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INFLUENCE OF DESIGN EVALUATIONS ON DECISION-MAKING AND FEEDBACK DURING CONCEPT DEVELOPMENT

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ABSTRACT

This paper aims to understand the following issues: how design flaws motivate the rejection of alternatives, and how they influence design feedback. A longitudinal, descriptive case study was carried out following the generation, evaluation and selection of design alternatives generated over two and a half years, with the following results: the lack of R3 evaluations during early design stages is confirmed; causes of rejection of earlier alternatives are repeated in later designs due to reusing working principles; and, design feedback lacks clarity in early stages, stated in a generic manner when present. Recommendations are given to capture designers' preferences and insight to address robustness and reliability in early stages, and to use this knowledge in order to support these attributes by prodding designers to propose countermeasures.

Keywords: Concept development, design evaluation, decision-making, design feedback

1. INTRODUCTION

Key design characteristics are established during early design stages, which determine the fitness and dependability of the intended solution to the market. These phases offer more room to decision-making [1], and development activities in these stages lead to more effective solutions that enhance the competitiveness of the manufacturing organization. Among other objectives, robustness and reliability stand out as critical goals companies need to achieve. As consequence, keeping good reputation will make customers to prefer their products. If approaches and methods to assessing reliability, robustness and safety (R3) issues require significant amount of data and expertise [2], there is need to know how designers address the challenge. This paper aims to evolve the issue of R3 considerations in early design stages by studying how they are assessed in an actual project. Following concept development activities in industry, a two-and-a-half-year longitudinal case study incorporates the role of the industry context in shaping how R3 issues are addressed in early design stages.

2. BACKGROUND

Models, methods and practice in conceptual design

<u>Models</u>: they are used for several purposes, from visualizing solution configurations up to prescribing how solutions should work [3]. Functional modelling decomposes an overall function into chains of energy, material and information flows [4]. Organ modelling can describe components and their links by sketches [5] or flow-charts [6]. Together with these methods, taxonomies aim to separate and structure design issues in manageable sets. Mechanical connections [4], design information [7], and robustness strategies [8] constitute examples supporting the elicitation of design issues.

<u>Methods</u>: they embed design knowledge in form of principles that constitute basis for opportunistic design [9]. The argument of design principles has been developed with focus on robustness and reliability for mechanism design, comprising guidelines for use at the conceptual, embodiment and detailed design stages [10]. Methods can also prompt designers to think systematically about problems, and offer opportunities to spot and communicate design flaws. Some have become widely used in industry with international standards available [11, 12, 13]. Others have their use restricted to designing, operating and maintaining large-scale systems with inherent technical risk [24, 25].

Practice: it may provide a generic overview on the design process [4] or can emphasize different views on the engineering design activity: managing as a nesting, multi-faceted set of activities [17]; and providing guidance on methodologies dealing with variation [16]. Such references evaluate options for design practice against technical risks, and assess its suitability to design cases and phases by the means of expert opinion [16]. Risk management is also a concern as a supporting process towards the best possible outcome from design [2].

Development management on conceptual design

Integrated multi-disciplinary development: Along with product development management, product design considerations had to change in order to accommodate new competitive needs. Multiple-technology and multi-domain designs, and the need for their fast integration, have given birth to product architecture considerations [18]. Modularity has particular importance, because it influences development management, design flexibility and product performance [19]. Also, overarching approaches to quality and robustness were developed to reconcile needs of management with design performance requirements [20, 16]. This body of knowledge shows the design process as a multi-faceted activity, with many parallel and nesting sub-processes underway [17].

Continuous learning and experimentation: the choice of simulation or prototyping for experimentation is influenced by factors such as simulation realism, cost of prototype-building, and information to correcting errors. Expensive prototype-building, risk-sensitive designs and complex error correction processes influence the need for increased simulation and increased headcount to screen design errors and reject bad designs [21]. More expensive test procedures and difficulties in fitting test conditions to design requirements will make parallel testing less attractive. Integrated, tight-packed architectures are more likely to require sequential and iterative testing that increases and improves learning. However, parallel testing on different alternatives will provide more options to choose the best design [22].

Concurrent and continuous engineering feedback: problem-solving cycles were made overlapping by early information exchange between engineers and smaller innovation leaps [23]; design lifecycle stakeholders were included in development tasks in multidisciplinary team management strategies in contrast to their absence in traditional practices [24]. Set-based development follows three basic principles: design feedback is anticipated and carried out as a continuous process since early design stages; designs for different subsystems and development stages are continuously fine-tuned and fit to each other up to a late design freeze; and, the development process includes continuous verification of mutual and conflicting constraints for adjustment [25].

Decision-making and feedback practice

Decision-making depends fundamentally on the set of values carrying the preferences of those involved in making the decision [26]. An experiment on decision-making has assessed the influence of time, methods and behaviour, obtaining the following respective results: relative importance of criteria was assigned short time; formal methods did not influence to the explicit justification of evaluation; and behaviour has not involved the production of thorough documentation [27].

Feedback is seen as neglected in design organizations, because of four main problems: neglecting previous outcomes; design-related errors are repeated; unreliability of feedback from outside; and the mostly negative nature of feedback received by engineers. [28]. Nevertheless, it is significant for learning from failure in design and preventing it by innovation. Besides that: successful correction of design flaws depends on the involvement of designers, and on evidence from warranty claims and/or testing; mechatronic (integration) problems are more often successfully corrected; and, flawed original designs are more often corrected successfully than adaptive ones. Effective cross-project communication and knowledge management should guide designers towards better solutions [29, 30].

3. RESEARCH METHOD

This work consists of an investigation about improving the ability to manage technical risks during early design phases. R3 methods would not be completed this scope because the information they need needs to be drawn from detailed design models [31]. In response to that, our aim is to investigate the following processes in industry: how design flaws motivate the rejection of alternatives, and how they influence design feedback. That will help to find ways to improve the management of technical risks by focusing R3 attributes in early stages.

This study deals with a mechatronic, precision-mechanics medical device. It is a performance-critical system, especially on R3 issues, due to life-threatening implications from failure and performance fluctuations on blood sugar concentration. The case study approach [32] involved analyzing concept design information generated over two and a half years within a product development project of an insulin injection pen, as shown in Figure 1. Timelines are shown in four layers: the product development timeline at the company, the product development stages [33], the stages of executing the case study, and, the timeline of collecting data from documentation and interviews. The study was started by March 2009 and finished by April 2010, with a timeline of information from December 2005 to March 2009. Deliverables to this paper are represented by R1 (concept development), R2 (rev. engineering plus design decisions) and R3 (rev. engineering plus technical risk management).

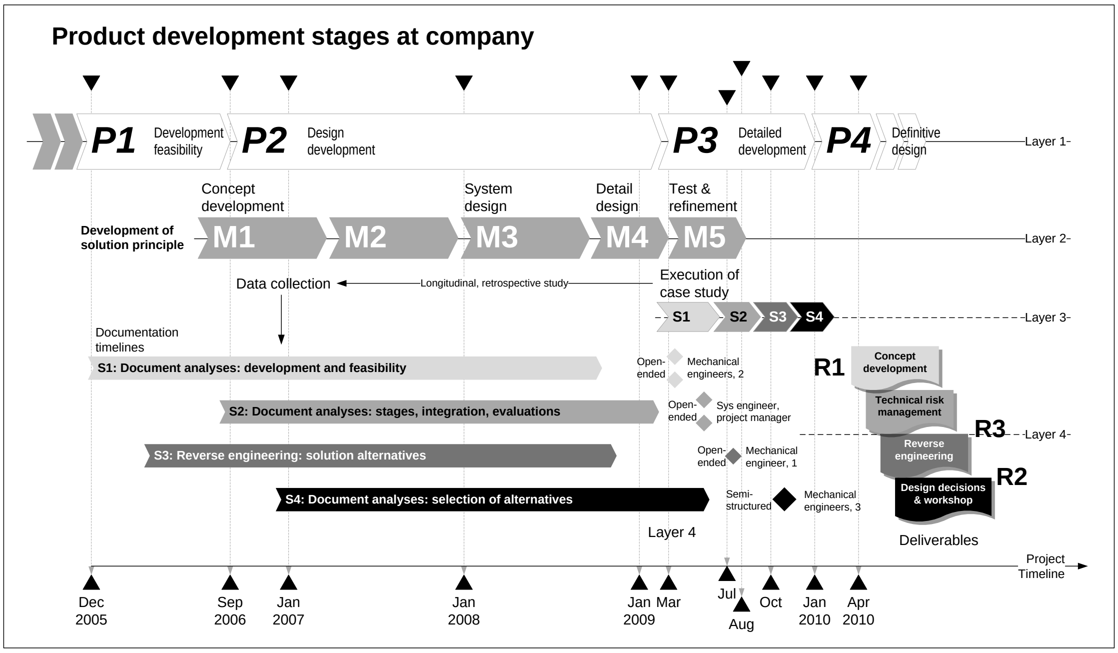

Figure 1 – Timeline of industrial case study

The execution of the case study is characterized in five elements as shown in Table 1. General characteristics of the case describe the involvement of the researcher and the conditions of study; document analyses describe evidences collected from project documentation with relevant information; reverse engineering describes characteristics of design alternatives that were relevant for the findings, interviews describe the approach used, the participants and their roles in the project, and the use of mediation and media to record information; modelling and representation describes relevant characteristics of findings represented in this paper. Document analyses, reverse engineering, and modelling and representation are also situated in relationship to interviews.

Table 1 – Research approach for industrial case study

Characteristics	Doc. analyses	Rev. engineering	Interviews	Modelling/represent
Case executed with actual project	17 partial/closure stage presentations	4 sketch sessions of work principles	5x open-ended on R3 development issues	9 function modules in all alternatives
Researcher observes project	5 technical risk stage reviews	20 alternatives of solution (concepts)	3 mechanical engineers, 1 system engineer and project manager	Several overview and close-up screenshots of alternatives
Longitudinal and retrospective study	14 feasibility reports on features	50 CAD variants with small changes	Not mediated, with video records. (45min each)	3 sequential/timeline development graphs
Comprehensive study of situation	4 matrices about set-based dev.	9 modules in system formulation	3x semi-structured on concept selection decisions	Total of 50 failure occurrences to reject
36 months from sketch to solution	Several reports from evaluations	61 work principles in all alternatives	Mechanical engineers: 2 veteran, 1 expert; Risk specialist	Total of 47 mentions to technical risks
Lead time launch in 6 to 8 years	Validated by interviews	Associated to interviews	Specialist as mediator, with video records (60 min each)	Developed upon interviews

The work has been carried out in a retrospective and longitudinal approach to the design process, fitting into a descriptive study approach [34]. Document analyses were carried out through the whole case, to understand when concepts were generated, which models were developed, which issues took place and when concepts were discarded. Reverse engineering [35] was used to identify the functions performed by design alternatives, their working principles [36, 37] and similarity between these. The project team was composed by the project manager, three mechanical designers (two veterans), one risk specialist, and three electronics engineers (one veteran). Open-ended interviews were carried out with all mechanical designers, one system engineer and the project manager. Semi-structured interviews were carried out with mechanical designers only. Questions asked to interviewees focused two types of issues: challenges and measures to manage technical risk (open-ended), and the rationale for selecting and rejecting design alternatives (semi-structured), to guide the search for information and validate the findings from documentation and reverse engineering, respectively

4. RESULTS

The study was carried out with support of system-related methodologies to undertake analysis and evaluation at a system level with the following considerations on concept development:

R1: Concept development timeline: this item represents the concept development process as found in industry, in the following aspects: the use of design models, their levels of detail and concreteness; the following milestones represent the development of alternatives: start, stand-by, reject, pass to detailed, reject detailed and change to solution principle; dashed lines identify occasions when R3 methods are used: to evaluate and select; to refine and select; and, to asses risk.

R2: Influence of procedure on failure modes: this item shows failure modes that motivated the rejection of design alternatives. These are identified as: primary failure modes explicit in documentation; and secondary failure modes found by validating rev. engineering with interviews; failure modes repeated due to reusing working principles from earlier alternatives that were rejected are identified with dashed hooks linking earlier and later occurrences.

R3: Technical risk feedback from failure modes: this item describes design feedback issues mentioned by designers, which denote design attributes that need to be improved in further alternatives. Issues are tracked down on when they appear and how their ranking changes throughout the stages of concept development. They are also characterized on whether they become most critical or least critical considering design attributes analyzed in design alternatives.

R1: Concept development timeline and methods

In early stages, only two alternatives were put on hold during development, all others to AS3 being rejected. Comparison matrices of alternatives (Cn) were the method of choice for early stages (milestones 1 to 4) along with others: a safety-focused product benchmarking (P1); feasibility analyses (Fn) up to milestone 3; and an assessment of the influence of working principles to sensors (T1). The last set-based comparison (S4) was performed along with a tolerance-based evaluation of alternatives (E1) and a Pugh matrix supported by comprehensive discussion (R1). As result, 4 further alternatives were generated and passed to proceed with system design. Later milestones were carried out to evaluate and refine the remaining alternatives. Milestones 5 and 6 involved conceptual DFMAs (Dn) to evaluate integration and production issues, and a further performance evaluation (E2). In milestones 7 and 8, math-based and FEA simulations (Q1, Q2) were performed along preliminary hazard analyses and introductory HAZOP (H1, H2). Only two system design alternatives were further developed to detailed design, so that a single solution principle was generated. Milestone 9 involved team-based evaluations with standard R3 methods: a linked HAZOP + FTA (H3) and a thorough FMECA (H4).

Figure 2 shows the concept development timeline. The developed alternatives are shown in the vertical axis, with the design stages shown in the horizontal axis along with available models throughout concept development. The legend in the figure indicates the development states of alternatives and the milestones of alternatives being rejected, put on hold and passed. Evaluation milestones, indicated by filled triangles along models providing design data, show when R3 methods, indicated in hollow inverted triangles were performed during the project. As result, 8 evaluations are performed on 14 alternatives, while the other 6 are evaluated with 12 instances. That the lack of R3 evaluations during early design stages, a problem this paper aims to explore with further detail.

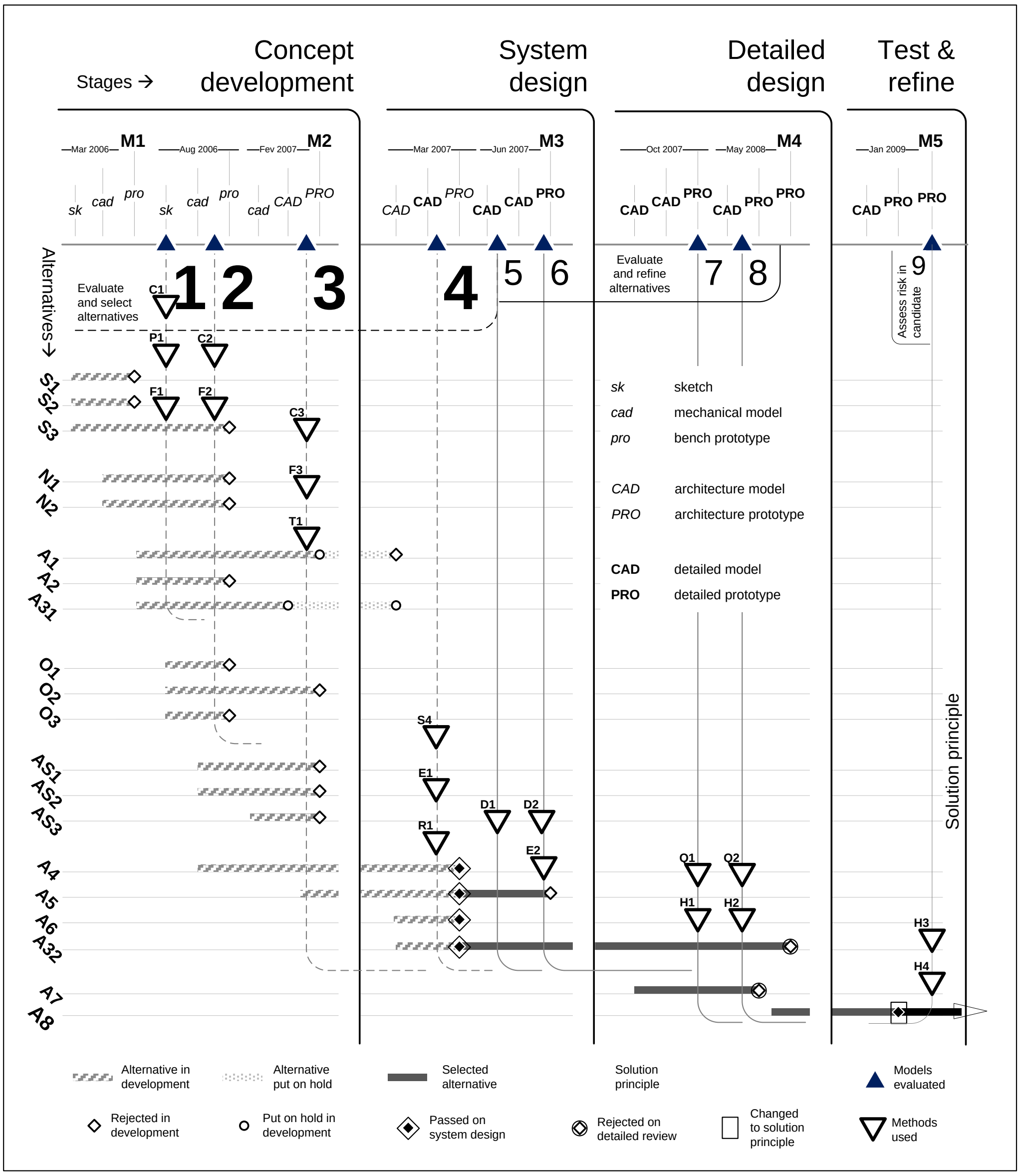

Figure 2 – Concept development timeline

R2: Influence of methods on the identification of failure modes

Milestones 1 to 4 emphasized design feasibility and confidence in meeting requirements, supported by brief tests on design models. A prescriptive use state diagram constituted the single instance of hierarchical or function/flow-based system representation found among documents. Alternatives from very early stages, up to A31, are affected by the following causes of rejection: 5 safety failures (one primary), 4 reliability failures (one primary), 7 robustness failures, and 4 integration failures. The following patterns are detected: a single secondary cause of rejection occurs several times (backlash) without association to working principle; a single primary cause of rejection occurs several times due to reusing similar interfaces; and a single cause for rejection has repeated occurrences with reusing the working principle. Safety failures were diverse, while robustness, reliability and integration failures were mostly due to the same problems.

Figure 3 shows the failure modes in design alternatives, which are assigned where they occurred and categorized on the design attributes affected. Alternatives are shown in the horizontal axis, with failures to rejection categorized on design attributes in the vertical. Design alternatives from early stages up to A32 are affected by: 8 safety failures, 8 reliability failures, 5 robustness failures and 4 integration failures. The following patterns are detected: two primary causes of rejection (safety) are repeated at least once due to reusing the same working principles; three secondary causes of rejection have the same problem of reusing the same working principles; and two other secondary causes for rejection occur several times without association to working principle.

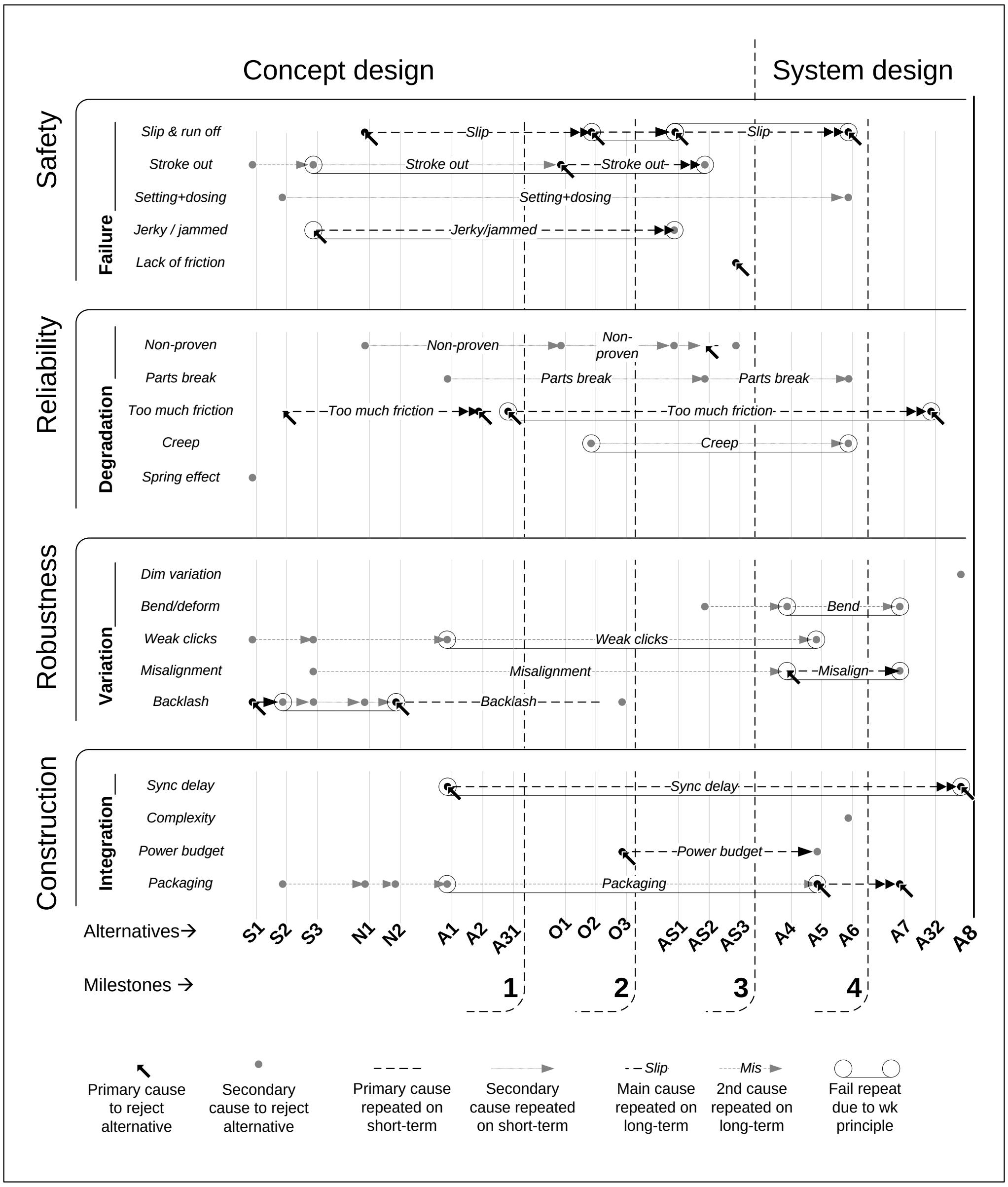

Figure 3 – Failure modes causing design alternatives to be rejected

Several failures affect all attributes considered, with reliability failures occurring more often on functionality (non-proven) and integrity (parts break) concerns. Along with safety, it becomes a primary cause of rejections due to many repeated occurrences with link to working principles. Other earlier robustness failures are repeated without link to working principles. As result, causes of rejection of earlier alternatives are repeated in later designs due to reusing working principles throughout design iterations. That is due to current R3 methods lacking support to identify and pinpoint problems without evidence from detailed embodiments.

R3: Technical risk feedback from failure modes

Figure 4 shows the project stages in the horizontal axis, and the issues of concern to design attributes in the vertical axis. Arrows show how these issue groups evolved through concept development, on whether the issue has become more important (continuous double arrow), less important (long-dashed single arrow) or kept the same rank (short-dashed single arrow). In the earliest stage (M2), robustness issues were the most important. Feasibility was given a score of 4, with additional two points for the ‘not ready’ issue. Integration (5 points) and reliability (4 points) were also considered relevant. No safety concern was found in that stage. Feasibility is the most important concern, reflecting the need for a solution that can embody all expected functions. Reliability also needs development because there is uncertainty on how the expected functionalities will be embodied. Safety is a missing concern due to the lack of evidence on harmful performance.

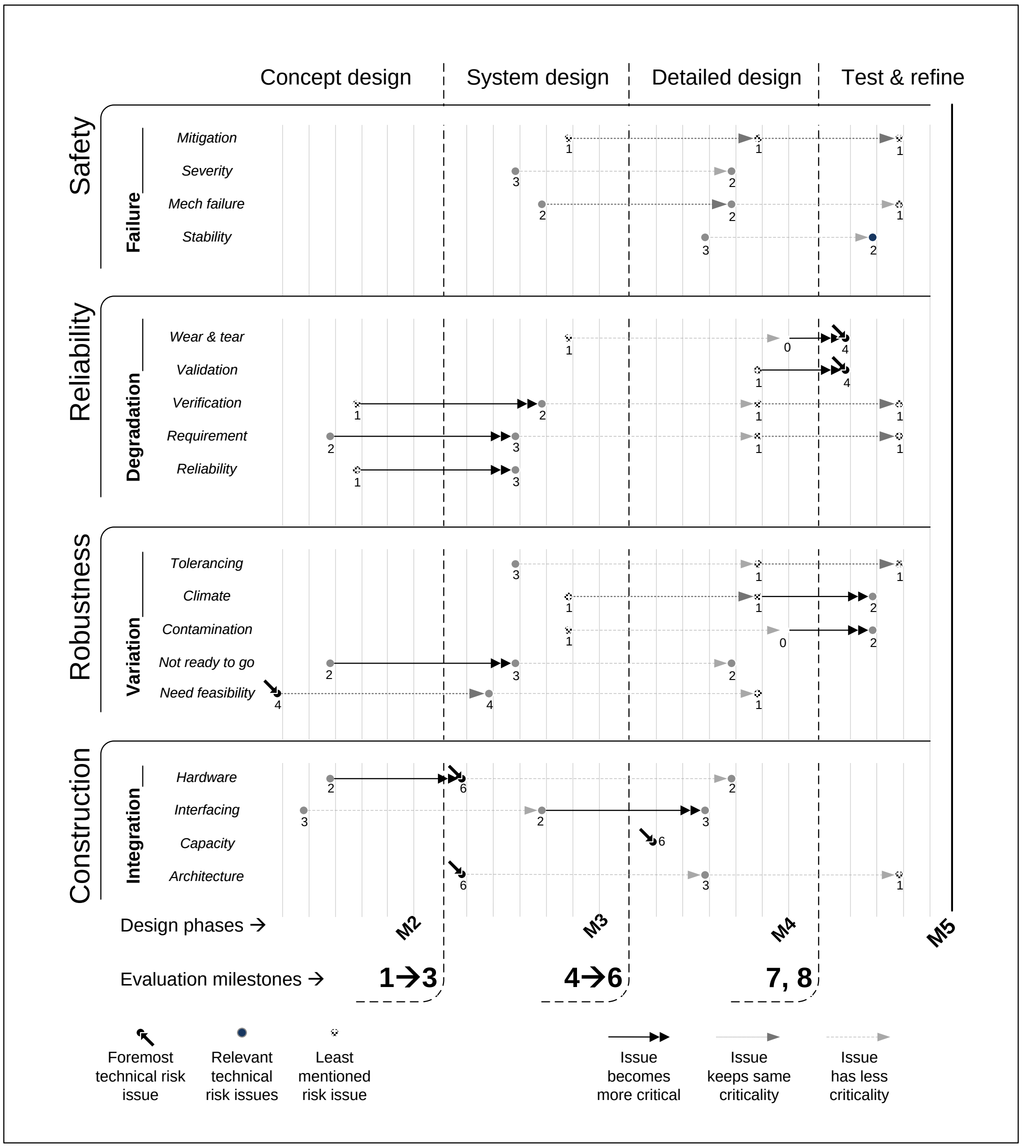

Figure 4 – Design feedback on technical risk issues and their behaviour over development

By the following stage, with alternatives undergoing R1 evaluation, integration issues were brought to the top (14 points). Robustness is the second relevant concern in this phase, with 12 points. The importance of reliability concerns increases in this stage (9 points). And safety concerns appear for the first time (6 points). System architecture is a new relevant concern in integration. The appearance of environmental factors causes renewed interest on robustness. Reliability is increasingly related to verification of requirements, with consciousness about wear and tear. Safety concerns first appear on the availability of evidence about harmful effects of performance.

Stage M4 increases focus on integration (14 points on capacity and interfacing), with robustness (4 points) and reliability (3 points) demoted. Safety grows in importance with new stability concerns (8 points); and stage M5 sees integration issues mostly solved (1 point), with renewed interest on robustness (5 points) and significant focus on reliability (10 points) with focus on long-term performance and its verification. Safety is demoted, with 3 points in the last stage.

Feedback on safety is absent in early stages, and appears only during system design, with increase in robustness and reliability. Design feedback issues were mostly found in early alternatives, as component-related generic attributes/problems that do not clearly indicate how to pinpoint and solve them. These conclusions confirm the lack of clarity of design feedback in early stages, due to the lack of resources that express enough knowledge to indicate strategies and measures to locate and solve the failure modes occurring in early concepts.

5. DISCUSSION

This section aims to discuss these results in the light of current knowledge and experiences. R3 methods were used to characterize design alternatives against perception, insight and preference of designers. They could identify failure modes quite early due to an all-out prototyping strategy on low prototype costs. However, causes of rejection of earlier alternatives are repeated in later designs due to reusing working principles throughout design iterations. Motivations and causes for feedback issues are not specified in the project, and issues are characterized as component + issue tags. Similar studies in literature constitute basis for comparison, as shown in Table 2.

Table 2 – Implications from results in this study and other industries

Industry/ref.	**Medical [this]**	**Automotive [25,37]**	**Oil & Gas [28]**	**Chemical [17]**
Size, no. parts	Small, n x 10^1	Medium, n x 10^3	Large, n x 10^4	Large, n x 10^2
Complexity	Low	High	High	High
R3 dependency	High	Medium	High	High
Focus area	Eng. Design, DFx R3	Product development	Eng. design, safety	Eng. design, process
Duration	36 months	6 months (interviews)	6 months (interviews)	38 months
Methods and frameworks to R3 issues	Lack of R3 methods to novel concepts; current tools based upon insight and perception.	Current R3 methods and frameworks [16] support adaptive designs; lack of support to novel designs	Current R3 methods work on front-end engineering; new tech needs experimentation	Weak spot techniques as in earlier editions of [4], insight on divergence and convergence
Available models with evidence	Bench CADs and prototypes in early stages; detailed models from system design	Same approach as in our case, with early body models supporting plans for further stages	Detailed CAD models, math-based simulations of partial structures, equipment	Overview schematics, CAD drawings with relevant assembly components
Architecture strategy of development	Integrated modular architecture from 2nd iteration; models with all functions	Platform and modular architecture from onset, several modules linked by common connections	Single modular architecture tailored for each customer, models with some functions	Integrated architecture, custom reactor vessel surrounded by on-shelf components
Evaluation and testing of alternatives	Brief tests on generic parameters, working principles earliest evaluated on tolerances	Single-domain (FEA) tests on partial modules linked by reciprocity on boundary conditions	Single- and multi-domain simulations on partial modules linked by reciprocal conditions	Math calculations and simulation of design parameters, components on individual factors
Sources and criteria for decision	Brief reviews performed by the team, criteria defined by interpretation of customer needs	Detailed reviews with FMEA-like approach, criteria from detailed trade-off analyses	Hazard identification and probabilistic risk assessments with network models, FEA	Morphological matrices, criteria defined by overall design requirements
Feedback mechanism on selection	Communicated mostly in generic terms, pursuit of further alternatives by exploring issues	Communicated mostly in generic terms, pursuit of further alternatives by exploring issues	Specific feedback on the single module tested, change/adaptation is then pursued	Design frozen after conceptual design, changes on individual issues upon embodiment
Discussion of results	**System approach to pinpoint problems, knowledge reuse needed to focus intended outcome**	**System/platform in use, supported by KBE: no alternative for early stages/new technologies**	**System approach with probabilistic methods, knowledge transfer needs development**	**Functions are carried/ represented by parts, no option to reuse/transfer knowledge**

In other examples as shown in the previous table, mass volume manufacturers appeal to standardizing technologies; automotive and oil&gas industries use modular architectures from the onset, to decompose work packages and to add flexibility against R3 issues. Most sectors use simulations like FEA and CFD on partial modules, coupled by common boundary conditions. And feedback is mostly given in an informal manner, without capturing knowledge to further alternatives and/or projects.

The following circumstances should also be acknowledged: Oil&gas and chemical industries do not build and iterate design alternatives as in set-based development; and these sectors plus automotive also use historical data and Monte Carlo inputs to carry out non-deterministic risk assessments on detailed FEA and network models. However, these resources cannot be used to approach novel problems from the onset, which was our case. Design principles could be used as alternative, but they are too context-specific and do not solve the need to share design knowledge to get innovations accepted. In response to such needs, knowledge transfer and reuse should be the best resources assisting early design stages, because there is not enough evidence and/or data to use probabilistic network models of FEA simulations to solve R3 issues.

6. CONCLUSIONS AND FUTURE WORK

This paper aimed at understanding the following issues in conceptual design: diagnose of design flaws; how they influence design feedback; and how the issue can be improved in early design stages. The work has been carried out by the means of a longitudinal case study following the development of an insulin pen. Results were obtained in the following areas: the lack of R3 evaluations during early design stages is confirmed; causes of rejection of earlier alternatives are repeated in later designs due to reusing working principles; and, design feedback lacks clarity in early stages, stated in a generic manner when present. Recommendation is given to incorporate design insight and knowledge to any approach to support concept development. Future work involves developing a knowledge-based tool to help design decisions and feedback, and the validation of scenarios considering failure modes, benefits and countermeasures.

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REFERENCES

[1] Andreasen, M. M., and Olesen, J. (1990) “The concept of dispositions”, *Journal of Engineering Design*, 1(1) pp. 17-36.

[2] McMahon, C, and Busby, J. (2005) “Risk in the design process”, in Eckert, C., and Clarkson, J. (Eds.), *Design Process Improvement: a review of current practice*, pp.286-305, 2005, (Springer, London)

[3] Bonnema, G. M., Van Houten, F.J.A.M. (2006) “Use of models in conceptual design”, *Journal of Engineering Design*, 17(6), pp. 549-562, Taylor and Francis

[4] Pahl, G., Beitz, W., Feldhusen, J., Grote, K. H. (2007), “Engineering Design: A Systematic Approach”, Springer.

[5] Andreasen, M. M., Hansen, C. T., and Mortensen, N. H., (1995), “On structure and structuring”, *Workshop Fertigungsgerechtes Konstruieren*, Anonymous .

[6] Harlou, U., (2006), “Developing Product Families Based on Architectures: Contribution to a Theory of Product Families”, *Ph. D. Thesis,* Department of Mech. Engineering, Technical University of Denmark.

[7] Ahmed, S. (2005) “Encouraging reuse of design knowledge: a method to index knowledge”, Design Studies, 26, pp. 565-592, Elsevier.

[8] Jugulum, R., Frey, D.D. (2007) “Toward a taxonomy of concept designs for improved robustness”, Journal of Engineering Design, 18(2), pp. 139-156, Taylor and Francis.

[9] French, M.J. (1992) “The opportunistic route and the role of design principles”, *Research in Engineering Design*, 4, pp. 185-190, Springer.

[10] Matthiassen, B. (1997) “Design for Robustness and Reliability”, *Ph. D. Thesis*, Institute for Control and Engineering Design, Technical University of Denmark.

[11] BS EN 60812 (2006), “*Analysis techniques for system reliability – procedure for failure mode and effects analysis (FMEA)*”, British Standards Institution

[12] BS EN 61025 (2007), “*Fault tree analysis (FTA)*”, British Standards Institution

[13] BS IEC 61882 (2001), “*Hazard and operability studies (HAZOP studies) – application guide*”, British Standards Institution

[14] Kaplan, S., (1982), “Matrix Theory Formalism for Event Tree Analysis: Application to Nuclear-Risk Analysis”, *Risk Analysis*, 2(1) pp. 9-18.

[15] Duijm, N. J., (2008), “Safety-Barrier Diagrams”, *Proceedings of the Instn of Mech Engnrs, Part O: Journal of Risk and Reliability*, 222(3) pp. 439-448.

[16] Yang, K, El-Haik, B. (2006) “Design for Six Sigma: a roadmap for product development”, 2003, McGraw-Hill

[17] Hales, C. (1993) “Managing Engineering Design”, Longman

[18] Ulrich, K., (1995) “The role of product architecture in the manufacturing firm”, *Research Policy*, 24, pp. 419-440.

[19] Hölttä, K., Suh, E. S., De Weck, O. (2005) "Tradeoff between modularity and performance for engineered systems and products" in: *Proc. International Conference in Engineering Design, ICED '05,* Melbourne, The Design Society.

[20] Mørup, M. "Design for Quality" (1993) *Ph. D. Thesis*, 1993, Institute for Engineering Design, Technical University of Denmark.

[21] Thomke, S. (1998) "Managing experimentation in the design of new products", *Management Science,* 44(6), pp. 743-762, Institute for Operations Research.

[22] Loch, C.H., Terwiesch, C., Thonmke, S. (2001) "Parallel and sequential testing of design alternatives", *Management Science,* 45(5), pp. 663-678, , Institute for Operations Research.

[23] Clark, K. B, Fujimoto, T. (1989) "Lead time in automotive product development explaining the japanese advantage", *Journal of Engineering and Technology Management,* 6, pp. 25-58

[24] Takeuchi, H, Nonaka, I. (1986) "The new new product development game: stop running the relay race and take up rugby", *Harvard Business Review*, Jan-Feb, pp. 137-146.

[25] Sobek II, D.K., Ward, A.C., Liker, J.K. (1999) "Toyota's principles of set-based concurrent engineering", *Sloan Management Review*, Winter 1999, pp. 67-83, MIT Press.

[26] Hazelrigg, G.A. (2009) "The Cheshire cat on engineering design", *Quality and Reliability Engineering International*, 25, pp. 759-769, Wiley.

[27] Girod, M., Elliott, A.C., Burns, N.D., Wright, I.C. (2003) "Decision-making in conceptual engineering design: an empirical investigation" *Proc Instn Mech Engnrs Part B: J. Engineering Manufacture*, 217, pp. 1215-1228, IMechE.

[28] Busby, J.S. (1998) "The neglect of feedback in engineering design organizations", *Design Studies*, 19, pp. 103-117, Elsevier

[29] Gries, B., Gericke, K., Blessing, L. (2005) "How companies learn from design flaws: results from an empirical study of the german manufacturing industry" in: *Proc. International Conference in Engineering Design, ICED '05*, Melbourne, The Design Society.

[30] Gries, B. (2007) "Design flaws and quality-related feedback in product development" *Ph.D. Thesis*, Faculty of Transport and Machinery Systems, Technical University of Berlin.

[31] Marini, V.K., Restrepo, J., Ahmed, S. (2010) "Evaluation of information requirements of reliability methods in engineering design", In: *Proc. International Design Conference, DESIGN 2010*, Dubrovnik, University of Zagreb, The Design Society.

[32] Yin, R.K. (1994) "*Case study research: design and methods*", Sage Publications

[33] Ulrich, K. T., Eppinger, S.D. (2004) "*Product Design and Development*", McGraw-Hill

[33] Blessing, L.T.M., Chakrabarti, A. (2009) "*DRM, a design research methodology*", Springer.

[34] Otto, K. N., Wood, K. L. (1996) "A reverse engineering and redesign methodology for product evolution" In: DTM-1523, *Proc. ASME Design Engineering Technical Conferences DTM '96,* American Society of Mechanical Engineers

[35] Hirtz, J., Stone, R.B., McAdams, D. A., Szykman, S., Wood, K.L. (2002) "A functional basis for engineering design: reconciling and evolving previous efforts" *Research in Engineering Design*, 13, pp. 65-82, Springer.

[36] Stone, R.B., Wood, K. L., Crawford, R. H. (2000), "A heuristic method for identifying modules for product architectures", *Design Studies*, 21, pp. 5-31, Elsevier.

[37] Legardeur, J., Boujut, J. F., Tiger, H., (2010) "Lessons learned from an empirical study of the early design phases of an unfulfilled innovation", *Research in Engineering Design,* 21, pp. 249-262.

Definitions: **HAZOP**: Hazard and Operability Studies; **FTA**: Fault Tree Analysis;
FMECA: Failure Mode, Effects and Criticality Analysis
DFMA: Design for Manufacture and Assembly

It will be a pleasure to address your questions,

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