Institution: Newcastle University		
Unit of Assessment: 12		
Title of case study: Workcraft – Saving Power in Consumer Electronics		
Period when the underpinning research was undertaken: 2000-2020		
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:**
Alex Yakovlev	Professor	1991-2021
Danil Sokolov	Principal Research Associate	2005-2020
Andrey Mokhov	Senior Lecturer	2009-2019
Victor Khomenko	Reader	2003-2021
Maciej Koutny	Professor	1985-2021
Period when the claimed impact occurred: 2015-2020		
Is this case study continued from a case study submitted in 2014? N		

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

Newcastle University research into formal modelling and design of asynchronous circuits and concurrent systems has laid the foundation to the development of industrial strength software "Workcraft". Workcraft has been used by the microchip industry (e.g., Dialog Semiconductor, Analog Devices) to develop power-management integrated circuits that are essential for saving electric energy and prolonging battery life in hundreds of millions of mobile devices around the world.

The design automation methodology that underpins Workcraft software improves productivity of electronic engineers from months to hours. Workcraft has also been used in training industry engineers and educating electronic engineering students.

2. Underpinning research (indicative maximum 500 words)

Due to the widespread popularity of portable electronics such as mobile phones, there is an increasing demand for integrated circuits which are smaller, more complex, and yet cost-effective. This has led to a rise in the use of Analogue and Mixed Signal (AMS) systems, in which both analogue and digital circuits co-exist on a single chip. Increasingly, both analogue and digital parts are designed by the same team of engineers as it allows the overall AMS system to be holistically co-optimized. AMS systems now play a vital role in monitoring a system's operating conditions, as well as distributing and regulating energy flows. However, AMS electronics is considered extremely hard to master, as the digital components must integrate seamlessly with the analogue parts, which are dynamic and notoriously hard to interface.

Newcastle University's longstanding research into the formal modelling of asynchronous and concurrent systems has inspired a new methodology for designing such systems, resulting in reduced inductor size and enhanced power conversion that responds to changes in demand more efficiently [R1-R4].With energy becoming the most valuable resource in modern electronics, the responsiveness and robustness of power converters are crucial. Today's chips make millions of control decisions every second, and a single mis-step could cause malfunction or permanent damage.

The traditional approach to designing AMS control circuits relies on conventional synchronous components that require a clock frequency to be as high as 1 GHz, in order to meet the requirement of minimum latency of response, e.g. 1 nanosecond, to events generated by analogue components. This results in inefficient use of energy and a risk of failure. In contrast, using asynchronous logic for AMS control allows the system to operate at a pace that is determined by current operating conditions. AMS systems, however, need to keep evolving to track the advances in heterogeneous multi-core systems architectures and of Internet of Things devices.

Newcastle University researchers tackled the issue of how to use asynchronous circuits as a control for analogue parts and as a front-end for analogue-to-digital interfaces [R1, R2]. The methodology particularly draws on research into the use of Petri nets and causal representations of concurrent behaviour in electronic circuits [R5]. This has resulted in better power conversion efficiency, lower output ripple, faster response to analogue events, and reduced inductor size [R3, R4].

Studies into the design of asynchronous VLSI circuits at Newcastle University date back to the 1990s, where Alex Yakovlev (Lecturer/reader/professor of Computer Systems Design: 1991-present) developed the first formal model of the concurrent behaviour of such circuits Signal Transition Graphs [R6]. The research has since been carried out jointly with Maciej Koutny (Lecturer/Reader/Professor), Victor Khomenko (Lecturer/EPSRC external research fellow/lecturer/senior lecturer/reader: 2003-present), Danil Sokolov (Senior/Principal research associate) and Andrey Mokhov (Lecturer/Senior lecturer) [R1].

The resulting methodology has been implemented in several software tools (such as Petrify, PUNF, MPSAT and PCOMP), and in novel electronic components for interfacing analog and asynchronous parts (WAIT, WAITX, SAMPLE). It has also been integrated into a visual usable framework called Workcraft [R1, R4].

Workcraft provides a flexible common framework for development of Interpreted Graph Models, including visual editing, (co-)simulation, synthesis and formal verification. With Workcraft, the user can design a system using the most appropriate formalism (or even different formalisms for the subsystems), while still utilising the power of Petri net analysis techniques. The applications of the Workcraft framework are wide-ranging: from modelling concurrent algorithms and biological systems to designing asynchronous electronic circuits and investigating crimes (see workcraft.org).

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

[R1] D. Sokolov, V. Khomenko, A. Mokhov, V. Dubikhin, D. Lloyd, A. Yakovlev: “Automating the design of asynchronous logic control for AMS electronics”, IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, March 2019. DOI: 10.1109/TCAD.2019.2907905

[R2] V. Dubikhin, D. Sokolov, A. Yakovlev, C. Myers: “Design of mixed-signal systems with asynchronous control”, IEEE Design & Test, v. 33(5), pp. 44–55, October 2016. DOI: 10.1109/MDAT.2016.2555916

[R3] D. Sokolov, V. Dubikhin, V. Khomenko, D. Lloyd, A. Mokhov, A. Yakovlev: “Benefits of asynchronous control for analog electronics: Multiphase buck case study”. Proc. of Design Automation and Test in Europe (DATE), (2017) 1751-1756. DOI: 10.23919/DATE.2017.7927276

[R4] D. Sokolov, V. Khomenko, A. Mokhov, A. Yakovlev, D. Lloyd: “Design and verification of speed-independent multiphase buck controller”. Proc. of International Symposium on Asynchronous Circuits and Systems (ASYNC), IEEE Computing Society Press (2015) 29-36. DOI: 10.1109/ASYNC.2015.14

[R5] J. Beaumont, A. Mokhov, D. Sokolov, A. Yakovlev: "High-level asynchronous concepts at the interface between analog and digital worlds", IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, vol. 37(1), pp. 61–74, January 2018. DOI: 10.1109/TCAD.2017.2748002

[R6] A. Yakovlev, L. Lavagno and A. Sangiovanni-Vincentelli. A unified signal transition graph model for asynchronous control circuit synthesis. Formal Methods in System Design (Kluwer), Vol. 9, No. 3, Nov. 1996, pp. 139-188. DOI: 10.1007/BF00122081

The research is based on the following funded projects:
EPSRC grants EP/L025507/1 (2014-2018) "A4A: Asynchronous design for Analogue electronics", £574,524 (PI-Yakovlev, CIs: Mokhov and Khomenko, Named RA: Sokolov); EP/N023641/1 (2016-2021) "Platform Grant: STRATA: Layers for Structuring Trustworthy Ambient Systems, £965,298 (CI: Yakovlev, Named RA: Sokolov); IAA project "Waveform-based design flow for A4A circuits" (2018-2019) £15,500 (PI: Sokolov)
Dialog Semiconductor R&D grants: "Tools for Asynchronous Logic" (2017-2020) £505,266 (PI-Yakovlev, CI: Khomenko, Named RA: Sokolov), "Asynchronous design automation (PhD studentship)" (2018-2021) £92,750 (PI: Yakovlev), "PhD studentship in Asynchronous design for Analogue Electronics" (2014-2017) £90,000 (PI: Yakovlev)
Analog Devices R&D grant: "INTUASYNC: Industrial Tutorial on Asynchronous Circuit Design" (2018), £26,635 (PI: Mokhov)

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

Researchers from Newcastle University's School of Engineering and School of Computing have developed new concepts, software and technologies that support the design and delivery of more reliable and efficient asynchronous systems. Their research has been incorporated into a visual toolset known as **Workcraft**.

Workcraft has been used by companies including electronic chip manufacturer Dialog Semiconductors, which paid for a bespoke version of the toolset to enhance the power conversion capabilities of its chips. Dialog's principal client – Apple Corporation – invested US$600million in October 2018 to license some of Dialog's power management technologies, acquire staff and assets, and support future research and development [E3].

The Workcraft toolset is an open-source project that is available publicly at workcraft.org. Additionally, after the initial stages of the R&D and impact creation in EPSRC project A4A (2014-2017), the project's industrial partner Dialog Semiconductor supported R&D with their direct funding. Under this project besides open-source software some novel bespoke functionality has been developed exclusively for Dialog Semiconductor. As a whole Workcraft was then used by the company to significantly enhance the power conversion capabilities of its chips. Dialog Semiconductor PLC is a multi-national company which develops highly integrated mixed-signal products for consumer electronics. It has approximately 1800 employees and offices in Europe, Asia and the USA [E1]. Its number one product is Power Management ICs. Its RapidCharge solutions for power adaptors boasted a 60% share of the rapid charge adapter market for smartphones at the end of 2017 [E4].

The A4A project developed a novel design flow for the systematic development of asynchronous controllers for analogue-mixed-signal (AMS) systems, which has since been used in Dialog production chips [E2]. Newcastle University and Dialog co-authored three papers in 2015 [R2], 2017 [R1] and 2019 [R4], demonstrating the advantages of asynchronous design methodology for AMS control. Simulation results indicated improved **reaction time, voltage ripple, peak current, and inductor losses, resulting in a higher efficiency of power conversion. These results meant that the size of coils could be reduced, a sizeable benefit for businesses such as mobile phone manufacturers, who see compact components and increased battery life and reliability as huge market drivers.** For example, it was reported at DATE 2017

[R3, E2] that for a 6µ load, an asynchronous control mentions peak current below 300mA using 1.8µH inductors. A synchronous control requires 10µH coils at 100MHz, 6.8µH at 333MHz, or 3.1µH at 666MHz [E2].

Dialog extended its collaboration with Newcastle University following the end of the A4A project, providing an R&D project of over £500,000 to fund the further extension of Workcraft with new capabilities. Besides that, to date University has provided Workcraft tutorials to approximately 100 Dialog employees a year (see: https://workcraft.org/training/start).

In October 2018, Dialog announced that it had agreed a US$600million deal with Apple Corporation. The deal was the largest of its kind by Apple. Apple agreed to pay US$300million in cash to license certain power management technologies from Dialog, as well as to receive certain assets and over 300 employees to aid with chip research and development. The company also pre-paid US$300million for Dialog products that would be delivered over the next three years. Dialog announced that it would continue to sell current and future generations of power management integrated circuits to Apple. Apple accounted for 75% of Dialog's total revenues this year, but the company expects that to drop to 35-40% by 2022 [E3].In third quarter figures announced at the end of October 2018, Dialog announced record quarter revenue of US$384million, including a 3% year-on-year revenue rise in its Advanced Mixed Signal business. These results were collated before the Apple deal [E4]. In January 2019, it announced that its unaudited preliminary revenue for the full 2018 year was approximately US$1,442million [E5].

Since 2017 a series of industrial track papers were produced in collaboration with Dialog Semiconductor for International Symposium on Asynchronous Circuits and Systems (ASYNC). These papers are co-authored with David Lloyd, who is a Senior Member of the Technical Staff at Dialog Semiconductor. Being research papers, they have a strong practical focus on the design aspects that are especially relevant to industry [E7, E8, E9]. The latter for example, is aimed to help engineers to perform automatic verification of their asynchronous handshake circuits with a generic usage, going beyond power-management circuits.
Notably, as a further illustration of the impact generated by Newcastle research, in December 2020, Danil Sokolov was hired as a full-time employee by Dialog to continue integrating Workcraft into the company's R&D process (Sokolov is remaining a Visiting Fellow at Newcastle University).

While Dialog is the main beneficiary of paid extensions to Workcraft functionality, a version of the toolset is available for free download. This makes advanced formal design techniques more accessible to industrial developers, rather than restricted to experts in the domain. Since 2014, there were 32 public releases of Workcraft that were downloaded 20K times from 4.7K unique IPs (data sampled on 23.01.2021). The availability of Workcraft attracts other companies and is increasingly featuring in the teachings of the future generation of engineers in this field.

- Other companies that have evaluated integration of Workcraft in their design flows, invested in training of engineers and, are able to use it in the design of products include: Analog Devices (evaluated in 2018, last training in 2019), Nordic Semiconductor (since 2015, last training in 2019) [E10].
- Universities that use Workcraft toolset in the learning process: Newcastle University (CSC3324, EEE8043, EEE8087, EEE8124) (see https://www.ncl.ac.uk/module-catalogue), Technical University of Denmark (02204: (http://www2.compute.dtu.dk/courses/02204), Southampton University (ELEC6233 - https://www.southampton.ac.uk/courses/modules/elec6233)

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

[E1] Dialog Semiconductor (dialog-semiconductor.com)

[E2] D. Sokolov, V. Dubikhin, V. Khomenko, D. Lloyd, A. Mokhov, A. Yakovlev: "Benefits of Asynchronous Control for Analog Electronics: Multiphase Buck Case Study". Proc. of Design Automation and Test in Europe (DATE), (2017) 1751-1756.

(This source confirms that Workcraft is used by Dialog Semiconductor, David Lloyd from Dialog Semiconductor is an author of the paper.)

[E3] https://uk.reuters.com/article/us-dialog-licensing/apple-gets-critical-iphone-technology-in-600- million-dialog-deal-idUKKCN1ML0IJ

(Reuters report announcing the Dialog/Apple deal, the largest of its kind by Apple)

[E4] https://www.dialog-semiconductor.com/sites/default/files/gb0059822006-q3-2018-eq-e-00_0.pdf

(Interim report for Dialog for the third quarter ending 28 Sept 2018)

[E5] https://www.dialog-semiconductor.com/sites/default/files/q4_2018_trading_update_14.01.19.pdf (Preliminary revenue and cash report for Dialog for Q4 2018 and full year 2018 – audited results TBC March 6 2019)

[E6] Letter from Dialog Semiconductor confirming use of Workcraft and benefit/impact on their work/revenues; Two letters of support from Dialog for EPSRC grant applications; plus a Confidential document: Yakovlev's FReng nomination with evidence provided by Dialog engineers, stating the volumes of products

[E7] J. Cortadella, A. Moreno, D. Sokolov, A. Yakovlev, D. Lloyd: "Waveform transition graphs: A designer-friendly formalism for asynchronous behaviours", Proc. of International Symposium on Asynchronous Circuits and Systems (ASYNC), San Diego, May 2017 (industrial track paper).

[E8] D. Sokolov, V. Khomenko, A. Yakovlev, D. Lloyd: "Design and verification of speed-independent circuits with arbitration in Workcraft", International Symposium on Asynchronous Circuits and Systems (ASYNC), Vienna, May 2018 (industrial track paper).

[E9] V. Khomenko, D. Sokolov, A. Yakovlev, D. Lloyd: "Handshake verification in Workcraft", International Symposium on Asynchronous Circuits and Systems (ASYNC), Snowbird, May 2020 (industrial track paper).

[E10] Confidential testimonials from e-mail exchange with engineers of Dialog Semiconductor, Analog Devices, Nordic Semiconductor; plus an endorsement letter from Analog Devices