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EMPIRICAL ANALYSIS OF PRODUCT DESIGN WITH DIFFERENT TIMES AND INTERRUPTION LEVELS

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ABSTRACT
Effective and robust engineering design processes are vital in early phases of a product life cycle, such as in product design. This highly dynamic field of work is influenced by many interacting, partly conflicting factors, which require methodical human input. However, there is little research on the education in product design. It is essential to teach junior engineering students systematic approaches which allow them to reliably cope with this volatile field of work. In this paper, the design and the results of a large-scale product design experiment (79 participants) with five product design tasks are presented. This experiment is based on the levels of systematic design by Pahl et al and on the description of human reliability by Rasmussen. It is part of an exam for the education of junior engineering students of mechanical engineering, which aims to teach junior engineering students design methodology which helps them to work effectively in this volatile field of work. In this setting, the effects of "interruption frequency" and "amount of available time" on both product requirement fulfilment and on the subjective workload are focused on. The analysis of these empirical results provides more insight in the fields of teaching design methodology in education and contributes to a better understanding of factors shaping human reliability in product design.

Keywords: Teaching design methodology, human reliability, product design, interruption, time

1 PRODUCT DESIGN

In this paper, the central question is how to teach and to test product design ability. Focus lies on the development of an empirically validated methodology which allows the evaluation of product design results. Pahl et al describe product design as the iterative fulfilment of product- and process-related requirements according to the respective requirement levels [1]. Product design requirements are often conflicting, because initial and final states can change rapidly and are often not fully known. In addition, requirements of the preceding and subsequent product life cycle stages have to be dealt with. According to Roth, requirement fulfilment is hard to automate, and therefore demands high levels of human input [2]. These multi-level requirements can be categorized by four levels of systematic engineering design [1]:

- The system interrelationship level deals with the product as a part of an overarching system. Processes establish external input-output-relations, and result is the systems structure of the product. Requirements on this level are very highly abstract.
- On the functional interrelationship level, processes describe the internal relations between input and output within the product, result is the functional structure of the product. Function requirements have a high abstraction level.
- The working interrelationship level focuses on processes which describe relevant laws of physics as well as geometrical and material constraints. Result is the working structure of the product. Working requirements have a medium abstraction level.
- On the constructional interrelationship level, processes concern the design of concrete components and assembly joints, and result is the constructional structure of the product. The abstraction level of constructional requirements is low.

Pahl et al describe that product designers prefer to work on the lower, concrete interrelationship levels, but that a deeper understanding of product design requires knowledge on the higher, abstract interrelationship levels [1]. Product design focuses on product- and process-related requirements, but provides only little information on the product designer. The influence of human factors is not evident.

2 HUMAN RELIABILITY IN PRODUCT DESIGN

Due to the volatility of product design, this field of work requires creative, methodological human input, which is often related to the level of real-life experience [2]. It is vital to teach inexperienced junior engineering students ways how to fulfil the complex, often contradictory requirements of product design, because a high level of human reliability on all levels of systematic design is essential. Rasmussen describes human reliability as the "human characteristic to perform the required function in the desired manner under all relevant conditions and during required time intervals" [3]. He points out humans are variable, adaptive and able to learn, so that human reliability can only be analyzed by taking the entire work system into account. Based on a complementary definition of human reliability and human malfunction, Rasmussen defines a "multi aspect taxonomy for description and analysis of human malfunction", in which he describes numerous factors [4]: e.g. "Performance Shaping Factors" relate to human workload, motivation or affection, "Personnel task" highlight task characteristics or physical environment, and "Situation Factors" concentrate on situational variables. Some factors are largely time-persistent, others are time-dependent. These aspects influence "External Mode of Malfunction", i.e. when the fulfilment of a requirement is omitted or not handled according to the respective requirement level. Frequency and severity serve as indicators for the level of human reliability. For workplaces with technical systems, Rasmussen and Lind describe a knowledge-based abstraction hierarchy with five levels [5]:

- Functional purpose, in which the main function must be interpreted correctly,
- Abstract functions, in which input-output relations have to be expressed,
- Generalized functions, which emphasizes listing all system-applicable laws of nature,
- Physical functions, which deals with right quantification of the relevant natural laws,
- Physical form, which focuses on correct physical dimensioning and structuring.

Both a general description of human reliability and a taxonomy of influence factors can be provided. To apply this taxonomy to product design, the requirements in this field of work must be included. Human reliability in product design focuses on the situational fulfilment of product- process-, environment-related product design requirements on all levels of systematic engineering design, dependent on product design-relevant aspects of human reliability. In addition, product design requirements are volatile, and the fulfilment is often iterative and takes time. To account for the time-dependant nature of product design, two temporal variables are included, namely T (i.e. available time of the entire product design process, derived from the project schedule) and t (i.e. elapsed time since start of the product design process). Three phases can be differentiated:

- Start of the product design process ($t<=0$), in which "time-persistent" factors are in effect, i.e. factors which hardly change during the process (e.g. the intended main product function)
- During the product design process ($0<=t<T$), both time-persistent and time-dependent factors of product design are in effect.
- After completion of the product design process ($t>=T$), the results and their consequences provide the base for the next iteration. These external modes relate to both person and product.

This phase-oriented taxonomy for description and analysis of human reliability in product design provides the base for an original definition of human reliability in product design:

Human reliability in product design is the human ability to fulfil time-persistent and situative product, process-, and environment-related product design requirements according to the respective requirement levels methodically with the use of creative-informational work. These requirements must be completely fulfilled at the end of stipulated times according to the system, functional, working and constructional interrelationship levels as well as further steps of product design, when results are forwarded to cooperating work persons in the same area, or to preceding and subsequent areas. This includes intermediate results, if e.g. multiple iterations are needed to search or to implement a design solution, or design malfunctions are identified or corrected.

3 DESIGN METHODOLOGY

Based on the above paragraphs, a methodology for an experiment with the aim of testing and teaching product design in educational settings on all levels of systematic design and according to the descriptions of human reliability in product design can be designed. This approach represents part of an exam for the education of junior product designers. The idea is to develop a basic, continuous product design process, in which every task corresponds to a level of systematic design, and every task consists of the fulfilment of product design requirements according to the respective requirement levels. Research hypotheses focus on variables which are relevant from the perspective of testing and teaching junior engineering students. In this paper, the factors "amount of available time" and "frequency of interruption" according to McFarlane are focused on, who describes interruptions as "process of coordinating abrupt change in people's activities" [6]. The effect on the "level of product requirement fulfilment" is analyzed, especially in connection with the level of systematic design, and also serves as an indicator for the level of human reliability. As an extraneous variable, the level of subjective workload is documented. Following research hypotheses are analyzed in this paper:

- H_1: "The higher the abstraction level of a task, the more product requirements are omitted."
- H_2: "The lower the abstraction level of a task, the more product requirements are unsatisfactorily fulfilled."
- H_3: "The higher the abstraction level of a task, the less product requirements are fulfilled."
- H_4: "The more frequently interruptions occur, the less product requirements are fulfilled."
- H_5: "The more time is available, the more product requirements are fulfilled."
- H_6: "The more frequently interruptions occur, the more subjective workload is felt."

Previously, Djaloeis et al. conducted a similar product design laboratory experiment with 111 participants [7]. It was observed that H_1 could be descriptively confirmed, because on higher abstraction levels, the participants omitted more requirements: concrete requirements seemingly are easier to begin with. However, H_2 was also confirmed, indicating that these more concrete requirements are harder to fulfil according to the respective requirement levels than more abstract ones. There was no conclusive statement for H_3, but for H_5, it was confirmed that the amount of available time significantly relates with the level of product requirement fulfilment, but not with the level of frustration (H_6) [7]. In other settings, Monk experimentally observed that participants, who were more often interrupted, resumed their work more correctly [8]. Basoglu et al. analyzed that interruption frequency correlates with the level of mental strain [9].

4 LABORATORY EXPERIMENT

Based on the above mentioned hypotheses, a two-hour laboratory study was designed, in which participants conduct a complete basic multi-part product design process. The product was a pencil sharpener with a crank. The experiment provides a methodology for teaching design which focuses on the examination of junior product engineers. In this experimental setting, each task corresponds to a single level of systematic engineering design. They are similar to the prior above mentioned laboratory experiment by Djaloeis et al. [7]:

- In Task FS, the participants sketch the functional structure of a given product, and in the next task FA, a functional analysis is conducted: both refer to the functional interrelationship level.
- In Task PS, improvements based on a set of additional requirements are designed and sketched in a principle solution, focusing on the working interrelationship level.
- In Task 3D_D, one part of the product is drafted using a Computer Aided Design (CAD) system, and in Task 3D_A, that part is used to digitally assemble the complete product: among others, these tasks highlight the constructional interrelationship level. As the CAD tool, the participants could either choose ProEngineer 3 or NX 5.

For each task, a product requirement list is compiled, and each requirement represents an item which allows evaluation of the respective result. For example, in task 3D_D, one generic requirement / item is "is the hole attaching the crank to the sharpener correctly dimensioned?" Possible outcomes are "requirement fulfilled", which represents the best possible outcome, and two external modes of malfunction, namely "low fulfilment" ("visible attempt to fulfil requirement, but fulfilment level is too low") and omission ("no visible attempt to fulfil requirement"). Because the experimental focus is educational, and the experiment therefore has a limited duration, the requirements are non-hierarchical, and the number of requirements is fewer and their respective fulfilment levels are lower than in real-life situations, where requirements are numerous, hierarchical and must adhere to strict industrial standards. By categorizing and counting the occurrence of fulfilments or the two above mentioned external modes of malfunction (omission or low fulfilment), an indication for human reliability in product design is provided, and the product design results of the participants in an educational setting can be provided. In addition, personal data, relevant academic and work experience, subjective workload according to the NASA-TLX assessment technique [11] as well as video footage and a 10-minute feedback interview is anonymously compiled. The experiment was carried out in the laboratories of the Institute of Industrial Engineering and Ergonomics at RWTH Aachen University. The participant sample consists of 79 junior engineers, all of them students in higher semester engineering classes at RWTH Aachen University. They participated on a voluntary basis and could earn extra credit for their engineering class, and only students who had successfully passed the university exam "Introduction to CAD" were considered. The participants were mostly male (92%), had a mean age of 22.98 (SD = 1.54), generally evaluated themselves as "medium or highly experienced" in technical drawing (70%), but only "little or not experienced" in the design of actual products (63%) as well as in mental calculating (81%). The main factor in this study is the frequency of interruption, where three factor levels INT_{none} (no interruptions), INT_{few} (nine interruptions) and INT_{many} (18 interruptions) are defined (see Table 1). In each interruption, the participants were presented with a sheet of paper with two four-digit numbers (e. g. "4512 + 8633"), which they had to mentally add and write down the answer. "Time on task" (TOT, i.e. available time) and "time on interruption" (TOI) are documented separately. The basic interruption pattern is regular, but to avoid anticipation, the concrete times are scattered using a normal distribution of up to 24 seconds. The secondary factor is the amount of available time, with two factor levels T_{less} (TOT=57 minutes) and T_{much} (TOT=71 minutes, see Table 1). The 79 participants are subdivided into six groups: $INT_{none}T_{less}$, $INT_{none}T_{much}$, $INT_{few}T_{less}$, $INT_{few}T_{much}$, $INT_{many}T_{less}$ and $INT_{many}T_{much}$. A between subjects design was chosen, and each person participated exactly once in this experiment, i.e. no repeated measure was carried out. The dependent variable is "fulfilment of product requirements", which is measured in three levels (successfully fulfilled, low level of fulfilment, or omitted) and "subjective workload" is documented extraneously.

Table 1. Experimental design with number of interruptions (int) and Time on Task (TOT)

	$INT_{none}T_{less}$	$INT_{none}T_{much}$	$INT_{few}T_{less}$	$INT_{few}T_{much}$	$INT_{many}T_{less}$	$INT_{many}T_{much}$
Functional structure (FS)	0 int, 5 min	0 int, 6 min	1 int, 5 min	1 int, 6 min	2 int, 5 min	2 int, 6 min
Functional analysis (FA)	0 int, 10 min	0 int, 12 min	2 int, 10 min	2 int, 12 min	4 int, 10 min	4 int, 12 min
Principle solution (FS)	0 int, 16 min	0 int, 20 min	2 int, 16 min	2 int, 20 min	4 int, 16 min	4 int, 20 min
CAD Design (3D_D)	0 int, 10 min	0 int, 13 min	2 int, 10 min	2 int, 13 min	4 int, 10 min	4 int, 13 min
CAD Assembly (3D_A)	0 int, 16 min	0 int, 20 min	2 int, 16 min	2 int, 20 min	4 int, 16 min	4 int, 20 min
Total	0 int, 57 min	0 int, 71 min	9 int, 57 min	9 int, 71 min	18 int, 57 min	18 int, 71 min

5 EXPERIMENTAL RESULTS

First descriptive analysis hints that several non-linear relations between the levels of systematic design and the quota of product requirement fulfilment can be observed (see Table 2).

- *H_1: "The higher the abstraction level of a task, the more product requirements are omitted.":* Regarding H_1, if the pen-and-paper tasks FS, FA and PS are analyzed, it is evident that the participants omitted the most requirements in the task FA, which relates to the functional level. However, further analysis is difficult, because in the tasks 3D_D and 3D_A, the level of omitted requirements was extremely high, hinting that in specialized CAD tasks, the score is more dependent on CAD ability than on the abstraction level of the task.
- *H_2: "The lower the abstraction level of a task, the more product requirements are unsatisfactorily fulfilled.":* For this hypothesis, the results are similar. In the pen-and-paper tasks FA, FS and PS, the task PS generally resulted in the highest quota of low, unsatisfactory requirement fulfilment: however, these numbers are eclipsed by the 3D_D and 3D_A tasks.
- *H_3: "The higher the abstraction level of a task, the less product requirements are fulfilled.":* It

was observed that the task FS produced the highest quota of fulfilled product requirements, followed by tasks PS and FA, and with tasks 3D_A and especially 3D_D delivering a very low rate of fulfilled requirements. At the first glance, the relation between abstraction level and fulfilment of product requirements seems unclear, but if it is taken into account that task FS was designed as a warm-up task which is less difficult than the other tasks, it becomes plausible.

- *H_4: "The more frequently interruptions occur, the less product requirements are fulfilled.":* For the effect of interruption frequency on product requirement fulfilment (H_4), in tasks FA, PS and 3D_D, the INT_{few} participants had the least probability to fulfilling a requirement, scoring worse than the INT_{none} and INT_{many} groups. In the 3D_D and 3D_A tasks, which had the lowest average scores, the INT_{many} groups outscored their INT_{none} colleagues: H_4 cannot be confirmed.
- *H_5: "The more time is available, the more product requirements are fulfilled.":* This relation seems clearer: the participants with more time (T_{much}) generally outscored their T_{less} colleagues. This indicates that H_5 can be confirmed, but the separation was lower than expected.
- *H_6: "The more frequently interruptions occur, the more subjective workload is felt.":* It was surprising to see that there was virtually no difference between the INT_{none} groups (average workload=65.7, SD=8.1), INT_{few} groups (63.5, SD=7.2) and INT_{many} groups (65.2, SD=8.6).

Regarding the interruptions themselves, the participants of both INT_{few} subgroups on average solved 84.9% (SD=15.8%) of all interruptions correctly and on average needed a TOI (time on interruption) of 14.1s (SD=7.2s), and the participants of both INT_{many} subgroups on average solved 82.6% (SD=10.9%) of all interruptions correctly and on average needed a TOI of 14.2s (SD=4.6s).

Table 2. Experimental probability of requirement fulfilment (n=79)

Task	Outcome	$INT_{none}T_{less}$	$INT_{none}T_{much}$	$INT_{few}T_{less}$	$INT_{few}T_{much}$	$INT_{many}T_{less}$	$INT_{many}T_{much}$
FS	Fulfilled	76.37%	66.15%	72.00%	74.29%	67.14%	63.33%
	Low level	9.09%	26.15%	12.00%	14.29%	20.00%	26.67%
	Omission	14.55%	7.69%	16.00%	11.43%	12.86%	10.00%
FA	Fulfilled	61.82%	69.23%	44.00%	60.00%	48.57%	76.67%
	Low level	16.36%	7.69%	17.33%	11.43%	20.00%	1.67%
	Omission	21.82%	23.08%	38.67%	28.57%	31.43%	21.67%
PS	Fulfilled	74.55%	58.46%	54.67%	60.00%	58.57%	48.33%
	Low level	10.91%	24.62%	33.33%	21.43%	24.29%	35.00%
	Omission	14.55%	16.92%	12.00%	18.57%	17.14%	16.67%
3D_D	Fulfilled	20.00%	36.92%	33.33%	28.57%	37.14%	33.33%
	Low level	20.00%	26.15%	26.67%	28.57%	22.86%	28.33%
	Omission	60.00%	36.92%	40.00%	42.86%	40.00%	38.33%
3D_A	Fulfilled	12.73%	9.23%	14.67%	21.43%	14.29%	15.00%
	Low level	34.55%	43.08%	46.67%	21.43%	40.00%	51.67%
	Omission	52.73%	47.69%	38.67%	57.14%	45.71%	33.33%

6 DISCUSSION AND OUTLOOK

The experiment presented in this paper represents an approach to test and teach junior engineering students in an educational product design setting, methodologically designed according to the levels of systematic design and to the descriptions of human reliability. Non-linear relations of the levels of systematic design on the fulfilment of product requirements were analyzed, which can be clarified by taking several extraneous effects into account. Descriptively, the results of the previously conducted experiment by Djaloeis et al. [7] are confirmed, in which functional requirements (FS, FA) are often omitted, hinting that the high level of abstraction is difficult to cope with. In return, more concrete tasks (PS, working level) are harder to conduct satisfactorily, indicating that these concrete requirements require more input. For successful requirement fulfilment, no clear analysis is possible, indicating a mix of both effects. In the prior experiment by Djaloeis et al., the respective FS task was evaluated as "too hard" and the respective CAD tasks "quite easy": in this updated design, the new FS task turned out to be very simple, and the new 3D_D and 3D_A tasks very hard, so the difficulty (or the lack of it) seems the greatest influence on the requirement fulfilment level, not the level of systematic design. If these effects are accounted for, the results of this experiment generally confirm the results of Djaloeis et al. [7], which indicate that the level of systematic design is relevant in these educational settings. This confirms that the experiment can be used to test and teach junior product designers, because it makes relevant engineering knowledge visible. However, several aspects of product design are difficult to reconstruct. The experiment focuses on the results at the end of the product design process, but not on the process itself. Especially in the CAD tasks, several participants created adequate solutions, but scrapped them after about half of the available time and attempted a second design, which was actually worse that the abandoned one. The reconstruction of this process would provide viable opportunities for further testing and teaching. Regarding the level of subjective workload and frustration, the participants generally interpreted the experiment as an exam-like setting, which explains the nearly equal values for all six groups. Interviews indicated that they generally did not seem disturbed by the interruptions, hinting that the disruption by the mental arithmetic was low. Preliminary analysis hints that the participants did not feel that the mental arithmetic interfered with their thought process, and that they also did not feel a high level of emotional invested. Also, even with participants who all passed the same CAD exam, applicable CAD experience seems an important covariate. A short hands-on CAD tutorial prior to the CAD task seems useful. For the use of this experiment as a means for teaching design methodology, the current setting with simple, unconnected and short tasks offers a viable way to quickly examine product design ability. To improve the validity, the task design could be changed. The tasks and the respective requirements can be designed as interdependent rather than isolated from each other. In addition, the tasks should be longer, or even without any time limits. Instead of providing five isolated tasks, the tasks could be interdependent, as often occurs in real-life product design situations. Also, interruptions with a higher disruptive force could be implemented (e.g. personal dialogue, simulated telephone calls), which have a higher impact. This way, a further contribution for testing and teaching design education can be provided.

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