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ORIGINAL PAPER

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Identification and application of requirements and their impact on the design process: a protocol study

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Abstract Establishing requirements is critical in designing, and therefore a central issue of design research. This article reports an empirical study, based on real-time protocol data about the design processes of four, experienced, individual designers, of how requirements get identified, clarified, and used in the design process, and how these influence the quality of its outcome - the emergent design. This is done by first identifying the activities and methods used by designers to identify and apply requirements during designing, and then investigating how these activities and methods relate to the success or failure of the eventual designs in terms of their degree of fulfilment of the requirements. The results indicate that the quality of the activities and methods used has a strong impact on the quality of the emergent design in terms of its degree of fulfilment of requirements, forming a basis for development of guidelines for effective requirement identification and application.

Keywords Requirements (engineering) · Requirements (management) · Protocol analysis · Design methodology · Descriptive study · Engineering design

1 Introduction

The purpose of design research is to support development of better products by developing a better design process. A design process is initiated with the recognition of a need, leading to the establishment of requirements for the intended product (Pahl and Beitz, 1984). Therefore, establishing requirements is essential, and should be a central issue in design research (Chakrabarti, 1994). A requirement is defined here as a characteristic which a designer is expected to fulfil through the eventual design. Several categories of requirments have been proposed and their importance proclaimed (French, 1985; Birkhofer, 1992). Several methods are suggested in the design literature for aiding requirement establishment, from check-lists (Pahl and Beitz, 1984; Shefelbine, 1998) and QFD methods (Pugh, 1991; Fox, 1993) to combination of both as a software support (Kruger and Knoll, 1994). The design process has been studied in several past studies and requirements remain part of these studies (Blessing 1994; Ullman et al, 1988; McGinnis and Ullman, 1994; Kruger, 1994). However, detailed investigation as to how requirements get identified, clarified and used in the design process and how they influence the quality of its outcome - the emergent design - has not been undertaken before. The research outlined in this article is a qualitative study aimed specifically at this. It uses protocol data gathered in an earlier research project about the design processes of four experienced, individual designers in a laboratory setting under which they designed a mechanical device, but uses new categorising and analysis techniques in order to suit the purposes of this study (details in Sect. 2).

The research reported here had two parts. The first part was an exploratory study of the protocol data in order to ask the following question: how do requirements get identified and clarified during the design process? The results are provided in terms of: a general overview of the design processes, a list of activities and methods used for requirement identification and application, and the various circumstances under which these requirements originated and the ways in which they were represented and stored.

The second part was an investigation of how these activities and methods relate to the success or failure of

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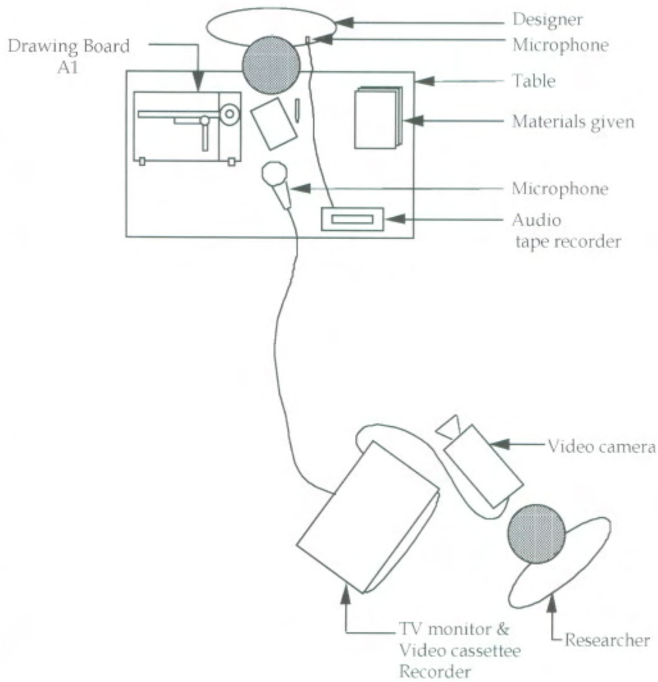
the eventual design in terms of its fulfilment of the requirements posed in the assignment[1]. This is then used to evaluate the usefulness of these activities and methods for requirement identification and application. The study was carried out by investigating three hypotheses: (i) many requirements remain insufficiently satisfied during design, (ii) requirement identification and application have a critical influence on this, and (iii) there are useful and harmful activities and methods for identification and application of requirements.

2 The design experiment

The experiment was originally carried out as part of a separate research project (Blessing, 1994), and was used for evaluating the effectiveness of a support tool in design. It used two groups of experienced designers (four in each group), one as control who were not allowed to use the tool during their design, and the other as the experimental group, who made use of the tool.

This research made use of the protocol data collected about the design processes of the four control designers. All the designers had more than ten years of experience in industry, and were experienced primarily in the area of mechanical design. Two of them, henceforth called CD1 and CD3 (i.e., control designers one and three respectively) were given a common assignment of individually designing a "swivel mounted mechanism" within a laboratory set up, see Fig. 1. The output of their individual design processes (i.e., sketches, comments, drawing of the final design and bill of materials) was collected. These were passed on to each of the other two designers, henceforth called CR1 and CR4 (to mean control re-designers one and four respectively), along with a slightly modified version of the assignment, for them to redesign the "swivel mounted mechanism" individually, within the same laboratory set up. Each designer was also supplied as further documentation several mechanical engineering handbooks, standard parts and materials catalogues and a description of the workshop in which the design was intended to be made. As a further information source, a researcher was at the designers' disposal, to whom questions could be asked and to which the researcher was to answer from a list of standardised, pre-prepared answers. Each designer, at the end of the design process, produced an embodiment drawing of the final design and a bill of materials and associated manufacturing instructions. The activities of each person during the design process were video and audio-taped. There was no time limit for completing the design. A 'think aloud' protocol (Simon and Newell, 1972) was used for externalising designers' activities during the design processes. The assignments for designers and re-designers are provided in Appendix 1.



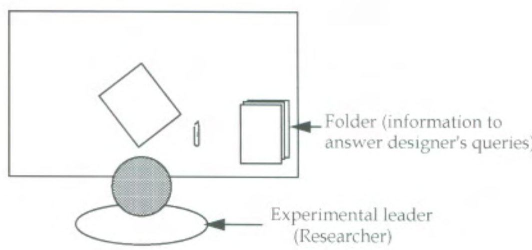


Fig. 1 Experimental Set-up (Blessing, 1994; Dwarakanath, 1996)

3 The exploratory study and its research method

Three questions were asked:

- *How does each single requirement get identified and applied?* To answer this, we need to detect the occurrence of requirements and associated activities and methods from the data.
- *Are there similarities among the requirement identification activities and methods employed by the various designers?* This will require bringing the identified requirements and their associated activities and methods, for all the designers, into a comparable form.
- *What are the circumstances under which these requirements identification activities and methods take place, and how are these handled?* For this, it must be possible to detect the circumstances of, and methods for handling each requirement.

[1] Choice of requirements fulfilment as a criterion for product success is common in design research (Fricke, 1993; Ehrlenspiel and Dylla, 1993; Blessing, 1994; Dwarakanath, 1996).

Table 1 Issues of events

No	Code	Category	Definition, Explanation
1	r	Requirement	A formulation of the characteristics which the design should fulfil.
2	i	Information	Any information related to a requirement that is neither a solution nor strategy.
3	s	Solution	A solution is a proposal of how a requirement or requirements can be fulfilled.
4	st	Strategy	A strategy is a plan of action of how to proceed through the design process.
5	e	Anything else	This refers to issues that are none of the above.

Table 2 Activities in events

No	Code	Category	Definition, Explanation
1	i	Identify	The designer comes across a specific instance of an issue for the first time.
2	g	Generate	The designer generates an instance of an issue (i.e., a specific solution).
3	r	Repeat	The designer re-utters an instance of an issue (i.e., a specific requirement).
4	e	Evaluate	The designer evaluates an instance of an issue (i.e., a specific information).
5	p	Interpret	The designer expresses an instance of an issue in a different form.
6	a	Ask	The designer asks about an instance of an issue, (i.e., a specific information).

Table 3 Combinations of activities and issues

No	Issue-Activity	Description
1	Identify requirement	Designer identifies a requirement, i.e., it appears for the first time in the protocol.
2	Identify information	Designer identifies any information except a requirement, a solution or a strategy.
3	Identify solution	Designer identifies a solution in a given design (only applies to CR1 and CR4).
4	Generate solution	Designer generates a solution.
5	Generate strategy	Designer generates a strategy to plan his course of action.
6	Repeat requirement	Designer repeats (remembers) a requirement.
7	Repeat information	Designer repeats (remembers) an information.
8	Repeat solution	Designer repeats a solution or parts of a solution generated or identified earlier.
9	Evaluate information	Designer evaluates an information.
10	Evaluate solution	Designer evaluates a solution as to how it fulfils a requirement.
11	Interpret requirement	Designer interprets a requirement, i.e., formulates it in another form.
12	Interpret information	Designer interprets an information.
13	Ask requirement	Designer asks about a requirement to the client (researcher).
14	Ask information	Designer asks for information, i.e., asks for, or states the need for more information.

3.1 Research method

Verbal data from the videos were already available, from the earlier project (Blessing, 1994), as a written transcription of chronological, textual events[2], with links to other information handled by the designer during these events, such as sketches made and documents consulted. In this project, these transcribed events were categorised in this project in terms of a new set of categories appropriate for the specific purposes of this study, and analysed. The analysis method had the following steps:

- *Obtaining a coarse understanding of the order, structure and connections between the parts of the data from the protocols.* In order to obtain this, several questions were asked: How did the sketches and drawings come up? How are these linked to one another?
- *Categorisation of the events in terms of a set of meaningful categories.* A set of "issues" and "activities" were chosen as the components for categorisation. Each event in the protocol was categorised in terms of an issue-activity pair, or as a set of issue-activity pairs.

  Issues of five kinds are considered: *requirement, solution, information, strategy* and *anything else* (see Table 1). Activities used were: *identify, generate, repeat, evaluate, interpret* and *ask* (see Table 2). Issue-activity combinations used are given in Table 3.

  Sometimes the same event is classified using a series of categories. When a designer handles more than one issue or carries out more than one activity in a single event, it is categorised with all these categories, in a logical order where possible. For instance, take the event where designer CD1 read part of the assignment "The mechanism is a one off product, to be manufactured as economically as possible in the workshop of the company". It is categorised by *identify information* ("the mechanism is a one-off product") and *identify requirements* ("to be built as economically as possible" and "in the workshop of the company").
- *Forming cluster of events based around each requirement.* This involves forming a history for each requirement in terms of a cluster of events related to it. For this, we need to decide where a cluster starts, and how far it continues. For each requirement, we go through all the events and isolate those that seem related. A cluster must start or resume with an event, which has nothing to do with the requirement that has links with the preceding event, but is related to the next requirement or some previous requirement. A cluster can contain several phases of the protocol. Take the following cluster from CD1's protocol as an example.

[2] Events are the smallest, meaningful chunks of utterances made by the designer.

It should be possible to position [swivel] the [optical] device at any angle within the range indicated
The [swivel] mechanism should be operated manually with minimum force The optical device should maintain its set position

In lines 2-3, the designer reads a requirement in the assignment. This is not related to the contents of lines 1 or 4. So this cluster (lines 2-3) can be marked off in this passage of the protocol. A cluster ends if the designer changes the issue. At later stages, these punctuations get blurred; a cluster starts or resumes with new requirement or information, and ends with the final form of the requirement or information, i.e., when it stops becoming detailed further.

- *Comparison of these clusters*. First the data is to be brought to a form that allows comparison of the clusters. In order to cope with the large amount of data within each cluster, and yet make comparison between them possible, they must be abstracted into a shorter form: a summary. Summarising each cluster is done in a "phenomenological" way (i.e., without basing it on any pre-formed hypothesis, see (Fricke, 1993)), by naming the methods of requirement identification employed in each cluster using keywords (e.g., *imagine kinematics*, *study own sketch*, *express in own words*, etc). New clusters are first seen in the light of the already used keywords; failing this, new keywords are introduced.
- *Categorisation of the circumstances of the requirements and their handling modes*. Further categorisation of the clusters is done in order to relate them to the circumstances under which they originate, i.e., their *sources* and *aspects* considered, and the modes by which they are handled, i.e., *expressed* and *stored*.

There are four sources from which requirements originate: the given assignment, the designers' own requirements, requirements arising out of the emergent designs, and requirements imposed by the given designs (this last one applies to re-designers only). A comprehensive list of important aspects are provided by Pahl and Beitz (1984); this includes, among others, kinematics, geometry, materials, manufacturability, ergonomics and safety.

Handling modes are expression and storage. A cluster can be either about the development and use of a requirement or related information. A requirement can be expressed as a statement of a requirement, as a solution which fulfils the requirement or other, related requirements, as a question, or is implicitly embedded within the related events. Storage can be done by expressing the requirement verbally, by writing it down, by noting its pros and cons, by noting (writing) it as a solution, by highlighting or marking it, or by drawing or sketching it. Expression and storage are strongly related, i.e., choice of one affects the other. An example of a cluster of categorised events and their categorisations are shown in Table 4. A cluster always consists of five different kinds of data:

- The corresponding extract out of the protocol, including a time-stamp, which is the main part of the cluster **(A)**.
- The basic categories **(B)**, and an index number **(C)** of the cluster. These, together, allow categorisation of each event.
- Descriptions of the cluster in the context of the whole process **(D)**, and a short summary of the applied methods **(E)**. These help in comparing clusters with one another.

4 Results from the exploratory study

This Section has three subsections. Sect. 4.1 gives a general overview of the design processes. Section 4.2 lists activities and methods used in identification and application of requirements during task clarification, conceptual design, and embodiment phases. Section 4.3 outlines the aspects and situations which lead to requirement identification and application.

Table 4 An example of a cluster

A		B		C
1:18:40	Weld or aluminium welded	g	s	42
1:18:50	So if that is true, then we can bring this fastener	i	i	42
1:18:52	Ah, that is useful isn't it	e	s	42
1:18:56	We can bring this fastener to this side	r	i	42
1:19:05	If you ?? is having a simple normal bend	r	s	41
1:19:10				
1:19:16	The only thing we have to be careful with is you make this slot a bit asymmetrical	i	r	42

D: CD1 now has got the solution of the β–bracket with a rectangular end coming to one side. He sees that the fastener could be brought through there and finds out by studying the sketch and imagining the kinematics, that the α–slot has to be asymmetrical, which means shifted to one side of the α–bracket.

E: study own sketch, imagine kinematic → understand problem → requirement

4.1 General overview

Figure 2 gives the actual duration of the design process of each designer. CR1 and CR4 did a re-design exercise, so they took longer on average than CD1 and CD3, although CD1 and CD3 also had a large difference between themselves, see Fig. 2.

Several trends can be seen from the analysed data about the design processes. In the beginning of the design process, a large number of requirements are generated, particularly when designers go through the assignment (Fig. 3). Requirements identification is less frequent during conceptual design than it is during task clarification (see Fig. 3), and less in embodiment design, except for CR1.

Study of given designs in the cases of re-designers CR1 and CR4 led to identification of several additional requirements. Considerable differences exist in terms of the time spent by the designers in studying the supplied documents (between 13 and 27 min.). Considerable correlation exists between the time spent in studying and the number of requirements identified and applied by the designers. The number of requirements applied is always less than but proportional to the number of requirements identified, see Table 5.

Distribution of requirements in the conceptual and embodiment design stages is given in Figs. 4 and 5. Re-designers spent more time at the embodiment stage compared to initial designers, although less so against their own percentage of time spent at the conceptual stage.

Figure 6 shows sources from which requirements arose. As expected, the assignment was a major source of requirements (the second highest average: 30%). However, most requirements were identified and applied when designers worked on their own design proposals (average

Fig. 2 Duration of the design processes

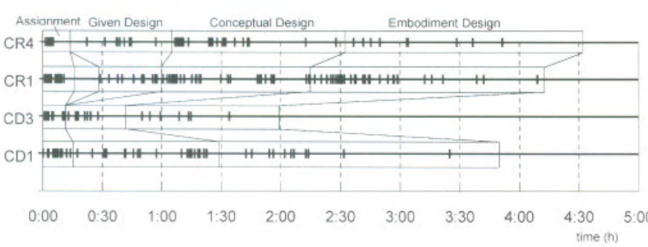


Fig. 3 Distribution of identified requirements during the design process

Table 5 Time spent on studying documents, number of requirements identified and applied

Designer	Time (min) spent on studying documents	No of requirements identified	No of requirements applied
CD1	18	51	41
CD3	8	42	33
CR1	27	81	69
CR4	13	57	48

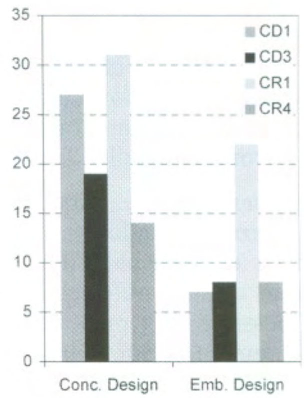


Fig. 4 No of requirements during conceptual and embodiment design

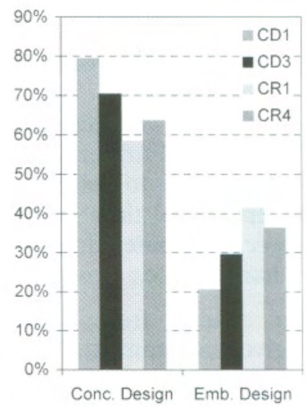


Fig. 5 Identified requirements during conceptual and embodiment design (%)

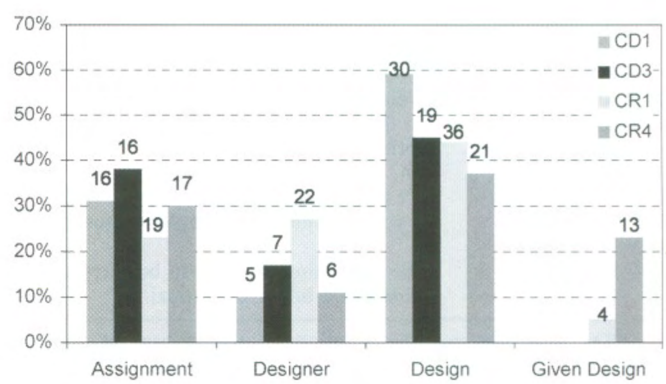


Fig. 6 Sources of requirements in absolute and percentage

of 46%),. This highlights the coupling that requirement identification and application has with solution generation, as shown quantitatively, by Nidamarthi et al. (1997), or indirectly by Ullman et al (1988) in terms of co-evolution of function and form. The third, surprisingly large number of requirements ensue from the designers' own concept of what must be required of a good design (average of 16%). For the re-designers, between 5% and 23% of the requirements came from the given designs. The general pattern of results obtained here matches well with the findings of McGinnis and Ullman (1992). They analysed the constraints handled during the design of a component, and found that constraints arose out of the assignment (which they call *given constraints*), designer (which they call *identified constraints*), or during design (which they call *derived constraints*).

On the whole, both CD1 and CD3 designed from scratch, so a larger percentage of requirements arose in the conceptual stage. Although CR1 was asked to re-design a given design, he too came up with a new design. Hence the pattern and number of requirements identified at the conceptual stage is comparable between these three designers. However, while CD1 and CD3 did a thorough job at the conceptual stage, and hence required less clarification of requirements at the embodiment stage, CR1 left many loose ends at the end of the conceptual stage, and therefore requirements identification in his case is high even at the embodiment stage. CR4 simply adapted the existing design for the redesign requirement and hence the number of requirements identified was low in his case throughout the design.

Very few questions were posed to the researcher during the design process. CR1 asked more questions than the others, throughout the design process.

4.2 Activities for requirement identification and application

Activities and associated methods for identification and application of requirements and related information are discussed in this section. These are divided into activities during task clarification, those during conceptual and embodiment designs, and those common to both - ways in which information is expressed and stored during design. At the end, these are summarised into major situations that led to requirement identification and application.

4.2.1 During clarification of the task

The task clarification phase is characterised by activities which serve to identify, collect, transform into a suitable form and store, for use during subsequent design, the requirements and associated information that the design must satisfy. The goal in this phase was to identify and transform, information residing in the assignment and associated documentation into the designer's own language. Methods applied at this stage are given below.

4.2.1.1 Reading and re-formulating of the assignment

The shortest treatment of the information was a *reading* of the text without any further comments. In some cases this was followed by a *direct rereading*, perhaps because the designer did not understand what was meant after the first reading (more in the next but one section below). Some numerical sizes were *repeated directly*, probably to store them, e.g., CD1: "... slide at last 175 mm along the column - 175 mm".

Frequently, information or requirements were *expressed in their own words*, e. g., the description of the aluminium tube (AlMgSi0.5, 25 mm square, thickness 2 mm) was expressed as "aluminium alloy" and "hollow tube" by CD1. A further problem for some designers seemed to be the *units* in which information was given (mm). CD1 sometimes expressed the given measurements in inches, and CR1 converted most of them to inches to imagine them better.

Another method used to get a better understanding of requirements is *expression in the form of solutions required or not required*. CD1, for example, described the corrosion resistance requirement as "that probably is not more than plating steel parts", which is a formulation in terms of a solution required. He also expressed the requirement as "You do not actually want me to put on rubber gaiters or things like that", which formulates it as a solution not required.

Requirements were often *summarised*, in most cases in the form of solutions or generic requirements. For instance, the requirements "enable $+/-15^{o}$ swivel; swivel axis should intersect in one point 150 mm out of the wall" often got expressed directly in form of "that must be a fine pivot point." On the whole, it appears that large amount of information and requirements were summarised in the form of generic terms.

4.2.1.2 Study of attached sketches

For a more detailed and better understanding of the text, the designers *studied the sketches* as an aid. Except for CR4, who read the assignment completely once, before he looked at the sketches, all other designers used the written text and sketches in parallel. This analysis of the sketches served mainly for the clarification of the kinematic and geometric requirements and context. For example, CD3 realised that the demanded ß-swivel in the context meant that the device must swivel away from the wall ("... it can not be minus because else it would go against the wall"). Sometimes, a direct *comparison of the text with the sketches* took place. CR1 read "A combination of movements in the α- and β-direction should be possible," and said immediately "...which is, what that area (pointing to the provided sketch) represents." On the whole, designers strove for a spatial picture of the desired design.

4.2.1.3 Second reading of the document

As mentioned before, CD1 and CR4 read through the assignment twice. Some reread in order to ensure, it seems, that *everything was understood* sufficiently and that no further information was needed. For instance, CD1 glanced for the second time at part of the assignment and commented "... and the - we know about that". This indicates that he had already stored this information. He skipped further reading of the information. Also, after CD1 read the assignment the first time, he paused for a moment and restarted reading after commenting "Um, I suppose, it would help if I had understood this thing more..."

Sometimes reading the assignment a second time seemed to be out of *routine or experience,* i.e. a method used before. For instance, even before looking at the assignment, CR4 said that he would read it once at first , then study the sketches and then read it a second time.

4.2.1.4 Evaluation of the given information and requirements

Another activity is the evaluation of given information and requirements, so as to *extend information* existing in the given assignment and design, or to *check the given information.*

One method for extending information was to derive further information using designer's own knowledge. For instance, CR1 read "the optical device can be mounted to a wall," and concluded directly that "an optical device is not likely to be very heavy." It seems that the word "optical device" triggered information as to what was "usual" for optical devices - a part of the designer's knowledge. Another method was to use evaluation. This started with the realisation of a lack of information in the assignment. Designers tried to fill these by means of evaluation of other available information. For instance, except for CD3, all designers realised that the corrosive environment within which the device was intended to operate was described insufficiently. CD1 and CR1 tried to specify the working environment by evaluating the information included in the assignment. CD1 tried to derive this using the fact that the device was to be mounted on a brick wall, whereas CR1 did so using the information that the slider tube was made of aluminium. Yet another method is by *definition or setting of requirements*, done by the designer. For instance, a "blurred" requirement was refined by CR1 who defined "operated manually with minimal force" as "... the force of a right hand if they are right handed". Another method was to *ask the researcher* to define a requirement, e.g. the corrosive surroundings.

The assignment was evaluated by checking for the completeness (i.e. what information is missing?) and consistency among the requirements and information contained in it. CD1, for instance, read the assignment, identified that information about the tolerance of accuracy was missing. (completeness check), and checked whether or not the column, which was 250 mm long, was capable of allowing the required sliding possibility of 175 mm (consistency check). This closer inspection lead to a more detailed understanding of the information.

4.2.1.5 Dealing with the description of manufacturing facilities and catalogues available

The workshop description and catalogues provided a large amount of data to the designers. It seems that designers tried to cope with this large amount of information in various ways, so that this can be remembered and used. Following the reference in the assignment, CD1 immediately started to study the material provided. He studied the workshop description by *looking for keywords* and *summarised it in terms of his own picture* of a "generally well equipped workshop". The study of the materials assured CD1 of the existence of usual materials such as brass and steel. CD3 did not carry out a further study of the provided material. He only read the line in the assignment and *presumed*: "... so it looks as if there will not be any very modern or way-out materials used, it could be good old engineering stuff". As CR1 read the corresponding sentences in the assignment he expressed his own picture of the given information. Probably not to get out of his train of thought, he *postponed* a detailed study of the given material. His analysis of the catalogues turned out to be detailed, which can be recognised from the long time he spent on this. However, instead of obtaining an overview, he dealt with specific details, and the analysis was carried out aimlessly. On the whole, each designer stored the workshop description in terms of his own picture of workshops, with or without making a comparison of his picture with the given one.

4.2.1.6 Additional clarification of the task

The designers' knowledge contributed to the process of clarification of the task in the form of additional requirements and information. CR1, in contrast to all the others, *asked for further requirements;* these had no direct connection with the information in the assignment. He asked if the product had to be cleaned, if it had to be capable of being dismantled and if any further spatial constraints were given. CD1 and CR4 asked if a scaling was needed, which is similar to those above, although more directly connected to the assignment. It seems CR1 had a *checklist of possible requirements* for a design, which he went through during task clarification.

4.2.1.7 Requirements arising out of one's own solutions

Within task clarification, designers did not generate many solutions. *Solutions were expressed only to illustrate requirements* so as to get a better picture of them (Morgenstern and Knaab, 1996). This was also observed by Nidamarthi et al (1997), and Blessing et al (1997). For instance, CD1 described the requirement "the swivel axis (must) intersect in one point" as a fine "pivot point" or "universal joint." After this, however, designers returned directly to the assignment. Even the additional clarification of the task that CR1 carried out after conceptual design was not connected to the solutions hitherto developed, and served as a general task clarification rather than specific problem solving. This largely solution-neutral clarification switched to a solution-specific handling in conceptual design, and will be described in Sect. 4.2.3.

4.2.1.8 Modification of the assignment

Occasionally designers tried to *modify* or even *ignore* the assignment. This arose when a proposed solution violated some requirements of the assignment. For example, CR1 discovered that his proposed solution did not fulfil the requirement that the swivel axes intersect in one point. He wanted to modify this requirement so that his solution would be acceptable, but was not allowed to by the client. At the beginning of his embodiment design, CD3 was not sure if his design would fulfil all the requirements of the assignment. He had doubts whether or not the column could be held steady. He wiped out these doubts by commenting, "I do not look upon that like a challenge" and "either the thing will work or not." At this point he ignored requirements of the assignment to allow his solution.

4.2.1.9 Questioning during task clarification

Given the small number of questions asked, it is difficult to find a consistent pattern among them. However, what seems recognisable in CR1 was that he treated each aspect of the design using a cluster of questions. For instance, after he read about maintenance requirements, his following question was whether or not the mechanism had to be capable of being dismantled. The same pattern accounts for his asking questions about spatial constraints. Fricke (1993) describes this pattern as "feature-orientated tactic of questioning". It seems that consideration of many different aspects of the design supports a comprehensive task clarification.

4.2.1.10 Parallels between the designers' use of methods during the task clarification phase

Table 6 shows the extent to which the methods discussed were applied by the designers. All designers read the assignment (*sole reading*), *studied the attached sketches* and frequently *expressed in their own words* the requirements and information. *Summarising requirements, checking information for completeness or consistency, using keywords and asking questions about further requirements*, were carried out by all but CD3. *Direct re-reading* (when a designer did not understand a requirement or information), *extending information* and *modification of assignment* were done by two of the four designers. *Presuming a picture* and *ignoring requirement* were done by one designer, while *repeating sizes* by another. Table 6 shows that many activities and methods get followed by more than one designer. Apart from studying sketches and reading documents, which were essential parts of the exercise, existence of others indicates more than individual idiosyncracy, and probable widespread use. In contrast, those found to have been used infrequently, or by a single person does not necessarily reduce the significance of their potential in affecting the design process. The relationship of the

Table 6 Application of methods by the designers during task clarification phases

No	Method	CD1	CD3	CR1	CR4
1	Sole reading	+	+	+	+
2	Direct rereading because not understood	o		o	
3	Express in own words, abstract	+	+	+	+
4	Transform units	o		+	
5	Repeat sizes directly	–			
6	Express as non/solutions	o			
7	Summarise requirement/s	o	o	o	o
8	Study attached sketches (compare with text)	+	+	+	+
9	Second reading to get uniform understanding	+			+
10	Second reading out of routine				o
11	Check information for completeness	o		o	o
12	Check information for consistency	+		o	o
13	Extend information	–		+	
14	Use keywords	o		o	o
15	Summarise as own picture	o		o	o
16	Presume picture		–		
17	Postpone studies			–	
18	Ask for further requirements	o		+	o
19	Define requirements			o	
20	Ask for definition	–		o	o
21	Modify assignment		–	o	
22	Ignore requirement		–		

Applied once (–) Sometimes applied (o) Applied frequently (+)

methods to the eventual success of the design is dealt with in Sects 5 and 6.

4.2.2 Methods within the conceptual and embodiment phases

These design phases are marked by solutions considered in detail unlike in task clarification where they are generated only to understand the problem. We term as conceptual design the phase where alternatives are generated, evaluated and sketched. The embodiment phase is marked by development of the design in terms of construction and use of its formal drawings.

Some requirements were identified and applied as a result of analysis of the evolving design. Often analysis revealed required, missing components or functions in the designs developed so far, which led to requirement identification. Designers then proposed solutions to fill in this gap, which were checked for their compatibility with the existing design, requirements from the assignment, and designer's own requirements. As a result, new, and often detailed requirements got identified. Sometimes requirements were identified after accidental realisation of the weakness of a design, and this led to further, more detailed analyses. In order to carry out the analyses, several methods were applied. These are described below.

4.2.2.1 Applying own requirements

Besides those in the assignment, designers applied their own requirements to the design during the analyses. The methods used in applying own requirements are applying *generic* and *specific* requirements.

Generic requirements can be applied to any solution and during any part of the design process. In general, four generic requirements were applied: the intended design should work, be simple and nice, must be manufacturable, and must not break. Although these requirements were implicitly part of the assignment, it seems that designers applied these from their own knowledge and practice, rather than from the assignment. The requirements appeared suddenly and without a planned checking of the assignment. They had special meanings to each designer. For instance, "simple" to CR1 and CR4 meant "fewer parts". The 'simplicity requirement' was applied at the evaluation phase, whereas all others were applied during the development of the solutions. Consequences varied between no further variation of the solution to completely new design proposals. For instance, CD1 proposed a new universal joint when the original solution was assessed to be too complicated.

Specific requirements are more specialised and apply to special circumstances only. These can be specific, detailed versions of the generic requirements, such as 'nice and simple' becomes 'few parts', 'easy to use', 'thread through the whole piece', or 'put chamfers'.

4.2.2.2 Visualisation of aspects

A way in which designers analysed a design proposal was by imagining the relevant features of the design, and how they (do not) meet the requirement under consideration. *Kinematic* and *geometric* problems were visualised, and designers seemed to achieve this by mentally 'moving' or 'adding' parts of the design. Thus problems could be understood and corrected. For instance, CD1 visualised how the β bracket moved under the β motion, or imagined the geometry of a part that he wanted inserted into the column. *Forces* acting on the mechanism were also visualised. For example, CD3 imagined the clamping force required in order to hold the column. It seems designers had a "feeling" for forces, on which they based their work. *Manufacturability* was imagined using designers' knowledge, and possible restrictions (e.g., normal milling machines only can mill straight slots) were remembered. *Assemblability* and *ergonomics* were also visualised. For example, CR1 recognised that one of his adjusting screws would be difficult to reach.

In order to determine geometric and kinematic aspects and acting forces in more detail than possible by unaided mental simulation, the designers used *calculation*. For instance, CD1 and CR1 calculated the swivel way of the column's top that corresponds to a 15° swivel. Before designers began the calculation, a clarification of the respective geometry, kinematics and the forces were carried out. For this, designers made basic sketches with the necessary sizes and forces. For example, CR4 sketched the swivel way of the column's top before his calculation. A method for visualising complicated motion was to use *simple sketches* to simulate the motion. CD1 and CR4 used this to decide how the top of the column moved vertically when swivelled. Sometimes, *kinaesthetic means* like a pen or an arm was also used.

Sizes, like diameters of screws or their positions, were set directly. However, it seems the designers carried out a mental *estimation* of them, in which they imagined several sizes. CD1 for instance expressed two different sizes of a bracket when he imagined its operation: "...well I suppose it, you know, lets say ... 8 mm brass ... 6 mm brass... what sort of the load this is actually put on there ... the greatest load being in the top position". The final size was set based on designer's feeling about what sizes to use for specific forces.

4.2.2.3 Questioning during conceptual and embodiment design

Questioning by designers during these stages were due mostly to a lack of information. CD1 for example asked if facilities to weld aluminium existed. Questions appeared also in situations where designers developed a solution that did not fulfil the requirements. CR1 for example generated a solution in which the swivel axis of the column did not intersect at a single point. The first

Table 7 Methods applied by the designers during conceptual and embodiment designs

No	Method	CD1	CD3	CR1	CR4
1	Imagine kinematics	•	•	•	•
2	Imagine geometry	•	•	•	•
3	Imagine forces	•	•	•	•
4	Imagine manufacturing	•	•	•	•
5	Imagine assembling	•	•	•	•
6	Imagine ergonomics	•	•	•	•
7	Apply high-level requirements	•	•	•	•
8	Apply stock requirements	•	•	•	•
9	Calculate	•		•	
10	Sketch motions	•		•	•
11	Kinesthetic simulation	•			
12	Estimation	•	•	•	•

Table 8 Modes of Handling and their effects on the application of requirements

No	Method	Effects
1	Express verbally	Information was sometimes forgotten or lost importance.
2	Write	Though the notes were not reused, none of the noted requirements were forgotten.
3	Note (dis-)advantages	
4	Note as solution	The noted solutions imply the requirement and so it is applied.
5	Highlight/mark	This was not applied often, so no judgements can be made.
6	Sketch	The sketched or drawn solutions satisfy the requirements and so they are applied.
7	Draw	

consequence if this was that he reread the assignment, and asked the researcher how rigid this requirement was. Designers did not note down the answers received, probably because these were used directly into their solutions.

4.2.2.4 Parallels between designers' use of methods during conceptual and embodiment phases

Use of methods by the designers is given in Table 7. CR4 skipped calculation and kinaesthetic simulation. CR1 did all but kinaesthetic simulation, and CD3 skipped all three. CD3 was the most experienced and CR1 least experienced of the designers. It seems that use of external aids and methods is less for designers with more experience.

4.2.3 Methods for expression and storage of information in the design phases

Once information is collected or worked out, it has to be stored in a form to be usable at later stages of the design. This section describes the methods designers applied to express and store requirements and related information. As thinking aloud protocol was used during the experiments, most of the information and requirements were *expressed verbally*. This is not a usual method for expression and storage for individual designers, as 'thinking aloud' is not part of usual design practice. Requirements sometimes got noted as *solutions (not) required*. A requirement that the ball at the bottom must be insertable, for instance, was noted by CR4 as "metallic-split" and "plastic-snap", which are possible solutions for this requirement.

Information and requirements were written down to a limited extent. Only CR1 and CR4 noted some information and requirements, but these included only a limited selection of requirements. As information was already given to the designers in written form, a further writing down may have seemed superfluous. Only CR4 noted requirements and information comprehensively during his study of the given designs, which included their *advantages and disadvantages*. After a design was selected, its areas for improvement were noted and complemented with detailed points. None of the notes was reused, although they may have served to organise the information. Sometimes, written requirements were highlighted. CD1 for example *marked* corresponding parts of the sketches and the written text with colour.

During the conceptual and embodiment designs, requirements were stored implicitly as designers' *sketches* or *drawings* of solutions fulfilling these requirements. Thus requirements used in conceptual design were automatically adopted in embodiment design if the concept chosen was embodied. However, designers often reread information or requirements during these phases, as they *forgot* them, or felt insecure about remembering them. Numerical sizes, in particular, were often looked up. *A deficient storage* of information led to faults in some cases. For instance, CR1 needed information about some given dimensions in order to calculate the strength of springs in his design. He could not remember them, searched for them in a wrong document, and finally assumed the dimensions and calculated. This lead to a fault that his design could not maintain its set position in some cases. Methods for expression and storage and their effects on the application of requirements are given in Table 8.

4.3 Aspects and situations that led to requirements identification and application

So far we have described the methods which the designers apply within the conceptual and embodiment designs in order to identify and apply requirements. In this section, we survey the design aspects and situations that lead to requirement identification and application.

Most of the requirements were developed (Fig. 7) while considering the aspects of geometry, kinematics and forces that the designs must withstand (consistent across the designers, average 37%, 23% and 16% respectively). Next, fairly consistent, important catego-

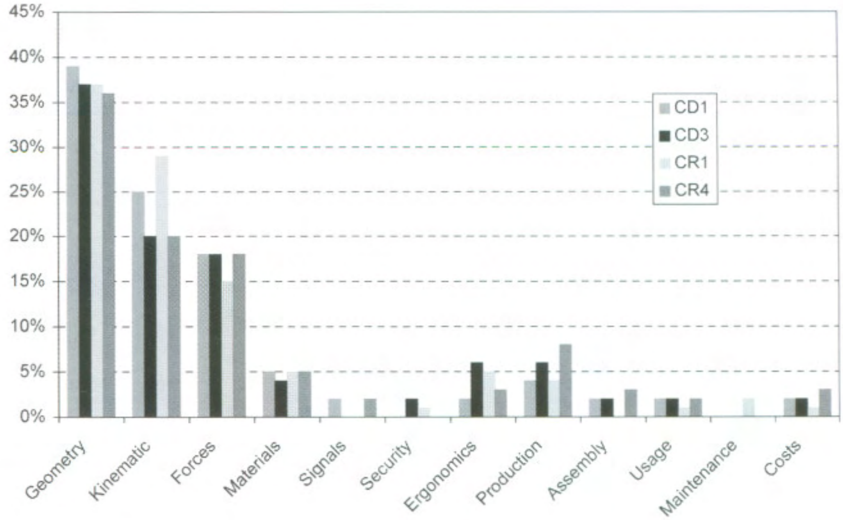


Fig. 7 Aspects considered that led to identification and application of requirements

ries are materials (5%), production (5%) and ergonomics (4%). Next important categories, considered by all, were usage and costs (2% each). Some designers considered assembly (1% average), maintenance, security and signals. This may be due to the nature of the task, which is mechanical, and the nature of the problem, which asked for embodiment rather than detailed design as the output. This broadly agrees with the *issues* identified by Kuffner and Ullman (1991) under which designers observed by them identified constraints, the top three of which are *location*, *operation* (these two are equivalent to geometry, kinematics, forces, ergonomics, usage and signals taken together in our research) and *construction* (equivalent to materials, production and assembly in our research).

The following are the situations that led to requirement identification and application:

1. *Based on previous requirements, a design is proposed, and in order to implement another requirement into this design, the requirement is expressed in a form specific to the present state of the design (solution-specific).* For instance, during conceptual design, CD3 developed as the bottom-hinge a universal joint. He already knew that the design must also include a locking mechanism, as the assignment required. This requirement was now detailed and specifically related to the universal joint solution ("...we need to clamp both those axes.").
2. *If a requirement is not fulfilled by the existing design, a new requirement is formed in order to fulfil the original requirement.* The requirement is a contextualised, solution-specific version of the original requirement such that it retains those features of the existing design which already fulfil other requirements. CD1, for instance, realised while drawing that his design would not hold the column steady. He studied this problem in detail, by imagining the kinematics and forces, and found the source of the fault. Though he had already realised the problem, and had a clear picture of it and the resulting requirement, he formulated the requirement once again in a short, detailed form, in order to aid search for its solution.
3. *If the solution features responsible for fulfilment of a requirement prevents fulfilment of a more important requirement, the less important requirement gets ignored or rejected in favour of the more important requirement.* For instance, in order to increase friction of the locking handle, CD3 proposed knurling its surface. At a later stage, he decided that the handle should be movable like a vice-handle and need not be knurled, thereby rejecting his earlier requirement of knurling it so as to enable it to slide through a hole like a vice-handle.
4. *After a solution is developed, possible spatial constraints for this solution are defined as further requirements.* CR1 for example worked out the detail of the space available for incorporating the locking mechanism at the bottom of the column, after the required slide-way of 175 mm was allowed. Before he calculated the remaining space, he studied the geometrical and kinematic circumstances once more and expressed them in a short form.
5. *A solution proposed is noted accidentally to have promise for fulfilling additional requirements, which then are consciously identified as intended requirements.* CD1, for instance, realised that his slotted-bracket solution allowed independent adjustment in two directions. He assessed this as positive and set as a requirement ("...the great advantage of that is that I can actually break the movements down into two distinctive movements").

5 Hypothesis testing and its research method

In the earlier sections, a general overview of the design process is given, and the various activities and methods involved in requirements identification and application are described. The study reported in this section in intended to demonstrate the importance of effective identification and application of requirements to the quality of the design process. Three hypotheses are formed in order to demonstrate this:

1. *Many requirements are not satisfied during design.* In order to test this, we need to see the degree to which requirements in the assignment are fulfilled by the designers.
2. *Requirement identification and application are critical to their satisfaction by the design.* In order to do this, we need to hypothesize the quality of identification and application activities for each requirement in the assignment, and how well these correlate to the quality of the fulfilment of the requirements by the eventual design.
3. *There are useful and harmful requirement identification and application activities and methods.* These can be identified from the results of testing hypothesis 2.

5.1 Research method

Data about the degree of fulfilment of requirements by the design in each case are already available from Blessing (1994). It is the average of the evaluation scores given by two evaluators who examined each design against the requirements in the assignment. In this research, it was necessary to link this data to the quality of identification and application of requirements in the cases studied.

Question is, what should be taken as (in-)sufficient identification and application? We hypothesized that the quality of identification and application depend on the nature and quality of activities undertaken during these activities. It is hypothesized here that effective identification is characterised by *spotting requirements, being critically aware* of information related to them, *evaluating them* and *giving them adequate importance*. Sufficient application is characterised by *remembering* the requirements and *using* them in the design process. An indirect way in which application of a requirement can happen is by application of other requirements that are strongly related to this requirement, which can be either designer's own requirements or other requirements from the assignment. Insufficient identification and application of requirements are characterised by activities and methods contrary to the above. Depending on the degree of appearance of these characteristics, it is possible for the quality of identification and application to be estimated. Categories formulated are given in Table 9.

Table 9 Activity chains for estimating quality of requirement identification and application

Activity	Instances
Bad identification	• Read (and reread) - no comment • Read (reread) - not study document or not evaluate information—express lack of understanding • Read (reread) - presume information without studying document or consulting researcher • Read (reread) - ignore requirement without studying document or consulting researcher
Insufficient identification	• Read (and reread) - comment (e.g., summarise/express in own words/transform units etc)
Sufficient identification	• Read (and reread) – study or evaluate or ask questions—comment
Bad application	• Making errors in applying requirement (copying, calculation, remembering wrongly etc) • Clear evidence that the requirement is not applied (forgotten, not copied etc)
insufficient evidence of application	• No clear sign of application of the requirement: this is because often designers use requirements while sketching or drawing the design, and protocol data can only capture so much of the actual happenings of the design process in designer's mind.
Sufficient application	• Use own requirement which is strongly related to the requirement • Use other, well-clarified requirement that has strong link to this requirement

Table 10 Overall quality of identification and application from individual qualities

Quality of requirements identification	Quality of requirements application	Overall quality (id. & appl.)
Bad identification	Bad application	Bad
Insufficient identification	Bad application	Bad
Sufficient identification	Bad application	Bad
Bad identification	Insufficient evidence of application	Bad
Insufficient identification	Insufficient evidence of application	Insufficient
Sufficient identification	Insufficient evidence of application	Sufficient
Bad identification	Sufficient application	Sufficient
Insufficient identification	Sufficient application	Sufficient
Sufficient identification	Sufficient application	Sufficient

Of the three degrees of application, bad application of any requirement identified to any degree should lead to bad quality of identification and application. Sufficient application, as this means the requirement is indirectly well clarified and applied, should mean sufficient quality of identification and application. Insufficient evidence of application is interpreted to give the benefit of doubt that the requirement was applied but verbal protocol did not capture this, and therefore did not reflect the degree to which it was clarified in the first place. Using these categories and rules (Table 10), an overall estimate of the degree to which a requirement was clarified and applied was made.

However, the above reasoning and classification is based on identification and application of requirements only, without taking into account the effect of the quality of solutions used to fulfil these requirements. Therefore, there can still be situations where requirements are well clarified and applied and yet not fulfilled adequately due to the poor quality of the solution chosen, or due to the negative effect of solutions chosen for other, related requirements. Similarly, it is possible that positive characteristics, of a solution chosen for a poorly identified and applied requirement or of a solution chosen to fulfil a related requirement, still produce an adequate fulfilment of the requirement. In the redesign cases, even if inadequate care is taken in identifying or applying a requirement, it may still be possible for an adequate fulfilment of this requirement due to the positive effects of the design being redesigned.

6 Results of hypothesis testing

The relationship between the quality of identification and application of requirements and the quality of their satisfaction in the eventual design is given in Table 11.

6.1 Hypothesis I

First, a fair number of requirements had a low or unsatisfactory degree of fulfilment (10 out of 66:15%). If we look only at the initial-design cases (as redesign cases are more likely to be fault-free), this percentage is higher (7 out of 32, i.e.22%). This substantiates the first hypothesis that many requirements are not satisfied during design, a major finding of this research. This was the case for experienced designers who worked on a relatively simple design problem for a relatively small amount of time (2-4 hours). It is therefore a reasonable extrapolation that there is scope for substantial improvement in the process, especially for designers working on complex designs, possibly in large, multidisciplinary teams, over long periods of time.

Two exceptions were observed. The first is that even though it seemed to have been sufficiently identified and applied, one requirement remains unfulfilled. The other is that four of the requirements that were insufficiently identified and applied were sufficiently fulfilled. Why did these happen?

The case of sufficient identification and application leading to insufficient fulfilment happened as the solution had a low quality. Clearly, requirement identification and application alone are not sufficient to guarantee their fulfilment, but must be aided by solutions of good quality. This issue is further discussed in Sect. 7.

Of the four cases of insufficient identification and application but still with sufficient fulfilment, three are the satisfaction of the constraint exerted by the use of the manufacturing capability and materials allowed in the exercise. These designers spent very little time on the descriptions of the workshop and materials provided, and presumed that they were "standard" workshops and materials. We believe that this is a case of workshop description matching the designers' usual picture of the work-place, although such quick, inadequate clarification is generally a weak identification activity. The fourth case was that of a re-designer's design satisfying a length constraint: the length within which the optical device must be able to slide. There are two possible explanations. One is that this constraint had little affect on the other requirements, and was incorporated at the drawing stage directly into the drawing. However, the constraint was only marginally satisfied, from which we can suspect that the design was satisfied because both the designs from which redesign was carried out had already satisfied it.

6.2 Hypothesis II

Of the 66 requirements taken together to be satisfied by the designers, 52 of the 53 requirements identified and applied well are also well satisfied (98%), and 9 of 13 requirements identified and applied insufficiently are inadequately satisfied (70%). For 61 requirements out of the total 66, it holds true that if a requirement

Table 11 Degree of identification/application of requirements and their fulfilment by design

Designer	Sufficient identification and application				Insufficient identification and application			
	Fulfilled	Low satis.	Unsatis.	Total	Fulfilled	Low satis.	Unsatis.	Total
CD1	10	0	0	10	0	4	2	6
CD3	13	0	0	13	2	0	1	3
CR1	15	0	0	15	0	1	1	2
CR4	14	1	0	15	2	0	0	2
total	52	1	0	53	4	5	4	13

Table 12 Useful and harmful activities and methods observed in the studied case

Generic activity	Sub-activities and methods	Quality
Identify	Define requirements, study assignment and documents; inspect for completeness and consistency; identify related requirements; re-study	Useful
Interpret	Express in own words; transform units; summarise; recognise requirement's importance; imagine context, geometry, forces, motion, operation, production etc	Useful
Evaluate	Evaluate requirement, info, assignment, and document (qualitatively and quantitatively); study solution; realise misunderstanding, calculate, suspect gap in assignment, check requirements frequently	Useful
Ask	ask questions, confirm suspicion, confirm understanding, clarify from client	useful
Remember	Be reminded; note requirement/info; repeat requirement periodically	Useful
Apply	Detail requirement; recognise relation to other requirements, express requirement as solution; evaluate solution using requirement; search for faults in solution	Useful
Others	Use design principles, draw, sketch	Useful
Not identify	Not study document, not ask questions, vary importance of requirement without consulting or studying	Harmful
Misinterpret	Assume without consultation, evaluation or studying relevant materials; modify requirement in order to keep preferred solution	Harmful
Forget	Forget requirements, solution, assignment, info, documents or earlier decisions	Harmful
Errors	Copy errors, calculation errors	Harmful

is insufficiently identified and applied, it is insufficiently fulfilled, and vice-versa. This indicates that there is a strong link between the quality of identification and application of the requirements and the success of the design process in terms of how well these requirements are satisfied by the final design. This validates the second hypothesis, which is another major finding of this research.

6.3 Hypothesis III

This third major finding is that there are useful and harmful activities and methods in requirement identification and application (listed in Table 12).

Useful activities and methods are those which supported identification and analysis of requirements, and remembering and application of requirements; harmful activities and methods contrary to the above.

7 Evaluation of the results

This section provides an evaluation of the degree of generality of the results, in terms of the limitations of this research.

1. *Limitations due to the assignment.* The given assignment contained the information, requirements and aims of the design in a precise form, which might have given an impression of completeness to designers. An additional comprehensive clarification of the task may have been considered unnecessary and therefore not carried out, or carried only to a limited extent.
2. *Limitations due to the experimental situation.* The experimental situation took place in an unusual, laboratory surrounding, which raises the issue of whether results arising from its analysis could be transferred to real-world situations. Designers were observed continuously by two researchers and recorded on video, which might have modified the design process. CD3, for instance, made some sketches, with the comment that he would not do that normally, but did it now to make it easier for the researcher to understand (even though designers were asked not to do this). The extent to which these factors had an influence is difficult to estimate. However, designers expressed that they were aware of being observed, although this, they felt, did not affect their work significantly. Also, the experimental situation was restrictive in that the designers did not have the possibility of discussion with other designers, a must as expressed by CR1. However, since analysis by Blessing (1994), who used the same protocol data, shows substantial similarity between design activities identified from this data and earlier data obtained by her from industrial case studies, the results seem transferable.
3. *Limitations due to the "thinking aloud" method.* The process of 'thinking aloud' may have affected the design process as designers were forced to express their trains of thought verbally. This may have led to different forms of thought than would be without having to express them out loud. Design problems discovered by the designers were expressed without the preceding processes of recognition and evaluation, perhaps because thoughts are too fast and complex (Ullman et al, 1988). During routine tasks, the designers' thought processes seemed unimportant to them, and they either remained silent or mumbled along. At the beginning, subjects were too conscious about the demand for thinking aloud, but got used to it as they progressed further. In summary, their activities (e.g., sketching) and results of their activities (e.g., commenting that "this is weak in bending")

can be recorded, but, mostly not the process that led to such results (e.g., how did the designer come to that conclusion?). Although the influence of this process is difficult to estimate, designers generally felt that 'thinking aloud' caused little or no distraction to their work.

4. *Motivational Aspects.* The wish to modify or ignore (part of) the assignment, as well as the wish to restrict the task to modifying a few components in contrast to a complete re-design, probably for a design process which is easy, quick and problem-free. CD1 for example developed a universal joint, which he re-designed or simplified, because he declared it to be "too complicated." However it is not clear to say at this stage, whether he did this so as to develop a really simple design, or because he did not want to draw and specify a complicated solution. An estimation of the importance of these influences is difficult, but all the designers said they found the design problem interesting, important to solve, enjoyed solving it, and had a moderate to high degree of concentration during the exercise.
5. *Limitations due to the data interpretation.* In the past, researchers have raised questions about subjectivity in using protocol study as a research method (Minneman, 1991; Nidamarthi et al, 1999). According to Stauffer et al (1991), however, data elicitation using real-time protocols and data analysis by content analysis, as done here, provide one of the most reliable and detailed analyses of subjective data. In this study, subjectivity could still be an issue in the following ways.

   - A problem in obtaining a rough understanding is that assumptions have to be made in order to link the spoken and drawn materials of the designers. Repeated observation of the protocol data, and the video and audio was used to reduce this problem.
   - Categorisation can be non-repeatable due to observer subjectivity in categorising the events. This was reduced by having the events categorised by two independent observers, and comparing them to see if they were similar. However, as to which categories should be important for this study still remained subjective, as is inherent in protocol studies.
   - Clustering of events may require making assumptions in order to make sense of the data as a coherent whole. Parallel categorisation (above) ensured, at least, consistent use of the categories to the data.

6. *Limitations due to the small number of designers.* The small number of cases investigated allows no statistical statements to be made about the requirements identification and should be seen as a qualitative, indicative description of actual activities and methods.
7. *Limitations due to the (specific) expertise of the designers.* All the designers were highly experienced, and were primarily experienced in the area of mechanical design. This may prevent the results from being used in interpreting design processes of designers with less experience and/or with experience in a different domain of technical expertise.

8 Discussion

The model of requirement identification and application activities which emerges from this study is as follows. Requirements during the task clarification phase result mainly from analysis of the assignment and associated information, while requirements during conceptual and embodiment designs result mainly from analysis of proposed designs, in which visualisation plays a vital role. The process of requirement identification is intimately related to solution generation and detailing, as has also been found by Ullman et al (1988) and Nidamarthi et al (1997). Therefore, requirements are identified, clarified, detailed and used throughout the design process. However, they are identified mostly during the task clarification phase and increasingly less in the subsequent phases. In order for requirements to be adequately fulfilled by the final design, they must be identified, understood, remembered and used. Good requirements identification and application activities and methods are those which encourage the above, and bad ones are those that do not, or discourage these.

The study also reveals that even experienced designers leave a fair number of requirements unsatisfied or inadequately satisfied, even for a small-sized project (each designer working for three and a half hours on an average) like this. The biggest problem was that of understanding the requirements in an informed way, both in terms of how they related to other requirements, and in terms of their relative significance. Another problem has been that of remembering the requirements for use during the design process. This indicates that there is scope for design support tools, especially those that could support understanding, evaluation and remembering of requirements throughout the design process. Many requirements, especially within the conceptual and embodiment designs, appear mainly due to analyses of developed solutions. Thus tools to improve and support these analysis activities are important, especially for frequent analysis of solutions using visualisation aids of varying complexity. There have been several occasions when designers could interrogate the client (researcher) in order to find out whether a specific requirement had to be satisfied, which ensured that they attempted to satisfy it. A support tool, which would remind, or could be interrogated to find out about the requirements, their relationships to others and their importance, should be of substantial support to designers, especially those working in teams on large projects. As designers seem to avoid longer analyses, the tool should enable the designer to carry out analyses of early, relatively inaccurate solutions, to allow assessments in a quick form. The tools should operate quickly and should be easy to use, as otherwise they are unlikely to be used.

This study has been restricted in several ways. One is its qualitative nature. Mostly the study was to see qualitative patterns of requirements identification, and was not particularly granular in terms of the smallest units to which it split the events. The second has been the limitation of its focus. Only requirements given in the assignment have been investigated. However, their relationships with other, more detailed requirements during the design process were not looked at in detail. Therefore, the full picture of the extent to which each requirement was identified and applied cannot be given, especially in any quantitative detail. The third was the omission of an investigation into the effects of solutions in the design process, either in terms of how they relate to requirements (i.e., the co-evolution issue) or in terms of their quality in meeting the requirements. Much work is necessary in comparing the findings here with design processes in real-life situations, where designers work in teams in order to solve imprecisely defined problems under time pressure. It is also important to identify how experience affects requirements identification and application, so that this can be captured and used for training inexperienced designers. Further work is in progress (Nidamarthi, 1996) in terms of a more in-depth, quantitative study into understanding the full impact of the quality of the processes of requirements understanding and solving, by individual designers as well as design teams, on the quality of the final design solution.

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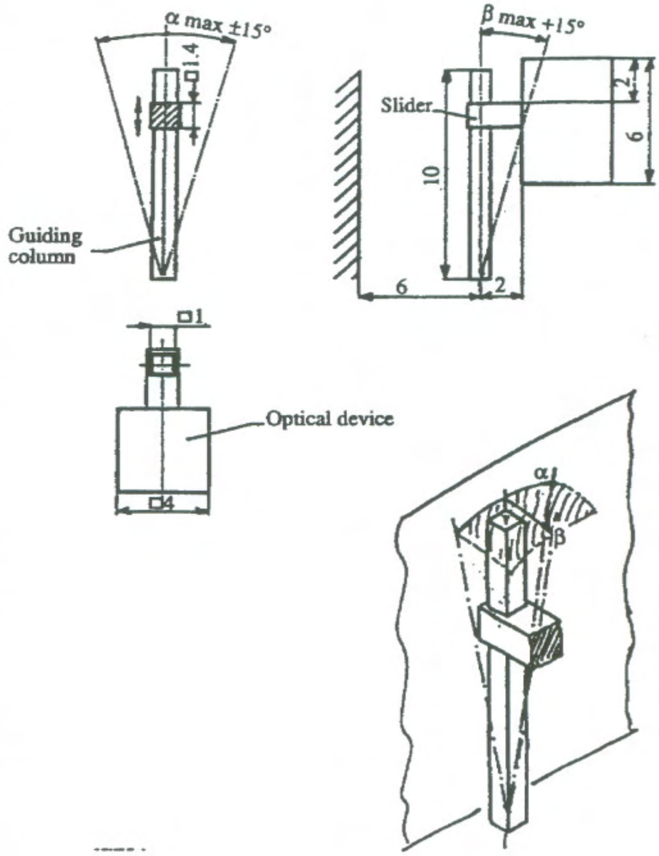
Appendix 1

The assignment and assembly drawing of one of the designs developed-a wall-mounted swivel mechanism

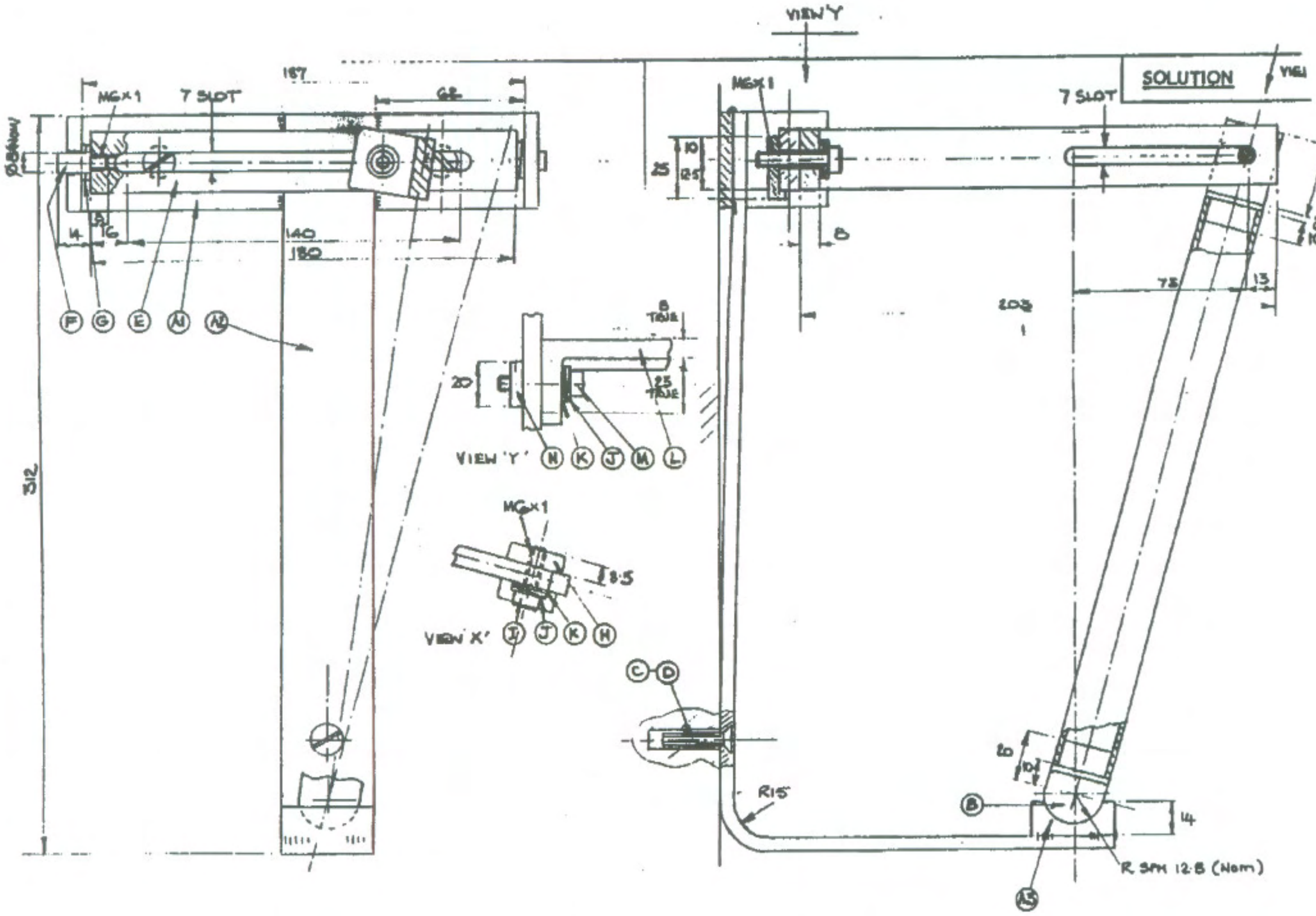


Structure 1 Attached sketch of swivel mechanism (inch)

Design a mechanism with which the guiding column of an optical device can be mounted to a wall (see the attached sketches). The operations for which the optical device is to be used do not put specific requirements on the positional accuracy of the optical device. The height of the optical device can be adjusted on the guiding column (AlMgSi0.5, 1 inch square, thickness 0.08 in.). The device should be able to slide at least 7 inches along the column. A method to lock the slider on the column exists (not drawn in the sketches). The mechanism should be able to carry the weight of the optical device (the mass is about 2 kg, the distance between the column's axis and the centre of gravity of the optical device is about 4 in.). The mechanism should enable the column to swivel (+/-15 degrees maximum in the alpha direction and +15 degree in the beta direction). A combination of movements in the alpha and beta directions should be possible. It should be possible to position the device at any angle within the range indicated. The mechanism should be operated manually and with minimal force. The optical device should maintain a set position. The swivel axes and the column should intersect in one point at the lower end of the column. This point should be at a distance of 6 inches from the wall. Any movements of the column, other than those specified above should be avoided if possible.

The wall is made of bricks. A method for connecting the mechanism to the wall should be provided. The mechanism is a one-off product to be manufactured as economically as possible in the workshop of the company. The production technologies available in this workshop are described in the green folder *(contains description of facilities available for turning, milling, sawing, drilling and welding)* on your desk. The use of raw materials and the standard components other than those available (see catalogues and books) is not allowed. All parts should be protected against corrosion.

(This additional part is given only to re-designers: A design solution for the assignment described above is contained in the documentation provided. It is now required to redesign the mechanism to allow for a precise adjustment of the position of the column for both angular movements, alpha and beta. The positional accuracy



A1, A2: Wall bracket assembly	A3: Wall bracket assembly socket	B: Ball end
C: Fixing screw	D: Wall plug	E: Pivoted slot
F: Pivot pin	G: Spring washer double	H: Top end
I: Caphead screw	J: Spring washer double	K: Washer
L: Forward slot	M: Caphead screw	N: Retainer

Structure 2 Assembly drawing of CD1's design, one of two designs supplied to re-designers

should be +/- 0.5 degree. All other requirements of the original assignment still apply.)

It is required that an assembly drawing (scale 1:1) of the product is produced including leading dimensions. This drawing should adequately define the geometry of all parts. The individual components should be numbered on the drawing and listed in a bill of materials. The bill of materials should include the materials used. Also included should be any standard components along with their reference number.

Instructions

The documentation available to you is listed at the end of this page. Further information can be acquired from the experiment leader. If you have any questions, please ask the experiment leader at any time. We need to build up a picture as representative as possible of your thought process and ideas. Please, speak your thoughts as you work through the problem, even if you think they might be irrelevant. Please try to THINK ALOUD!!

There might be occasions when you are not able to express your thoughts that occur to you at a certain moment. In this case, try to describe them immediately afterwards. When you pause for a longer period of time, the experiment leader will remind you to think aloud, or, if that is not possible at that moment, he or she will ask you to describe what happened to you. Also speak your thoughts when you are not thinking about the problem directly but on something else (see the sign!). Do you have any questions?

Documentation provided: Machinery's handbook, 19th edition; Shigley, Mechanical Engineering Design, 1st metric edition; BSI Education, Engineering Drawing Practice for Schools and Colleges; J.Smith and Sons Limited, Metals Handbook; GKN Steelstock, Stock Range; Description of machines available in the workshop.

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