Institution: University of Surrey		
Unit of Assessment: 11 Computer Science and Informatics		
Title of case study: Solving complex vehicle design problems using many-objective optimisation		
Period when the underpinning research was undertaken: 2010-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Yaochu Jin	Professor in Computational Intelligence, Distinguished Chair	June 2010 – present
Period when the claimed impact occurred: 2014-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

In modern engineering, design problems often need to balance multiple, often conflicting, considerations. By creating and making widely available a Platform for evolutionary multi-objective optimisation, complex design problems can now be solved *in-silico*. The Platform enables solutions to be generated that are demonstrably superior to competing designs. It has been used to generate solutions for advanced designs of hybrid electric vehicle controllers and the optimisation of vehicle dynamics across a range of different driving scenarios. It is in routine use in Honda Research & Development. The Platform has been made available in GitHub for more widespread use. Thus, beneficiaries are development organisations in a wide range of industries, the public and the environment, since the design solutions are able to incorporate multiple factors, including those relating to cutting emissions, for example.

2. Underpinning research (indicative maximum 500 words)

Evolutionary algorithms have been in use for solving complex engineering problems since the 1990s. However, many real-world complex engineering problems require a solution that is a trade-off between multiple, possibly competing, objectives.

Jin has led Surrey's research contribution in this area since 2010. Whilst many evolutionary algorithms were developed that were successful in obtaining Pareto optimal solutions (*i.e.*, where there is no way of improving any objective without degrading at least one other objective), the efficiency of such Pareto-based multi-objective evolutionary algorithms (MOEA) seriously degraded when the number of objectives was more than three **0**. The latter was a situation that was widely seen in many real-world problems. These are distinguished as many-objective optimisation problems and required a new generation of evolutionary algorithms to be developed.

Our work on the development of a knee-point driven evolutionary algorithm addressed this problem by preferring knee points of the nondominated fronts in the current population of candidate solutions in selection for the next generation. The work presented in **0** showed this approach to be very effective in accelerating the convergence of the population to the Pareto optimal front and maintaining diversity of the solutions.

An alternative to the convergence enhancement approach of **0** and others is to divide a complex problem into a number of sub-problems and solve them in a collaborative manner. In **0**, we proposed a reference vector-guided algorithm for many-objective optimisation. The reference vectors can be used not only to decompose the original problem into a number of single-objective sub-problems but also to elucidate user preferences to target a preferred subset of the whole Pareto front (PF). As well as providing competitive performance when evaluated against benchmark test suites, we also showed that reference vectors are effective and cost-efficient for preference articulation, an important requirement for real-world problems.

As the research community continued to expand the range of many-objective evolutionary algorithms, they were extensively evaluated using a set of benchmark test problems. However, these, in turn, were mostly based on general optimisation problems where the performance was evaluated using performance indicators originally proposed for multi-objective optimisation with two or three objectives. To bridge the gap between this state of academic research and industrial need, we compared three state of the art algorithms to solve a seven-objective optimisation problem in hybrid electric vehicle control **0**. By proposing a novel generic preference articulation method, we demonstrated that the three algorithms were capable of identifying optimal solutions preferred by the decision-maker and showed that our algorithm **0** achieved the best balance between convergence and diversity and was most effective in articulating the user preference.

Whilst playing an active role in the development of evolutionary algorithms, we noticed that there lacked an up-to-date and comprehensive software platform for researchers to properly benchmark existing algorithms and for practitioners to apply selected algorithms to solve their real-world problems. The demand for such a common tool was even more urgent, given that the source code of many proposed algorithms had not been made publicly available. To address these issues, we developed a MATLAB platform for evolutionary multi-objective optimisation, called PlatEMO **0**, which now includes more than 150 many-objective evolutionary algorithms (including ours) and more than 300 multi-objective test problems, along with several widely used performance indicators.

We continue to address the current limitations of evolutionary algorithms, which are especially an issue when applied to many-objective optimisation problems **0**. We are currently able to evaluate these against 15 objective real-world problems. They are added into PlatEMO as soon as they have been evaluated and peer-reviewed.

Overall, our research's two distinguishing features are: (1) its leading role in pushing forward the numbers of objectives that can be handled, and (2) the evaluation of our algorithms on real-world problems in addition to the public benchmark data sets.

3. References to the research (indicative maximum of six references)

The quality of the underpinning research is evidenced through the publication of scientific papers in peer-reviewed journals and conferences.

[R1] Y**.** Jin, "Surrogate-assisted evolutionary computation: Recent advances and future challenges" in *Swarm and Evolutionary Computation,* vol. 1, pp. 61-70. (2011) DOI: 10.1016/j.swevo.2011.05.001

[R2] X. Zhang, Y. Tian, and Y. Jin, "A knee point driven evolutionary algorithm for many-objective optimization" in *IEEE Trans. Evol. Comput*., vol. 19, no. 6, pp. 761–776. (2014) DOI: 10.1109/TEVC.2014.2378512

[R3] R. Cheng, Y. Jin, M. Olhofer, and B. Sendhoff, "A reference vector guided evolutionary algorithm for many-objective optimization" in *IEEE Trans. Evol. Comput.*, vol. 20, no. 5, pp. 773-791. (2016) DOI: 10.1109/TEVC.2016.2519378

[R4] R. Chen, T. Rodemann, M. Fischer, M. Olhofer and Y. Jin, "Evolutionary Many-Objective Optimization of Hybrid Electric Vehicle Control: From General Optimization to Preference Articulation" in *IEEE Transactions on Emerging Topics in Computational Intelligence*, vol. 1, no. 2, pp. 97-111. (2017) DOI: 10.1109/TETCI.2017.2669104

[R5] Y. Tian, R. Cheng, X. Zhang, and Y. Jin, "PlatEMO: A MATLAB platform for evolutionary multi-objective optimization [educational forum]" in *IEEE Computational Intelligence Magazine*, vol. 12, no. 4, pp. 73-87. (2017) DOI: 10.1109/MCI.2017.2742868

[R6] Q. Liu, Y. Jin, M. Heiderich, T. Rodemann and G. Yu, "An Adaptive Reference Vector-Guided Evolutionary Algorithm Using Growing Neural Gas for Many-Objective Optimization of Irregular Problems" in *IEEE Trans. Cybern.* (2020) DOI: 10.1109/TCYB.2020.3020630

4. Details of the impact (indicative maximum 750 words)

Modern engineering design problems need to meet multiple, often conflicting, objectives. Research work undertaken at Surrey has a wide range of applicability but has demonstrated impact in three specific areas:

1. Optimisation of hybrid vehicle energy management controllers;
2. Optimisation of vehicle dynamics in various driving scenarios;
3. Making available a comprehensive, general-purpose platform for evolutionary multi-objective optimisation under an open-source licence.

Hybrid Vehicle Energy Management:

Hybrid vehicles, with both electric and internal combustion power sources are gaining popularity as a means of reducing greenhouse gas emissions. Approximately 240,000 of these vehicles have been registered in the UK alone since 2012.

Hybrid vehicle energy management has, in the past, been seen as simply a matter of minimising fuel consumption. However, more objectives need to be taken into account if we are to optimise the overall reduction in environmental impact and take into account the overall driving experience. Whilst CO_2 emissions are closely correlated with fuel consumption, the emission of other greenhouse gases is associated with other phases of the internal combustion engine running cycle; emissions of nitrous oxides, for example, mostly occur when the engine is on, and the catalytic converter has not yet reached its operating temperature. In addition, the control strategy needs to minimise the usage of the engine within urban environments. However, recent studies have shown that hybrid vehicles can exhibit higher pollution levels in use than those claimed by the manufacturers **[S1]**. As a result, the overall assessment of the environmental impact of hybrid vehicles is now recognised as vitally important to avoid a backlash against their usage **[S2]**. For example, drivers may alter their driving practices to optimise their own preferences for noise reduction and charging frequency and this, in turn, can negatively impact vehicle emissions **[S2]**. Thus, it is important for the controller to optimise against a broader range of objectives to ensure a satisfactory driving experience is obtained whilst still meeting the pollution reduction objectives.

We therefore worked with Honda Research and Development to demonstrate that our research work can optimise against seven objectives: fuel consumption; battery charge/discharge cycling; engine operation changes; engine emissions; perceived engine noise; engine usage in urban operation; average battery state of charge level. This work showed that our "RVEA" algorithm **0** provided an effective balance between convergence and diversity of solutions, supporting an approach that achieved the objectives preferred by the decision-maker **0**. This positive experience has motivated the continued usage of MOEAs at Honda Research & Development Europe.

{*Text removed for publication*}

Optimisation of vehicle dynamics:

Vehicle stability at higher speeds is another important and challenging factor that must be addressed in vehicle design. For both safety and comfort, the vehicle must remain stable, predictable and controllable under a wide variety of road surface conditions and maintenance states. The vehicle behaviour is mainly influenced by the interaction of suspension components, the steering subsystem and tyre characteristics. This leads to a high number of adjustment factors and results in many possible variations depending on the vehicle targets. The trade-off between vehicle dynamics, ride comfort and road holding capability makes the definition of the perfect chassis setting challenging. This is normally tested using pre-production prototypes but testing and corrections to the design at this phase are both very expensive, usually requiring a number of redesign-test cycles. Honda R&D Germany has developed a simulation-based optimisation and evaluation approach that both reduces the cost and enhances the effectiveness of this design phase **[S4]**. Our algorithms are providing an important contribution to this technology. Honda R&D has been using our optimisation platform PlatEMO **0** since 2019. Although PlatEMO contains a broad range of candidate algorithms, in an independent evaluation our "KnEA" algorithm was shown to be amongst the first class of performers on benchmark 7-objective problems **[S5]**. {*Text removed for publication*}

Open Science support:

Our generation of impact is not just focused on Honda. All the algorithms, together with reports on their evaluation against real-world problems, are in the public domain. In addition, the evolutionary multi-objective optimisation platform PlatEMO **0** (co-developed with the Institute of Bioinspired Intelligence and Mining Knowledge of Anhui University, China) is available free of charge to academia and industry **[S6]**. The importance of PlatEMO in building external confidence in the claims of the research community has been recognised by over 1,200 scientists from 40 countries who have (co-)authored papers citing it. In addition, PlatEMO is now (December 2020) in use at 22 industrial and public sector organisations, including Honda, Jaguar, Huawei, Ericsson, Diehl Aviation (Germany), AIST (Japan), Caterpillar Propulsion AB (Sweden) **[S7]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] https://www.transportenvironment.org/press/plug-hybrids-new-emissions-scandal-tests-show-higher-pollution-claimed, Accessed December 2020.

[S2] P. Plötz, C. Moll, G. Bieker, P. Mock, Y. Li, "Real World Usage of Plug-in Hybrid Vehicles: Fuel Consumption, Electric Driving and CO_2 Emissions", The International Council for Clean Transportation White Paper, September 2020, https://theicct.org/sites/default/files/publications/PHEV-white%20paper-sept2020-0.pdf

[S3] Testimonial {*Text removed for publication*}

[S4] M. Heiderich and T. Friedrich, New approach for improvement of vehicle performance by using a simulation-based optimization and evaluation method, Honda R&D Europe Technical Report, 2016, https://link.springer.com/content/pdf/10.1007/978-3-658-14219-3_21

[S5] K. Li, R. Wang, T. Zhang and H. Ishibuchi, "Evolutionary Many-Objective Optimization: A Comparative Study of the State-of-the-Art" in *IEEE Access*, vol. 6, pp. 26194-26214, 2018, DOI: 10.1109/ACCESS.2018.2832181

[S6] PlatEMO GitHub Repository https://github.com/BIMK/PlatEMO

[S7] Analysis of PlatEMO Usage (.xlsx file)