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EVALUATION OF INFORMATION REQUIREMENTS OR RELIABILITY METHODS IN ENGINEERING DESIGN

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Keywords: robustness & reliability, assessment methods, information requirements

1. Introduction

Product designs can be evaluated in terms of their reliability and robustness (R&R) by quantitative and qualitative methods. The former, such as structural reliability [1] and statistical approaches [2], require significant amounts of design data; whilst the latter, like Failure Mode and Effects Analysis [3], require significant design expertise.

With more room to decision-making being available during early phases of product development [4], qualitative approaches better support design decisions where they are most cost-effective. In our view, qualitative methods fit better to early design stages; they allow designers to avoid failure early rather than spend time and effort correcting it later, because they focus on applying engineering judgment.

In this context, there is need to unfold knowledge required by different R&R assessment methods and compare it to available information during conceptual design, so that:

- there is better guidance to look for product information on early R&R assessments;
- available information at early design stages is more effectively used; and,
- Designers have better support to evaluate design R&R during conceptual design.

This paper aims to characterize the information needed to perform selected R&R methods, and to verify their applicability to early design stages. This paper contributes to the field of design methods with the following results: it diagnoses the availability of design information to using R&R methods through the design process; and verifies the feasibility of R&R methods for application in early design stages.

2. Robustness, Reliability and Information Taxonomies

2.1 Reliability

Reliability reflects the ability of a system to perform its task with adequate availability. Current methods to design for reliability (DFR) take reliability as a function of failure probability on operation, looking to provide means to decrease that probability. The following methods meet these criteria:

1. FMEA/FMECA: [3];
2. HAZOP: [5];
3. FTA: [6];
4. ETA: Event Tree Analysis [7]
5. Safety-barrier diagrams [8].

DFR methods enable designers to use their knowledge and expertise by prompting them to think about reliability in a systematic way [9], enabling designers to prioritize critical design issues. Many of these methods rely on complex data, and significant expert input. Nevertheless, using them allows designers to take advantage of their knowledge to improve product design on safety and reliability.

2.2 Robustness

Robustness is understood as the insensitivity of a system to uncontrollable conditions such as in operating conditions, manufacturing variability, and throughout the product lifecycle. There are methods for robustness improvement, prompting designers to think about how deviations take place and on ways of controlling them. Methods with such objectives are:

1. Axiomatic design [10];
2. Quality engineering/Robust design [11] and,
3. Parameter-based decision method [12].

While axiomatic design aims to minimize coupling between functional requirements and design parameters, robust design looks at determining and minimizing the influence from disturbances in performance (signal-to-noise ratio) using experiments. The decision method uses robust design and axiomatic design principles by combining signal-to-noise ratio with assessment of parameter independence.

2.3 Design models and taxonomies

Design models and taxonomies help decompose, separate and structure the design problem, simplifying it into less complex issues. They are often empirically derived because they depend on specialist language, either from experience or research. These models are explained in three tracks:

- Techniques for function and system modelling;
- Classifications of system design entities and design process entities; and,
- Specific classifications of R&R engineering knowledge:

Functional modelling decomposes an overall purpose into chains of energy, material and information flows [13]. Organ modelling describes components and their links in two ways: by sketches [14]; or by flow-charts [15]. The functional basis provides a standard vocabulary [16] to be used in function structures. These methods aim to separate and structure design issues in manageable sets.

A classification of mechanical connections, also in [13], supports proceeding with embodiment design while the links between components are yet to be fully understood. An integrated taxonomy [17] uses an ontological approach to describe engineering design activities and their context. These propositions support structured descriptions to design relationships both in product as in process, respectively.

Other taxonomies of mechanical failure come basically from accumulated knowledge through research and experience [18, 19], describing factors and processes that cause failure. Means to achieve robustness on design principles [20] are described from patent search. Those taxonomies show R&R information depending on system behaviour and control strategies used by designers in controlling it.

3. Evaluation of R&R methods

3.1 DFR applicability to early design

DFR methods have been formerly assessed on their applicability to different design stages. One report reviews how DFR methods’ support risk management [21]. Other review of DFR methods on hazard identification provides a more general perspective [22]. They recommend DFR methods throughout the design process, but question their effectiveness to early stages.

According to both sources, DFR methods require extensive information and knowledge on the design under development. Other issues to using DFR methods are: (a) they may not cover all issues within a single analysis; (b) they consume significant time and require expert input; and, (c) many of them have limited reach within human factors.

3.2 Robustness on early phases

Original robustness methods, such as [23], require both significant data and rigorous formalism. to be used effectively. No prior assessment exists on the applicability of original or adapted robustness methods to concept development such as with DFR methods. Nevertheless, there are relevant cases where robustness fundamentals are demonstrated to be applicable.

Design strategies are proposed to avoid failure modes in concept design, considering design parameters and acceptable ranges [24]. An approach to conceptual design retains robustness fundamentals specifically adapted to the design synthesis process [25]. These examples show there is room for improvements in the area.

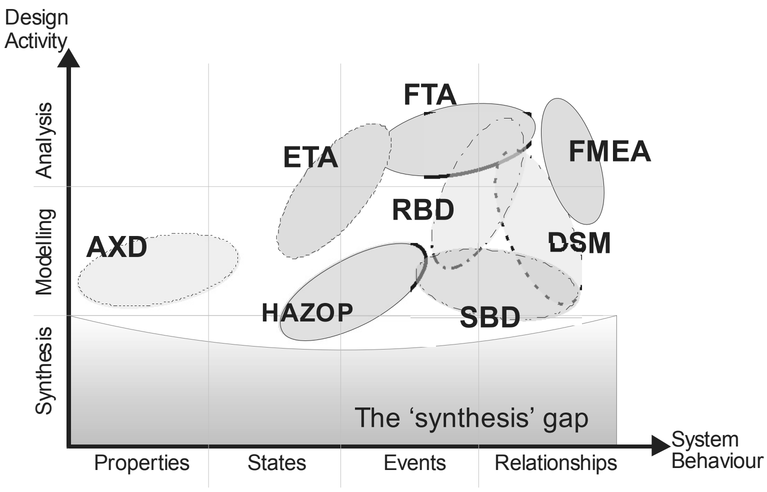
3.3 Our preliminary evaluation of R&R methods

The suitability of R&R methods to early phases has been diagnosed in different extents. DFR methods were shown to be assessed on their applicability to different stages of the design process; and, early robustness methods were demonstrated with mock examples. That does not bring meaningful answers to how R&R determine requirements on necessary product design information.

For that reason, a preliminary comparison of R&R methods has been performed. The methods are compared in two metrics:

- Contribution of R&R methods to create or describe design characteristics, on design activity progress (synthesis, modeling and analysis); and,
- Characterization of design information on system behaviour, on progressive level of detail (properties, states, events and relationships).

This evaluation considers current instructions and prescriptions to use R&R methods in design tasks, as stated in our references. The graph in Figure 1 shows our assessment of how methods' prescriptions cover design activity and design information.



AXD	Axiomatic design [10]
DSM	Design Structure Matrix [26]
ETA	Event Tree Analysis [7]
FTA	Fault Tree Analysis [6]
FMEA	Failure Mode and Effects Analysis [3]
HAZOP	Hazard and Operability Studies [5]
RBD	Quality Engineering/Robust Design [11]
SBD	Safety-barrier diagrams [8]

Figure 1. Evaluation of design information output from R&R methods

The evaluation on output to design activities clarified our grasp on the lack of R&R methods whose output can directly support design synthesis.

Few methods, such as HAZOP and Safety-barrier diagrams, get close to directly orienting design synthesis to mitigate risks. On other R&R methods – DSM [26] has been considered due to its wide application on product development – synthesis knowledge come as result from significant effort on modelling and analysing the system under development.

3.4 The synthesis gap of R&R methods

The preliminary evaluation has shown there is a gap in how current R&R methods directly lend support to design synthesis.– see the 'synthesis' gap in the figure. Parameter-based approaches were

presented as ways forward by literature, as commented on item 3.2: However, they direct design responses to disturbances and do not directly refer to why design problems should be corrected.
The current assessment shows an opportunity window for methods directly addressing design R&R showing *why and how* to avoid failure.

4. Research method

This work is carried out as a partial descriptive study within a design research framework [27]. The strategy to collect the data and gather insight follows a case study framework [28]. With the objective of extracting further research criteria and preliminary insight on the problem, it is to be considered as a pilot case study. The research methods used for extracting the information from the context were selected among the following alternatives: literature review; document analyses; and action research.
Literature review created awareness on current R&R methods and helped evaluate which should be selected. It also supported the preliminary analysis to choose the methods to be performed on the following criteria: the insight they provide on design risks; and, the extent of their application in industry. Hence, three methods were selected: (a) FTA; (b) FMEA; and, (c) HAZOP.
Then the product under analysis is defined with the following criteria: it is readily available; its main functions are mechanical; and, descriptions can be quickly found. For those reasons, a washing machine was selected. It uses action research on the ground of active participation of the researcher in gathering documentation and carrying out the assessments with R&R methods.
The product evolution methodology [29], is used as framework for this case, where the approach to followed the Reverse Engineering stage. The method prescribes steps for doing product analysis, whose result will feed the R&R methods chosen. Complementing that methodology, the following procedures were performed:

- Disassembling the product and getting technical data;
- Modelling the product in functions and organs;
- Considering the issues to reliability and robustness;
- Performing FTA, FMEA and HAZOP methods;
- Documenting the information used in the methods;
- Classifying the required information, related to design models; and,
- Comparing the methods on their applicability to early design phases.

The documentation procedure includes acquiring product references from: product disassembly; and, use and maintenance prescriptions by manufacturers and third-party support services. The assessments involved using function and product modelling approaches [13, 14, 30] to describe the system, find out the prominent design issues and carry out the R&R analyses with the chosen methods.
The analyses were documented so that to evaluate R&R methods on their information requirements. In this study, these are assigned to information fields from the methods and assessed on the detail level they require, following information characteristics of different stages in the design process [13].

5. Results

A review of R&R methods supported the choice of three methods for a case study with a washing machine. The methods were applied in describing a design issue and evaluating the information requirements for using them. The results are shown in a retrospective order.

5.1 Information structures of R&R methods

The objective of this item is to grasp the information requests of the selected R&R methods, and what input engineers have to provide in order attend to each of these requests. To achieve that goal, the selected R&R methods are decomposed into information structures that separate and explicit their information units. Each method is then described on its units and their classification, as in Figure 3.
Information units from FTA are individualized following the symbol notation and the associated meanings. The division is made on symbol groups, as shown in the figure: FTA gates, top and intermediate events, and primary events. Information is individualized following sets of symbols:

primary events follow the types prescribed in [6] as found in the problem: basic event (quantified), external event (certain) and conditional event (condition on gate).

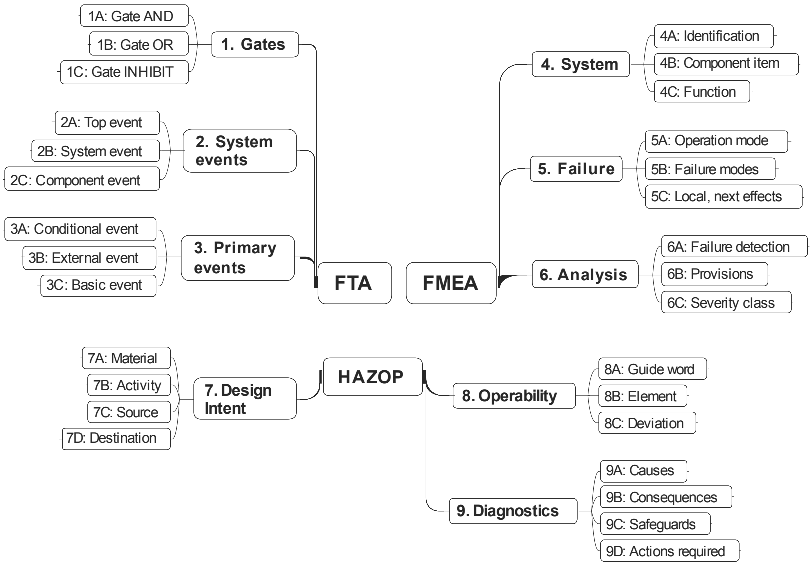


Figure 2. Information hierarchies and units of R&R methods: FTA, FMEA and HAZOP

Information units from FMEA are individualized following the column fields from its spreadsheet format. The group division is made considering the focus of column fields through the spreadsheet: system, failure and analysis. Information is individualized following column designation: system information follows part identification, component item and function, as shown in [3]: the system field is composed by identification, component item and function.
HAZOP information units are derived in similar way to FMEA's. The group division is done by separating information groups from sheet designation and assessment columns: design intent, operability and diagnostics. Information units are derived from these scopes following the spreadsheet. [5]: operability groups guide word, element and deviation columns.
The resulting hierarchies help separating specific information from similar types, and assigning information units to their corresponding design information. The information units are individualized and coded to be assigned to design information they require and assessed on how complex that information is.

5.2 System models and information to R&R methods

Following the research approach, system models were created to represent different detail levels of an engineering problem in the design of the washing machine. Consequences to product functions were related to system-wide risks, whose most relevant issue was the integrity of components supporting the drum during spinning. The 'slip' condition indicates when the machine starts sliding upon the floor, and the 'tip' condition indicates the situation in which the machine leans and tends to fall aside [30].
Function and organ models help relating system functions to system-wide parameters, to find out causes of the vibration problem. For instance, dampers under the drum (organ) help decrease (function) its displacement (body parameter) against the body of the washing machine. The dampers are assembled along metallic guideways to avoid excessive buckling. That condition would cause them to break, causing serious failure. Their properties, such as the elasticity modulus 'E', can be related to system-wide behaviour where the motion equation applies. Figure 3 shows system representations and the elements they support in reliability methods.

The figure shows system models used in the study. While the function structure [13] is expressed as block diagram, the body sketch is used for the organ model [14]. The body model and its equations

link to system parameter formulations [30]. The figure shows system representations, and respective components, feeding information to R&R methods and their information units, as in Figure 2.
The unit arrangement reveals R&R methods require variety of system descriptions to cover the system scope in increasing detail. Such requirement is neither uniform nor structured, which means all models are needed to carry out R&R analyses with these methods. The arrow directions hint R&R methods do not generally take advantage of early design models.

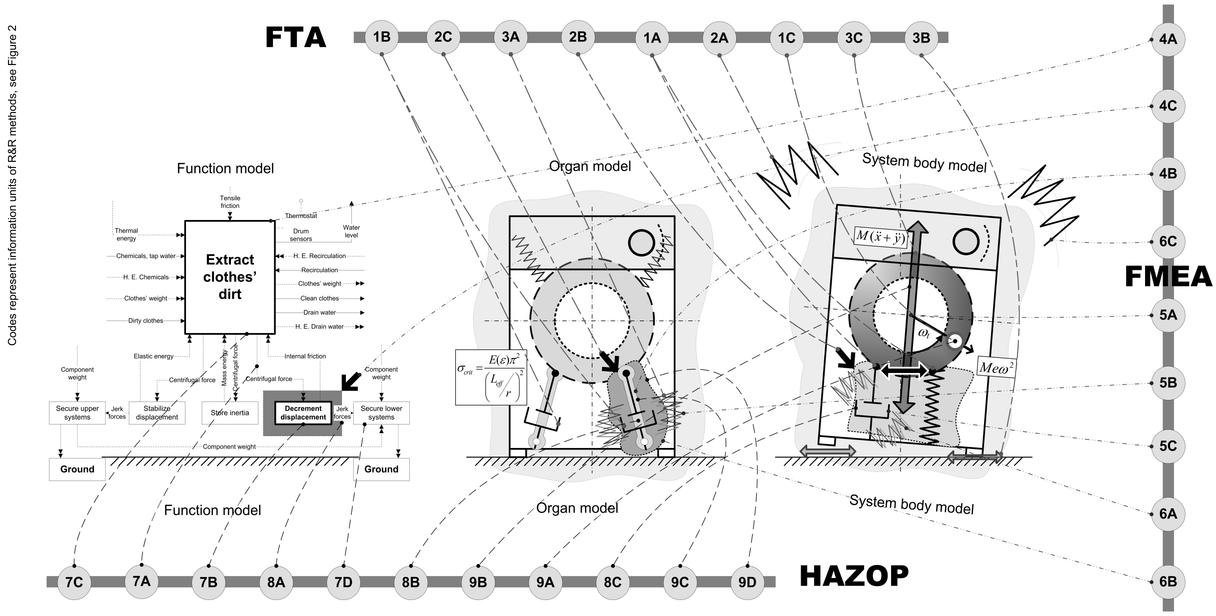


Figure 3. Information units from R&R methods and its sources (see also Figure 2)

5.3 Taxonomy to R&R information in design

This item aims to propose a classification of the information required to carry out R&R assessments with DFR methods. It joins current knowledge from literature with insight acquired throughout the reverse engineering approach. A number of 273 keywords were collected from the dataset, and classified to main keywords from existing taxonomies and new keywords coming from data.
Current engineering taxonomies, providing main keywords to the R&R taxonomy, are referenced in the item 2.3. On current taxonomies, EDIT has lent most of the support to classifying design information with focus on R&R assessments. As shown in Table 1, all its information subunits – product, issue – have been retained. However, its original form does not lend sufficient support to describing design content related to assessing and improving R&R characteristics.
Subunits from current taxonomies with little or no relation to dataset keywords were discarded. New main keywords were synthesized on aggregating meanings of remaining dataset keywords, once there was no corresponding concept in current taxonomies. The set of main keywords used, shown in the Table 1, forms the R&R information taxonomy.
R&R keywords are described on the following characteristics: original reference, classification definition, subunit relations to original concept, and information source on models (Figure 3).

Table 1. Main keywords for classifying engineering R&R information in design

Keyword	Reference	Definition	Processing	Source
Function	Functional basis [16]	Structured actions and system flows achieving a definite technical purpose	Retained original	Function model
Product	Engineering design (EDIT) [17]	Constructive elements, characteristics and relations from the designed product	Retained original	Organ model
Issue	Engineering design	Relations, characteristics and requirements	Retained	Body

	(EDIT) [17]	to be considered during product design	original	model
Failure mode	Mechanical failure[18, 19]	Processes and phenomena causing degradation of performance or failure	Changed original	Body & organ
Event	Product dataset (Current research)	An occurrence where system properties and/or the functional state is changed	Created from data	Body model

Figure 4 shows an approximate correspondence between system models and R&R taxonomy keywords. They are followed by descriptions of specific system parts they apply to. For instance, component failure is illustrated by a buckling damper. Bold-contoured keywords have been either changed from original or created from data, whose subunits are shown.

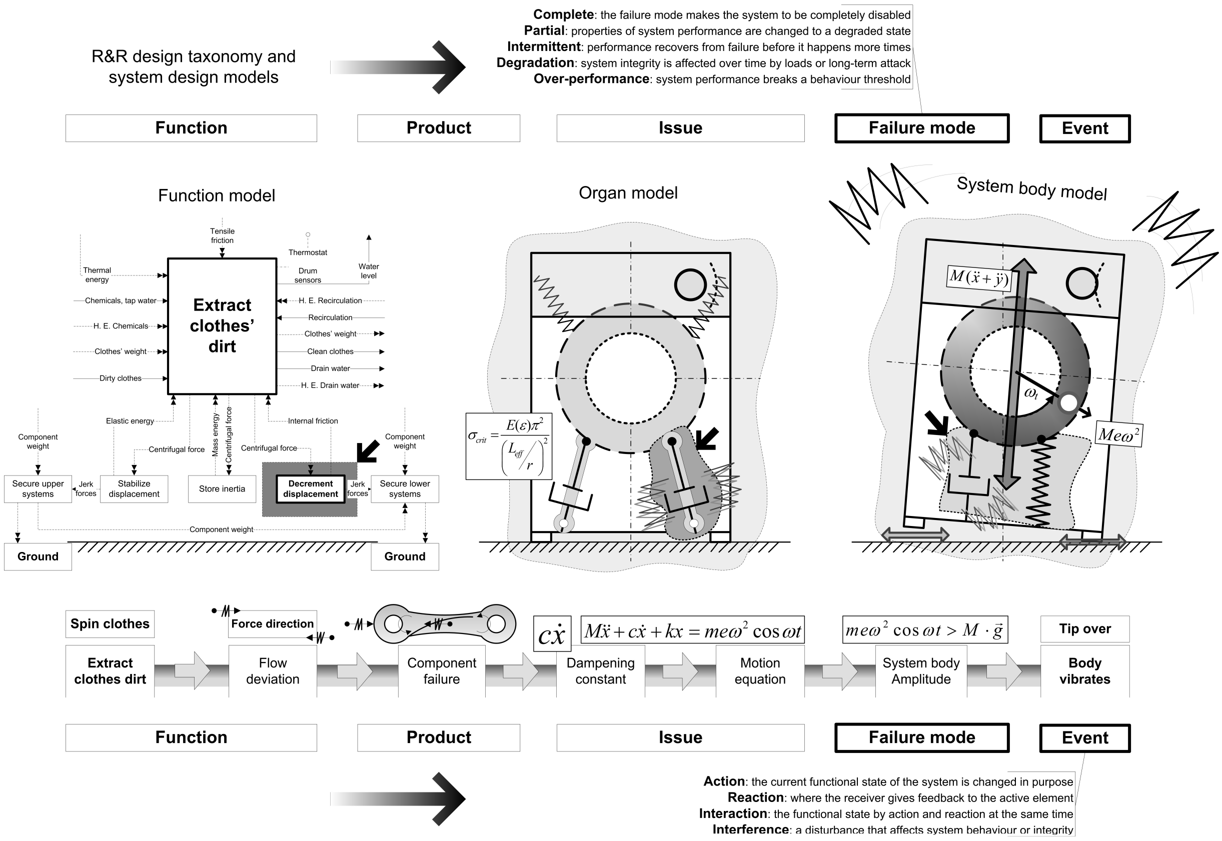


Figure 4. R&R taxonomy: main keywords in correspondence to system design models

Therefore, new keywords were developed in order to fill the gaps. Mechanical failure information is considered by a separate keyword because of its relevance in the research context. With redundancies found, a new classification on mechanical failure is proposed. The event concept is added as main keyword from the remaining information that did not fit to any of the other main keywords.

5.4 Tracing information demands from R&R methods to design models

This item aims to describe the information requirements of R&R methods throughout the analysis process. The assignment of metrics is made on the design information acquired from the system descriptions such as shown in Figure 3 and Figure 4. The squares in the table indicate the level of detail of product information, classified under the R&R taxonomy, which corresponds to information requirements from elements in R&R methods according to the information structures in Figure 2.

Design information is classified in detail, where system models on function, organ and body represent conceptual, embodiment and detailed design input, respectively. The subunits are positioned in rows and mapped to information units from R&R methods, assigned to columns. The mapping of information demands is shown in the Table 2 with letters indicating its availability on design stages.

Table 2. Information requirements for the R&R assessment methods

Information availability
- ■ Concept design
- E Embodiment design
- d Detail design

R&R Taxonomy	R&R methods	FTA: 1. Gates			2. System_ev			3. Primary_ev			FMEA: 4. System			5. Failure			6. Analysis			HAZOP: 7. D. Intent				8. Operability			9. Diagnostics			
		Gate OR	Gate AND	Gate INHIBIT	Top event	System event	Component event	External event	Conditional event	Basic event	Identification	Function	Component item	Operation mode	Failure mode	Failure effects	Failure detection	Severity class	Provisions	Flow element	Activity	Source	Destination	Guide word	Element	Deviation	Consequences	Action required	Causes	Safeguards
Function	Function	■	■	■	■	■	E	■	E	E	■	■	E	■	■	■	E	E	E	■	■	■	■	■	E	E	E	■	E	E
	Flow	■	E	E	■	■	E	E	E	d	■	■	E	■	E	E	E	d	d	■	■	E	E	E	E	d	d	E	E	d
Product	Component	■	E	E	■	E	E	E	■	E	■	■	E	■	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
	Interface	E	E	d	E	E	E	E	E	d	■	■	E	E	E	d	E	d	d	E	E	E	E	E	d	d	d	E	d	d
	Geometry	d	d	d	E	d	d	E	d	d	■	E	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
Issue	Environment	■	■	E	■	■	■	■	■	E	■	■	■	■	E	E	E	d	E	■	E	E	E	■	■	E	E	E	E	E
	Requirement	■	■	E	■	■	E	E	E	E	■	■	■	■	E	E	E	E	E	■	■	E	E	■	E	E	E	E	E	d
	Characteristic	E		d	E	E	d	E	d	d	■	E	E	E	d	d	d	d	d	E	E	d	d	E	E	d	d	d	d	d
Failure Mode	Complete	■	■	E	■	■	■	E	E	E	■	■	■	■	E	E	■	E	E	■	■	■	■	E	■	E	E	E	E	E
	Over-performance	■	E	d	■	E	E	E	E	E	■	E	E	E	E	E	E	E	d	■	■	■	■	E	E	E	E	E	E	d
	Intermittent	E	d	d	E	E	d	E	d	d	E	E	E	E	E	E	E		E	■	E	E	E	E	E	d	E	E	E	E
	Partial	E	E	d	E	E	E	E	E	d	E	■	E	E	d	d	E	d	d	■	E	E	E	E	E	d	d	E	d	d
	Degradation	E	E	E	■	d	d	d	d	d	E	E	d	d	d	d	d	d	d	■	E	E	E	E	d	d	d	E	d	d
Event	Action	■	■	■	■	■	■	■	E	■	■	■	■	■	E	E	E	E	E	■	■	■	■	■	■	E	E	d	E	E
	Disturbance	■	■	■	E	E	E	E	E	E	■	■	■	E	E	E	E	d	d	■	■	■	■	■	E	E	E	E	E	d
	Reaction	E	E	E	E	E	d	E	d	d	■	■	E	E	d	d	d	d	d	■	E	E	E	E	E	d	d	d	d	d
	Interaction	E	d	d	E	E	d	E	d	d	E	E	E	d	d	d	d	d	d	■	E	E	E	E	d	d	E	d	d	d

OBS: Numbers refer to information structure group divisions, as indicated in Figure 2

Black squares indicate the information is readily available with function models; grey squares indicate embodiment design information is required (represented by organ models); and, white squares indicate detailed design characteristics are needed to meet the information requirement of a given filed from R&R methods.

The information demands from FTA show the method requires functions to be considered system-wide, and then developed with progressive detail to link with component problems. Relevant requirements from FTA are:

- Top and intermediate events require action events and environment characteristics to be related with functions, which is feasible with early design models;
- Gates AND and INHIBIT require events to be understood as reactions and interactions, whose information is not readily usable with early design models; and,
- Basic events require product geometry and interaction events to be assigned and related to failure modes, information only available with detailed design representations.

FMEA requirements are primarily defined by the focus of the tool on system components. The FMEA analyses consider each component as an individual issue, which may manifest by different failure modes. Relevant FMEA characteristics are:

- System information in general and operation modes can be identified and set with function definitions and knowledge of complete failures, which is available in early models;
- Much about all other types of failure mode requires system models to provide at least information at the embodiment design level; and,
- Analysis fields such as provision, severity class and failure detection require degradation failure and product geometry to be described, requiring most design detail.

The results from HAZOP show emphasis in the link between function and flow parameters. HAZOP enables early identification of failure modes and events with early models, earlier than other methods HAZOP characteristics on this study are:

- Functions and flows bring significant input to describing the design intent and therefore to approach the operability problem;

- Design intent and operability fields are significantly accessible with intermediate design models, where mitigation requirements can also be established; and,
- While all fields require detailed information in product geometry and characteristics, deviations and safeguards are the most difficult to make clear;

6. Conclusions and future work

By carrying out a pilot case study with a reverse engineering approach, information requirements to R&R methods were assessed. R&R methods were decomposed in information units; graphic descriptions were organized onto system models; and, text descriptions into keyword data. System models and keywords were associated to existing taxonomies supporting R&R-specific classification.

Scoping information such as FTA system events, FMEA system description and HAZOP design intent are readily available with early design models. However, fundamental information such as FTA gates, FMEA effects, and HAZOP deviations is linked to product characteristics, and hence appears only in intermediate/detailed system models.

That means current methods can be initiated in early design stages, but cannot be concluded without significant effort in developing embodiment and detailed design information. The R&R taxonomy could support classifying available design information at early stages orienting new, specific R&R assessment techniques to concept designs.

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