Institution:
University of Lincoln

Unit of Assessment:
11 – Computer Science and Informatics

Title of case study:
AI-enabled Safe and Efficient Food Supply Chain

Period when the underpinning research was undertaken:
2017 – 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:
KOLLIAS Stefanos	Professor of Machine Learning	8 Sep 16 to date
YE Xujiong	Profession of Vision and Medical Imaging	16 Jul 12 to date
YU Miao	Senior Lecturer (Machine Learning)	1 Mar 17 to date
DUAN Wenting	Senior Lecturer (Vision)	27 Jan 12 to date
LEONTIDIS George	Senior Lecturer (Machine Learning)	1 Mar 17 – 2 Mar 20
SWAINSON Mark	Professor of Industrial Food Technology (National Centre for Food Manufacturing)	10 Dec 07 to date
PEARSON Simon	Professor of Agri-food Technology (Director of LIAT)	22 Sep 14 to date

Period when the claimed impact occurred:
2018 - 2019

Is this case study continued from a case study submitted in 2014?
N

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

Food and drink processing is the largest manufacturing sector in the UK, but faces significant challenges around safety, waste, and energy use. AI offers a transformative solution, and Deep learning (DL) research by the *Mlearn* Research Group in the School of Computer Science (SoCS) has innovated AI-enabled efficient and safe food chains in energy management and food labeling. In collaboration with sector partners, Mlearn's DL research has 1) **optimised energy consumption across a large** network of retail refrigeration systems, with financial benefits and reduced pressure on the National Grid, and 2) **ensured safety of packaged food** by enabling 100% inspection of the use-by date for consumption along the food production line.

2. Underpinning research (indicative maximum 500 words)

Since 2017 the *Mlearn* Research Group of SoCS has performed innovative R&D work on DL algorithms and applications. A sector of particular multidisciplinary focus has been agri-food, as food and drink processing is the largest manufacturing sector in UK, contributing over £28.2billion to UK economy and employing 420,000 people. Internationally the wider food chain generates GVA of £108billion, with 3.9m employees (DEFRA 2017). AI offers a transformative opportunity for the food supply chain to improve effectiveness, efficiency and address issues around food safety, food waste, public health, reduction of water and energy usage, environmental impact and overarching climate crisis. To address these key challenges in the sector, in collaboration with key industrial partners, *Mlearn* has led research in: (a) AI-enabled Food Retailing Refrigeration Systems to optimise power consumption, and (b) AI-enabled Quality Control in Retail Food Packaging, to reduce food waste and improve food safety.

(a) **AI enabled Food Retailing Refrigeration Systems**

Food refrigeration accounts for over 14% of UK's electricity demands, and mass refrigeration is responsible for around 12% of UK carbon emissions. When energy consumption exceeds certain limits, this can cause unmanageable spikes in energy usage through the National Grid (NG), with unpredictable problems. To reduce load, the NG imposed response times on large

retail energy consumers, requiring them to react urgently or face high financial penalties. For large companies with thousands of refrigerators, meeting this requirement relies on staff reactiveness, a highly manualized, resource intensive, non-synchronous procedure. In partnership with IMS Evolve and Tesco Superstore, Mlearn led a programme of research on AI-based intelligent distribution systems to handle this monitoring at scale. Mlearn developed a hybrid parallel framework (Nemesyst), using RNN/LSTM and GAN models coupled with MongoDB **[3.2]**, using 110,000 real-life datasets (from about 1000 refrigerators) provided by Tesco. This resulted in a new method for predicting which refrigerators to select and how long to turn them off, whilst maintaining food quality and safety, in a Demand Side Response setting that modifies power demand load proportionally to available energy on NG. Lincoln research **[3.2]** was the first study to show how to optimise refrigeration systems with ML at scale, whilst ascertaining food temperature does not reach certain thresholds. All developed code is reachable under permissive licence, https://github.com/DreamingRaven/Nemesyst.

(b) **AI enabled Quality Control in Retail Food Packaging**

The scale of food sector has significant implications on environment, particularly in energy use wastage and safe supply of food and drink. Up to 30% (8.4MT, WRAP 2017) of food is wasted each year, and food poisoning (including over 64,000 annual incidents in the UK from Campylobacter alone) is costly for the NHS and individuals affected. Food manufacturing faces the risk of product recalls and emergency product withdrawals (EPWs) caused by human error on packaging lines; if the *Use By* date is incorrectly listed as too early, consumers may believe that the product has reached the end of its shelf life and not consume (waste) it. Conversely, if the *Use By* information exceeds the actual date, consumers may use the product beyond its safe timeframe, risking illness or potential fatality. Due to prevalence of inkjet printers in food industry, characterized by high degree of quality variability, traditional Optical-Character-Recognition based vision systems have not been widely implemented, as they struggle with varied or distorted text. SoCS (Mlearn and Laboratory of Vision Engineering) developed DL systems that identify and verify the presence and legibility of use-by date on food packaging photos captured as products pass along production lines. We developed appropriate Convolutional Neural Networks for Optical-Character-Verification/Recognition of datasets from different food processing and packaging environments **[3.3, 3.5]**. We were provided with 500,000 non-labelled food packaging images by OAL company and developed novel approaches to estimate uncertainty and adapt decision making (Deep Bayesian self-training **[3.1]**, Capsule Net routing **[3.6]**), multi-source Domain Adaptation **[3.4]**).

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

3.1 F. Ribeiro se Sousa, F. Caliva, M. Swainson, K. Gudmundsson, G. Leontidis, S. Kollias, “Deep Bayesian Self-Training”, Neural Computing and Applications, vol. 32, pp. 4275-4291, 2019. https://doi.org/10.1007%2Fs00521-019-04332-4

3.2 G. Onoufriou, G. Leontidis, R. Bickerton, S. Pearson, Nemesyst, “A hybrid parallelism deep learning-based framework applied for internet of things enabled food retailing refrigeration systems”, Computers in Industry, 113, pp. 1-11, December 2019. https://doi.org/10.1016/j.compind.2019.103133

3.3 L. Gong, M. Thota, M. Yu, W. Duan, M. Swainson, X. Ye, S. Kollias, “A Novel Unified Deep Neural Networks Methodology for use by date recognition in retail food package images”, Signal, Image and Video Processing, Springer, pp. 1-9, September 2020. https://doi.org/10.1007/s11760-020-01764-7

3.4 M. Thota, S. Kollias, M. Swainson, D. Leontidis, “Multi-Source Deep Domain Adaptation for Quality Control in Retail Food Packaging”, Computers in Industry, December 2020. https://doi.org/10.1016/j.compind.2020.103293

3.5 F. Ribeiro de Sousa, L. Gong, F. Caliva, M. Swainson, K. Gudmundsson, M. Yu, G. Leontidis, X. Ye and S. Kollias, “An end-to-end deep neural architecture for optical

character verification and recognition in retail food packaging", 25th IEEE International Conference on Image Processing, 7-10 October 2018. https://doi.org/10.1109/ICIP.2018.8451555

3.6 F. Ribeiro de Sousa, D. Leontidis, S. Kollias, "Analysis of uncertainty in capsule networks through variational inference", NeurIPS 2020, Vancouver, Canada, 6-12/12/2020. Available on request.

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

Mlearn's research has been pivotal in enabling our industrial partners to address key challenges within the food supply chain.

(a) AI-enabled Food Retailing Refrigeration Systems

Our system was designed using data from Tesco's fleet of refrigerators along with a purpose-built demonstration/experimental store (the 'barn') in our Riseholme Campus. The system's key benefits are the ability to predict when food temperature breaches a legally defined set point, intelligently selecting which refrigerators to shed electrical load/turn off, across their massively distributed network of fridges/freezers. This enables dynamic decision making across thousands of fridge/freezer packs in UK through Tesco's IoT infrastructure. Implementation of the system has enabled Tesco to **optimise demand side response for reacting to the requirements of the NationalGrid**, contributing to Tesco's strategic priorities on decarbonisation. More specifically Tesco report that this research:

> *"...allowed, among other things, Tesco's refrigeration systems to flex their energy consumption in response to changes in Grid frequency, thus providing Ancillary Services to National Grid. … Conceptually this helps both Tesco and the UK as a whole on their decarbonisation path toward Net Zero.I can confirm that the system went live and successfully operated in 20 stores and that a wider deployment within the Tesco estate is possible in the future".* **[5.1]**

Further to these benefits to responsiveness and carbon reduction targets, Tesco report that UoLs research prompted a revision of strategy yielding significant economic and environmental savings:

> "*In addition to the above, the UoL team conducted a feasibility study that showed an opportunity for Tesco around fine tuning cooling set points in refrigerated cabinets. This study prompted Tesco to review its control strategy and resulted in c. £2m of annual energy savings, and the associated carbon reduction"* **[5.1]**

Our research collaboration also enabled IMS Evolve **[5.2]:**

- to develop new business models including new approaches to track and trace food in supply chains; this includes leadership of the £9M Digital Sandwich project funded by the ISCF Made Smarter program
- to significantly expand their business with major success in the US, with their systems now controlling the retail refrigeration network of the world's largest food retailer.

Our research-led solution generated a lot of media coverage for Tesco **[5.3].**

Our open access framework has already been picked up by 15 users as well: https://github.com/DreamingRaven/nemesyst

(b) AI enabled Quality Control in Retail Food Packaging: APRIL Eye.

A direct outcome of SOCS research was the co-development of the first date code verification, AI-enabled vision system, APRIL™ Eye. Developed in collaboration with Olympus Automation Ltd (https://www.oalgroup.com/) and National Center for Food Manufacturing (UoL). APRIL Eye

automates the date code verification process, achieving a full 100% inspection rate to reduce the risk of product recalls and EPWs caused by human error on packaging lines. Reaching speeds of over 1000 packs a minute, APRIL Eye significantly improves process control, increasing safety, quality and efficiency, as well as achieving substantial cost savings.

> *"APRIL Eye combines machine learning and artificial intelligence to transform the traditional date code verification process. Instead of relying on operators to check the date code is printed correctly, it offers a fully automated solution that removes human error inherent in these boring, repetitive tasks. By taking photos of each date code, the system can read them back using scanners to ensure they match the programmed date code for that product run, allowing food processing businesses to introduce unmanned operations and achieve 100% inspection with full traceability, at an increased throughput without compromising product safety. A fantastic safety measure is that the production line comes to a complete stop if a date code doesn't match, ensuring that no incorrect labels are released into the supply chain, protecting consumers, business margins and their brand"* **[5.4]**

The system deals with variations such as lighting, positioning, print quality and placement inherent in a food or beverage plant and can read anything that is also legible to the naked eye. Not only does this enable highly accurate date checking necessary to eliminate the waste and safety issues arising from poor labelling, but it also improves over time, safeguarding long term operations and enabling process sustainability in a rapid and changing market.

OAL launched APRIL Eye as a main product in 2019 in a high profile event (https://connected.oalgroup.com/faq/april-eye-launch) and reported successful international rollout, stating that *"the system was first deployed with two leading global manufacturers and has since been rolled out across existing OAL Connected customers, with no EPWs related to date code errors to date"* **[5.5].**

APRIL Eye has won a series of awards within the packaging and food industries. In 2018, APRIL Eye won the "Innovative Vision Solution Award" at the processing and Packaging Machinery Association (PPMA) Awards, the UK trad associate for suppliers for both domestic and overseas markets (https://www.oalgroup.com/news1/double-win-for-oal-at-ppma-2018) **[5.6].** Also in 2018, APRIL Eye were awarded the "Robotics and Automation" award at Food Processing Awards (https://www.oalgroup.com/news1/food-processing-award-2018) **[5.7]** which 'acknowledge and recognize companies for their excellence and innovation within UK food and beverage engineering sector.

Harry Norman, OAL Managing Director, comments, "*It's another great achievement for us. APRIL™ Eye was developed as part of our Food Manufacturing Digitalisation Strategy, supported by the University of Lincoln and Innovate UK grant funding, and designed to investigate how AI could revolutionise this key area of food manufacturing process."* **[5.4]**

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

5.1. Testimonial email from Tesco

5.2. Testimonial from IMS Evolve

5.3. News items re Tesco refrigeration:

- https://www.current-news.co.uk/news/tesco-trials-offering-up-fridges-for-frequency-response
- https://www.foodserviceequipmentjournal.com/imitation-supermarket-helps-tesco-test-boundaries-of-its-refrigeration-systems/
- https://www.theguardian.com/business/2019/jun/23/cool-running-supermarket-fridges-could-help-power-uk

- https://ktn-uk.org/casestudy/tesco/
- https://www.ims-evolve.com/news/supermarkets-cold-storage-could-provide-national-battery-for-uk-grid.html

5.4. Testimonial letter from Olympus Automation Ltd (OAL) company

5.5. Online materials announcing technology launch and Lincoln / Prof Kollias involvement.

- APRIL™ Eye launches across the globe" https://connected.oalgroup.com/faq/april-eye-launch
- You Tube Commercial End Product Demonstration. https://youtu.be/7n868Vj3_AQ
- APRIL Eye Commercial Product Website. APRIL™ Eye label and date code verification https://connected.oalgroup.com/april-eye

5.6. APRIL Eye wins Innovative Vision Solution Award at PPMA 2018.

- https://www.oalgroup.com/news1/double-win-for-oal-at-ppma-2018

5.7. APRIL™ Eye wins Food Processing award 2018:

- https://www.oalgroup.com/news1/food-processing-award-2018