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DEFINING SAFETY OBJECTIVES DURING PRODUCT DESIGN

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ABSTRACT

In previous research, a systematic method for human-safety integration early in the design process has been proposed. Called IRAD (Innovative Risk Assessment Design), this method facilitates the generation of safety requirements through past experience analysis and design choices analysis all along the design process. Design parameters thus result simultaneously from technical and safety functional requirements. This paper deals with the problem of defining safety objectives early in the product design process. It highlights the mechanism offered by IRAD for generating non-technical design objectives when preparing the requirements and constraints list. It shows that there are different typologies of safety objectives depending on the evolution of the product. In fact, there is a specific type of safety objective to be taken into account in a specific design stage. Finally, the applicability of the method is demonstrated through the application to a water faucet case study and mechanical person-machine interfaces.

Keywords: IRAD method, design methods, Axiomatic Design, safety objectives, water faucet, ski bindings.

1 INTRODUCTION

Current means of safety integration that consist of safety barriers implementation for risk reduction have reached their limits. In fact, safety barriers are implemented in the end of the design process (add-on safety solutions), and are rapidly increasing in variety, size, complexity and sophistication.

Hollnagel [2008] relates risks to the increase of new systems' complexity and thus, to the increase of systems coupling. In this regard, many authors [Fadier, 2006; Fadier, 2008; Lo and Helander 2007; Sklet, 2004] have shown that the more complex the system is, the more complex the control will be. And then, the implementation of efficient safety solutions becomes more complex. The surveillance and control role of the operator is therefore increased.

From a product design point of view, the current support tools available to assist designers in safety integration tasks are limited [Shupp, 2006 and Bernard, 2002]. The existing techniques for risk assessment and design review generally intervene quite late in the design process, often only during the detailed design stage, when significant decisions about product principles and structures have already been made. Existing methods that are used early in the design process, generally set constraints and are used to verify and validate, rather than being more effective design methods, which can make safety part of the design objectives. Current safety solutions can lead to various delays and cost increases when safety problems are considered too late in the product design process.

The information relative to past experience often arrives to designers in a relatively haphazard and narrative way, and is usually related to specific accidents in a specific context. There is no support that abstracts this information in order to integrate it, independently of any potential solution, in the preliminary design phases.

In our research, we study the possibility of integrating safety inherently early in the design process. We consider that safety must be implemented during the design process and must take part of the design functionality.

The question that we tried to answer in this paper is: what is a safety requirement? Consideration of this question is based on the definition of design objectives (functional requirements and constraints) given by Suh [2007].

Suh [1990] defines "functional requirements as the minimum set of independent requirements that completely characterize the functional needs of the product; constraints are bounds on acceptable solutions".

This paper deals with the problem of defining safety objectives early in the product design process. Firstly, the IRAD method for systematic human-safety integration is reviewed. Secondly, the way to define safety objectives from the beginning of the design process and all along design is developed. Finally, it gives the nature (requirements versus constraints) and the typology of safety objectives.

2 INNOVATIVE RISK ASSESSMENT DESIGN METHOD (IRAD)

In recent work, we have proposed a systematic human-safety integration method to be used early in the design process Ghemraoui *et al.* [2009a, 2009b], called IRAD (Innovative Risk Assessment Design).

Firstly, IRAD was based on a conceptual risk reduction model. This model is developed in the framework of the Systematic Approach [Pahl and Beitz, 2007] that offers a specific description and modelling of the product according to three points of view. The asset of the Systematic Approach is its algorithmic description of the design in the sense that it

describes the best way to satisfy the design goals. At the beginning of the design process, functional requirements are identified through the customer needs and the experience feedback, if it exists. We consider that depending on the typology of these requirements, they will intervene in a specific design stage (conceptual, embodiment or detail stage). Indeed, in our approach, the design functional requirements and specifications and thus the task clarification stage are considered parallel to the three conceptualisation stages of the systematic approach (Figure 1). Then, we considered that risks are identified at each of the design stages and are considered as evolving with and dependent on the design technological choices. Risks are identified through the design parameters analysis and are defined through the nature of the interaction of the human with design resources at each stage. Risks result from the interaction of the human with the design resources such as functions, energy, space, time, performances, etc. So, these interactions are analyzed and potential risks are listed. In fact, this analysis consists of defining the compatibility of the human characteristics with the design parameters' ones. Then, we propose to convert the defined risks into functional safety requirements, integrated into the specification document and taken into account in the following design stage. These requirements are enhanced and specified throughout the design process through risk analysis related to the design choices and are considered as evolving simultaneously with the product development. Safety requirements are defined throughout design and added to the specification documents. Consequently, the specification document is enhanced through the possible undesirable events and serves for verification and validation. Integrating the safety functional requirements into the technical product design, all along the product development, constitutes the risk reduction process. These operations of design synthesis, analysis, risk and safety requirements identification correspond to the conceptual model of the proposed approach.

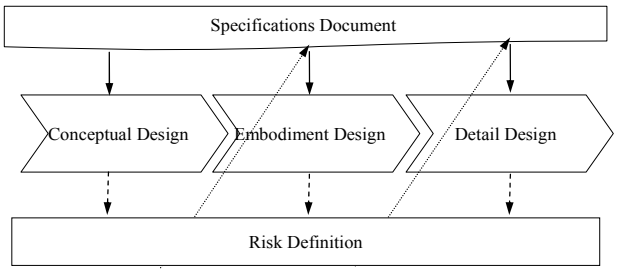

Figure 1. Conceptual risk reduction model.

Finally, for safety needs we adopt a representation for the design process relating the systematic approach to the Axiomatic Design [Suh, 1990; Suh, 2001; Brown, 2005]. Therefore, the design process is both algorithmic and iterative. Safety integration in design consists of analysis and synthesis, which mutually reinforce each other in a feedback loop. Consequently, each stage of the design process is divided into two domains: the functional domain that constitutes the technical requirements and the physical domain that corresponds to the technical solution. Hence, the design process is divided into six phases noted Pi (i=1...6).

Ge *et al.* [2002] gave a similar representation of the relation between the systematic approach and axiomatic design. This representation, called the extended axiomatic design (EAD), considers that the three conceptualization stages of the systematic approach, which are conceptual, embodiment and detail design, are divided in two domains: the functional and physical domains. Nevertheless, we consider only a representation in 2D as shown in Figure 2.

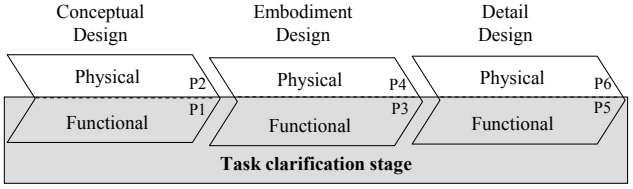

Figure 2. Representation of the design process.

As the design parameters' characteristics typology depend on the design stage, the potential risks depend on the considered design stage as well. This observation leads us to consider that there is a mapping process between design and risk describing the compatibility between the design and the human characteristics. Therefore, the design process communicates with a "risk process" which is divided similarly into three steps according to the abstraction level of the solution. Thus, we noticed the Human-Principle Interaction (HPI), Human-System Interaction (HSI) and the Human-Machine Interaction (HMI). The HPI corresponds to the interaction between the human and the design solution in the conceptual design stage. The HSI corresponds to the interaction between the human and the design solution in the embodiment design stage. Finally, the HMI corresponds to the interaction between the human and the design solution in the detailed design stage. This "risk process describes the safety requirements generation and the risks identification processes.

In addition, the typology of safety requirements depends on the considered design stage. Therefore, similarly to the design process, the risk process has functional and physical domains and is divided into six contexts noted Ci (i=1...6) (Figure 3). These two processes are conducted simultaneously and the result of one affects the other [Ghemraoui *et al.*, 2009].

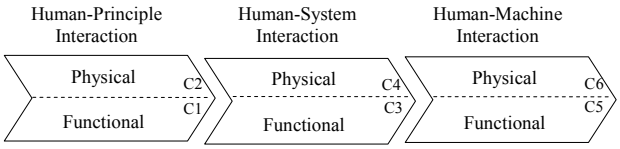

Figure 3. Representation of the risk process.

2.1 THE HUMAN-PRINCIPLE INTERACTION

The HPI corresponds with the conceptual design stage. From the design point of view, at this level the overall functional requirements are decomposed into sub-requirements less abstract and one or more working principles are selected. Therefore, the potential interaction with human could be related either to the environment of the product or to the chosen working principle. From this interaction safety requirements related to the environment and to the solution's principle will result.

2.1.1 THE HUMAN-SYSTEM INTERACTION

The HSI corresponds with the embodiment design stage. The conceptual design working principles are structured and the occupied as well as available spaces are defined. In addition, the way in which the product will function is also specified. The dangerous zones and the intervention zones of the user are defined. The user location is related to functional and physical structures. At this step, the interaction with human is related either to the human activity or to the nature of the structuring parameters.

2.1.2 THE HUMAN-MACHINE INTERACTION

The HMI corresponds with the detail design stage. From the design viewpoint, the product components, layouts, etc. are defined. Notice that traditionally, at the end of this stage, risks are analyzed and corrective actions are implemented. Normally, in our approach, potential accidents and ergonomics are handled at previous levels. Here, less important risks related to components, final forms, etc. are studied. At this stage, potential interaction mainly involves the design technical choices.

Consequently, IRAD considers design as an iterative activity between a design process and a risk process (Figure 4). These two processes are evolving simultaneously, and one influences the other. The design process is divided into six phases (Pi, i=1..6). Similarly, the risk process is divided into six contexts (Ci, i=1..6).

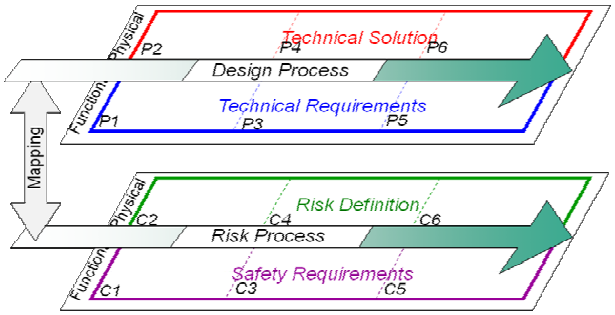

Figure 4. IRAD: Mapping between design process and risk process.

This paper aims to complete the approach recently proposed by giving the mechanism of functional requirements generation in order to integrate safety objectives more efficiently and more naturally early in the design process. To do so, we introduce the concept of safety requirements versus technical requirements. We give typologies of safety goals according to the considered design stage. And finally, we show that if safety constraints are integrated lately to design it leads to the generation of safety requirements and consequently to the complication of the design.

3 SAFETY OBJECTIVES DEFINITION DURING DESIGN

3.1 RISK PROCESS

The risk process, resulting from the mapping between design and safety, describes the relation between designers and ergonomists all along the design process. Designers propose the solution that may satisfy technical requirements supported by constraints, while ergonomists associate risks with the resources available in design. Our approach requires an additional effort from ergonomists to translate potential risks into design objectives, called safety objectives, in order to facilitate communications between designers and ergonomists. To facilitate safety integration in design, IRAD gives guidelines to risk definition that are transformed into safety objectives. Safety objectives thus depend on the design stage under consideration, and have different typologies at each stage.

As stated previously, the proposed risk process is divided into a functional domain and a physical domains Due to the differences in the inherent characteristics between the design stages (Pi, i=1..6) , the risk contexts' Ci (i=1..6) characteristics are similarly inherently different (Figure 5).

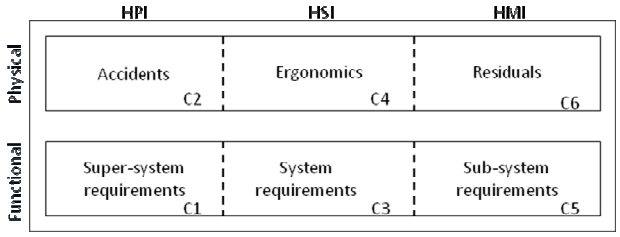

Figure 5. Risk process.

The risk functional domain is divided into three types of safety requirements:

3.1.1 C1: SUPER-SYSTEM REQUIREMENTS

We call the elements in interaction with the product in a given lifecycle situation "super-systems". They may correspond to physical, human, environmental, etc., components. This context outlines safety requirements related to the use context of the product. These requirements are deduced from risks arisen in ground (experience feedbacks) due to the use of the same or similar products. At the associated design phase (P1), the product is described through its desirable functionalities (mainly technical), design constraints, characteristics and super-systems. The context C1 completes these technical requirements with others ensuring the minimisation of risks generated by the super-systems. This kind of risk exists and is totally independent of the design choices. In this regard, this type of safety requirements is expressed by an infinitive verb connecting two or more super-systems that belong to the considered use situation. In this context, safety requirements are input requirements and are specific to the overall design goals. Here, safety imposes the designer to take specific actions that could be well specified.

3.1.2 C3: SYSTEM REQUIREMENTS

We call the product's structure and architecture the "system". This structure is based on the solutions' principles organization and structuring. This context describes the safety requirements leading to the product's structure identification. From the human point of view, this structure induces a procedure resulting from the product functioning mode. A procedure is a set of activities cooperating in a chronological way in order to reach a specific goal. Therefore, we consider a procedure as the succession in time and space of the multiple tasks that a user must do. At this stage, design consists in functions allocation between the solution and the human in an

ordered way. Functions' allocation is directly affected by the working principle chosen at the phase P2 which defines the nature of the activity (automated or manual) as well as the human intervention degree and its frequency. This will set constraints to point out the better product's structure. Here, human safety is characterized by the human spatial position, his activity temporisation and his anthropometric data. In addition, the nature of the human activity is involved by his physical efforts limitations. These physical limitations will involve product functioning mode as well as dimensioning and materials choices. At this design stage, human characteristics are input constraints defined at the beginning of the design process. These constraints may result from either the experience feedback or the standards. The main characteristic of this context is to describe spatial and temporal separation between the product and the human. Besides these constraints, this context contains system safety requirements. These requirements consist of input constraints specification according to the physical design choices.

3.1.3 C5: SUB-SYSTEM REQUIREMENTS

We call the product's components that allow finishing the product at the detail design level the "sub-system". This context describes safety requirements involving the components choices. A large number of these components constitute the human-machine interface. The human-machine describes the interaction between the user and the product in the use phase. This interface results from the nature of the human activity. More precisely, this context describes the safety requirement that leads to the product's final components choice according to the required human characteristics (vulnerability and ergonomic). The difference with the previous types of interaction is that here, safety requirements have minor effects on the global product safety. At this level, safety is expressed as functional requirements induced by the previous levels. These requirements result from the risk remaining in the previous levels.

The risk physical domain is based on three types of risk:

3.1.4 C2: ACCIDENTS

This context describes the possibility that an accident occurs. At this stage of design, accidents could be related either to the use context or to the chosen working principle. We consider that an accident must be generated by a source of energy and the potential risk depends on the nature of the energy. In case of new product design, the typology of risk of a used energy is identified through the use of standards. Risks are thus assessed according to the energy's nature and intensity. At the conceptual design level, we focus on the energy's intensity used in the selected physical concepts. Obviously, the intensity may be transformed and thus, the potential effects may be reduced during design. Reducing the energy intensity makes the product safer. Indeed, the transformations that may occur in the following stages allow this energy to be hidden but not to be totally eliminated. Moreover, the effects of the technical choices decrease while evolving in design.

3.1.5 C4: ERGONOMICS

This context describes the violation of the human anthropometric and physical data by the chosen structure in phase P4. The product's structure allows the dangerous zone (D-Z) as well the user locations to be described. The task allocated to the user could be specified. A dangerous zone is a geometrical zone delimitating a dangerous phenomenon. It could be permanent or accidental. At this level of design a dangerous phenomenon may take effect if the allocated task violates the ergonomic constraints or if the user is in an energy zone. In this context, safety requirements are divided into two types; system requirements describing ergonomics needs and input requirements resulting from a previous design stage. The second type describes the risk of accidents not eliminated at the conceptual design. Ergonomics are mainly specified by a task. A task defines a posture, a movement and physical efforts. Dangerous zones are defined by a form, location, volume and gravity. Here, we distinguish two types of dangerous zones: (1) those imposed by the use context and (2) those resulting from the solution. The first type of dangerous zone is considered as existing to the overall design and the solution has to compensate its effects. The second type is generated by the decisions-making during design and corresponds to the system's risk. Finally, this context studies the compatibility of the design skeleton with the human one.

3.1.6 C6: RESIDUALS

We call residuals the risks related to the design choices having little effects on the human-safety. In this context, the risk resulting from the physical design choices may generate either accidents or ergonomic problems. At the corresponding design phase P6, the product components and then their structures are selected. This context describes the potential risks related to the components. These risks may be generated by the component's structure, or by the energy incorporated in these components. This type of risk is entirely related to the decision made during design. Risks are identified due to the experience feedback related to the use of these components in other designs by studying the interaction of the components skeleton with the human members' skeleton. Figure 6 summarizes the concepts of IRAD.

3.2 SAFETY OBJECTIVES TYPOLOGY

To define safety objectives correctly, IRAD gives several typologies of safety requirements and constraints according to each stage of design. These typologies are described by the proposed risk process (Figure 5).

In IRAD, humans are described by (1) vulnerability, (2) morphology, (3) physical capability and (4) ergonomic postures. All of these descriptions constitute constraints when starting the design process.

In order to define safety objectives, it is important to distinguish between input safety objectives and system safety objectives.

Input safety objectives are those defined at the beginning of design and are true for the overall design. They are those arisen from past experience. At the conceptual design stage, they are defined in terms of functional requirements, are related to the use context of the product and are independent of any possible solution. These requirements describe the minimization of the energy accumulated in the product environment. This type of requirement describes the risks of the product even before the product is created. However, at

the embodiment and detail design stages, safety objectives consist of input constraints (morphological and ergonomic data). More specifically, at the detail design stage, safety constraints describe the members' ergonomic constraints (Figure 7).

System safety objectives are defined during design and are true for a specific design and are the consequence of the design choices. Risks related to the design parameters choices are converted into safety requirements and are to be taken into account in the following design stages. System safety objectives are functional requirements. This type of functional requirement is created during the design process when some constraints are not satisfied (Figure 8). More precisely, it consists of unsatisfied constraints that are converted into safety requirements to be taken into account in the following design stages. In fact, unsatisfied constraints are specified when progressing in design and necessitate design parameters.

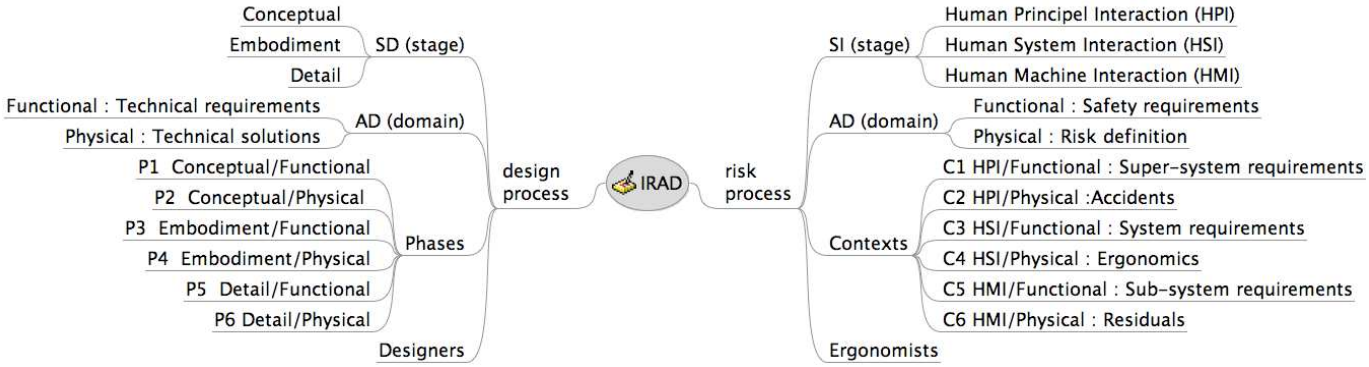

Figure 6. The concepts of IRAD.

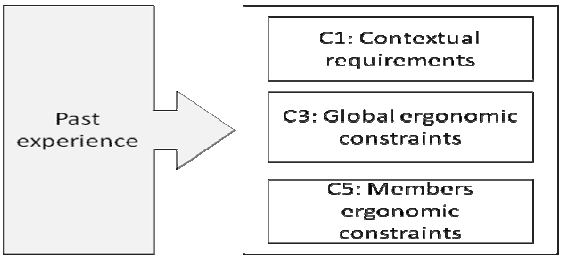

Figure 7. Definition of input safety objectives.

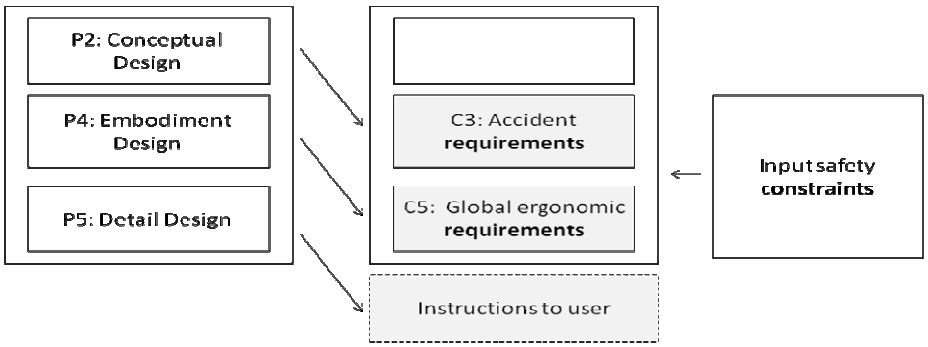

Figure 8. Definition of system safety objectives.

3.3 SAFETY DESIGN SYNTHESIS

In IRAD, design synthesis is based simultaneously on technical requirements (TRs) and safety requirements (SRs).

Safety design synthesis should satisfy the independence axiom of the Axiomatic Design. These design solutions could be uncoupled or decoupled. Decoupled designs have triangular design matrices and therefore require a certain sequence of operations.

Design matrices are thus either diagonal (uncoupled) or triangular (decoupled). Decoupled matrices can be either upper or lower triangular.

$$\begin{Bmatrix} TR_1 \\ SR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \quad (1)$$

$$\begin{Bmatrix} TR_1 \\ SR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \quad (2)$$

Design synthesis based on technical and safety requirements allows the consideration of safety as an integral part of the entire design solution.

4 CASE STUDY 1: DUAL KNOB FAUCET

The most common injuries from using domestic hot water are skin burns. Accidents affect mainly children and older people because of their limited mobility. Hot water can reach the 60°C, exceeding the 38°C the legal safety temperature. In addition, over 50°C, hot water causes serious burns.

The technical functional requirements of dual knobs faucet are:

FR1: Control the temperature of water;

FR2: Control the flow of water.

4.1 DEFINITION OF WATER FAUCET INPUT SAFETY OBJECTIVES

The analysis of past experience provides the input safety objectives. The use of hot water leads to burnings. This constitutes the risk of an accident. This event is thus placed in the C2 context "accident" of the risk process and generates a safety requirement in the context "C1 super-system". In this case, a "safety requirement" generated is « Maintain a safe temperature ».

This requirement is then integrated to the requirements list and is measured by Figure 9:

Functional requirements	Measures
FR1 : Control the temperature of water	0 ≤ Tm ≤60°C
FR2 : Control the flow of water	1,5 ≤ Pm ≤ 4 bars
SR3 : *Maintain a safe temperature*	0 ≤ Tm ≤38°C

Figure 9. Requirements list integrating input safety requirements.

Tm and Pm are respectively the temperature and the pressure of the outlet water.

In addition, limited mobility is an ergonomic problem and is thus placed in the context "C4 ergonomic". This risk generates a "safety constraint" «Take into account the mobility of the users» to be taken into account during the embodiment design stage.

The consideration of the experience has lead to a new FR noted SR3.

In this case the design matrix is Figure 10:

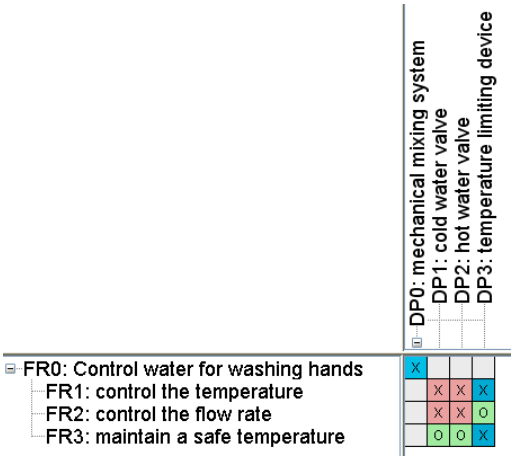

Figure 10. Design matrix of the dual knob faucet integrating input safety requirement

4.2 DEFINITION OF THE WATER FAUCET SYSTEM SAFETY REQUIREMENT

Here, we will consider that the conceptual design of the water faucet is validated. The system safety requirement thus results from design parameters analysis. The design matrix, representing the relation between the functional requirements and the design parameters, of the water faucet is shown in Figure 11:

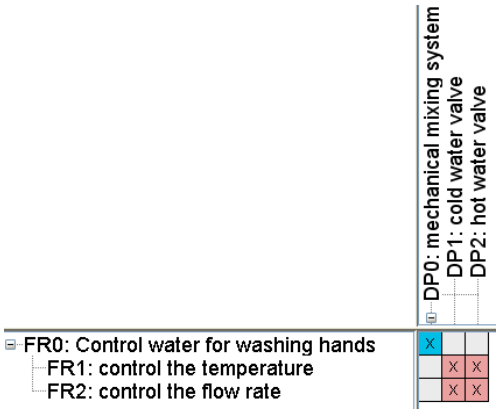

Figure 11. Design matrix of the dual knob faucet

In this case, the design parameters are:

DP1: Cold water valve;

DP2: Hot water valve.

The analysis of the design parameters shows that the outlet water temperature may reach the 60°C and thus exceeds the legal safety temperature. If the conceptual design is validated, this risk is converted into a system safety requirement at the embodiment design stage as following Figure 12:

Functional domain	Physical domain
	C2 : Accident Tm>38°C → burning
C3 : System requirements ***SR2.1:*** *Minimize the intervention of the user to assess the outlet water temperature*	

Figure 12. Definition of system safety requirements through the analysis of the design choices.

The little consideration of the experience at the conceptual design (HPI) stage has lead to a new "system FR" Figure 12 in the "embodiment design stage" (HSI). In addition, Figure 11 shows the expected coupling in the classic water faucet problem [Suh, 1990]. It also shows an interaction between the temperature limiting device and FR1 to control the temperature. The designer's task is to decouple the functional requirements. This could be accomplished by selecting alternative DPs. In the absence of FR3, the solution would be driven to a lower triangular. It would be better to first control the temperature and then control the flow. The presence of FR3 to limit the temperature could remove the risk of burning. The presence of an X between FR1 and FR3 in Figure 10 indicates an expected interaction between the temperature control and the device to maintain a safe temperature.

5 CASE STUDY 2: ALPINE SKI BINDINGS AS SPECIAL HUMAN-MACHINE MECHANICAL INTERFACES

Mechanical human-machine interfaces, such as an alpine ski bindings, hand power tools or vehicle steering columns, need to transmit control loads from the user to the machine. The potential to transmit injurious loads to the user should be avoided. The top FRs is to transmit control loads and the top SR is to filter injurious loads. Steering columns filter injurious loads by collapsing under impact in a collision. The collision and normal driving loads are different enough so that there is no mistaking one for the other and there is no inadvertent collapsing of steering columns. It is known from experience that ski bindings however suffer from inadvertent release, i.e., mistaking non-injurious loads for injurious loads. In the "conceptual design stage (HPI)" in the context "C1 super-system requirements" one or two safety requirements can be defined. SR1 is "to avoid transmission of injurious loads". This is common to all such mechanical interfaces. In the case where SR1 is satisfied by a release system, whereby control might be lost, such as, a conventional releasable ski binding with explosive bolts, or an ejection seat, then SR2 would be "to avoid inadvertent release" (Figure 13).

At this point, the design is similar in some ways to the previous case study on the faucets. It is necessary to separate FR1 and 2. At the HSI stage, two sub-systems could be envisioned based on the magnitude of the loads, provided that there is a clear difference in the control and injurious loads. Experience shows however that high loads, even potentially injurious loads, can be sustained without injury for short durations. If the binding releases in these situations, then loss of control and serious injury from collisions can result. In the HSI stage this calls for a method to systematically discriminate between actual injurious situations and non-injurious, high-level, short-duration load spikes.

Two system level approaches have been developed to avoid inadvertent release. One is impulse-based and has been developed at the detailed level electrically. It tests that the load is of sufficient duration to approach injury potential before release [DiAntonio, 1983]. The other is work-based and has been developed at the detailed stage using preloaded springs to transmit control loads below the preload without significant displacement until the preload has been exceeded. It assures that work is done on the mechanism at sub-injurious loads adsorbing energy that would have caused injury or release [Havener and Brown, 2010]. The preloaded spring mechanism can change the off-diagonal Xs in the of the control matrix shown in Figure 13 to Os, because it filters injurious loads while faithfully transmitting control loads and adsorbs energy that could cause inadvertent release.

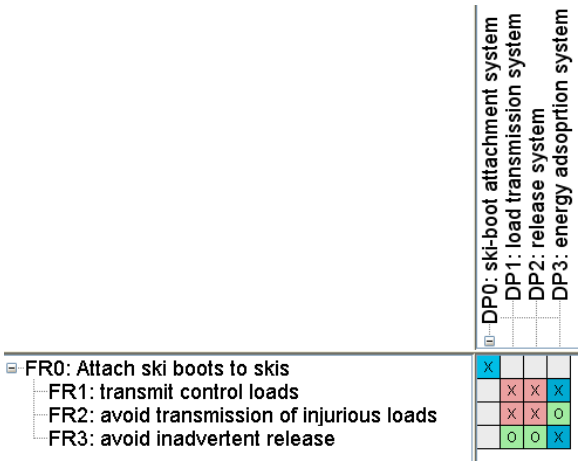

Figure 13. Design matrix of the alpine ski binding integrating input safety requirements.

6 CONCLUSION

This paper deals with a method for the definition of safety objectives early in the design process. The recently proposed IRAD method gives the typology of safety objectives at each stage of design. When the design process is started, safety objectives are contextual requirements and ergonomics constraints. In this paper, it is shown that safety requirements generated during design are functional requirements. These requirements are the specification of safety constraints initially defined in design. Like technical objectives, safety objectives consist of input and system objectives and are described in terms of functional requirements and constraints. The application of the method to the water faucet and the ski bindings has been shown.

In future work, the development of design tools in order to facilitate the implementation of this approach and support design should be examined. Future research should focus on the problem of integrating safety aspects without affecting technical design aspects, such as, performance and quality. The

formalization of safety requirements expression independently of the intentions and the perceptions of the decisions makers should be handled. The idea is to examine the activity of the decision maker in charge of expressing safety requirements (designers or ergonomists).

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