CO-EVOLUTION IN DESIGN

A Case Study of the Sydney Opera House

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Abstract. A design process is traditionally viewed as a sequential process model from the formulation of the problem to the synthesis of solutions. Simon (1981) regards design as a state-space search where a problem leads to the solution. To be more practical, there are many versions of solution generated during design, where each current one is an improvement over the previous one. This kind of synthesis of solutions can be viewed as an evolutionary system over time. We propose to apply the metaphor of "exploration" to design, and further argue that evolution occurs in the problem space as well as in the solution space. Co-evolutionary design is introduced to remove the assumption of having a fixed goal (problem). The problem is allowed to change over time. Two algorithms for co-evolution are presented. Their characteristics and differences are highlighted. The paper moves on to review the design history of the Sydney Opera House and to show how observations from this *real life* example confirm our co-evolutionary model.

1. Introduction

A common computational view of design considers it as a sequential process model from the formulation of the problem to the synthesis of solutions. This perspective is often modelled as a state-space search where a problem leads to the solution. The major criticism of this model is an assumption that a problem is defined once-and-for-all.

We propose design as an exploration of both the problem space and design solution space. Exploration has been defined verbally as "a problem is never final", "new dimensions are created during the process" and "the design focus always changes". The focus of a problem-design exploration model (PDEM) for design is to address the changing nature of problem and solution, and their mutual influences. The PDEM is also viewed as the evolution of two spaces, which we call co-evolution in design.

The co-evolution model of design can be implemented using a modified simple genetic algorithm (SGA) (Goldberg, 1987). The SGA is a computational paradigm which is modelled after neo-Darwinism. In neo-Darwinism, nature selects the fittest individuals that can adapt well to their environments. The favourable traits are passed to the next generation through their genetic materials. However, the SGA does not support co-evolution and modifications are required. Two approaches are proposed in Section 3: a tightly-coupled co-evolution using a combined gene approach and a loosely-coupled co-evolution using 2-interacting populations approach.

The Sydney Opera House is chosen as a case study for co-evolution in design in Section 4. We present a selection of the history of its design and development. Since there are many unique features with this building, we only concentrate on a few issues. After a brief outline of its history, the design process is further analysed and observations are highlighted. The observations confirm our proposed co-evolutionary model of design.

2. Problem-Design Exploration Model

The view of design as state-space search has dominated the research direction of the AI-in-Design community for some time. This is an attractive assumption because what is once a complex human activity is reduced to a relatively manageable computing task. However, this simplified view faces many challenges (Corne and Smithers and Ross, 1994; Gero, 1994; Maher and Poon, 1996b). The central tenet behind the opposing views is that design should be considered as an iterative process where there is interplay between problem reformulation and solution generation.

The search space for design is usually ill-defined and accompanied by ill-defined goals. Hence, part of a design process is to *search* for the definition of the problem. Exploration has been defined verbally as "problem is never final" (Logan and Smithers, 1993), "new dimensions are created during the process" (Gero, 1994) and "the design focus always changes" (Maher and Poon, 1996b). To follow up these definitions of exploration, a formal model is shown where the Problem-space (or Behaviour-space) is represented by ***P***, and the Design-space (or the Structure-space) is represented by ***S***. Exploration is defined as a phenomenon in design where ***P*** interacts and evolves with ***S*** at the same time (Maher and Poon, 1996b). This model, Problem-Design Exploration Model (PDEM), is graphically illustrated in Figure 1. The diagram highlights the co-evolution of the Problem-space with the Design-space over time and has the following characteristics:

1. There are two distinct search spaces:
   - Problem-space or Behaviour-space (***P***) and
   - Design-space or Structure-space (***S***)
2. These state spaces interact over a time spectrum.
3. Horizontal movement is an evolutionary process such that
   - Problem-space P(t) evolves to P(t+1), which will evolve to P(t+2) and so on in the Problem-space Dimension.
   - Design-space S(t) evolves to S(t+1), which will evolve to S(t+2) and so on in the Design-space Dimension.
4. Diagonal movement is a search process where goals lead to solutions. This can be the
   - Downward arrow: *"Problem leads to Solution"* or *synthesis*. The Problem-space P(t) is the design goal (the required behaviour) at time *t* and S(t) is the Design-space which defines the current search space for design solutions.
   - Upward arrow: *"Solution refocusses the Problem"* or *reformulation*. The Design-space S(t) becomes the goal and becomes the fitness for evaluating individuals in the Problem-space at time *t*+1.

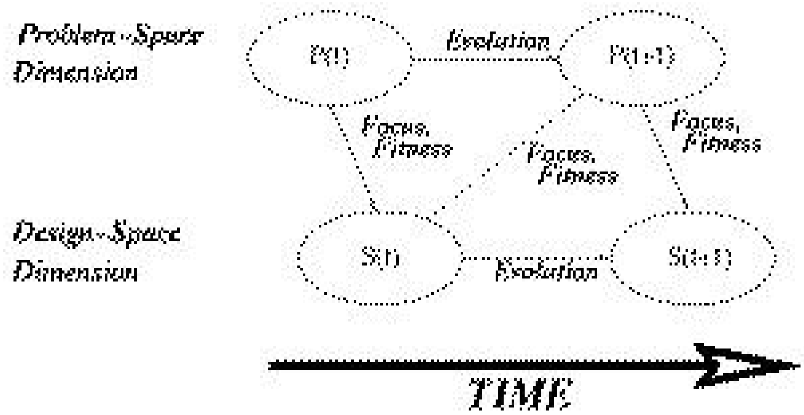

Figure 1. Co-evolution of problem-space and Design-space

The evolutionary characteristic in design exploration finds its roots in Darwinism. The Darwinian theory is about the evolution of nature and this theory offers a mechanism to explain how a species comes into existence. The theory does not predict what new species will emerge. Likewise, the PDEM follows its counterpart in nature which only provides a framework to ***explain*** the phenomenon in design. The model cannot predict what design product will emerge when initial requirements[1] are given. However, PDEM

[1]In this paper, requirements and problem are used interchangeably.

can lead us into a world of possibilities and to explore what kind of design can be generated.

3. Co-evolutionary Algorithms

When computational implementation is considered for the Problem-Design Exploration Model, the Simple Genetic Algorithm (SGA) is an appropriate candidate to implement the co-evolutionary characteristics of the Problem-space and Design-space. The SGA is an adaptive search algorithm where the performances of individuals in a population are evaluated by a fitness function. If an individual has a high fitness score, this individual has a better chance to be selected as parent in the next generation. Genetic information of an offspring in the next generation is modified by means of crossover or mutation.

There are two approaches to representing co-evolution. The two approaches share the common characteristics that they have the advantage to modify and adjust the, once assumed, fixed evaluation criteria. The emphasis of interaction between solution and requirements of these two approaches does not only help to identify complex interaction between structure variables, but also the less attended behaviour variables. Highlights of the two approaches are as follows:

- **CoGA1**: A single composite genotype is formed by the combination of an expected behaviour and a design solution (Maher and Poon, 1996a). Since the fitness function is defined locally for each design solution, the measurement of a phenotype represents a local fitness value. This approach can be viewed as a tightly-coupled, or a host-parasite, co-evolution where each parasite tries to adapt to a specific host.
- **CoGA2**: Two spaces are modelled as two sets of genotypes and phenotypes: one for modelling expected behaviour and one for modelling design solutions (Maher and Poon, 1996b). Hence, fitness of individuals in the population of the problem requirements and population of design solutions is evaluated alternatively, i.e. one generation will have behaviours being evaluated and the other generation will have the structures evaluated. The current best individual from a population serves as the fitness measurement for individuals in another population in the next generation. This approach can be viewed as a loosely-coupled, or a prey-predator, co-evolution where the prey has to adapt to a variety of predators.

4. Case Study: Sydney Opera House

Having gone through the formal and technical description of the co-evolutionary model, we turn to examine a case study to verify our model. This section traces the history of the design of Sydney Opera House. The design of the opera house is then modelled and explained with observations using PDEM.

Sydney Opera House is a landmark of the city of Sydney. Its unique sail-like architecture does not only attract serious architects, it is also eye-catching to curious tourists. This is the only architectural form in the 20th century that is classified as world heritage. However, when considering its design process, this privilege does not differentiate it from its humble neighbouring buildings.

The story started in 1946 when the Sydney Symphony Orchestra had a new conductor, Sir Eugene Goossens. Soon after his arrival in July 1947, he called for the provision of '*a fine concert hall for the orchestra with perfect acoustics and seating for 3,500 people, a home for an opera company, and a smaller hall for chamber music*' (Drew, 1995). In the following year, he insisted on a dual-purpose auditorium which could accommodate 3,500 - 4,000 people.

It was not until May 1955 that the then Premier of New South Wales made the final decision to go ahead with the idea. A committee was set up and recommended Bennelong Point as the site. Two halls were proposed with seating 3,000-3,500 and 1,200 people. The requirements were listed in a 25-page booklet when an international competition was held in 1956. The nominated completion date of the selected design was expected to be on the Australia Day in 1963.

The result was announced on January 29, 1957. The winner was a Danish architect called Jorn Utzon. His submission was a simple line drawing (shown redrawn in Figure 2) when compared with other competitors. The diagram was nowhere near a working drawing and was very much in its conceptual stage. This winning design consisted of two halls with capacities of 2,800 and 1,200, an experimental theatre with a seating of 400 and a chamber music room for 300 people.

The revolutionary design of Utzon had many problems that were unique and the solutions had to be generated from scratch. Two of these problems are discussed in this case study. The first one was particular to Utzon's design and another one was implicit in the requirements.

The first problem was the roof. Though the sail-like roof was eye-catching, the shapes were not defined by regular geometry and the engineers had great difficulty in defining precisely the 'free-form' shapes, which led to problems in calculating the loads the shells would have to carry.

The engineer, Ove Arup, and Utzon worked side-by-side for six years to solve the roof problem. Many schemes were proposed and tried. The breakthrough came in 1961 when Utzon proposed the spherical geometry solution. Utzon realised that the surface of the *regular form of a sphere* could be sliced to give the necessary pieces for the shells. The uniformity over a curved surface not only gave the shells well-defined shapes, but also a simple and economic process of prefabrication. This final solution for the shells, however, had an obviously different shape from the original roof design in 1957 (Figure 2).

Another problem was an implicit problem in the requirements: the dual-purpose usage of the auditorium, i.e. the hall used for both concert and opera performance. This requirement was due to the then prevailing rationalist view of economy and greater efficiency. However, the duality posed a dilemma in acoustic standard and seating arrangement.

The quality of musical sound is measured by the length of time it takes to fade away, called reverberation time (r.t. for short). Two seconds (r.t. 2.0) is considered pleasing for orchestral instruments and one point four seconds (r.t. 1.4) is ideal for opera. Hence, to achieve the two ideal standards in a single hall is in direct conflict and this posed a difficult problem for engineers and architects.

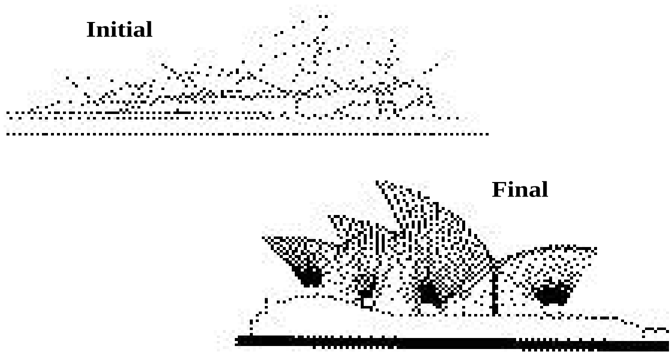

Figure 2. Initial and final Sydney Opera House (Sykes, 1993)

At the same time, Utzon had to fit *enough* seats for concerts and *well placed* seats for opera. The audience has different expectations for these two types of performance: seeing the orchestra is not as important as hearing it for a concert, while seeing and hearing are both important to an opera. The dual-purpose hall posed serious technical difficulties and the design was a formidable technical task.

It was in 1966 that the General Manager of the ABC (Australian Broadcasting Commission) pushed for a hall with seating capacity of not less than 2,800 and to have a reverberation time of 2.0 seconds. The current architect finally recommended to have the major hall for concert performance only, and the opera would only be performed in the minor hall. After removing the requirement for a multi-purpose hall, engineers and architects could concentrate on designing acoustics and seating capacity that were specific for the two functions.

Although there were many hiccups in the construction of the Sydney Opera House, the building was officially opened on October 20, 1973 by Queen Elizabeth II. Figure 3 is a simple diagram to highlight the design of this controversial building.

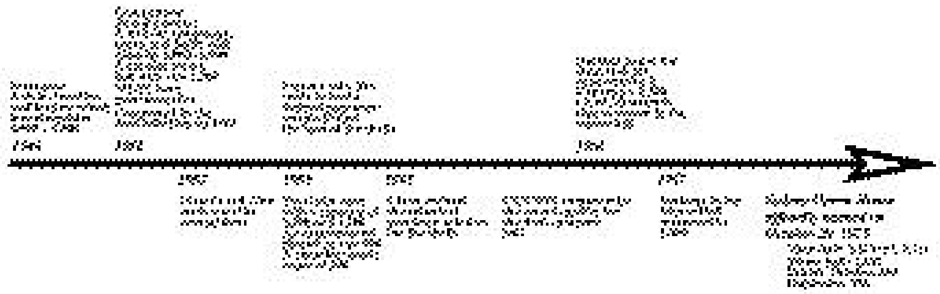

Figure 3. A timeline of the design of the Sydney Opera House

4.1COMPUTATIONAL MODEL FOR THE CO-EVOLUTIONARY DESIGN OF SYDNEY OPERA HOUSE

In this section, we discuss the design of the Sydney Opera House using our Problem-Design Exploration Model. The PDEM is used to re-organise the problem elements and the design solutions in Figure 3 to give a co-evolutionary view of the design process (Figure 4). New items or changed items in each state are highlighted in italics, while unchanged items brought forward from previous generation are printed in regular font. The following conclusions explain the previous observations.

- ***Final Solution***. The current Sydney Opera House does not meet all of the initial requirements (R_{init}). For example, the initial requirements include a dual-purpose hall with seating capacity of 3,000 to 3,500. However, the Opera House had two single-purpose halls, with the larger one with a capacity of 2,679 people, which is roughly 11% less than the expected minimum capacity (or almost 24% off the maximum desired capacity). In fact, the final design satisfies more requirements in the last reformulated problem than the initial requirements. However, the design does not deviate from R_{init} completely, we still have halls that are built for opera and concert performance. The final design is a response to R_{init} and intermediate requirements.

- ***Changing Requirements***. The evolution of problem in Figure 4 shows that the different problems across time in the PDEM is a result of the intermediate solutions. Let the notation $P_{t=0}$ and $D_{t=0}$ represent the problem and design solution at t=0. $P_{t=1}$ is different from $P_{t=0}$ by having a new item: *"define loading of roof"*. This is due to the intermediate design solution, $D_{t=0}$, which is the winning entry submitted by Utzon. $P_{t=0}$ does not carry the problem of roof loading calculation until the recognition of the unique shape in the submission. The major difference between $P_{t=1}$ and $P_{t=2}$ is the change of the dual-purpose hall to single-purpose hall. This outcome is largely the effect of the unsatisfactory intermediate design solutions ($D_{t=1}$) which do not achieve the required r.t. Hence, the formulation of $P_{t=2}$ is a result of $D_{t=1}$.

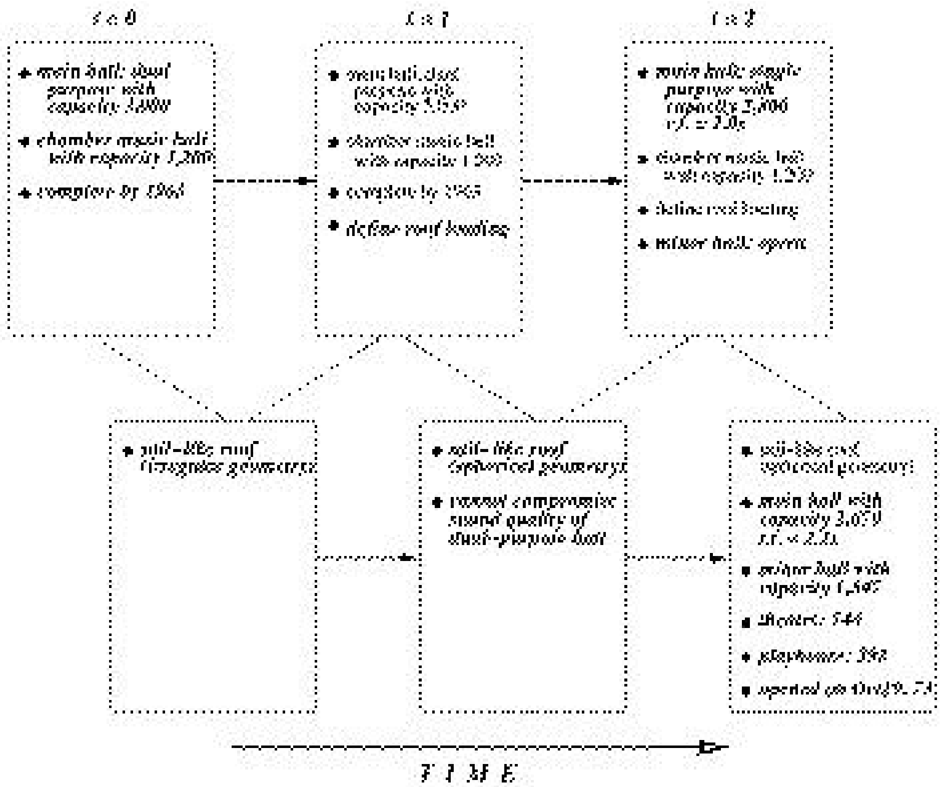

Figure 4. A PDEM view on the design of Sydney Opera House

- ***Changing Solution***. Although we have a solution $D_{t=0}$ for $P_{t=0}$, this winning design does not complete the process. $D_{t=0}$ has met some of the initial requirements but this intermediate design introduces new problems. The Sydney Opera House at t=1 is similar to the previous design except the roof has a more regular geometry than $D_{t=0}$. The roof has changed shape because of the identification of a spherical geometry solution by Utzon. $D_{t=1}$ is an improvement over $D_{t=0}$ but the sound quality in the dual-purpose hall is not yet resolved. The solution at t=2 differs from its predecessors in having a hall for concert and another hall for opera. This change in design reflects the latest change in requirements. As a result, design solutions are observed to evolve over time.

- ***Mutual Influence of Problem and Solution***. When Utzon won the competition, the winning design raised an additional problem - the definition and construction of the shells. This problem is not in the booklet of requirements; this is generated because of Utzon's design (the solution for the competition's requirements). This new problem, the search for a precise shape for the shells, demanded an intensive effort for the team to resolve. In addition to the design of the shells, the technical difficulty in designing a dual-purpose hall eventually shares part of the reason to abandon this criterion. The discussions of "changing requirements" and "changing solutions" highlight the interactivity between Problem-space and Design-space. According to PDEM, the identification of new requirements (P_t) or an intermediate solution (D_t) are the joint effort of R_{init} (the building of halls for concert or opera performance) and the previous solution (D_{t-1}) or requirements (P_t).

The final Sydney Opera House does not satisfy the initial requirements, not to mention all the requirements. The case study also shows clearly that the requirements change in response to the solution. There are many intermediate requirements and solutions before the final artefact is developed. The importance of these observations is that: the Sydney Opera House is not an isolated case, they are common phenomena in design. It has been stated earlier that the co-evolutionary model cannot predict the final design at the end of the process, however, the model can explain the co-evolutionary characteristics of a *real* project.

5. Conclusion

Design as a sequential process from requirements to solution is insufficient. The final artefact from a design process is a result of the numerous interactions between intermediate problems and interim solutions. This forms the main tenet in our Problem-Design Exploration Model. To take an alternative view to this model, we find that the Problem-space and Design-space co-evolve at the same time. This co-evolutionary model can be implemented in two computational approaches: combined gene approach

(CoGA1) and 2-interacting populations approach (CoGA2). Our experience has shown that they are not only two different algorithms which display co-evolution, they have different characteristics and model different types of co-evolution. CoGA1 models host-parasite co-evolution which is appropriate for multi-criteria optimisation type of problem. On the other hand, CoGA2 models prey-predator co-evolution. If the problem is akin to pattern matching and the search for design variables is necessary, this algorithm is a better candidate. The design of Sydney Opera House is discussed using our PDEM. The model explains why the current Sydney Opera House does not meet the initial requirements, and highlights the co-evolutionary characteristics in the design process, and the interaction between the Problem-space and Design-space.

Acknowledgments

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