Using AI Based Generative Design Systems to Trade Off Weight, Waste and Complex Performance Criteria

Prof. M Price, Dr I Friel, Dr A Colligan, Mr J Francis, Prof T Robinson,
School of Mechanical and Aerospace Engineering, Queen's University Belfast, UK;

Prof AM Tyrrell, Dr S Hickinbotham, Dr E Buchannan
School of Physics, Engineering and Technology, University of York, UK.

Abstract

Following an artificial evolution paradigm the Re-Imagining Engineering Design (RIED) Programme is developing new design methods and systems to enable superfast design of complex engineering problems. The solution engine called the "RIED Engine" provides concept solutions which can account for manufacturing constraints as well as complex performance constraints such as buckling. The ethos in RIED is to develop key responses to a given state of stress or temperature, for example, and then evolve large populations of these over many generations. The responses are stored as a neural network which is an analogy for gene regulation in nature. The neural network effectively contains the instructions to generate the final shape and form of the design. An engineering tool chain can then be used to generate simulation or manufacturing models as needed for evaluation or can even in some circumstances provide a detailed model-based definition for manufacture.

1. Background

The production of sustainable products and processes, especially the larger, energy hungry engineered systems in transport and infrastructure, is becoming increasingly complex. These systems no longer operate in isolation and the trade-offs needed are ever more inter-twined. Existing design systems can no longer cope with these many faceted problems, resulting in restricted design spaces that reduce any opportunity for the innovation needed. In contrast, natural systems deal with such complex trade-offs by shifting their focus to responding locally to inputs and essentially evolving that local response over long time periods. The result is that organisms adjust their shape and size to account for the local conditions they encounter in the natural environment. Successful species are those groups that can best respond and adapt to the environment, and these are not necessarily the best in the sense of any given attribute, like speed or height, at any given time. It is fundamentally about change and rate of change. In contrast, the engineering design process typically develops solutions and choses the absolute best in a given scenario with rates of change used as guides rather than being the focus of the design decision. The potential of processes which mimic the evolution of natural systems has long been recognised in engineering design as exemplified by genetic algorithms which have been much used in design optimisation. However, these algorithms still focus on finding an optimal (or best) solution within current design system frameworks by overly restricting the design space.

Building on a series of initiatives in engineering design three UK institutions (Queen's Belfast, York and Loughborough) teamed up to form the Re-Imagining Engineering Design (RIED) Programme[1]. With funding from the Engineering and Physical Sciences Research Council (EPSRC) and support from ten industrial partners RIED has been exploring alternative bio-inspired design systems and in particular novel approaches to artificial evolution more reflective of the neo-Darwinian synthesis than existing genetic algorithms. The result is the innovative generative design system outlined here.

2. Generative Design & C-K Theory

Recently there has been much interest in generative design systems to help find design concepts rapidly and to generate geometric representations of these to support concept selection and preparation for more detailed design. A number of commercial tools are now available and are proving useful in generating innovative design solutions in particular driven by topology optimisation. Such systems, while powerful, remain limited with significant post processing required and the formalisation of solutions via more conventional design processes is still needed to bring concepts through to manufacture.

C-K Design theory is a concept of reasoning in design[2] which offers an opportunity to place modern digital design tools and capability in a context akin to Darwinian evolution. In C-K theory existing knowledge is used to explore new concepts and as understanding is generated from this concept exploration it generates new knowledge which can in turn be used for further exploration. As a process it behaves remarkably like Darwinian evolution, where each individual concept is analogous to an individual in a population, and new concepts akin to the new generation of a population.

3. Artificial Evolution

To create a design framework and process within this concept that matches closely to Darwinian evolution, the corresponding artificial evolution[3,4] process needs to be built around how the design concept changes and responds to its operational conditions. The genes in this system must now control the change, or rate of change, rather than the value of a design parameter. The consideration of change and response is powerful because it opens the opportunity to add design variables or new features (e.g. a flange) or introduce a topological change (e.g. a hole), all of which can expand the design space.

In the case of such changes a generative process is required to generate the actual parameter value or design feature from which the state of stress, temperature etc can be calculated. This in turn requires that the overall process needs a growth stage, where an individual solution grows (or develops) just as a young organism would in nature[5]. This developmental stage offers significant opportunity for diversity in the population of solutions with every individual having different rates of response across all design parameters.

4. Application of AI Technology

The consequence of this diversity in the shape and form of solutions brings out the issue that design parameters have both direct and indirect consequences on the state of the system. Changes in one parameter affect many measured behaviours. In recognition that this mapping between design parameters and state (i.e. performance parameters) is many to many, it points towards a graph network as being a good representation of the system.

The complexity of the mapping represented by the network is a natural fit for using machine learning algorithms to generate networks that can learn good responses to the given inputs. In this case the inputs to the network are the current state of stress, temperature etc and the outputs are the changes in design parameters such as thickness, modulus of elasticity etc. Moreover, because it is a network it easily accommodates other metrics, such as manufacturing parameters, which allows the network to learn how to change to accommodate say certain lengths of bars, or depth of cut. Complex trade-offs thus naturally emerge through individuals in the population of solutions. **Figure 1** illustrates a sample of the type of solutions emerging in the case of a simple beam design. The minimum weight solution is shown and then some individuals form the population with different weight and waste measurements.

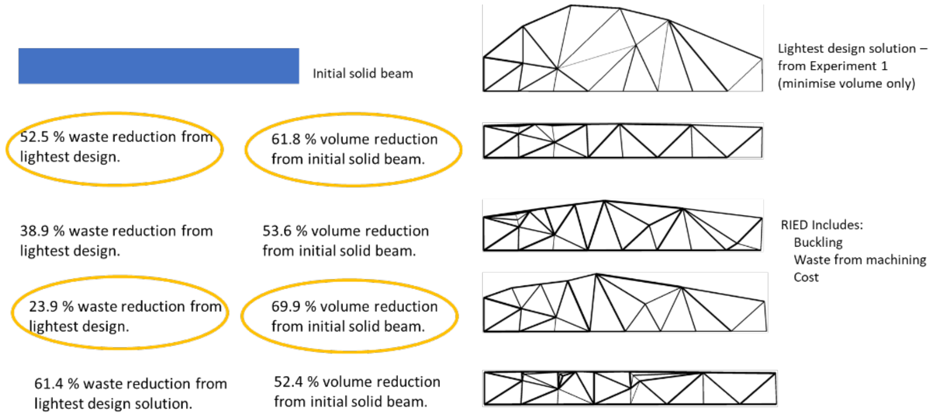

Figure 1: The original, baseline, beam is shown top left with the lightest solution from the RIED Engine top right. The remainder are samples from the population with different weight and waste measurements. All viable solutions are non-buckling.

5. Example - Wing Rib

The wing rib shown in **Figure 2** shows an idealised scenario with the rib represented as being in simple shear. The rib is intended to be machined from plate such that the final structure is a machined framework. With many framework members being slender and loaded in compression it is necessary to include buckling performance in the design space, as well as considering the weight of the rib and the waste from the manufacturing process. The minimum weight design is less than 20% of the original rib plate but this wastes a lot of material in the machining process. However, the evolutionary system produces a range of designs in the solution space with weight reductions as much as 60% but with less than half the waste of the lightest design.

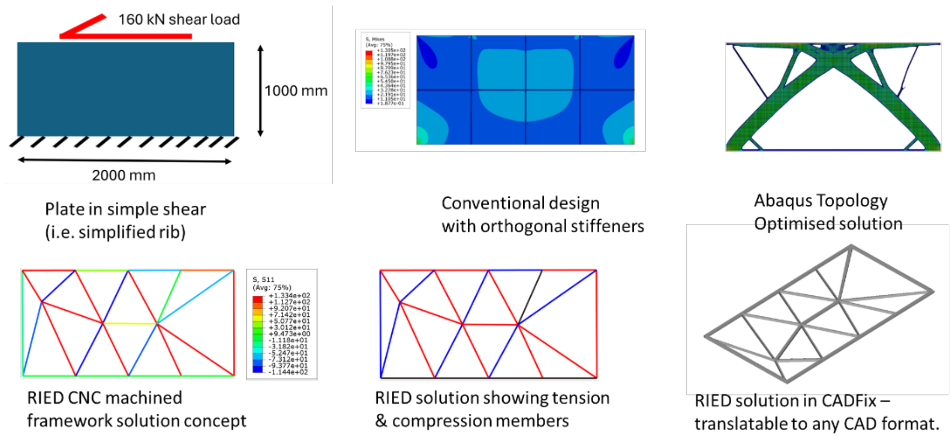

Figure 2: Design of an idealised wing rib under a simple shear load. The RIED solution along the bottom row of images can be contrasted with the topology optimised solution (not accounting for buckling) in the top right corner.

6. References

1. Price et al, The RIED Programme, https://riedesign.org/ , 2025
2. Hatchuel A. and Weil B., C-K design theory: An advanced formulation, Research in Engineering Design, 19(4):181–192, 2009
3. S Hickinbotham, R Dubey, I Friel, A Colligan, M Price, A Tyrrell "Evolving design modifiers", IEEE Symposium Series on Computational Intelligence (SSCI), 1052-1058, 2022
4. S Hickinbotham, R Dubey, E Buchanan, I Friel, A Colligan, M Price, "Theory of Evolutionary Systems Engineering", IEEE Symposium Series on Computational Intelligence (SSCI), 1084-1089, 2023
5. Price, M; Zhang, W; Friel, I; Robinson T, McConnell R, Nolan D, Kilpatrick P, Barbhuiya S, Kyle S. "Generative design for additive manufacturing using a biological development analogy." Journal of Computational Design and Engineering, Vol. 9, No. 2, 01.04.2022, p. 463–479, 2022