Moving Integrated Product Development to Service Clouds in the Global Economy
J. Cha et al. (Eds.)

doi:10.3233/978-1-61499-440-4-223

Human Expertise as the Critical Challenge in Participative Multidisciplinary Design Optimization - An Empirical Approach

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Abstract. Research into future air vehicles incorporating novel technologies is characterized by a high number of interacting disciplines which need to be considered. Despite advances in numeric interfacing techniques for participative Multidisciplinary Design and Optimisation (pMDO), it is not well understood how to build a team of specialists who jointly operate shared tools and gain system level insight. This contribution shifts focus to the human MDO participants and their working environment. Three aspects of collaboration are considered: (a) design of cognitive experiments to measure engineering performance in different settings; (b) integration of prior experience through a Lessons Leaned process; and (c) the application of the above into the enhancement of Integrated Design Laboratory (IDL). The pronunciation of competence and working environment, rather than software tools or data, opens opportunities for attractive use cases..

Keywords. Collaborative performance, expert interview, performance measures, empirical research, aircraft design, multidisciplinary design and optimisation (MDO), participative MDO (pMDO).

Introduction

Research into future air vehicles incorporating novel technologies is characterized by a high number of interacting disciplines which need to be considered [1,2]. High levels of fidelity are often mandatory. Multidisciplinary Design and Optimization (MDO) provides techniques which interlink heterogeneous analysis tools in distributed work-flows to drive the design into optimum solutions. Although numerical approaches have become powerful enough to solve many complex problems of computing, the operation of extensive analysis systems still poses a major challenge today. However, in contrast to numeric interfacing techniques, it is not well understood how to build a team of specialists who jointly operate shared tools and gain system level insight [3,4].

This contribution discusses three critical aspects of collaborative performance. Firstly, experimental investigations are presented that specify relevant psychological and cognitive aspects [5]. Specifically, a tool-box of collaborative performance measures is introduced and first results are shown. Next a Lessons Learned approach at

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the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) is presented that can support the quest to understand human factors in participative MDO. The fundamental knowledge about mechanisms of collaboration is informative for the development of DLR's Integrated Design Lab (IDL). Finlay, the IDL is introduced as working space for both - to conduct collaborative design in aerospace projects, and to investigate collaboration methodologies. Besides visualization and communication, techniques for handling knowledge constitute a central element of the IDL.

Experience shows that design in teams of heterogeneous experts requires innovative practices and methodologies in collaboration, taking into account the different stakeholders' views. The paradigm shift toward the pronunciation of competence, rather than tools or data, opens opportunities for a joint system competence with attractive business cases for all stakeholders.

1. Experimental Research

We designed an experimental paradigm to probe how different forms of visualisations can influence engineering performance. The experimental design is based on preceding numerical tests [6] and pilot experiments [5], which helped narrow down a set of input and output parameters for an aircraft design. Experiments are performed via a Graphical User Interface (GUI) task that allows to (a) control different visualisation versions; (b) simplify the usage for the participants; and (c) track participants behaviour.

1.1. Participants

A total of 14 engineering students (four female) who had not yet taken any courses in aircraft design were recruited to participate in the experiment. According to the ethics regulations of the German Psychology Associations (DGB and BDP) [7], each participant provided voluntarily informed consent.

1.2. Material

Two high-performance laptops were set up with the necessary software tools. To keep laboratory investigation close to real work scenarios, experimental studies are based upon VAMPzero [8,9], which is the software tool used to study preliminary aircraft design configurations at DLR. Calculations are initialised with a data set comparable to the Airbus aircraft A320-type that is provided as a CPACS file (CPACS is a xml-based common language for aircraft design, see [2]). To create new designs, participants can interactively modify control parameters of the A320-type data set and then iterate VAMPzero through a GUI. In a previous study [6], a set of control (i.e. input) and output parameters were narrowed down, as given in Table 1. The control parameters are *Bypass Ratio (BPR), Wing Span*, and *Design Range*; and the output parameters are *Direct Operating Costs (DOC)* and *Operating Empty Mass (OEM)*.

Table 1. Input and Output parameters of the aircraft design task.

type	control parameters			output parameters	
name	design range	wing span	bypass ratio	DOC	OEM
range	350 - 7000	14 - 44	3.5 - 7	4000 - 12000	3 - 130
step-size	eight discrete	continuous	continuous	n/a	n/a
unit	[km]	[m]	[-]	[EUR/h]	[t]

Input and output parameters ware displayed either as plots or as tables, depending the respective experimental condition, Plots or Tables. Thereby two different versions of the GUI were used, both are shown in Figure 1. Each GUI is divided in three sub-panels:

- input parameters could be set and trails iterated via the Control panel (top);
- the history of input values was displayed in the Input Display panel (middle);
- the resulting output history was the Output Display panel (bottom).

Figure 1. Plots and Tables versions of the experimental GUI.

1.3. Procedure

Participants were randomly assigned to either the *Plots* or *Tables* condition. On each trial, they could manipulate the given control parameters (Table 1) and then run VAMPzero. When the iteration was completed, the input- and output parameters were displayed in the respective GUI panels (Figure 1). Based on these results, participants could interactively optimise an aircraft design.

All participants were explicitly advised that they should optimise their designs with respect to both output parameters *DOC* and *OEM*. They had a maximum of 25 trials or 40 minutes, whichever came first, to complete the optimisation.

1.4. Analysis

For each participant, all input and output parameters (Table 1) were recorded per trial. For trials with non-feasible designs, the outputs were set to *NaN*. A time-step for each start of a trial and the duration of the entire experiment were also recorded. Additional data-items were also collected but are not subject of the current analysis. The focus here is on the effects of Quality of information that is compared in the Plots versus the Tables conditions. The effects of the experimental control variable Quality are analysed with respect to the following dependant variables:

min-DOC the minimal *DOC* value, that a participant has achieved;

min-OEM the minimal *OEM* value, that a participant has achieved;

min-COMB the combined minimum of (*OEM+10DOC*), which a participant has achieved among all their values (the factor 10 was selected to offset the different orders of magnetite in VAMPzero calculates the two parameters);

Duration the time a participant needed to finish the design session (out of maximal 40 minutes);

Trials the number of trials a participant needed to finish the design session (out of maximal 25 trials).

The dependent variables are reported in Figure 2 in dedicated subplots from top to bottom. Each subplot shows how the dependent measurements (values on the y-axis) change with respect to the experimental condition (it assumes the values Plots or Tables on the x-axis, these are aliened among subplots). Note that for compression these values of the dependent measures are scaled to a decimal power of two. Per subplot, the following is shown:

(a) values of the experimental variable for each individual participant (narrow light grey bars);

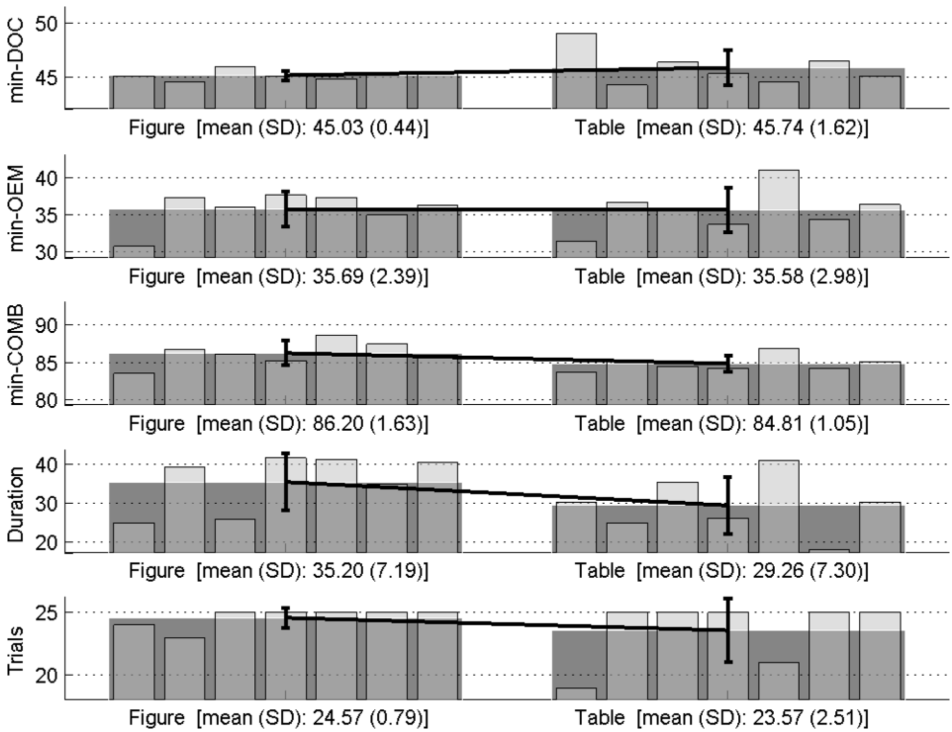

Figure 2. Experimental results: in each subplot a dependent measure is plotted on the y-axis against the experimental condition on the x-axis.

(b) means of the experimental variable among participants in the given condition (broad dark grey bars);

(c) standard deviation per condition (black error-bars, assigned to the means in (b), means are connected with a black line);

(d) mean values and standard deviation values are reported in the labels for each combination of control and dependent variables.

No significant effects could be found. This might be due to the small number of participants of only seven per conditions. Thus, we are continuing to collect data. Few interesting tendencies can be observed. It is worth noting that these tendencies persist when the same analysis is done with an extended data set of additional seven participants who performed the same task but were provided with more information [5].

On average, participants in the *Table* condition tend to be faster and to achieve a better combined minimum, *min-COMB*, than these in the *Plots* condition. The later is a surprising finding, as we were anticipating that global patterns would be easier to identify in the *Plots* condition. What might be the case, is that participants in the *Plots* condition focus more strongly on minimising the *DOC* values. This, in turn and better to be seen in plots than in tables, might be because the *DOC* parameter is more sensitive to changes of the input parameters than *OEM*.

That the *Table* condition is faster, both shorter *Duration* and less *Trials*, is less surprising. Subject tend solve the task more efficiently when using tables because, as some of them report, they simply optimise values and, with exceptions, do not try to conceptualise what the aircraft design is about. This highlights the need to compare the results of the numeric iterations task at hand with a task that requires conceptual thinking. Such an experimental extension will help indicate which types of task are better supported with which visualisation type.

1.5. Conclusion

The focus of this study is to identify the role of context: Do different types of visualization have an impact on how people of an aircraft design task? To measure the impact of visualisations, the underlying task is intentionally kept simple. The critical observation from the above Analysis and the proceedings studies [5,6] about the experimental approach is that we need find way to extend the task to assess conceptual level thinking. Still, the task needs to be as simple as possible but also as complex as necessary. One avenue to better capture the right level of complexity is to investigate how people operate in current participative MDO projects. For this, a lessons learnt process should be implemented in the participative MDO projects. Lessons learnt are based on debriefing project members and aim to capture what worked well in project and what has failed. To gain a comprehensive empirical approach to the human factors in participative MDO, the experimental studies should be linked to a systematic Lessons Learnt process.

2. Lessons Learnt

The innovative nature of projects entails that the project participants gain new insights constantly during a project [10, p. 5]. If they document such new knowledge in an appropriate manner, this knowledge becomes organisational experience value or “Lessons Learnt”, especially for the project participants. Lessons Learnt, both of positive and of negative experiences are derived project experience and describe accordingly optimisation opportunities, chances or risks.

Lessons Learnt can relate to aspects of management (e.g. organisational) and the project object (e.g. project approach). The main feature of Lessons Learnt is that it is based on practical experience and is not derived theoretically. In the right context, the benefit of Lessons Learnt is therefore very high, but is has to be clear to all project partners, that Lessons Learnt is not only a document which has to be created to close a project formally. More than that, Lessons Learnt can be of a high value if they are available for other project managers in the same organisation before they start a new project [11, p. 133f.].

DLR has gained a lot of experience with Lessons Learnt. As many organisations worldwide, DLR uses the standards of the Project Management Institute (PMI) in project management. To close a project, it is necessary to have the Lessons Learnt document finished and accepted. On the other hand, Lessons Learnt are an important part of the project quality management [10, p. 214].

To increase the value of Lessons Learnt it is recommended, that Lessons Learnt are understood as a periodic process which accompanies a project during its life cycle [12, p. 288f.]. The project manager can use the methodology of Lessons Learnt during the project fulfilment. A good Lessons Learnt process starts with the project itself. It has to evaluate both the positive and also the negative results and incorporate the causes / actions in a standard process for projects. The positive aspects are important to confirm the process and consolidate. The negative experiences are required to identify the causal relationships between cause and false results in order to derive meaningful measures or action plans for the future. Measures are necessary to avoid the repetition of experienced negative results. This implies that such a standard process for Lessons Learnt exists.

The knowledge management team of DLR developed an improved standard process for internal Lessons Learnt, captured in Figure 3. If the process is implemented, it raises project quality. For instance, Lessons Learnt methods show that many problems can be observed at an early stage and can be solved before they affect the project success.

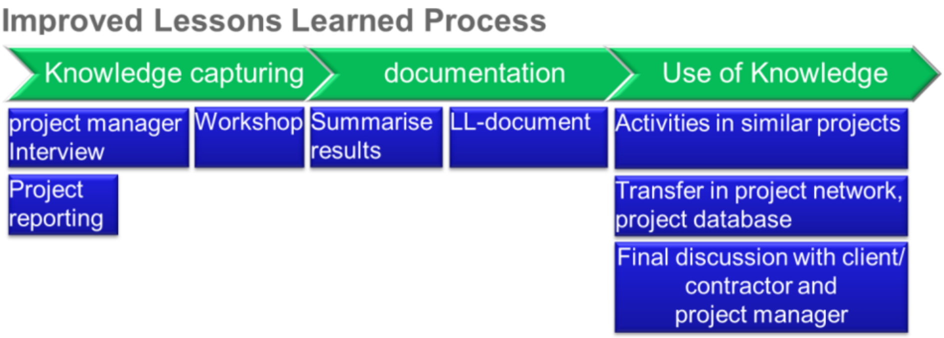

Figure 3. The DLR Lessons Learnt three step process.

In the first step, the project knowledge gets captured (Figure 3). Information about the output data (cost, time, results etc.) can be found in the project controlling or reporting. Not only the project manager has the relevant information about the project but the project team members have it, too. Besides a debriefing of the project manager a workshop with all relevant project members should be taken into account periodically in a project. Then the relevant information must be summarised and written down into the Lessons Learnt document (step 2). To have an advantage in further projects from the Lessons Learnt they need to be disseminated. Therefore, in step 3 the knowledge gained has to be transferred in databases, networks other projects etc. Knowledge management techniques can help to share the Lessons Learnt with other employees of the organisation with social collaboration tools like wikis. After the dissemination of Lessons Learnt, a final discussion with the customer considering the Lessons Learnt should lead to close the project. This way the Lessons Learnt are still available for other projects.

This process is most effective, if Lessons Learnt from other related or similar projects are regarded before a project begins. In this way the project team members can learn from other projects by avoiding failures and adopting positive effects which were found out before.

3. The Integrated Design Laboratory

In order to extend DLR's capabilities for tightly coupled multidisciplinary collaboration processes, the development of a real, tangible laboratory plays an equally crucial role in testing innovative concepts as assessing Lessons Learnt and developing new modes and methods for interdisciplinary software integration. The DLR project iTALENT was initiated at the institute of Air Transportation Systems and subsequently funded by the city of Hamburg in 2010/2011 [13]. The project targets the use of laboratory rooms and to provide essential equipment for participants and research personnel.

The original goal of iTALENT was to establish a laboratory and simultaneously determine what tools and techniques are needed for engineers to work most efficiently in it. The mustered total of all tools, know-how, and equipment gathered in the laboratory is supposed to provide a blueprint for further instantiations of similar labs, and by steady recurrent self-critical analysis, improve collaborative teamwork within the IDL on site. The agile, Lessons Learnt approach allows to be flexible enough to include intermittent research results within the time scope and between related projects. One of these derived laboratories is scheduled to be set up within the *Center for Applied Aeronautical Research* (ZAL) [14] which is currently under construction and being staffed in Hamburg.

When the project was initiated, there were mainly strategic goals, which had to be translated into more technical, measurable objectives. The former include the strengthening of aviation clusters between industry, research, and education (knowledge triangle), as well as boosting the competitiveness of manufacturers and suppliers in the larger Hamburg region. Viewed from a different angle, the aim is to improve system comprehension of highly complex (air transport) systems and accelerate the assessment and development of new technological concepts by approaching them in a holistic way. Since mistakes made in early program phases bear the highest costs, this again has the potential to re- duce overall cost [1,4], time to production and allow more studies to be performed before deciding on one concept.

To reduce the large option space for the laboratory construction, several live project examples and artificial or potential use cases were examined to elicitate requirements. By pairing use cases and technical options, a morphological analysis was performed to look for a prevalence of unambiguity or variability instead in the solution space. Obviously not all technical solutions would satisfy all use cases alike as there is still a lot of variability; we found, however, strong tendencies to certain solutions that allowed maximum flexibility for most considered cases.

For example, we consider the question what kind of video signals might need to be routed from where to where. This includes the question of transfer medium (analogue or digital, fiber or copper, software or hardware) but also scenarios of duplicating signals or having a M:N routing vs. central recoding of video signals (M:1:N). Another field is the provision of network connectivity vs. security concerns; how can we provide most convenient data connections while maintaining cleanly separated networks for different work groups and confidentialities? At least, we consider the technical requirements for the availability of computing resources. We have four different preferred solutions for the examined use cases, ranging from locally distributed, remotely distributed, centralized to remote access only. With our technical choice to use the Remote Component Environment (RCE) framework [15], in combination with virtual machines for other services, we could satisfy all requirements. This assessment of technical options led to the first laboratory prototype which is available since 2012 and has seen further iterations due to annual reevaluations. The laboratory rooms were initially opened for internal projects [13]. The IDL is divided into a capacious main design room of about 190 m^2, a conference room, a server room, and a catering/communication area “Lounge”. The IDL rooms aggregate to about 440 m^2 and are set on the elevated ground floor and, thus, easily accessible.

Figure 4. Initial display setup (left), possible desk arrangements (both sides).

During the first project year, the main prototype display was built from a three-fold divided reflective screen with front projectors, ten working tables on reels with built- in monitors, an arsenal of cables, adaptors and converters, and a video streaming sys- tem (Figure 4). It became obvious, however, that the location of two structurally necessary pillars of the building had adverse effects for seating arrangements within the main room, because they shadowed the line of sight to the main screen for participants in the back area. This can be circumvented by aligning working desks in a relatively narrow U-shape, which is incidentally the most favourable arrangement in most cases anyway (Figure 5). From workshop participants we received feedback that having a large tilt-able, rotatable monitor available at every working desk, in addition to the participants’ own portable computers brought along used as primary display was seen as very beneficial during meetings. It restored a equipment level more familiar and similarly equipped as their static office work spaces, but also allowed better technical foundation to discuss details with seat neighbours or within small ad-hoc groups. This two-display setup has the additional benefit sharing only one display via network streaming while at the same time the user’s notebook monitor remains private.

The U-shape of table arrangement proved to be used most often and optimizes the physical communication distances. A good viewing angle is important during presentations; this is less an issue for discussion-oriented meetings (and so far we have not received complaints about stiff necks). When the group is split into smaller subgroups, an "island" desk configuration can be used; the disadvantage of it is the slightly bigger effort in setting up power connections. The advantage is better use of available space, since all sides of tables can be used (O-shape), and it's possible to place more people at the table corners, if not much personal table space is required.

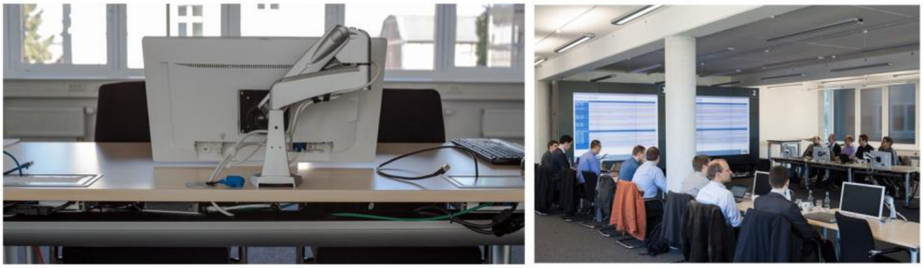

Figure 5. Fully connected movable desk (left), typical workshop situation (right).

The Lounge has successfully been used for catering and socializing during breaks. While keeping the lab itself clean of food and drinks, the "change of scenery" also fosters creativity. After the evaluation phase with the prototype setup, it became obvious that the three- projector divided screen setup was simply too massive and unwieldy for the available lab area, and the divison of signals between three projectors was neither logical nor justified. The immersive, curved screen setup was thus replaced by a segmented display fitted to the room size, consisting of 18 backlit LED mirror projection systems (Figure 6). This enables an overall larger resolution of 8400:2150 pixels with an extremely improved image contrast which spares operators from shading the room from sunlight. We kept the software-based video streaming system that allows placing contents anywhere on any connected displays; for daily use, however, a very simplified and user-friendly wireless hardware appliance for user screen scraping is preferred now due to its better performance and easier setup.

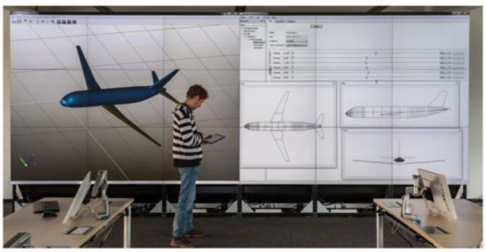

Figure 6. The new main screen of the IDL since 2013 (left), official IDL logo (right).

The working desks have been updated to connect with two separate networks - one for user communication, and another for dedicated video streaming. The latest addition to the previous development phases is the purchase of more powerful computing hardware to consolidate often used simulation software on site. This tremendously improves data transfer speed between scientific codes as well as between user machines, since all tools reside on servers within the same hardware rack. The existing infrastructure of DLR- wide distributed simulation codes will of course continue to offer the same tools for interdepartmental distributed collaboration as before by means of the RCE framework.

4. Conclusion

The steady observation of collaboration processes within the IDL enhances the physical as well as methodological environment for engineers that work there. The systematic experimental research and the application of Lessons Learnt processes support the fundamental understanding of how to improve the IDL as productive working environment. This results in improved understanding, quicker assessments and time reduction. The outcome of iTALENT and its upcoming follow-up projects is a comprehensive manual consisting of a technical system description, best practices and a generic laboratory blue- print for the generation of similar research facilities.

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