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CAPTURING THE CONCEPTUAL DESIGN PROCESS WITH CONCEPT-CONFIGURATION-EVALUATION TRIPLETS

Ehud Kroll and Alexander Shihmanter
Technion–Israel Institute of Technology

ABSTRACT
Design knowledge is a key asset that companies find difficult to capture and access. Since most design is redesign, being able to use prior knowledge effectively is crucial. A record of the design process and the decisions that were made is necessary in order to understand, recreate and modify a design. Not less important is capturing the rationale behind rejected ideas. Various design methods can be used for the conceptual design phase, but most fail to explicitly capture the history and rationale of the process, including the reasons for discarded efforts. This paper demonstrates the need for capturing the design rationale with a textbook example that uses functional decomposition and morphology as the conceptual design method. It then introduces a simple and effective scheme that uses a sequence of triplets of the form *concept-configuration-evaluation* to describe the desired information. This scheme is based on a conceptual design methodology called parameter analysis, but we show that the proposed means of rationale capture is generally applicable.

Keywords: Design rationale, design capture, parameter analysis

1 INTRODUCTION
The description of the final design of a product can be found in various documents, such as reports, personal notebooks, drawings and bills of materials. However, too often projects fail to leave the proper documentation regarding why the design was made the way it was, as opposed to what was made, which is usually well documented. Design rationale is the reasons behind a design decision, the justification for it, the other alternatives considered, the tradeoffs evaluated, and the argumentation that led to a decision [1]. Such descriptions are very valuable to companies, because using prior knowledge can substantially reduce future design efforts and costs. When redesigning, it is important to also know what design options were considered and rejected. Maintaining the design knowledge is a difficult task, as team members, the environment and technology change. Redesign without full knowledge and understanding of the design rationale may not be effective.
Research in the area of design capture can be divided into two main groups [2]: (i) understanding, formulation and validation of models and theories behind the rationale, and (ii) developing software tools to capture the design rationale. Most of the work to date has focused on developing computerized tools for design rationale capture, while our current study is concerned with *what* needs to be captured during conceptual design.
Issue-based information systems (IBIS) [3] aim to enable problem solvers to model and communicate their solution process by recording the issues addressed, options considered, and the arguments both pro and con. Many derivatives of the basic IBIS concept have been proposed and specifically focused on design and not just general problem solving. The gIBIS model [4] is a refinement of the IBIS concept by adding a graphical interface. The DRCS [5] language system was created to allow designers to express their design reasoning in a natural way while making it formal enough for computational services. It provided an integrated and generic framework for capturing rationale in team contexts. Many of these tools lacked the widespread use throughout industry, and therefore have not been tested outside the academic setting. Moreover, most research efforts in this area have not studied the influence of employing different design methods while using the tool, and therefore the design methods had to be adapted to the tools or turned out to be very time consuming, instead of the opposite [6].
The requirements for a rationale capture tool for complex systems were outlined in [7]. This kind of tool, suitable when designing very complex systems such as NASA's, might be too complex for

simpler designs and miss some aspects needed in other industries or when using different design methodologies. Another tool, the Design Rationale editor (DRed) [8], enables information representations to be stored in graphs. Previous IBIS-based tools were studied and many problems fixed before implementing DRed. This software tool has successfully been used by a major aerospace company, followed by work on how to efficiently retrieve the information from the system [9]. DesignWebs [10] is a framework for capturing design rationale visualized in an interactive tool to access and search stored data. An upgrade of a common management tool by implementing additional nodes for rationale capture was claimed to increase its effectiveness; however, it was not mentioned whether it could also capture rejected ideas [11]. Another aspect of a design capture model is the influence of the interface and display on the user. Research conducted on this issue [12] showed that a graphic interface could be useful in design. Reinforcement for this argument is available in [13], where a survey of aeronautical engineers showed that a graphical scheme, rather than simple text based documents, improved design understanding.

The efforts discussed so far regard various tools for capturing the information, but more relevant to the present work is the issue of the nature and essence of the information that constitutes the design rationale to be captured. Reich [14] suggested abandoning the rationale capture tools to reduce the overhead required by them. He introduced an improved QFD-based method for capturing design rationale, and claimed that this approach did not involve significant overhead because most companies used QFD as a standard method while designing. Brissaud [15] introduced a tool where the design is conducted iteratively with two spaces, the problem and solution space, with movement between the two spaces by a conjecture move – solution of a specific design problem, and criteria move – indicating the demands made due to a design update. Some research studied the need for knowledge and how to access it. Ahmed [16] found that four main taxonomies existed in descriptions of design knowledge: functions, issues, products and design process steps. He proposed to use the four classes for indexing the information for reuse. The same study also found significant differences between experienced and novice designers in the search methods used. The proposed indexing method would encourage the novice designers to think as experts and therefore improve their performance.

Most of the existing conceptual design methods focus on doing design, and do not deal with capturing the rationale behind it. A popular method of conceptual design, usually taught under systematic design [17-20] is functional decomposition and morphology. We shall show that this method fails to include the proper rationale behind the design decisions and certainly does not explain the rationale behind rejected design solutions. Conceptual design in systematic design is described as a simultaneous development of many concepts and does not capture the time dependency of events, which contributes substantially to the understanding of the design rationale.

The paper is organized as follows: the functional analysis and morphology method from systematic design is briefly explained with an example from the literature. The proposed scheme for capturing conceptual design information with triplets of the form *concept-configuration-evaluation* is introduced next, and then applied to the previous case-study. A discussion of the benefits of the method follows.

2 BILGE PUMP CONCEPTUAL DESIGN EXAMPLE

Many design textbooks prescribe systematic design's functional decomposition and morphology as the method for doing conceptual design. Under this scheme, the main function of the artifact is decomposed into finer and finer subfunctions and solution principles or concepts are sought for each subfunction. Finally, when a good breadth of ideas and technologies has been listed in the morphological chart, the concepts are combinatorially assembled to form multiple overall design concepts. The conventional way of documenting this process is by showing the functional decomposition, the collection of concepts for each subfunction in a morphological chart, and finally sketches of several product conceptual designs.

The bilge pump example used here is taken from a textbook [18] and might also be representative of a design record created in industry and maintained for future use. The only information available to us while studying this example was what the textbook contained. The goal was to design a device to remove water from the bilges of unattended pleasure boats by using natural energy sources. The design requirements included a minimum of 8 L/hr of water removal capacity, size of less than 1 m^3, and cost of less than \$50. Figure 1 shows the "black box" model for the bilge pump, describing its main function with inputs and outputs. Figure 2 is the function structure developed from the black box model of Figure 1. It shows all the subfunctions that need to be provided by the design.

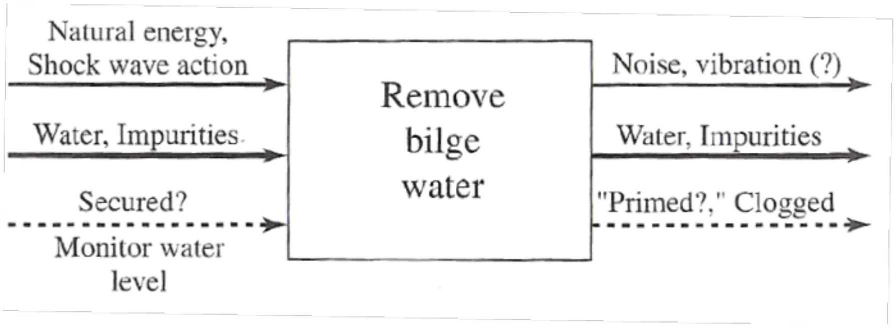


Figure 1. "Black box" model of the bilge pump [18]

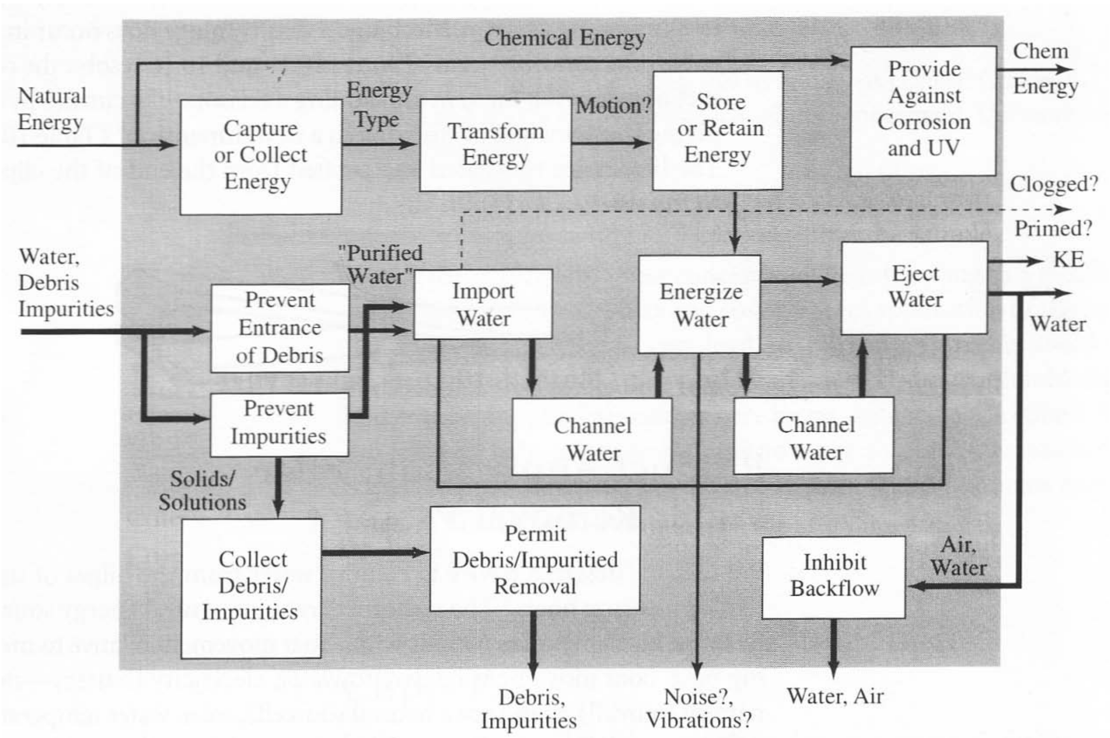


Figure 2. Function structure of the bilge pump [18]

Next, the subfunctions were entered as the first column in a morphological chart, and solution principles for each subfunction were sought and entered too. A portion of the chart is shown in Figure 3. Several combinations of product concepts were formed by selecting subfunction concepts in each row of the chart. One such combination consisted of the marked items in Figure 3, leading to the product concept of Figure 4. It included capturing wind energy with a propeller, transmitting the rotary motion through gears and a crankshaft to a reciprocating pump, with the latter producing suction and pressure to move the water through a screen filter, tubes and flapper valves. Other combinations led in the original example to several other concepts that were shown as sketches similar to Figure 4. Typically, the several concepts developed will be evaluated against each other using a set of criteria in a method such as Pugh's [21]. This means that in addition to the information about the design as captured in Figures 1 to 4, the final design record may also include the evaluation criteria and scores assigned to the different concepts.

Close examination of the above description of the bilge pump conceptual design process clearly shows a significant gap between the listing of the individual subfunction concepts chosen (e.g., the marked combination in Figure 3) and the sketch of Figure 4. Even in the textbook, when the final concept sketches are shown, the authors state (page 463): "*Notice in the concept figures that mapping ideas from the morphological matrix to actual geometry is nonlinear and filled with design decisions. Again, sketches are needed, which must be continually refined and modified through iteration.*" [18]. It is exactly those design decisions, sketches and iterations that constitute the rationale that we seek to capture with the scheme proposed in this paper.

Energy / Sub-function	Mechanical	Fluid
Capture Energy	**Linear spring,** Torsional spring, Pendulum, Elastic, Mass / spring	Air: Propeller, Vanes, Cup Water: Hydraulic head, Turbine, Float
Transform Energy	Crank shaft, Gears, Belt / sprocket, Four bar, Cam, Rack & Pinion	Pneumatic / Hydraulic
Import Water	Lift, Wheel (rotary) Archimedes screw, Carousel,	**Suction**, Siphon,
Channel	Conveyor, Lift, Archimedes screw	**Tube**, Funnel, Jet, V-notch
Energize	**Reciprocating**, Screw or Rotary **pump**	Jet pump, Vaporize, Water column,
Channel	Conveyor, Lift, Archimedes screw	**Tube**, Funnel, Jet, V-notch
Eject	Lift,	**Pressure**, Jet
Inhibit Back flow	**Flapper**, **Ball**, or Butterfly **valve**,	
Prevent Debris / Impure.	**Screen**, Filter, Permeable membrane	Float, Skim, Vortex

Figure 3. A portion of the morphological chart for the bilge pump [18]. We added markings of one combination

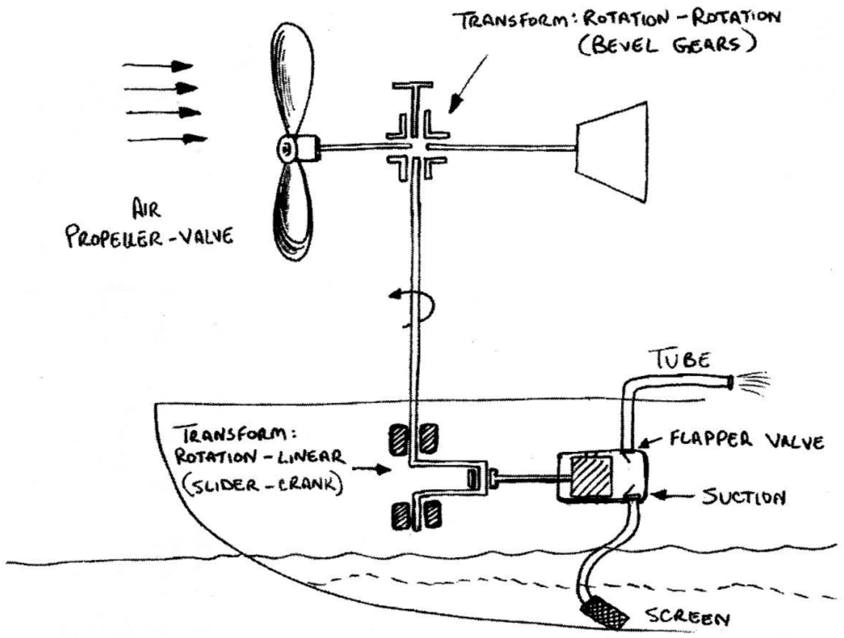


Figure 4. One bilge pump concept that uses wind energy, propeller and reciprocating pump [18]

3 CONCEPT-CONFIGURATION-EVALUATION TRIPLETS

We propose to use sequences of *concept-configuration-evaluation* triplets for capturing the conceptual design process rationale. This scheme is derived from the *parameter analysis* methodology for conceptual design [22]. Parameter analysis is based on the recognition that human design thinking takes place at two different levels, called concept space and configuration space. According to this descriptive model, shown in Figure 5, conceptual design is done by back-and-forth movement between these two spaces.

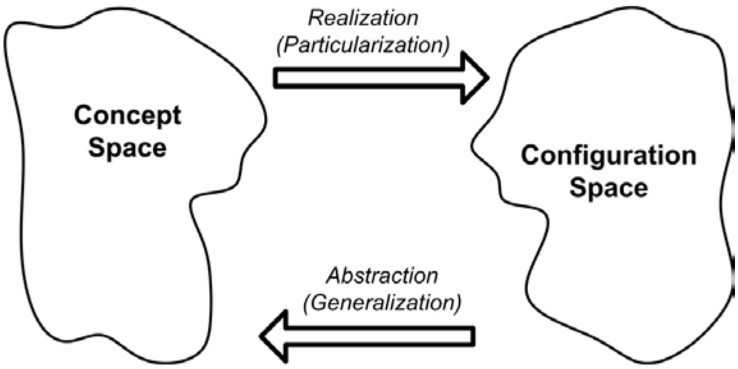


Figure 5. A descriptive model of conceptual design

Configuration space contains the representation of the evolving design. Movement from one point to another in configuration space cannot be made directly, but rather, through a "visit" to concept space. Concept space deals with "parameters", which in this context are conceptual issues and ideas 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.

This model has been developed into a prescriptive model, i.e., a methodology that instructs the designer as to what needs to be done at any given moment during the conceptual design process. Parameter analysis states that moving between concept and configuration spaces is carried out by breaking the thought process into three distinct steps that are applied repeatedly (Figure 6):

1. *Parameter identification* is the recognition of the most dominant issues at any given moment during the design process. The term "parameter" specifically refers to issues at a conceptual level, such as 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 parameters within a problem are not fixed; rather, they evolve as the process moves forward.
2. *Creative synthesis* is 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.
3. *Evaluation* 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 to the weaknesses of the configurations. Evaluation should not usually resort to analysis of physical configurations that goes any deeper than is required to create a fundamental understanding of its underlying elements. Evaluation is not a filtering mechanism that finds fault, but rather, is intended to generate constructive criticism. A well-balanced observation of the design's good and bad aspects is crucial for pointing out possible areas of improvement for the next design cycle.

As can be seen in Figure 6, there is a cycle that consists of three steps (PI-CS-E) representing a single advancement in the design process. The whole design process can be represented as numerous PI-CS-E cycles applied repeatedly, as demonstrated in [22]. When carrying out a design with parameter analysis, the trace of repeated PI, CS and E steps constitutes a sequence of *concept-configuration-evaluation* triplets, so capturing the process is "built-in" the record of the conceptual design process.

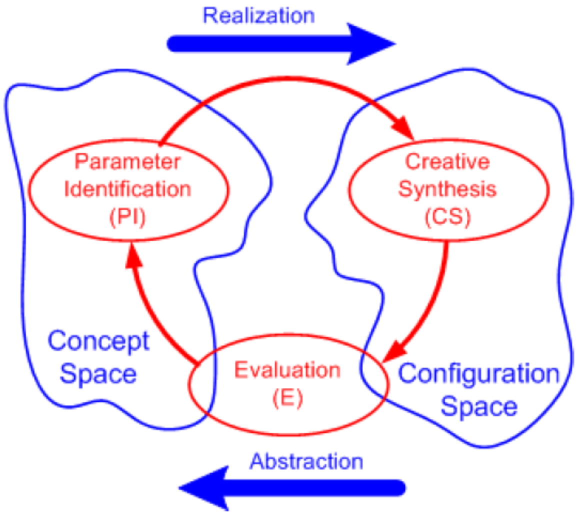


Figure 6. The 3-step prescriptive model of parameter analysis drawn on top of the 2-space descriptive model

But even if the conceptual design has been done by another method, the same sequence of *concept-configuration-evaluation* triplets is very useful for capturing the design rationale, by virtue of its information contents and simplicity. This is demonstrated on the bilge pump example in the next section.

4 CAPTURING THE RATIONALE OF THE BILGE PUMP DESIGN

We do not know the exact process by which the combination of individual concepts for the subfunctions, as marked in Figure 3, was elaborated to yield the sketch of Figure 4. However, we shall hypothesize a logical design process that follows the spirit of parameter analysis, and show the richness of rationale capture obtained by triplets of *concept-configuration-evaluation*, as detailed in Figure 7. This hypothetical design process begins with choosing an initial concept for capturing wind energy and continues by developing the conceptual design of the bilge pump. The main point to notice in Figure 7 is the kinds of information captured by the proposed scheme.

5 DISCUSSION

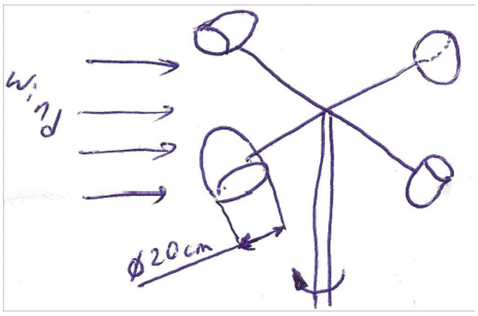
Comparing the record of the bilge pump design as given in [18] and reproduced here in Figures 1-4 with the hypothetical sequence of *concept-configuration-evaluation* triplets in Figure 7, a few points become apparent:

1. The complete trace of the thought process that has led to the final design now includes a wealth of information not available before, and consists of ideas and their realization, with continuous assessment of the state of the design progression.
2. Rejected ideas are captured too. In the future, no one would ask, for example, whether air cups were considered as a possible solution.
3. Quantitative considerations become an integral part of the decision-making rationale. In a future reuse it would be easy to see why the air cups concept was rejected, how efficiencies were accounted for, etc.
4. A quick examination of the description of the design process also reveals what was not considered by the designer, and might have been a good concept; for example, using a vertical-axis wind turbine that could transmit its power through the vertical shaft without using bevel gears.
5. Design mistakes are also captured in a way that can be traced. For example, the choice of a reciprocating pump may not have been a very good idea in the bilge pump case, because it necessitated the conversion of rotary to rectilinear motion. The exact point in the design process where this choice was made can be identified, together with the absence of any particular reason for it. The use of a rotary pump as a better alternative can be suggested in a future redesign.

It is unknown to us what were the exact questions raised and issues examined during the original conceptual design process of the bilge pump because they were not captured explicitly. However, a

Concept: Capture wind energy with air "cups" as a power source.

Configuration: The wind turns 4 air cups. The minimum required removal capacity of 8 L/hr and assumed head of 3 m translate into a power requirement of ~0.07 W. This should be increased by ~50% to account for losses (e.g., pumping water through tubes), so ~0.1 W is needed. The air cups produce power by drag force times velocity. The drag force is $\frac{1}{2}\rho S C_d V_{wind}^2$ *(ρ=1.225 Kg/m*^{3}*, S is the cup's frontal area).*

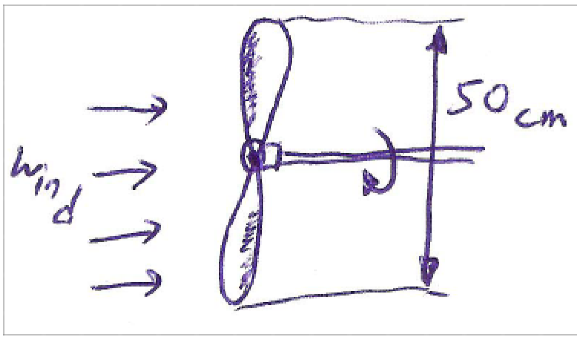


If the wind speed is V=3 m/s and the drag coefficient C_d *is either 1.4 or 0.4 (for cup's opening facing upwind or downwind, respectively), then a cup diameter of 20 cm will yield about 0.5 W. However, efficiency of converting this power to pumping can easily be as low as 20%, resulting in 0.1 W generated.*

Evaluation: If the wind speed is lower than 3 m/s, there won't be enough power even with these large cups. A more efficient way to capture wind energy is needed.

Concept: Capture wind energy with a propeller.

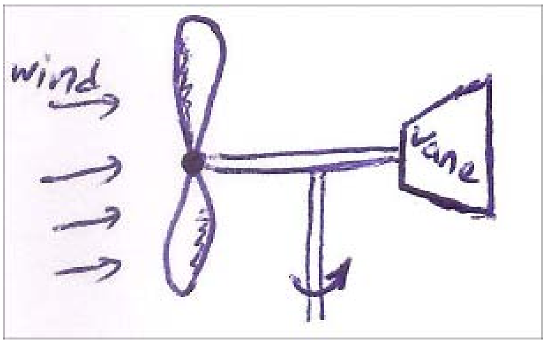
Configuration: Assuming average wind speed of 3 m/s and a 50-cm dia. propeller, the maximum power that can be extracted from the wind is $P = \frac{1}{2}\rho S V^3$*, where* $S = \pi \cdot 0.25^2$*. This yields about 3.2 W. The Betz limit says that the maximum percentage that can be extracted is about 60%, therefore P ≈ 2 W. Another 40% can be assumed lost mechanically, so the estimated power that will be produced is ~1.2 W.*



Evaluation: The power available is about 10 times the required; however, the propeller needs to face the wind at all times to generate this much power.

Concept: Align the propeller with a wind vane.

Configuration:

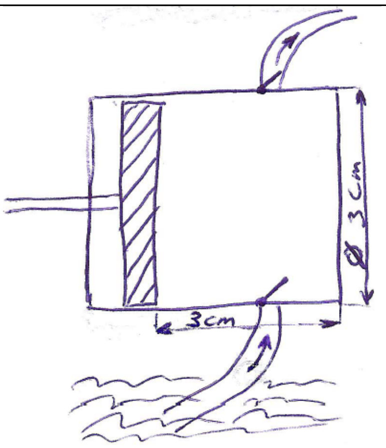


Evaluation: Satisfactory power generation has been obtained. A pump is now needed.

Concept: Use a reciprocating pump to create suction to extract water from the boat, and pressure to eject it.

Figure 7. Hypothetical design rationale for the bilge pump captured with concept-configuration-evaluation triplets (continued on next page)

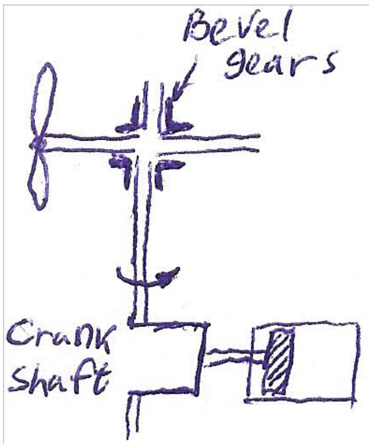
<u>Configuration</u>: The average speed of operation of the propeller in slow winds is about 50 RPM. To achieve the desired removal capacity a small pump of ~21 cm³ is required.



<u>Evaluation</u>: The propeller's rotation needs to be transmitted to the pump and converted to reciprocating motion.

<u>Concept</u>: Use bevel gears and crankshaft.

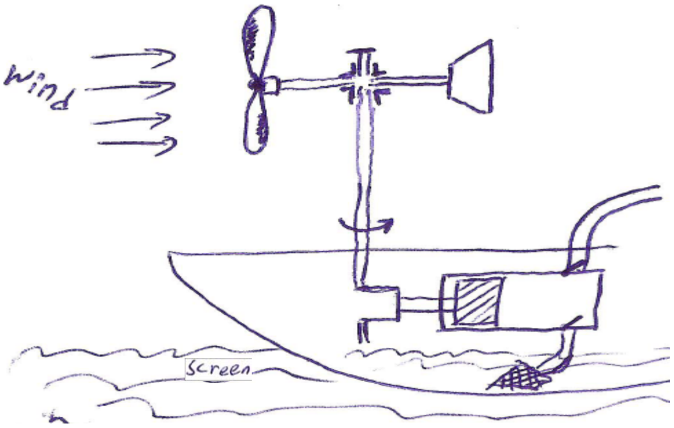
<u>Configuration</u>:



<u>Evaluation</u>: Dirt and debris can enter the pump and clog it.

<u>Concept</u>: Use a screen at the inlet to prevent contaminating the pump.

<u>Configuration</u>:



<u>Evaluation</u>: There seems to be enough power to overcome the pressure drop due to the added resistance of the screen even when partly clogged. The last configuration seems to work and satisfy the requirements.

Figure 7. (Continued)

thought process similar to what we have described in the previous section is assumed to have taken place, and therefore should be captured fully in the format of *concept-configuration-evaluation* triplets. This type of record is relatively easy for the designer to create, and convenient for other people to examine.

6 CONCLUSION

As opposed to efforts in the area of design rationale capture that focused on creating computer-based tools for this task, we investigated the essence of the information that needs to be captured. We used an existing conceptual design methodology, parameter analysis, which follows closely the natural thought process. It allowed us to conclude that a meaningful record can be maintained if the following three types of knowledge are captured explicitly: *(i) concept* – the idea to be realized for some functional reason, *(ii) configuration* – how the last idea is incorporated in the evolving hardware, and *(iii) evaluation* – examination of the current state of the design, assessing whether it will perform as desired and identifying what is still missing. We argue that these triplets can be chained together to form a long sequence for capturing the whole design rationale.

A typical textbook example of the conceptual design of a relatively simple product, a bilge pump, was used to demonstrate the proposed method for rationale capture. It showed how many questions regarding the reasons for certain design decision, discarded ideas, unused alternatives, etc. can be answered easily if the *concept-configuration-evaluation* triplets serve as the record of the design process.

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Contact: Ehud Kroll
Technion–Israel Institute of Technology
Faculty of Aerospace Engineering
Technion City
Haifa 32000
Israel
Phone: +972 4 8293813
Fax: +972 4 8292030
Email: kroll@aerodyne.technion.ac.il
URL: http://ae-www.technion.ac.il/staff/pages/236

Ehud Kroll teaches design and manufacturing in the Faculty of Aerospace Engineering at the Technion in Israel. His research is in the areas of design theory and methodology, with emphasis on conceptual design, systems engineering, life-cycle design, rapid-prototyping and aerospace applications.

Alexander Shihmanter is an M.Sc. student in the Faculty of Aerospace Engineering at the Technion in Israel. His thesis is concerned with capturing conceptual design knowledge and rationale.