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Engineering for Africa: Our Internet of Things

MJ (Thinus) Booysen

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2022

Professorial Inaugural Lecture

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Engineering for Africa: Our Internet of Things
Ubunjineli be-Afrika: Kwi-Intanethi Yethu yeZinto
Ingenieurswese vir Afrika: Ons Internet van Dinge

Inaugural lecture delivered on 10 May 2022

MJ (Thinus) Booysen
Faculty of Engineering
Stellenbosch University

MJ (Thinus) Booysen

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Biography of author

MJ (Thinus) Booysen is a professor and the chair in the Internet of Things at the Faculty of Engineering at Stellenbosch University. He has been with Stellenbosch University from 2009 and conducts research on the Internet of Things, with a focus on smart energy, water and vehicles (specifically its application to paratransit in sub-Saharan Africa). He is also a founder of BridgIoT (Bridge to the Internet of Things), the founder of Green X Engineering and a co-creator of Geasy and Count Dropula. He is the director of the MTN Mobile Intelligence Lab and a partner in the Stellenbosch Smart Mobility Lab. He is a senior member of the Institute of Electrical and Electronics Engineers, a member of the Institution of Engineering Technology, a Chartered Engineer with the UK Engineering Council and a Professional Engineer (Pr.Eng.) with the Engineering Council of South Africa. He has over 10 years' international industry experience in the aerospace and automotive industries with companies that include SunSpace, Rolls-Royce, Boeing, BMW and Jaguar Land Rover. He has supervised more than 30 postgraduate students and published more than 40 articles in journals and over 50 articles in conference proceedings.

Engineering for Africa: Our Internet of Things

MJ (Thinus) Booysen

Abstract

Our country faces many painful challenges that are tough to solve. The quality of primary education at some of our poorest communities borders on being a crime against humanity. Our levels of inequality and unemployment are unmatched globally. The realities of living in a region with water scarcity and limited energy supplies confront us daily through restrictions. The threat of climate change looms large over our collective existence on the southern tip of Africa. Our road fatalities are some of the highest in the world. The minibus taxi sector, which transports most of our commuters, is notoriously inefficient and unsafe.

Over the past decade I have been fortunate to be in a position where I can use my experience and skills in engineering to work on these challenges experienced by vulnerable communities. In this lecture, I will share several case studies from our joint work, describing both the problems and our journey towards an implemented solution.

Keywords:

Water heater, smart water metering, Internet of Things, minibus taxis, electric vehicles, pothole detection, driver behaviour, user behaviour, energy savings, green buildings, drought response, grid collapse, vehicular networks.

Engineering for Africa: Our Internet of Things

Prof MJ (Thinus) Booysen, Inaugural lecture, Stellenbosch University, May 2022

Engineering for Africa: Our Internet of Things

To understand my research, you need to know a bit about me, who I am and how I came to be this way. I therefore need to take you on a short journey.

I love learning about new things and finding out how things work. Like most embryo engineers, as a child I would take things apart to peek inside and then try to reassemble them. Sometimes successfully. Being the son of a teacher, I also love teaching. More so than my children appreciate. I love to help people, resolve problems and make things better and more just. These things are packaged with a monthly salary in a job that I love very much, most of the time.

From a young age my parents impressed on me the incredible privilege we enjoyed as a family. To start with, we had two steady incomes. My parents reminded us that what we had was not a right or entitlement, and that we should not take anything for granted. They reminded us of the many people who had fewer good things, and more bad things to deal with. This was an early eye-opening to the injustices in our society to which we've become desensitised. And to their credit, this was long before Mandela was released. So, although my dad and mum had to set off for work before 7 every morning, they returned every evening to our safe and comfortable house, sober, cheerful and on time. We had all we needed and then some.

Until age 16 I was drifting. With effort and support from my parents, three teachers put me on my feet. My maths, science and computer science teachers, Teresa Buys, Trudie du Plessis and Sukie van Zyl, changed the direction of my life and unwittingly laid the foundation for a career in engineering.

After living in the UK in the early 2000s, my wife Ronelle and I were struck anew by the inequality and social injustice in SA. In the UK, nobody had to live in a shack. Nobody had to watch effluent flow past their front door. Nobody had to squat over a pit latrine or bucket. Nobody had to wait hours next to the road for a minibus taxi that might never come, and if it finally did might put your life at risk.

So, I am old enough to have experienced the fall of apartheid. However, I have seen enough to understand and bear witness to its legacy and continuing injustices.

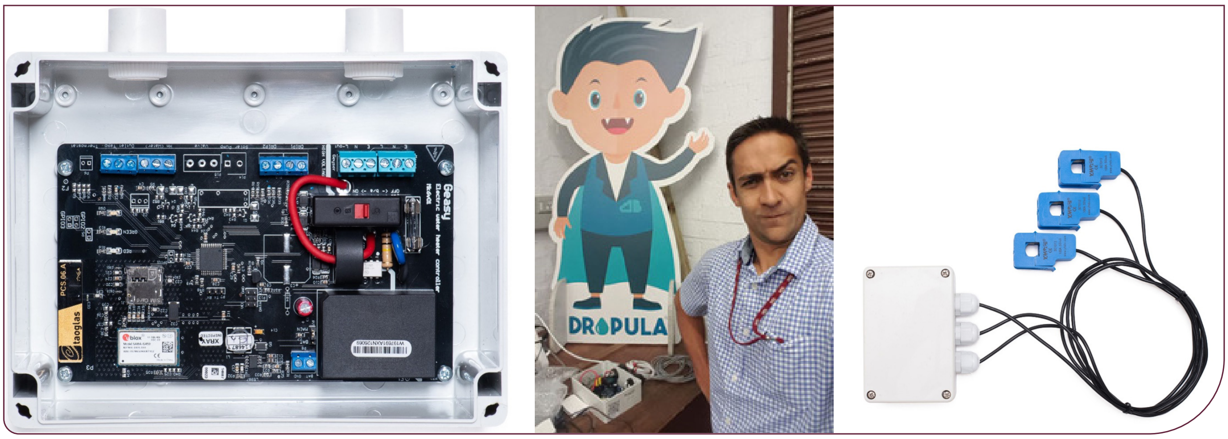
Another factor in my formation was Landsdiens, or "Land service", an environment-oriented youth movement in South Africa. There I learned to appreciate our environment and about our custodianship over it.

In the following whistle-stop tour, I will whisk you through my research on water, energy, schools, minibus taxis and computer vision. Along the way I will mention the names of some of the gifted collaborators and students who were part of these projects. As much as this is a lecture about my research on a technical level, it shows how my research career is inextricably linked to these people and all of us working together. I conclude with a look at the damage the 2020/21 lockdown did to our engineering students' mental health.

Most of our research is funded by Marco Gagiano and his team at MTN through the MTN Mobile Intelligence Lab.

Utilities (Water heating and Day Zero)

1. Booysen, M. J., Engelbrecht, J. A. A., & Molinaro, A. (2013). Proof of concept: Large-scale monitor and control of household water heating in near real-time. http://hdl.handle.net/10019.1/85478



The Internet of Things troika: Geasy smart geyser controller, Dropula smart water meter and Watts-on smart energy meter.

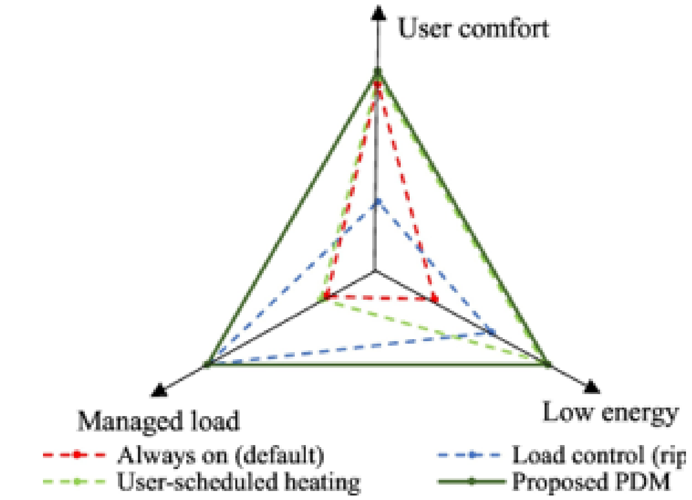
Let's start with energy and water.

Only our colleagues from abroad may be surprised to learn that our electrical grid cannot meet the demand and we therefore suffer rolling regional blackouts, or "load shedding", to keep the grid from collapsing. The problem is one of load, or kilo-Watt, and of energy, or kilo-Watt-hour. This problem was predicted from the late nineties and has been with us since April 2008. To compound the issue, our electricity generation is heavily dependent on coal, which means that for every unit of electricity generated, Eskom pumps a kg of earth-warming CO_2 into the air we breathe. This may be adding to one of our country's other problems – severe water scarcity and recurring droughts. In 2017/2018, Cape Town faced the so-called "drought of a century" and came very close to the fateful "Day Zero", when our taps would run dry. Gqeberha (Port Elizabeth) is currently in a similarly dire state.

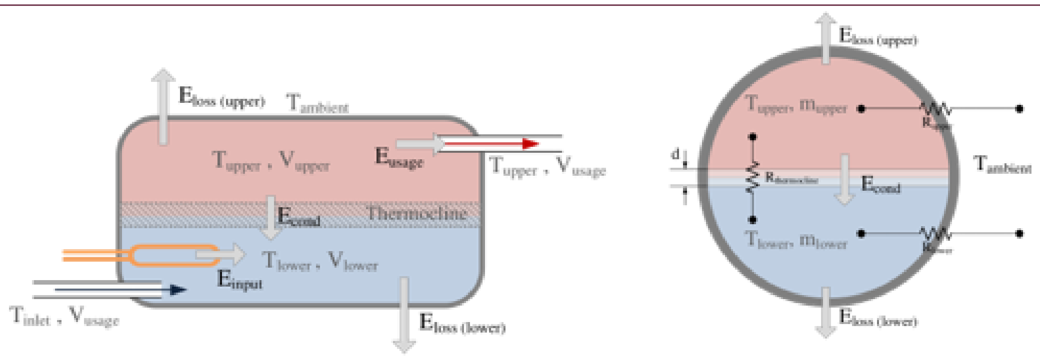
In that context, let's consider three Internet-of-Things devices we've developed in the last few years. We have used these in many of our research projects. The first is Geasy, our home-grown smart electric water heater controller, which remotely controls and monitors temperature, electricity, water and a few other things. Then there is its younger sibling, Count Dropula, which does high resolution water metering. And there is Watts-on, which measures and reports electricity usage. We have made a few other devices, such as a mobile phone-based spectrophotometer to measure water quality, a driving behaviour sensor, quite a few mobility trackers, and other devices. But those three are the devices that we've used to generate most of the research you'll see in the following slides.

2. M.J. Booysen, A.H. Cloete, "Sustainability through intelligent scheduling of electric water heaters in a smart grid", IEEE International Conference on Big Data Intelligence and Computing (Datacom), Auckland, New Zealand, 2016. https://doi.org/10.1109/DASC-PICom-DataCom-CyberSciTec.2016.145

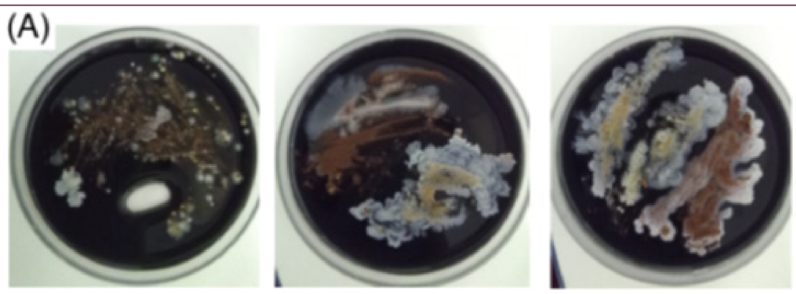
3. Nel, P. J. C., Booysen, M. J., & van der Merwe, B. (2016). A computationally inexpensive energy model for horizontal electric water heaters with scheduling. IEEE Transactions on Smart Grid, 9(1), 48-56. https://doi.org/10.1109/TSG.2016.2544882



Electric water heaters (geysers) with user comfort, grid load, energy efficiency and bacterial control (not shown) pulling in different directions.



Two-node stratification model for horizontal water heaters.



Legionella cultures collected from decommissioned water heaters.

4. Roux, M., Apperley, M., & Booysen, M. J. (2018). Comfort, peak load and energy: Centralised control of water heaters for demand-driven prioritisation. Energy for Sustainable Development, 44, 78-86. https://doi.org/10.1016/j.esd.2018.03.006

5. W. Stone, T.M. Louw, G. Gakingo, M.J. Nieuwoudt, M.J. Booysen, "A potential source of undiagnosed Legionellosis: Legionella growth in domestic water heating systems in South Africa", Energy for Sustainable Development, Volume 48, pp. 130-138, Feb 2019. https://doi.org/10.1016/j.esd.2018.12.001

Let's start with electric water heaters, or "geysers", as we call them in South Africa. In 2012 Martin Weiss introduced me to the world of smart control of geysers, with the aim of doing energy management, reducing the burden on Eskom with demand management, and detecting leaks before water damage can occur. Because of their capacity to store thermal energy and their large power burden on the grid, these devices were early on identified for smart control in Internet-of-Things applications.

In 2014 we started developing our own geyser controller, the Geasy, as part of the master's research by Philip Nel, Jonathan Brown, Andrew Cloete, Nico Naude, Matthias Thoma and Lowku Leeuwner. In 2015 Martine Visser from the University of Cape Town (UCT) introduced me to Jay Bhagwan from the Water Research Council. He was quick to see the benefits of our smart geyser controller. He funded a pilot project in Mpumalanga, through which we installed 200 Geasies for demand management.

But effective demand management must balance user satisfaction, total energy used, load on the grid at any moment, and health concerns due to bacterial growth at lower temperatures. To achieve this balance, while at the same time processing the flood of sensor data from the five million devices in South Africa, requires computationally efficient thermo-electric models. Several factors influence the effective management of these devices: heat losses and thermal conduction to the environment, the amount of warm water used, the temperature of the water used, the inlet water temperature, and stratification inside the tank due to buoyancy. The orientation of the device is therefore important. Horizontal water heaters are ubiquitous in developing countries, but no computer model had been created for this orientation, as developed countries more commonly usie vertical water heaters. Another factor we had to find a way to model was the thermal impacts of loadshedding and the South African habit of switching the heater on and off to save costs. In 2016 Philip Nell, Brink van der Merwe and I published the first model for horizontal water heaters that also made provision for electrical scheduling. This model has allowed us to start evaluating control strategies so we can propose balanced control for large-scale management, like the one we published with Mark Apperley and Marcel Roux in 2018.

Since we expected the water heater to be colder at the bottom, we expected bacterial growth. Wendy Stone and I, with the support of PlumbGuarantee, cut open decommissioned water heaters, and took water samples from active water heaters. With the help of Tobi Louw and Martin Nieuwoudt, we published the results, which showed the presence of Legionella in every sample we took.

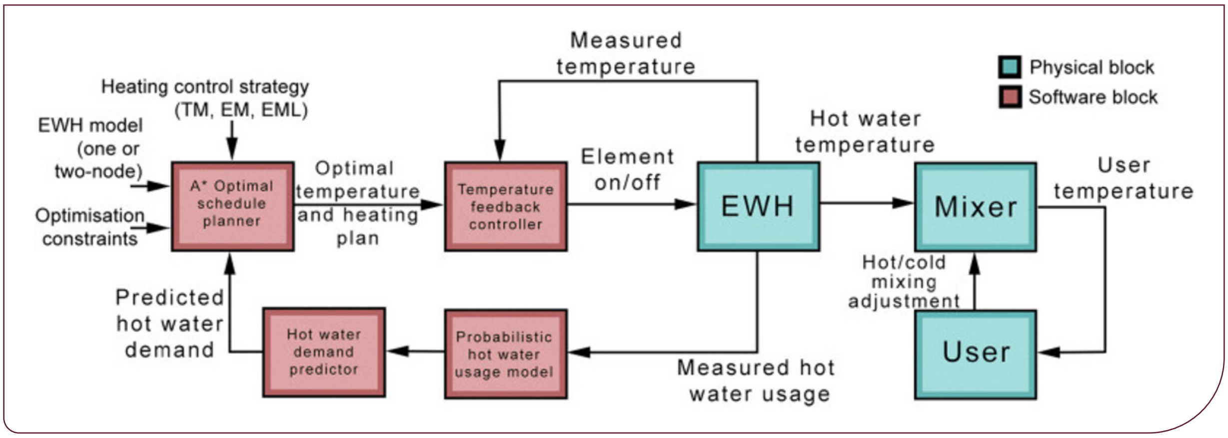
However, just like my children, users in the real world do not submit readily to controlled environments. As my students and colleagues can attest, we strive to generate results from research that answer actual real-world questions. To ensure that our simulations did not stay just that, in 2021 Japie Engelbrecht, Michael Ritchie and I used our records of usage from actual water heaters to develop a probabilistic hot water usage model for all and sundry to use. With this model, realistic users can be simulated to get more realistic, though less impressive, results. A further step towards realistic results was to use exergy, or thermal energy per volume of water, a more appropriate metric, as suggested by Andrew Cloete. From this, Michael created a mixer tap model, to include the effect of people using the hot and cold taps to get the desired temperature. And then we struck gold – we took advantage of Japie's PhD aircraft control expertise to develop a proper optimal control with Dynamic Programming and the A* method, which accommodated the realistic variations in user behaviour. Our results demonstrated savings of between 8 and 18% for a known usage profile. The savings for predicted usage were 2% for a temperature-matched strategy, and 10% for energy-matched strategies. In the process Michael published seven journal articles in just under three years and effectively

6. Ritchie, M. J., Engelbrecht, J. A. A., & Booysen, M. J. (2021). A probabilistic hot water usage model and simulator for use in residential energy management. Energy and Buildings, 235, 110727. https://doi.org/10.1016/j.enbuild.2021.110727. 13 citations in 2 years.

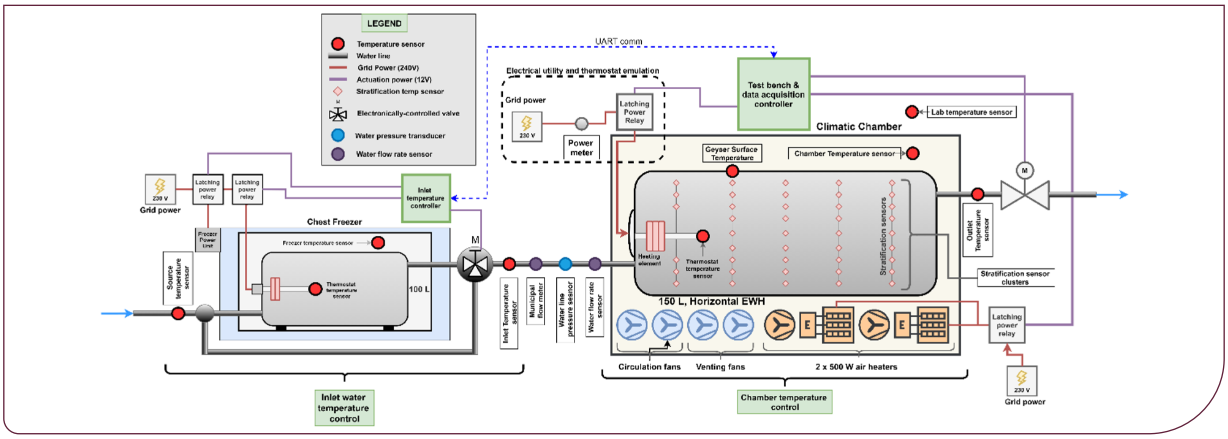
7. Booysen, M. J., et al. "How much energy can optimal control of domestic water heating save?." Energy for Sustainable Development 51 (2019): 73-85. https://doi.org/10.1016/j.esd.2019.05.004.

completed a master's and PhD in two years.

With the introduction of increased renewable generation to the South African grid, an important question is to what extent large solar PV can be used at a city level to offset the heavy demand from water heaters, and to what extent machine learning can be used to manage the scheduling. This is what Paseka Mabina, Peter Masuku and I are currently exploring.



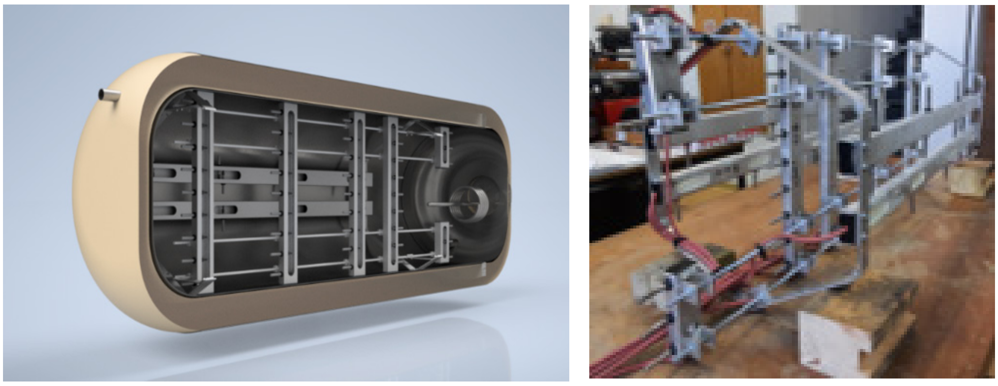
Our simulation setup, with which we implement and assess water heater control strategies with realistic user patterns.



Our setup with which we characterise the stratification of hot water inside horizontal electric water heaters.

8. van Schalkwyk PD, Engelbrecht JAA, Booysen MJ. Thermal Stratification and Temperature Variation in Horizontal Electric Water Heaters: A Characterisation Platform. Energies. 2022; 15(8):2840. https://doi.org/10.3390/en15082840

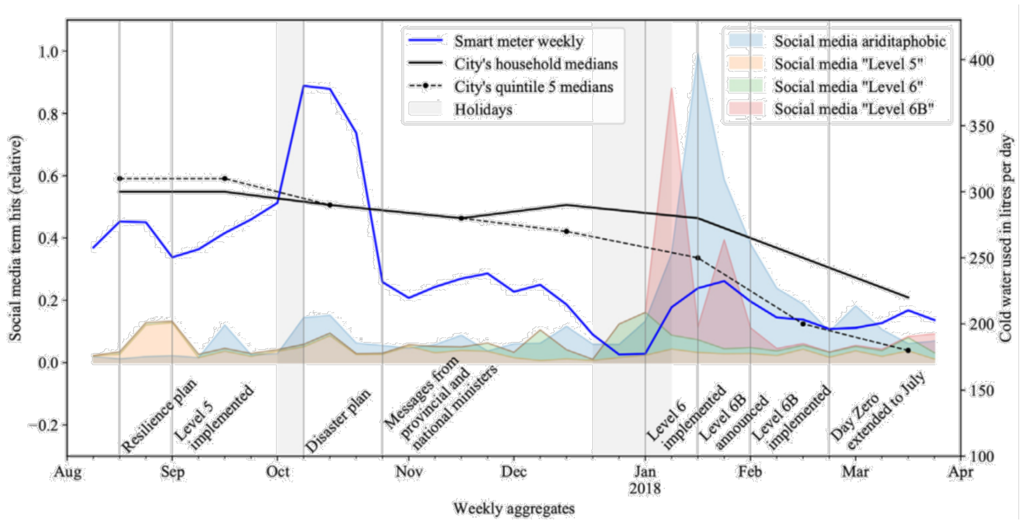
9. Booysen, M.J., Visser, M., & Burger, R. (2019). Temporal case study of household behavioural response to Cape Town's "Day Zero" using smart meter data. Water research, 149, 414-420. https://doi.org/10.1016/j.watres.2018.11.035



The designed and actual sensor system measuring the temperatures inside the tank.

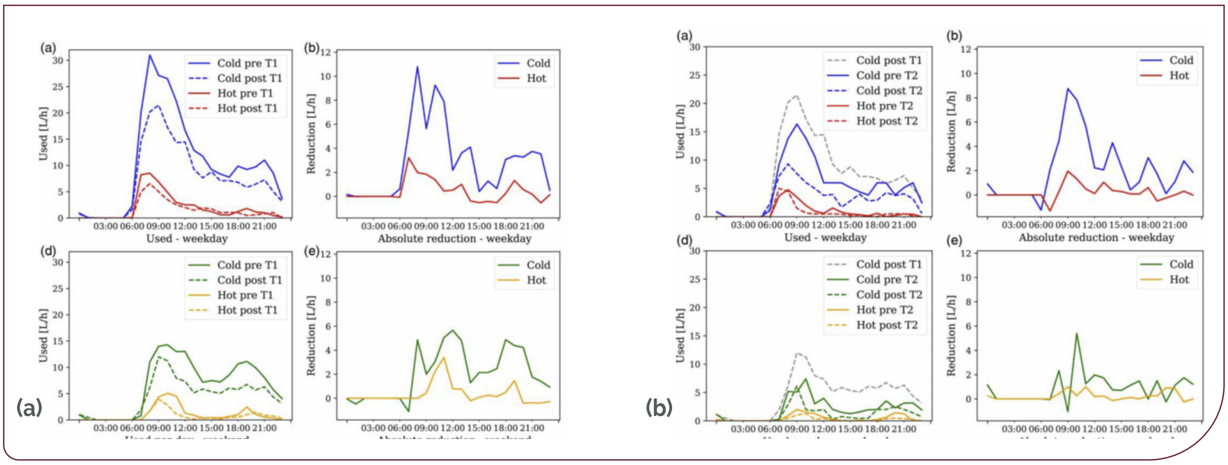
In the same spirit of questioning the validity of our results, we then turned to the geyser's innards. We asked ourselves the difficult question: do we really understand what is happening inside this obscure body of pressurised hot water in the horizontal orientation? To answer this question, we built ourselves an environmentally controlled characterisation system that controls all the parameters for the water heater and measures what happens inside the tank. It controls multiple valves (including the mixer), heaters, fans, the power, two geyser's elements, a freezer to cool down inlet water to icy winter temperatures, and so on. It also measures air and water temperatures and the temperature at various points inside the tank with a series of 67 temperature sensors. We did tests in which the tank heats up and cools down, both with and without water being drawn, to represent typical usages.

The results, which Daniel van Schalkwyk, Japie, and I published in April 2022, revealed a fascinating world of buoyancy, thermal conduction and vortices, hitherto unimagined. The next step will be to develop a state space estimation for the temperatures in the tank and give machine learning a chance to improve the model further.



The Day Zero drought response as seen by Count Dropula, our smart water meter.

Let's move on from energy to another passion: water. In 2017/2018 Cape Town faced an existential crisis that now seems like a distant memory. Because of my neuroticism and subscribing to the world according to our local worrywart, talk radio host John Maytham, I goaded my team into action to respond to the drought as dam levels dropped and anxiety mounted. We converted our geyser controllers into water meters and had a few Geasies and Dropulas installed in Mpumalanga and the Western Cape. These gave us a unique vantage point to observe in real time, not in months but in minutes and hours, how households responded to the drought as the crisis unfolded. Specifically, we were able to see how water consumption changed as water restrictions were imposed, politicians dithered and damage-controlled, and the media sensationalised. Ronelle, Martine Visser and I also looked at behavioural changes in reaction to the monthly usage on municipal bills and the panic on social media. We found that our sample group did not respond to the restrictions, but they did respond to the panicky fallout from the government's Disaster Plan and the resulting media frenzy.



The daily user response at different times of the Day Zero drought. Top is weekdays and bottom weekend days; (a) Change in October 2017; (b) Change in February 2018.

The study clearly showed the value of smart metering for analysing and managing a natural disaster like a drought. Cheroline Ripunda and I then analysed in more detail the responses to the drought at different stages. We wanted to see at what hours of the day people changed their behaviour at two key points during the drought. We found that at the beginning people mainly reduced their morning and evening usage, probably using less water for showering or bathing. In the later dire stage of the drought, water usage dropped by an even larger percentage in the mid-mornings, when householders were not at home. We realised that in their initial efforts to save water people had not taken into account the water their domestic workers used for household cleaning – an important lesson for the next drought.

Let's move to schools. Having had a good education myself and being aware of what it has done for me, I find the South African educational landscape distressing. It kills me that the divide is so wide that many of the privileged are unaware of, or do not acknowledge, the squalor and brokenness of our poor schools. I

10. M.J. Booysen, C.K. Ripunda "When usage matters: time-of-use analysis of Cape Town's Day Zero drought response", Water Science and Technology, 2021. https://doi.org/10.2166/wst.2021.324

believe that at the post-mortem, with hindsight, primary education will be fingered as the worst failure of the development project in South Africa, both before and after apartheid. The advocacy work done in this domain makes Servaas van der Bergh and Nic Spaull two of our university's and our country's most important researchers and living legends in my eyes.

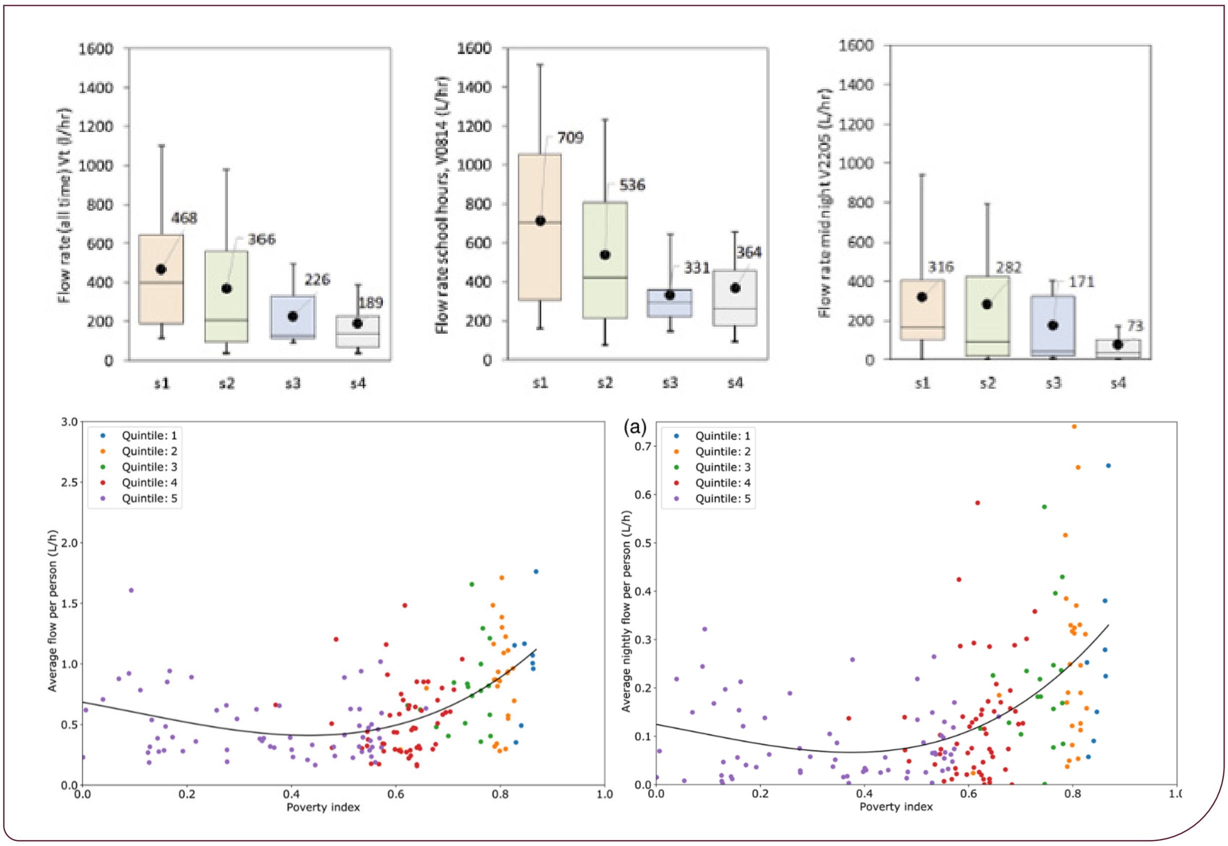
Six schools of different levels of affluence, all withing a 5 km radius.

My engineering background does not give a direct avenue to the improvement of education, but there was one need in the education ecosystem that I could help with: infrastructure and monthly water and electricity bills. To start off with, we looked at the property and building size and facilities in aerial photos of six schools, primary and secondary, arranged in order of affluence from left to right. On the left we see swimming pools and tennis courts and green playing fields; on the right we see smaller and smaller properties with buildings occupying more and more of the space. The schools on the left had an average of 650 children; those on the right 1,300. All six schools are within a 5 km radius of this very spot, this high-tech podium from which I speak.

Schools

11. Booysen, M. J., Visser, M., & Burger, R. (2019). Temporal case study of household behavioural response to Cape Town's "Day Zero" using smart meter data. Water research, 149, 414-420. https://doi.org/10.1016/j.watres.2018.11.035.

12. M.J. Booysen, C.K. Ripunda "When usage matters: time-of-use analysis of Cape Town's Day Zero drought response", Water Science and Technology, 2021. https://doi.org/10.2166/wst.2021.324



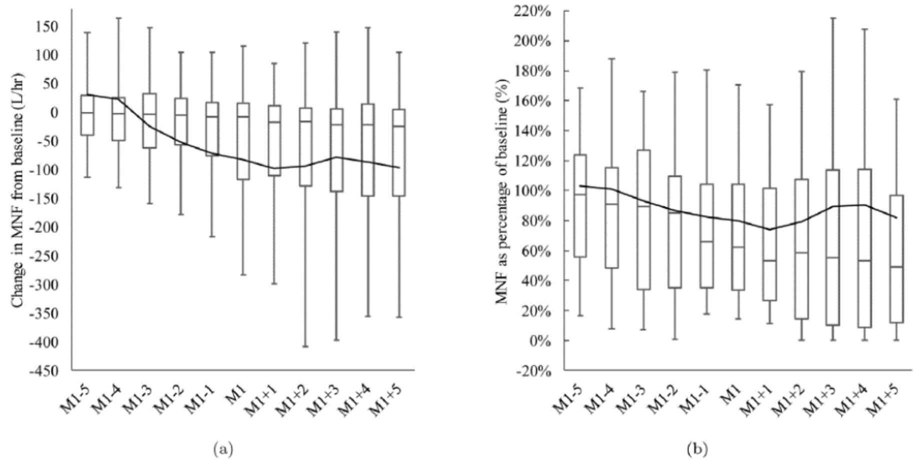
Water usage at schools of different affluence at different times of the day.

Let's look at how these schools compare in their water consumption. Count Dropula, our smart water meter, gave us a treasure trove of time-based information. By breaking up the usage into hourly segments, we could analyse daily usage separately from school-hour usage and midnight-hour usage. The upper plots show the hourly flow for the buildings and the lower ones the hourly flow per pupil. Each of the plots captures the flow rate according to the schools' affluence. In the top plot the poorest schools are on the left and in the bottom plot they are on the right. It is striking how much more water the poor schools use per hour than the affluent schools. The difference is starker yet during the midnight hours, when no one is supposed to be at school and any apparent flow is essentially wasted water and money. These losses are especially prevalent in schools with large and old infrastructure that they cannot manage. However, this failure is a consequence of lacking skills, accountability and awareness rather than budgetary constraints. My understanding is that principals can apply to use their maintenance budgets to plug other holes, leading to breakdowns that must be funded centrally at much greater cost.

Ashantha Goonetilleke, Buddi Wijesiri, Cheroline Ripunda, Stefan Gerber and I published on this topic in 2019 and 2021. I have not seen evidence of any improvement, and am not sure if I expect to.

13. Samuels, J. A., Grobbelaar, S. S., & Booysen, M. J. (2020). Light-years apart: Energy usage by schools across the South African affluence divide. Energy Research & Social Science, 70, 101692. https://doi.org/10.1016/j.erss.2020.101692.

14. Booysen, M. J., Samuels, J. A., & Grobbelaar, S. (2021). LED there be light: The impact of a lighting efficiency campaign at poor schools in South Africa. https://doi.org/10.1016/j.enbuild.2021.110736.



Results of a maintenance campaign at schools during the Day Zero drought.

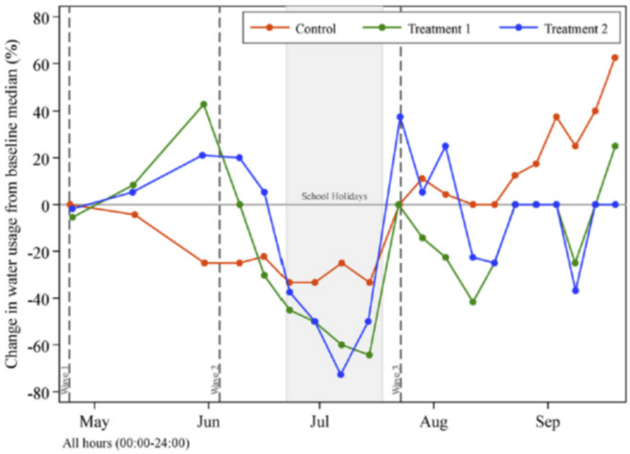


Fig. 1. Median change in water usage from baseline median by treatment group.

Results of a behaviour change campaign at schools during the Day Zero drought.

During the drought we teamed up with Cape Talk, Shoprite, the Western Cape Education Department, UCT and Bridgiot, our InnovUS spinoff, to run a water-saving campaign at 350 schools. We were delighted that 93 corporates signed up to sponsor maintenance and behavioural campaigns at the schools, which Jurie, Jackie, Heinrich, Philip, Arno and the rest of the Bridgiot team executed. In the first phase we spent R5,000 per school on very basic maintenance such as replacing tap washers. The results, published with Cheroline and Martine, showed the average reduction in midnight flow was 28% after the maintenance. For the median school, the savings paid for the investment within five weeks, despite the relatively low cost of water. A year

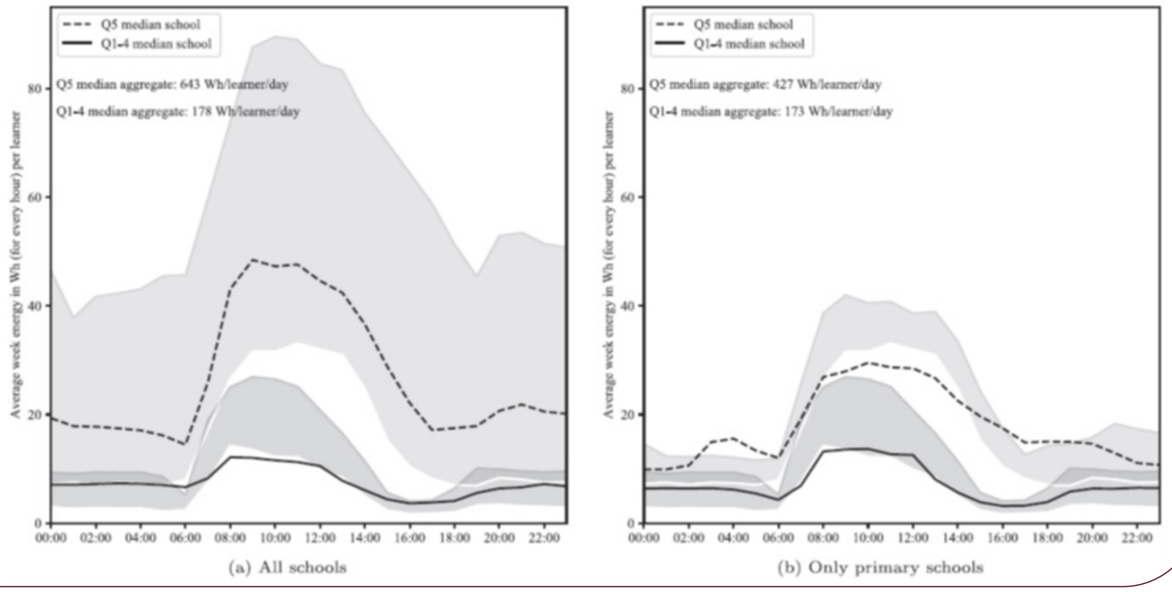
15. Samuels, J. A., Grobbelaar, S. S., & Booysen, M. J. (2020). Light-years apart: Energy usage by schools across the South African affluence divide. Energy Research & Social Science, 70, 101692. https://doi.org/10.1016/j.erss.2020.101692.

16. Booysen, M. J., Samuels, J. A., & Grobbelaar, S. (2021). LED there be light: The impact of a lighting efficiency campaign at poor schools in South Africa. https://doi.org/10.1016/j.enbuild.2021.110736.

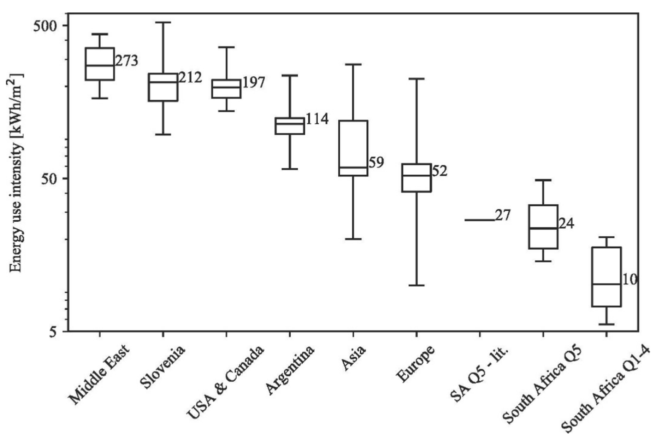
later Stefan and I showed that unfortunately only the affluent schools were able to sustain their reduced losses with continued maintenance.

Also during the drought, we did a controlled study where we placed the schools into three groups. The first (the control group) were left in the dark about their usage, the second were notified of their usage, and the third were notified and able to compete for a reward. Compared to the control group, the two behavioural intervention groups reduced their water usage by 15 to 26%, as shown in the paper I published with Martine and her team at UCT.

Next, we moved on to electricity. We investigated the energy footprint of schools with support from Stellenbosch Municipality.

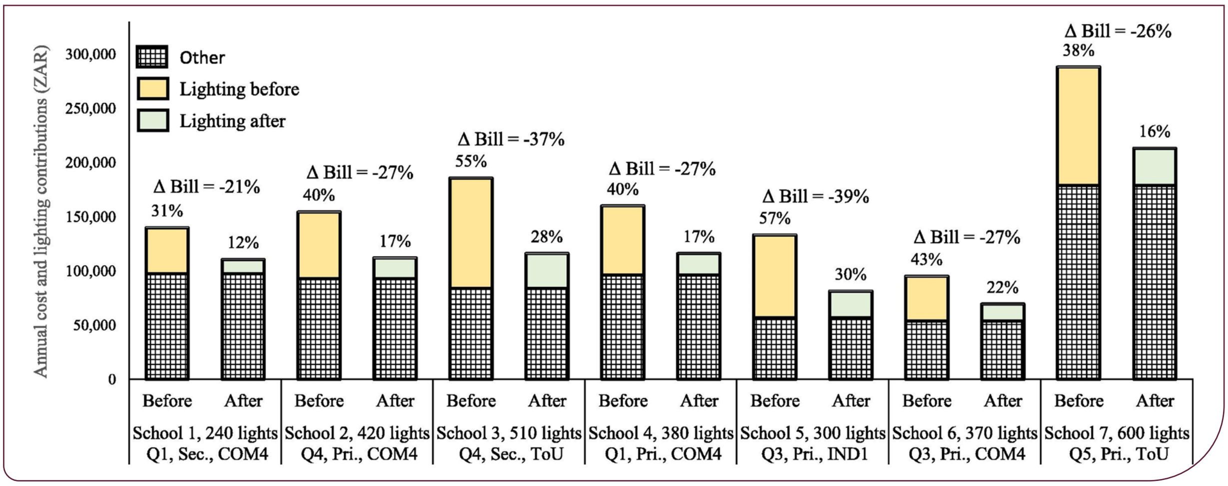


The yawning gap between the electricity used in affluent (Q5) and poorer (Q1-4) schools.



Energy densities for schools in the rest of the world, compared with those in South Africa.

Although we expected a difference between the rich and poor schools, even we were surprised by its magnitude. Jason Samuels showed in his publication with Saartjie Grobbelaar and me that a yawning gap exists between the haves and the have-nots. The median Quintile 5 primary school uses 427 units of electricity a day; the median Quintile 1 to 4 school a mere 173. You may think the poorer schools are being energy-efficient, but no: they just lack infrastructure investment. An outlier is the poorer fee-paying schools that used to be Model-C (in other words, whites-only) schools in the old dispensation. They have large buildings and depend on mostly poorer parents' contributions and are on punitive tariffs. Jason held interviews with their principals, who were close to tears over their out-of-control electricity bills. We also compared our schools' usage, or "energy densities", with that of schools in other countries. Our affluent schools have energy densities only 13% as much as those in North America, and our poor schools only 5%. We found that lighting accounted for 40% of electricity costs at our schools, with a singular floodlight being responsible for 7% of one school's bill.



The contribution of lighting to electricity bills at schools (yellow) and the potential for savings when rolling over to LED lighting (green).

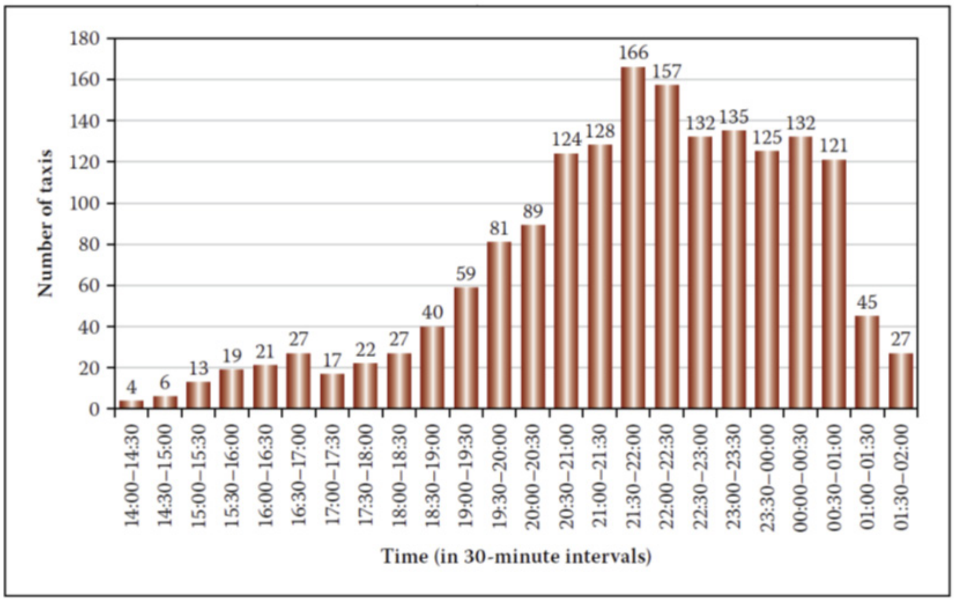
Hence our attention turned to lights at schools. We established that most schools were using old fluorescent tubes. Given the large contribution of lighting to their bills, the cost saving of using more efficient LED lights would be substantial, to say nothing of the energy saving. Jason ran some lab experiments and predicted that a poor school would save approximately 27% on its electricity bill if we could help them upgrade their lights. Leslie van Rooi and his team at Stellenbosch University's Division for Social Impact quickly grasped the huge potential benefits of the project and funded the replacement at local schools in poorer areas. Well, Jason is not one to let the grass grow under his feet. Before I knew it, we had secured additional funding from Salie Abrahams' and Gerrit Coetzee's team at the Western Cape Education Department to support 25 schools in Stellenbosch and Paarl, with support from Frans Rossouw and Mario Roos. The savings were enormous, with some schools reducing their total bill by as much as 39%.

17. M.J. Booysen, B. Wijesiri, C. Ripunda, A. Goonetilleke "Fees and governance: Towards sustainability in water resources management at schools in post-apartheid South Africa," Sustainable Cities and Society, vol 51, 2019. https://doi.org/10.1016/j.scs.2019.101694.

18. M.J. Booysen, S. Gerber "Water scarcity and poverty Water scarcity and poverty: The lasting impact of a maintenance campaign at South African schools across the affluence divide", Water Science and Technology, 2021. https://doi.org/10.2166/wst.2021.424

Subsequently, we spun off GreenX with Anita Nel and the University's Technology Transfer Office, InnovUS and Jason is currently working on installing smart meters and replacing lights at even more schools in the Western Cape. We are also in advanced discussions with the Department of Basic Education to take the programme national.

Currently, Rita van der Walt, Saartjie and I are busy with a sensing system with which we will measure the temperatures, air quality, light quality, and so on in various classrooms. At the same time, Terhemba Michael-Ahile, Jason and I are developing an electricity synthesiser, with which we will be able to build a digital twin for schools.



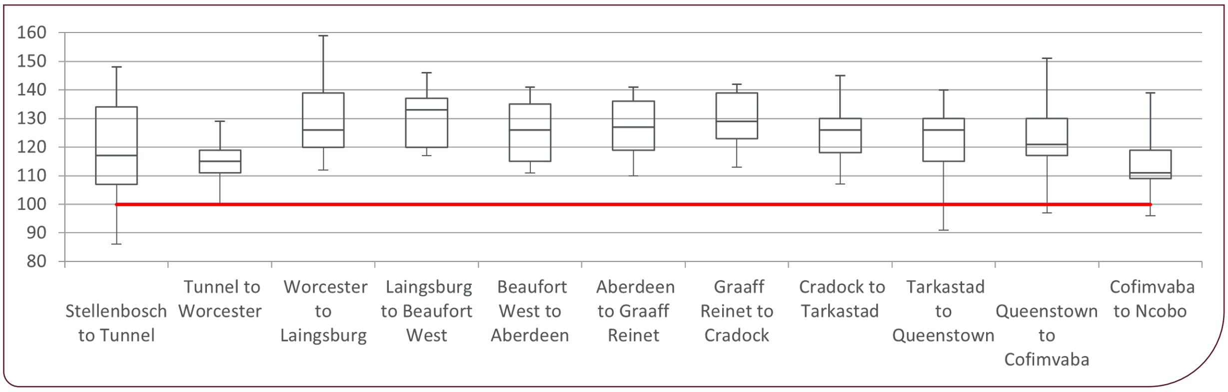
Minibus taxis counted driving on the N1 from the Western Cape to the Eastern Cape on a Friday evening.

One of the Stellenbosch taxis we tracked, which was on the road again a few weeks later.

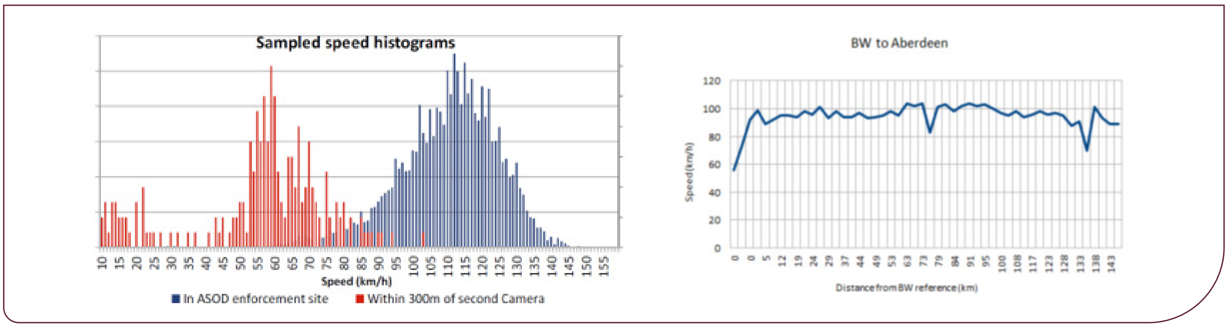
One of the many things that stayed with me upon our return from the UK and New Zealand, was the confidence with which you could expect to survive a simple road trip in those countries. Another was the efficiency of the public transport systems. Getting places was safe, reliable and relatively efficient, albeit rigidly organised. While struggling with the corrections to my PhD thesis a decade ago, I took a sneak peek at our local, ill-understood and disorganised public transport system to see whether there were opportunities for improvement. My fascination with the informal minibus taxi sector was quickly piqued and we started investigating two things: driver behaviour and system efficiency.

The minibus taxi sector, a transport system operating somewhere between the public and private spheres, known as "paratransit" in North America, carries most commuters in South Africa and sub-Saharan Africa. Unfortunately, this civil society response to an unsupportive apartheid government has become uncivil. It is notorious for violence, unsafe driver behaviour and inefficiency. But the other side is also true: it is organic in nature, responds to passenger demands, serves the poor with more enthusiasm than the government does, and is a major job creator. Just in South Africa there are approximately 200,000 minibus taxis.

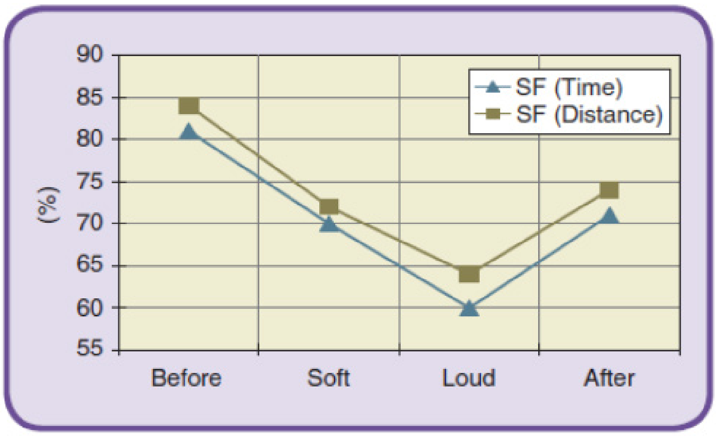
A breakthrough was when I received funding for a bursary from then Dean of Research, Willie Perold, and 10 tracking devices sponsored by Catherine Lewis from MiX Telematics. The trackers, installed in Stellenbosch taxis, allowed us to capture mobility data for over two years, providing a wealth of material for interesting research. It is amazing how the active participation of key people at crucial times can kick open doors to unforeseen opportunities.



Speeds recorded between the Western Cape and the Eastern Cape.



Speeds observed within 300m of Average Speed Enforcement camera, and on the rest of the journey.



Response to our auditory speed adaptation.

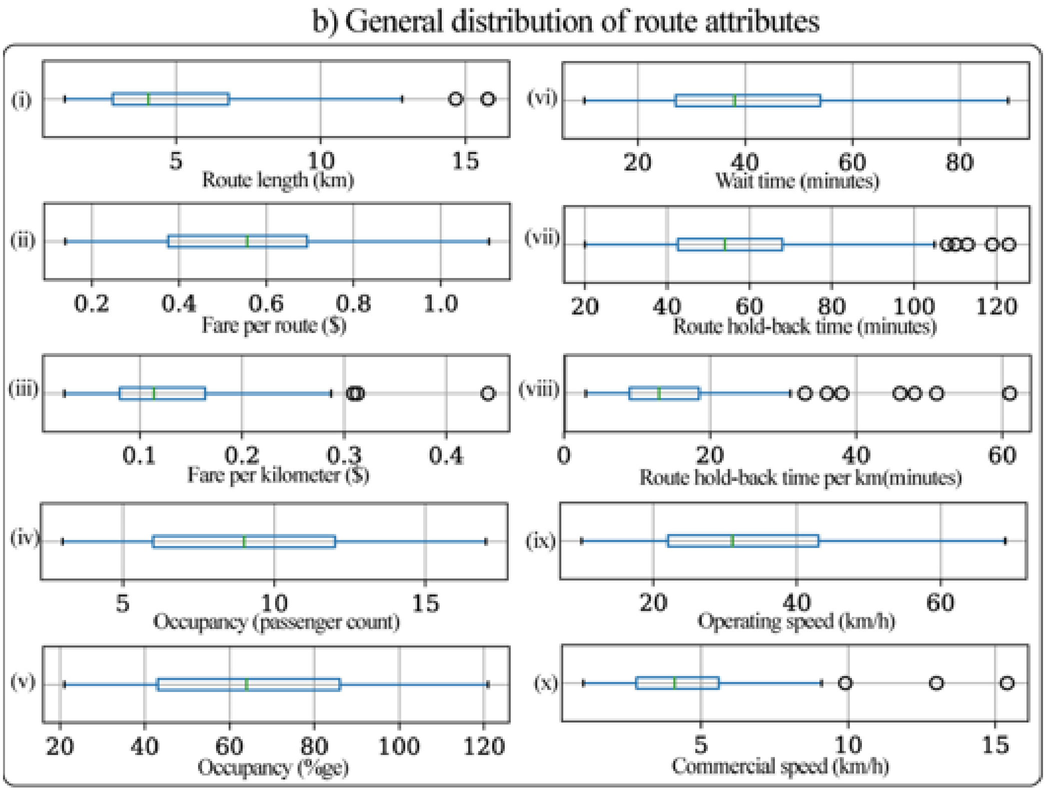
The first item we tackled was safety. You may not realise this, but while most people in our sphere of privilege are fast asleep on a Friday night, many people who hail from there take part in a miniature Groot Trek to the Eastern Cape. These journeys are often undertaken for funerals, weddings and other ceremonies. The taxi departs at around 9 pm on a Friday evening and returns from its 2,400 km journey 56 hours later, in time for the 15 passengers to start work by Monday morning. Minibus taxis are allowed to drive at speeds of up to 100 km/h. We recorded average speeds exceeding that for every leg of the journey. But worse than that – they exceeded the 120 km/h legal limit for a normal passenger vehicle for most of the journey.

When we evaluated compliance to the average-speed-over-distance speed enforcement, we found that most drivers did not understand how it worked, as evidenced by their slower speeds 300 m away from the speed camera. To try to influence their behaviour, we installed auditory speed adaptation (a speed-triggered buzzer) that activated when the driver exceeded the limit. In the first phase the buzzer was so low the driver could drown it out with music. In the second phase it was too loud to be ignored. Through this very simple technological intervention, we managed to bring the speeding frequency down from 81 to 60% of samples. After we disabled the sound, the frequency returned to 71%, still lower than the original 81%.

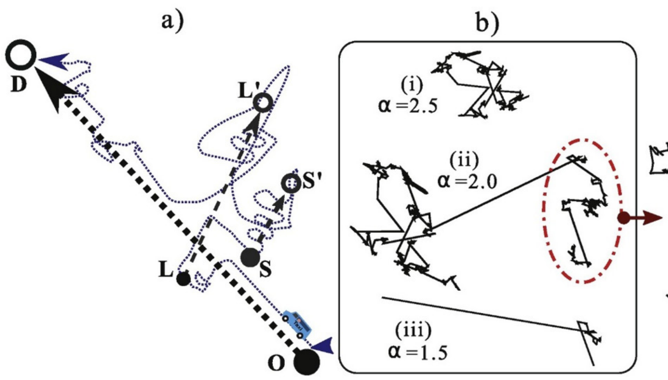
Publications by Adriaan Zeeman and Nelson Ebot Eno Akpa, with me, Marion Sinclair and Johann Andersen, brought us into close contact with this alternative transport world. For one thing, lily-white, Afrikaans-speaking, and unlicenced Adriaan ended up driving a taxi on the N1 when the driver was too tired. Unfortunately, we had zero impact on policy and were unsuccessful in securing further funding for this important line of research. Interesting factoid: the Toyota Quantum minibus was developed for the local market and is based on the popular international Toyota Hiace. The main difference? The engine: the international Hiace has a top speed of 135 km/h; the local Quantum can reach 175 km/h. It appears that despite our inseparable fates on our shared potholed roads, the lives of the poor do not matter enough for the authorities to take notice.

19. M. Visser, M.J. Booysen, K. Berger, J. Brühl , "Saving water at Cape Town schools by using smart metering and behavioural change", Water Resources and Economics, 2021. https://doi.org/10.1016/j.wre.2020.100175.

20. Booysen, M. J., Ripunda, C., & Visser, M. (2019). Results from a water-saving maintenance campaign at Cape Town schools in the run-up to Day Zero. Sustainable Cities and Society, 50, 101639. https://doi.org/10.1016/j.scs.2019.101639.



Operational analysis of urban minibus taxis.

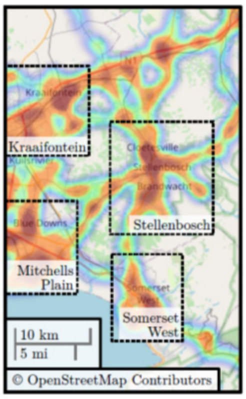


Lévy flight describes the movement pattern of taxi drivers when "hunting" for passengers.

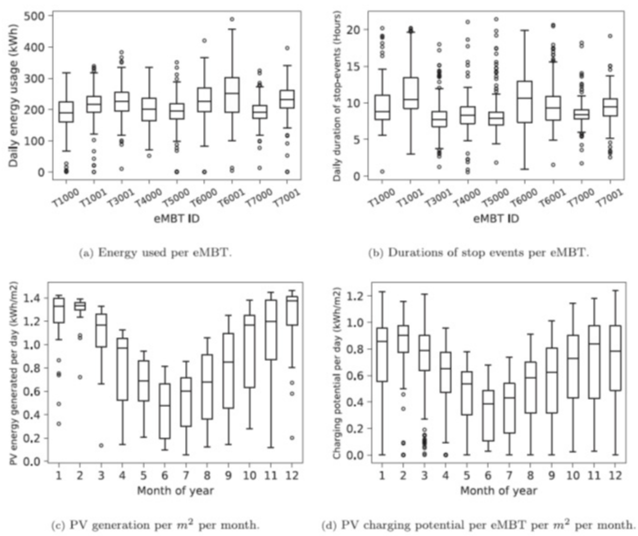
21. Samuels, J. A., Grobbelaar, S. S., & Booysen, M. J. (2020). Light-years apart: Energy usage by schools across the South African affluence divide. Energy Research & Social Science, 70, 101692. https://doi.org/10.1016/j.erss.2020.101692.

22. M.J. Booysen, J. Samuels, S.S. Grobbelaar, "LED there be light: The impact of a lighting efficiency campaign at poor schools in South Africa", Energy and Buildings, 2021. https://doi.org/10.1016/j.enbuild.2021.110736.

In addition to safety, we also evaluated the minibus taxis' efficiency and mobility patterns. This work was mostly spearheaded by my first PhD student, Innocent Ndibatya from Uganda. We used tracking devices to characterise the mobility of minibus taxis in Kampala and were the first to measure and quantify the "hold-back" time, so common with urban minibus taxis waiting at informal stops to fill up with passengers. We broke further ground by recording the taxis' movement patterns and demonstrating that the drivers, on the hunt for passengers, perform what is known as a "Lévy flight", a term used by biologists to describe the patterns made by foraging animals. Little did Innocent and I realise that we were in fact laying the foundation for research on decarbonising paratransit.



Area investigated for electrification of minibus taxis in and around Stellenbosch.



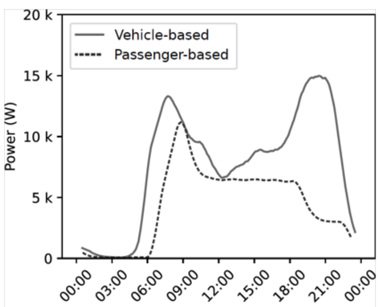
Energy requirements and charging potential for electric minibus taxis in Stellenbosch.

Paratransit

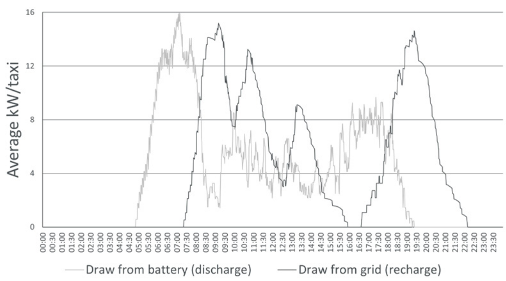
23. Akpa, E. E. N., Booysen, M. J., & Sinclair, M. (2016). A comparative evaluation of the impact of average speed enforcement on passenger and minibus taxi vehicle drivers on the R61 in South Africa. Journal of the South African Institution of Civil Engineering, 58(4), 2-10. http://dx.doi.org/10.17159/2309-8775/2016/v58n4a1

In 2018 Mark Apperley, from Waikato University, and I discussed the sustainable electrification of transport in Africa and roped in Kevin Buresh to do the heavy lifting. We looked at the potential for saving the grid by offering solar photovoltaic charging points at large employers like the University. Then in 2020 a Mechatronic Engineering graduate from East London, Chris Abraham, joined our team to work on the electrification of the paratransit system. Supervised by me and Arnold Rix, he developed a simulation platform that incorporates a mobility model, an electric vehicle model and renewable solar generation. Since then, Chris has published three ground-breaking papers and a book chapter on the electrification of minibus taxis in various sub-Saharan cities and has another paper under review. We established the energy needs of urban electric minibus taxis and their drain on the grid. With support from Larissa Füßl from Reutlingen, we also evaluated the impact of wind power and battery storage to reduce the taxis' load on the grid. All these efforts won us a World Bank contract, in a consortium with Transitec and Oxford University, to assess the effect of decarbonising a fleet of minibus taxis on the vehicles, the taxi rank's electrical infrastructure and the local grid.

Again, testing the validity of our assumptions and models, we are developing a micro-mobility energy model for minibus taxis by measuring their every move on various routes. This is proving to be extremely useful to confirm the energy requirements of electric minibus taxis in realistic scenarios. This work is being done by Johan Giliomee and me in collaboration with Chris Hull, Katherine Collett and Malcolm McCulloch at Oxford University.



The problem with paying people to do a device's job.



Average taxi's draw from the vehicle battery when moving and drawing power from the grid when charging the battery while stationary.

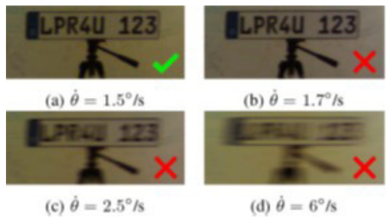
24. Booysen, M. J., Andersen, S. J., & Zeeman, A. S. (2013, October). Informal public transport in Sub-Saharan Africa as a vessel for novel Intelligent Transport Systems. In 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013) (pp. 767-772). IEEE. https://ieeexplore.ieee.org/document/6728324/

25. Akpa, N. E. E., Booysen, M. J., & Sinclair, M. (2016). Auditory intelligent speed adaptation for long-distance informal public transport in South Africa. IEEE Intelligent Transportation Systems Magazine, 8(2), 53-64. https://doi.org/10.1109/MITS.2016.2533979.

We evaluated publicly available datasets and quickly established that passenger-based transport-engineering datasets are not good enough for modelling the electrical demand of vehicles or the grid. This can be seen when comparing the electrical demand modelling based on standardised passengers with that using vehicle-based tracking data. To model demand accurately, we need GPS tracking data, which is not susceptible to human hours and tendencies and, more importantly, stays with the vehicle, come what may.

Through all this research, it became clear very quickly that Eskom, even if it were 100% operational, would not be able to cope with the surge of demand from electric minibus taxis after peak transport hours, and that it would be necessary to soften the blow with renewable energy sources, stationary battery storage and charge rate limiting. As the graph shows, the vehicle batteries discharge during the peak hours, and then recharge in the subsequent hours. The peaks are dependent on the charger rate, which could be as high as 150 kW if left unregulated.

a.) Detected potholes.



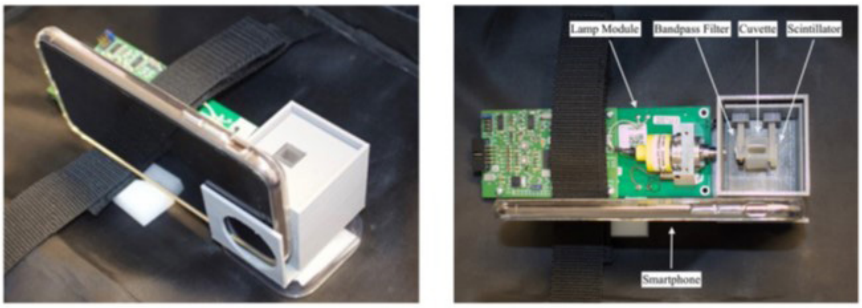
b.) Vehicle-based number plate recognition for indirect crowd-sourced tracking.

c.) Detecting highly pigmented faces with the infrared spectrum.

d.) Detecting passengers using SANRAL's existing infrastructure.

26. Booysen, M. J., Andersen, S. J., & Zeeman, A. S. (2013, October). Informal public transport in Sub-Saharan Africa as a vessel for novel Intelligent Transport Systems. In 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013) (pp. 767-772). IEEE. https://ieeexplore.ieee.org/document/6728324/

27. Akpa, N. E. E., Booysen, M. J., & Sinclair, M. (2016). Auditory intelligent speed adaptation for long-distance informal public transport in South Africa. IEEE Intelligent Transportation Systems Magazine, 8(2), 53-64. https://doi.org/10.1109/MITS.2016.2533979.



(a) View of sensor with phone (b) Top view with optics exposed

e.) Water quality sensor using a mobile phone and spectrophotometry.

A sample of images from some of our computer vision projects.

"Computer vision" is another area of research I have been involved in. The term refers to the capture and processing of images to extract useful information. Lack of space and time prevents me from going into detail about some interesting computer vision projects I have been privileged to be part of, so what follows is a brief summary:

- First, detecting potholes in collaboration with Steve Kroon and Sonja Nienaber. In this project we sent Sonja up to Gauteng to drive around and capture pictures of a few thousand potholes. It did not take long to find them. Our public dataset has been downloaded more than 17,000 times.
- Second, improving facial recognition of dark-skinned people with the infrared spectrum, in collaboration with Rensu Theart, Alex Muthua and Katlego Mbatha. Using infrared and full spectrum photos we found that recognition improves from 97.6 to 99.1%.
- Third, vehicle-based number plate recognition, in collaboration with Arno Barnard and Martin Rademeyer. The idea is to use all vehicles as eyes on the road, resulting in an indirect multi-sensor tracking system.
- Fourth, a project using mobile-phone cameras that uses ultraviolet spectrophotometry and a scintillator to measure the level of nitrates in water, acting as a low-cost mobile water quality sensor, in collaboration with Tobi Louw and Joelcia Ingles.
- Finally, automated pedestrian counting with SANRAL's existing cameras, in collaboration with Johann Andersen and Hardie van der Merwe.

28. Ndibatya, I., & Booysen, M. J. (2020). Minibus taxis in Kampala's paratransit system: Operations, economics and efficiency. Journal of Transport Geography, 88, 102853. https://doi.org/10.1016/j.jtrangeo.2020.102853. 20 citations in 2 years.

29. Ndibatya, I., & Booysen, M. J. (2021). Characterizing the movement patterns of minibus taxis in Kampala's paratransit system. Journal of Transport Geography, 92, 103001. https://doi.org/10.1016/j.jtrangeo.2021.103001.

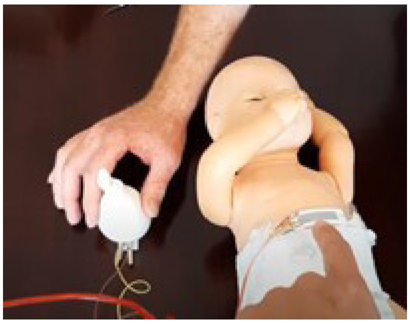
Let me briefly mention four more recent projects.

The first is a conductive ink smart nappy with a printed glucose sensor that Francois Snyders, Tobi and I worked on. This technology could enable the early detection of malnutrition or diabetes in infants and the elderly.

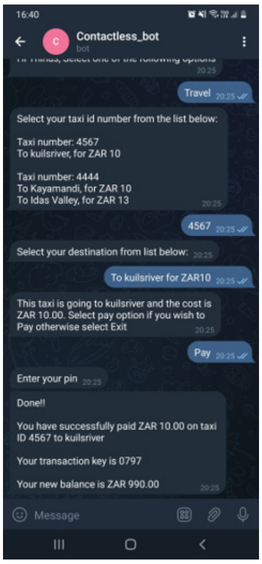
Second, which I am excited about as part of my new Chair in the Internet of Things, is the development of smart greenhouse tunnels with Keegan Hull and Arno Botha, in collaboration with Dave Drew, Ethel Phiri, Kim Martin and Mosima Mabitsela from the Faculty of AgriSciences.

Third is a cashless payment and passenger tracking platform for minibus taxis that run on USSD or Telegram messenger, developed by Kudzai Tenderere, Kitso Motlola, Lourens Visagie and me.

Fourth is a synthesiser for household electricity that Jason Avenant is developing with me and Arnold Rix. This will allow us to do demand management and renewable planning.



Smart nappy that measures glucose in the urine with a printed conductive ink sensor.

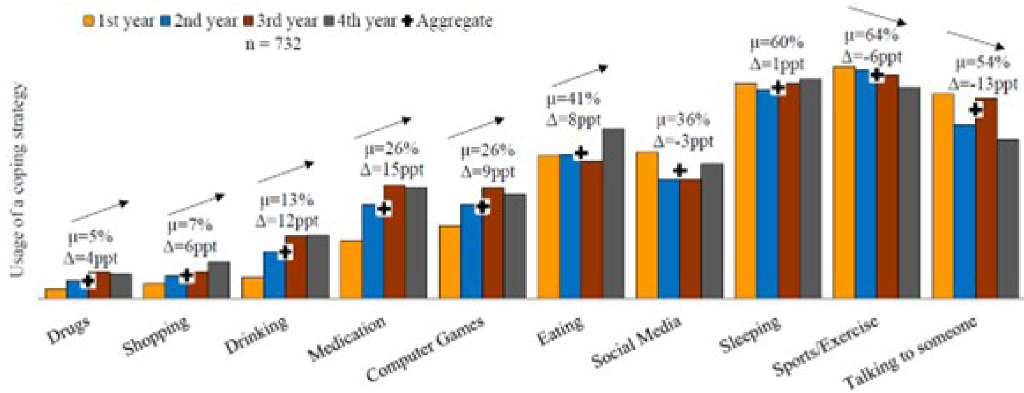


Telegram-based cashless payment system for minibus taxis.

30. Buresh, K. M., Apperley, M. D., & Booysen, M. J. (2020). Three shades of green: Perspectives on at-work charging of electric vehicles using photovoltaic carports. Energy for Sustainable Development, 57, 132-140. https://doi.org/10.1016/j.esd.2020.05.007. 22 citations in 2 years.

31. C.J. Abraham, A.J.Rix, I. Indibatya, M.J. Booysen "Ray of hope for sub-Saharan Africa's paratransit: solar charging of urban electric minibus taxis in South Africa", Energy for Sustainable Development, 2021. https://doi.org/10.1016/j.esd.2021.08.003. 8 citations in 1 year.

Smart planter box for aquaponics and a smart greenhouse tunnel. Both with AgriSciences.



Reported coping mechanisms used by engineering students.

Despite all that evidence of research progress, the years 2020 and 2021 were devastating for our faculty. Because of the lockdown, we were subjected to teaching into muted cameras in the early hours of the morning. When I first started teaching at Stellenbosch, I stuck a piece of paper on my wall that read *Ke dueletswa go ba ruta*, roughly translated from Setswana as "I am here to teach". Although I have shown you a lot of my research, my real passion is to teach. Not being able to engage with the students directly was tough for me. However, I believe what we had to face was nothing compared with what the engineering students, who are already stressed in a normal year, went through and still do.

In 2021 Karin Wolff, Nikkie Korsten and I conducted a survey to identify their sources of stress and the coping strategies they employed. As expected, the students reported that they found the written and practical exams and writing reports the most stressful. Many reported feeling overwhelmed and struggling with the pace and workload, especially under emergency remote teaching. Most worrying was the apparent change, from first to fourth-year cohorts, from what I consider healthy to less healthy coping mechanisms. I am happy to report that the Dean, Vice Deans and Heads of Departments view our findings seriously and have already taken remedial and supportive steps where appropriate.

Lest we forget, it is, after all, the students we are here for.

32. Booysen, M. J., Abraham, C. J., Rix, A. J., & Ndibatya, I. (2022). Walking on sunshine: Pairing electric vehicles with solar energy for sustainable informal public transport in Uganda. Energy Research & Social Science, 85, 102403. https://doi.org/10.1016/j.erss.2021.102403

33. Booysen, M. J., Abraham, C. J., Rix, A. J., & Ndibatya, I. (2022). Walking on sunshine: Pairing electric vehicles with solar energy for sustainable informal public transport in Uganda. Energy Research & Social Science, 85, 102403. https://doi.org/10.1016/j.erss.2021.102403

Computer vision

34. Nienaber, S., Booysen, M. J., & Kroon, R. S. (2015). Detecting potholes using simple image processing techniques and real-world footage. http://hdl.handle.net/10019.1/97191.

35. J.M.D.F.P Ingles, T.M. Louw, M.J. Booysen, "Water quality assessment using a portable UV optical absorbance nitrate sensor with a scintillator and a smartphone camera, Water SA, vol 47 no 1, " 2021. https://doi.org/10.17159/wsa/2021.v47.i1.9453

36. H. van der Merwe, M.J. Booysen, S.J. Andersen, "Optimal use of existing freeway management surveillance infrastructure on pedestrian bridges with computer vision techniques", SATC 2016, Pretoria, South Africa. https://repository.up.ac.za/handle/2263/57985

37. M.C. Rademeyer, A. Barnard, M.J. Booysen, "Optoelectronic and Environmental Factors Affecting the Accuracy of Crowd-sourced Vehicle-mounted License Plate Recognition," IEEE Open Journal for Intelligent Transportation Systems, vol 1, 2020. https://doi.org/10.1109/OJITS.2020.2991402

Mental health and students' wellbeing

38. M.J. Booysen, K.E. Wolff, "Exclusion from Constructive Alignment unmasked by Emergency Remote Teaching", Research in Engineering Education Symposium (REES 2021), Dec 2021, Perth, Australia. https://doi.org/10.31224/osf.io/cxmht

39. N. Korsten, K.E. Wolff, M.J. Booysen, "Time for mentally healthy engineering students", World Engineering Education Forum (WEEF 2021), Dec 2021, Madrid, Spain. https://doi.org/10.1109/WEEF/GEDC53299.2021.9657375