15 Scientific models from empirical design research

John S Gero and Jeff WT Kan

For many designing is an unknowable mystery. Science is founded on the axiom that things are knowable. Can designing be "known" through science? Science takes the approach that there are observables called phenomena that can be represented separately from the phenomena themselves and that these phenomena exhibit regularities. Further, science assumes that these phenomena can in some sense be measured. Hypotheses are conjectures about the regularities of these phenomena that can be tested against the data acquired through measurement. Tested hypotheses form the basis of the construction of models that can be used both to describe the regularities and to make predictions about the phenomena underlying those regularities. It has been argued that since the result of designing is a unique design, i.e., when you carry out the same design task again you produce a different design, where is the regularity that is required for science to apply to designing? The regularity in designing is not necessarily in the resultant design but in the process that produces that design – designerly behavior. Using science to study designerly behavior results in scientific models describing designerly behavior based on empirical evidence rather than on personal experience. The remainder of this chapter will introduce a method for the capture of empirical data on designing. This is followed by the description of an ontology of designing that maps onto the phenomena of designing that are capturable. The rest of the chapter describes some of the scientific models that can be produced from this empirically-grounded data.

15.1 Empirical research in designing

Science allows for such questions as: what are the differences between designerly behavior and problem solving? how does the task affect designerly behavior? how does education affect designerly behavior? how does the domain background of the designer affect designerly behavior? and how does education affect designerly behavior?

Studying designers requires that there be phenomena to be studied. Since designing is an activity of the mind its study can be carried out using concepts from cognitive science and brain science. In this chapter we focus on cognitive studies of designing called *design cognition*. Cognitive science is the scientific study of the mind and its processes. It infers the activities and processes of the mind through the observable behaviors of individuals. Similarly design cognition is the scientific study of the minds of the designers through their observable behaviors – designerly behavior.

Studies of design cognition have fallen into five methodological categories: questionnaires and interviews (Cross and Cross 1998); input-output experiments (where the designer is treated as a black box which produces the behaviors in the outputs for changes in inputs) (Purcell et al 1993); anthropological studies (Lopez-Mesa and Thompson 2006), protocol studies (Ericcson and Simon 1993; van Someran et al 1994) and more recently cognitive neuroscience (Alexiou et al 2010). While each of these methods has produced interesting results, the most useful method continues to be protocol studies and it has become the basis of the current cognitive study of designers (Atman, et al. 2008; Badke-Schaub et al 2007; Christensen & Schunn 2007; Gericke et al 2007; Gero & McNeill 1998; Kavakli & Gero 2002; McDonnell & Lloyd 2009; McNeill et al 1998; Suwa et al 1998; Suwa, Gero & Purcell 2000; Williams et al 2015; Williams et al 2013; Yu et al 2015). Protocol analysis is a rigorous methodology for eliciting verbal reports of thought sequences as a valid source of data on thinking. It is a well-developed, validated method for the acquisition of data on thinking. It has been used extensively in design research to assist in the development of the understanding of the cognitive behavior of designers. Protocol analysis involves capturing the utterances and gestures of designers while they are designing and converting them into a sequence of segments of coded design issues, where each segment contains one and only one coded design issue. The sequence of segments with their codes form a symbol string in a limited alphabet, which can then be analyzed for a large variety of structures that form the basis of the development of models based on empirical data.

15.2 An ontology of designing

What are the phenomena of designing? This question raises many issues that are not pursued here. One way to develop the phenomena is to observe designers in action but this assumes that the observer knows what to observe. Another approach is to develop an ontology of designing that guides the observations. An ontology of designing can commence with the following axiom: the foundations of designing are independent of the designer, their situation and what is being designed. This leads to the claim that: all designing can be represented in a uniform way. In this chapter designing is modelled as transforming design requirements from outside the designer into design descriptions. The Function-Behavior-Structure ontology (Gero 1990; Gero and Kannengiesser 2014) models this transformation of requirements (R) into design descriptions (D) in terms of three classes of variables: function, behavior, and structure. The function (F) of a designed object is defined as its teleology; the behavior of that object is either expected (Be) or derived (Bs from the structure (S) which is the components of an object and their relationships. Requirements can be expressed in terms of function, behavior or structure. Description can be function, behavior or structure. Thus, no new ontological variables are needed to express requirements and description. These six variables become the ontological issues of designing, called *design issues*. Fig. 15.1 shows the relationship among those transformation processes and the design issues. The eight ontological designing processes are a consequence of the transformations between design issues and are: formulation (1), synthesis (2), analysis (3), evaluation (4), documentation (5) and three types of reformulations (6-8).

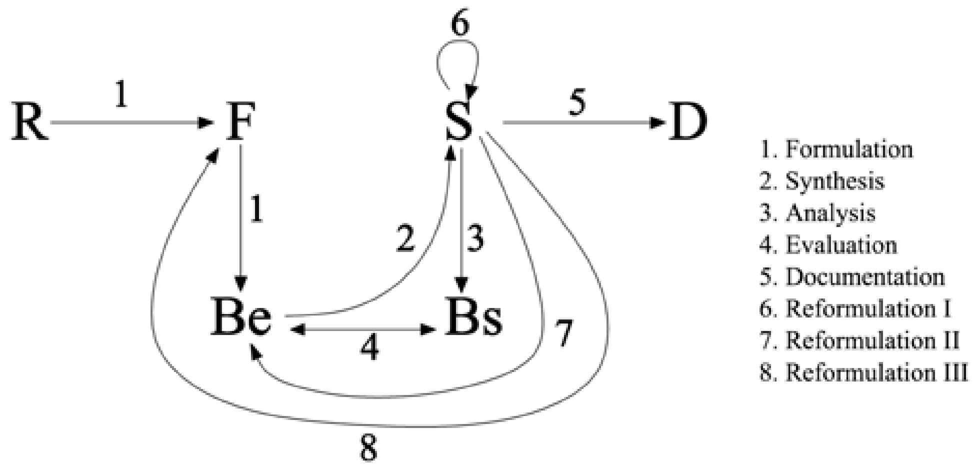


Fig. 15. 1 The FBS ontology of designing (after Gero, 1990 and Gero and Kannengiesser, 2004)

15.2.1 FBS coding

The empirical protocol data in this chapter was produced using a coding scheme that mapped onto the six design issues of requirement (R), function (F), expected behavior (Be), behavior derived from structure (Bs), structure (S), and description (D). The protocols are segmented strictly according to these six issues. In protocols, utterances that are not about designing are not coded as design issues; these may include jokes, social communication and management issues. These fundamental FBS classes denote the state of affairs of designing of each coded segment. They capture the essence of design activities, which will then be modeled, using statistical and mathematical methods.

15.3 Models for design issues

The protocols, after transcription, segmentation and coding, result in a chronologically ordered list of the six design issues identified by their codes (R, F, Be, S, Bs, D). This represents the distribution of cognitive effort across the design session captured by the protocol video. Descriptive statistics of design issues can quantify the distribution of cognitive effort while designing, producing a simple statistical model that characterizes one regularity of designing. This can be produced for a single design session as a case study or can be aggregated across many design sessions by different designers commencing with the same set of requirements, to produce a statistically robust model.

15.3.1 Statistical model of design issues

Knowing the distribution of design issues can characterize a design session and make comparisons possible among different conditions and domains; for example Williams et al (2011) explore the effect of education on design cognition by recording protocols of students designing before and after taking a design course. Participants (twenty eight students, sixteen in semester 1 and 12 in semester 2) were asked to attend two out-of-class experiments. They were paired up and given 45 minutes to generate a design solution that meets the requirements. The distributions of design issues before and after the introductory design course are illustrated in Fig. 15.2. It is observed that students spent the majority of their cognitive effort on the design issue of structure (37~40%), followed by behaviour from structure (30~32%). These two design issues accounted for two-thirds of their cognitive effort. Much less cognitive effort was spent on the design issues of description (9~15%), expected behaviour (6~11%), function (2~7%), and requirement (2~3%). The variations between before and after taking the design course have been identified for each design issue. The percentages of their cognitive effort related to function and description have increased approximately 5% and 6% respectively, whereas the percentages for all the other design issues decreased.

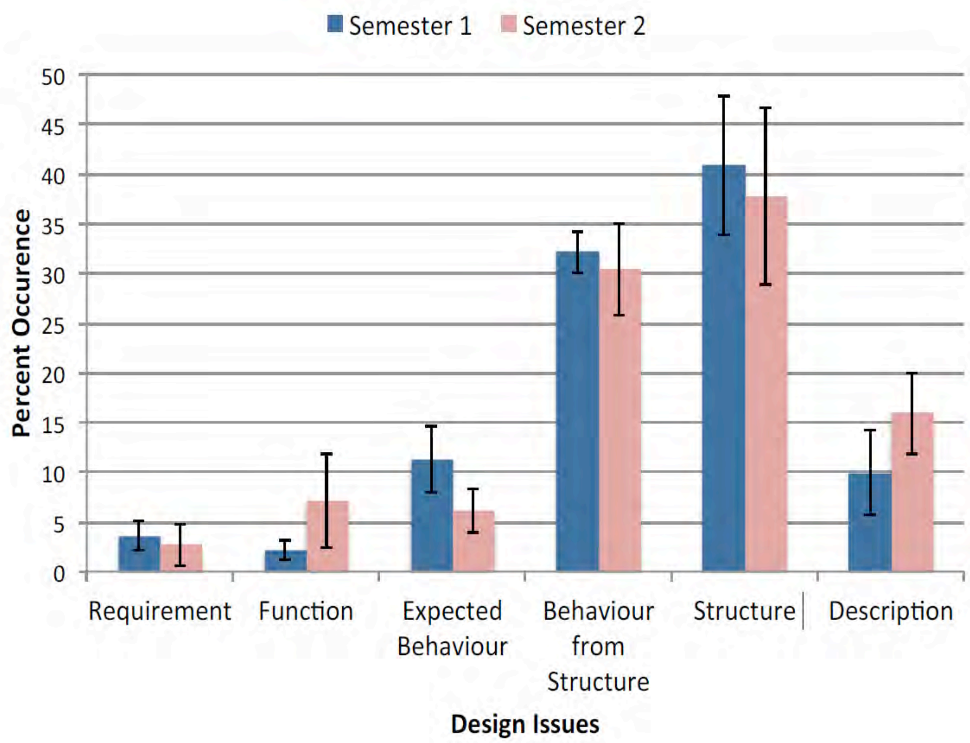


Fig. 15. 2 Percent occurrences of design issues before (Semester 1) and after (Semester 2) taking a design course

Are these differences statistically significant? Standard statistical significance techniques are used to test this. The results in Table 15.1 indicate that there are statistically significant differences for the percentages of cognitive effort on the three design issues of function, expected behaviour and description between the two semesters. This implies that students expended more cognitive effort on function, expected behaviour and description after taking the design course and that these differences were not the random results. These increase could be due to the major learning goals of the course: exploring the intention space and increasing effective oral and written communication of design. With the conjecture that issues of function will spawn issues of expected behavior, the percentage of cognitive effort on expected behaviour significantly decreased from semester 1 to semester 2 is unexpected. It is possible that this cognitive change could be caused by the specific pedagogy of the design course.

Table 15.1 Statistical significance testing of design issues before (Semester 1) and after taking the design course (Semester 2)

Design issue	t (z) statistics	p-value
Requirement	-0.925	0.137
Function	2.904	0.003**
Expected Behaviour	-3.495	0.004**
Behaviour from structure	-0.879	0.409
Structure	-0.717	0.490
Description	2.685	0.021*

*p < 0.05, **p < 0.01

Quantifying design activates with descriptive statistical models of design issues shows where cognitive effort is focused during designing, making it possible to compare designing across a wide range of scenarios. In this instance two such descriptive statistical models are compared to examine the effects of an educational intervention.

15.3.2 Problem-Solution (P-S) Index model

Herbert Simon's seminal work on artificial intelligence (Simon 1969) had a strong and continuing influence on design research; the paradigm of designing as problem solving dominated design research for many years. Jiang, Gero and Yen (2014) mapped the FBS design issues onto problem and solution spaces, Table 15.2, and produced a metacognitive model of designing as the problem-solution (P-S) index defined as the ratio of the sum of occurrences of the design issues concerned with the problem space to the sum occurrences of the design issues concerned with the solution space, Equation 15.1.

Table 15.2 Mapping FBS design issues onto problem and solution spaces

Problem/solution space	Design issue
Problem space = Problem-focused design issues	Requirement (R) Function (F) Expected Behavior (Be)
Solution space = Solution-focused design issues	Behavior from Structure (Bs) Structure (S)

$$\text{P-S index} = \frac{\sum(Problem-related\ issues)}{\sum(Solution-related\ issues)} = \frac{\sum(R,F,Be)}{\sum(Bs,S)} \tag{15.1}$$

The P-S index value quantifies the relative focusing on problem to solution. When the P-S index equals one, it indicates that equal cognitive effort was spent on both the problem and solution spaces. A design session with a P-S index larger than 1 can be characterized as having a problem-focused designing style, and a session with a P-S index value less than 1 can be characterized as having a solution-focused design style.

In a study on the effect of designers' educational domain and the effect of class of requirements on design cognition, Jiang, Gero and Yen (2014) examined the design style of twelve Industrial Design students and twelve Mechanical Engineering students. Two participants, either from the same discipline or different ones, were paired to work collaboratively in two conceptual design tasks: design a coffee maker (CM) for the existing market and design a next-generation personal entertainment system (PES) for the year 2025.

Industrial Design teams' PES sessions had higher P-S index values than the other sessions, demonstrating a strong tendency of focusing on problem-related issues, Fig 15.3. The P-S index value of the Industrial Design CM sessions are around the threshold of problem-solution division. The results suggest that industrial design student teams have a design style that is more focused on the design problem than mechanical engineering student teams in both design tasks.

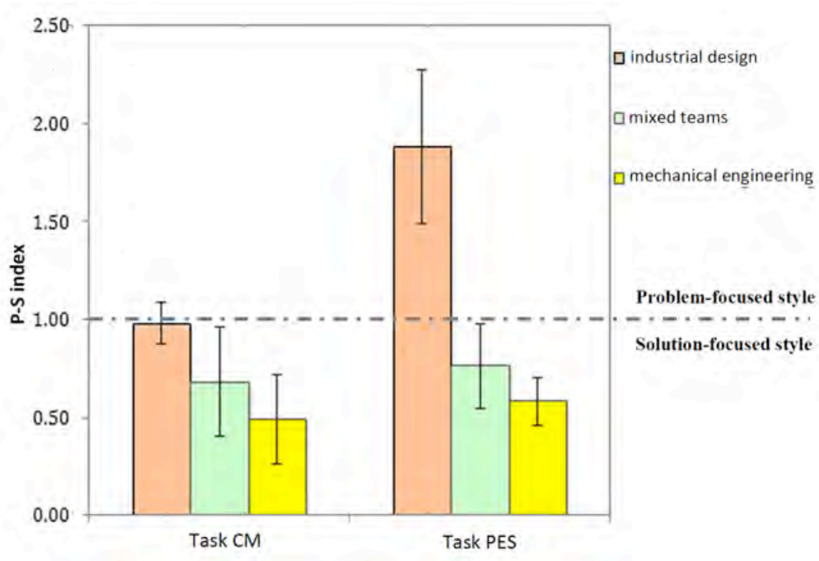


Fig. 15.3 Aggregated P-S index values and design style

The P-S index can be considered as the meta-level structure over the cognitive processes behind design problem and solution spaces; in other words how problem or solution focus is organized in the design cognitive process. This, in a narrow sense, models the style of metacognition of designing.

15.3.2 Cumulative occurrence model of design issues

Another simple model of designing based on the segmented and coded protocol is the cumulative occurrence model of design issues, defined as the cumulative occurrence (c) of design issue (x) at segment (n) in Equation (15.2).

$$c = \sum_{i=1}^{n} x_i \qquad (15.2)$$

where (x_i) equals 1 if segment (i) is coded as (x) and 0 if segment (i) is not coded as (x)

Equation (15.2) can be expressed in a graphic form; the following five measures can be derived for each of the six classes of design issues and used to characterize designing:

- First occurrence at start: whether a design issue first occurs near the start of designing?
- Continuity: whether a design issue occurs throughout designing?

- Shape of the graph: is the cumulative occurrence graph linear or non-linear? This measures whether the cognitive effort for that design issue is expended uniformly across the design session
- Slope: of the linear cumulative linear graph, it measures the rate at which the cognitive effort represented by that that design issues is expended.
- R2 (coefficient of determination): A measure for the linearity of the graph.

Gero, Kannengiesser and Pourmohamadi (2014) used a cumulative model of design issues in a case study to investigate the commonalities across designing using data from thirteen existing design studies. These studies were highly heterogeneous including students and professional, novices and experts, architects, software designers, web designers and mechanical engineers, individuals and teams ranging in size from two to nine members. Figs 15.4 and 15.5 show the un-normalized cumulative design issues of function and structure of the protocols from 13 different studies. Since the protocols have different time span and segments so the graphs have different lengths. However, the five measures are independent of the heterogeneity of the data. Their empirical results (not presented here) indicate that there are commonalities across designing. For example function issues occur from the start of a design session but are discontinuous, Fig 15.4. The cumulative occurrence model shows that structure issues, Fig 15.5, occur from the start of the design process (for 11 of the 13 studies) indicating that designers tend to commit to specific solutions early on with high continuity, linearity and at a rate of expenditure of cognitive effort that are very similar.

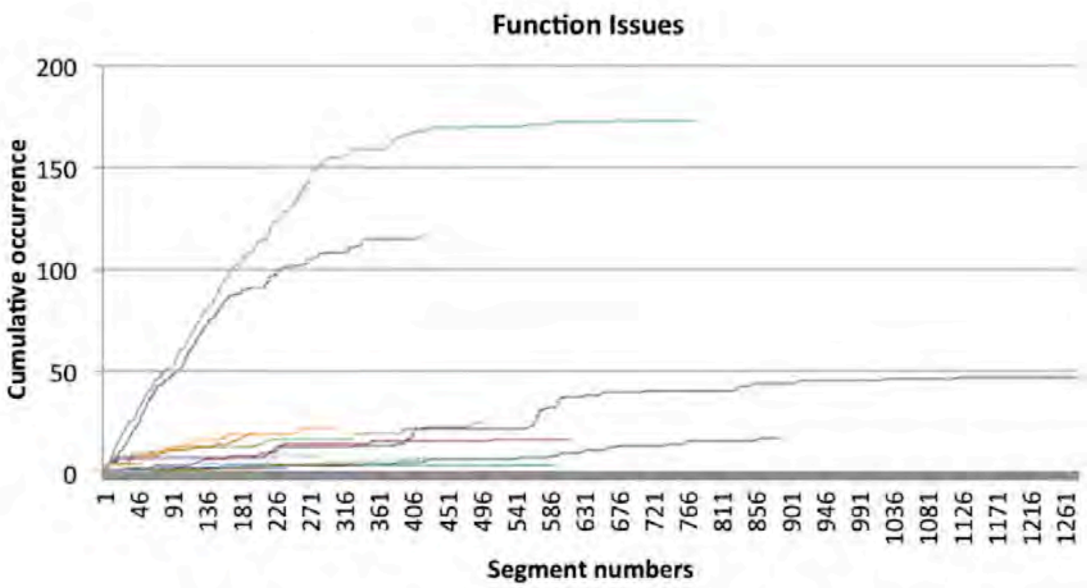


Fig. 15.4 Cumulative occurrence of function issues of the 13 design protocols

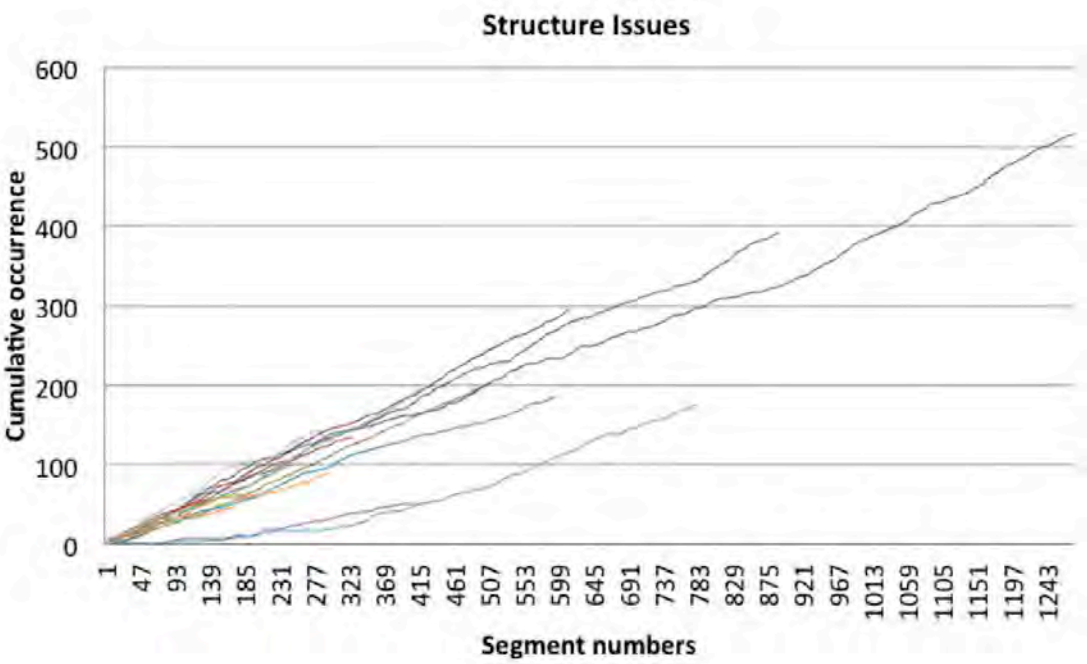


Fig. 15.5 Cumulative occurrence of structure issues of the 13 design protocols

Further, the results in Fig 15.5 indicate that the cumulative effort expended on structure issues is linear across almost all the design sessions, an observation that has been confirmed by further studies (Gero, Kannengiesser and Pourmohamadi 2014).

Results from using these three models based on FBS design issues provide support for the premise that designing can be studied as a distinct human activity that transcends disciplinary boundaries and specific design situations. Each provides an opportunity to investigate human designing in a way that can provide further insights of designerly behaviour.

15.4 Models for designing processes

Asimow (1962) described the design process using two orthogonal two structures; a vertical structure involved a sequence of phases (from abstract to detail) and a horizontal structure containing decision making that is common to all phases. His model of designing can be characterized by a series of cycles through analysis of the problem, synthesis of a solution, and evaluation of the solution. His terminology is not the same as the named FBS processes. Much design research codes protocols using coding schemes based on Asimow's three generic processes, however the FBS processes can be directly derived from the FBS ontology and the relationship between coded segments, instead of coding them separately. In this section, two models of deriving these FBS design processes are depicted.

15.4.1 Markov models

Markov chains, also referred to as Markov analysis and Markov models, produce a statistical model of the sequence of events; they describe the probability of one event leading to another (Kemeny and Snell 1960). More formally, a Markov chain is a discrete-time stochastic process with a number of states such that the next state solely depends on the present state. Here syntactic design processes is defined as the transformation of cognitively related design issues by assuming that each design issues is directly related to its immediately preceding issue. This produces a syntactic linkograph. In Fig 15.6 the first four segments (50-53) formed three syntactic design processes: formulation (Fe to Be), synthesis (Be to S) and analysis (S to Bs). Here, the design process of documentation (S to D) does not meet this definition.

how do you get in? (gesturing without confirming)	50	F
You want to get in	51	Be
through here (gesturing south side).	52	S
this is the left.	53	Bs
(draw arrows on the south side)	54	D

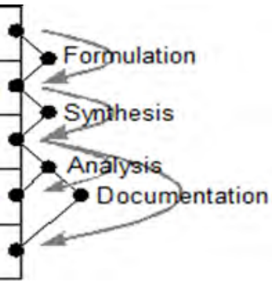


Fig. 15.6 Example of sequence of design issues, linkograph, and design processes

Derivable from the Markov model or directly from the data, the mean first passage time is the average number of segments traversed before reaching a particular design issue from the current issue. Kan and Gero (2011) demonstrated, with a case study, that Markov models of syntactic design processes can be used to compare design activities across domains. They compared the mean first passage time and the Markov models (through the transition probabilities) of a mechanical design, a software design, and an architectural design session. The transition probabilities is the probability of one design issue leading to another design issues. Table 15.3 contains the five shortest first passage time, indicating differences in design cognition of processes across domains.

Table 15.3 Five shortest mean first passage time of the three sessions

Architectural Design	Software Design	Mechanical Design
Be>S (Synthesis)	F>Be (Formulation)	Bs>S
D>S (Reformulation I)	R>S	S>S (Reformulation I)
S>S (Reformulation I)	Bs>Be (Evaluation)	D>S (Reformulation I)
F>Be (Formulation)	D>S (Reformulation I)	Bs>Bs
Bs>S	Be>S (Synthesis)	S>Bs (Analysis)

Gero, Jiang and Williams (2013) employed a Markov model to produce design processes as part of their study of design cognition while using two different creativity techniques. Twenty-two senior mechanical engineering students were formed into teams of two. Each team was given the same two design tasks, respectively using an unstructured concept generation technique (brainstorming) and a structured technique (TRIZ). They found that students using brainstorming sessions have higher percentages of analysis, documentation and reformulation I syntactic design processes. When using TRIZ, students have higher syntactic design processes of formulation and evaluation, Fig 15.7.

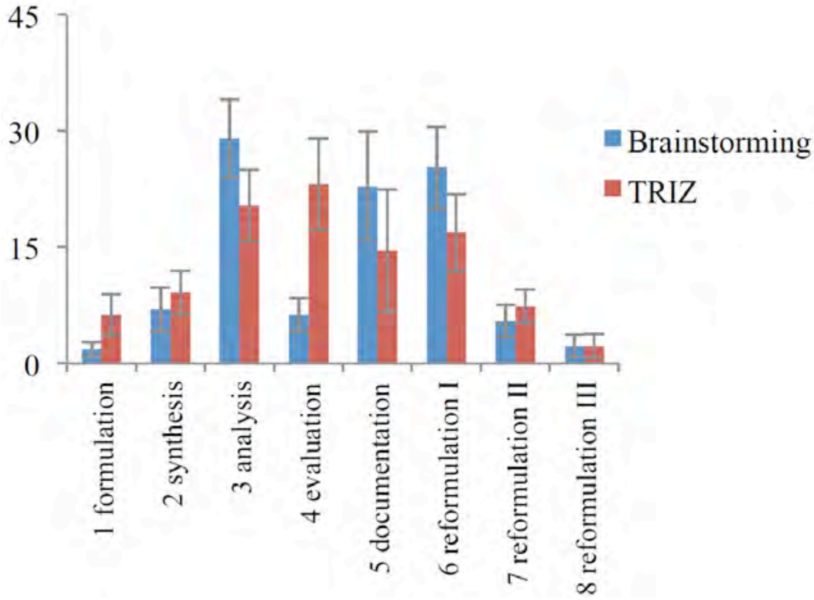


Fig. 15.7 Frequency distribution syntactic design processes (%)

15.4.2 Models from linkographs

Semantic design processes are the design processes that are derived by considering the semantic linkage of design issues, as opposed to their syntactic linkages. After constructing the linkograph, if there are n links there will be *n* processes. A standard statistical model can be used to model the distribution of these design processes. Fig 15.6 shows four semantic design processes derived from the linkograph, in which the first three overlap with the syntactic design processes (simple sequence of issues).

Kan (2008), in a case study, compared a pair of designers collaborating face to face with the same designers using a 3D-world, an Internet based virtual collaboration environment. The semantic design processes of the two sessions are shown in Fig 15.8. All three types of reformulations were present in the face-to-face session, but only a type one reformulation was found when designing in the 3D-world. Both sessions have a relatively high type one reformulation. The face-to-face session has higher analysis, synthesis and evaluation processes. In the 3D-world session the predominant process was the reformulation of structure, the re-making of forms.

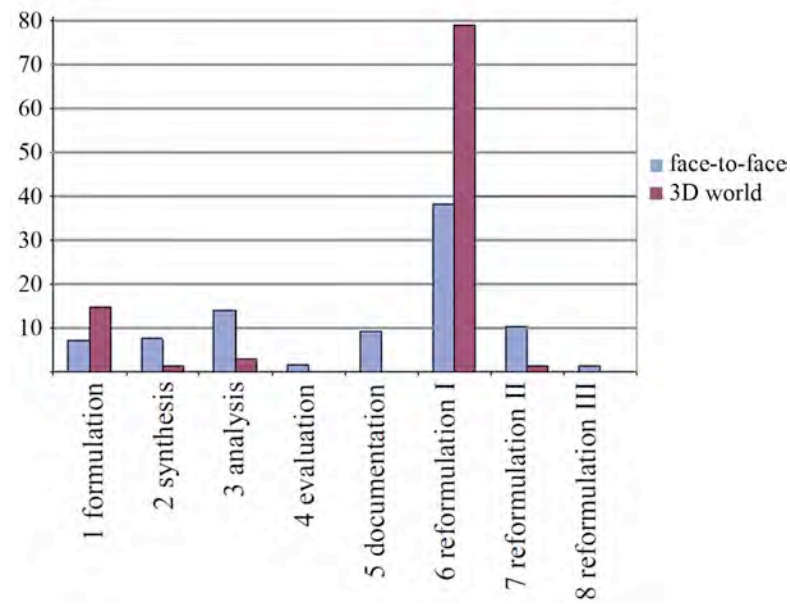


Fig. 15.8 The semantic design processes (%) of the face-to-face and the 3D-world sessions

The same statistical models used to describe overall design sessions can be used to investigate individual behavior in teams. Statistic models of syntactic and semantic design processes show the distributions of team designing processes and individuals' designing cognitive processes. These provide the basis for further quantitative comparisons based on empirical design data.

When modeling designerly behavior it is possible to analyze the semantic linkograph of a team-based design session and construct a model of the design processes of individuals who make up the team. Kan and Gero (2011) present such results for a 7-person team industry. Two of the team members' models are presented graphically in Fig 15.9, which presents the design process interactions of team members "Allan" and "Tommy". The results presented include their behavior in the first, middle and last thirds of the design session (shown respectively in blue, red and white) to provide information on any time-based change in behavior. The horizontal axes show the design issue interactions with themselves and the other members of the team. The results for the two design processes of analysis and reformulation 1 are presented.

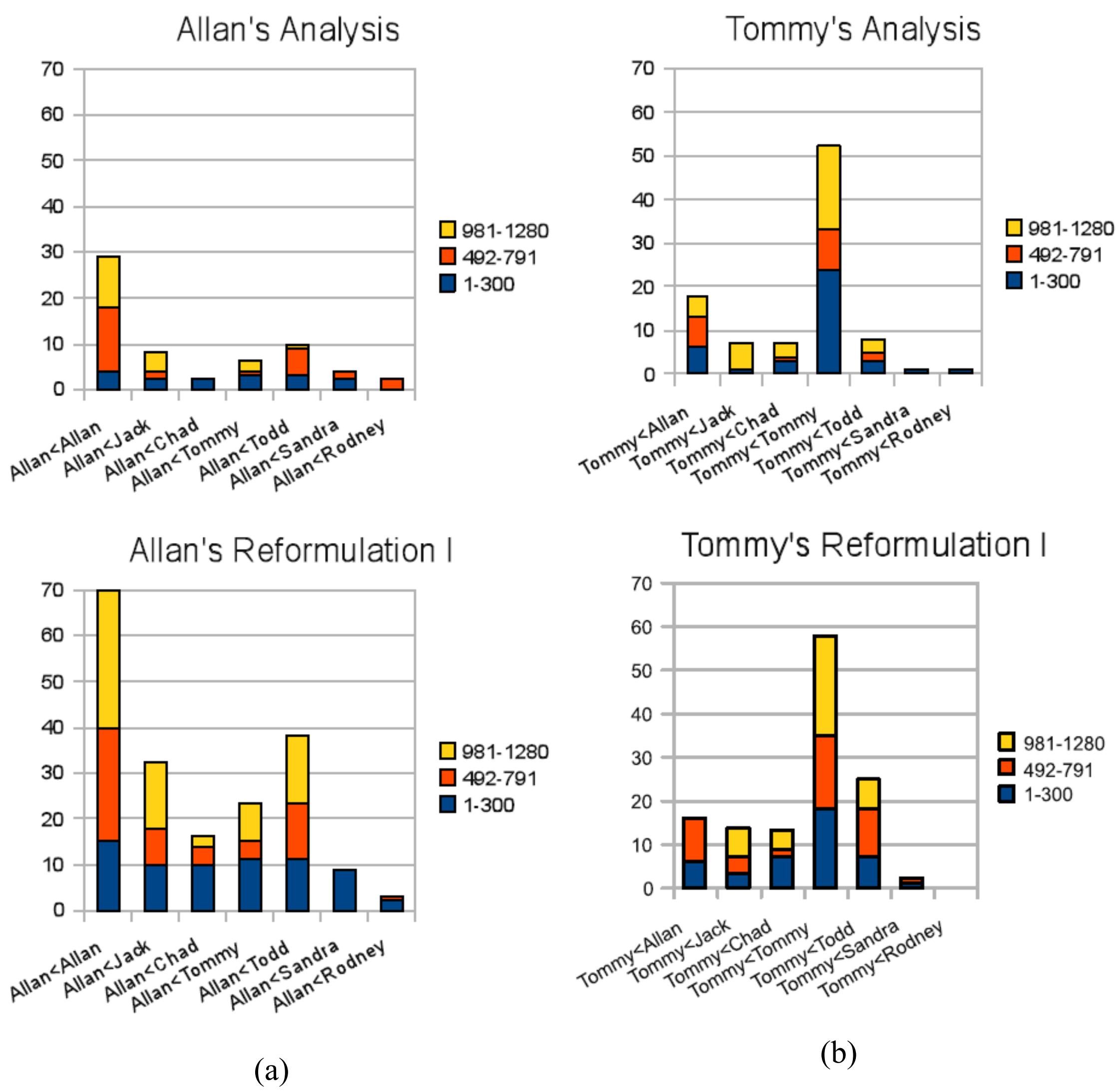
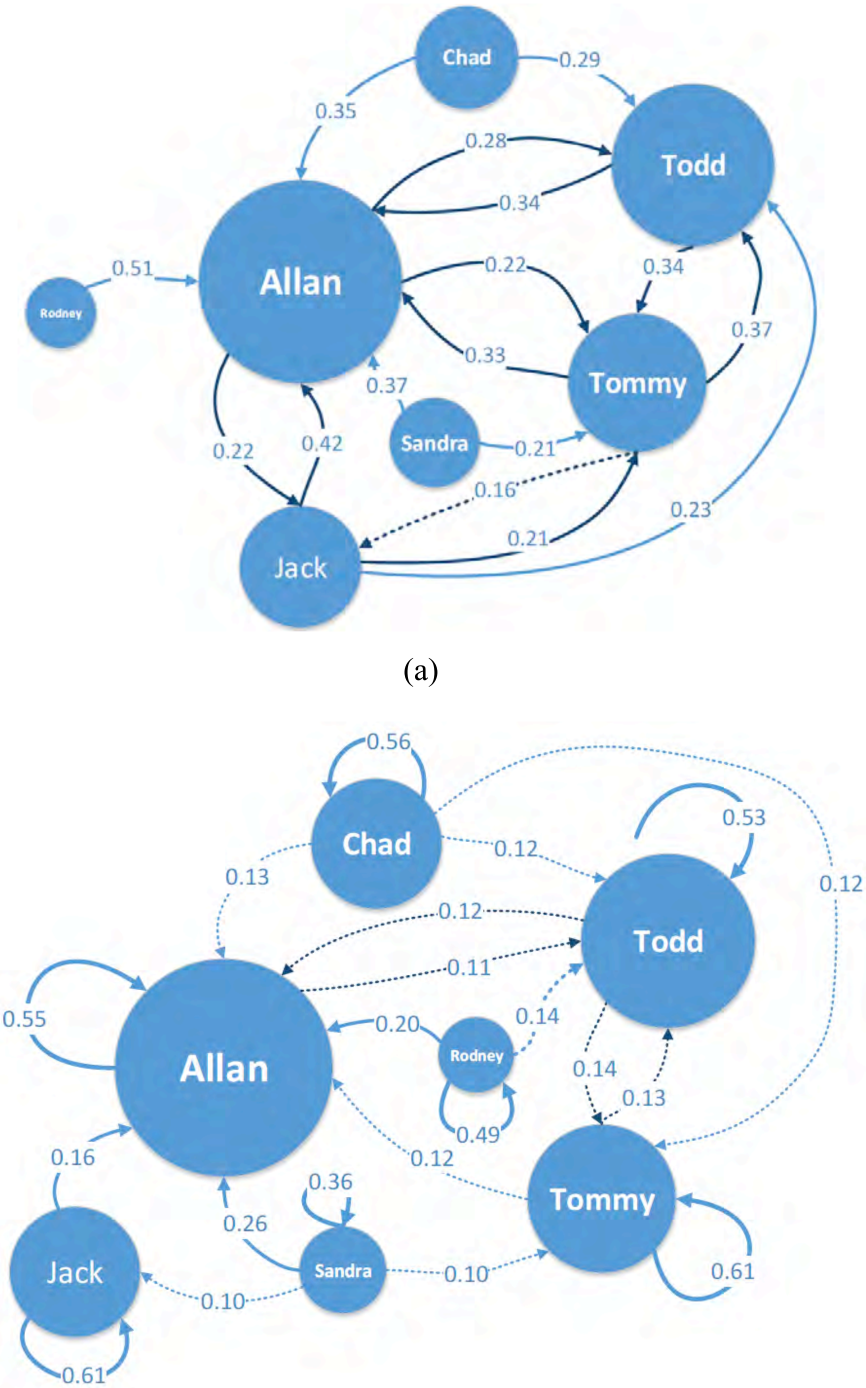


Fig. 15.9 Comparing the team design processes of (a) Allan and (b) Tommy

These results indicating that self is the primary source of design processes are surprising as many believe that brainstorming and group processes are the major sources for interactions.

With the same data, Gero et al (2015) differentiated the structure of "communication while designing" and "design communication"; the former was modelled as conversational turn-taking among participants regardless of the content of utterances, the latter was concerned with the design issues in synthesis, analysis and evaluation. The syntactic structure of the two communications is then modeled as a sequence (first order Markov model) of turn-taking and design issues respectively. The resulting two structures, in the form of graphical models, are presented in Fig 15.10, with the size of circle corresponding to the proportion of the transition probabilities.



(a)

(b)

Fig. 15.10 The team structure of (a) “communication while designing” and (b) “design communication”

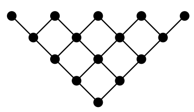
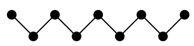
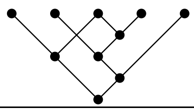
The team structure of “design communication” produces a richer graph than that for communication while designing”; they concluded that some members’ contributions can only be revealed by modeling “design communication”.

These studies illustrate that using semantic and syntactic models of FBS-derived design processes go beyond the surface of communication and reveal hidden relationships of team designing and individuals' contributions.

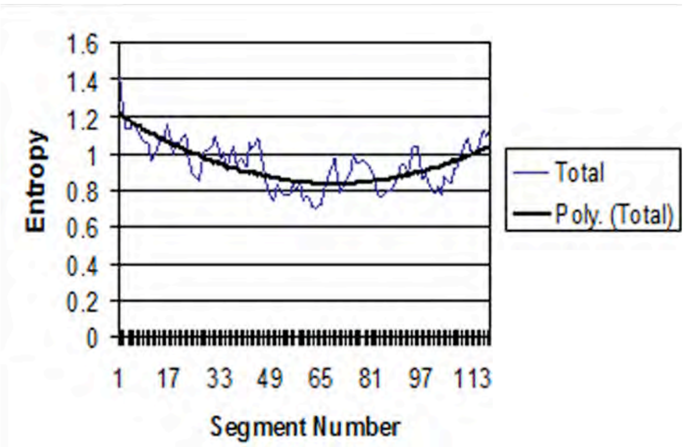
15.5 Entropy model

Kan and Gero (2005) proposed an approach to describing designerly behavior based on using Shannon's information theory (Shannon 1948) to build entropy models of linkographs. They suggested that a rich idea generation process is one where: (1) the structure of ideas is reasonably integrated and articulated, and (2) there is a variety of moves. They argued that an empty linked linkograph can be considered as a non-converging process with no coherent ideas and a fully linked linkograph represents a fully integrated process with no diversification (Kan and Gero 2009). Table 15.4 shows the entropy measurement of four hypothetical cases. Kan and Gero (2005) provide the details of the calculation of linkograph entropies of this model while Gero, Kan and Pourmohamadi (2011) describes a software tool to calculate the entropy. This model computes entropy based on the probabilities of the connectivity of each segments (either fore- or back- linked) together with the probabilities of distance among links. Entropy becomes a measure of the potential of the design space being generated as the designer(s) design.

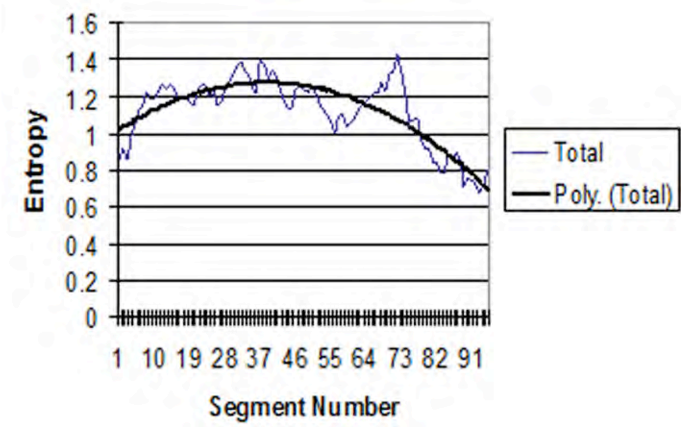
Table 15.4. Hypothetical linkographs, their interpretations and their entropies.

	Linkographs	Interpretations	Entropy
Case 1		Five moves are totally unrelated; indicating that no converging ideas, hence very low opportunity for idea development.	0.00
Case 2		All moves are interconnected, this shows that this is a total integrated process with no diversification, hinting that a pre-mature crystallization or fixation of one idea may have occurred, therefore also very low opportunity for novel idea.	0.00
Case 3		Moves are related only to the last one. This indicates the process is progressing but not developing indicating some opportunities for ideal development.	5.46
Case 4		Moves are inter-related but also not totally connected indicating that there are lots of opportunities for good ideas with development.	8.57

Kan, Bilda and Gero (2007) compared 12 design sessions under two different conditions, normal versus blindfolded during designing, their design artifacts had been double-blind reviewed by three judges according to criteria including creativity, flexibility and practicality. Kan and Gero (2005) reported that the score differences between the two conditions were insignificant and the score is not correlated to the overall entropy value of the linkograph. However when they compared the highest and lowest ranked three sessions with entropy variations across their sessions, they found all the three high-scoring sessions have concave-shaped or negative curvature in the quadratic fit curves, Fig 15.11a, and all the low-scoring sessions have convex-shaped or positive curvature curves, Fig 15.11b. The increase in entropy at the end of a session meant a better connections of segments / moves at the end, which might indicate a consolidation of ideas. More experiments are needed to verify if there is a correlation between. However, what this does indicate is that models derived from empirical data have the potential to reveal regularities that are not available by looking at the source data alone.



(a)



(b)

Fig. 15.11 Comparing entropy variation, the top graph (a) represents a high-scoring session and the bottom graph (b) represents a low-scoring session

The entropy model potentially provides a means to measure idea development opportunities. It provides another way to abstract information from a linkograph. The entropy variation during a design session is shown in Fig 15.12. The linkograph was semi-automatically generated by connecting the noun synonyms in each segment of the protocol in Wordnet (Fellbaum 1998, Kan and Gero 2009). With the advance of voice recognition technology and computational power, it becomes possible to report entropy in near real-time. This could potentially provide feedback to designers on their design productivity and idea generation opportunities.

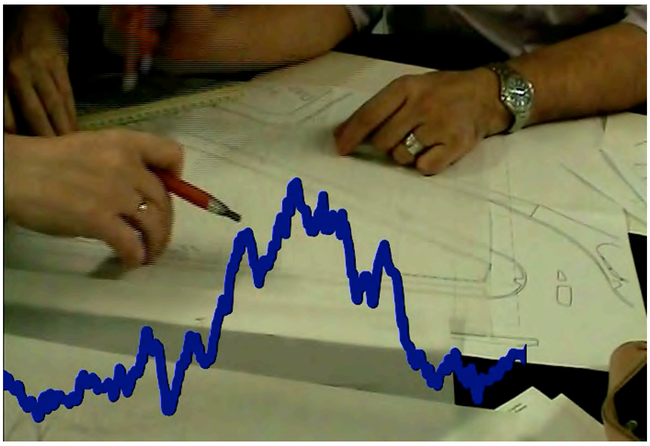


Fig. 15.12 Entropy variation overlaid on the video of a design session; time runs from left to right.

15.6 Conclusions

Designing is not a unitary activity and it is unlikely that a single coding scheme will be capable of capturing all its cognitive nuances. However, as in all science, the claim is made that there is a regularity in designing that transcends any individual and it is that regularity that is being studied. An ontology is one means to provide a framework for that regularity. Depending on the focus that is being taken a number of potential ontologies could be constructed, however, very few general ontologies have been produced for designing.

The scientific quantitative models in this chapter are founded on one highly referenced ontology of designing and are based on data from empirical studies. They all have as their goal the elucidation of the regularities that are part of designerly behavior. They demonstrate that designing need not be an "unknowable mystery" and that designing can be investigated using the method of science. This does not make designing a science, just as using the same programming language for two different tasks does not make those tasks the same.

With common tools it becomes possible to disassociate the analysis from the researcher, from the task and from the environment of the task through the development of models of designerly behavior. These models can be utilized to test hypotheses and theories to gain a better understanding of designing, provide tools for design educators to assess the effectiveness of educational interventions, and inform design practice in managing designing and design teams.

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