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Commonalities across Designing: Empirical Results

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This paper presents empirical evidence of commonalities across designing that appear to be independent of the designers' geographical location, expertise, discipline, the specific design task, the size and composition of the design team, and the length of the design session. Our evidence is founded on thirteen highly heterogeneous design case studies that differ along these dimensions but exhibit some commonalities. We analysed the results from protocols of these case studies produced by a variety of researchers, using a method that is independent of any domain- or situation-specific parameter. We found that some design issues tend to occur from the beginning of the design process for all thirteen case studies. We also found that some issues are generated at a constant rate across all thirteen case studies. Our findings support the claim that designing can be studied as a distinct human activity that appears in different expressions but shares the same fundamental characteristics.

Introduction

Designing is a complex activity that has attracted a significant amount of attention from different research domains, trying to demystify its manifold process. One of the biggest challenges in this regard is to define designing as a unique activity while it is used in a vast range of domains such as engineering, software, graphical interfaces, and electronics, to name a few. Understanding the commonalities amongst different expressions of design is a prime step in offering a universal definition of it [1, 2, 3]. Currently, interviews and protocol studies are two of the most credited and frequently used methods to study the behaviour of designers in solving different design problems. Despite their validity in obtaining insight into the thoughts of designers [4], the *ad-hoc* dependency of these methods on the data has been a barrier for generalising the results of these studies across different designers, design situations and design researchers [5]. In addition, the complexity of designing *per se* makes aggregating the results of empirical studies in large, statistically significant scales a challenging task.

In this paper we use an approach to the analysis of multiple design protocols that allows studying their commonalities independently of any environmental parameter. It is based on the cumulative occurrence of design issues over the course of designing, coded according to the Function-Behaviour-Structure (FBS) design issue system. The results of applying this method indicate that there are significant commonalities across different instances of designing.

Source Data: Thirteen Design Protocols

Our source data consists of thirteen segmented and coded design protocols produced by various research groups. These protocols differ from one another in multiple ways. Table 1 presents the state space covered by the thirteen protocols, in terms of seven independent variables and their ranges of values.

Table 1 The state space covered by the thirteen design protocols

Variable	Range of values
Source location of data	Australia, Singapore, Taiwan, UK, USA – seven states: CA, IL, MN, UT, VA
Design task	Designing of: • an assistive window raising device • an assistive door opening device • a novel thermal ink pen • a software system to simulate road traffic controls • an art gallery • a teaching device • a future personal entertainment system • a coffee maker • a pedometer to encourage running • a commercial website
Participants'	Professional designers, Undergraduate students, High

expertise	school students
Participants' knowledge domain	Architecture, Business, Electronics, Ergonomics, Industrial design, Interface design, Mechanical Engineering, Mechatronics, Psychology, Software, Web design
Team size	From 2 to 9 designers
Team composition	Homogeneous, Heterogeneous
Length of design protocol (in number of segments)	From 192 to 1,280 segments

As shown in Table 1, the protocols originate from four different continents and address a wide variety of design tasks. The participants include designers with different levels of expertise and with varying education and training in different disciplines. The team sizes vary from small teams of only two designers to larger teams of up to 9 designers. Some of the teams are homogeneous (consisting of designers with the same knowledge background), while others are heterogeneous (consisting of designers with different knowledge backgrounds). The lengths of the design sessions vary from 192 to 1,280 segments of the coded protocols.

Table 2 shows the specific characteristics of each of the thirteen design protocols.

The thirteen protocols were segmented and coded by nine different coder teams from various research groups. All coders used the same coding scheme based on the FBS framework [6, 7]. It consists of six design issues:

- *Requirements*: includes all requirements and constraints that were explicitly provided to the designers at the outset of the design task.
- *Function*: includes teleological representations that can cover any expression related to potential purposes of the design. These representations may be flow-based or state-based [8].
- *Expected Behaviour*: includes attributes of the design used as assessment criteria or target values for potential design solutions. They may include technical, economic, ergonomic and other characteristics [9, 10].
- *Behaviour derived from structure* (or, shorthand, "structure behaviour"): includes attributes of the design that are measured, calculated or derived from observation of a specific design solution.
- *Structure*: includes the components of a design and their relationships. They can appear either as a set of general concept solutions or as detailed solutions. This is consistent with similar distinctions of solution structure in the design literature [2, 10].
- *Description*: includes any form of external representation produced by a designer, at any stage of the design process. Descriptions may

come as sketches, (CAD) models, physical prototypes, calculations, textual expressions or other observable outcomes of designerly activity.

Table 2. The thirteen design protocols

	VARIABLES						
Design Protocol	**Source Location of Data**	**Design Task**	**Participants' Expertise**	**Particpants' Knowledge Domain**	**Team Size**	**Team Composition**	**Length of Design Protocol [number of segments]**
P1	Virginia, USA	Designing an assistive window raising device; design method: unstructured	Undergraduate students	Mechanical engineering	2	Homogeneous	891
P2	Virginia, USA	Designing an assistive window raising device; design method: brainstorming	Undergraduate students	Mechanical engineering	2	Homogeneous	614
P3	Virginia, USA	Designing an assistive door opening device; design method: morphological analysis	Undergraduate students	Mechanical engineering	2	Homogeneous	500
P4	United Kingdom	Designing a novel thermal ink pen	Professional designers	Electronics, mechatronics ergonomics, business	7	Heterogeneous	1280
P5	California, USA	Designing a software system to simulate road traffic controls	Professional designers	Software	2	Homogeneous	596
P6	Sydney, Australia	Designing an art gallery	Professional designers	Architecture	2	Homogeneous	192
P7	Utah, USA	Designing an assistive window raising device	High school students	–	2	Homogeneous	426
P8	Illinois, USA	Designing a teaching device using protoyping	Undergraduate students	Mechanical engineering, psychology	3	Heterogeneous	328
P9	Illinois, USA	Designing a teaching device without using protoyping	Undergraduate students	Mechanical engineering, psychology	3	Heterogeneous	424
P10	Singapore	Designing a future personal entertainment system	Undergraduate students	Industrial design	2	Homogeneous	418
P11	Singapore	Designing a coffee maker	Undergraduate students	Industrial design	2	Homogeneous	782
P12	Taipei, Taiwan	Pedometer to encourage running	Undergraduate students	Industrial design	2	Homogeneous	304
P13	Minnesota, USA	Designing a commercial-level website	Professional designers	Interface design, web design, business analyst	9	Heterogeneous	289

The coders arbitrated their coding using the Delphi method [11], discussing any differences until reaching agreement on the assigned codes. The average agreement between coders across the thirteen protocols is 89.8%.

Analysis Method: Cumulative Occurrence of Design Issues

Our approach for analysing and comparing the thirteen design protocols is to calculate the cumulative occurrence of each of the six design issues for every segment in a protocol. Specifically, the cumulative occurrence (c) of design issue (x) at segment (n) will be $c = \sum_{i=1}^{n} x_i$ where (x_i) equals 1 if segment (i) is coded as (x) and 0 if segment (i) is not coded as (x). Plotting the results of this equation on a graph with the segments (n) on the horizontal axis and the cumulative occurrence (c) on the vertical axis will visualise the occurrence of the design issues. Figure 1 shows a general representation of such a graph.

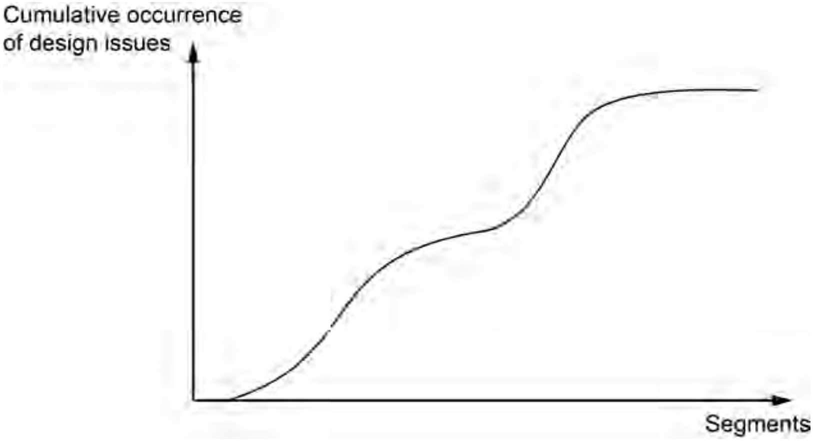

Fig1 Graphical representation of the cumulative occurrence of design issues in design protocols

Based on the notion of cumulative occurrence of design issues, we determine the following qualitative measures for each of the six classes of design issues:

- *First occurrence at start*: Do design issues occur near the start of the design session, or later?
- *Continuity*: Do design issues occur throughout the design session, or are there discontinuities?
- *Shape of the graph*: Is the graph linear or non-linear?

In addition, we will determine the following quantitative measures:

- *Slope*: This is a measure for the speed at which design issues are generated.
- *R^2 (coefficient of determination)*: This is a measure for the linearity of the graph. We will set a minimum value of 0.950 as a condi-

tion for linearity.

All of these measures are independent of the length of the design session. This allows comparing design protocols with different numbers of segments.

Results

Requirement Issues

Figure 2 shows the cumulative occurrence of requirement issues graphically. Table 3 provides quantitative and qualitative measures for all but six design protocols – as indicated by the asterisks, in these protocols the number of data points was too low (less than 10) to allow meaningful statements and statistical analyses. The remaining seven design protocols all exhibit the same qualities:

- Requirement issues in all protocols analysed occur from the start of the design session.
- Requirement issues in all protocols analysed occur discontinuously, as the graph tends to flatten out with increasing numbers of segments.
- The cumulative occurrence of requirement issues in all protocols analysed is non-linear. The mean R^2 value of 0.791 (standard deviation of 0.122) is below the threshold value of 0.950.

The mean slope of the graphs is 0.033, with a standard deviation of 0.016.

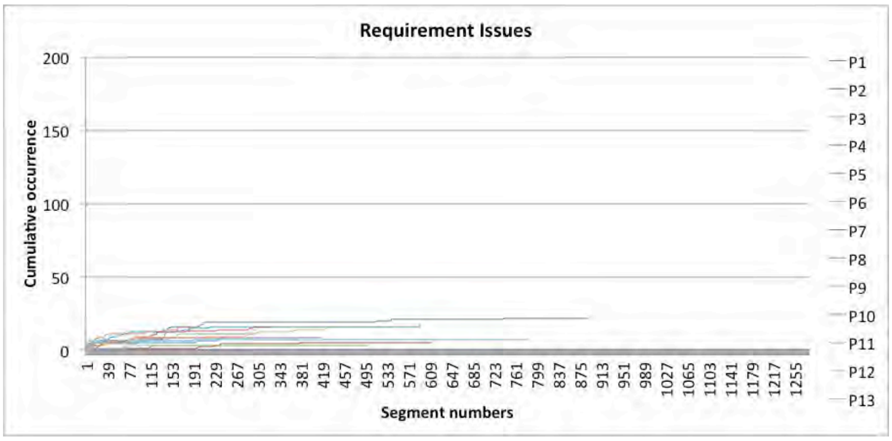

Fig2 Cumulative occurrence of requirement issues

Table 3 Quantitative and qualitative measures related to the cumulative occurrence of requirement issues

Protocol	Slope	R^2	First occurrence at start	Continuity	Shape
P1	0.018	0.646	Yes	No	Non-Linear
P2*	---	---	---	---	---
P3*	---	---	---	---	---
P4*	---	---	---	---	---
P5	0.014	0.621	Yes	No	Non-Linear
P6	0.055	0.791	Yes	No	Non-Linear
P7*	---	---	---	---	---
P8	0.043	0.882	Yes	No	Non-Linear
P9	0.028	0.900	Yes	No	Non-Linear
P10*	---	---	---	---	---
P11*	---	---	---	---	---
P12	0.025	0.772	Yes	No	Non-Linear
P13	0.047	0.928	Yes	No	Non-Linear
Mean	0.033	0.791			
Stdev	0.016	0.122			

* No results produced due to small dataset (< 10 data points)

Function Issues

Figure 3 shows the graphs representing the cumulative occurrence of function issues. Table 4 provides the corresponding quantitative and qualitative measures, with the exception of five protocols that have too small datasets (as indicated by the asterisks in the table). Across the protocols we analysed, we can make the following observations:

- Function issues in all protocols analysed occur from the start of the design session.
- Function issues in most protocols analysed occur discontinuously, as their graphs flatten out towards the end of the design session. There are continuous occurrences in protocols P1 and P6; however, the total number of data points in these protocols (22 and 16, respectively) is fairly low, which makes their qualitative assessment less reliable.
- The cumulative occurrence of function issues in most protocols analysed is non-linear. The mean R^2 value is 0.888 (standard deviation of 0.071), which is below the threshold of 0.950. We found linearity only in protocol P3 (R^2 value of 0.960), yet based on a fairly small dataset (24 data points).

The mean slope of the graphs is 0.090, with a standard deviation of 0.091.

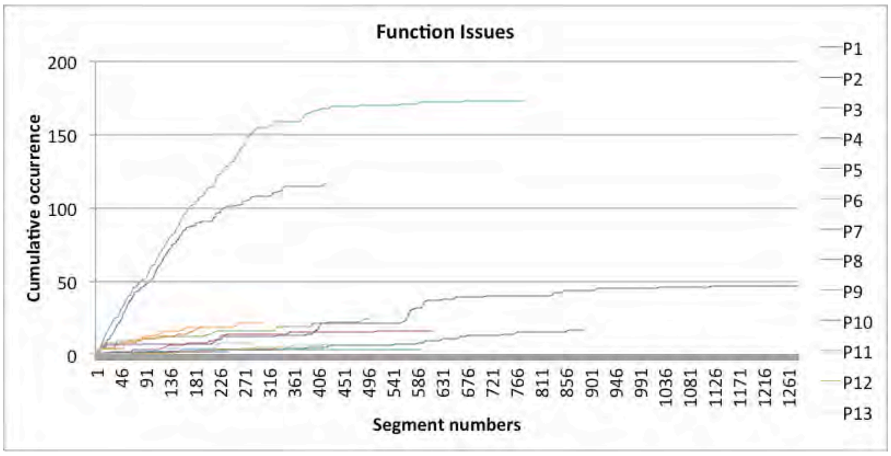

Fig3 Cumulative occurrence of function issues

Table 4 Quantitative and qualitative measures related to the cumulative occurrence of function issues

Protocol	Slope	R^2	First occurrence at start	Continuity	Shape
P1	0.019	0.929	Yes	Yes	Non-Linear
P2	0.028	0.830	Yes	No	Non-Linear
P3	0.034	0.960	Yes	No	Linear
P4	0.041	0.923	Yes	No	Non-Linear
P5*	---	---	---	---	---
P6	0.074	0.948	Yes	Yes	Non-Linear
P7*	---	---	---	---	---
P8*	---	---	---	---	---
P9*	---	---	---	---	---
P10	0.271	0.884	Yes	No	Non-Linear
P11	0.190	0.745	Yes	No	Non-Linear
P12	0.064	0.883	Yes	No	Non-Linear
P13*	---	---	---	---	---
Mean	0.090	0.888			
Stdev	0.091	0.071			

* No results produced due to small dataset (< 10 data points)

Expected Behaviour Issues

Figure 4 shows the cumulative occurrence of expected behaviour issues graphically. Table 5 summarises quantitative and qualitative measures.

Most of the thirteen protocols exhibit similarities:

- Expected behaviour issues in most protocols occur from the start of the design session. There is one exception in protocol P2; expected behaviour issues here occur with some delay.
- Expected behaviour issues in most protocols occur continuously. Exceptions are protocols P2, P3 and P11, where the occurrence of expected behaviour issues drops off towards the end of the design sessions.
- The cumulative occurrence of expected behaviour issues in most protocols is linear. The mean R^2 value is 0.972 (standard deviation of 0.022), which is above our threshold of 0.950. Only two protocols exhibit non-linearity in the occurrence of expected behaviour issues; these are protocols P3 and P11. This is probably related to the discontinuity observed in these protocols.

The mean slope of the graphs is 0.213, with a standard deviation of 0.135.

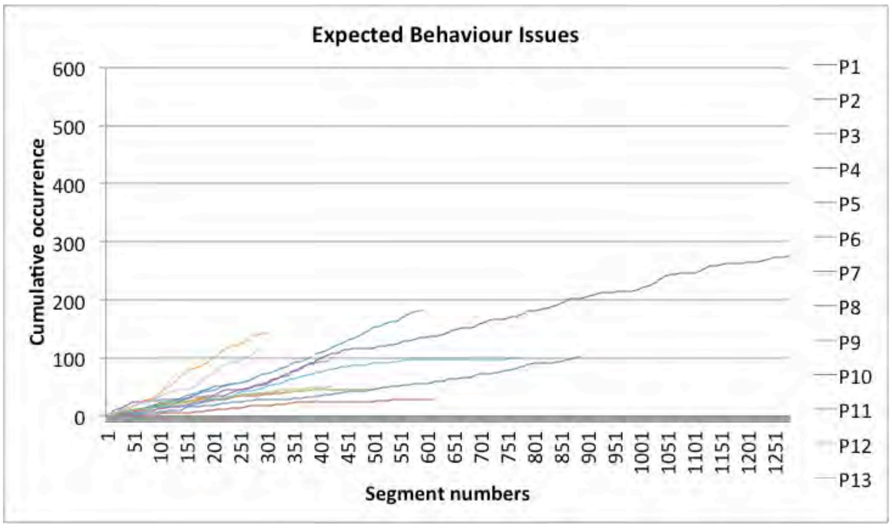

Fig4. Cumulative occurrence of expected behaviour issues

Table 5 Quantitative and qualitative measures related to the cumulative occurrence of expected behaviour issues

Protocol	Slope	R^2	First occurrence at start	Continuity	Shape
P1	0.110	0.984	Yes	Yes	Linear
P2	0.056	0.954	No	No	Linear
P3	0.090	0.929	Yes	No	Non-Linear
P4	0.222	0.995	Yes	Yes	Linear
P5	0.314	0.986	Yes	Yes	Linear
P6	0.175	0.975	Yes	Yes	Linear
P7	0.240	0.979	Yes	Yes	Linear
P8	0.130	0.989	Yes	Yes	Linear
P9	0.118	0.981	Yes	Yes	Linear
P10	0.239	0.959	Yes	Yes	Linear
P11	0.150	0.930	Yes	No	Non-Linear
P12	0.530	0.993	Yes	Yes	Linear
P13	0.397	0.984	Yes	Yes	Linear
Mean	0.213	0.972			
Stdev	0.135	0.022			

Structure Behaviour Issues

Figure 5 shows the cumulative occurrence of structure behaviour issues, with Table 6 providing quantitative and qualitative measures, except for one protocol, P13 (as indicated by the asterisk in Table 6), that had too few occurrences of structure behaviour issues to be taken into account.

Again, there are strong similarities across the protocols analysed:

- Structure behaviour issues in most protocols occur from the start of the design session. There are exceptions in protocols P3, P10 and P11, where structure behaviour issues occur with some delay.
- Structure behaviour issues in all protocols analysed occur continuously.
- The cumulative occurrence of structure behaviour issues in most protocols is linear. The mean R^2 value is 0.982 (standard deviation of 0.019), which is above the threshold of 0.950. Only one protocol, P12, exhibits non-linearity.

The mean slope of the graphs is 0.246, with a standard deviation of 0.092.

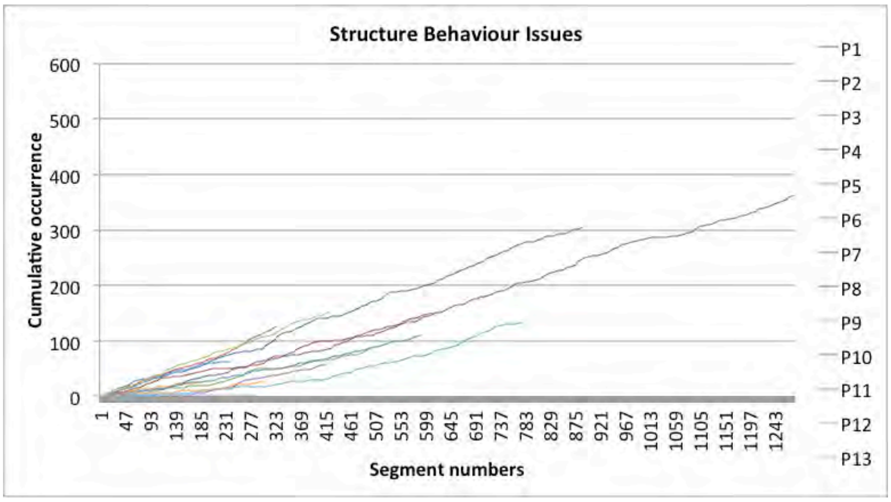

Fig5. Cumulative occurrence of structure behaviour issues

Table 6 Quantitative and qualitative measures related to the cumulative occurrence of structure behaviour issues

Protocol	Slope	R^2	First occurrence at start	Continuity	Shape
P1	0.352	0.997	Yes	Yes	Linear
P2	0.235	0.987	Yes	Yes	Linear
P3	0.179	0.982	No	Yes	Linear
P4	0.296	0.995	Yes	Yes	Linear
P5	0.186	0.991	Yes	Yes	Linear
P6	0.138	0.973	Yes	Yes	Linear
P7	0.283	0.975	Yes	Yes	Linear
P8	0.372	0.989	Yes	Yes	Linear
P9	0.361	0.998	Yes	Yes	Linear
P10	0.219	0.992	No	Yes	Linear
P11	0.254	0.974	No	Yes	Linear
P12	0.079	0.928	Yes	Yes	Non-Linear
P13*	---	---	---	---	---
Mean	0.246	0.982			
Stdev	0.092	0.019			

* No results produced due to small dataset (< 10 data points)

Structure Issues

Figure 6 shows the cumulative occurrence of structure issues, with Table 7 providing quantitative and qualitative measures.

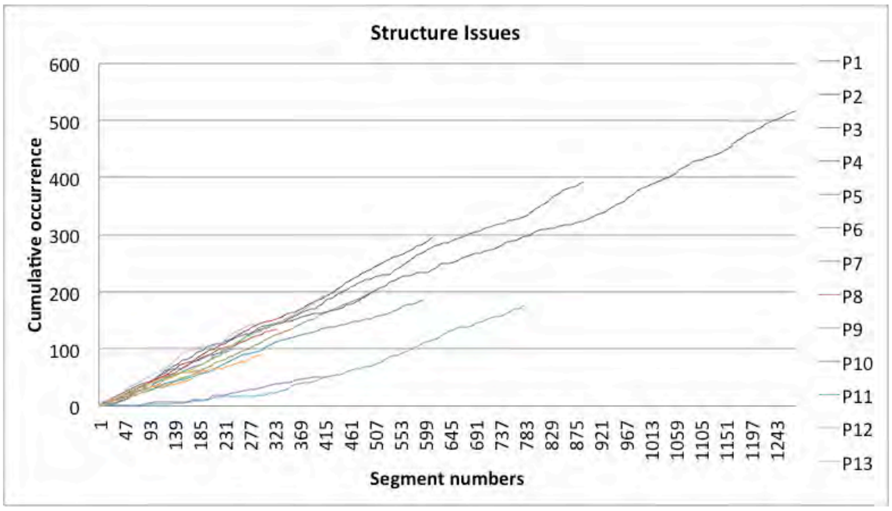

Fig6. Cumulative occurrence of structure issues

Table 7 Quantitative and qualitative measures related to the cumulative occurrence of structure issues

Protocol	Slope	R^2	First occurrence at start	Continuity	Shape
P1	0.437	0.999	Yes	Yes	Linear
P2	0.476	0.999	Yes	Yes	Linear
P3	0.417	0.998	Yes	Yes	Linear
P4	0.378	0.993	Yes	Yes	Linear
P5	0.313	0.994	Yes	Yes	Linear
P6	0.372	0.988	Yes	Yes	Linear
P7	0.411	0.997	Yes	Yes	Linear
P8	0.424	0.998	Yes	Yes	Linear
P9	0.469	0.995	Yes	Yes	Linear
P10*	0.186	0.993	No	Yes	Linear
P11**	0.336	0.993	No	Yes	Linear
P12	0.287	0.990	Yes	Yes	Linear
P13	0.507	0.989	Yes	Yes	Linear
Mean	0.386	0.994			
Stdev	0.088	0.004			

* The first 160 segments of the protocol are ignored in linearity calculation

** The first 300 segments of the protocol are ignored in linearity calculation

Commonalities across the thirteen protocols include:

- Structure issues in most protocols occur from the start of the design session. There are exceptions in protocols P10 and P11, where the designers did not generate structure issues until later in the design session.

- Structure issues in all protocols occur continuously.
- The cumulative occurrence of structure issues in all protocols is linear. The mean R^2 value is 0.994 (standard deviation of 0.004), which is above the threshold of 0.950. In this analysis we ignored the initial segments of P10 and P11 based on the late beginning of a clearly linear part of the graphs representing these protocols.

The mean slope of the graphs is 0.386, with a standard deviation of 0.088.

Description Issues

Figure 7 shows the cumulative occurrence of description issues. Table 8 summarises quantitative and qualitative measures. Protocols P8, P9, P12 and P13 were not taken into account in this analysis because of the small dataset they provide for description issues.

We can observe the following commonalities:

- Description issues in most protocols do not occur from the start. Exceptions include protocols P2, P3 and P10.
- Description issues in most protocols occur continuously, except in P1 and P4.
- The cumulative occurrence of description issues in most protocols is linear, except in P4 and P7. The mean R^2 value is 0.964 (standard deviation of 0.036), which is above the threshold of 0.950. In this analysis we ignored the initial segments of P6 based on the late beginning of a clearly linear part of the graph representing this protocol.

The mean slope of the graphs is 0.166, with a standard deviation of 0.086.

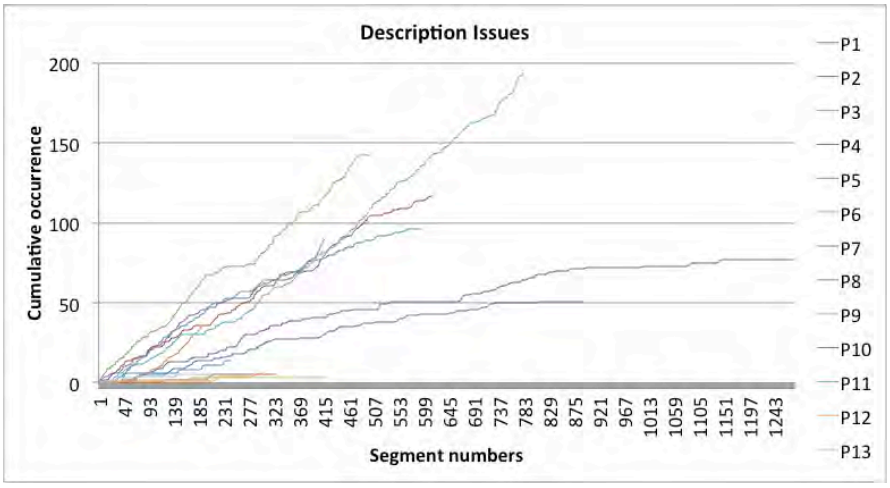

Fig7 Cumulative occurrence of description issues

Table 8 Quantitative and qualitative measures related to the cumulative occurrence of description issues

Protocol	Slope	R^2	First occurrence at start	Continuity	Shape
P1	0.064	0.970	No	No	Linear
P2	0.196	0.994	Yes	Yes	Linear
P3	0.274	0.992	Yes	Yes	Linear
P4	0.063	0.934	No	No	Non-Linear
P5	0.170	0.973	No	Yes	Linear
P6*	0.238	0.962	No	Yes	Linear
P7	0.051	0.881	No	Yes	Non-Linear
P8**	---	---	---	---	---
P9**	---	---	---	---	---
P10	0.192	0.979	Yes	Yes	Linear
P11	0.249	0.986	No	Yes	Linear
P12**	---	---	---	---	---
P13**	---	---	---	---	---
Mean	0.166	0.964			
Stdev	0.086	0.036			

* The first 46 segments of the protocol are ignored in linearity calculation

** No results produced due to small dataset (< 10 data points)

Summary of Commonalities Found

Our analysis has uncovered a number of commonalities among the protocols. Table 9 summarises our findings.

Table 9 Summary of commonalities

Design issue	Mean slope (Stdev)	Mean R^2 (Stdev)	First occurrence at start	Continuity	Shape
Requirement	0.033 (0.016)	0.791 (0.122)	Yes	No	Non-Linear
Function	0.090 (0.091)	0.888 (0.071)	Yes	No*	Non-Linear*
Expected Behaviour	0.213 (0.135)	0.972 (0.022)	Yes*	Yes*	Linear*
Structure Behaviour	0.246 (0.092)	0.982 (0.019)	Yes*	Yes	Linear*
Structure	0.386 (0.088)	0.994 (0.004)	Yes*	Yes	Linear
Description	0.166 (0.086)	0.964 (0.036)	No**	Yes*	Linear*

* for at least 75% of the protocols analysed

** for 66% of the protocols analysed

Some of the commonalities are not surprising, given existing assumptions, observations and hypotheses about designing. For example, it is often assumed that the design process commences with clarifying a set of requirements and functions [9, 10]. This is confirmed by our empirical data that indicates that requirement issues and function issues occur from the start of a design session. Our graphs also show that these two issues occur discontinuously and non-linearly, which is consistent with many design theories that see a diminishing role of requirements and functions in the later stages of designing. Further, our finding that structure issues occur from the start of the design process confirms observations by other design researchers [2, 12], namely, that designers tend to commit to specific solutions early on.

There are other commonalities that have not been observed in previous studies. One observation is that expected behaviour issues, structure behaviour issues, structure issues and description issues occur continuously throughout design sessions. They also occur at a highly linear rate, with most R^2 values exceeding the threshold of 0.950. A comparison of the slopes in Table 9 indicates that the rate at which structure issues are generated is significantly higher than for any other design issue. There is very little variance in the slopes for structure issues and structure behaviour issues across different design protocols.

Conclusion

Our empirical results indicate that there are regularities across designing that are independent of individual parameters including location, knowledge domain, expertise, team size, team composition, design task and length of the design session. Many of these regularities can be seen as significant, based on the heterogeneity of the data and on the statistical evidence. It supports the premise that designing can be studied as a distinct human activity that transcends disciplinary boundaries and specific design situations [13, 14].

The findings presented in this paper provide a starting point for two future research avenues. One avenue includes increasing the empirical basis of our findings by analysing a larger number of design protocols using the same method. The other avenue includes investigating some of the unexpected results of our analysis. This includes the strong focus of designers on structure issues, in terms of the high rate at which they are generated, and the high continuity and linearity with which they accumulate. What research is needed to explain this phenomenon? Are there any implications for design theory or design education? Future work may also address some of the exceptions we found in our analysis. For example, what are the causal factors for the designers' delayed focus on structure issues in protocols P10 and P11? Is there a link to the designers' educational background in industrial design? Similar questions may be asked for the other design issues. Possible ways of enquiry may use fMRI-based cognitive neuroscience [15].

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References

1. Asimow M (1962) Introduction to Design. Prentice-Hall, Englewood Cliffs, NJ
2. Lawson B (1980) How designers think: The design process demystified. Architectural Press, Amsterdam
3. Dym C (1994) Engineering Design: A Synthesis of Views. Cambridge University Press, Cambridge, MA
4. Ericsson KA, Simon HA (1993) Protocol Analysis: Verbal Reports as Data. MIT Press, Cambridge, MA
5. Gero JS (2010) Generalizing design cognition research. DTRS8: Interpreting Design Thinking. DAB documents, Sydney, pp. 187–198
6. Gero JS (1990) Design prototypes: A knowledge representation schema for design. AI Magazine 11:26–36
7. Gero JS, Kannengiesser U (2004) The situated function-behaviour-structure framework. Design Studies 25:373–391
8. Chittaro L, Kumar AN (1998) Reasoning about function and its applications to engineering. Artificial Intelligence in Engineering 12:331–336
9. Hubka V, Eder WE (1996) Design science: Introduction to the needs, scope and organization of engineering design knowledge. Springer, London
10. Pahl G, Beitz W (2007) Engineering Design: A Systematic Approach. Springer, Berlin
11. Gero JS, McNeill T (1998). An approach to the analysis of design protocols. Design Studies 19:21–61
12. Ullman DG, Dietterich TG, Stauffer LA (1988) A model of the mechanical design process based on empirical data. Artificial Intelligence for Engineering, Design, Analysis and Manufacturing 2:33–52
13. Cross N (1982) Designerly ways of knowing. Design Studies 3:221–227
14. Visser W (2009) Design: one, but in different forms. Design Studies 30:187–223
15. Alexiou K, Zamenopoulos T, Gilbert S (2011) Imaging the designing brain: A neurocognitive exploration of design thinking. Design Computing and Cognition'10. Springer, pp. 487–503