Institution: London Metropolitan University		
Unit of Assessment: UoA11 Computer Science and Informatics		
Title of case study: The impact of Qucs/Qucs-S Software Tools on Verilog-A Standardization and their use as a Vehicle for Emerging Technology Model Construction		
Period when the underpinning research was undertaken: 2014 – 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:**
M.E. Brinson	Associate Lecturer Visiting Professor Professor of Communications Technology	10.07.1997 - 23.11.2009 1.5.2010 - 30.10.2020 10.02.2020 - present
Period when the claimed impact occurred: 1 January 2014 to December 2020		
Is this case study continued from a case study submitted in 2014? No		

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

With the accelerating pace of semiconductor device technology, especially over the last decade, industry has become aware of the need for improved modelling and simulation software tools for emerging technologies. This research has resulted in the implementation of an innovative next generation software tool that benefits individuals and Small to Medium Enterprises (SME), including:

- The modelling and development of novel and potentially life changing medical devices
- Enabling an ethical and security conscious company to develop an innovative smartphone to address a gap in the market

Allowing a small high tech company to overcome financial barriers in the semiconductor industry

2. Underpinning research (indicative maximum 500 words)

New semiconductor device technologies, shrinking device sizes and improved modelling and analysis algorithms are all factors driving next generation simulation software development. Increasing public awareness and demand for FOSS circuit simulation software highlights restrictions imposed on individual and SME by the high cost of commercial software licences. The research, undertaken jointly by Prof. M. E. Brinson and Dr Vadim Kuznetsov, Bauman Moscow State Technical University, Russia, began in 2014 with a "fork" of the "Quite universal circuit simulator" (M. Margraf 2003). This fork was specifically chosen as a starting point for the construction of a new modelling and simulation software package called Qucs-S. The primary aims of the research were to remove device and circuit design limitations imposed by primitive equation-defined compact device modelling, rectify the lack of hardware device language modelling, improve the rudimentary high frequency simulation features found in existing circuit simulation software, and to implement a FOSS General Public Licence Electronic Design Automation package. Qucs-S is capable of running advanced simulation engines (Ngspice and Xyce), from a well-developed graphical user interface (GUI) with enhanced non-linear Equation-Defined Device (EDD) and hardware description language modelling features, and for the first time implements model synthesis from subcircuit schematics. By the end of 2017, the initial phase of the research was largely complete with results reported in three peer-reviewed journal publications. These included accounts of original modelling tools for the synthesis of Verilog-A compact device modules [R1]

and XSPICE Code-Models [R2], extended non-linear behavioural device modelling with hardware device language scripts [R3], and simulation with swept device parameters [R2] and swept non-electrical quantities, for example temperature and light wavelength [R1]. The research also supports the international effort to establish Verilog-A as the professional standard for compact modelling and model interchange. To further demonstrate the capabilities of Qucs-S [R1] presents a synthesised Verilog-A phototransistor module, [R2] describes a synthesised XSPICE EKV v2.6 nMOS transistor Code Model, and [R3] outlines an extended behavioural model of an emerging semiconductor technology GaN high-electron-mobility transistor. Brinson and Kuznetsov also stress the relationships between Qucs-S EDD, Verilog-A modules and previous generation XSPICE Code Models. The first stable version of Qucs-S was released in October 2017 (Qucs-S-0.0.20), with the latest release in January 2020 (Qucs-S-0.0.22). In parallel with these software releases Brinson and Kuznetsov also published three additional device modelling and simulation papers in peer-reviewed journals [R4], [R5], [R6]. These informative papers report the results from advances in Harmonic Balance device modelling and simulation [R4], new EDD and Verilog-A current conveyor macromodels for wideband radio frequency design [R5], and improvements to non-linear frequency domain modelling and simulation of integrated circuit spiral inductors on silicon [R6].

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

R1. Mike Brinson and Vadim Kuznetsov (2016), “A new approach to compact semiconductor device modelling with Qucs Verilog-A analogue module synthesis”, International Journal of Numerical Modelling: Electronic Networks, Devices and Fields, November/December; 29(6), pp. 1070–1088. ISSN 1099-1204, https://doi.org/10.1002/jnm.2166 .

R2. Mike Brinson and Vadim Kuznetsov (2017), “Recent developments in Qucs-S Equation Defined Modelling of Semiconductor Devices and IC’s”, International Journal of Microelectronics and Computer Science. 8(1), pp. 29-35, ISSN 2080-8755, eISSN 235-9607

R3. Mike Brinson and Vadim Kuznetsov (2018), “Extended behavioural device modelling and circuit simulation with Qucs-S, International Journal of Electronics”, December 105(3), pp. 412-425, 2018, ISSN 0020-7217, https://doi.org/10.1080/00207217.2017.1357764 .

R4. Brinson, Mike and Kuznetsov, Vadim (2015) Qucs Equation-Defined and Verilog-A Higher Order Behavioral Device Models for Harmonic Balance Circuit Simulation. International Journal of Microelectronics and Computer Science, 6 (2), pp. 49-58. ISSN 2080-8755, eISSN 235-9607.

R5. Brinson, Mike and Kuznetsov, Vadim (2017) Current conveyor equation-defined macromodels for wideband RF circuit design. International Journal of Microelectronics and Computer Science. 8(2), pp. 65-71. ISSN 2080-8755, eISSN 235-9607.

R6. Brinson, Mike (2018) Frequency Domain Non-Linear Compact Modelling and Simulation of IC Spiral Inductors On Silicon. International Journal of Microelectronics and Computer Science, 9 (1). pp, 19-26. ISSN 2080-8755, eISSN 235-9607

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

Technology developments and the public’s desire for smaller, thinner, and more powerful devices has increasingly presented manufacturers with practical challenges in the design and testing of new product concepts, in particular ability to test the individual components that connect together to make integrated circuits, such as in smart phones, which may include over a billion components on a single chip. The only possible way to obtain performance assessments of such components is by simulating the compact models representing the components. Qucs/Qucs-S, devised by Brinson and Kuznetsov, has allowed the facilitation of compact device modelling and simulation replacing

the prohibitively costly testbench testing associated with earlier technologies.

Standardisation of Verilog-A

Qucs/Qucs-S research has benefited international efforts to establish Verilog-A as the professional standard for compact device modelling. Originally devised as an engineering language for describing the components used to construct analogue electronic circuits, Verilog-A was not fully compatible with the compact device modelling needed for the development of existing and emerging semiconductor technologies. Verilog-A is a subset of the IEEE standardized Verilog-AMS hardware description language. Following the August 2014 release of Verilog-AMS V2.4 international efforts to rectify the language deficiencies needed for efficient compact modelling have resulted in Verilog-A being adopted for device modelling and model interchange amongst different simulators (both commercial and FOSS), and industry. Work on Verilog-A standardization is an international ongoing project. As Wladek Grabinski, of MOS-AK's MOS Modelling and Parameter Extraction Working Group, addressing Brinson's promotion of standardisation through Qucs/Qucs-S, advised "*The Verilog-A standardization supported by FOSS ADMS tool and EDD modeling concept introduced in QUCS design environment*" has provided significant benefits to users, including model developers who *"are developing a model once, [focusing] on the model equation, not on its software implementation [and the] new model can run*" on any software platform.[S1]

Brinson's Qucs/Qucs-S is the only modelling and simulation software tool to include Verilog-A model synthesis from circuit schematics and it includes Verilog-A modelling facilities that are freely available to all interested users from individuals to small, medium and large enterprises.

A vehicle for emerging technology model construction

Brinson's Qucs/Qucs-S research has contributed to individuals' and SMEs' model design, particularly in relation to building emerging semiconductor technology models [S2], and also through the application of the research in non-semiconductor domains including the mechanical domain [S3], and product design [S4].

Mechanical domain device modelling

The contribution of Brinson's Qucs/Qucs-S software to simulation and compact device modelling has resulted in significant developments in the field of medical devices where physical application of experimental models is not a feasible option. As Dr Daniel Tomaszewski, the Instytut Technologii Elektronowej (ITE), Warsaw, commented, Qucs has had an "*important role*" in the ITE's successful work between 2014-2016 in the "*design and modelling of thermal energy conversion into mechanical energy followed by the conversion of mechanical energy into electric field energy, and application of open-source circuit simulation programs for the device model parameter extraction.*"[S3]. ITE carries out R&D projects, from concept development, through multi-domain computer simulations, to the development of a prototype of a specialized instrument.

Human medical implants, such as pacemakers, powered by a lithium battery present the patient and their medical team with the inevitable need for battery replacement through invasive and potentially life-threatening surgery. Tomaszewski's model of an Energy Harvester is the first step in the concept development of a battery that in drawing its power from its environment will represent a profound benefit and improvement for patients and medical staff. As Tomaszewski states, Brinson's Qucs with its Verilog-A related functionality has been of "*particular importance for a development of compact models of non-standard electronic and heterogenous* [sic] *devices and systems. Such models can be used in the simulation for the system operation prediction. The systems under consideration can be further developed and optimized.*" [S3] Earlier SPICE based simulators, centred on electrical analogue simulation, lack the tools to model the conversion of mechanical energy to electrical energy required for this work; Brinson's Qucs is the only FOSS modelling and simulation software tool that has the modelling tools sufficient to support the work

concentrated on converting mechanical energy (from body movement) into electrical energy that is stored to provide a power source for operating implanted electronic devices. As Tomaszewski notes *"Solving such a task is not possible using dedicated software for the electrical simulations of circuits with lumped elements.* ***Qucs/Qucs-S was the tool of choice*****"** [S3]

Knowm's memristor models

The Qucs-S/Xyce Verilog-A version of the "Kmowm" memristor model is a central part of an industrial "start-up" tool chain for the design and manufacture of memristor semiconductor products. Knowm Inc. "*exists to lead the computing industry toward neuromemristive processors*" [S2]. Originating in 2002, Knowm has been awarded several US government grants to develop Knowm memristor computing technology. The existence of the memristor was first hypothesized by Leon Chua in 1971 with a practical realisation constructed in 2005. Knowm Inc is a high-tech company making a small range of memristor products that contain the basic devices on integrated circuit chips [S2]. Knowm Inc used Qucs-S because it has allowed new symbols to be built for the memristor and simulation of its performance using Xyce. Qucs-S has provided Knowm with the functionality to model and simulate memristors for new circuit designs.

The availability of Qucs-S as a FOSS software tool allowed Knowm, an SME, to launch into the emerging semiconductor technology market without the cost implications associated with commercial packages.

Speaking of their decision to use Qucs-S and financial and ethical benefits it brings to the company, Knowm's founder and CEO, Alex Nugent said, "*It was free and provided elements that were needed."* The commercial suppliers of Electronic Design Automation (EDA) tools pose *"a major barrier"* to the semiconductor industry and Nugent *"would prefer memristor technology was not locked by the same EDA cartels, preventing small business and individuals and many students from developing the technology. As a small company ourselves"* the cost of EDA tools *"represent a significant barrier and we are always on the look for affordable and capable EDA tools."* When addressing the long-term benefits of Qucs-S to Knowm's research, Nugent outlined the broader benefit to the semiconductor industry of software, such as Qucs-S, being available through FOSS licences, *"Open source EDA and the open-source hardware movement is incredibly important to development of novel electronics. Many people around the world would otherwise not have access or even be able to participate*." [S6]

Knowm's software developer, spoke of the importance and benefits of Qucs/Qucs-S to an independent developer, "*I was previously using Verilog-A to implement various memristor models for simulating memristors and running these models in trial versions of commercial tools like Keysight ADS. These tools were way beyond my budget and so I started looking to open-source alternatives like Xyce."* This personal experience of the affordability and accessibility of Qucs/Qucs-S was reinforced while working at Knowm, where the these benefits supported nanotechnology development: *"The ability to support ADMS and the open-source hooks to add support for additional open-source simulators like Xyce were game changers when I started to work with Knowm and their memristors. Having this option lowered the barrier to entry to working with their technology. Along with Knowm's memristors which are affordable and the ability to use lower cost EDA tools it is possible for anyone to conduct their own research into advanced nanotechnologies".* [S6]

The software developer noted that improvements and benefits because of using Qucs-S, "*were immediate in that we were able to have an easy-to-use circuit layout and editor as a front end to various simulators . . . The flexibility and access to the source code allowed for implementing our own Knowm memristor symbol and model implementation. In addition, we were able to create sub-circuit libraries for the various topologies of the Knowm kT-Synapse. This allowed us to simulate complete circuits that use several synapses to simulate things like generalized and reconfigurable logic gates. Using Qucs-S we were also able to simulate dynamic pulse response and other critical design features and have the ability to easily view the simulation output from Xyce in both graphical and plot formats*". [S6]

Librem 5 smartphone

Purism is a tech company founded in 2014 out of concern "*for the exploitative direction of the tech industry."* It is dedicated to delivering "*freedom respecting, privacy protecting, and security focused products and services that people trust, and feel safe in using.*" The Librem 5 phone was designed to fill a gap in the smartphone market for the security conscious and ethical user. Librem 5 was fully developed utilising free and open source software, including Brinson's Qucs-S. As Eric Kuzmenko, hardware engineer at Purism, explained Purism "*used a free software tool called Qucs-S and the free software SPICE-compatible simulation kernel called Xyce to simulate our headphone detect circuit, which included a zener diode used to protect the respective GPIO from too high or too low of input voltage from the audio codec's HP DAC output*." It was the combination of "*Qucs-S and Xyce allowed [Purism] to use the MMSZ4688T1G diode's SPICE model in a circuit that best represented the physical conditions of nothing being inserted into the 3.5mm jack but the HP DAC output being active*." [S4]

Todd Weaver, Purism's CEO and Founder, speaking of the benefits of using Brinson's Qucs/Qucs-S notes that, "*Bringing SPICE compatibility to Qucs significantly widens the applicability of the software to such a large extent that it became the go-to software for all of our simulation needs."* The availability of Qucs-S through a FOSS licence has ensured that Purism is able to develop its products. Weaver stated *"Without Qucs-s there would be no user-friendly way of simulating our circuits with purely free (as in freedom) software. With the current state of FOSS schematic capture software, short of writing huge patches for some other application, the only way to simulate a circuit with Xyce without the use of Qucs-s would require writing a netlist by hand and displaying the results in something like LibreOffice Calc. Qucs-s has made free and open source simulation easily accessible to the world of electronics designers, and we love It".* [S5]

By November 2020, the USD 2,200,000 crowdfunded Librem 5 phone had been mass-produced and shipped to Purism's customers. [S7]

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

S1. Testimonial letter Dr. Wladek Grabinsky, 2020, GMC, Switzerland,

S2. "Knowm – Self Directed Channel Memristors specification", 2019, Knowm Inc., USA, https://www.knowm.com.

S3. Testimonial letter Dr Daniel Tomaszewski, 2020, Instytut Technologii Elektronowej, Warsaw, Poland.

S4. Eric Kuzmenco, "How we designed the Librem 5 Dev Kit with 100% free software", (2019), Purism SPC, San Fransisco, California, USA. Application note available from https://wp.puri.sm/posts/how-we-designed-the-librem-5-dev-kit-with-100-free-software/.

S5. Testimonial letter Todd Weaver, 2020, Purism SPC, San Francisco, California, USA.

S6. Questionnaire Knowm Inc, 2020, Santa Fe, NM, USA.

S7. Purism press statement 18 November 2020 "Librem 5 mass production phone has begun shipping" puri.sm/posts/librem-5-mass-production-phone-has-begun-shipping/