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DESIGN RESEARCH REFLECTIONS – 30 YEARS ON

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ABSTRACT

At ICED 83 in Copenhagen, we presented a paper describing the start of a large participant observation study in industry. That paper expressed our early views about the issues that needed to be addressed by design research. At ICED 85 in Hamburg we presented an interim report on the project, and at ICED 87 in Boston a summary of the final results. Subsequently one author continued to work in academic design research in the UK and the other moved into accident investigation in the USA. Looking back, it is interesting to reflect on what we learnt from our design research project and from design research in general. We observe that despite all the advances in design research, many engineering companies either ignore well-established methods or are unaware of them. We also observe there are many instances of failures to address the well-established engineering fundamentals in both practice and research. A particular engineering failure has been selected as an example, from many hundreds investigated, to highlight typical shortcomings, even in a long-established company that prides itself on its design capability.

Keywords: Design research, observational study, design methods, case study, forensic engineering

1 INTRODUCTION

In 1963 the need to improve the engineering design process in the UK was brought home in the Feilden Report [1]. It was emphasised that a deeper understanding of the design process was required, so academic researchers set to work, many trying to produce better models and more relevant design methods. A series of conferences on design methods was organized in the UK [2, 3, 4], and, unlike many modern engineering design conferences, these were well attended by representatives from industry. Several important books on engineering design were published at that time, for example Asimow's book in 1962 [5], the translation of Matousek's book in 1963 [6], and French's book in 1971 [7]. Interest in design research increased steadily during the 1970s and in 1977 the first edition of Pahl and Beitz's classic text *Konstruktionslehre* was published [8].

Successful design teams appear to achieve a balance in their overall execution of the design process through managing their activities carefully, applying the relevant design methods, and being sensitive to the particular context and all the influencing factors. Their experience allows them to assimilate and apply appropriately all the relevant engineering and non-engineering knowledge in order to achieve an effective and efficient design process that results in a successful outcome. One area of design research is to study designers and design teams, both successful and unsuccessful, in order to improve our understanding of their procedures and thus identify good practices that can be transferred as models and methods to other design teams to help them improve their performances. In 1979 Gregory published a review paper entitled *What We Know About Designing and How We Know It* in which he listed 32 observation-based studies of the design process [9]. Our own interest in such a study started in 1978 when one of us (supervisor) became a Lecturer in Engineering Design at the University of Cambridge, where there existed a culture of encouraging engineering design education and research. The project started in 1982, when the other of us (researcher), having completed a Masters in Engineering Design at Loughborough University followed by six years designing high-pressure vessel systems in Chicago, decided to undertake research towards what would become the first PhD in the field of engineering design theory at Cambridge. It was clear to both of us that much more was known and published about good engineering design practice than was being applied in industry. Our research addressed the following questions:

- How can engineering design methods be introduced into the normal working pattern of a design team operating in industry?
- Once adopted, do engineering design methods improve the effectiveness of the team using them?

2 ICED 83 – BEGINNING OF OUR RESEARCH PROJECT

In our ICED 83 paper [10] we wrote: “There is general agreement that the effectiveness of the engineering design process is in need of continual improvement in order to match the needs of an increasingly complex world. It is also evident that direct application of design methods or procedures based on developed models does not in itself ensure effective performance. There are many other influencing factors involved and it is the delicate, continually varying balance of all the factors within the overall design activity that determines the outcome of a venture.” We were interested in identifying these influencing factors.

We were convinced that design research needed to blend the approaches adopted in the physical sciences and the social sciences. After a multidisciplinary literature review it was decided to undertake an observational study in industry that would address three areas: the application of design methods; the management of the design process; and the psychological aspects of designing. The project was viewed as a *pilot* with the aim of gathering as much data as possible about a complex design project in industry and then seeing what patterns might emerge from the data and what insights might be gained from those patterns. There was no initial hypothesis. We hoped to set a benchmark that could be critically reviewed and improved upon by other design researchers. The plan was to share the data gathered with other researchers, hoping for answers to questions such as: If you do not think we collected the right data, what data would you have gathered? If you do not agree with our analyses, how would you have done them? Is this type of empirical research the right way to proceed to gain new insights into the engineering design process, if not is there a better way? We were fully aware of the limited conclusions one can draw from a single observational study, which may be far from representative or typical, but concluded that participant observation would contribute to a better identification and understanding of the influencing factors critical to the effectiveness of engineering design.

A design project in industry was needed. The Research Division of British Gas was about to design a slagging coal gasifier test rig. This was a one-off design to undertake experiments on coal at very high temperatures and pressures. In engineering terms it was of medium size and technically challenging. The design process was expected to take three years. The project matched the researcher’s previous design and management experience, so British Gas agreed to fund the research and to allow participant observation of the project in return for the researcher’s design expertise.

We needed an organising framework. This goes somewhat against the idea expressed above of having no preconceived hypothesis or pattern, but design research has to start somewhere and be pragmatic, so some compromises are necessary. The translation and editing of Pahl and Beitz’s *Konstruktionslehre* [8] by the supervisor was nearing completion. It was considered to be one of the most comprehensive texts on the engineering design process, so it was selected to provide the organising framework. The first English edition appeared as *Engineering Design: A Systematic Approach* in 1984 [11]. We were keen to try out this approach on a real project in industry and to observe what happened.

3 ICED 85 – MIDDLE OF OUR RESEARCH PROJECT

By the time of ICED 85 in Hamburg the project was over half-way through, so our paper [12] presented a mid-term assessment on the progress made. The gasifier test rig had passed through the Task Clarification, Conceptual Design and Embodiment Design Phases and the researcher had:

- continuously captured detailed case history data
- developed a structure for categorising the raw data
- analysed the data to try and identify the influencing factors that contribute to the successful application of design methods
- used the data to test some propositions put forward in the design research literature.

The complexity of design research and the challenges of undertaking observational studies were becoming apparent. Apart from the huge volume of data that was collected, issues arose in the following two areas:

- finding a comprehensive model of the design process that showed all the influencing factors
- identifying and linking the many disciplines that impinged on the engineering design process.

Many excellent models of the design process existed, each adopting a slightly different point of view. Most included a similar set of phases and steps, along with inputs and outputs, to varying degrees of detail. However, none enabled us to map all the aspects of the design process that were emerging from the data collected. We needed a model that adopted a broader view, namely one that:

- combined the ‘designed system’ and the ‘human activity system’ within an industrial context
- was relevant to other disciplines
- showed different levels of resolution with a coherent structure
- complemented existing models and used accepted terminology
- showed major influences on the design process and their interactions.

A preliminary version of our model was presented in the 1985 paper [12]. This was later developed and the final version, see Figure 1, appeared in *Managing Engineering Design* [13]. Looking back, it is surprising just how long it took to develop this model.

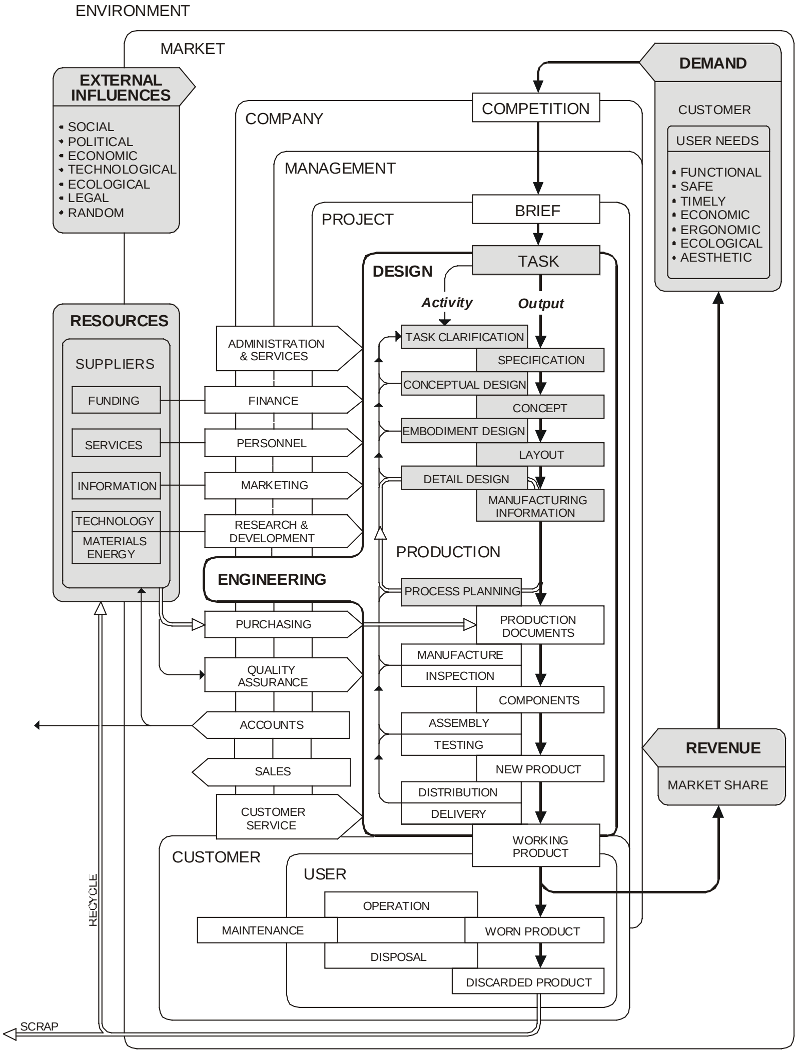

Figure 1. Engineering design process within an industrial context

As the research progressed 20 disciplines linked to engineering design research were identified [10]. First these were classified into two central working disciplines: Engineering Design and Management Studies. These were surrounded by six interactive disciplines: Sociology, Social Psychology, Anthropology, Manufacturing Technology, Engineering Science, and Industrial Design. Finally, twelve reference disciplines were identified: Philosophy, Geography, Economics and Politics, Education, Language, Information Technology, Computer Science, Product Consumption, History of Technology, Mathematics and Science, Architecture, and Art. Linking fields between the disciplines were then identified, see the model in [10]. It soon became clear that the linking fields were the ones most relevant to our research, so over a 100 experts working in these linking fields were visited. We concluded that it was important to apply the methods of neighbouring disciplines and multi-disciplinary research teams would be needed. By 1985 the importance of profiling the influencing factors in order to manage the design process more effectively was gaining strength in our minds.

3 ICED 87 – END OF OUR RESEARCH PROJECT

By the time of ICED 87 in Boston the PhD project had been completed. In order that that the case data should be available to other researchers, it was listed in the appendix of the thesis along with details of how the data was processed [14]. At ICED 87, we presented two papers: one summarising the results of the project [15]; the other reflecting on the challenges of studying the design process in industry [16]. The latter emphasised: (1) the need for social science field research techniques to gather data; and (2) the importance of practical engineering design experience to interpret the results. Our observational study was large. We do not think there has been a larger one undertaken by a single researcher since. The project was rather specialised in that it involved the design of a one-off experimental test rig rather than, for example, a mass-produced consumer product, but the scale and timing allowed the project to be observed through all its design stages for a period of 34 months.

In all 37 people were involved in the project, including the researcher, and 1373 interchanges were recorded. These covered 2368 hours of work effort recorded in time intervals down to 0.1 hour. The raw field data comprised 1180 pages of diary notes, 76 hours of audio recordings, 116 weekly reports and 6 design reports. For every hour spent recording data on the project, at least another hour was needed to write up and reference the data for future use. The field notes were converted into data sheets and put into a database. Summary files were produced and patterns sought [14, 15].

General observations included the importance of spending time and care on the Task Clarification phase; and the negative impact on project progress caused by late changes to the design requirements.

Many detailed observations were made from the quantitative analysis including the following:

- Only 47% of the work effort on the project could be matched to the design activities represented by Pahl and Beitz’s model of the engineering design process [11].
- The remaining 53% of work effort was made up of activities not included in most models of the design process at that time.
- Six categories of work effort were identified that accounted for the work effort not covered by Pahl and Beitz’s model: personal work scheduling; reviewing and reporting; cost estimating; information retrieval; social interactions; and informally helping with other projects.
- The use of ‘design methods and techniques’ commonly described in the literature accounted for only 22% of the engineering design effort.
- A further 74% of the engineering design effort could be accounted for by adding 5 working techniques, 4 communicating techniques and 4 motivating techniques to the use of ‘design methods and techniques’ heading. In the end only 4% remained unclassified.
- Analysis of the project effort by month revealed the nature of the project phases and the extent of overlap between them, which gave rise to the concept of using ‘ideal’ and ‘actual’ phase diagrams for measuring engineering design effort and assessing percentage of project completion.

The *quantitative analysis* based on work hours characterised the project in terms of activities and outputs, but did not explain why things happened the way they did – that required a *qualitative analysis*, with all its subjective limitations. From the data 103 factors that could influence the engineering design process were identified, an influence being a person or thing having power. These were divided into 20 categories at 5 levels of resolution [14, 15]. Influences can change slowly or rapidly, and can have a positive or negative impact on a project. The factors that had most influence on our project were, by category: External Influences (political and economic); Resource Availability (people and information); Corporate Systems (clarity of objectives); Management Style (benevolent); Design Team (commitment and motivation); and Design Techniques (systematic design approach). A profiling technique using checklists was later developed by the researcher and published as a comprehensive way of assessing design project progress and performance [13].

We fully realised that we were not going to be able to draw any generally valid conclusions from a single project and hoped that design researchers would collaborate to generate a matrix of projects and share their data. However this took much longer to happen than we envisaged at the time.

4 DISCUSSION – DESIGN RESEARCH

In 1983 the Lickley Report was published [17], prompting the Design Initiative by the Engineering and Physical Sciences Research Council (EPSRC), which eventually led to the setting up of seven Engineering Design Centres (EDCs) in the UK. A similar initiative in the USA by the National Science Foundation (NSF) led to the setting up of the Design Theory and Methodology Program [18].

In Germany a standard on the design process, VDI 2221, was written by a Committee of experts that included Professors Pahl and Beitz. It was published in German in 1986 and subsequently translated into English [19]. In the UK a standard on the management of design, BS 7000, was published in 1989 [20]. It is disappointing that the design methods developed out of design research programmes, some even published as national standards, are often ignored by industry. For some evidence of this see [21, 22].

Our research project taught us a great deal about *design research methodology* and about the *design process*. For the supervisor, observational studies in industry became the research approach underpinning much of his research for the rest of his career. For the researcher, the lessons learnt provided a basis for analysing accidents and explaining the causes, frequently in courts of law.

Design Research Methodology: At the start of our project there existed a considerable number of publications on the design process, but few of the models and methods proposed had been tested in practice. We came to the view that one of the best ways to increase our understanding of the design process and the effectiveness of design methods was to try them out in practice and observe the results. We soon learnt that combining the roles of participant designer and researcher was extremely demanding and required engineering design skills, experience of the technology and a wide range of research skills. Ideally a multi-disciplinary team would undertake such a project.

Design Process: While analysing the data, it became clear that a new model was needed to place the engineering design process within an industrial context and to show the many factors that influence the design process. It was also clear that simply applying 'methods' is not sufficient – it necessary to be aware and, where possible, control the influencing factors. Feedback from the design team indicated that the systematic approach used had improved their design process. For example, on previous projects the team had never undertaken a formal Task Clarification phase and this proved extremely beneficial during the design of the test rig. Over 40% of the design requirements came from sources other than the immediate design team. In particular, 19% came from the staff responsible for manufacture, who were never previously consulted. This ensured that comprehensive criteria were prepared for evaluating design concepts and this forestalled a number of later difficulties [23].

5 EXAMPLE – RING GEAR FAILURE

In the USA on 3 November 1999 a 5 metre diameter ring gear driving a tower diffuser for extracting sugar from sugar beet suffered a catastrophic failure only 43 days into a 5-month sugar beet season (referred to as a 'campaign' in the industry). Luckily no-one was injured. One complete tooth broke off and it was discovered that numerous other teeth were cracked to the point of imminent failure. As the plant was in round-the-clock production, processing about 8000 tonnes of beets a day, seven days a week, immediate emergency repairs were required to prevent financial disaster. The fracture surface at the root of the failed tooth was ground down and successive layers of weld metal were built up to replace the entire missing tooth. The welded steel was then ground by hand to match the profile of the other teeth. While the fractured tooth was being reconstructed, some of the cracks found in other teeth were ground out and repaired by welding. The plant managed to keep the tower diffuser operating for the rest of the season by combining digital photography along with mapping of the crack propagation on each tooth with periodic 12-hour shutdowns to repair specific cracks. Thus the season was completed without having to ship the beets to another processing plant. The production loss was minimised by the care with which the staff balanced the operating torque against the speed of crack propagation, once the scale of the problem was clear and countermeasures developed. Nevertheless, the result was a multi-million dollar insurance claim by the sugar producer in the USA and a subsequent lawsuit by the insurance company against the plant design company in Germany and the manufacturer of the ring gear in France.

In operation the beets are first sliced into thin noodle-like strands called 'cossettes' and these are conveyed to the base of the tower. The 28 metre tall cylindrical tower has a series of stationary 'flights' fixed to the inside wall, interleaved with a second set of flights attached to a rotating central hollow shaft. At the top of the tower, eight synchronised pinion motors drive the large ring gear fixed to the central hollow shaft. The shaft rotates at around 0.18 rpm and the moving flights lift the beets upwards from the bottom of the tower to the top. Hot water cascades down from the top of the diffuser, flowing over the cossettes as they rotate and proceed upward. The hot water diffuses out the sugar in the beets and this is removed from the base of the tower. Two screw augers at the top of the tower push the processed beet pulp onto conveyors that transport it away.

It is critical for the 19 teeth of each pinion to drive with the same force and to mesh precisely with the 356 teeth of the ring gear in order to avoid creating varying forces from one tooth to another and along the 370 mm face width of each tooth. Differential forces from tooth-to-tooth and across the face of each tooth can lead to local overstressing of the tooth material and consequent premature failure by the initiation and propagation of fatigue cracks. In order to prevent this type of failure, each motor/gearbox/pinion assembly is mounted on a pivoting system, designed to allow sufficient differential float between the pinion shaft axis and the ring gear shaft axis to maintain optimum meshing of the gear teeth. Embodiment guideline: ‘balancing forces’ [11].

Of all the components in a tower diffuser, the ring gear is the most critical:

- It is the most costly single part – about 180,000 dollars
- It has a very long lead-time – about 5 months
- It is large and heavy, requiring precision manufacture
- It has to transmit large forces 24 hours a day for at least 180 days a year
- It consists of a large number of highly stressed gear teeth, each cyclically stressed
- It cannot be replaced without a complete shutdown of the diffuser and loss of production
- If it is damaged, production rates are lowered and specialist repair is required.

These characteristics are inherent in the design as soon as the decision was made to use the concept of a single large ring gear driving the tower diffuser by means of a central shaft. Therefore, all the above considerations must be addressed during the design process so that the equipment meets the expectations of the user.

The first phase of the engineering design process involves making sure that the *Design Specification* includes a complete list of customer requirements and preferences, together with the constraints. In Germany, where the diffuser tower was designed, this is described as Stage 1 in VDI 2221 [19]. Following this come further phases in the design process to develop the chosen concept into a practical and reliable working system that meets the customer’s requirements. In this case the *Embodiment Design* and *Detail Design* phases (see VDI 2221) were critical. At the time the ring gear was being designed, embodiment design guidelines were readily accessible in [8, 11].

VDI 2221 and *Konstruktionslehre* were written in order to avoid the type of failures experienced with the ring gear. Publicity material of the German design company claimed a high level of technical excellence at the forefront of sugar processing technology.

A review and analysis of the documents produced by the design company revealed that in January 1991, when the tower diffuser was ordered, they knew two important things regarding their diffuser drives. First, they knew that the reliability of the drive system was financially critical to their customers: “… we know how critical a gear failure can be at a sugar factory expecting a permanent 100% availability…” Second, they knew that there were reports of ring gear failures with other customers.

In embodiment design terms, when those two pieces of information are linked together it sets a clear and logical path for the design of the ring gear. If the reliability of a proposed system is critical and the designers know from failures reported by customers that the performance of similar systems supplied previously was marginal, the *weak spots* should have been identified and addressed in order to improve the reliability of the system [8, 11, 19]. In the case of the ring gear, the weak spot had already been identified as tooth cracking by various users. It was then a matter of addressing the problem with the aim of providing the required 100% availability. For this there is a well-established 4-level design approach. First try to design out the problem; if that is not practicable then add protective systems; if that is not possible use warnings; and, finally, rely on training and instruction. For the case of the ring gear, this design procedure may be visualised in the form of the design logic diagram shown in Figure 2.

Level 1: Direct Approach – Avoid Fractures

Safe-Life Design: The evidence indicated that the French gear manufacturer was given only 25,000 hours as the design life of the gear for calculation purposes. If they then designed the gear for zero failures below 25,000 hours, that could be considered a ‘safe-life’ design, but only if the customer was explicitly instructed to replace the ring gear every 25,000 hours, no matter what its condition.

***Fail-Safe Design**:* This design approach is quite different, and perhaps more appropriate for such a large and costly part. While there is no fixed time limit on hours in service, if and when the component starts to fail the designer ensures that sufficient capability exists to keep operating, albeit at reduced capacity. So, even though the gear might still be designed for zero failures before 25,000 hours, replacement at that time is not required because the designer also makes sure that when any failure does occur, it is not catastrophic and allows production to continue. This may be accomplished in various ways, such as having dual or multiple components sharing the load (redundancy), transferring the load to different components in the event of a failure or, in the case of the ring gear designing it to make sure that failure due to contact fatigue occurs before failure due to bending stress. Whether it was intentional or not, this is effectively what occurred with earlier ring gears because the roots of the teeth were hardened as well as the flanks and it was not necessary to replace the gear after a defined number of hours. Pitting and other visible contact fatigue or wear damage would appear and develop over time, reaching a point at which a decision would be made to turn the gear over (to use the back faces of the teeth) or replace it. For the ring gear that failed, the decision was taken only to harden the tooth flanks, which made it more likely that failure by bending fatigue would occur before failure by surface fatigue.

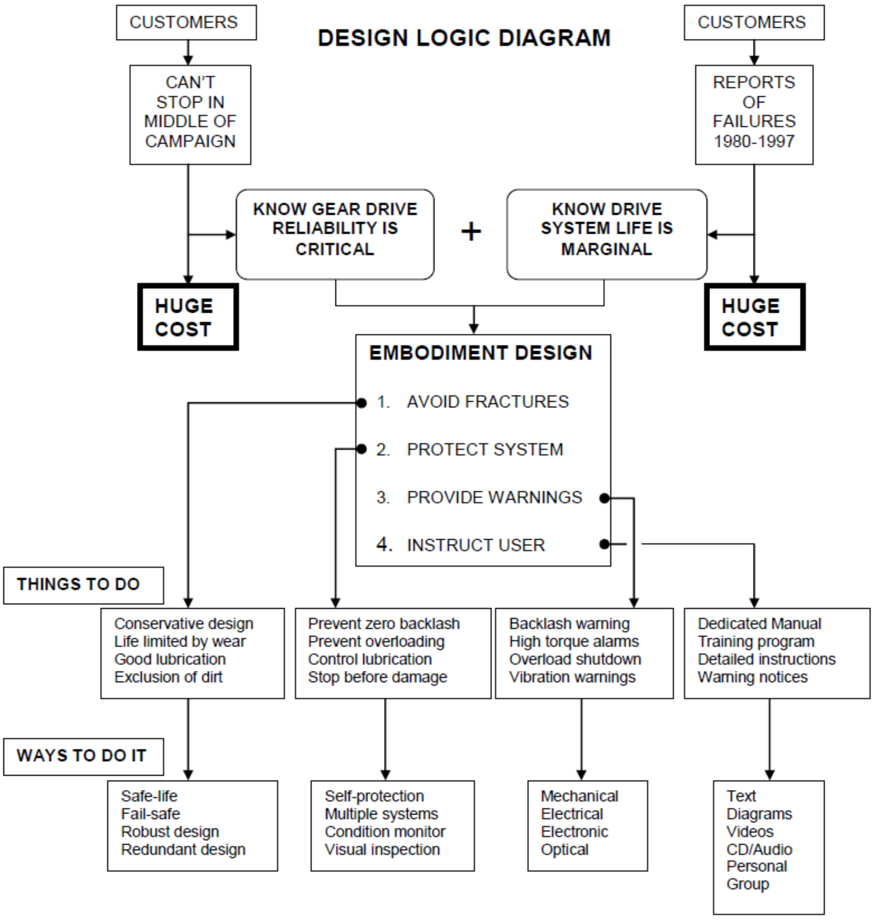

Figure 2. Design logic diagram for the embodiment design of the critical gear drive

***Robust Design**:* Another design approach is to design the ring gear to be so strong that all stresses would be below the fatigue limit of the material and no failure would occur under normal loads, no matter how many hours of operation. Although this is possible for many mechanical components, and may have been the approach used by the French company for earlier ring gear designs, there are physical limitations with such a large part that tend to make such an approach impracticable. Nevertheless, there is no doubt that a service life of far more than 25,000 hours could easily have been achieved. In fact, after the ring gear failure in 1999, the German company itself submitted a proposal to the sugar producer for a replacement ring gear designed for a service life of 120,000 hours. This translates to a life of 27-29 years in USA sugar beet campaign terms. Thus, it appears that the shorter design life of 25,000 hours specified to the gear designer and manufacturer in France was selected for economic or other reasons, as a more robust ring gear was in fact a practicable proposition.

***Redundant Design**:* The documents related to the overall design of the drive system for the diffuser tower indicated some confusion with regard to the number of drive units that had been specified and used for design purposes. Initially in 1990 the design company had proposed the use of seven units to drive the ring gear, but this was increased to eight by the time the order was finalised. The reason for the additional drive was because the tower height had been increased to provide more residence time for the beets, thereby improving sugar yield. The provision of the eighth motor was understood to more than make up for the increase in torque needed for the longer central shaft, and therefore would also add a beneficial level of redundancy to the *pinions*. For example, it would allow one motor to be removed for service or replaced during a campaign if necessary, while the diffuser continued to be driven temporarily by the remaining seven drives. However, no such redundancy was provided with regard to the *ring gear*, nor was the *design specification* changed to accommodate the potential increase in number of stress cycles per hour through being driven by eight pinions instead of seven. Having eight instead of seven motors could effectively *reduce* the service life of the ring gear, as each tooth would experience the same stress peak eight times every revolution of the gear instead of seven times, unless the limit on maximum torque available from each motor was reduced in accordance with appropriately revised gear tooth stress calculations.

Level 2: Indirect Approach – Protect System

In various cases of ring gear failure in other plants, engineers from the gear manufacturer carried out investigations and prepared reports on their findings. The findings in these reports tended to focus on two issues: backlash and dirt. In general, the conclusions were either that the customer allowed the teeth of the pinions to engage too deeply with the teeth of the ring gear (insufficient backlash), or that the customer allowed the lubricant to become contaminated, thereby feeding foreign matter between the pinion and ring gear teeth. In either case it appeared that the customer was being blamed, yet each of these problems is a design issue and should have been addressed as such. If the tooth engagement can ever reach the point of zero backlash, i.e. no clearance between teeth, while the drive is operating, then obviously this will cause damage from contact between the pinion teeth and the back side of the ring gear teeth. Therefore some kind of *protective system* is needed in the design to make sure that this condition can never occur, even if there are problems with a bearing in one of the rollers. Similarly, if oil contamination by particles entering the system from external sources can foreshorten the life of the ring gear, despite the oil filtration system provided as part of the drive train, then this is a problem to be addressed by the designers. Condition monitoring of the oil or some form of enclosure to prevent any contamination is needed.

The possibility of inadvertent overload on the drive system is an obvious foreseeable situation with any system having the potential for jamming. In fact the potential overload issue had been discussed between the design company and its customers over the years, and was addressed to a certain extent in the design of this particular plant by the fitting of a torque-measuring device on one of the eight drive motor units. However, the calibration of the torque measurement transducer had been problematic from the time of commissioning, so the plant personnel had worked out an alternative way of monitoring the torque based on the electrical current drawn by the motors. In this way they could ensure that the overall torque applied to the ring gear was kept within the limits set by the design company. Had the ring gear been designed for a life limited by contact fatigue, the single torque measuring device may have been an acceptable approach for load monitoring, but for a gear with its life limited by bending fatigue, it is not. In this case, it is far more critical to control and limit the torque by overload protection designed into the system. It is also important to monitor and record the actual torque cycles as they occur, so as to provide the plant personnel with a way of predicting the remaining gear life based on the cumulative damage history.

Level 3: Provide Warnings

For a large gear designed with no redundancy and liable to fail catastrophically, it is vital that the operators are provided with sufficient warning should overload or damaging conditions occur during operation. The torque meter that was fitted to one of the eight drive units is only of marginal help in this regard. It cannot provide the operators with a reliable warning of an overload condition because of: (1) calibration problems; and (2) no guarantee that each motor is transmitting the same torque. A more comprehensive warning system is required if this design of ring gear is to be used. Similarly, if the damaging condition of zero backlash is something that cannot be prevented by design and perhaps not even by adding a protective system, then there needs to be some positive means of alerting the operators to this condition when it is about to occur.

Level 4: Instruct User

The German design engineers knew the limitations they had designed into the drive system, as specified to the French gear manufacturer, and also knew the type of catastrophic failure that could occur when the life limitation was exceeded. However, they did not pass this information on to their customers. At least they could have provided proper instructions with regard to the ring gear life and the need for replacing the gear after its design life of 25,000 hours, together with a reliable way of checking the gear teeth for cracks during its operational life. Sufficient instruction and training could have been provided for the customer to understand the risk of failure and to and to have a procedure in place for when signs of failure appeared.

6 DISCUSSION – EXAMPLE

The cause of the ring gear failure lay in flaws in the *design process*. Well-established design procedures and *embodiment guidelines* were not applied.

Design Process: If the team had undertaken a more rigorous Task Clarification phase, as strongly recommended in VDI 2221 and *Konstruktionslehre*, both of which were readily available before the design was started, some of the ensuing problems could have been avoided. It is clearly of no use if the relevant knowledge exists, as it did in this example, but that knowledge is not identified and transferred to where it is needed, and then applied appropriately. This is mainly the responsibility of design management. In addition there was a basic communication failure. The information that the design company had regarding the potential for catastrophic tooth failures, based on their own gear life specification to the gear manufacturer, was not provided to the customer in the form of warnings, instructions or training. This left the customer vulnerable to unexpected production losses without any agreed contingency plans.

Embodiment guidelines: The main engineering reason for the failure was a change from ring gears limited by wear and contact fatigue life (tooth pitting) to ring gears limited by bending fatigue life (tooth cracking). The gear ring was a critical component, but the design team failed to adopt the embodiment guidelines for such a situation. Increasing the number of drive units from seven to eight at first appeared to increase the redundancy in the overall system, but if more care had been taken it would have been realised that this had a serious negative effect on the fatigue life of the ring gear teeth. The need to avoid zero backlash conditions and oil contamination was not addressed, nor was reliable torque monitoring. These design problems were not difficult to solve and the time and the cost of doing so would have saved millions of dollars in the long run.

7 CONCLUSIONS

We believe that participant observation in industry is a powerful design research method. The data gathering and analysis involves techniques from a number disciplines and is probably best undertaken by multi-disciplinary research teams. We are pleased to see that this approach has since been adopted by a number of research groups. We are also encouraged there are moves to consolidate design research findings; to agree a common research methodology; to share data; and to collaborate in building up a matrix of research projects.

From analysing our data, we tentatively concluded that the appropriate and flexible application of design methods can improve the effectiveness and efficiency of a design team. However, design methods in themselves are not sufficient and the many factors that influence the design process must be taken into account and, where possible, monitored and controlled.

The example of the ring gear failure demonstrates that an experienced design team can fail to follow the design process recommendations set out in a national standard and neglect well-established embodiment guidelines. Designers are under considerable pressure to meet deadlines and probably do not see it as part of their jobs to go through the literature to find new methods. The gear ring failure, just one example from many, shows that this can be a costly mistake. Managements should ensure that somebody is responsible for knowledge transfer.

There are many outstanding products that are safe and reliable. However, costly failures and accidents due to poor design, some resulting in deaths and injuries, will continue to occur unless more attention is paid by design managers and designers to identifying the most appropriate methods and transferring them in to practice. It appears that in many companies nobody is given the responsibility for this crucially important task.

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