INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

A STRUCTURE FOR REPRESENTING PROBLEM FORMULATION IN DESIGN

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ABSTRACT

Much study has been done on many aspects of design. Although problem formulation is believed to play a major role in a creative design of high quality, it has gained less attention. In our larger study, we are investigating the role of problem formulation on design creativity. In order to conduct such studies, a formal representation of design problems is needed. In this paper, a taxonomy for representing the design problem space is proposed. We call this static representation *the problem map*. It can provide a basis for comparing how different designers perceive a problem and help demonstrate the co-evolution of problem and solution. Our preliminary study was based on the design of a model aircraft by an expert and two groups of novice designers. The examples of the *problem maps* showed that the expert had a richer set of attributes of design entities and relations among them, which the novices missed.

Keywords: Problem formulation, protocol study, design taxonomy, problem maps

1 INTRODUCTION

In the past few decades, the study of design has gone through major changes in the areas of interest and methodology of research. The field has seen a shift from providing descriptive and prescriptive models of design activity to offering support in computer-aided design and decision making [1]. Managerial implications of product development, called for the proposition of general processes [2, 3] and prescriptive models, most notably the systematic approach described by Pahl and Beitz [4]. Some methods, like QFD [5] and the Taguchi robust design [6], introduced techniques to relate and quantify customer needs into design parameters. However, prior knowledge about those parameters is central to them which is often not available, especially in innovative designs.

More fundamentally, the debate on whether design can be regarded as a science, has raised questions about what methodologies to implement and what directions to follow. It also has led to less direct views towards design. An anti-systematic vision, for instance, emphasizes discourse as a response to the problem of rationality, which seeks to balance design efforts with emotions, pragmatism, phenomenology, and narrative. This in turn changes how research questions should be altered for design in the post-structural era [7]. Yet, more direct and simple questions remain relevant. Dorst [8] believes we need a new paradigm shift focusing on designer, context, and the design itself rather than the design process—which has drawn the most attention in the design community so far. To decide which area to focus on, it is interesting to remember that Simon regarded the work of the designer as creating an interface for the design and the context, that is, the inner and outer environments [9]. This suggests that the designer should be the center of attention. Then the key question becomes, what is the first thing when the designer faces a problem; or how is the designer aware of the given design problem? The short answer is how he or she formulates the problem.

In the rest of this paper, we first review the relevant research in engineering design. Then we propose a framework for problem formulation and provide the results based on an exploratory protocol study and draw conclusions.

2 PROBLEM FORMULATION IN DESIGN

We should begin with a review of the relevant literature in design. The empirical literature over the past three decades contains relatively few results about problem formulation, even though studies on the topic suggest its key role in creative design. Several papers report major differences between good and poor designers, with the former spending more time on problem formulation and on producing more flexible and dynamic problem representations. Some of these studies relied on introspection or informal observations rather than controlled experiments, but there is sufficient evidence to explore this idea more extensively and to examine its implications in improving creativity in engineering design.

2.1 Problem formulation in process

Early studies related to problem formulation introduced descriptive models of the cognitive processes of design in whole, from conceptual to final design [10-12]. Later works focused on particular aspects in design, of which, probing into the closer stages to the exposure to the problem lied in ideation [13-15]. Problem definition and formulation, or what Harfield calls ‘Problemization’, has not received much attention in literature [16].

A variety of researchers have employed protocol studies to examine early stages of design. Thomas and Carroll [17] found that designers prefer to treat problems as ill-defined rather than reformulating them as well-defined. Cross and Cross [18] argued that expert designers adopt a systemic approach and creatively frame the problem by deliberately treating it as ill-defined. Darr and Birmingham [19] showed that, in combinatorial selection of existing components, the solution time was proportionate to the perceived problem space. Atman et al. found that senior designers produced higher quality by gathering more information early, considered more alternative solutions, and transitioned more frequently between design steps, while Eisentraut [20] maintained that such behavior relates to different styles of problem solving that are independent of the situation of the design episode.

Research on the co-evolution of problem and solution suggested that recognition of partial structures in the problem space, shapes the structure of the solution space [21, 22]. Harfield [16] claimed that designers need ‘proto-solutions’ to compare the goal and the problem state, while Cross and Cross [18] claimed that creative designers, while holding experience of previous solutions at the back of their minds, use first principles as stimuli to build bridges between problem and solution space through key concepts.

Harfield also added that naïve designers make fixed assumptions while creative designers question requirements. Darlington and Culley [23] saw that, in reality, requirement capture is not as methodologists offer. It is affected by the level of trust and risk perceived by customer about the designer and the experience, discipline, and the complexity of the project. Others suggested designers set boundaries for particular aspects of attention in framing a problematic design situation [24] and a more successful design team considered more of such framings than an unsuccessful one [25].

Problemization is also dependent on the designer’s state, skill, style, biases, and preferences [7, 16]. Gero and Kannengiesser [26] stated that designers use their own experiences to interpret representations augmented with implicit requirements which lead them to the same problem differently. Kruger and Cross [27] grouped designers into problem-driven, solution-driven or their variants, information-driven or knowledge-driven, and find that the overall results of the main strategies are close. Ho [28] stated that expert designers decompose a problem explicitly, approach directly the goal state first, work backward for required knowledge and then forward for solution while novices decompose a problem implicitly and eliminate a problem when they fail to handle it. Ball et al. [29] found that experts lean on schema-driven analogies (experiential abstract knowledge) while novices rely on case-driven analogies—which maps the source problem and solution to a target problem—and that surface-level cues drive case-driven analogizing. Gero and McNeill [30] classified the different strategies designers adopt into analysis, proposition and making explicit references (micro strategies) and top-down, bottom-up, decomposition, opportunistic and backtracking (macro strategies).

2.2 Problem types

In attending to a design problem, the design type should also be considered. In product development, product types are defined based on the complexity of the applied technology in two directions; product structure and production process. Under this classification, products fall under three categories: breakthrough, platform, and derivatives. For instance, a breakthrough product is one with radical changes in design, realized by radical changes in manufacturing technology [2]. In general design practice, designs can be defined as novel designs or modifications. There is a slight difference, however, between the two classifications. The novelty of a design should not necessarily rely on a radical change in the product or process. Often we encounter designs that are considered novel and yet the technology that is employed in their production is rather mature. The same applies to designs that in the former definition would be considered derivatives of an existing product and yet qualify for being rewarded for their novelty (take the Magic Bullet juicer for example).

Goel and Pirolli [31] presented an extensive account of how design problems are different from non-design ones. Some of these differences are having invariant characteristics of information processing system, distinct solving phases, near decomposability of solutions and a limited-commitment-mode control. Dixon et al. [32] have proposed a taxonomy for problem types in the domain of mechanical components and assemblies. The design problem is classified into one of the six mutually exclusive states; initial state of knowledge and final desired state of knowledge, combinations of which specify the problem type. For example, conceptual design occurs when there is an initial state of knowledge about the function and final desired state of knowledge is an embodiment, or when there is an initial state of knowledge about the artifact type and final desired state of knowledge is an artifact instance, the design is parametric. Fricke [33] mentioned that the completeness of the design brief affects problem solving strategy. Imprecise problems require a solution-neutral approach while precise problems require more solution-attached approaches, and excessive expansion and unreasonable restriction of the solutions space should be avoided.

2.3 Problem representation structures

A few researchers have attempted to develop models for representing the structure of design problems. Maher et al. [22] linked problem definition states to solutions. Goldschmidt [34] drew linkographs of figural representations as states and conceptual representations as operators. Eisentraut and Gunther [20] coded sketches for concreteness and completeness as a measure of level of abstraction, Fricke [33] implements temporal models and Goel and Pirolli [31] chose a Task-Operator-Phase model. Akin and Chengtah [35] suggested that modes of representation can be extended from verbal and visual to more activity modes such as examining, drawing or writing, thinking and their echo, speaking. They observe that novel decisions occur in multi-modal episodes and data modalities are dependent. Different models have been presented to represent information handling in design. Baya and Leifer [36] created a framework based on information fragments in design activity, level of detail and level of abstraction. Grebici et al. [37] investigated a generic question-based approach in triggering improved pathway of design thinking considering a taxonomy of knowledge indexes with entities such as process, function, attribute, product structure, feature, issues and resources.

3 FRAGMENTS OF THE PROBLEM FORMULATION STRUCTURE

The approaches we discussed previously in the last section, however, are process oriented. As we discuss later, temporal representations of the states of design can be just as informative. They are quite novel even though they might appear familiar. Yet we have benefited from a process view to initially organize the information relevant to design and from there we propose a state representation that we call the *problem map*. We reached the proposed framework in two steps. First is the recognition of the entities, or in the object-oriented terminology, classes, in design activity. Second is the organization of the problem formulation fragments (PFF), the above entities, into groups of similar characteristics. These steps were taken after observing a few design sessions (exploratory protocol studies) as explained in more detail in the following section. We argue later that the formality of the model is less important, at least in the early stage of this study, than how it represents transition—the main intention behind the problem map. Thus, we are less concerned with the choice of what should and should not be considered. Therefore there are no references to any existing descriptive or prescriptive models unless specified.

3.1 Design entities

To lay a framework for problem formulation in design, the first step is to try to recognize the entities one encounters in a design process. To help such recognition, an early categorization was made where we found three categories. This was in accord with our observations from the protocols as we give examples shortly. The categories are: what the designer discovers; what the designer exploits and how the designer approaches the problem.

What the designer discovers relates mostly to the design itself which is usually embodied by a design solution. Yet to stay focused on the problem side, one should try to avoid any specificity rendered by a proposed solution to the extent possible; however this is difficult, as in defining design parameters. The category contains *functional requirements*, *constraints*, *system hierarchy* and *design parameters*.

What the designer exploits relates to what the designer considers and implements to decide why a specific design should be the way it is. This includes *static domain knowledge* (in different domains), *rules* (physical behaviors), *relations* (among requirements, between requirements and constraints, etc), *best practices*, *proto-solutions* and *insights*.

How the designer approaches the problem relates mostly to the designer and the way what was mentioned in the previous category is implemented. It includes *priorities, perceptions* and *decision*.

To explain better, we provide examples of direct observations from our design protocols. We conducted a preliminary protocol study with two groups of four senior undergraduate mechanical engineering design students at Arizona State University, working on the Design/Build/Fly competition held by AIAA[1] [38]. Its goal was designing a multiobjective RC (remotely-controlled) model plane, where speed of the plane and its load carrying capacity would be tested with different scoring weights for each mission. The goal was a balanced design demonstrating good flight handling and affordable manufacturing. We complemented our analysis of problem formulation by collecting data from an expert designer in the form of a depositional interview.

Our protocol studies involved data from a single design session within a series of sessions. Participants were part way through the process of designing their solutions when we collected our data. This allowed us to examine their representations once the most relevant conceptual units had been identified. We chose this strategy to ensure that the formalism would be complete, a necessary feature for supporting future investigations of the mental states as they emerge in the process of design. We should emphasize that our study was in the exploratory stage and as much as its results were represented in terms of the proposed structure, they were the basis for coming up with the structure in the first place.

There were two design sessions for each of the student groups and a depositional interview with the expert designer which were recorded using two video cameras. The durations of the sessions ranged from forty minutes to an hour and a half. We examined the videos for evidence of conceptual structure, seeking a representation that captured as many of the statements they made as possible. We also sought to align similar statements across participants, for instance statements identifying drag as an important factor to consider. After multiple iterations of this process we came up with the presentations for the problem maps as we will explain in section 4.

Some of the observations are direct quotes from the protocols and some of them are based on a series of events that the subjects went through. Some quotes pointed to more than one category, depending on interpretation. A summary of the observations of one of the groups is listed in Table 1.

Functional requirements are highlighted when the expert describes in order, lift, payload, thrust, launching, landing and control of the RC plane. The first novice group goes through objectives of the design and sparsely mentions the functional requirements. It realizes that *"...they test the strength of each wing right after the flight..."* or that *"...it has to land, it can't sustain too much damage..."*. The second novice group considers different functions when it says *"...with the weights that we have and the power system [selected], we'll be able to determine the velocity required to get the lift needed ..."*. This last quote clearly can be interpreted to underline the discovery of parameters such as weight and their relations to physical behaviors such as lift.

Vast knowledge, of rules of physical behavior, is one of the main advantages of the expert to the novices where he reveals pivotal rules concerning the problem. He quickly points out that *"…the ratio of the wing surface to plane speed should be in this area [of the chart]…"*. The second group postulates *"…maybe our plane doesn't fly that high and this [variable] in the formula could be one…"*. They also highlight *"… the smaller surface areas at the front, the better for the aircraft to fly; there is minimum drag…"*.

Another example is the designers' priorities. The expert goes through his notes and explicitly says *"… first one that is listed here, volume constraint …"*. The first novice group follows the design brief and tries to rank the three missions in order of importance and later becomes concerned about knowing on what aspects the emphasis should be laid *"… musts and wants… we have to figure out more"*. The second novice group highlights what should be the emphasis of their design in a brief statement *"We're going to build for lift…"*.

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[1] The American Institute of Aeronautics and Astronautics

Table 1 Observations from the protocols for the fragments of problem formulation structure

Aspect	Element	Observation
What the designer discovers	Function	*“...it has to land, it can’t sustain too much damage...”*
	Constraint	*“...at what velocity it needs to get in the air... if somebody can throw it like that...”*
	System hierarchy	*“...I think we need to get a basic design of the whole thing...”*
	Design parameters	*“...its called the aspect ratio, 0.4 is a good number...”*
What the designer exploits	Domain knowledge	*“...that’s why you throw it up... so the acceleration back down gives us a boost...”*
	Rules of physical behavior	*“...the smaller surface areas at the front, the better for the aircraft to fly; there is minimum drag...”*
	Relations	*“...what’s affecting you the most is surface area, and that’s for drag...”*
	Insights	*“...maybe our plane doesn’t fly that high and this [variable] in the formula could be one...”*
How the designer treats the problem	Priorities	*“...that's a good goal, with the weights that we have and the power system [selected] well be able to determine the velocity required to get the lift needed...”*
	Perceptions	*“... we can have two pieces of fuselage if we want...”*
	Decisions	*“... we have to decide for pusher or puller...”*

3.2 Problem maps

In this section, we discuss the changes to the initial PFFs. We reorganized the PFFs into new groups. We draw relations among the PFFs and we called the figural representation, a *P-map*.

Some of the classes introduced in the last section, carried features of a process view. Not that process data cannot be represented in a static way (as a metamodel), but this does not bode well with the interest of showing snapshots of the problem. Therefore, an entity such as decisions, which might show how a choice of a specific parameter was done over another, is abandoned. The new PFFs are classified as function, structure, behavior, usage, concerns, and knowledge, see Table 2.

The first three groups are similar to the Function-Behavior-Structure model [39]. The group *Structure* relates to the embodiment of a physical solution structure in a hierarchical system and can serve to some extent to differentiate levels of abstraction corresponding to different levels of detail on the problem side [31]. In addition, a class of *Trade-offs* reveals the relationships among parameters, highlighting their interactions especially when they have opposite effects. This as will be seen in results, is a central point in discovering issues. The group *Usage* relates to the entities that determine what constraints should be considered in realizing the problem. This is not limited to the constraints that are directly imposed by the design brief but also what the user environment requires which might also contain fictitious, redundant, and unnecessary requirements. The group *Concerns* relates to the questions that are raised, issues that are deemed to be pivotal in the feasibility of the solution and the priorities that are set during the design episode. This group can represent why decisions were made and what insights occurred to the designer. It partly captures the process of design. *Knowledge*, corresponds to the application knowledge [27] in design problem solving. We exclude problem solving methods and strategies as they represent a process view. Finally, *Proto-solutions* [16] refer to inferences of experiential knowledge that can be temporally attached to any of the fragments.

Table 2 A taxonomy for problem maps in design

Function	Structure	Behavior	Usage	Concerns	Knowledge	Proto-solutions
Function	Structure Component Parameter	Physical behavior Trade-off	Constraint Use environment	Questions Issues Priorities	Physical rules	Proto-solutions

4 EXPERIMENTAL PROCEDURE

In section 3, we presented the data from our protocol study. In this section we extend our initial analysis to represent the data in the form of the p-maps whose fragments we just discussed.
Though the two novice groups had different results, the difference was negligible compared to their differences with the expert designer. Thus, the comparison is provided in two parts. First we demonstrate progress in problem formulation for one of the novice groups at the end of their first and second sessions, labeled with time stamps 1 and 2, see Figure 1. Then we contrast the formulation of the other novice group with that of the expert, labeled time 2 at the end of the second session for the novices, and time 1 for the depositional interview with the expert, see Figure 2. For the sake of simplicity, much of the attributes are omitted here. The existing attributes were selected mainly based on what was similar among all designers. The attributes that were related to the similar ones, were also added to demonstrate what relations were missed (in this case only the novice groups missed those relations).

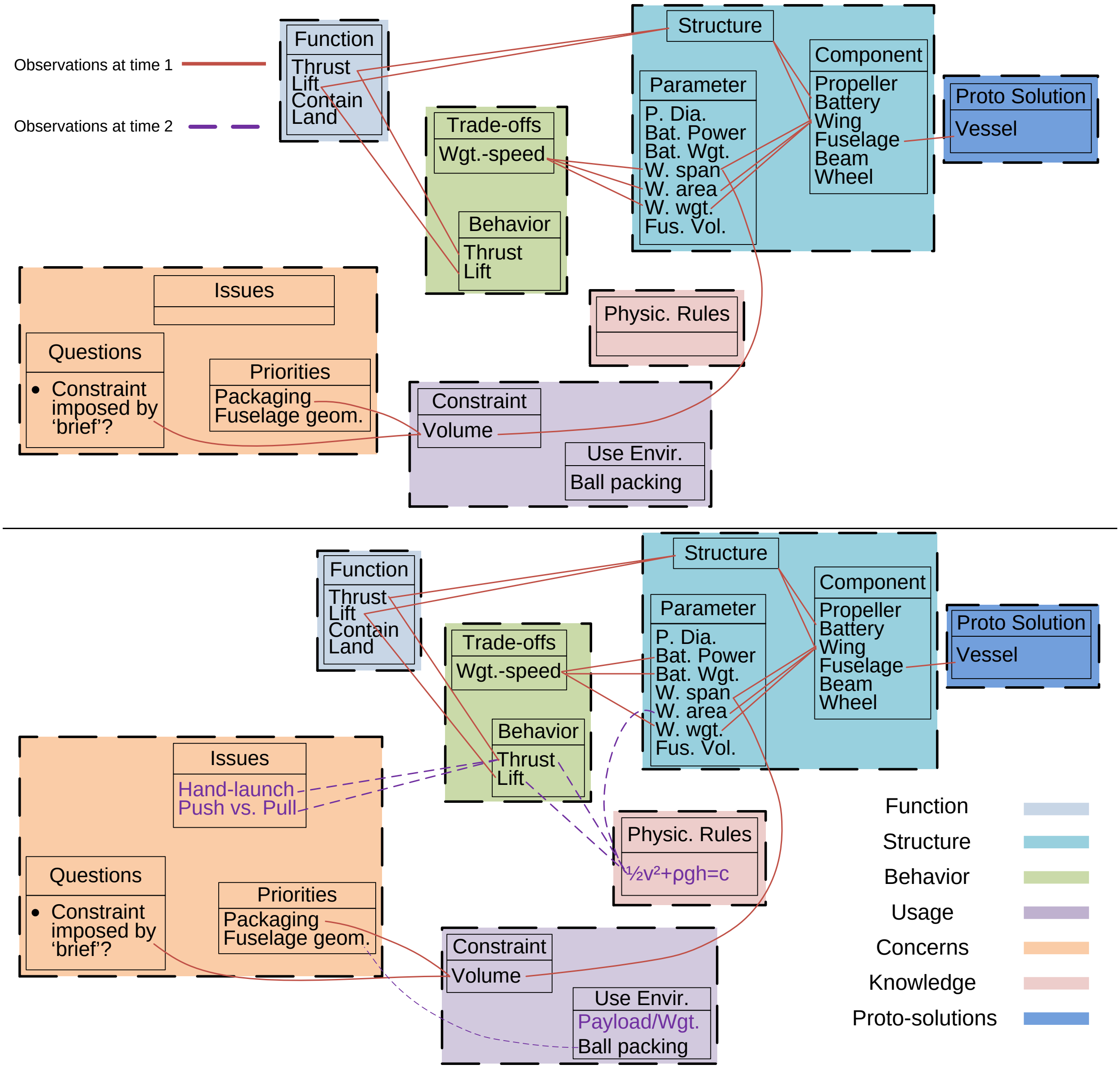

Figure 1 Change in the p-maps for novice group 2: top- at time 1, bottom-at time 2

The novice designers in our case started with questions about constraints which were imposed by the competition rules. They quickly found the volume of the package that should contain the plane to be their first priority. This constraint which would affect the parameters related to the wing, namely the wing span. This implied that in their mental model at that instance, they had a picture of a physical architecture or component as a wing. They later referred explicitly to this component in various occasions and specifically when they laid out a functional decomposition of the aircraft. The students used proto-solutions to attach specific temporal embodiments to a component, e.g. a vessel to a fuselage. They could also find trade-offs among some of the parameters prior to contemplating more sophisticated physical rules. For example they found that the larger their battery, the more power they could get however at the same time the plane would be heavier.

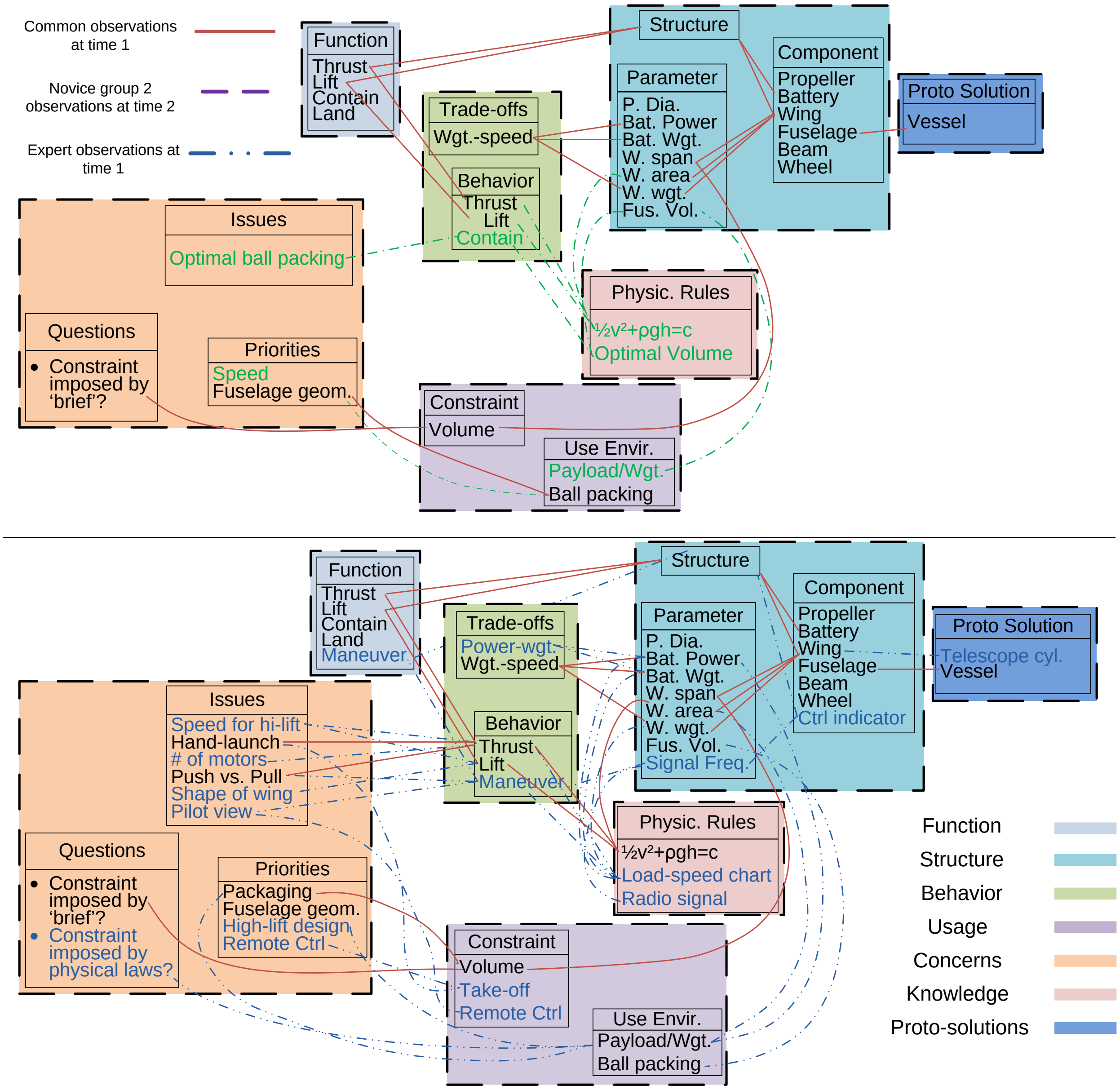

Figure 2 Comparisons of p-maps: top-novice group at time 2, bottom-expert at time 1

As the designers went ahead, and with the emergence of new parameters in relation to a sophisticated physical rule such as the *Bernoulli* law, issues started to be raised in realizing the functional requirements. Such realization would only be meaningful when it was related to the relevant behavior. For example the relation between the thrust and the lift behaviors through the *Bernoulli* law, prompted the designers of the restriction of not using any runways for takeoff. The first novice group raised an issue early on about how the ball packing in the fuselage could be optimized. They saw this as a challenging geometrical problem. They also chose designing for higher speed as their priority. This was in contrast with the approach of the other novice group and the expert designer. Lacking the domain knowledge, the first group took priorities arbitrarily based on the design brief. The second novice group avoided such predilections, and left those choices to later stages when their domain knowledge would improve. This observation means that a richer problem map is not necessarily an evidence for a better design.

The expert designer as it can be seen in Figure 2, had a richer representation of the problem and the main contrasting advantage of his formulation, was the awareness of more physical rules upfront, as a result of deeper domain knowledge, and the way he addressed more usage constraints and issues. A contrasting example was the consideration of the maneuvering function and his concerns about how the test pilot could have a view of the mission path during flight especially on deciding when to turn.

Though a model plane can have sophisticated product structure, in this case and probably due to the time limit, neither of the designers elaborated on a hierarchical structure of components except for the ‘landing gear’ which was decomposed to a ‘beam’ and ‘wheels’. Therefore the entity *Structure* is similar to the class of component and for simplicity, it is left blank.

5 DISCUSSION

P-maps are based on the idea of *Concept maps* or *Mind maps* in cognitive psychology. Concept maps, however, are not structured systematically. Their structure is usually based on natural language grammar, i.e. verbs, pronouns and adverbs which is not totally representative of the tentative ontology of design; e.g. functions could be translated to verbs but pronouns could refer to the designer expressing the cognitive task or a component or a constraint.

The proposed data ontology is rather flexible. We emphasize that the given entities are based on a suggested model. Other entities might be added in necessity. Nevertheless one should first propose a structure with the intended characteristics of the tentative taxonomy and then try to improve it. Some of the characteristics which we seek in the *P-map* are time dependence and the ability to compare different cognitive states. As in a regular map, another beneficial characteristic might be the ability to generate a design episode based on a map or, in opposition, reflect one. The map then becomes a tool for design education.

We emphasize on the way our proposed *P-map* depicts a static view of the problem formulation process. Such static structure is rich enough for representation since it is complicated by a web of dependencies among relationships. The dynamic structure, however, offers a few simple relations in creating a feasible solution [40]. Main issues, their dependencies and the dominant issues become the starting point in our p-maps. One key difference between the expert and the novices was the richness of the relations which were captured. We showed examples of how the novices find some attributes but leave them in vacuum while the expert detects how they are related.

P-maps give a state description of design as opposed to a process description, according to Simon [9]. It can be worth investigating whether the study and the representation of cognitive states would be easier than that of cognitive processes, in which case, p-maps provide a more useful basis for a tentative aid system. It will be easier to show cognitive transition through snapshots of states i.e. p-maps than it is to arduously demonstrate how the transition took place. A simple analogy in geometry is to consider the transition from point A to point B in a Cartesian coordinate system. Unless the path from A to B is straight, the information needed to show the transition, using the coordinate of the two points, is less than when one point is used. In the latter case, the information of the path will be more than that of the other point.

Another aspect of the p-map is the way it might help organize the inter-entity and intra-entity relationships. As it was seen in the given examples, one key difference between the expert and the novices was the richness of the relations which were captured. Closer examination of those relations might become a platform to decide how decomposable design problems are and possibly lead to a measure of complexity beyond what existing taxonomies offer.

Different levels of granularity might be accommodated with our proposed structure. For example a class of standard units (like length or time) might be amended under the group Structure in search of finer relations in designs considering dimension-less ratios. The main reason is that this structure resembles an object-oriented data model which is well-established and opens ways to implementation and modification more rapidly.

Finally, the resemblance to the object-oriented data model may help integrate a creative design tool onto a Product Life-cycle Management platform. With well-known and well-structured design ontology, automating design tasks becomes a trivial matter of technicality [41]. This may be the missing link in offering comprehensive design solution software.

6 CONCLUSION

The study of design problem solving has less focused on capturing how problems are formulated at the early stages of design. We proposed a taxonomy for representing design problem formulation based on an exploratory study of a design case. The intention of representing how problems are formulated and what structure they could pertain in a co-evolution of the problem and solution, was served accordingly by the proposed problem maps. Though in our case, the problem was rather well-defined and the experience of the expert designer was superior to that of the novice group. The richness of the relations captured among different attributes of different classes in the expert p-map, in addition to the abandonment of some attributes in vacuum in the novice p-map can be easily noticed in the proposed structure. This work is still in its early stage. Further investigations are being conducted currently, with a less well-defined and less domain-specific problem, on a group of senior undergraduate design students and a group of professional designers.

ACKNOWLEDGMENTS

This study is supported by the National Science Foundation, CMMI grant number 1002910. The opinions expressed in this paper are those of the authors and are not endorsed by the National Science Foundation. We thank Sara Brimhall for her contribution in conducting the protocol studies. We should also thank Professor Kenneth Huebner of Arizona State University for his help in this study.

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