

Research Article

Cite this article: Koskela L, Kroll E (2020). Demonstration, extension, and refinement of the re-proposed notion of design abduction. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* **34**, 286–297. <https://doi.org/10.1017/S0890060420000165>

Received: 12 February 2019
Revised: 18 November 2019
Accepted: 26 November 2019
First published online: 16 March 2020

Key words:

Abduction; design reasoning; dynamic abduction; model-based abduction; strategic abduction; Wright brothers

Author for correspondence: Lauri Koskela, E-mail: l.koskela@hud.ac.uk

© Cambridge University Press 2020. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted re-use, distribution, and reproduction in any medium, provided the original work is properly cited.

Demonstration, extension, and refinement of the re-proposed notion of design abduction

Lauri Koskela¹  and Ehud Kroll²

¹School of Art, Design and Architecture, University of Huddersfield, Huddersfield, UK and ²Department of Mechanical Engineering, ORT Braude College, Karmiel, Israel

Abstract

The original ideas on design abduction, inspired by treatments in philosophy of science, had a narrow conception on how novelty emerges in design, when looked at in terms of logic. The authors have previously presented a re-proposed notion of abduction in design, taking the differences between science and design into account. Now, in this article, the invention of the airplane by the Wright brothers is analyzed as a retrospective case study. Key parts of the re-proposed notion of design abduction are demonstrated, and two new types of design abduction are identified, namely strategic abduction and dynamic abduction. Perhaps even more importantly, a new hypothesis on the cognitive basis of design abduction is reached. While the importance of model-based abduction (and reasoning) is confirmed, the case also pinpoints the central role of verbalization and discussion in supporting design reasoning in general and especially abduction. All in all, it seems that an improved understanding of design abduction and its cognitive basis would be instrumental in promoting more effective and efficient designing.

Introduction

According to the seminal views of Peirce (1865, 1913), an abduction leads to a new idea, still hypothetical, by means of often subconscious, uncontrolled mental processes. Peirce examined abduction in relation to scientific inquiry, where it is triggered by an anomaly such as a surprising observation. Interest in design abduction derives from the seminal treatment by March (1976), which started a stream of research that has continued up to this day. However, for several reasons, abduction in design has been a challenging topic, and the results of related research show gaps in coverage, lack of depth, and diverging outcomes (Koskela *et al.*, 2018b). One reason is arguably that the meaning of the term abduction has become diluted. In addition to the original, Peircean understanding of abduction as the generation of hypotheses (Aliseda, 2006), abduction is understood as a justification of hypotheses (Gabbay and Woods, 2005). In the latter case, abduction is seen as an inference to the best explanation (IBE) (Douven, 2017). The main difference between these two understandings is that a Peircean abduction creates a novel explanation, whereas an abduction in the IBE sense chooses the best explanation among alternatives. Another form of dilution is that the Peircean abduction has started to be viewed as covering selection among known alternatives. This view misses the creative nature of the Peircean abduction. A second reason is related to the observation that abduction in the philosophy of science carries implicit contextual assumptions, which are not compatible with the context of design. Although already March (1976) noted differences between science and design in this respect, this issue has not been addressed systematically in subsequent research.

In view of such problems, the authors have recently endeavored to re-propose the conception of abduction in design (Kroll and Koskela, 2016, 2017; Koskela *et al.*, 2018b). The new conception was developed by analyzing the differences between science and design as well as by identifying abductive inferences based on empirical knowledge of different phenomena comprising design.

This paper presents further steps in this line of research. It has three objectives: firstly, to provide an additional demonstration to the re-proposed concept of abduction in design; secondly, to extend it; and thirdly, refine it further. All three objectives are supported by a retrospective case study, addressing the invention of the airplane by the Wright brothers.

Regarding demonstration, we ask: Can the characteristics attached to the re-proposed concept of design abduction be found in the case? Are abduction types, as proposed, used in the case?

Regarding extension, we ask: Can further characteristics of design abduction be identified in the case? Are there new design abduction types, not identified earlier?

Regarding refinement, we are especially interested in deepening our understanding of design abduction from a cognitive viewpoint. We ask: are the recent cognitive categorizations

of abduction in philosophy of science, such as the distinction between sentential and model-based abduction (Magnani, 2004), usable in design?

The paper is structured as follows. The re-proposed notion of abduction is introduced in the next section. After that, the case study on the Wright brothers is presented, followed by sections addressing, respectively, the demonstration, extension, and refinement of the re-proposed notion of abduction in light of the case. Sections on discussion and conclusions, with suggestions for future research, complete the paper.

Re-proposed concept of abduction in design

It is argued by Koskela *et al.* (2018b) that given the differences of context, abduction in design has characteristics not found or even discussed in science. Design abduction may occur in any part of the design process – not just at the beginning as in typical accounts on abduction in science. Abduction can occur in connection to practically all inference types in design – rather than just through regressive inferences as commonly assumed in science. Design abduction usually leads to an idea new in the context – rather than to entirely new ideas as in science. The primary characteristic of an abduced insight in design is its utility – rather than its validity as in science. Thus, based on the knowledge of the authors regarding practice and theory of design, several types of abductive inference in design were identified and discussed in Koskela *et al.* (2018b), as summarized in Table 1.

There are interesting implications from this outcome for design theory and philosophy of science. The mental moves, which lead to new ideas in design, have for the first time been determined (although this list cannot be considered to be exhaustive as it is not based on a systematic search). Abduction has now been defined in a way that is compatible with our understanding of the phenomena occurring in design. However, as abduction as a mental move is ubiquitous and generic, the hypothesis arises that the conception of abduction, originating in science and covering only regressive inferences, has generally been too restrictive.

Nevertheless, in the current stage of the development of the re-proposed notion of design abduction, empirical research for demonstrating (both in the sense of illustrating and giving evidence) the re-proposed notion of design abduction and extending it, if possible, is opportune – these are the first two objectives of this treatment, as outlined above. Furthermore, as the classical theory of abduction has been unable to explain from where a new idea emerges (at least if the somewhat apologetic argument that its origin is in intuition or subconsciousness is not accepted as satisfactory), it is justified to try to refine the notion of design abduction through concepts from the domain of cognition. In this respect, of special interest is model-based reasoning (Koskela and Kroll, 2019), which has gained popularity in cognitive psychology (Johnson-Laird, 2006) and philosophy of science (Magnani, 2017; Magnani and Bertolotti, 2017) over the last few decades. Empirical exploration into these topics makes up the third objective of this presentation.

Abductive reasoning in designing the first airplane

To demonstrate, extend, and refine the re-proposed notion of design abduction, we chose the invention of the airplane by the Wright brothers (WB for brevity) as a retrospective case study. The WB' design process is extensively described in the literature, with many details of the reasoning that took place. Some relevant

Table 1. Types of abductive inferences in design identified in Koskela *et al.* (2018b)

Type of abductive inference	Meaning
Abductive regressive inference	Reasoning from ends (desired behavior or function) to means (structure, form)
Abductive composition	Spatial or relational (abstract) arrangement of component parts of a system
Manipulative abduction	Using an external medium, such as images, models or concrete apparatus, and instruments to clarify the suggested hypotheses
Abductive transformation	Seeing the problem from another point of view; creating a new problem that is easier to solve
Abductive decomposition	Dividing functions and structures to their constituent parts
Abductive analogical reasoning	Transfer of information from a source situation to a target situation
Abductive invention of requirements	Discovering desired functionalities and implicit constraints

sources are Bereiter (2009), Crouch (2002), Jakab (1990), Johnson-Laird (2005), Johnson-Laird (2006, chap. 25), Wright (1953), and Wright and Wright (1922). We briefly recount this design process here, followed by the analysis of several specific aspects. The treatment is based both on recent commentaries and contemporaneous testimonials.

Brief description of the WB' design process

The WB realized at the outset that an airplane needed three components: wings for lift, engine for propulsion, and a system for the pilot to control it. They chose to begin by addressing the control aspect, so initially, they focused on gliders (no propulsion yet), with some of the development effort carried out with the help of kites, specially made testing equipment, and wind tunnels. To design a control system, they incorporated a front-mounted horizontal rudder, or elevator, for pitching the aircraft up or down, and twisting, or "warping", wings for banking or turning. The wings' role as lift provider was addressed next. A minimum speed to get the glider airborne was estimated based on available data, and various launching methods were considered, finally choosing flying against strong winds in Kitty Hawk, North Carolina.

Repeated testing and modifications to the gliders' wings were necessary for the WB to develop the required understanding of lift and drag and their relation to wing profile shape. It also turned out that several design aspects were coupled; for example, controlling the aircraft by wing warping was influenced by the changes needed to increase lift, and occasionally new problems were discovered, such as controlling the location of the center of pressure. The WB' evolving theory of flight had to be updated continuously. At last, they added a steerable rudder at the rear connected to the control wires of the warping wings and thus established a full system of control for their glider.

Next, they turned into the propulsion system design, just to discover that there was no theory of propeller design. This led them to develop a new theory, whereby a propeller blade is regarded as a lift-producing wing moving in spirals and thus producing thrust. They also decided to use two counter-rotating

propellers to overcome the torque effect. When they could not find a suitable engine, they designed and made their own engine and connected its output shaft to the propellers by means of bicycle chains, one of them twisted through 180°. The powered Flyer was the WB' fourth aircraft after three gliders and flew successfully on December 17, 1903, after less than 5 years of development. It was the first heavier-than-air aircraft flown under its own power and under the pilot's control.

The WB' design strategy

Wilbur Wright wrote (Wright and Wright, 1922, p. 16):

The difficulties which obstruct the pathway to success in flying machine construction are of three general classes: (1) Those which relate to the construction of the sustaining wings. (2) Those which relate to the generation and application of the power required to drive the machine through the air. (3) Those related to the balancing and steering of the machine after it is actually in flight. Of these difficulties two are already to a certain extent solved. Men already know how to construct wings or aeroplanes which, when driven through air at sufficient speed, will not only sustain the weight of the wings themselves, but also that of the engine, and of the engineer as well. Men also know how to build engines and screws of sufficient lightness and power to drive these planes at sustaining speed. As long ago as 1893 a machine weighing 8,000 lbs. demonstrated its power both to lift itself from the ground and to maintain a speed of from 30 to 40 miles per hour; but it came to grief in an accidental free flight, owing to the inability of the operators to balance and steer it properly.

The WB chose control over lift and propulsion as the most difficult aspect of designing an aircraft, and consequently as the problem to start with. This choice was based on picturing an airplane whose engine failed and the pilot was trying to land it safely but lost control over it and crashed. But if the pilot could maintain control over the plane, he would have landed it safely, and therefore control was more important than propulsion. Regarding lift, the WB initially put this aspect aside, assuming that the knowledge to design wings was available and therefore this task would be easier.

Johnson-Laird (2006) attributes the success of the WB to their choice of control as the most important aspect of the design, something that other aviators failed to see. Bereiter (2009) contrasts the WB's quest to maximize control with Samuel Langley's pursuing maximum stability and overlooking the control aspect. At the time of the WB, the success criterion was the ability to fly some distance and land at a height no lower than the starting point (to rule out gliders). So while flying in a straight line required thrust, lift, and stability (mainly in roll), the WB opted for an inherently unstable airplane that could be kept under control by a skilled pilot. The resulting greatest innovation that came as an unintended byproduct, according to Bereiter, was a plane capable of making banked turns.

Designing the control system

When faced with the anomalous situation of controlling an airplane, the WB managed to introduce several innovations that stemmed from model-based abductions. When their rivals were looking for stability, the WB drew an analogy (a model-based abduction) from the world of bicycles (their business) to the world of aircraft: just as bicycles are not stable, aircraft too should not be stable, but rather, be controllable by the pilot (Johnson-Laird, 2005). So, just as in the bicycle world model, the

rider balances and controls it by steering the front wheel and leaning it to the side, pilots should steer an aircraft left or right, bank it to the side, and nose it up or down (an added dimension). In the WB' own words (Wright and Wright, 1922, p. 2):

We therefore resolved to try a fundamentally different principle. We would arrange the machine so that it would not tend to right itself. We would make it as inert as possible to the effects of change of direction or speed, and thus reduce the effects of wind-gusts to a minimum. We would do this in the fore-and-aft stability by giving the aeroplanes a peculiar shape; and in the lateral balance by arching the surfaces from tip to tip, just the reverse of what our predecessors had done. Then by some suitable contrivance, actuated by the operator, forces should be brought into play to regulate the balance.

Bereiter (2009) explains that the bicycle-airplane analogy consisted of forming connections between ideas at the level of sensory-motor patterns rather than at the level of conceptualized structural features and that such analogies do not directly yield conclusions, but influence the way we think and perceive. This means that the WB may have imagined themselves riding a bicycle along a very bumpy street, feeling the twists and tilts, and liking it to piloting an airplane that is being buffeted by gusts of wind. This would be a basis for the WB seeing the control problem as essentially the same in the two cases, leading them to look for ways to make constant small adjustments to the tilt of an aircraft.

A horizontal "rudder", or elevator, was assigned the role of controlling climbing and diving, but banking presented a new anomalous situation. An insight came from an analogy to birds: just as birds point their wingtips in opposite directions in order to turn, the aircraft wing could be twisted, or "warped", to produce a bank or turn. Wilbur Wright wrote in a letter (Wright, 1953, p. 18):

My observation of the flight of buzzards leads me to believe that they regain their lateral balance, when partly overturned by a gust of wind, by a torsion of the tips of the wings. If the rear edge of the right wing tip is twisted upward and the left downward the bird becomes an animated windmill and instantly begins to turn, a line from its head to its tail being the axis. It thus regains its level even if thrown on its beam ends, so to speak, as I have frequently seen them. I think the bird also in general retains its lateral equilibrium, partly by presenting its two wings at different angles to the wind, and partly by drawing in one wing, thus reducing its area.

Orville Wright somewhat downplays the role of observing birds in inventing wing warping, saying that it was used only to confirm the concept (Wright, 1953, pp. 1168–1169):

I cannot think of any part bird flight had in the development of human flight excepting as an inspiration. Although we intently watched birds fly in a hope of learning something from them I cannot think of anything that was first learned in that way. After we had thought out certain principles, we then watched the bird to see whether it used the same principles. In a few cases we did detect the same thing, in the bird's flight.

How to obtain wing warping was the next challenge. The wing needed to be both flexible in torsion and stiff laterally. This new anomalous situation was solved by an analogy that came as an insight while twisting a square-section inner tube box (a physical model, in this case) and imagining its top and bottom surfaces to correspond to the warped upper and lower wings of a biplane. Orville Wright writes that the insight involved just the mechanical implementation, while the concept of operation had been known to them before (Wright, 1953, p. 1143):

It was one of our few discoveries made purely by accident of observation rather than as a result of study. It was not the revelation of a basic principle – it was merely a better mechanical embodiment of a basic principle which we had already discussed for several months. The basic idea was the adjustment of the wings to the right and left sides to different angles so as to secure different lifts on the opposite wings.

A physical model of the wings, made of bamboo and tissue paper, was constructed to check the idea, followed by another physical model, a 5-foot span biplane kite with cords connected to the wingtips. It was tested and confirmed the banking ability by wing warping.

Designing the wings for lift

Having established the role of the wings in controlling the aircraft, the WB turned into designing the wings for their other role: provision of lift. They used available knowledge (Otto Lilienthal's data) on the lift and drag to design the wings for their man-carrying glider (no engine yet). Lift (and drag) are related to the aircraft speed, and a minimum speed is required to get the aircraft airborne. So the next problem to be solved was: how to give the aircraft the initial speed?

The WB considered the contemporaneous practice of using gravity, either jumping with the glider from the crest of a hill or dropping it from a balloon, to be too dangerous. They considered constructing a catapult to launch the glider but thought it would be too challenging. Then they had an idea that came from another way of looking at the problem, what we may call "abductive transformation": speed the air past the glider. Instead of imagining an airplane being accelerated to produce enough speed for lift, the WB imagined the background (the air) speeding past the aircraft. This is model-based reasoning: a world model of an aircraft moving through the air is replaced by a visualization of air moving around the aircraft. But how could air be speeded past the wings? The idea was to fly against strong winds, so they chose Kitty Hawk in North Carolina as the location for flying. They built the glider and flew it with the pilot laying on the lower wing to reduce drag. They practiced controlling it.

They discovered that the wings did not produce the expected lift and identified three possible hypothetical explanations: either the wing section had a too shallow camber, or the fabric on the wings was not airtight enough, or the wing area was too small. A second glider was constructed with modifications to the wings, but lift was still low and control difficult. The core of difficulty was attributed to controlling the center of pressure, and this led to experimenting with flying the upper wing alone as a kite (use of a physical model). Corresponding modifications were incorporated in the glider, but now the wing warping did not work well. It turned out that the higher lift generated by the upward twisted wing was more than counterbalanced by the increased drag on that wing, causing the aircraft to bank to the "wrong" side (Wright and Wright, 1922, pp. 3–4):

We also discovered that in free flight, when the wing on one side of the machine was presented to the wind at a greater angle than the one on the other side, the wing with the greater angle descended, and the machine turned in a direction just the reverse of what we were led to expect when flying the machine as a kite. The larger angle gave more resistance to forward motion, and reduced the speed of the wing on that side.

All in all, the problems with lift and warping presented a new anomalous situation, that of a discrepancy between the WB's

mental model of aircraft wings and the empirical evidence. Again, by regressive reasoning (which may have been selective or abductive), they created possible explanations or hypotheses and went on to test them. They constructed a device mounted on a horizontal bicycle wheel to measure the lift produced by various wing profiles. They confirmed the hypothesis that Lilienthal's data were wrong and concluded that they needed to generate their own data, which was accomplished by building wind tunnels and conducting experiments.

The WB used the new aerodynamic knowledge to design their third glider. By analogy to birds (buzzards vs. eagles and hawks), they introduced a slight negative dihedral (a downward slope of the wings relative to the horizon when viewed head-on) to the wings to improve stability. Vertical tails were also added to help with the warping problem. Testing the glider still did not show good results until a new idea emerged after a sleepless night (thus hinting that it was a sudden insight coming in a flash, as often characterizing abductive reasoning; see Peirce, 1903), to turn the fixed tail into a steerable rudder, and connect its control wires with those that warped the wings. A full aircraft control system was thus established.

The propulsion system

When addressing the propulsion aspect, the WB discovered that no theory existed for propellers. Their rivals used flat propeller blades, and the WB realized that they needed to create their own theory and knowledge about propellers.

It took the WB several months to develop a clear understanding of this anomalous situation. They drew an analogy that the blade is like a wing traveling in a spiral course. This analogy depended on visualizing a mental model of a wing carrying out a rotation, and regarding the lift produced as thrust. A flat blade does not generate much lift/thrust, so the blade should be cambered like a wing, and wing theory could be used to design the propeller. They designed a propeller and the theory turned out to be very accurate. They decided on two propellers instead of one to obtain the required volume of air flow, counter rotating to balance torque, and mounted behind the wings to minimize turbulence.

The WB next turned into designing the engine. While their rivals looked for the most powerful and lightest engine, they used their theory of flight (wing area, lift, drag, estimated weight, minimum air speed for taking off, etc.) to estimate the minimum power requirement. They could not find a manufacturer with the right engine, so they designed, tested, and re-designed their own engine. Finally, they figured out a way to connect the engine to the two oppositely rotating propellers by another analogy to the world of bicycles: an arrangement of sprockets and chains transmitted the power.

Demonstration of some types of abduction in design

The case of the invention of the airplane by the Wright brothers is instrumental in demonstrating – and to some extent validating – the re-proposed notion of abduction in design. As shown in Table 2 (which by no means represents an exhaustive account), several abductive inference types identified previously, especially analogy, composition, transformation, and manipulation were employed. On the other hand, two novel types of abduction were present, to be discussed below.

Furthermore, it is found that all the assumptions underlying the re-proposed concept of abduction turn out to be true in the case studied. It was assumed that design abduction may emerge

Table 2. Types of abduction identified in Koskela *et al.* (2018b) as they appear in the development of the first aircraft by the Wright brothers.

Abductive problem	Abduced solution	Source of abduction/other comment	Type of abductive inference
How to create enough speed for takeoff?	By flying against strong winds	The problem was transformed	Transformation
How to improve the stability of wings?	By introducing a slight negative dihedral angle to the wings	Observation of buzzards versus hawks and eagles	Analogy
How to effect the lateral control of an aircraft?	By introducing mechanisms for the pilot to bank it to the side	Familiarity with riding on bicycle	Analogy
How to effect banking?	By twisting or “warping” the wing to produce a bank or turn	Analogy to birds: birds point their wingtips in opposite directions in order to turn	Analogy
How to effect wing warping?	By a biplane (two wings) with an arrangement of wires and pulleys for twisting the tips.	Observation of twisting a square-section inner tube box and imagining its top and bottom surfaces to correspond to the warped upper and lower wings of a biplane	Analogy
How to improve the warping solution of the wings (which was not effective enough)?	By adding a steerable rudder instead of a fixed tail	Analogy to steering a ship	Analogy
How to shape the propeller?	By using the knowledge developed regarding wings	The aerodynamic similarity between wing and propeller was observed	Analogy
How to determine whether Lilienthal’s data on lift and drag are correct?	By constructing a device mounted on a horizontal bicycle wheel to measure the lift produced by various wing profiles and experimenting with a wind tunnel	Familiarity with bicycle technology and also improvement of contemporary wind tunnel practices (Jakab, 1990)	Manipulation
How to implement propulsion?	By having two propellers face the back instead of the front	Four considerations were taken into account (Jakab, 1990): maximizing the volume of air acted upon, allowing a greater pitch angle to propellers; neutralizing the gyroscopic effects of the blades; preventing the disturbance of airflow over the lifting surfaces.	Composition
How to transmit the engine’s power to the counter-rotating propellers?	By an arrangement of sprockets and chains, one chain twisted 180°.	Familiarity with bicycles propulsion	Analogy

in any part of the design process. Indeed, abductions occurred throughout the design process by the WB, starting from the very beginning. It was assumed that abduction can occur in connection to practically all inference types in design. It turned out that several types of abduction could be observed: analogical, transformational, manipulative, and compositional. It was assumed that abduction usually leads to an idea new in the context (rather than historically new as required in science). The problems encountered by the WB and their novel solutions were deeply contextual; however, the abduced ideas and solutions were often also historically new, due to the novelty of the context; moreover, it seems some ideas and solutions were previously known to the WB in the context of bicycles. The assumption was that the characteristic of an abduced insight in design is its utility. Abduced solutions were usually straightaway tested by the WB in practice (although also the empirical validity of previously published data was in some cases addressed).

It is also interesting to note that some types of abductive inferences, such as analogy, seem to have been dominating in this case, whereas other types, especially abductive regressive inference, were not present (at least among the main creative abductions). Abductive regressive inferences occur especially when natural science or engineering knowledge is used in an innovative way; that kind of knowledge simply did not exist to any considerable extent. Rather, design solutions had to be invented based on analogies from other domains.

Extending to new types of abduction

Two new types of abduction, in comparison to the original proposal (Koskela *et al.*, 2018b), are visible in the WB case: strategic abduction and dynamic abduction. Both represent an extension to the previous notion of design abduction.

Strategic abduction

In the case of the WB, the strategic abduction was related to first focus on the control of the aircraft, when other inventors in aviation prioritized the two other functions, lift and propulsion. The defining characteristic of strategic abduction is, besides novelty, that its outcome does not directly relate to the evolving artifact, but rather to the unfolding of the design process [for a discussion on strategic abduction in science, see Paavola (2004)]. Thus, the domain of abduction in design is extended from artifact to process.

What is the importance of strategic abduction? Decisions about the order of tasks are made in design projects intuitively, habitually or based on known recommendations. What is the role of strategic abduction? Especially, it would seem that strategic abduction is unnecessary when applying such known recommendations as the “systematic design” methods, where all the design functionalities are handled concurrently and where all the relevant knowledge is already available (Kroll, 2013). If all the functions and sub-functions can be known at the beginning

of the design process, and if solutions that satisfy all these functionalities can be listed, then by a sort of deductive logic, combinations of the solutions will constitute the desired artifact.

However, in innovative design cases, the functionalities may not be fully known and decomposable, and solutions are not readily available, so another strategy is needed. Choosing to address more difficult problems first is justified by assuming that problems and solutions are coupled, and therefore it should be more efficient to add the solution of easier problems to those of the difficult ones than vice versa. This is an approach that has been called “steepest-first” in the context of the parameter analysis method (Kroll *et al.*, 2014): the most challenging aspect of the design task is addressed at a given moment in the process.

Abduction as a way of decision-making has no intrinsic value if usable theoretical knowledge exists. Although even now little known, and almost certainly not known to the WB or their contemporaries, there is actually a theoretical guideline, presented by Peirce in 1879 (Peirce, 1967), that can be applied to increase the economy of design processes:

The utility of knowledge consists in its capability of being combined with other knowledge so as to enable us to calculate how we should act. If the knowledge is uncertain, we are obliged to do more than is really necessary, in order to cover this uncertainty. And, thus, the utility of any increase of knowledge is measured by the amount of wasted effort it saves us, multiplied by the specific cost of that species of effort.

This guideline is applicable to design where there is uncertain or missing knowledge, and this uncertainty can be reduced or minimized through design activities and tests but also through research. Thus, the objective is to reduce the cost of wasted efforts. Especially, there are two types of wasted efforts that need consideration in this context: (1) The wasted cost of design efforts if the intended design turns out to be impossible; (2) The wasted cost of unnecessary design iteration. Indeed, the above principle by Peirce seems to be the theoretical justification for using the steepest-first strategy, for the design structure matrix, seminally proposed by Steward (1981), to organize design tasks for eliminating unnecessary iteration (Ballard, 2000), as well as for the suggestion of rapid prototyping and testing of partial solutions, presented in the context of design thinking (Brooks, 2010).

Suh’s (2001) axiomatic design may also be related to the process economy when recommending prioritization in decomposing functional requirements (FRs) in the coupled design cases. However, for coupling to be established, design parameters (DPs) need to be proposed, and this means that the design process has moved beyond the purely functional domain. In addition, such prioritization is inconsistent with the two design axioms, as noted in Suh (2001) (p. 58).

Dynamic abduction

A cue to the direction of dynamic understanding of abduction is given in the comment on the significance of the inner tube cardboard box twisting insight by Orville Wright, as quoted above: “It was not the revelation of a basic principle – it was merely a better mechanical embodiment of a basic principle which we had already discussed for several months.” This implies that what (above) has been conceived as an independent abductive inference can be seen as part of a longer process. This finding resonates with the arguments by Gruber (1981), who contends that sudden moments of insights and slow construction of ideas should be

seen as complementary. Actually, also Peirce presented an example where a slow process of compilation of ideas culminates in an abductive inference (Peirce, 1898):

Suppose I have long been puzzling over some problem, – say how to construct a really good typewriter. Now there are several ideas dimly in my mind from time, none of which taken by itself has any particular analogy with my grand problem. But someday these ideas, all present in consciousness together but yet all very dim deep in the depths of subconscious thought, chance to get joined together in a particular way such that the combination does present a close analogy to my difficulty. That combination almost instantly flashes out into vividness.

From the viewpoint of this presentation, moments of insights represent abductions as Peirce characterized them. We propose that the slow construction of ideas is called dynamic abduction. Paavola (2014) has discussed such dynamically evolving abduction and proposed it as an extension to the classical view on abduction in science. Furthermore, he presents a tentative list of strategies for guiding this kind of dynamically evolving abduction.

Thus, the notion of design abduction has to be extended in the temporal sense: whereas the classical view, abduction was seen as an event or phase, now abduction evolving dynamically over longer time periods is also covered. Of course, designers should be familiar with the sometimes long process of “incubation”, where one constructs a mental model of the situation, the relevant possibilities and constraints, and this serves as background knowledge to the sudden insight that has been traditionally associated with abduction.

Refining abduction through cognitive concepts

Since the 1980s, the understanding of human reasoning as operating by means of mental models, through which the world is simulated, rather than only through formal rules of logical inference, has gained foothold in psychology (Johnson-Laird, 2010). As in discussions on reasoning in general, research on abduction has initially focused on logical inferences (Kapitan, 1990). Peirce discussed abduction through syllogisms, logical sentences, and the subsequent literature has largely taken the same approach, called “sentential” by Magnani (2004, 2009). Magnani has extended the discussion on abduction to models, especially in science, and hence the terms model-based abduction and model-based reasoning, which refer especially to construction and manipulation of visual representations, thought experiments and analogical reasoning. Although there has been a recent growth of work related to this topic (Magnani and Bertolotti, 2017), model-based reasoning in design has received little attention. Thus, one aim here is to explore the significance of mental models, and their external projections, in design abduction.

Theory of mental models

A number of variants of the model theory have been developed over the last decades; here, the approach of the seminal advocate, Johnson-Laird (2001), is adopted. Up to the 1980s, the mainstream theory held that in reasoning, language-like representations of propositions are manipulated based on formal rules. The newer theory holds that based on linguistic representations of the meaning of propositions, mental models of the considered situation are constructed. Then, the reasoning is based on these mental models. According to Johnson-Laird (2010), no clear

distinction is drawn in reasoning among deduction, induction, and abduction – reasoning based on mental models “is more a simulation of the world fleshed out with all our relevant knowledge”. Furthermore, he forwards the ability to refute an inference through counterexamples as the heart of human rationality.

The theory of mental models is based on three assumptions. First, a mental model is characterized as an internal model of a possibility (Johnson-Laird, 2001); it represents what is common to a distinct set of possibilities. Second, a mental model is iconic; it is structurally similar to what it represents: “A natural model of discourse has a structure that corresponds directly to the structure of the state of the affairs that the discourse describes” (Johnson-Laird, 2010). Third, mental models represent what is true; we usually construct models of what is possible and true, as opposed to what is not possible (Johnson-Laird, 2010).

How are these unobservable mental models related to observable internal and external models? Visual (internal) images are iconic, and they can underlie reasoning, argues Johnson-Laird (2010). However, he contends that images may impede reasoning, and visual imagery is not necessary for reasoning. Visual imagery is thus not the same as building a mental model but there may be a close relation, as behind an internal image may lie a mental model (Johnson-Laird, 1998).

External diagrams (or graphs) are closely related to mental models; they are often used to help reasoning. It is noteworthy that here, a diagram represents a model in the mind (Johnson-Laird, 2002), rather than an external entity. Tversky (2011, 2015) and Tversky and Kessell (2014) have interestingly focused on such projection of thought into the world. It is argued in Tversky (2015) that when thought overwhelms the mind, the mind puts it into the world in diagrams or gestures. Thus, human actions organize space to convey abstractions; accordingly (Tversky, 2011): “The designed world is a diagram”.

How is spoken and written language related to mental models? In his seminal treatment, Johnson-Laird (1983) argues that in the mind, utterances are held through propositional (sentential) representations which interact with mental models. Ljungberg (2018) interestingly discusses how iconicity is fundamental to communication and mutual understanding, in oral conversation, as well as in writing and reading. However, it seems that in the recent literature on reasoning, the interaction between mental models and language-based representations has been considerably less addressed than the interaction between mental models and internal and external visual models.

Model-based abduction

Magnani (2004) has seminal discussed model-based abduction, especially in the context of science and mathematics. With the term model-based abduction, he refers to visual abduction but also abductions involving analogies, diagrams, thought experiments, and visual imagery. In turn, according to Magnani, manipulative abduction is a kind of abduction, usually model-based, that exploits external models; it happens when we are thinking through doing, and not only about doing (Magnani, 2009). Insights gained through geometrical constructions or sketching provide examples of manipulative abductions.

He recognizes three types or roles of external representations (models), which help to provide abductive outcomes towards explanation or creation of novel concepts (in the latter case, the results are non-explanatory as there is no pre-existing concept or phenomenon to explain), namely (Magnani, 2013):

- Mirror role (to externalize mental models)
- Unveiling role (to reveal imaginary entities)
- Optical role (to see what otherwise would not be visible, due to smallness, largeness, or other obstacles)

The discussions on model-based abduction tend to emphasize the role of this kind of reasoning, and the impression emerges that model-based abduction and generally model-based reasoning are the only, or at least the most important and effective forms of thinking. Especially, the role of sentential abduction and reasoning (internal or external speaking and verbalization) remains unclear.

Model-based and verbalization-based abduction in the WB case

Most of the identified types of abduction used by the WB are model based, as defined by Magnani (2004): abductive analogy and abductive manipulation. However, arguably also abductive transformation and abductive composition are model based: in the former, the underlying model is transformed, and in the latter, the composition implies a structural model.

In his analysis of the success of the WB, Johnson-Laird (2005) offers their genial ability in visualization as the key factor. He characterizes this ability in many ways:

- Construction of mental models of three-dimensional entities
- Animation of such representations
- Using models in an imaginative play to design novel solutions
- Manipulation of models for checking consequences of an assumption, deriving counterexamples and finding explanations, and diagnosing a malfunction
- Using a model of one thing as analogy for another.

Thus, it would seem that visualization as part of model-based reasoning was the dominant basis for their success.

However, the writings of the WB indicate that verbalization and sentential reasoning also played an important role. Generally, they were brothers who often discussed between themselves (Wright, 1953, p. vi):

From the time we were little children my brother Orville and myself lived together, played together, worked together and, in fact, thought together. We usually owned all of our toys in common, talked over our thoughts and aspirations so that nearly everything that was done in our lives has been the result of conversations, suggestions and discussions between us.

The discussions in connection to the design of propellers illustrate the intensity of this kind of reasoning (Wright and Wright, 1922, p. 6):

What at first seemed a simple problem became more complex the longer we studied it. With the machine moving forward, the air moving backward, the propellers turning sideways, and nothing standing still, it seemed impossible to find a starting point from which to trace the simultaneous reactions. After long arguments, we found ourselves in the ludicrous position of each having been converted to the other's side, with no more agreement than when the discussion began.

The role of such arguments is cogently revealed in the description by Charles Taylor (1948), the mechanic, who closely worked with the brothers:

The boys were working out a lot of theory in those days, and occasionally they would get into terrific arguments. They'd shout at each other

something terrible. I don't think they really got mad, but they sure got awfully hot.

One morning following the worst argument I ever heard, Orv came in and said he guessed he'd been wrong and they ought to do Will's way. A few minutes later Will came in and said he'd been thinking it over and perhaps Orv was right. First thing I knew they were arguing the thing all over again, only this time they had switched ideas. When they were through though, they knew where they were and could go ahead with the job.

In the previous quote, the last sentence tells the key message: through this kind of fierce debate, the matter was clarified and they could act on it.

In turn, Jakab (1990) pinpoints the role of questions for the WB. He argues that the WB seem to have asked themselves the same basic set of questions when encountering a new problem: What information is needed to solve the problem? Where can it be found or what techniques and tools must be employed to obtain it? How can this information be successfully and practically incorporated into the design?

How do these findings resonate with the current literature? The role of verbalization and dialogue/debate in design, especially in terms of questions and answers, has recently been found influential, even if the evidence is scattered. Wetzstein and Hacker (2004) found that question-based reflective verbalization in terms of describing, explaining, evaluating, and justifying one's own solutions of design problem solving leads to significant specific improvements of the design procedure. These authors contend that this dialogue-specific question-answering style of verbalization gives rise to a specific way of thinking that is an analytic solution style. Reimann and Dörner (2004) found a relationship between the use of self-questioning and the quality of the solution in engineering design. The generative role of questions in design was discussed by Eris (2003). Aurisicchio *et al.* (2007) contend that engineering designers advance their tasks by asking questions and finding satisfactory answers. They empirically identified categories of questions used by product designers.

Interestingly, all these findings made in the domain of design align with suggestions made in related fields. In philosophy of science, Hintikka (2007) has proposed to view abductive reasoning as a Socratic process of questions and answers. In turn, Meyer (2017) has proposed a re-interpretation of rhetoric as questioning and answering in language and thought. Littleton and Mercer (2013) advance the concept of interthinking to refer to using talk to pursue a collective intellectual activity.

Thus, it seems that there is definite but scattered support in the literature for the claim of the importance of verbalization and debate for the inventive activities of the WB. Their discussions on a topic, which could last several months, can indeed be seen instrumental in the creation of new solutions. Of course, such a series of discussions (along with other related activities) can be interpreted as constituting dynamic abduction, as treated above.

All in all, it seems that the relatively recent discovery of the role of the visual in reasoning, both internally and externally to the mind, has unnecessarily turned the attention away from the role of spoken and written language, verbalization, and debate as important enablers of thought and invention.

Discussion

Demonstrating the re-proposed notion of design abduction

Regarding the re-proposed design abduction, this research named and illustrated many of the previously defined types of design

abduction. It is worthwhile to compare our results to Johnson-Laird, an eminent scholar of psychology, who has analyzed this case from the viewpoint of reasoning and creativity. While all the instances of design abduction analyzed by us regarding their type are also described by Johnson-Laird, he neither identifies them as abduction nor pinpoints their type, except regarding analogy. The reason for this is that he, on one hand, seems to misunderstand the Peircean abduction as selective (Johnson-Laird, 2005) and treats it only in connection to a diagnostic problem. On the other hand, in his next treatment on the Wright brothers (Johnson-Laird, 2006), he defines abduction as IBE.

Furthermore, the research showed that the underlying assumptions behind the re-proposed notion of abduction are valid in this case; this provides initial evidence on the claim of their validity across design situations. It can be asked whether it is possible to generalize through a test in the form of one case study. However, as argued by Flyvbjerg (2006), case studies can indeed be used for testing hypotheses.

This case is also helpful in addressing wider questions arising in the context of discussion on abduction. Why is it important to identify abductive inferences in design? If we follow Peirce's ideas, a hallmark of an abductive reasoning step is novelty. It was argued in Kroll and Koskela (2017) that novelty in design is relative, and that whenever there is an anomaly – a problem that cannot be readily solved with available knowledge – then some degree of novelty will be needed. The invention of the airplane required novel solutions on a wide front, leading to the paramount role of abductions among the mental moves needed. So while we are mostly concerned with reasoning activities that produce significantly innovative outcomes, such as designing the first airplane, abductive inferences can also occur in many routine design tasks. An exception may be the very habitual design, wherein the designer is aware of only one “rule” that is applicable. Such situations are similar to Brown and Chandrasekaran's (1985) “class 1” activity or Gero's (1990) “routine” design.

After having identified much of the WB' reasoning process as various types of abduction, it may be asked: is all reasoning in design abductive? Clearly, there are also other inference types, especially deductive and inductive steps, such as analysis of the needs, evaluation of the evolving artifacts by testing and simulation, etc. In the WB's case, their experimental work can be regarded as deductive and inductive (in addition to abductive): after forming hypotheses (e.g., banking by wing warping; using Lilienthal's data for wing design; using their own experimental data to design the wings, etc.), they planned the set-up for testing them (bamboo and paper model of the wings followed by a 5-foot kite; manned gliders for wing testing followed by an upper-wing kite; mounting wing profiles on a horizontal bike wheel followed by their own wind tunnels, respectively), and inductively drew general conclusions (wing warping will work on the actual airplane; Lilienthal's data are wrong; their own lift and drag experimental data will be applicable to the real airplane, respectively). In addition, after they (inductively) established theories (computational models, formulas) for wing design, propeller sizing, required takeoff speed, etc., they used the new knowledge to deduce the particulars required for their airplane.

Extending the re-proposed notion of design abduction

The case was instrumental in helping to identify two new types of design abduction, namely strategic abduction and dynamic

abduction. While the formerly identified types of design abduction are distinguished based on the type of the underlying inference, these two are characterized by other criteria. Strategic abduction is identified as bringing novelty regarding the process of design, rather than regarding the product of design. In turn, dynamic abduction is identified based on its temporal characteristics: it is a process rather than an event (like an abductive inference usually). The question arises whether it is justified to extend the concept of design abduction, up to now underpinned by the assumptions that abduction is a momentary event and related to the object of design, in this way. However, as the case showed, both types of abduction were instrumental in creating a solution when novelty was needed. Furthermore, support for these types was found from the literature on abduction in science.

Refining the re-proposed notion of design abduction

The consideration of the cognitive basis of design abduction in the case of the invention of the airplane produced an unexpected and novel result. While model-based abduction and reasoning could be widely observed, the much-discussed instrument of them, visualization, was not found as prevalent as argued in the literature – rather verbalization was identified as playing a major role. Thus, it is deserved to look at the evidence underlying the claim on the major role of visualization.

Johnson-Laird's (2005, 2006) justification for seeing visualization as the main success factor is based on two prior books (Jakab, 1990; Ferguson, 1992) and a quote from Wilbur Wright (who says: "My imagination pictures things more vividly than my eyes"). However, a close reading of the sources of Johnson-Laird reveals that the evidential basis of his claim is surprisingly shallow. In fact, Ferguson (1992) does not discuss visualization at all in relation to the WB. In turn, Jakab (1990) forwards a different main explanation to their success, while also providing arguments for their visualization skills. The two following quotes are representative of Jakab's (1990) argumentation (well digging refers to the plane's sudden diving to the sand):

...the use of graphic imagery is not discussed overtly by the Wrights in their accounts of well digging and of the movable rudder. But it is readily apparent from what they do say that mentally picturing the forces involved and their effects was at the center of how they puzzled through the dilemma.

Again, the primacy of visual thinking in their thought processes can only be inferred from the content of their verbal descriptions and, in some instances, from their sketches.

When judged critically, this circumstantial evidence for the significance of imagery and visual thinking, as presented by Jakab, is not strong, and he fails to pay attention to verbalization that occurred alongside visualization, and indeed to the possible synergy between visualization and verbalization.

Which were the causes of success in the invention of the airplane?

An overarching question emerges from the case and its analysis: Which were the causes of the success of the WB in inventing the airplane? The invention of the airplane was one of the major technological breakthroughs of the twentieth century, which required novel solutions on many fronts, as evidenced by Table 2. Orville Wright himself wrote: "Isn't it astonishing that

all these secrets have been preserved for so many years just so that we could discover them" (Wright, 1953, p. 313). This case is relatively well documented and it has been analyzed by several scholars – however, it seems that there is little agreement on which were the causes of success of the WB.

Jakab (1990) forwards a strict and systematic engineering approach, including the capability of thinking in terms of the total problem rather than focusing on isolated aspects, as the main success factor for the WB. He also mentions their superior ability in mental manipulation of images as an underlying factor. Furthermore, he attributes the WB's success to their choice of control over other aspects as the initial focus.

From the topics mentioned by Jakab, the ability to manipulate images was commented above; in addition, the initial choice of control deserves comments. The choice of control as the initial focus may indeed be a key factor, but we do not really know it for sure. They could have figured the control and then not find a way to build large enough wings that were also lightweight or find an engine that was powerful enough and lightweight. In fact, they put the engine issue to be last (and not the wings), probably because their control system design involved also the wings. When they turned into propulsion, they built their own engine but discovered that an engine was not enough and a good propeller was also necessary. Undoubtedly, in addition to their excellent reasoning skills, they were also lucky. This connects with the notions of guessing and intuition that Peirce mentions as characteristic of abductive reasoning, and the fact that abduction does not guarantee correct results.

Johnson-Laird (2005, 2006) forwards luck and the WB's ability to think, especially their visualizations skills as the key factors. The WB had luck especially in the knowledge base they happened to have about bicycles, which provided fertile analogies to flying. And visualization of the many technical solutions needed, along with imaging the still poorly understood physical phenomena involved, was very important according to Johnson-Laird (this was critically discussed above).

Bereiter (2009), in turn, proposes that the WB had an overall approach that was compatible with the situation characterized by lack of knowledge. He mentions especially the extensive problem analysis and progressive design, embracing the construction of partial and complete prototypes and their testing, and the pursuit of situated knowledge. This approach is contrasted with that of Langley, a contemporaneous scholar and inventor in aviation, who endeavored to develop general theoretical knowledge and apply it to the invention of airplanes. This finding, which as such seems correct, is closely related to two historically important styles of engineering, namely theoretically based and empirically based engineering (Kranakis, 1989) (Bereiter fails to mention this). Epistemologically, Langley applied a Platonic approach, characterized by the practical application of existing theoretical knowledge through deduction, while the WB adopted an Aristotelian approach where also induction from experiments and trials is emphasized (Koskela *et al.*, 2018a).

While agreeing on the four main success factors forwarded by Jakab, Johnson-Laird, and Bereiter (a strict engineering approach as such, visualization, luck, empirically based engineering), we contend that there is a fifth, namely systematic verbalization and discussion/debate during the various activities of invention and design, concomitant with the nature of the team: brothers who were used to discuss and debate everything they were doing. Recent research has consistently found verbalization in connection to design activities to improve the quality of design

output, as presented above. It seems this aspect has been overlooked in prior analyses into the invention of the airplane.

Limitations

The analyses concerning the WB have their limitations; they are mostly based on secondary sources, and in the case of primary sources, these are often made up of recollections. This means that they may suffer from recall bias, the inaccuracy or incompleteness of recall to the memory of past events or experiences (Spencer *et al.*, 2017). For his part, Johnson-Laird (2005) comments that his attempt to reconstruct the thinking of the brothers is speculative, and based on scattered clues in their writings and recent theorizing in cognitive science. It may be that it is not possible to achieve a definitive explanation of the role of different causes of success of the brothers. However, these limitations do not hinder the discovery and development of hypotheses, to be tested in further research.

Conclusion and future research

For better enabling novelty in our design activities, we need to identify, characterize, and understand the different mental moves through which new ideas emerge, and how those moves are triggered. This, broadly, is the rationale for studying design abduction. However, the seminal ideas on design abduction, inspired by treatments in philosophy of science, had a narrow conception on how novelty emerges in design when looked at in terms of logic. In prior work, we endeavored to re-propose the concept of abduction in design, taking the differences between science and design into account, and to identify common types of abductive inferences therein.

In the research reported here, we interpreted the emergence of novelty in a retrospective case through the lens of the re-proposed notion of design abduction. This case study provided rich results, by no means visible in advance. In particular, contributions to knowledge were created in three respects. First, we were able to pinpoint and characterize the abduction type for a fair number of (partial) inventions created in the case. Although these inventions have been previously analyzed in the literature, they have not been characterized as different types of abduction. This demonstrates the applicability of the re-proposed concept of abduction and also produces initial evidence in support of it.

Second, from the case, we identified two new types of design abduction: strategic abduction and dynamic abduction. We could justify and characterize these through discussions in prior literature on analogous phenomena in the domain of scientific research.

Third, we refined the re-proposed concept of abduction by examining the cognitive processes underlying abductive inferences. In alignment with the recent literature, many model-based (rather than sentential) abductive inferences used in the case were found. However, the case materials also strongly indicated that verbalization played an important role underlying abduction. Thus, a new hypothesis explaining, for its part, the emergence of novelty was created.

The seminal suggestions by Peirce on abduction represented a somewhat surprising attempt to conceptualize creative insights from the viewpoint of logic. Research on design abduction is a continuation of this tradition. We contend that the results discussed show that this line of research continues to be relevant and generative. We recommend further empirical and theoretical work to validate and extend the re-proposed notion of abduction

in design, to better understand the underlying cognitive processes, and to ideate on the practical application of the knowledge gained.

The proposed empirical research can include case study research of additional innovative design processes, as in Kroll and Farbman (2016). This would require locating appropriate sources of information – either retrospective accounts or real-time reporting through interviews – on those cases to allow analyzing the design processes from the cognitive viewpoint. Abductive reasoning steps could then be either classified to their various previously defined types or identified as new types of design abduction. Also, the specific roles of visualization and verbalization to support abductive inferences could be explored.

Regarding theoretical work, the starting point is that while design abduction research has its unique and seemingly useful perspective, it is not well integrated into other theorizing on (or relevant to) design. It is worth repeating our earlier call (Kroll and Koskela, 2016) for research on the general connections between abduction, creativity, and intuition. The efforts in philosophy of science to clarify abduction, cognitively and epistemologically (for example, Magnani, 2009, 2017), will probably be fertile also for understanding design abduction. Specifically, the extant knowledge in different fields could advantageously be connected for a better understanding of parts and aspects of abductive inferences, such as the triggering factors, incubation and novelty. A related, and complementary, approach would be to study design abduction from the design theory perspective. While outside the scope of the present article, recent advances in design theory seem to offer means to deepen our understanding of cognitive aspects of design and provide valuable explanations. Among the relevant design theories, one can mention General Design Theory (Yoshikawa, 1981), Coupled Design Process (Braha and Reich, 2003), Infused Design (Shai and Reich, 2004), Function-Behaviour-Structure (Gero and Kannengiesser, 2004), and C–K theory (Hatchuel and Weil, 2009).

In particular, C–K theory's explicit modeling of the knowledge space may help study design abduction and account for innovation and creativity. Hatchuel *et al.* (2013) offer a rigorous mathematical derivation of the relative position of design, scientific modeling, and optimal decision-making. They emphasize the generative power of design and attribute it to creating new knowledge and objects with desired properties. Salgueiredo and Hatchuel (2016) use C–K theory to model biomimetic design processes and show how analogies from nature can lead to expansive partitioning of concepts, thus generating innovative design paths. This, in turn, guides the expansion and revision of the knowledge bases used. In other words, analogical abduction may be viewed as contributing to forming new mental models in the designer's mind, and not just a direct transfer of properties from the source to the target domain. Brun *et al.* (2016) study non-verbal reasoning in design, mostly based on sketches, and attribute the success of producing novel ideas to the restructuring and reordering of the knowledge space. C–K theory has been used by Le Masson *et al.* (2017, chap. 3) to study “conceptual models”, which summarize the available knowledge relevant to a design task, and “generative models”, which are “recipes” of rules that can be used to generate improved artifacts. Both types of models may be related to model-based reasoning.

References

- Aliseda A (2006) *Abductive Reasoning: Logical Investigations into Discovery and Explanation*. Dordrecht: Springer.

- Aurisicchio M, Bracewell RH and Wallace KM** (2007) Characterising design questions that involve reasoning. *DS 42: Proceedings of ICED 2007, the 16th International Conference on Engineering Design*. Paris: The Design Society.
- Ballard G** (2000) Positive vs negative iteration in design. In *Proceedings Eighth Annual Conference of the International Group for Lean Construction, IGLC-6*. Brighton, UK: The University of Brighton, pp. 17–19.
- Bereiter C** (2009) Innovation in the absence of principled knowledge: the case of the Wright Brothers. *Creativity and Innovation Management* **18**, 234–241.
- Braha D and Reich Y** (2003) Topological structures for modelling engineering design processes. *Research in Engineering Design* **14**, 185–199.
- Brooks F** (2010) *The Design of Design: Assays from a Computer Scientist*. Upper Saddle River: Addison-Wesley.
- Brown DC and Chandrasekaran B** (1985) Expert systems for a class of mechanical design activity. In Gero JS (ed), *Knowledge Engineering in Computer-Aided Design*. Amsterdam: Elsevier, pp. 259–282.
- Brun J, Le Masson P and Weil B** (2016) Designing with sketches: the generative effects of knowledge preordering. *Design Science* **2**, e13.
- Crouch TD** (2002) *First Flight: The Wright Brothers and the Invention of the Airplane*. Washington, DC: The Division of Publications, Harpers Ferry Center National Park Service, U.S. Department of the Interior.
- Douven I** (2017) Abduction. In Zalta EN (ed), *The Stanford Encyclopedia of Philosophy, Summer 2017 edition*. Available at <https://plato.stanford.edu/archives/sum2017/entries/abduction/>.
- Eris Ö** (2003) Asking generative design questions: a fundamental cognitive mechanism in design thinking. *DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design*. Stockholm: The Design Society, pp. 587–588.
- Ferguson ES** (1992) *Engineering and the Mind's Eye*. Cambridge, MA: The MIT Press.
- Flyvbjerg B** (2006) Five misunderstandings about case-study research. *Qualitative Inquiry* **12**, 219–245.
- Gabbay D and Woods J** (2005) *The Reach of Abduction: Insight and Trial*. Amsterdam: Elsevier.
- Gero JS** (1990) Design prototypes: a knowledge representation schema for design. *AI Magazine* **11**, 26–36.
- Gero JS and Kannengiesser U** (2004) The situated function-behaviour-structure framework. *Design Studies* **25**, 373–391.
- Gruber HE** (1981) On the relation between ‘aha experiences’ and the construction of ideas. *History of Science* **19**, 41–59.
- Hatchuel A and Weil B** (2009) C-K design theory: an advanced formulation. *Research in Engineering Design* **19**, 181–192.
- Hatchuel A, Reich Y, Le Masson P, Weil B and Kazakçi AO** (2013) Beyond models and decisions: situating design through generative functions. *DS 75-2: Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol. 2*. Seoul, Korea: Design Theory and Research Methodology, pp. 233–242.
- Hintikka J** (2007) *Socratic Epistemology: Explorations of Knowledge-Seeking by Questioning*. Cambridge: Cambridge University Press.
- Jakab PL** (1990) *Visions of a Flying Machine: The Wright Brothers and the Process of Invention*. Washington, DC: Smithsonian Books.
- Johnson-Laird PN** (1983) *Mental Models: Towards A Cognitive Science of Language, Inference, and Consciousness*. Cambridge, MA: Harvard University Press.
- Johnson-Laird PN** (1998) Imagery, visualization, and thinking. In Hochberg J (ed), *Perception and Cognition at the Century's End*. San Diego, CA: Academic Press, pp. 441–467.
- Johnson-Laird PN** (2001) Mental models and human reasoning. In Dupoux E (ed), *Language, Brain, and Cognitive Development: Essays in Honor of Jacques Mehler*. Cambridge, MA: The MIT Press, pp. 85–102.
- Johnson-Laird PN** (2002) Peirce, logic diagrams, and the elementary operations of reasoning. *Thinking & Reasoning* **8**, 69–95.
- Johnson-Laird PN** (2005) Flying bicycles: how the Wright brothers invented the airplane. *Mind & Society* **4**, 27–48.
- Johnson-Laird PN** (2006) *How We Reason*. New York, NY: Oxford University Press.
- Johnson-Laird PN** (2010) Mental models and human reasoning. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 18243–18250.
- Kapitan T** (1990) In what way is abductive inference creative? *Transactions of the Charles S. Peirce Society* **26**, 499–512.
- Koskela L and Kroll E** (2019) Model-based abduction in design. In Gero J (ed), *Design Computing and Cognition '18, DCC 2018*. Cham: Springer, pp. 247–264.
- Koskela L, Ferrantelli A, Niiranen J, Pikas E and Dave B** (2018a) Epistemological explanation of lean construction. *Journal of Construction Engineering and Management* **145**, 04018131.
- Koskela L, Paavola S and Kroll E** (2018b) The role of abduction in production of new ideas in design. In Vermaas PE and Vial S (eds), *Advancements in the Philosophy of Design*, Chapter 8. Cham: Springer, pp. 153–184.
- Kranakis E** (1989) Social determinants of engineering practice: a comparative view of France and America in the nineteenth century. *Social Studies of Science* **19**, 5–70.
- Kroll E** (2013) Design theory and conceptual design: contrasting functional decomposition and morphology with parameter analysis. *Research in Engineering Design* **24**, 165–183.
- Kroll E and Farbman I** (2016) Casting innovative aerospace design case studies in the parameter analysis framework to uncover the design process of experts. *Design Science* **2**, e2.
- Kroll E and Koskela L** (2016) Explicating concepts in reasoning from function to form by two-step innovative abductions. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* **30**, 125–137.
- Kroll E and Koskela L** (2017) Studying design abduction in the context of novelty. *DS 87-7 Proceedings of the 21st International Conference on Engineering Design (ICED 17)*, Vol. 7. Vancouver, Canada: Design Theory and Research Methodology, pp. 61–70.
- Kroll E, Le Masson P and Weil B** (2014) Steepest-first exploration with learning-based path evaluation: uncovering the design strategy of parameter analysis with C–K theory. *Research in Engineering Design* **25**, 351–373.
- Le Masson P, Weil B and Hatchuel A** (2017) *Design Theory: Methods and Organization for Innovation*. Cham: Springer.
- Littleton K and Mercer N** (2013) *Interthink*. Abingdon: Routledge.
- Ljungberg C** (2018) Iconicity in cognition and communication. *Historical Social Research / Historische Sozialforschung. Supplement*, 66–77.
- Magnani L** (2004) Model-based and manipulative abduction in science. *Foundation of Science* **9**, 219–247.
- Magnani L** (2009) *Abductive Cognition: The Epistemological and Eco-cognitive Dimensions of Hypothetical Reasoning*. Heidelberg: Springer.
- Magnani L** (2013) Thinking through drawing: Diagram constructions as epistemic mediators in geometrical discovery. *Knowledge Engineering Review* **28**, 303–326.
- Magnani L** (2017) *Abductive Structure of Scientific Creativity*. Cham: Springer.
- Magnani L and Bertolotti T** (2017) *Springer Handbook of Model-Based Science*. Cham, Switzerland: Springer.
- March I** (1976) The logic of design and the question of value. In March I (ed), *The Architecture of Form*. Cambridge: Cambridge University Press, pp. 1–40.
- Meyer M** (2017) *What is Rhetoric?* Oxford: Oxford University Press.
- Paavola S** (2004) Abduction as a logic and methodology of discovery: the importance of strategies. *Foundations of Science* **9**, 267–283.
- Paavola S** (2014) From steps and phases to dynamically evolving abduction. Presented at *The Charles S. Peirce Int. Centennial Congress 2014: Invigorating Philosophy for the 21st Century*. Lowell, MA.
- Peirce CS** (1865) Harvard lectures on the logic of science. In Fisch M et al. (eds), *The Writings of Charles S. Peirce, Vol.1*. Bloomington: Indiana University Press.
- Peirce CS** (1898) Association. CP 7.498. In Arthur W. Burks (ed), *Collected Papers of Charles Sanders Peirce, Vol. 7*. Cambridge, MA: Harvard University Press.
- Peirce CS** (1903) Harvard lectures on pragmatism: Lecture VII, CP 5.181. In Arthur W. Burks (ed), *Collected Papers of Charles Sanders Peirce, Vol. 5*. Cambridge, MA: Harvard University Press.
- Peirce CS** (1913) Letters to F.A. Woods. CP 8:385–388. In Arthur W. Burks (ed), *Collected Papers of Charles Sanders Peirce, Vol. 8*. Cambridge, MA: Harvard University Press.
- Peirce CS** (1967) Note on the theory of the economy of research. *Operations Research* **15**, 643–648.

- Reimann R and Dörner D** (2004) Die Auswirkung von selbstadressierten Fragen auf die Entwurfsqualität beim Konstruieren: Eine explorative Studie. *Zeitschrift für Psychologie/Journal of Psychology* **212**, 1–9.
- Salgueiredo CF and Hatchuel A** (2016) Beyond analogy: a model of bioinspiration for creative design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* **30**, 159–170.
- Shai O and Reich Y** (2004) Infused design: I theory. *Research in Engineering Design* **15**, 93–107.
- Spencer EA, Brassey J and Mahtani K** (2017) Recall bias. In: *Catalogue of Bias*. Available at <https://www.catalogueofbiases.org/biases/recall-bias>.
- Steward DV** (1981) The design structure system: a method for managing the design of complex systems. *IEEE Transactions on Engineering Management* **28**, 71–74.
- Suh NP** (2001) *Axiomatic Design: Advances and Applications*. New York, NY: Oxford University Press.
- Taylor C** (1948) My story of the Wright brothers. *Collier's Weekly*, December 25, pp. 27, 68, 70.
- Tversky B** (2011) Visualizing thought. *Topics in Cognitive Science* **3**, 499–535.
- Tversky B** (2015) The cognitive design of tools of thought. *Review of Philosophy and Psychology* **6**, 99–116.
- Tversky B and Kessell A** (2014) Thinking in action. *Pragmatics & Cognition* **22**, 206–223.
- Wetzstein A and Hacker W** (2004) Reflective verbalization improves solutions – the effects of question-based reflection in design problem solving. *Applied Cognitive Psychology* **18**, 145–156.
- Wright W** (1953) *The Papers of Wilbur and Orville Wright, Including the Chanute-Wright Letters and Other Papers of Octave Chanute*. New York, NY: McGraw-Hill. Available at <https://catalog.hathitrust.org/Record/001114607>.
- Wright O and Wright W** (1922) *The Early History of the Airplane*. Dayton: The Dayton-Wright Airplane Co. Available at <http://hdl.handle.net/2027/uc2.ark:/13960/t8df6n987>.
- Yoshikawa H** (1981) General Design Theory and a CAD System. In Sata T and Warman E (eds), *Man-Machine Communication in CAD/CAM, Proceedings of the IFIP WG5.2-5.3 Working Conference*. Amsterdam: North-Holland Pub Co, pp. 35–57.

Lauri Koskela is a Professor of Construction and Project Management at the University of Huddersfield in England. In 2004–2014, he had a professorial position at the University of Salford. Prior to that, Dr. Koskela worked at VTT Technical Research Centre of Finland. He is a founding member of the International Group for Lean Construction. In his research, he has advanced theories of production and design.

Ehud Kroll is an Associate Professor of Mechanical Engineering at ORT Braude College in Karmiel, Israel. In 2008–2015, he was a Senior Research Fellow in the Aerospace Engineering Department of the Technion–Israel Institute of Technology. Dr. Kroll also held faculty positions at Texas A&M University and the University of Missouri, Kansas City. His research interests include design theory and methodology; methods for conceptual and systems design; design cognition; design for manufacturing, assembly and disassembly; and design education.