MODELING PARAMETER ANALYSIS DESIGN MOVES WITH C-K THEORY

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ABSTRACT

The parameter analysis methodology of conceptual design is studied in this paper with the help of C-K theory. Each of the fundamental design moves is explained and defined as a specific sequence of C-K operators and a case study of designing airborne decelerators is used to demonstrate the modeling of the parameter analysis process in C-K terms. The theory is used to explain how recovery from an initial fixation took place, leading to a breakthrough in the design process. It is shown that the efficiency and innovative power of parameter analysis is based on C-space "de-partitioning". In addition, the role of K-space in driving the concept development process is highlighted.

Keywords: parameter analysis, C-K theory, conceptual design, design theory

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1 INTRODUCTION

Studying a specific method with the aid of a theory is common in scientific areas (Reich et al., 2012; Shai et al., 2013). It allows furthering our understanding of how and why the method works, identifying its limitations and area of applicability, and comparing it to other methods using a common theoretical basis. At the same time, interpreting and demonstrating the method from the theoretic perspective can provide empirical validation of the theory. The current study focuses on using C-K theory to clarify the (implicit) theoretical grounds and logic of a pragmatic design method called Parameter Analysis (PA). It also helps to explain some practical issues in C-K design theory.

C-K theory (Hatchuel and Weil, 2009; Le Masson et al., 2010; Hatchuel et al., 2013) is a general descriptive model with a strong logical foundation, resulting in powerful expressive capabilities. The theory models design as interplay between two spaces, the space of concepts (C-space) and the space of knowledge (K-space). Four operators, C→K, K→C, C→C and K→K, allow moving between and within these spaces to facilitate a design process. Space K contains all established, or true, propositions, which is all the knowledge available to the designer. Space C contains "concepts", which are undecidable propositions (neither true nor false) relative to K, that is, partially unknown objects whose existence is not guaranteed in K. Design processes aim to transform undecidable propositions into true propositions by jointly expanding spaces C and K through the action of the four operators. This expansion continues until a concept becomes an object that is well defined by a true proposition in K. Expansion of C yields a tree structure, while that of K produces a more chaotic pattern.

PA (Kroll et al., 2001; Kroll, 2013) is an empirically-derived method for doing conceptual design. It was developed initially as a descriptive model after studying designers in action and observing that their thought process involved continuously alternating between conceptual-level issues (concept space) and descriptions of hardware[1] (configuration space). The result of any design process is certainly a member of configuration space, and so are all the elements of the design artifact that appear, and sometimes also disappear, as the design process unfolds. Movement from one point to another in configuration space represents a change in the evolving design's physical description, but requires conceptual reasoning, which is done in concept space. The concept space deals with "parameters", which in this context are functions, ideas and other conceptual-level issues that provide the basis for anything that happens in configuration space. Moving from concept space to configuration space involves a realization of the idea in a particular hardware representation, and moving back, from configuration to concept space, is an abstraction or generalization, because a specific hardware serves to stimulate a new conceptual thought. It should be emphasized that concept space in PA is epistemologically different from C-space in C-K theory, as explained in (Kroll, 2013).

To facilitate the movement between the two spaces, a prescriptive model was conceived, consisting of three distinct steps, as shown in Figure 1. The first step, Parameter Identification (PI), consists primarily of the recognition of the most dominant issues at any given moment during the design process. In PA, the term "parameter" specifically refers to issues at a conceptual level. These may include the dominant physics governing a problem, a new insight into critical relationships between some characteristics, an analogy that helps shed new light on the design task, or an idea indicating the next best focus of the designer's attention. Parameters play an important role in developing an understanding of the problem and pointing to potential solutions.

The second step is Creative Synthesis (CS). This part of the process represents the generation of a physical configuration based on the concept recognized within the parameter identification step. Since the process is iterative, it generates many physical configurations, not all of which will be very interesting. However, the physical configurations allow one to see new key parameters, which will again stimulate a new direction for the process. The third component of PA, the Evaluation (E) step, facilitates the process of moving away from a physical realization back to parameters or concepts. Evaluation is important because one must consider the degree to which a physical realization represents a possible solution to the entire problem. Evaluation also points out the weaknesses of the configurations and possible areas of improvement for the next design cycle.

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[1] Hardware descriptions or representations are used here as generic terms for the designed artifact; however, nothing in the current work excludes software, services, user experience and similar products of the design process.
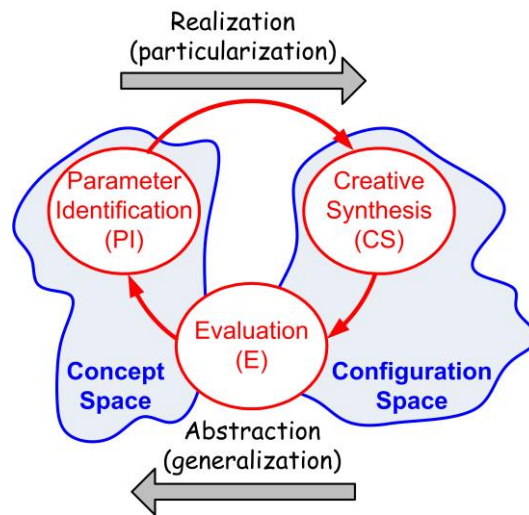
Figure 1. The prescriptive model of parameter analysis consists of repeatedly applying parameter identification (PI), creative synthesis (CS) and evaluation (E)

PA's repetitive PI–CS–E cycles are preceded by a Technology Identification (TI) stage of looking into fundamental technologies that can be used, thus establishing several starting points, or initial conditions. A cursory listing of each candidate technology's pros and cons follows, leading the designer to pick the one that seems most likely to succeed. PA proved to be useful and intuitive, yet more efficient and innovative than conventional "systematic design" approaches (Kroll, 2013).

The present study attempts to address some questions and clarify some of the fundamental notions of both PA and C-K theory. Among them:

- What exactly are the elements of C-space and K-space? C-K theory distinguishes between the spaces based on the logical status of their members ("undecidable" propositions are concepts, and "true" or "false" ones are knowledge items), but it can still benefit from a clear and consistent definition of the structure and contents of these spaces.

- What is the exact meaning of the C-K operators? In particular, is there a C→C operator, and does it mean that one concept is generated from another without use of knowledge?

- How should C-K diagrams be drawn? How can these diagrams capture the time-dependence of the design process? How exactly should the arrows representing the four operators be drawn?

- If PA is a proven design method and C-K is a general theory of design, does the latter provide explanation to everything that is carried out in the former?

- Does C-K theory explain the specific design strategy inherent in PA, and in particular, the latter's claim that it supports innovative design?

The PA method of conceptual design is demonstrated in the next section by applying it to a design task. The steps of PA are explained next with the notions of C-K theory, followed by a detailed interpretation of the case study in C-K terms. The paper concludes with a discussion of the results of this study and their consequences in regard to both PA and C-K theory. For brevity, the focus here is on the basic steps of PA, leaving out the preliminary stage of TI. The role of the case study in this paper is merely to demonstrate various aspects; the results presented are general and have been derived by logical reasoning and not by generalizing from the case study.

2   PARAMETER ANALYSIS APPLICATION EXAMPLE

The following is a real design task that had originated in industry and was later changed slightly for confidentiality reasons. It was assigned to teams of students (3-4 members in each) in engineering design classes, who were directed to use PA for its solution after receiving about six hours of instruction and demonstration of the method. The design process presented here is based on one team's written report with slight modifications for clarity and brevity.

The task was to design the means of deploying a large number (~500) of airborne sensors for monitoring air quality and composition, wind velocities, atmospheric pressure variations, etc. The sensors were to be released at an altitude of ~3,000 m from an under-wing container carried by a light aircraft and stay as long as possible in the air, with the descent rate not exceeding 3 m/s (corresponding to the sensor staying airborne for over 15 minutes). Each sensor contained a small battery, electronic

circuitry and radio transmitter, and was packaged as a ϕ10 by 50-mm long cylinder weighing 10 g. It was necessary to design the aerodynamic decelerators to be attached to the payload (the sensors), and the method of their deployment from a minimum weight and size container. The following focuses on the decelerator design only.

The design team began with analyzing the need, carrying out some preliminary calculations that showed that the drag coefficient C_D of a parachute shaped decelerator is about 2, so to balance a total weight of 12-15 g (10 g sensor plus 2-5 g assumed for the decelerator itself), the parachute's diameter would be ~150 mm. If the decelerator were a flat disk perpendicular to the flow, the C_D reduces to ~1.2, and if it were a sphere, then $C_D \cong 0.5$, with the corresponding diameters being about 200 and 300 mm, respectively. It was also clear that such large decelerators would be difficult to pack compactly in large numbers, that they should be strong enough to sustain aerodynamic loads, particularly during their deployment, when the relative velocity between them and the surrounding air was high, and that being disposable, they should be relatively cheap to make and assemble. Further, the sturdier the decelerator is made, chances are that it would also be heavier. And the heavier it is, the larger it would have to be in order to provide enough area to generate the required drag force.

Technology identification began with the team identifying deceleration of the sensors as the most critical aspect of the design. For this task they came up with the technologies of flexible parachute, rigid parachute, gas-filled balloon and hot-air balloon. Reviewing some pros and cons of each technology, they chose the flexible parachute for further development. Figure 2 is a detailed description of a portion of the PA process carried out by the design team.
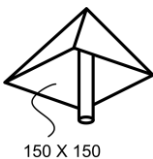
PA step	Reasoning process	Outcome
PI_1	The first conceptual issue (parameter) should be the chosen technology.	Parameter: "Produce a large enough drag force using a flexible parachute"
CS_1	Which particular physical configuration would realize the flexible parachute concept?	Configuration: A 150-mm dia. hemispherical parachute, connected to the sensor with cords. Ø 150
E_1	Given the physical configuration, what is the behavior?	Drag force is ok and compact packing can be done by folding, but the parachute may not open and cords may tangle.
	Shall we try to improve the last configuration or backtrack?	Try another technology from the TI stage.
PI_2	Use the new technology for the decelerator design.	Parameter: "Use a rigid parachute to generate drag force"
CS_2	Which particular physical configuration would realize the rigid parachute concept?	Configuration: A 150-mm diagonal square pyramid with the sensor rigidly attached. 150 X 150
E_2	Given the physical configuration, what is the behavior?	Drag force is ok but compact packing is impossible because these configurations cannot nest in each other.
	Shall we try to improve the last configuration or backtrack?	Try to improve the design by finding a way to pack it compactly.
PI_3	How can the last configuration be improved? Combine the idea of flexible parachute that can be folded for packing with a rigid parachute that doesn't have cords and doesn't require a strong "pull" to open.	Parameter: "Use a frame + flexible sheet construction that can fold like an umbrella; use a spring for opening"

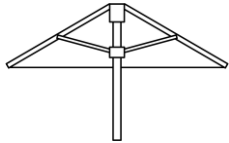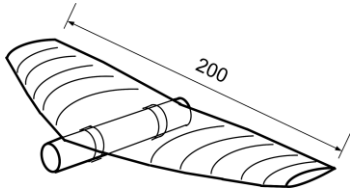*Figure 2. Description of the reasoning process used to design airborne decelerators*

CS₃	Which particular physical configuration would realize the "umbrella" concept?	Configuration: Lightweight skeleton made of plastic or composite with "Saran wrap" stretched and glued onto it. Hinges and slides allow folding. A spring will facilitate opening.
E₃	Given the physical configuration, what is the behavior?	Drag force and compact packing are ok, but this structure is unreliable and expensive to manufacture because of the many moving parts.
	Shall we try to improve the last configuration or backtrack?	Parachutes (flexible and rigid) are problematic. Abandon this concept and try something else.
PI₄	Let's look at the problem differently, from an energy dissipation viewpoint instead of producing retarding force. Dissipation of the sensor's initial potential energy can be carried out by a long enough distance over which a smaller drag force can act.	Parameter: "Use a small aircraft that glides in spirals"
CS₄	Which particular physical configuration would realize the glider concept?	Configuration: Wings with a span of 200 mm and a small twist to produce a 30-m diameter downward spiral. The wings can be made of Styrofoam and the sensor attached with plastic clips.
E₄	Given the physical configuration, what is the behavior?	This would work, seems cheap to make, and shouldn't have deployment problems. But how will the "gliders" be packed and released in the air?
	Shall we try to improve the last configuration or backtrack?	Continue with this configuration: design the container, packing arrangement, and method of deployment.

Figure 2. continued

The first concept (PI₁) is based on a small parachute that will provide the necessary drag force while allowing compact packing. The following creative synthesis step (CS₁) realizes this idea in a specific hardware by sketching and sizing it with the help of some calculations. Having a configuration at hand, evaluation can now take place (E₁), raising doubts about the operability of the solution.

The next concept attempted (PI₂) is the rigid parachute from the TI stage, implemented as a square pyramid configuration (CS₂), but found to introduce a new problem—packing—when evaluated (E₂). A folding, semi-rigid parachute is the next concept realized and evaluated, resulting in the conclusion that parachutes are not a good solution. This brings a breakthrough in the design: dissipating energy by frictional work can also be achieved by a smaller drag force over a larger distance, so instead of a vertical fall the payload can be carried by a "glider" in a spiraling descent (PI₄). The resulting configuration (CS₄) shows an implementation of the last concept in words and a sketch, followed by an evaluation (E₄) and further development (not shown here).

It is interesting to note a few points in this process: First, when the designers carried out preliminary calculations during the need analysis stage, they already had a vertical drag device in mind, exhibiting the sort of fixation in which a seemingly simple problem triggers the most straightforward solution. Second, technology identification yielded four concepts, all still relevant for vertical descent, and all quite "standard". A third interesting point is that when the "umbrella" concept failed (E₃), the designers chose not to attempt another technology identified at the outset (such as gas-filled balloon), but instead used the insights and understanding gained during the earlier steps to arrive at a totally new concept, that of a "glider" (PI₄). And while in hindsight, this last concept may not seem that innovative, it actually represents a breakthrough in the design process because this concept was not apparent at all at the beginning.

3 INTERPRETATION OF PARAMETER ANALYSIS IN C-K TERMS

Technology identification, which is not elaborated here, establishes the root concept, C_0, as the important aspect of the task to be designed first. The actual PA process consists of three steps that are applied repeatedly (PI, CS and E) and involves two types of fundamental entities: parameters (ideas, conceptual-level issues) and configurations (hardware representations, structure descriptions). In addition, the E step deduces the behavior of a configuration followed by a decision as to how to proceed. The interpretation in C-K terms is based on the premises that because knowledge is not represented explicitly in PA and because a design should be considered tentative (undecidable in C-K terms) until it is complete, both PA's parameters and configurations are entities of C-K's C-space.

The parameter identification (PI) step begins with the results of an evaluation step that establishes the specific behavior of a configuration in K-space by deduction ("given structure, find behavior"), and makes a decision about how to proceed. There are three possible decisions that the evaluation step can make:

1. Stop the process if it is complete (in this case there is no subsequent PI step), or
2. Try to improve the undesired behavior of the evolving configuration (this is the most common occurrence), or
3. Use a specific technology (from technology identification, TI) for the current design task. This can happen at the beginning of the PA process, after establishing (in TI) which is the most promising candidate for further development, or if the evaluation results in a decision to abandon the current sequence of development and start over with another technology.

In C-K terms, current behavior and decision on proceeding are knowledge items in K-space, so generating a new concept (for improvement or totally new) begins with a K→C operator. This, in turn, triggers a C→C operator, as shown in Figure 3. The K→C operator carries the decision plus domain knowledge into the C-space, while the C→C operator performs the actual derivation of the new concept. Two cases can be distinguished: the PI step can begin with a decision to improve the current design (case 2 above), as in Figure 3a, or it can begin with a decision to start with a new technology (case 3 above), as in Figure 3b. In both cases, the result of the PI step is always a new concept in C-K terms, which in PA terms is a parameter. In the following diagrams we shall use round-cornered boxes to denote C-K concepts that stand for PA parameters, and regular boxes for C-K concepts that represent PA configurations. The red numbers show the order of the process steps.
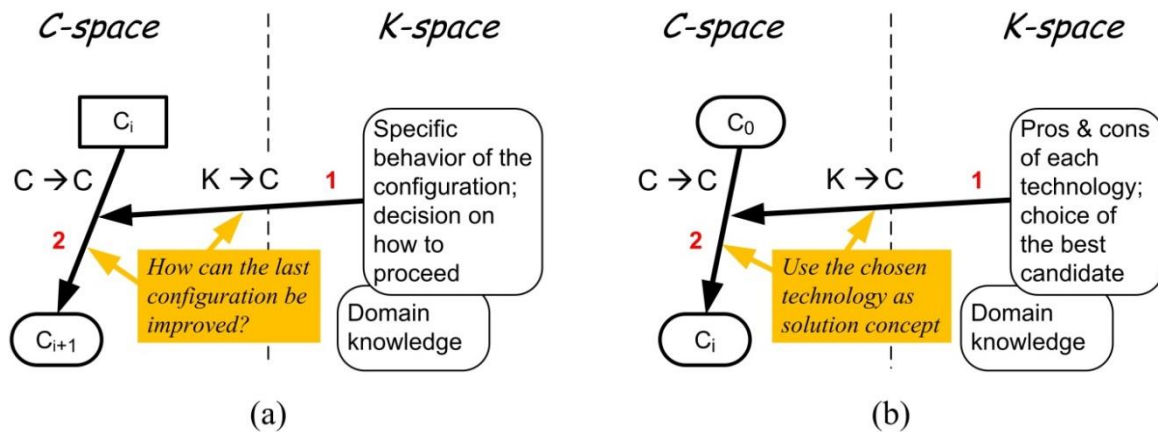

Figure 3. C-K model of parameter identification (PI): (a) applies to the common case encountered during PA and (b) shows starting with a new technology

The creative synthesis (CS) step starts with a parameter, a PA concept, and results in a new configuration. It involves a realization of an idea in hardware representation by particularization or instantiation (the opposite of generalization). It usually requires some quantitative specification of dimensions, materials, etc. that are derived by calculation. In terms of C-K theory, if PA's parameters and configurations are elements of C-space, then the CS step should start and end in C-space. However, because knowledge is required to realize an idea in hardware and perform quantitative reasoning, a visit to K-space is also needed. The CS step therefore begins with searching for the needed knowledge by a C→K operator that triggers a K→K (deriving specific results from existing knowledge). The new results, in turn, are used by a K→C operator to activate a C→C that generates

the new concept, which is a PA configuration that realizes the parameter in hardware. This interpretation of CS as a sequence of four C-K operators is depicted in Figure 4a.

In PA, parameters (concept, ideas) cannot be evaluated, only configurations. This means that the evaluation (E) step begins with a configuration or structure and tries to deduce its behavior, from which it will make a decision (any one of the three described above). This means that a C→K operator is used to trigger a K→K; the former is the operation of looking for the knowledge necessary for the evaluation, while the latter is the actual deductive reasoning that leads to deriving the specific behavior and making the decision as to how to proceed. This is shown in Figure 4b.
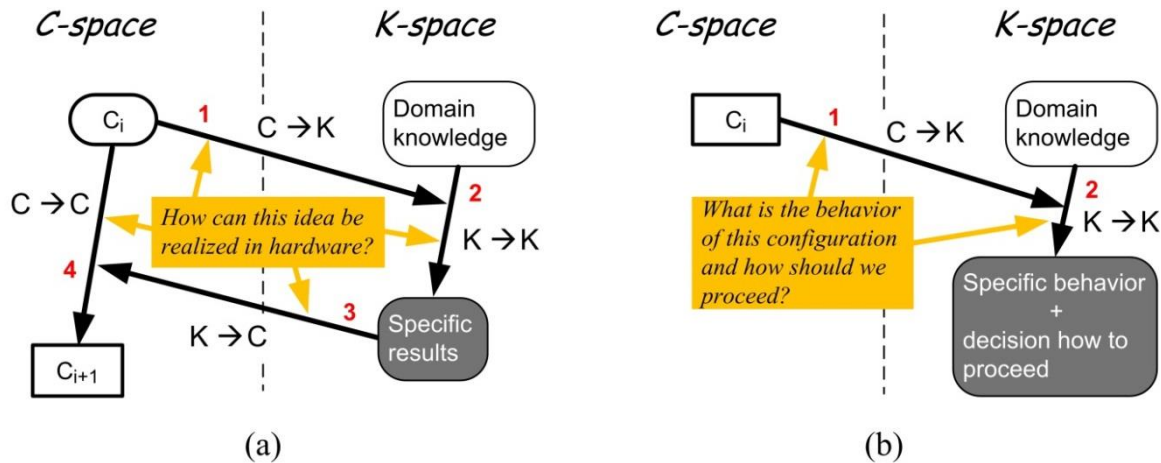

Figure 4. C-K model of (a) creative synthesis (CS) and (b) evaluation (E). Dark background denotes a new knowledge item

4   PA PROCESS DEMONSTRATION IN C-K TERMS

The design process began with the need, the problem to solve, as stated by the customer. A need analysis stage produced greater understanding of the task and the design requirements. This took place entirely in K-space and is not shown here. Next, technology identification focused the designers on the issue of deceleration (C_0), found possible core technologies, listed their pros and cons, and made a choice of the best candidate. The following description of the PA process commences at this point. Figure 5 shows the first cycle of PI–CS–E as described in Figure 2 and depicted with the formalism of Figures 3 and 4. Note that while C_0 does not have a meaning of parameter or configuration in PA terms, the result of the first partition, C_1, is a PA parameter, while the second partition generates the configuration C_2. This first cycle ended with a decision to abandon the flexible parachute concept and use another technology identified earlier (in TI) instead.

For brevity, the demonstration now skips to the last PI–CS–E cycle as depicted in Figure 6. It began with the evaluation result of step E_3 (see Figure 2) shown at the lower right corner of Figure 6. The designers concluded that parachutes, flexible or rigid, were not a good solution path, and called for trying something different. They could, of course, opt for the balloon technologies identified earlier, but thanks to their better understanding of the problem at that point, they decided to take a different look at the problem (PI_4 in Figure 6). They realized that their previous efforts had been directed at designing vertical decelerators, but that from the energy dissipation viewpoint a spiraling "glider" concept might work better. The C-K model of this step depicts a "de-partition", or growing of the tree structure in C-space upward, at its root. This phenomenon, also demonstrated in chapter 11 of Le Masson et al. (2010), represents moving toward a more general or wider concept, and in our case, redefining the identity of C_0:*decelerator* to C_0':*vertical drag decelerator* and partitioning C_7 to C_0' and C_8.

5   DISCUSSION

C-K theory has been clarified by this study with regard to its spaces and operators. Elements of C-space correspond to both PA's parameters (concepts) and configurations (structures), thus they have the following structure: "there exists an object *Name*, for which the group of (behavioral) properties $B_1, B_2, ...$ can be made with the group of structural characteristics $S_1, S_2, ...$". For example, concept C_2 (a PA configuration) and concept C_5 (a PA parameter) in Figure 6 can be described as:

"there exists an object C_2, for which the group of properties
    B_1 = *produces vertical drag (inherited from C_0')*
    B_2 = *based on flexible parachute (inherited from C_1)*
can be made with the group of characteristics
    S_1 = *150-mm dia. hemispherical canopy*
    S_2 = *cords for sensor attachment"*

"there exists an object C_5, for which the group of properties
    B_1 = *produces vertical drag (inherited from C_0')*
    B_2 = *based on rigid parachute (inherited from C_3)*
    B_3 = *built as an umbrella, i.e., folding frame and flexible skin*
can be made with the group of characteristics
    S_1 = *150x150mm square pyramid shape (inherited from C_4)"*
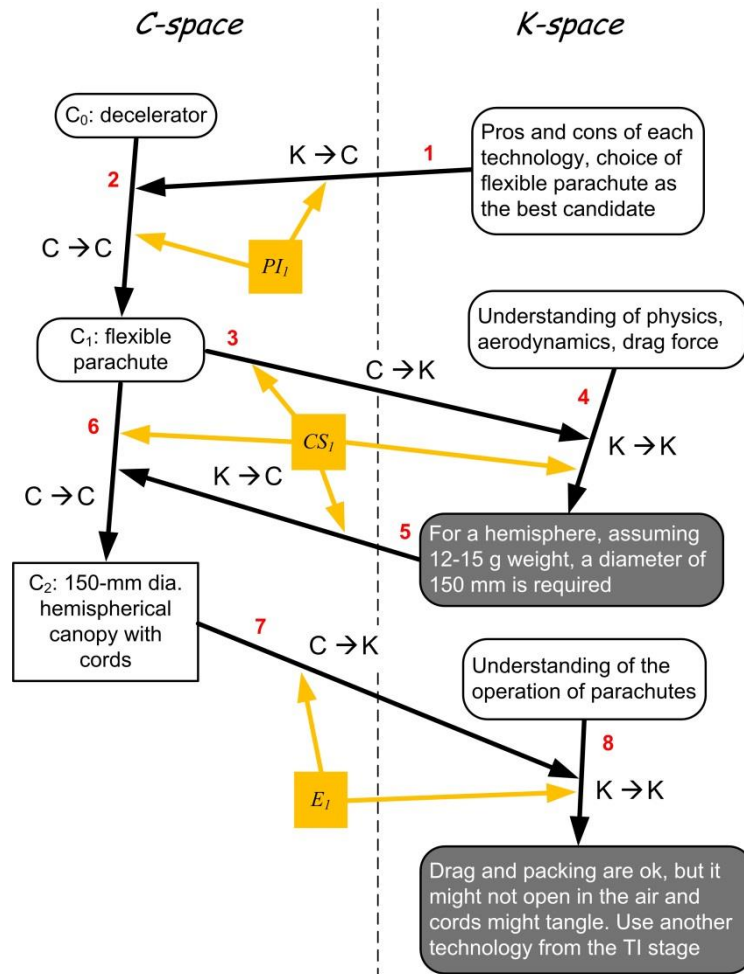

Figure 5. C-K model of the first PI-CS-E cycle of the decelerator design

The interesting thing to note is that except for the root concept in C-K (which is not defined as a PA entity), all other concepts have some attributes (properties and/or characteristics). But because a C-K concept can be either a PA parameter of configuration and PA excludes the possibility of having configurations without parameters to support them, the concepts in C-K sometimes have only properties (i.e., behavioral attributes), and sometimes properties plus characteristics (structural attributes); however, a concept cannot have characteristics and no properties.

Need analysis, although not elaborated here, is the stage of studying the design task in terms of functions and constraints, and generating the design requirements (specifications). It takes place entirely in K-space. Technology identification also takes place mostly in K-space. The basic entities of PA, parameters (conceptual-level issues, ideas) and configurations (embodiments of ideas in hardware) have been shown to reside in C-K's C-space. However, all the design "moves" in PA—PI, CS and E— which facilitate moving between PA's spaces, require excursions to C-K's K-space, as shown in

Figures 3 and 4. In particular, the importance of investigating K-space when studying design becomes clear by observing how the acquisition of new knowledge (modeled with dark background in Figures 5 and 6) that results from evaluating the evolving design is also the driver of the next step.
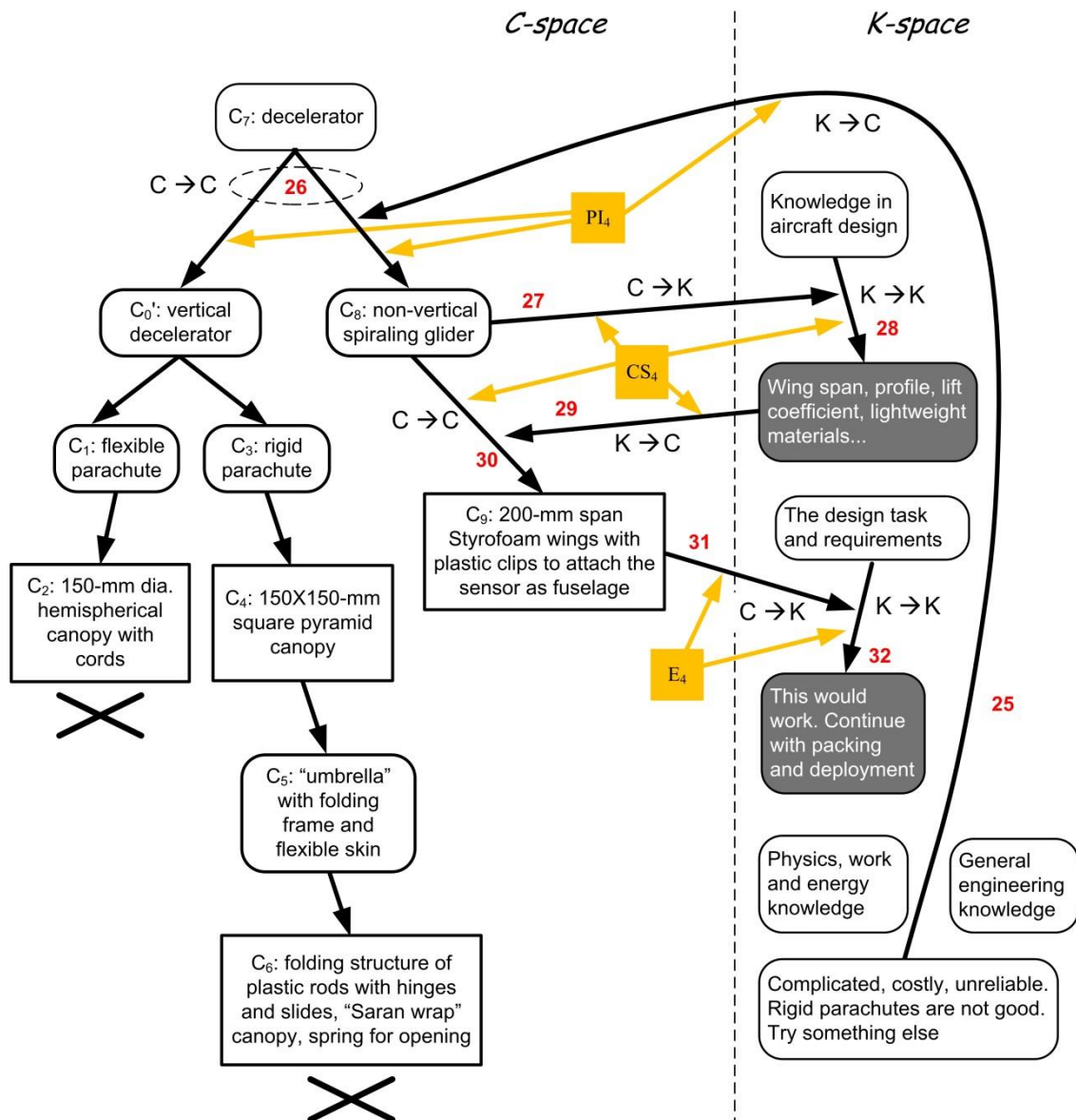

Figure 6. C-K model of the fourth PI-CS-E cycle, demonstrating a "de-partition"

It was shown that K→K operators represent deductive reasoning, generating new knowledge from existing one, but their action needs to be triggered by a reason, a purpose, and this is represented by a C→K operator. Likewise, a K→C operator uses knowledge for triggering a C→C operator. As demonstrated in this study, C→C operators do exist, representing the derivation of a new concept from another. However, this operation does not happen by itself in C-space, only if triggered by a K→C operator. The importance of having a C→C operator can be explained by the need to capture the relation of new concepts to their ancestors, including inheritance of their attributes. It should be noted, however, that the tree structure of C-space is not chronological, as demonstrated by the de-partition that took place. To capture the time-dependence of the design process, C-K's concepts were labeled with a running index and the operator arrows numbered. This method of drawing C-K diagrams is useful for providing an overall picture of the design process, but is incorrect in the sense that when a C-K concept is evaluated and found to be deficient, leading to abandoning its further development (as with concepts C_2 and C_6 of Figure 6, for example), it should no longer show in C-space, as its logical status is now "decidable." Some of the ancestors of such 'false' concepts may also need to be dropped from C-space, depending on the exact outcome of the pertinent evaluation.

C-K theory is, by definition, a model of the design process, and does not contain a strategy for designing. However, modeling PA with C-K theory helps to clarify the former's strategy in several respects. First, PA is clearly a depth-first method, attempting to improve and modify the evolving design as much as possible and minimizing backtracking. It also uses a sort of heuristic "cost function" that guides the process to address the more difficult and critical aspects first. This strategy is very different from, for example, the breadth-first functional analysis and morphology method of systematic design (Pahl et al. 2007), where all the functions are treated concurrently.

A second clarification of PA regards its support of innovation. As many solution-driven engineers do, the designers of the decelerator example also began with straightforward, known solutions for vertical descent (parachutes, balloons). This fixation often limits the designer's ability to innovate; however, the PA process demonstrated here allowed recovery from the effect of the initial fixation by learning (through the repeated evaluation of "standard" configurations) during the development process (generating new knowledge in C-K terms) and discovery of a final solution that was not included in the fixation-affected initial set of technologies. Moreover, C-K theory allowed identifying de-partitioning of concept space as the exact mechanism through which the innovation was achieved.

6   CONCLUSION

C-K theory was shown to be able to model PA's steps, which are fundamental design "moves": generating an idea, implementing an idea in hardware representation, and evaluating a configuration. It also showed that PA supports innovative design by providing a means for recovering from fixation effects. Conversely, PA helped to clarify the structure of C-K's concepts, operators and C-space itself, and to emphasize the importance of K-space expansions. Many interesting issues still remain for future research: What particular knowledge and capabilities are needed by the designer when deciding what are the most dominant aspects of the problem in TI, and the most critical conceptual-level issues in each PI step? What exactly happens in K-space during PA as related to the structures of knowledge items and their role as drivers of the design process? Are there additional innovation mechanisms in PA that can be explained with C-K theory? Can C-K theory help compare PA to other design methodologies? In addition, we have already begun a separate investigation of the logic of PA as a special case of Branch and Bound algorithms, where design path evaluation is used for controlling the depth-first strategy in a way that ensures efficiency and innovation.

REFERENCES
Hatchuel, A. and Weil, B. (2009) C-K design theory: an advanced formulation. *Research in Engineering Design*, Vol. 19, No. 4, pp. 181-192.

Hatchuel, A., Weil, B. and Le Masson, P. (2013) Towards an ontology of design: lessons from C–K design theory and Forcing. *Research in Engineering Design*, Vol. 24, No. 2, pp. 147-163.

Kroll, E. (2013) Design theory and conceptual design: contrasting functional decomposition and morphology with parameter analysis. *Research in Engineering Design*, Vol. 24, No. 2, pp. 165-183.

Kroll, E., Condoor, S.S. and Jansson, D.G. (2001) *Innovative conceptual design: theory and application of parameter analysis*. Cambridge: Cambridge University Press.

Le Masson, P., Weil, B. and Hatchuel, A. (2010) *Strategic management of innovation and design*. Cambridge: Cambridge University Press.

Pahl, G., Beitz, W., Feldhunsen, J. and Grote, K.H. (2007) *Engineering design: a systematic approach*. 3rd edition, London: Springer.

Reich, Y., Hatchuel, A., Shai O. and Subrahmanian, E. (2012) A theoretical analysis of creativity methods in engineering design: casting and improving ASIT within C–K theory. *Journal of Engineering Design*, Vol. 23, No. 2, pp. 137-158.

Shai, O., Reich, Y., Hatchuel, A. and Subrahmanian, E. (2013) Creativity and scientific discovery with infused design and its analysis with C–K theory. *Research in Engineering Design*, Vol. 24, No. 2, pp. 201-214.