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THE WILLIAMS CARP CAGE: ENGINEERING-BASED DESIGN ENHANCES A SCIENCE-BASED INVENTION

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1 Introduction

This paper tells a story. Considered broadly, it is a story about environmental intervention to overcome the negative impact on biodiversity being caused by an introduced fish species. Considered more narrowly, from the standpoint of engineering design, it is the familiar story of how an engineering problem is distilled from an idea and solved via the design process, culminating in a designed solution ready for implementation to address a human need.

In this case, the “idea” initiating the engineering design exercise was well developed: an invention by a team of fisheries scientists (our client) based on observations of fish behaviour, and known as the Williams Carp Separation Cage [1]. Yet the invention was not complete. The basic concept had been tested by a prototype in some field trials, but the prototype lacked a number of capabilities essential to its practical deployment. The invention was essentially a proposal for a specialised device (yet to be designed) having certain specified features, and requiring a number of additional functions to be implemented. The engineering design contribution was made at this point. This paper relates the story of that contribution.

2 Environmental background

2.1 Carp in Australia

The common carp (Cyprinus carpio), often wrongly called the European carp, is a pest species in Australian waterways. It is one of the most common freshwater fish in the world, and is extensively farmed in Europe, Asia and the Middle East. Carp is a very popular angling fish in Europe, but in North America, Canada and Australia, the species is considered a pest [2]. Since its introduction to the Australian environment in the mid 1800s, and more particularly since its illegal importation and release into southern waterways in1961, the carp has come to dominate fish populations within the Murray Darling Basin (MDB), in which recent surveys show it as constituting over 80% of total fish biomass in the entire basin and as much as 96% in some river stretches [3]. Carp are prolific breeders and highly migratory — tough, adaptable and destructive filter feeders blamed variously for silting up water, undermining river banks and destroying the habitat of native plant and water species.

2.2 Fishways

Major waterways often have dam walls constructed across their path to regulate flow and store water for irrigation purposes. The Torrumbarry Weir on the Murray River is one of several such examples of major dam structures in the MDB. "Locks" (large gate systems) can be used to permit the passage of shipping past the dam wall, but these may be opened only occasionally. The dam structure therefore represents a serious obstacle to migratory fish species that need to travel upstream to spawn, or downstream to continue their life cycle. This threat to fish populations has long been recognized.

A fishway can be constructed to allow fish to swim past the dam. One type of fishway is a long water channel (up to several hundred metres in length) connecting to the river on the upstream and downstream sides of the dam. It has a series of restrictor walls built across it, with a narrow slot in each wall to impede the flow of water. Fish species can make their way through these slots in a properly designed fishway, and so continue on their journey up or down the river. The diagram below illustrates the layout of a fishway.

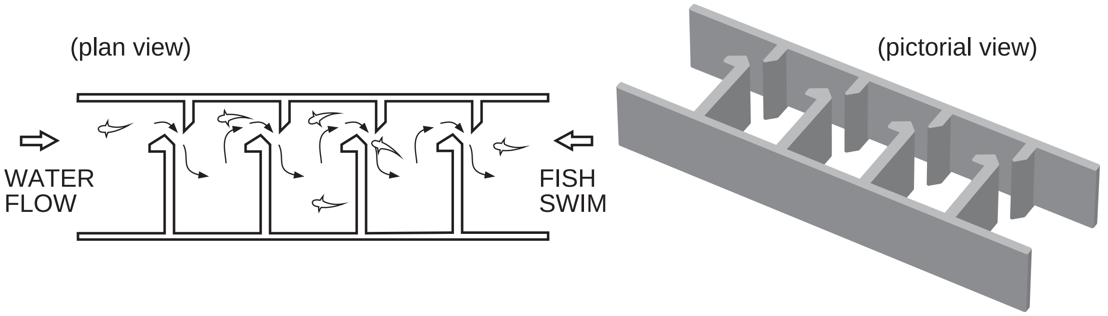

Fig. 1. Layout of a vertical-slot fishway

Unfortunately, a fishway also facilitates movement of non-native fish species, particularly the common carp that are considered to be an introduced pest because they contribute to water turbidity and present a competitive threat to native fish populations. However in terms of its role in the propagation of this pest species, the fishway presents an opportunity. The fishway is effectively a single narrow gateway through which all fish must pass as they traverse the river. It is an ideal location for intercepting pest species.

To date, carp have been removed from fishways through labour intensive trapping, but this method is expensive and places considerable stress on native fish. A better method of trapping and removing carp is required. And since the fishway is a confined channel, artificially constructed and therefore having well-defined layout and dimensions, it also presents an ideal location for the placement of a separation device.

3 Enformulation of the problem

3.1 Initiating idea: the Williams Carp Separation Cage

A novel scientific invention, the Williams Carp Separation Cage, has been recently devised by staff of the Victorian Department of Sustainability and Environment (DSE) to address the need for removing carp selectively from rivers throughout the MDB [4, 5]. The invention has received wide publicity and acclaim [6]. However its successful deployment on a large scale requires that a number of practical and functional problems associated with the operation of the cage be overcome. These are essentially problems in engineering design, and their resolution demonstrates the powerful synergy between science and engineering in tackling environmental concerns on the one hand, and the relevance and contribution of structured engineering design methods on the other.

One aspect of carp behaviour can be used to separate them from native species — carp can jump clear of the water surface, but native fish species cannot. There are many observations of carp jumping within the rivers and lakes of the MDB but few native freshwater fish species are known to display jumping behaviour. Such observations constitute one significant scientific contribution by DSE personnel that led to their invention of the carp cage.

The carp separation cage being developed by the client (DSE) to automatically separate adult carp from native fish, exploits jumping behaviour. The diagram in Figure 2 is the client's conceptual sketch for the carp separation cage located in a fishway.

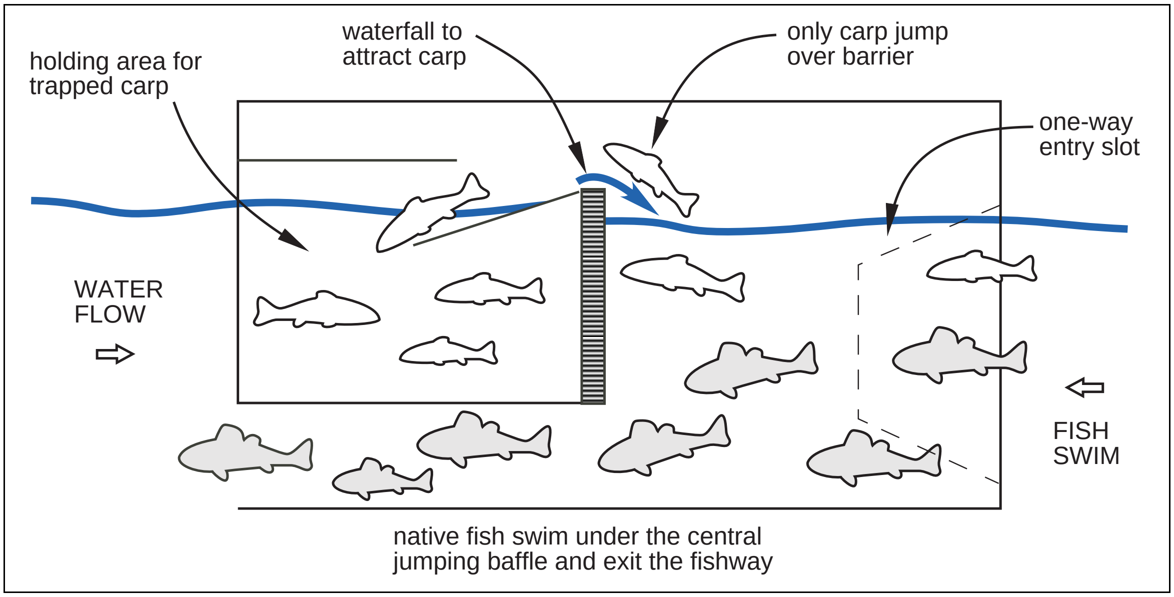

Fig. 2. Early concept diagram of a carp separation cage, suitable for a fishway, to separate adult carp and native fish (adapted from drawing by M. Mallen-Cooper).

It is interesting to compare the above conceptual sketch with the (almost identical) diagram in Figure 3 showing the actual prototype used by the client for field trials.

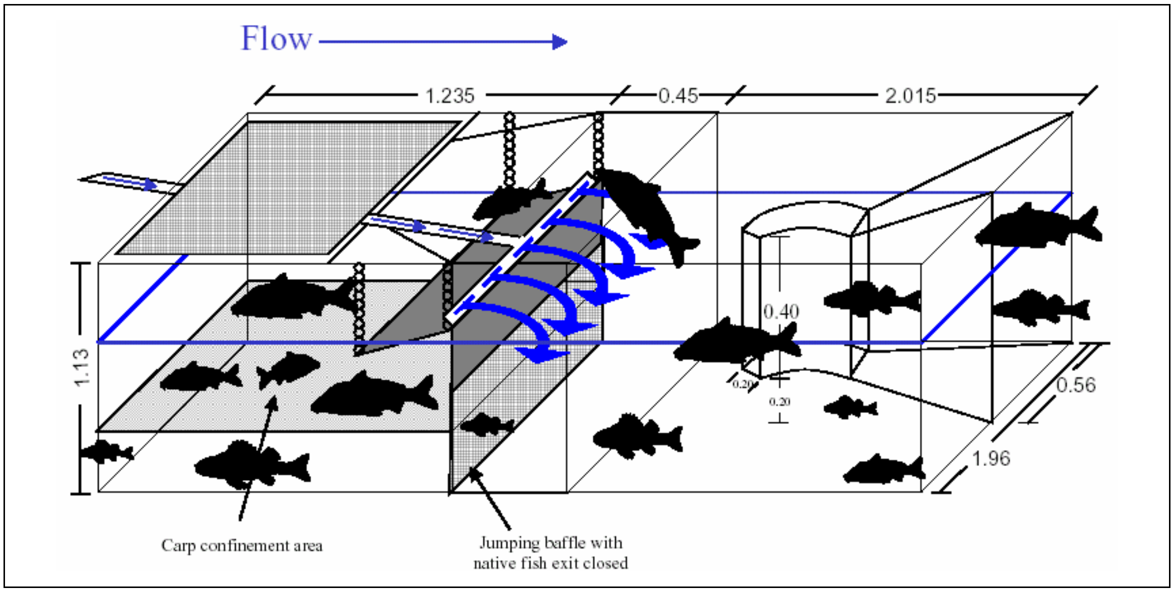

Fig. 3. The current prototype Williams carp separation cage

The client's prototype, a unitary structure constructed of galvanised steel angle sections and mesh, follows the layout of the conceptual sketch very closely. It possesses a vertically sliding exit gate that is opened manually at suitable intervals to permit native fish to continue upstream. It is also built to dimensions suited to fish behaviour, as ascertained by the client.

The overall aim of the client in developing the Williams Carp Separation Cage is to develop a low cost, efficient method of carp extraction that has wide application throughout the MDB. The current "carp cage" invention is known to work effectively in field trials, but has serious practical limitations. Specifically:

- the current prototype is highly labour intensive to operate, requiring frequent human intervention to open access ways to allow native fish to pass through the device. For fully automated operation, the carp separation cage will need to have some internal gates that open and close intermittently, on an adjustable 2-hour cycle.

- Additionally the device must be durable under highly variable seasonal fish-loads, and suitable for operation remote from the electrical power grid.

With the aim of resolving the above limitations, developers of the carp cage at DSE sought the assistance of an engineering design team at the University of Melbourne to bring the proposed product to fruition. The client's conceptual sketch and prototype were starting points for the present engineering design project.

3.2 Elicitation of functional requirements

Beyond the essential elements of the invention, as summarised in the conceptual sketch for a carp separation cage located in a fishway (Figure 2), and some key dimensions thereof (Figure 3), the form of the final product was relatively unconstrained. The detailed functional requirements of the carp cage internal gates were elicited in negotiation between the design team and the client (DSE), using interviews and a site visit to the Torrumbarry Weir to achieve immersion in the problem. These were:

(a) Automatic opening of the native fish exit;

(b) Cage automations to be programmable;

(c) Cage to have its own power source (for installation remote from power grid).

Additional crucial (but initially unstated) functions were uncovered during this enformulation stage, notably the functional requirements of:

(d) Automatic closure of the cage inlet;

(e) Automatic mechanism designed to encourage native fish to leave the cage;

(f) Simultaneous occurrence of actions (d) and (e) with (a) automated opening of the exit.

The provision in the cage of the "fish-herding" mechanism described in (e) above, to gently encourage lazy native fish through the internal gate, turned out to be a key determinant of the design problem. Interestingly, it was not part of the initial client discussions, but arose from further scientific observations gathered during field trials with the prototype cage, which were ongoing during the course of the design project. These observations concluded that native fish would not reliably leave the cage's temporary confinement area within 10 minutes of the exit gate being opened, with sometimes 50% of the native fish remaining in the cage. Such a high proportion of non-departing fish was unacceptable, so the provision of a "fish-herding" mechanism became an important additional design objective for the cage. It is noteworthy that the addition of requirements (d), (e) and (f) after engineering design was begun, made for a much more challenging design task than perhaps first envisaged by the client, and a much more useful outcome from the project overall.

In addition to the above functional requirements, the following required attributes filled out the list of design constraints specified by, or elicited from, the client:

(g) Cage life of at least ten years;

(h) Manufactured cost to be less than A$5,000.

All eight of the design constraints listed above were ultimately achieved in the engineering design process that is outlined in the ensuing sections of this paper.

4 Environmental Design?

This project is proposed under the heading of "Environmental Design", and is regarded by the authors as an example of engineering design for environmental sustainability. And yet it amounts to an exercise (straightforward in some respects) in basic mechanical engineering design, with some structural, electrical and control-system elements. So the question arises, "What constitutes environmentally-conscious design?" We hope we can be forgiven for addressing such a big question in the context of such a small and prosaic case study.

We suggest the elements of environmentally sustainable engineering design are threefold:

1. It is motivated by a concern to achieve environmentally beneficial outcomes, in which any negative environmental impact of the proposal is outweighed by positive benefits to the environment (often a difficult cost-benefit analysis to perform!).

2. It uses concepts pertaining to environmental impact and benefit in the development of design criteria to be used for assessing the effectiveness of the design. This will often require the engineering designer to think quantitatively about measures that are usually assessed only qualitatively.

3. It is prepared to consider the sustainability of a proposal in direct engineering terms. Under such terms, definitions of sustainability are not fluffy or folkloric, but quantifiable and therefore accountable. For example, consider this hard definition of sustainability: "A sustainable action is one for which the system it impacts recovers from that impact faster than the rate at which impact occurs."

5 Problem-solving process

Once the sub-functions required of the carp cage had been defined in an abstract form, function-means trees and morphological analysis [7] were used to lay out a number of possible configurations of the solution. By collapsing multiple sub-functions into common subsystems of the solution wherever possible, a particularly elegant solution was ultimately proposed. The key feature of this solution lay in the concept of tilting the whole of the temporary confinement cage such that the entry is raised above the water surface and the floor is angled, thus achieving objectives (d), (e) and (f) of section 3.2, above, in a single motion.

5.1 Design objectives and criteria

Table 1. Objectives and criteria for automated Carp Separation Cage

Design objective	Design criteria	Units	Rank
Ease of Operation			
1. Autonomous operation	• Start up time • Number of operator interventions • Ease of operation	[secs] [#inputs/time] [training time required]	1
2. Designed to fit current configuration	• Number of alterations to existing cage	[cost of #changes]	3
Resistance to Probable Failure Modes			
3. Structural stresses	• Stress within acceptable material limits, taking into consideration maximum loads	[Safety factor achieved]	1
4. Wear	• Material deterioration occurring during operation	[system life]	2
5. Corrosion	• Material deterioration occurring during cage life	[system life]	1
6. Environmental	• Resistance to atmospheric and aquatic conditions	[Temperature tolerance ◦C] [degree of water-proofing]	1
Reliability & Maintenance			
7. Cleaning & repair	• Downtime expected • Mean time/cost to clean/repair • Ergonomic acceptability	[#inspections/yr] [mins or $A] [subjective]	3
Durable Construction			
8. Life	• Achieves desired lifetime	[yrs]	2
9. Useful life	• Ability to withstand fouling	[yrs]	2
10. Resistance to water damage	• Electrical circuits etc. should be sealed and water tight	[yrs]	1
Size			
11. Efficient energy dissipation	• Dissipation of energy generated by system	[W]	2
12. Size	• Maintain a compact design	[m^3]	3
Safety			
13. Safety	• Adherence to International Standards	[Y/N]	1
Manufacturing Considerations			
14. Ease of production	• Number and complexity of components	(#;-)	2
15. Installation	• Minimize complexity of operation	[time & $A]	2
16. Cost	• Low manufacturing cost	[$A]	2
Operating Considerations			
17. Environmental impact	• Trauma to native fish population • Overall effect on local environment	[#hrs held in confinement] [amount of pollution]	2
18. Cost	• Low operating cost	[$A]	2

In addition to the eight design constraints (a) to (h) listed in section 3.2, the set of design objectives and associated criteria listed in Table 1 were identified by the design project team. In the final column of this table, Rank 1 is highest priority, 3 lowest. In essence this is a scale of the relative importance of the objectives defined above, used in designing the gate system.

5.2 Definition of design system boundary

In defining the boundary of this design problem, it was recognised that the automation task extended only to one region of the Carp Cage. Therefore the system under consideration for design was confined to the "automated cage", being that region of the cage between the inlet cone and the native fish exit as shown in Figure 3.

5.3 Sub-goaling

Conceptual design development was applied to a number of separate sub-systems within the overall system of the automated cage. These components include:

(1) the cage design and its kinematics;
(2) power source selection;
(3) drive system design; and
(4) control system design.

Sub-system (1), the cage design and its kinematics, was further sub-goaled as:

(1.a) a fish entry;
(1.b) a mechanism or process that would allow a native fish exit to open automatically;
(1.c) a fish crowding mechanism to effectively herd native fish through the exit; and
(1.d) a mechanism that would deny the entry of more fish to the cage while the native fish exit was open.

To some extent, each of the above sub-systems could be treated separately during conceptual design (although the final design selection would seek to use synergies between sub-systems).

5.4 Idea generation

Morphological Chart					
Native Fish Exit Gate	Vertical lifting gate	Vertical axis swinging gate	Horizontal axis swinging gate hinged at top	Horizontal axis swinging gate hinged at bottom	Vertical axis "scissor-lift" type action
Crowding Mechanism	Vertical axis swinging gate	Horizontally collapsing cage	Lifting floor	Screening of cage volume	Sweeping of cage volume
Inlet Cone Fish Removal	Lifting cone	Tilting cone	Collapsing cone		
Inlet Closing System	Vertically closing sliding gate	Vertical axis swinging gate	Lifting cage entrance out of water	Rotary Valve	

Table 2. Morphological chart used to record ideas for components of the cage design

Structured combinatorial techniques such as morphological analysis were used frequently throughout the ideation process. An example of such technique is given in Table 2, above.

Sketching and 3D visualisation were used to explore and develop a range of ideas for each sub-system, particularly in the case of the cage design, as this problem is highly spatial. Some of the concepts considered are indicated below in Figures 4, 5 and 6.

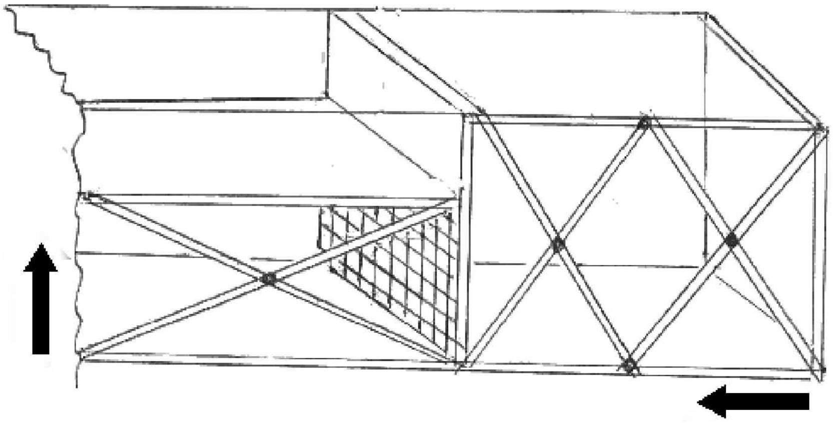

Fig. 4. The "collapsible cage" design

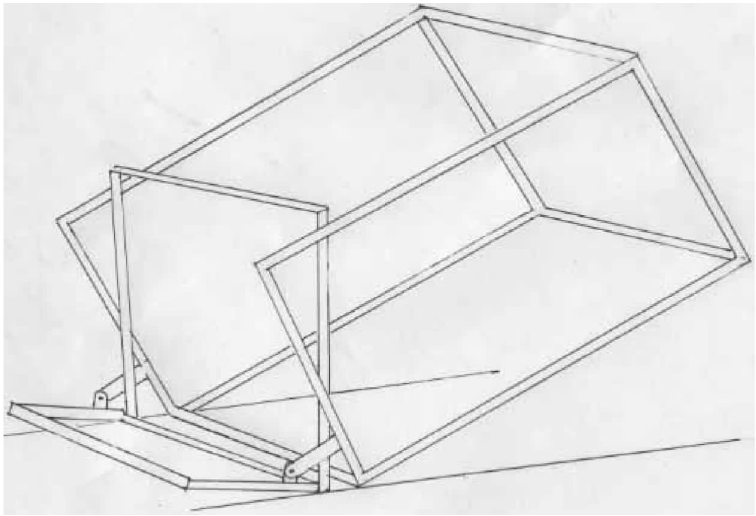

Fig. 5. The "lifting cage" design

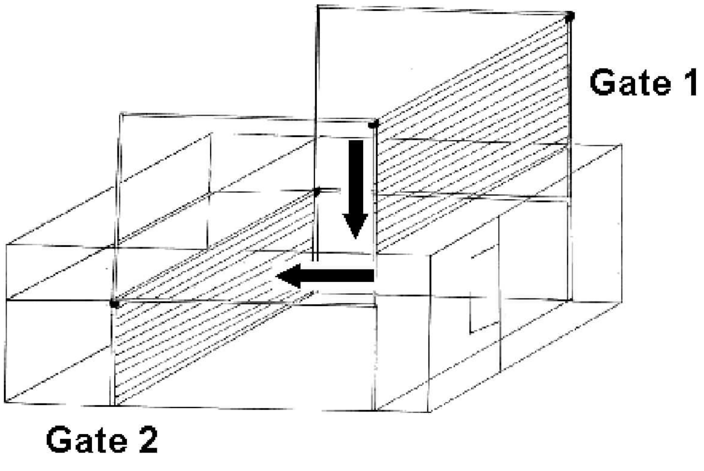

Fig. 6. The "revolving gates cage" design

It was recognised that with the "Lifting floor cage" idea there was potential for fish injury/death during the lowering of the floor. Hence, there was a need to develop a way of preventing fish from entering this area. Some initial ideas for this "guarding mechanism" are presented in Figures 7(a)–(d), below.

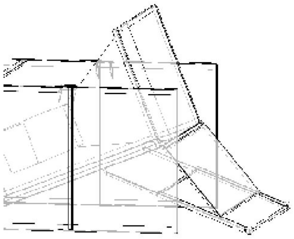

Fig. 7(a) Sliding screens

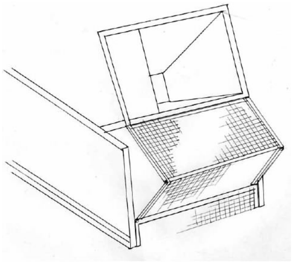

Fig. 7(b) Collapsible screens

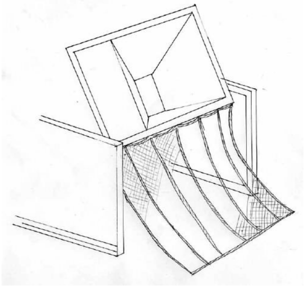

Fig. 7(c) Trailing net

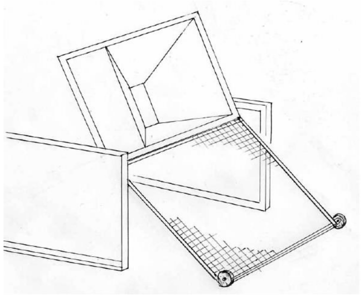

Fig. 7(d) Trailing screens

5.5 Evaluation against criteria

For each sub-system listed in section 5.3, a number of ideas were generated, and usually around two or three of these were identified as being sufficiently feasible to warrant further consideration. These ideas were evaluated according to the relevant requirements (objectives and criteria) nominated from those summarised in Table 1. For example, ideas for the guarding mechanism in Figures 7(a)–(d) were evaluated according to the following requirements:

- risk of fish injury/death;
- mechanism length (limited by the length of straight channel section);
- complexity;
- ability to perform task reliably (i.e. withstand sediment build-up and fouling resulting from underwater service);
- weight; and
- likelihood of mechanism encouraging fish to reverse direction and swim back downstream.

Promising ideas for the various sub-systems were frequently evaluated using decision matrices. Where these involved the numerical scoring of competing alternatives, weighting factors were employed reflecting the relative importance of criteria based on Table 1.

5.6 Formal design tools

In order to manage the heavy mental load on the design team, formal design tools were employed widely during each of the enformulation, ideation, and evaluation phases of the design process. Some of these have already been mentioned. The list includes:

- Tabular arrangement of design objectives, criteria and constraints;
- Function/Means trees;
- Morphological analysis;
- Input/Output analysis;
- Decision tables;
- Causal network analysis (for considering overall system reliability); and
- Failure modes and effects analysis (particularly in drive system design).

6 Summary of solution

Ultimately a cage design was selected, based on the “lifting floor” concept of Figure 5, and the “sliding screen” arrangement of Figure 7(a). The device is controlled by PLC, driven by a geared electric motor and chain winch, and powered by solar photovoltaics, all using standard, modular subsystems. A key feature is that simultaneous exit gate opening and entry closure (*via* the lifting floor) are obtained kinematically using a four-bar linkage, with fish herding inherent to the lifting-floor design. All specified design objectives were achieved, and within budget. The general form of the device is illustrated in Figures 8 to 11, below.

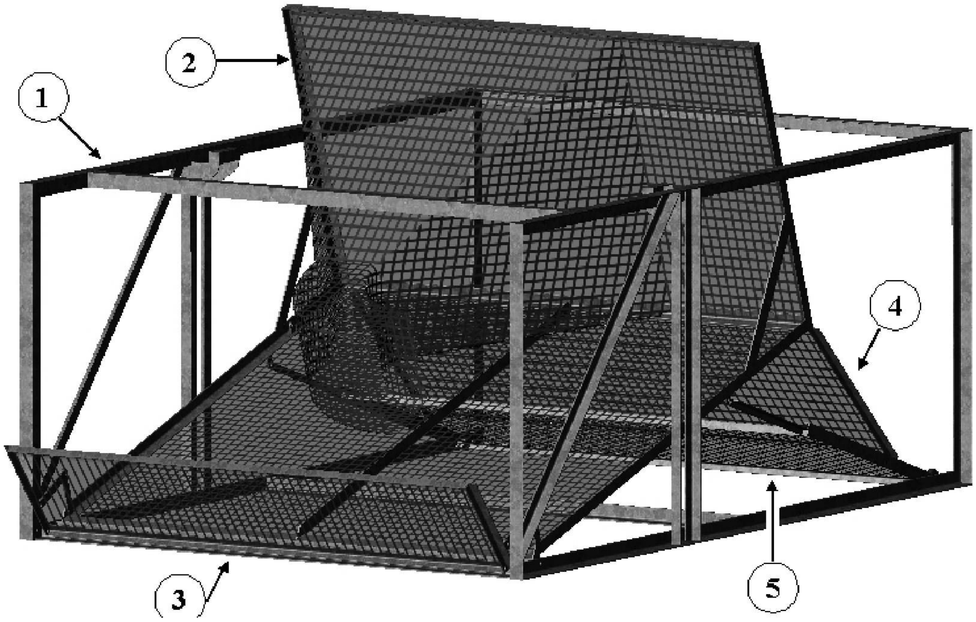

Fig. 8. Downstream 3D view of cage

In Figure 8 (above) and Figures 9 and 10 (below), item (1) is the frame; item (2) is the inlet cone and floor sub-assembly; item (3) is the native fish exit, item (4) is the upper guarding screen; and item (5) is the lower guarding screen.

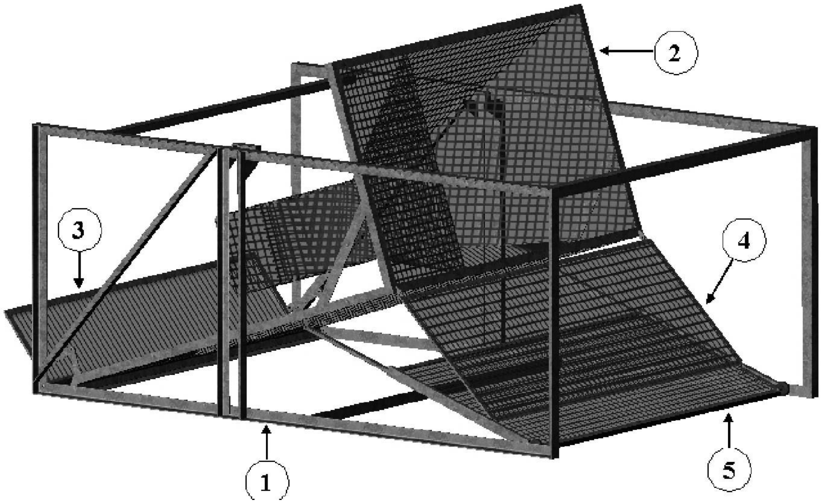

Fig. 9. Upstream 3D view of cage

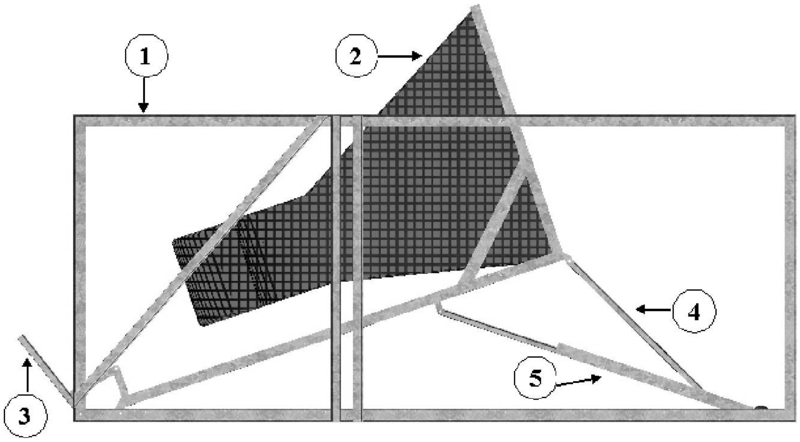

Fig. 10. Side view of cage (upstream to downstream = right to left)

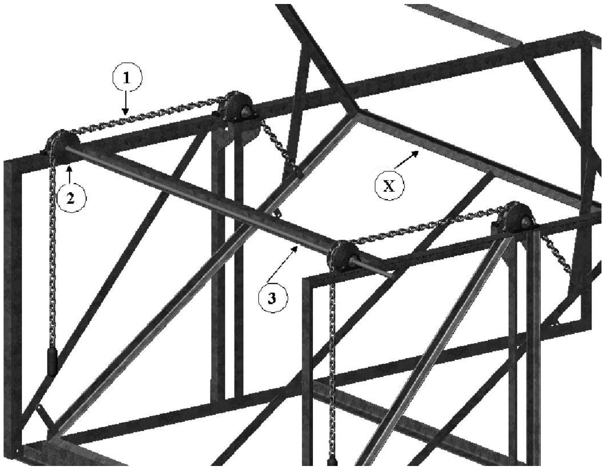

Fig. 11. Drive system attached to cage

In Figure 11. item (1) is the lifting chain; item (2) is the chain wheel; item (3) is the drive shaft; and item (X) is the frame of the cage floor assembly. The small four-bar chain used to connect the lifting floor and exit gate can just be seen in the lower left corner of Figs (9)-(11).

7 Conclusion

The final, engineered solution was surprisingly different to that envisaged by the inventors, more comprehensive in function, and yet more elegant in form.

Using this case study, we have illustrated the indispensable role that engineering design plays in the practical realization of scientific inventions — particularly through the application of formal engineering design methodologies [7, 8]. The paper also reports on the contribution of engineering design in addressing an important environmental concern.

Acknowledgments

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