



HAL
open science

Linkographic Analysis of Design Ideation Session: Idea Graph Representation and Additional Tools for Analysis

Abdellatif Dkhil, Mickaël Gardoni, Lamine Belgacem, Remy Houssin

► **To cite this version:**

Abdellatif Dkhil, Mickaël Gardoni, Lamine Belgacem, Remy Houssin. Linkographic Analysis of Design Ideation Session: Idea Graph Representation and Additional Tools for Analysis. 15th IFIP International Conference on Product Lifecycle Management (PLM), Jul 2018, Turin, Italy. pp.715-725, 10.1007/978-3-030-01614-2_65 . hal-02075546

HAL Id: hal-02075546

<https://inria.hal.science/hal-02075546>

Submitted on 21 Mar 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Linkographic analysis of design ideation session: idea graph representation and additional tools for analysis

Abdellatif Dkhil¹, Mickael Gardoni¹, Lamine Belgacem², Remy Houssin³

¹ ETS Montréal, 1100 Notre-Dame West, H3C 1K3, Montreal, Qc, Canada
abdellatif.dkhil.1@ens.etsmtl.ca, mickael.gardoni@etsmtl.ca

² Bombardier Canada, 500 Boulevard Côte-Vertu Outest, Dorval, Qc, H4S 1Y9, Canada
lamine.belgacem@aero.bombardier.com

³ INSA Strasbourg, 24 Boulevard de la Victoire, 67000 Strasbourg, France
remy.houssin@unistra.fr

Abstract. Linkography is a method for analysis of ideation process in the conceptual design stage. This method has been used to provide information about the ideation session, to investigate the structure of idea generation process and to compare idea session productivity. The progress of an ideation session is made observable through the analysis of connection between ideas. The main goal of this paper is to improve the analysis of idea generation session. Through the use of graph theory for visualizing and analyzing the connection between ideas.

Keywords: Linkography, conceptual design, ideation, Graph, Analysis tools.

1 Introduction

The ability to invent, create, and innovate is the center of engineering and product development. The conceptual design stage is an interactive endeavor involving the evolution of ideas between two or more participants in discussion. The ideation process has the most significant impact to generate innovative products and this is essential for any organization to maintain its competitive position [1]. To better understand dynamics that take place in the ideation, the Linkography research approach proposes a method for recording, visualizing and analyzing connections between actions, ideas or events. The proposed method is seen as a system of notation and design analysis process that focuses on links between design moves, design ideas or decisions developed by Goldschmidt : [2], [3], [4], [5] [6], [7] and extended by others [8] [9], [10], [11], [12], [13], [14]. Van-der-Lugt [15], adapted Linkography approach was further developed as a method for assessing the idea generation process by means of investigating the connections between ideas produced in the ideation. The Van-der-Lugt research work aims to understand the black box of the ideation process to better understand the inner processes under which ideas are elaborated. This process starts with the selection of design ideation team and the definition of the design problem. Then, the application of particular ideation method to permit ideating. Finally, the protocol of the ideation or the record of

design team's ideation meeting will be analyzed. In the last step, the Linkography approach are used to analysis and understanding the ideation session. Fig 1 gives a description of application of Linkography approach steps. The first step permits the identification of ideas listed by segmentation of protocol. Then the link between ideas will be generated in matrix form. Ideas link matrix permit the generation of Linkography representation, called linkograph. This representation enters links among ideas as an input and displays structural idea reasoning patterns as an output. The ideation process can then be looked in terms of the patterns in the linkograph, which display the ideation reasoning and the structure of process. Finally, in the third step, the connections between ideas are analyzed to provide information, investigate the structure and compare productivity [7],[16]. The linkograph pattern of productive ideation team will be different from that of less productive group. Productive team will elicit ideas that have a high potential for connectivity to other ideas, while less productive team will have more random trails with ideas that did not have a high potential contribution.

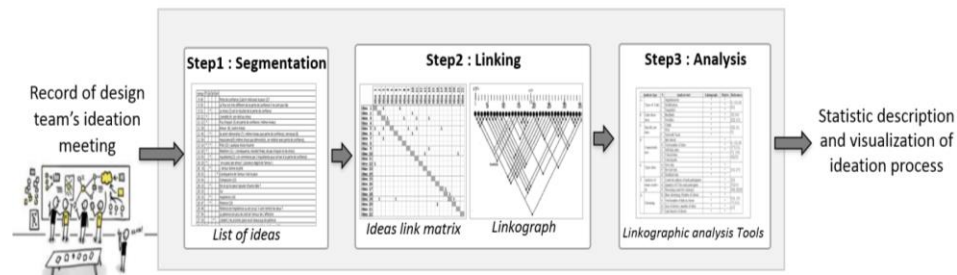


Fig. 1. Steps for application of Linkography approach

Several authors discussed the limits of the Linkography approach as developed by Goldschmidt's, in particular its subjectivity [15], [17], [18]. The interpretations of a linkograph lack objectivity. The authors studied the possibility of using objective methods to acquire information from the Linkography. They proposed different metrics for linkographic analysis. Some are studies used sophisticated mathematical tools to improve linkographic analysis, such as Kan et al [18] and Cai et al [19]. Our work is a part of the improving linkographic analysis perspective. In this study, we propose to use graph theory for visualizing and analyzing the ideation session. We will define an idea graph as a graph in which the nodes represent ideas and the lines represent the relation between them. Idea graph has several noticeable benefits compared to linkograph. The great advantage of this representation is the possibility to use a large number of analysis tools proposed by the Graph theory. In addition, on its pictorial representation, graph theory offers a wide range of structural analysis tools. These tools allow a quantitative analysis of connectivity and relationships between ideas.

Following this introduction, the next section presents a bibliographic review of the linkographic analysis tools. In the third section, we start by given the advantages of using ideas graph representation in linkographic analysis. Then, we present a methodology for obtaining references graph based tools for idea graph analysis. After, we put the finger on the application of some analysis tools in order to illustrate the utility of graph-based tools in linkographic analysis applied in real case study.

2 A bibliographic review of Linkographic analysis tools

According to the literature, different tools of linkographic analysis has been proposed. These tools can be adapted and used to study the ideation session. In Table 1 we present a bibliographic review of linkographic analysis tools. These identified Tools are classified by type of analysis and the type of data: Linkograph and link matrix (Fig. 1).

Table 1. Bibliographic review of linkographic analysis tools

Analysis type	N	Analysis tool	Linkograph	Matrix	References	
A	Types of Link	1	Supplementary	*	*	[9, 15], [16, 20]
		2	Modification	*	*	
		3	Tangential	*	*	
B	Links directions	4	Backlinks	*	*	[2], [7]
		5	Forelinks	*	*	[21], [8]
C	Specific patterns	6	Chunk	*		[21], [15], [4]
		7	Web	*		
		8	Sawtooth Track	*		
D	Connectedness	9	Link Density (LD)		*	[9, 15], [16] [14] [8], [4], [7], [5],[21]
		10	Total number of ideas		*	
		11	Self-link index		*	
		12	Critical Ideas (CI)	*		
		13	Critical path	*		
E	Types ideas	14	New idea	*	*	[8], [14]
		15	Revised idea	*	*	
		16	Modified idea	*	*	
F	Analysis of teams creativity	17	Creativity indices of each participants		*	[22],
		18	Quantity of CI for each participant		*	[4],[10]
		19	Measuring creativity (entropy)		*	[23], [5],[16]
G	Clustering	20	Ideas clustering, Number of cluster	*	*	[10], [12, 14], [8], [10]
		21	Total number of link in cluster	*	*	
		24	Size of cluster (number of idea)	*	*	
		25	Link density of cluster	*	*	

- A. Analysis of link types indicate the nature of the connections between ideas. Categorizing the links permits to see the possible transformation between two or more ideas. Van-der-Lugt [15] proposed three links categories. For a modification link, the existing line of thought is kept, but structural changes in the idea are provided. This link indicates direct variations. Supplementary correspond to a small and auxiliary changes: relationship between ideas is based on minor improvements on the same general idea. Tangential is based on free association and indicate the big leaps between ideas into a different direction.
- B. Each link can have two directions: Backlinks and Forelinks [9]. Backlinks are links that has a specific idea with each of the previously generated ideas. Backlinks tend to signify analysis, verification, evaluation, assessment, and refinement. Forelinks, on the other hand, signify the specific ideas impact on idea generation to come and are marked in the row next to the idea. Goldschmidt [9] pointed out the Forelinks indicate new ideas, proposals, prospects, even breakthroughs.
- C. Ideas Links distributions reflects the structure of ideation session and the status of ideation reasoning. When the reasoning is productive, the distribution acquires particular patterns, which are geometrically discernable in the Linkograph [9]. Low

productivity yields unstructured Linkographs in which no patterns are discernable. Goldschmidt [9] identifies three geometrical patterns: chunk, Web and Sawtooth.

- D. Link density (LD) of an ideation process or a portion of it is the ratio between the number of links and the number of ideas that form them[15]. High LD indicates that the ideas have many connections with earlier ideas, which means that participants have been building on earlier ideas. Low L.D's were found in the cases of inexperienced teams and those the experiencing difficulties in dealing with a particular design problem. The Self-link index is the ratio of the links that participants make with their own prior ideas, in relation to the total number of links made. Thus, an ideation team with a low self-link index is a team that generates ideas by building on each participant's ideas. This index indicates to what extent participants interact when generating ideas. According to Goldschmidt, ideas that generate a notably higher number of links, in one or both directions (backlinks, Forelinks), are particular interest: she calls them CI and she postulates that they are more important than the other ideas in terms of advancing the ideation [3]. There is relationship between CI and the number of links that maintain. Core ideas could be CI, in the sense that they generate a large number of links, and very good ideas are those that spin the largest number of links among themselves and other ideas. The sequence of all CI in a process is defined as its critical path. Goldschmidt used these numbers and the critical path to benchmark the productivity of a design session. The critical path reflects the essence of the reasoning process and exhibits the issues and the notions, which are foremost on the designer's mind.
- E. An idea is a form that emerged from the consciousness through the ideation process. Contemplating ideas is associated with the ability of reasoning, self-reflection, of the ability to acquire, apply intellect, intuition and inspiration, etc. In Wu et al [8] analysis of ideas are identified by three different types of ideas : new , revised and modified. The idea that team discussed it for the first time in the ideation session is called new idea. Revised idea is to observing the repetition of the idea, and then it is revisited. Modified idea occurred when a revisited idea is modified or elaborated.
- F. The Creativity indices and the quantity of CI calculate, what could be called, the creativity indices of participants using the number of ideas proposed by each participants [22]. Kan and Gero [23] suggested using entropy for measuring creativity. The higher entropy reflects a richer idea generation process in the sense that degree of uncertainty has similar meaning to the design creativity. A dense links merely implies high participations and are not requirements for the generation of creativity.
- G. According to Goldschmidt [2], [21] a cluster is a series of successive ideas that explore same specific issues. Different ways to cluster ideas has been proposed [10],[14]. For example, Link cluster can be determined by visual inspecting of the Linkograph. The 'cluster size' is the number of ideas in the cluster. For further details, we refers to this research work; Bilda and Gero [14] and In Wu and al [8].

- **Limits of linkographic analysis tools.**

Several authors discussed the limits of the linkographic analysis tools as developed by Goldschmidt's, and studied the possibility of using objective methods to acquire information from the linkographic analysis [17], [12] . The availability of tools and metric

for the structural ideation process analysis is biggest limitation of Linkography approach: this is due to the representation way. According to Goldsmith [2], some specific patterns in linkograph have a low frequency of occurrence. This decreases the utility and the use of some proposed tools in analysis. In addition, using linkograph has some communicative limitations due to the relationships between ideas, which are sometimes difficult to interpret by novice users. The most difficulty concern the representation and the analysis of a linkograph with a big number of ideas and a large variety of relations between themes. Hence, the description often lost the complexity and richness of the idea process. Linkograph has a limitation in describing the entire structure of ideas with multiple relationships. In the linkograph, the sequence of ideas generation is not clearly apparent compared to the graph representation. With linkograph it is difficult to retrace the path of ideas construction. Van-der- Lugth used only the link matrix to represent ideas and their relationships [16], [20]. He did not use the linkograph and only link matrix as input data are used.

3 Graph based tools for Linkographic analysis

The proposed approach is based on the use graph for visualizing and improving the analysis of the ideation session. In this section, we highlight advantage of using graph representation compared to linkograph. Then we present our methodology to identify a reference graphs based tools to linkographic analysis. Finally, we put the finger on the application of some analysis tools in order to illustrate the utility of graph-based tools in linkographic analysis applied in real case study.

3.1 Advantages of using ideas graph representation.

Idea graph has several noticeable benefits compared to linkograph representation. It simplify the representation and the relations between ideas by using standard representation allowing a comprehensive structure of ideation processes. This representation provides a more lucid representation to understand the characteristics of each ideations process and identify the differences intuitively. Graph has long provided visual languages and have been widely used in many different disciplines as formal representation system. The ideas graph described in the best ways the richness and complexity of the ideation process. It can be seen as a graphical representation of the ideation process and aimed at representing the comprehensive structure of a cognitive process while describing the relationships and ideation flows.

Ideas graph seems to be a particularly good way of organizing the ideas generated. Thus the graph of idea has a long idea flow which represents progressive development of an idea because it provides a view of the entire structure of the ideas elements in a ideation process. Ideas graph display describes the diversity and the depth of the entire ideation process as well: this provide accurate and highly structural information then linkograph representation. Ideas graphs are effective tool for making the structure of ideas generation process explicit because this is essential for the ideation team to clarifying their thinking and verifying the establish links. Graph can serve the ideation team

in understanding their own ideas better and simplify the representation and the relations between ideas. Organizing and prioritizing new ideas permit stimulating creative thinking allowing for understanding. This representation showed notifiable differences in exploration of precedents, and generation and development of ideas. Graph can also be used in other ideation meeting to stimulate the process of ideas generation. In new ideation session, the ideas graph can be used for several purposes such as to generate ideas or brainstorming, to develop complex structures, to communicate complex ideas. Visual learning as identified for the ideation team.

The other great advantage of this presentation way is the possibility to use a large number of structural analysis tools proposed by the theory of graphs. These tools allow a qualitative and a quantitative analysis of connectivity and relationships between ideas.

3.2 References graph based tools for Linkographic analysis

In the literature, a large wide of graph based analysis tools have been proposed. It is evident that not all these tools are useful or applicable in our study context. For this reason, we propose to select and identify the most important tools and we called them References graph based tools. The Methodology to identify a reference graphs based tools to linkographic analysis is given by **Fig. 2**. The first step correspond to a bibliographic review of graph analysis tools. In order to identify the most useful tools for analysing idea graph we propose a contextual analysis in the step 2. After, we propose in step 3 a statistical analysis. The goal of this second analysis is to evaluate the relevance of the selected tools applied to a real data. The measure indicators for each tools must be defined. The selected tools corresponds to the referential tools and will be used to linkographic analysis.

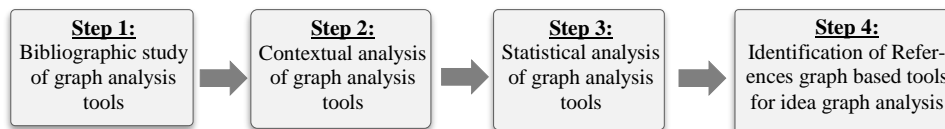


Fig. 2. Methodology for obtaining References graph based tools for idea graph analysis

3.3 Example of using graph based tools for linkographic analysis

This section aimed to present some example of analysis tools issues from graph theory and their utility in the analysis of ideas graphs. We use a real case study for this illustration. The used case study correspond to a brainstorming session to resolve a specific design problem kept anonymous for confidentiality reasons. The duration of the session is one hour. The experiment employed a ideation design team composed of four designers. The Linkography approach, given by **Fig. 1**, is used to analyse the brainstorming session. The application of step 1 (segmentation) and step 2 (linking) permit the obtaining of ideas links matrix. This ideation session allowed the generation of 22 ideas. **Fig. 3** present the Application of brainstorming method and the obtained ideas link matrix.

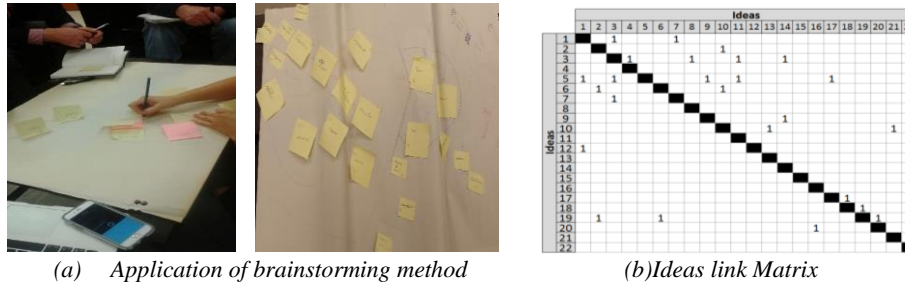


Fig. 3. Application of brainstorming method and the obtained ideas link matrix

1. **Linear Order:** consists in sorting the ideas set in order to minimize the Feedback Arc Set (FAS). This concept is an extension of the level concept, to cyclic graphs and it permits the identification of the main flow in the studied system. The Fig. 4 shows the linear ordering of ideas before the application of linear ordering tool: this correspond to chronological ordering of the ideas generation. The FAS rate correspond to 32 % (Number of FAS (8) divided per the total number of link (25)). We Use the Tabu search algorithm developed by Zhou et Al [24] to identify the optimal linear ordering given by Fig. 5.
2. **Levels :** The linear ordering allows to identify the minimum FAS. A graph without FAS is a directed acyclic graph (DAG). Vertices of a DAG can be partially ordered. Each vertex is assigned with a rank such that the initial vertex of an edge which has a lower rank than the terminal vertex of this edge. The set containing vertices with the same rank defines a level. This concept can be measured by the number of vertices per level corresponding to the rate of level. In this study the Level rate: 36.36% (Nb of level (8) / Nb of ideas (22)).The level decomposition given by Fig. 6 is very useful for understating the structure of ideas generation session. It highlights a “main” flow in the idea generation session. In addition, the precedence relationship among ideas is clearly visible. This is interesting during the ideation session analysis. If the level ratio is low: this informs that the number of ideas produced from an initial idea is small. The rate of divergence of ideas is low. Then, If the level ratio is high: this informs that the number of ideas produced from an initial idea is high. The rate of divergence of ideas is high.
3. **Degree of vertex :** The adjacency list of vertices is used for degree of vertex analysis. The INdegree of a vertex v or the half degree of entry of a vertex v is the number of edges incoming to v and is denoted by $d^-(v)$.The OUTdegree of a vertex v or the half degree of exit from a vertex v is the number of arcs outgoing from v and is denoted by $d^+(v)$. The degree of a vertex v denoted by $d(v)$ is the sum of the INdegree and the OUT degree $d(v) = d^-(v) + d^+(v)$. The degree of vertex inform the Criticality of ideas. Critical ideas are those that have a significant number of links to other ideas. The Fig. 7 (a) show the graph representation with the degree of ideas.
4. **Sources /sink:** A vertex is called as a source vertex if no incoming edge exists (see Fig. 7 (b)). Thus a vertex v is a source if $d^-(v) = 0$. A vertex is called as a sink vertex if no outgoing edge exists. Thus a vertex v is a sink if $d^+(v) = 0$. In general, we have only one source called the root of graph correspond to the initial generated idea. The

sink give a measure of the opportunity for new creations or initiations. Pointed out the sink indicate new ideas, proposals, prospects, even breakthroughs.

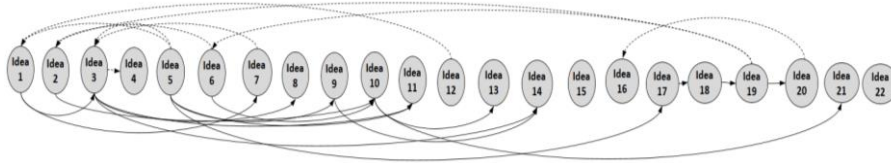


Fig. 4. Initial Total ordering of idea (rate of FAS = 32%)

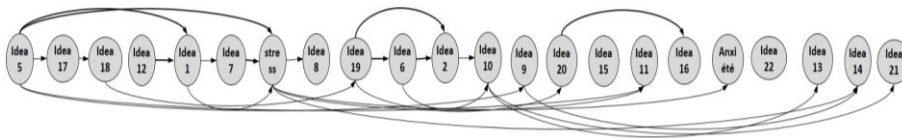


Fig. 5. Optimal total ordering of ideas (rate of FAS = 0)

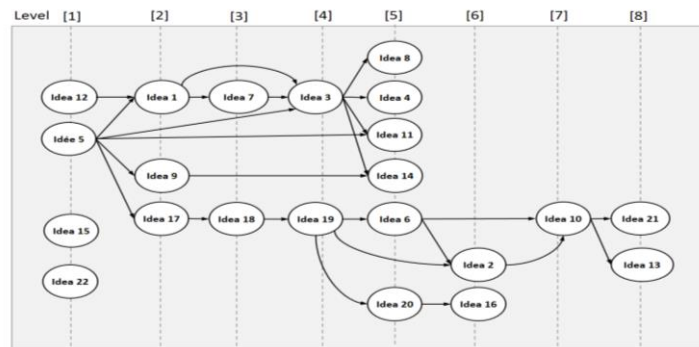
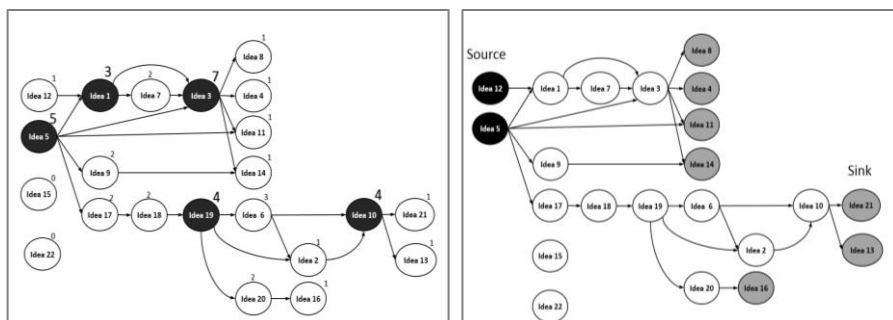


Fig. 6. Decomposition of ideas graph by level



(a) Degree of Vertex

(b) sink and source in ideas graph

Fig. 7. Application of the degree of vertex and Source/ Sink Tool

4 Conclusion

Our work intent to improving linkographic analysis. We shed the light on the usefulness of graph theory in analysing and representing of idea generation session. We started with an overview of Linkography approach and followed by a bibliographic review of linkographic analysis tools. Then, the advantages of using ideas graph representation are given. Ideas graph display describes the diversity and the depth of the entire ideation process perfectly: this provides an accurate and high structural information better than with linkograph. Another important advantage of this representation is the possibility to use a large number of structural analysis tools proposed by the theory of graphs. To illustrate the utility of graph-based tools in linkographic analysis we put the finger on the application of some analysis tools applied in real case study. These tools allow quantitative analysis of connectivity between ideas. In addition, we proposed a methodology to identify a reference graphs based tools to do linkographic analysis. This methodology will be applied in our future work. Firstly, we will elaborate a bibliographic review of graph analysis tools. Secondly, we will propose a contextual analysis to identify the most useful tools. Finally, we will propose a statistical analysis to evaluate the relevance of the selected tools applied to a real data. The selected tools correspond to the referential tools will be used to linkographic analysis.

5 References

1. Escandón-Quintanilla, M.-L., M. Gardoni, and P. Cohendet. *Big Data Analytics as Input for Problem Definition and Idea Generation in Technological Design*. in *13th IFIP WG 5.1 International Conference, PLM* July 11-13, 2016,. Columbia, SC, USA,.; Revised Selected Papers (pp.468-477) DOI 10.1007/978-3-319-54660-5_42
2. Goldschmidt, G., *Linkography: Assessing design productivity*. 1990. 291-298.
3. Goldschmidt, G. and M. Weil, *Contents and Structure in Design Reasoning*. Design Issues, 1998. **14**(3): p. 85-100 . DOI 10.2307/1511899.
4. Goldschmidt, G., *Cognitive economy in design reasoning*, in *Human Behaviour in Design: Individuals, Teams, Tools*, U. Lindemann, Editor. 2003, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 53-62 . DOI 10.1007/978-3-662-07811-2_6.
5. Goldschmidt, G. and D. Tatsa, *How good are good ideas? Correlates of design creativity*. Design Studies, 2005. **26**(6): p. 593-611 . DOI <https://doi.org/10.1016/j.destud.2005.02.004>.
6. Goldschmidt, G., H. Hochman, and I. Dafni, *The design studio "crit": Teacher-student communication*. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 2010. **24**(3): p. 285-302 . DOI 10.1017/S089006041000020X.
7. Goldschmidt, G., *Linkographic Evidence for Concurrent Divergent and Convergent Thinking in Creative Design*. Vol. 28. 2016. 115-122 . DOI 10.1080/10400419.2016.1162497.
8. Wu, P.-F., J. Yen, and K.-Y. Fan, *investigating the design behavior of animation expert-the difference of idea links mode on story ideation*. Bulletin of Japanese Society for the Science of Design, 2011. **57**(5): p. 27-36. DOI: 10.11247/jssdj.57.27_2

9. van der Lugt, R., *How sketching can affect the idea generation process in design group meetings*. *Design Studies*, 2005. **26**(2): p. 101-122. <https://doi.org/10.1016/j.destud.2004.08.003>.
10. Kan, J. and J. Gero. *Design behaviour measurement by quantifying linkography in protocol studies of designing*. in *Human Behaviour in Design '05*, . 2005. Key Centre of Design Computing and Cognition, University of Sydney,.
11. Kan, J. and J. Gero, *Quantitative Methods for Studying Design Protocols*. 2017.
12. KAN, J.W., Z. BILDA, and J.S. GERO, *comparing entropy measures of idea links in design protocols*, in *Design Computing and Cognition '06*, J.S. Gero, Editor. 2006, Springer Netherlands: Dordrecht. p. 265-284.
13. Bilda, Z., J.S. Gero, and T. Purcell, *To sketch or not to sketch? That is the question*. *Design Studies*, 2006. **27**(5): p. 587-613.
14. Bilda, Z. and J.S. Gero, *Idea Development Can Occur Using Imagery Only*, in *Design Computing and Cognition '08: Proceedings of the Third International Conference on Design Computing and Cognition*, J.S. Gero and A.K. Goel, Editors. 2008, Springer Netherlands: Dordrecht. p. 303-320.
15. Van der Lugt, R., *Sketching in design idea generation meetings*, in *Industrial Design Engineering*. 2001, Delft University of Technology: Netherlands.
16. Van der Lugt, R., *Functions of sketching in design idea generation meetings*, in *Proceedings of the 4th conference on Creativity & cognition*. 2002, ACM: Loughborough, UK. p. 72-79. DOI : 10.1145/581710.581723.
17. Perry, G.T. and K. Krippendorff, *On the reliability of identifying design moves in protocol analysis*. *Design Studies*, 2013. **34**(5): p. 612-635.
18. Kan, J.W.T. and J.S. Gero, *Acquiring information from linkography in protocol studies of designing*. *Design Studies*, 2008. **29**(4): p. 315-337.
19. Cai, H., E.Y.-L. Do, and C.M. Zimring, *Extended linkography and distance graph in design evaluation: an empirical study of the dual effects of inspiration sources in creative design*. *Design Studies*, 2010. **31**(2): p. 146-168 [doi:10.1016/j.destud.2009.12.003](https://doi.org/10.1016/j.destud.2009.12.003).
20. van der Lugt, R.v.d.G., A., *Context Indicators for Determining Links Between Design Ideas*, in *DS 30: Proceedings of DESIGN 2002, the 7th International Design Conference, Dubrovnik*, M. D., Editor. 2002: Dubrovnik. p. 261-266.
21. Goldschmidt, G., *Criteria for Design Evaluation : A Process-Oriented Paradigm*, in *Principles of Computer-Aided Design: Evaluating and Predicting Design Performance*. 1992, John Wiley & Sons: New York, NY. p. 67-79.
22. Ardaiz-Villanueva, O., et al., *Evaluation of computer tools for idea generation and team formation in project-based learning*. *Computers & Education*, 2011. **56**(3): p. 700-711 . <https://doi.org/10.1016/j.compedu.2010.10.012>.
23. Kan, J. and J.S. Gero, *Can Entropy Indicate the Richness of Idea Generation in Team Designing?*, in *Digital Opportunities: Proceedings of the 10th International Conference on Computer-Aided Architectural Design Research in Asia*. 2005, Architexturez Imprints: New Delhi. p. vol1, 451-457.
24. Jiand, Z., B. Marc, and D.G. Roland, *Quasi-Source Heuristic for the Production Line Formation of Manufacturing System"*,. *Journal of Integrated Design and Process Science*, 2003. **7**(1): p. 25-58.