FACING HUMAN FACTORS IN AIR TRAFFIC CONTROL: A NEW APPROACH TO INCLUDE ERGONOMIC REQUIREMENTS IN WORKSTATION DESIGN

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OVERVIEW

The HERA (Human Error in ATM) analysis shows a distinctive occurrence in incidents wherein the visual perception of information plays a key role in German air traffic control. The reasons can be partially traced back to workstation design, where basic ergonomic rules and principles are not sufficiently followed in some cases. In retrospective however, it is difficult if not impossible to determine why a system engineer came to a non-ergonomic design solution. Therefore an explorative, qualitative study was conducted to analyze how system designers work and reach certain decisions. It was found that although employees are willing to address human factors and show a high level of empathy to those performing air traffic control tasks, organizational aspects and the non-ergonomic focus in educational background make it difficult to do so. To improve the current situation knowledge acquisition, knowledge application, and knowledge transfer were identified as the most relevant factors during system design. Therefore this paper suggests the development and implementation of a Design Process Guide, a software tool that offers a contextual and process oriented access to ergonomic information.

1. INTRODUCTION

In a world with a continuously growing number of aircraft movements, air traffic control (ATC) is under pressure to increase its performance without sacrificing the high level of safety. To meet this goal several measures are being discussed within the frameworks of “NextGen” in the US and “SESAR” in Europe. Alongside these mainly technology-driven approaches there is one major aspect that always has to be taken into account: Human performance, and more specifically, human performance variability. In the history of aviation Human Error is often taken as the cause in up to 90% of incidents and accidents within the airspace system [1]. There is a large potential in increasing safety by understanding and solving human performance issues. FAA puts it this way:

> *“[Human Error as an accident theme] represents one of the greatest opportunities for advancing safety by the application of targeted interventions which are intended to reduce the risks of human error” [2].*

The most prevalent perception is that Human Errors are the cause of incidents and accidents. This view leads to the misconception that a problem is solved as soon as there is *somebody* to accuse of having done something wrong. The associated action would be removing that person from duty. This conception is dubbed the “old view” by Dekker [3]:

> *“In the old view of human error, progress on safety is driven by one unifying idea: unreliable people undermine otherwise safe systems.”*

The “old view” does not help in understanding why the identified error happened and thus nothing can be changed at the level of development and problem interactions. On the other hand, the described mindset makes it very easy for the investigator to present “results”. Considering this, Dekker suggests a “New View”: Human Error is the *result* of a systemic problem. In this understand the *Human Error* is seen as a symptom for deeper problems in the system. This means incidents develop from unanticipated interactions of system elements functioning within their design envelopes. The New View baseline is the paradigm shift from blaming the individual to analyzing the system.

The theory of Resilience Engineering describes the ATM system as complex and interactive, wherein a causeeffect quotation of incidents is no longer sufficient. Erik Hollnagel stated that

> *"… untoward events more often are due to an unfortunate combination of a number of conditions, than to the failure of a single function or component" [4].*

HERA at DFS is used under these theoretical principles: Human Error is a symptom not a cause and the combination of the components of a system leads to undesirable outcomes.

If a work system is analyzed in a structured way that these interdependencies are understood, errors may be anticipated and avoided. This assumption is supported by a NASA investigation which states that within the *same* environment and with access to the *same* information, most experienced personnel would be prone to make similar errors [5].

A recent development is NASA's and FAA's intention to better coordinate their human factors research efforts "to achieve the intended benefits of investments in NextGen" [6]. Against the background of a lengthy transition period to new systems, the possibility of a proactive approach seems highly attractive.

2. HUMAN ERROR IN ATM TECHNIQUE (HERA)

2.1. Theoretical Background and Methodology

The new way of looking at how Human Error manifests itself is an investigation method called Human Error in ATM (HERA), developed by Eurocontrol in close cooperation with FAA [7]. It uses a systematic approach to enable investigators finding explanations for incidents in the overall context of the ATM system. "Incident" in this context, means the loss of the required separation between two or more aircraft. To collect enough information for creating a useful database, even though incidents are fortunately rare, HERA is a pan-European proposition. Ultimately, such a database could be used for statistical tests and analyzing trends.
HERA uses the following working definition of Human Error [8]:

> *"Any action (or inaction) that potentially or actually results in negative system effects, where more than one possible course of action is available."*

However there are trends to exchange this definition: Deutsche Flugsicherung GmbH (DFS), the German Air Navigation Service Provider, is in a process to replace the term *Human Error* by *Decision Point*. This re-labeling helps to shift the blame and causation away from the operator. The theory behind is that failure and success have the same source: A *Decision Point*. The result determines the decision as error or success [9].

During the HERA investigation, the structure is broken down further into Error Type, Error Mechanism and Information Processing level. These three layers of categorization can be rephrased into the questions "What?", "How?" and "Why?" and represent a psychological perspective.

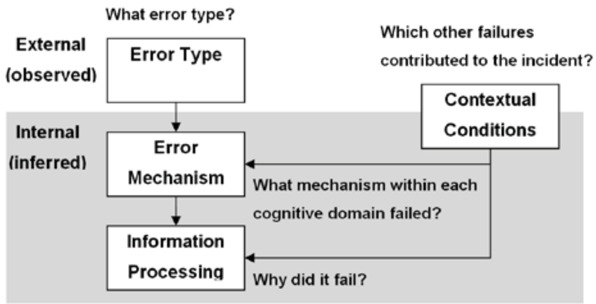

FIG. 1 *Flowchart of HERA procedure. Based on [10]*

The analysis starts with objective, observed facts, or in other words, the description of what happened (Error Type). Error Mechanisms, etc., are inferred from the facts and with help of the structured HERA procedure (fig. 1). The cause(s) are then found by tracing further upwards through the layers and by broadening the scope. This corresponds to the "spheres of influence" as depicted in figure 2. Each domain covers more area of the actual elements of the whole (work) system "Air Traffic Control".

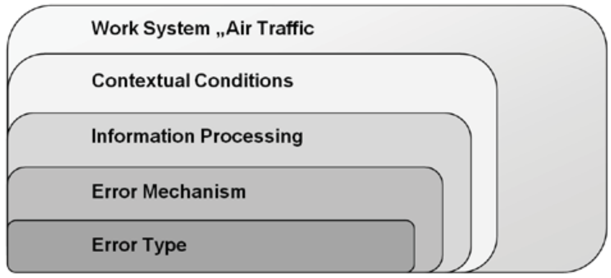

FIG. 2 *Spheres of influence of Error Type, Error Mechanism, Information Processing and Contextual Condition within the work system air traffic control. Based on [1]*

The final layer to be taken into account is the overall context. This is achieved by collecting information about pre-specified Contextual Conditions. These can be defined as internal as well as external factors which had an influence on the controller and thus affected performance. Again rephrased into questions, they could be described in terms of "When?", "Who?", "How (temporal)?", and "Which information?".

Among others, some examples are:

- Workplace design and HMI: Broken down into type of equipment and corresponding problem, like "Surveillance – Conflicting Information"
- Personal Factors: Distraction by personal thoughts, boredom, etc.
- Training and Experience: Novel situation, inadequate mentoring, etc.

Within HERA, the Contextual Conditions are the factors that ultimately provoke Human Error-induced incidents.

For a more thorough description of the HERA method and the underlying theoretical background, see [1], [8] and [10].

2.2. Exemplary Results for German Air Traffic Control

DFS provided an evaluation of HERA incident reports from 2005 to 2009. This included cognitive domains of error types and the corresponding error mechanisms (table 1).

When looking at the totals in the different Error Detail categories, two major accumulations can be identified: Perception & Vigilance and Planning & Decision-making. While the totals are decreasing over the years, their relative shares remain high – 27.7% and 52.9% respectively in 2009 (see figure 3).

Figure 4 depicts the corresponding accumulated numbers of Error Mechanisms. The by far most frequent mechanism is "No detection of visual information". This means that some malfunction occurred in the controller's visual perception of the presented information. Though this may be due to several different causes ranging from distraction to expectation bias (see again table 1), DFS at the time had the strong suspicion that ergonomic issues of the utilized equipment were causative.

This suspicion was confirmed by an analysis of incidents from Swedish airspace between 1988 and 1998 with the HERA technique. Very similarly to the German cases, 21% of the identified failures fell within the domain of "Perception & Vigilance". Even more striking is the fact that "workplace design and HMI" was the predominant group of Contextual Conditions [11].

For a further investigation of these findings, workstations and HMI were evaluated by the Institute of Ergonomics in Darmstadt. As expected, some weaknesses could be detected, even in newly acquired or designed systems. HMI displays, which are the main mode of visual information presentation, suffered from issues concerning font sizes and types, viewing distance problems, overlapping information etc. These could be mostly resolved.

Still the question arose of how and why design flaws keep appearing despite the undoubted expertise of DFS' equipment designers and engineers.

2.3. Implications and research objectives

As discussed above the HERA-Analysis indicates that system design and errors are related. However, HERA gives no hints for how to ergonomically improve current systems in order to reduce errors. HERA follows the premise that Human Errors appear during the operation but in fact the origin may date back several years. It is very difficult if not impossible to determine the beginning of a Human Error. They may lead back to the very early stages of system design [12]. In retrospect it is hard to understand why a designer chose an inappropriate design option and how the design process needs to be modified for minimizing the risk of Human Errors in future systems. However, this information is essential to define areas for improvement regarding the overall workstation design process.

Possible reasons for poor ergonomic design are multifaceted. According to [13] potential influencing factors may be:

- Employee (constitutional, dispositional and adaptive characteristics, qualification and competences)
- Organization (structural and/or process organization)
- Group- and teamwork
- Environmental conditions (social, technical, and physical environment)

For deciding appropriate actions it's essential to gain a thorough understanding how German ATC designers think, work and come to certain decisions. Moreover, this study intends to identify, which of the above described factors may influence ergonomic design solutions and how the designers can be supported.

3. METHODOLOGY

To achieve the described objectives a qualitative explorative study was conducted over a period of more than two years. The base population of this study is quite small ($N \leq 30$) due to the number of workstation designers inside the German ATC. Fortunately, almost all relevant workstation designers were available and participated in at least one workshop or scenario.

All in all, six workshops were conducted, each with eight to fifteen participants. Table 2 provides a summary of these workshops.

Alongside workshops, this study used scenarios as an additional method to understand current approaches and ergonomic problems of the designers. Scenarios are stories that can describe the fictitious use of fictitious tools by a fictitious user [14, 15]. Scenarios are very powerful, especially in a complex context, as they give meaningful insight as to how new or modified tools may be used and how current approaches may improve.

To achieve this, workstation designers were asked to describe informal ergonomic issues they were challenged. Each real ergonomic subproblem was then transformed to a problem-scenario and a use-scenario, which was discussed with the project owners afterwards. The use-scenario described characteristics of a fictive tool that could help to solve the problem. An important incentive for the participants was their expectation that reported ergonomic subproblems were actually solved during the scenario process and that they could use the results in practice. Figure 5 shows how this study applied scenarios for analyzing the ATC design context. For detailed information on how scenarios were used during this study refer to [16].

***TAB. 1** Relation between cognitive domains, Error Mechanisms and Information Processing level. Based on [6]*

Cognitive domain	Cognitive function	Error Mechanisms	Information Processing levels
Perception & Vigilance	Detection Identification Comparison	Hearback error Mishear Late/No detection Late/No auditory detection Late/No visual detection Misperception Misidentification Misread	Visual search failure Monitoring failure Expectation bias Association bias Visual/Sound confusion Spatial confusion Discrimination Distraction/Preoccupation Tunneling Out of sight bias Information overload Vigilance
Planning & Decision-making	Judgment Planning Decision-making	Misjudgment Incorrect decision or plan Late decision or plan No decision or plan Insufficient plan	Incorrect knowledge Lack of knowledge Integration failure Failure to consider side effects Cognitive fixation Incorrect assumption Risk recognition failure Denied risk Misunderstood communication

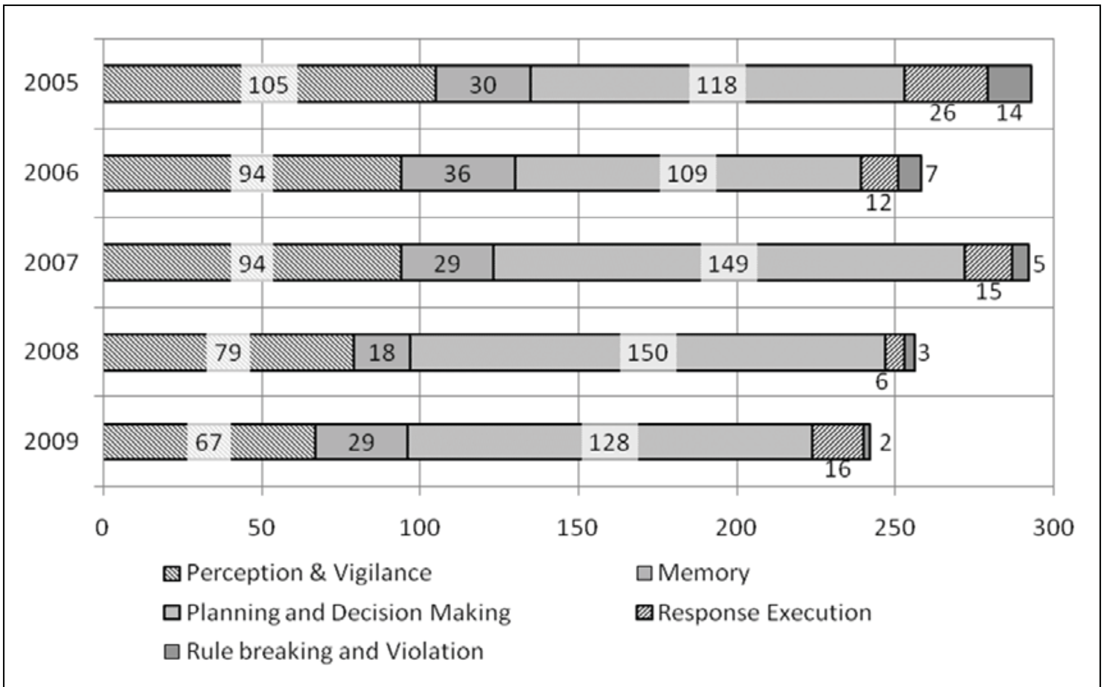

***FIG. 3** Error Types of total annual HERA incident reports 2005-2009*

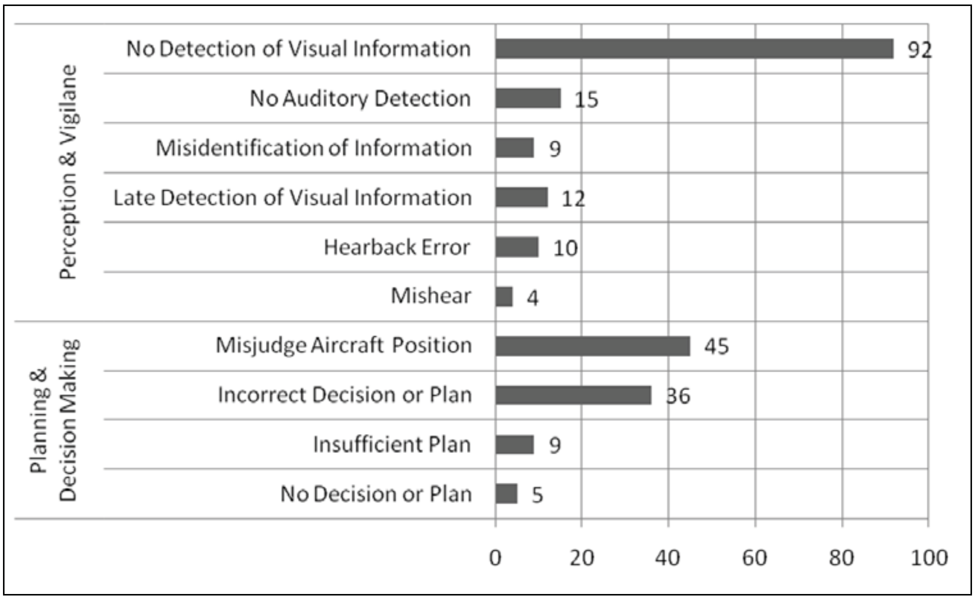

FIG. 4 *Accumulated numbers of Error Mechanisms (EM) for incidents in upper German airspace between 2005-2009*

TAB. 2 *Overview of the conducted workshops*

Nr.	Name	Content	Number of partici-pants	Duration in hours
1	Preliminary workshop 1	Identification of relevant design elements from a Human Factors point of view	15	3:00
2	Preliminary workshop 2	Detailed examination of the identified design elements from workshop 1	15	3:00
3	*Macroergonomic view on system design:* Methods and approaches of the designers	▪ Presentation of past and current design project by the participants and discussion of typical difficulties that occurred ▪ Identification of methods, approaches and processes that are used to address ergonomic issues	12	5:00
4	*Microoergonomic view on system design:* Processes and relationships during system design	▪ Identification of typical process-related and non-process-related relationships between typical design elements ▪ Visualization of identified relationships	12	5:00
5	*Group work:* Solving a practical ergonomic task	▪ Group work: Designing lighting conditions using ergonomic literature, guidelines and standards ▪ Observation and documentation of the participants behavior	13	5:00
6	Mock-Up presentation	Presentation and discussion of a first software concept to support work place designers	8	3:00

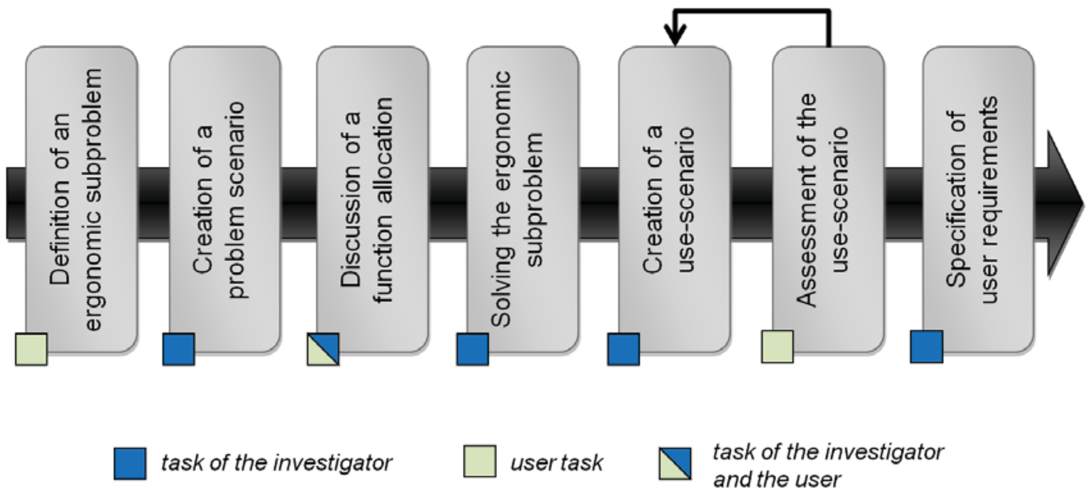

FIG. 5 *Application of scenarios for analyzing the context of use*

4. RESULTS

The following section introduces the key findings of this study according to the potential influencing factors described in the previous sections.

4.1. Employees

No evidence was found that constitutional or dispositional characteristics (e.g. age distribution or the preponderance of a specific personality inside German ATC) impacts ergonomic design. There is also no evidence that adaptive characteristics, like job satisfaction or motivational aspects, can explain ergonomic weaknesses in system design. All designers were extremely concerned about human factors and highly dedicated in finding an adequate ergonomic solution.

A typical design team usually consists of studied engineers and former air traffic controllers (often with subsequent academic degrees). Therefore, most designers have an excellent educational background. Designers with little ATC experience usually complete a training (lasting several weeks) to strengthen the empathy for air traffic controllers and their needs. However, none of the designers had specific educational background in ergonomics or human factors. This indicates room for improvement in personnel development. There is a Human Factors unit inside the German ATC organization but it brings only general safety aspects into focus, rather than providing ergonomic consulting services to the designers. Hence all designers have to face ergonomic issues on their own. Identifying the right sources of ergonomic information and putting this information in the right context is one of the main difficulties for designers. Besides, they are uncertain which methods to use and how to apply them in a user centered design approach.

4.2. Organization

The workstations are designed in a decentralized manner. There is no central body that coordinates workplace design propositions inside the German ATC. Thus, every branch office applies different approaches and methods, which leads to completely different interaction concepts (e.g. inconsistent color patterns or modalities of input). Indeed there are some companywide process standards such as a project management handbook. However, they just contain general guidelines and give no focused information on how to design a workstation for air traffic controllers.

A particular design project may last for more than ten years. Therefore it is not unusual that the project staff changes during this period. Even though there is a formal handover process, a lot of information remains with the predecessors. Once the predecessors leave the company all of their personal implicit knowledge is lost for the whole organization. In hindsight, it often is impossible for the successors to comprehend why specific decisions were made and which circumstances led to this decision.

4.3. Group- and Teamwork

The lack of a central body which methodically supports and coordinates several workplace design projects highlights the importance of the personal social network inside the German ATC. The informal exchange of ideas and experiences among the designers is currently one the most important sources of ergonomic design. However, it is difficult for an individual to establish an informal network, as German ATC designers are widespread not just organizationally, but also geographically. Designers with an excellent personal network are more aware of ergonomics and its implementation. But even these designers were uncertain of where to acquire ergonomic information, how to assess it with respect to a specific context, and how to apply this information finally in practice. Furthermore, the designers were especially interested in past projects: If a previous project encountered a similar problem they wanted to know how the project staff faced it.

4.4. Environmental working conditions

Though the internal German ATC servers offer access to plenty of research or project reports, it allows no systematic inquiries. The database is more or less a loose conglomerate of various files. Additionally, it does not show a complete image of the available explicit knowledge. Designers are free to make their findings available to the public. However, there is no defined process entailing what kind of information should be released and how this information should be presented. Furthermore there is no approval or review. Designers have difficulty evaluating whether the information is reliable or not and to comprehend under which conditions a proposal was made. There also is no central access to licensed external knowledge (e.g. ergonomic literature or international standards). If a designer purchases specialized literature, his or her colleagues will not necessarily be aware.

5. DISCUSSION

5.1. Interpretation

Before deriving improvements, this study is intended to illustrate how designers in ATC think and work. According to the findings described in the previous chapter a procedure model was developed, which describes typical steps of a design proposition in German ATC (figure 6). As most designers share an educational background in engineering, it’s not surprising that this model reflects typical engineering processes delineated in technical literature [17, 18]. Usually, the designers start with a context specification and define the operators’ characteristics, the controller task, and environmental conditions. Second, they identify relevant parameters that need to be designed (e.g. colors, fonts, labels in an HMI) and define concrete (usually solution-neutral) specifications for these. Afterwards they deliberate about practical technical solutions that meet the defined specifications and reach a decision. As discussed, design projects may last 10 years or longer. Therefore the estimation of possible impacts for further development was emphasized by the designers. For instance, a specific lighting decision may limit the solution space for a later display design. This idea corresponds to the last step of the presented model.

Three major challenges were identified that designers faced during these steps and this is also where new support systems could make a contribution: *Knowledge acquisition*, *knowledge application,* and *knowledge transfer*. These are mainly a result of organizational aspects and the focus on non-ergonomic competencies in human resources.

5.1.1. Knowledge Acquisition

During their daily routine, designers need to be aware that their current design task is affected by ergonomic requirements. As trivial as it may seem, awareness for ergonomic issues was found to be a basic condition for ergonomic design. But even if the designers are aware, they need to formulate an adequate ergonomic problem description in order to obtain the relevant results from either a search engine or a human. Therefore they need to identify which design elements exactly are affected by ergonomics.

Another concern is to find a reliable source for ergonomic information. A lot of different sources like standards, guidelines, books, and journals are available, as aviation is one of the most discussed topics in Human Factors. For a non-ergonomist it seems impossible to find an overview of the field and to evaluate which information is essential and which can be neglected in some cases. Moreover, deadline pressure does not allow for an intensive analysis of available sources and their relevance.

In addition, relevant information may not be available in the organization (e.g. standards) and even if it is available, it is not obvious whom to ask for it. Another problem occurs when two reliable sources offer conflicting information and designers need to prioritize the results.

A support system could assist with identifying relevant ergonomic design elements and act as a single point of reliable information.

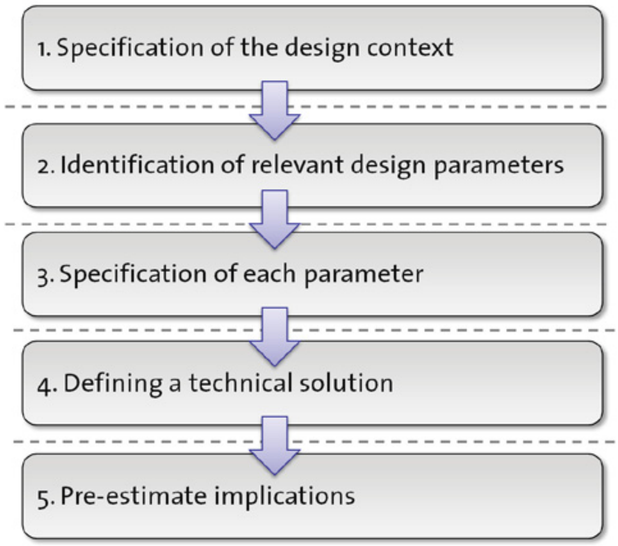

FIG. 6 *Procedure model for workstation design in ATC*

5.1.2. Knowledge Application

Once the designers have collected the relevant information, they need to transfer it to their specific context. There are a multiple unique ATC characteristics that need to be taken into account for this purpose. The question at hand for a typical designer is: Is this specific ergonomic information approved for usage in the ATC context? FAA’s Human Factors Design Standard offers ergonomic guidelines particularly for usage in air traffic control [19]. Although the document is on public domain, very comprehensive and specific, designers rarely use it. One reason is that guidelines often do not reflect designer’s design strategies adequately [20].

Our finding is that designers usually think in design elements: They have a specific task to fulfill (e.g. designing a HMI) and strive for this goal step by step. There is a risk that they may ignore other related ergonomic design issues. For example, the font height inside a HMI results from the viewing distance between the operator and the display. This again is constrained by the operators working position (leaned forward, upright or relaxed position) and this in turn is related to the defined controllers’ task. All these factors which impact the font height are not just a matter of HMI design. Therefore the designers need a holistic approach which includes a processual dimension.

Furthermore, some design elements may only be related with regards to content without a mandatory sequence. There are a lot of constraints that should be considered before a certain decision is made. The font height of an HMI is not only a function of the viewing distance, but rather related to the reading task, lighting conditions, display quality, visual acuity of the controller, and other font characteristics.

Once a specific decision is made, designers usually estimate how the solution may impact future design propositions. For instance, if a designer selects daylight as a modality for lighting, ergonomic studies suggest using a positive display polarity (black text on white background). Our study shows that designers have difficulties to review future ergonomic implications of today's decision. The available ergonomic literature gives some indicators, although they are scattered and not systematized.

Thus, relevant ergonomic knowledge needs to be validated for usage in ATC by ergonomic experts. Furthermore, it was found that a pure ergonomic information basis is not sufficient. It is essential to show the systemic interrelations between different design issues in terms of content and processual relation.

5.1.3. **Knowledge Transfer**

As discussed above, design projects in ATC may last a decade and the course of the project is often hard to understand in retrospect. There is no overall process that manages the transfer of knowledge and assures general availability to the whole DFS design community. But if knowledge is generated during a project, regardless of it affects the content or the interrelations, it should be documented, especially if the designer chooses to differ from an ergonomic proposal. Interested employees should be able to understand the reasoning behind a modification in ergonomic requirements.

5.2. Intended Improvements

As discussed above, three areas for improvement regarding ergonomic design in German ATC were found: *Knowledge acquisition*, *knowledge application*, and *knowledge transfer*. These three fields will be integrated company-wide by a software tool called *Design Process Guide*, which is ideally managed by a central organizational unit inside the German ATC (figure 7).

The intention is to reduce the current necessity of a personal private network, to build a reliable knowledge base, and to objectify ergonomic decisions during a project. By this, designers also have a central contact for ergonomic questions and direct access to ergonomic expertise whenever information inside the *Design Process Guide* is insufficient. The presented knowledge can then be modified or expanded, becoming tailored to application in air traffic control.

The name *Design Process Guide* indicates that this tool exceeds the classic functions of an ergonomic database. It offers a "design element" based access, shows processual and content related topics, and shows implications of certain design decisions. Furthermore, it serves as documentation, detailing why a designer came to a decision under a particular set of conditions. All the content and relations are entered and administrated by ergonomic experts. This may take time and effort, but ensures reliable and ATC focused information in the long term. Figure 8 shows early design drafts of the *Design Process Guide*.

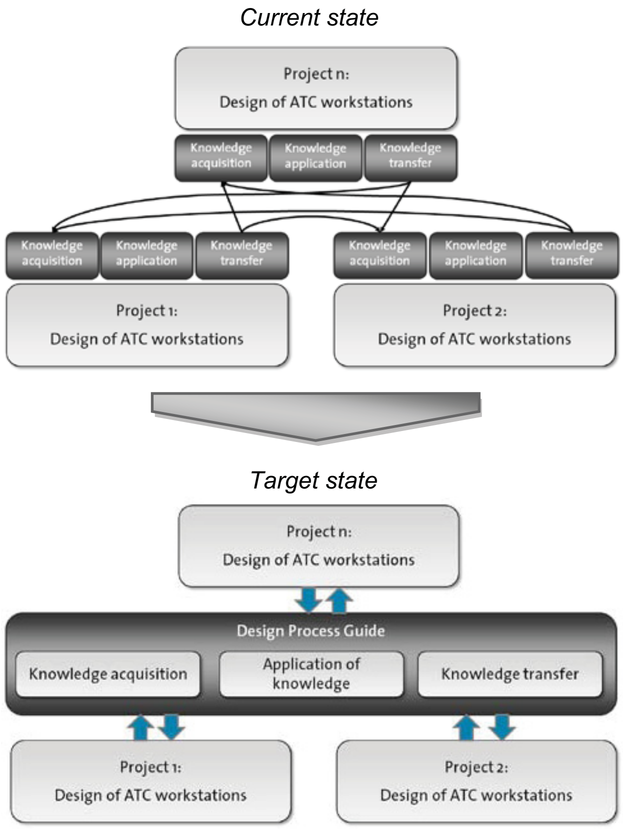

FIG. 7 *Current and target state in comparison*

6. OUTLOOK & CONCLUSION

The reader should bear in mind that the findings of this qualitative study are limited to design propositions in German ATC. Further research could investigate, whether the general procedure model can be applied to a broader range of contexts (e.g. control room design) and if the identified areas for improvement remain valid. Furthermore, this study could be extended to an international scope as literature shows similar problems in other countries. The rising base population could then allow a quantitative study that goes along with the appliance of statistical methods.

It was concluded that ergonomic weaknesses in the design of current workstations in ATC are mainly a result of a non-ergonomic focus in the current organization and in human resources. Employees are willing to address human factors and they show a high empathy for air traffic controllers, nevertheless organizational aspects and the non-ergonomic focus in the educational background make it difficult to do so. To support the designers with their tasks, this study found *knowledge acquisition*, *knowledge application*, and *knowledge transfer* as areas for improvement. Thus, the implementation of a Design Process Guide is suggested. This software tool offers a contextual and process-oriented access to ergonomic information.

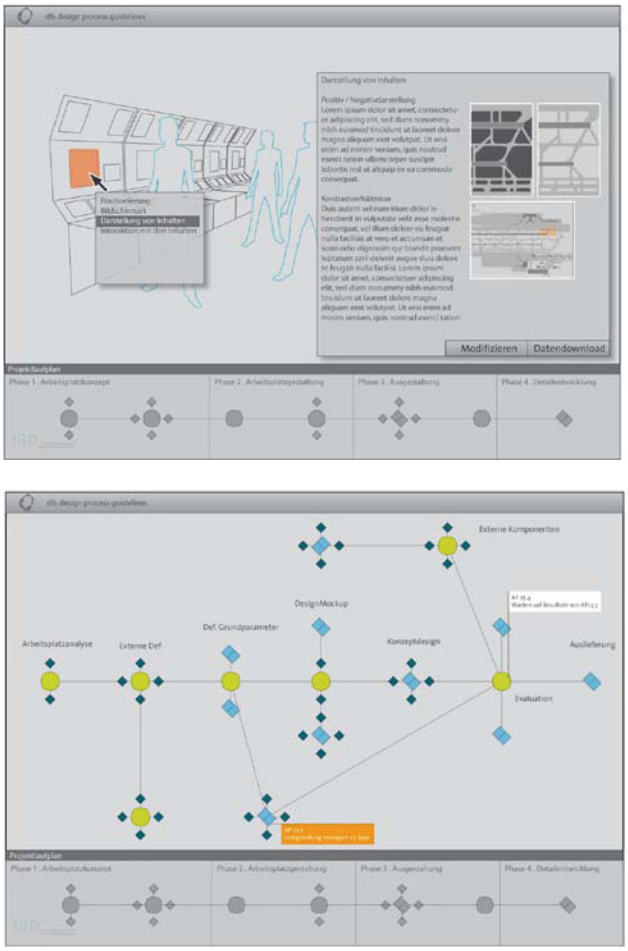

***FIG. 8** Design Process Guide design studies*

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