

Institution: Maxwell Institute for Mathematical Sciences		
Unit of Assessment: UoA 10 – Mathematical Sciences		
Title of case study: Global food solutions via optimal diet formulations		
Period when the underpinning research was undertaken: 2000-date		
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:
Julian Hall	Reader	1990-date
Ken McKinnon	Professor	1972-date
Andreas Grothey	Senior Lecturer	2002-date
Period when the claimed impact occurred: 2013 - date		
Is this case study continued from a case study submitted in 2014? No		
1. Summary of the impact		
<p>Format Solutions is the world's leading supplier of software for food formulation, and this requires high performance optimization software. The solutions obtained using the EMSOL and HiGHS optimization software developed by Hall and colleagues enabled Format Solutions' clients to make savings [text removed for publication] of ingredient costs, [text removed for publication]. The reach of this impact is global, and its significance is demonstrated by the dependence of Format Solutions on the University of Edinburgh technology when selling its software [text removed for publication].</p>		
2. Underpinning research		
<p>The need for high-performance solution of large-scale linear programming (LP) problems is widespread throughout industry, the public sector, and scientific world. The development of computational and algorithmic techniques for solving this optimal decision-making problem has driven Hall's research for over thirty years. When studying the behaviour of Hall's simplex solver (EMSOL) on an LP problem provided by Format International, Hall and McKinnon identified the property of hyper-sparsity [3.1] that is exhibited by many important classes of LP problems. Developing techniques to exploit hyper-sparsity led to major improvements in the performance of EMSOL. In the case of Format's LP problems, the solution time for their larger, more representative test problem (DCP2) improved by a factor of more than five, and the cost of post-optimal analysis was reduced by a factor of more than eight [3.1]. In the early 2000's, one client of Format wanted to solve "pooling problems" so, to solve the underlying nonlinear optimization problem, Grothey and McKinnon developed a sequential linear programming (SLP) solver [3.2] that used EMSOL to solve the underlying sequence of LP problems.</p> <p>In 2009, Hall recommenced research into high performance implementations of the simplex algorithm. His PhD student, Qi Huangfu, was partially funded by Format to work in the area, leading to the development of serial and parallel implementations of the simplex algorithm that offered significant performance improvements over EMSOL and, academically, represent the state of the art [3.3-3.4]. These solvers, together with LP pre-processing techniques, now form the core of the HiGHS open source linear optimization software. HiGHS solves Format's indicative test problem DCP2 a little over ten times faster than EMSOL. Independent of advances in machine speed, HiGHS is three orders of magnitude faster than the simplex</p>		

solver originally written by Format, with post-2000 research and development accounting for a factor of more than 50.

3. References to the research

[3.1] “Hyper-sparsity in the revised simplex method and how to exploit it”, J. A. J. Hall and K. I. M. McKinnon, Computational Optimization and Applications 32(3), 259-283, 2005.

<https://doi.org/10.1007/s10589-005-4802-0>

[3.2] “On the Effectiveness of Sequential Linear Programming for the Pooling Problem”, A. Grothey and K. McKinnon, Submitted to Annals of OR, 2020. [arXiv:2002.10899](https://arxiv.org/abs/2002.10899).

[3.3] “Novel update techniques for the revised simplex method”, Q. Huangfu and J. A. J. Hall, Computational Optimization and Applications 60(3), 587-608, 2015.

<https://doi.org/10.1007/s10589-014-9689-1>

[3.4] “Parallelizing the dual revised simplex method”, Q. Huangfu and J. A. J. Hall, Mathematical Programming Computation, 10 (1), 119-142, 2018.

<https://doi.org/10.1007/s12532-017-0130-5>

Articles 3.1, 3.3 and 3.4 won the journal's best paper prize for that year. See

<http://users.clas.ufl.edu/hager/coap/Best/> [3.1,3.3] and

<https://www.springer.com/journal/12532/updates/17226372> [3.4]

4. Details of the impact

The blending of simple raw materials to manufacture food is an industry that is worth approximately a hundred billion USD per annum, and is dominated by the petfood market, where small percentage savings are significant. The competitive position of the world's leading supplier of food formulation software, Format Solutions, depends on techniques and software developed by the University of Edinburgh Optimization group. This software is used to identify raw material blends and production strategies [text removed for publication]. With the solution of optimization problems being the overwhelmingly dominant computational cost of Format Solutions' software, post-2000 research and development by the Edinburgh group has led to its performance improving by more than an order of magnitude (independent of the computing platform).

Manufactured food for both farmed animals and domestic pets, as well as some human food, is produced by simple blending and binding of fundamental raw materials. A particular food mill will produce multiple recipes for different animals, with shared use of the same raw materials. However, the nutritional properties of the resulting food are important, particularly when raising farm animals to provide optimal yields of meat, milk and offspring. Thus, the amounts of raw materials that are combined to produce a particular recipe must satisfy many linear constraints on its nutritional properties, and the total amounts of raw materials used must not exceed their availability. Food manufacturers wish to manufacture their products at minimum price. This extension of the classical single diet problem is an example of the optimal decision-making problem that, mathematically, is referred to as linear programming (LP). The problem size increases with the number of recipes and raw materials, and larger companies wish to consider raw material usage over a number of mills. A secondary, but potentially very profitable enterprise is to consider substituting materials when it is more valuable to trade ownership or purchase options for them on global commodity markets. To obtain the information for all this manufacturing and economic activity requires the solution of large-scale LP problems.

To place the post 2013 impact in context, it is necessary to consider the involvement of Hall, McKinnon and Grothey of the University of Edinburgh Optimization group with Format International (as it was known at the time), that began in 1997. The company was seeking to

improve the quality of its implementation of the simplex algorithm for solving the LP problems generated by its animal feed formulation software. It was immediately clear that Hall's simplex solver, EMSOL, was far superior. For problems with a large matrix size, EMSOL returned the optimal solution up to 15 times faster than Format's own version, so Format bought a copy of EMSOL for incorporation in their software. In the early 2000's, Hall's development of techniques to exploit hyper-sparsity in the type of problems Format needed to solve provided a further major performance enhancement. The result of adopting EMSOL had significant impacts on the company's growth. It was able to win new business with larger clients [text removed for publication].

The SLP solver developed for Format by McKinnon and Grothey gave the company the unique ability to solve pooling problems, in which production requirements dictate that ingredients are used to produce several pre-mixed combinations, before final blending into products. Such problems are often found in industries such as pet food and dried milk production. The development therefore gave Format a significant commercial advantage over its competitors, who simply were unable to solve these types of problems. The solutions presented by the new solver enabled Format clients to streamline production and supply chains resulting in significant savings to them [text removed for publication]. Format was therefore able to open new markets and win new business, particularly in the pet food industry. This included several of the world's leading pet food manufacturers [text removed for publication].

In 2015, Cargill Inc., one of the world's leading animal feed manufacturers and a long-time customer of Format, acquired Format International, renaming it Format Solutions. This purchase was made following a review of the future direction of their formulation software solutions across the world-wide business. The Cargill review identified that Format's own software developments, coupled with its optimization capabilities and the talent in the Format team were far ahead of Cargill's own in this area, and to match them would have taken many years and expense. The purchase of Format International, bringing with it the ability to acquire the software, its I.P. and solvers, was assessed as a far better option than developing their own solution. The Format-Edinburgh relationship spanned many years of highly rewarding interaction and resulted in some industry significant developments. Format's turnover and profitability during the period grew four-fold [text removed for publication].

Format Solutions is now (2020) the world's leading supplier of food formulation software, so is dependent on high performance optimization software for the reliability and performance of its products. As the modelling capabilities of its software have developed over the years, so has the size of the underlying optimization problems that must be solved. Continued collaboration with the Edinburgh Optimization Group has given Format Solutions the necessary enhancements of its optimization solvers. The most significant advance in this respect has been the performance improvement offered by HiGHS, that has been used by Format since 2017. In the case of LP problems, Format's customers are now able to *"optimize larger feed formulation problems, and at significantly greater speed"* [5.2]. The Format product for pooling problems that requires the SLP solver *"enables customers to significantly improve on the cost and quality of their feed-mix products and solve new classes for problems that were not tractable before"* [5.2]. This has *"contributed to Format's world market-leading position and allowed them to gain new important clients"* [5.2]. A significant illustration of this is the fact that Format's software is used to formulate petfood for the world's top manufacturer [text removed for publication] who chose Format specifically because of this solution capability [5.2]. HiGHS offers Format Solutions a tenfold performance improvement over EMSOL, and will contribute significantly to maintaining Format's world market-leading position in feed formulation software into the future.

5. Sources to corroborate the impact

[5.1] Letter from Former Managing Director, Format International Ltd and Format Solutions Ltd and Former Head of Operations, Format International Ltd and Director, Format Solutions

Ltd.

[5.2] Letter from Managing Director of Format Solutions