing by side of tractor
    - DP1.6: fixed jointing by side of implement
  - DP2: power transmission system
    - DP2.1: rotating axis system
    - DP2.2: safe guarding
      - DP2.2.1: conical guard by side of tractor
      - DP2.2.2: tubing telescopic guard
      - DP2.2.3: conical guard by side of implement
      - DP2.2.4: restraining member

- FR0: operate implement through tractor energy
  - FR1: allow different positions between two shafts
    - FR1.1: allow a rotation around 2axes perpendicular to PTO shaft axe
    - FR1.2: allow a rotation around PTO shaft
    - FR1.3: allow a translation along 2axes perpendicular to PTO shaft
    - FR1.4: allow a translation along PTO shaft
    - FR1.5: connect the system to PTO shaft of tractor
    - FR1.6: connect the system to PTO shaft of implement
  - FR2: transmit power form tractor to implement
    - FR2.1: transmit power with rotation
    - FR2.2: make the system rotating safe
      - FR2.2: cover universal joint by side of tractor
      - FR2.2.2: cover telescopic member
      - FR2.2.3: cover universal joint by side of implement
      - FR2.2.4: prevent rotation

Figure 11. DPs and FRs hierarchies of a PTO system.

	DP0	DP1	DP11	DP12	DP13	DP14	DP15	DP16	DP2	DP21	DP22	DP221	DP222	DP223	DP224
FR0	X														
FR1		X							0	0	0	0	0	0	0
FR11			X	X	0	0	0	0	0	0	0	0	0	0	0
FR12			0	0	0	0	0	0	0	0	0	0	0	0	0
FR13			X	X	0	X	0	0	0	0	0	0	0	0	0
FR14			X	X	0	X	0	0	0	0	0	0	0	0	0
FR15			0	0	0	0	X	0	0	0	0	0	0	0	0
FR16			0	0	0	0	0	X	0	0	0	0	0	0	0
FR2		X	0	0	0	0	0	0	X			0	0	0	0
FR21		0	X	X	0	X	X	X		X	0	0	0	0	0
FR22		0	0	0	0	0	0	0		0	X				
FR221		0	0	0	0	0	0	0	0	0		X	0	0	X
FR222		0	0	0	0	0	0	0	0	0		0	X	0	X
FR223		0	0	0	0	0	0	0	0	0		0	0	X	X
FR224		0	0	0	0	0	0	0	0	0		X	X	X	X

Figure 12. PTO system design matrix.

4.9 SYNTHESIS

To conclude, the results of applying the proposed FRE on the PTO system, is presented in the Table 5.

Table 5. Results FRE of PTO system accident analysis.

	PTO system accident
Hazard	Entanglement by PTO drive shaft with missed, broken, damaged or badly fitting safeguard
DP	Enclosing guard
FR	Make the system rotating safe
DF_h	$56 \leq DF_H \leq 70$

Based on these results in the case of missing, broken, damaged or badly fitting safeguards, there is always a high probality of an accident occuring. The first idea; to safely operate implement with the tractor energy is to make a robust design with a guard through applying axiom 2 of AD. The other idea is to improve new solutions for safeguard design. And the third idea is to search for new concepts of transmitting energy with respect to safety objectives.

5 CONCLUSION

The term 'design for safety' captures the effort to integrate the knowledge of safety in the design process. Therefore, in order to provide a more effective design to safety, in the present paper, a FRE driven by AD has been developed. The proposed method can distinguish the components, design parameters and function requirements of an existing system and define the hazard related to each component, the design parameter and the functional requirement. The PTO system is used to illustrate the proposed method. The following work will focus on functional re-engineering to propose safe requirements, safe design parameters and finally safe solution. A technology for software support of proposed method is in the process of being developed.

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6 ACKNOWLEGMENTS

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