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Lessons to learn from roadmapping in cleaning and decontamination

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ABSTRACT

The UK's Engineering and Physical Sciences Research Council supported a series of meetings in 2021 to develop a roadmap for future research in Quantitative Modelling in Cleaning and Decontamination. Quantitative modelling in this context is the development of numerical and predictive tools, based on scientific principles, which can support design, operation and decision making associated with cleaning and decontamination. The activity involved identifying past and current activities on this topic across a range of different fields, including food and drink, consumer goods, healthcare, pharmaceuticals, nuclear, civil defence and biofilms. Input was received from operators, manufacturing companies, government agencies and researchers. The exercise identified a series of common needs which span sectors, and the challenges which need to be addressed to facilitate transfer of knowledge between sectors and develop the expertise required to tackle new challenges including those posed by sustainability.

1. Cleaning – The context

Cleaning is the removal of unwanted material from a surface, an object or a fluid, and is a universal activity, practiced worldwide in the home, in industry, in the built and the natural environment (Tragardh, 1989). Decontamination involves removal down to the organism or molecular level and represents a rigorous and intensive level of cleaning (Noynaert, 2012). Cleaning can relate to unwanted species on a surface (including solid walls, flexible sheets, skin, porous and non-porous materials) as well as within a bulk fluid. In the food and drinks manufacturing sector, particularly in process lines that are used for multiple products, cleaning can also involve *purging*, *i.e.* the removal of residual material between production runs for different products. Rigorous and intensive cleaning can focus on inactivation of microbiological species rather than absolute removal, *e.g.* in pasteurisation and sterilisation steps. The term cleaning is used subsequently to include all these operations.

Cleaning is performed to allow the material or unit with the affected surface to be used again (restoring operation), used for a different product or service (avoiding cross-contamination), to be sold, or to function safely. In addition, cleaning can be used to remove or inactivate microbial species (which may be pathogenic or spoilage related) and also

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to remove non-microbial health risks such as allergens, as well as organoleptic potentials and to improve processing issues (*e.g.* heat transfer). On manufacturing lines in the food and drinks and pharmaceutical sectors cleaning is often performed by cleaning-in-place (CIP) systems, with the majority of cleaning operations employing liquids, with those in the former sector being primarily water-based and those in the latter being water- or solvent-based. The regularity and number of cleaning operations performed daily worldwide means that it consumes large amounts of resources, both in terms of staff and operating time, energy, chemicals and water, and affects the financial and environmental sustainability of many human activities. For example, the costs associated with fouling and cleaning can constitute 80 % of the production costs in the dairy industry (van Asselt et al., 2005). Eide et al. (2003) reported that up to 30 % of the energy consumed in dairy processing is linked to cleaning, while each litre of milk processed requires about 1.8 litres of fresh, clean water (Rad and Lewis, 2013), increasing to 7 per litres per litre of beer (Brewers Association, 2022). Schug (2016) reported that cleaning can take up to 60 % of the water usage of food process plant. In addition, cleaning affects capital utilisation and hence effective capital cost, with loss of production time influencing production costs. For example, in some plants the processing of a co-product can be limited by equipment availability, so extra cleaning time leads to loss of production which can be the dominant cost.

Cleaning is critically important in the food and drink (and related) sectors since microbiological contamination can also have significant detrimental impacts on business, particularly with strains such as *Listeria monocytogenes*. Scallan et al. (2011) reported this organism to be responsible for 1591 episodes of domestically acquired foodborne illness per year in the USA, with 1455 hospitalizations and 255 deaths. Food poisoning imposes additional pressure on health services, businesses and families due to sick leave and associated costs. The United States Department of Agriculture (Hoffmann and Ahn, 2021) has estimated that there was a total economic burden associated with food pathogen issues of over US$17.6 billion per year in 2018, with 90 % of that burden arising from *Salmonella, Toxoplasma gondii, Listeria monocytogenes, Campylobacter* and norovirus.

On ships' hulls, the frictional resistance due to build-up of a range of organisms increases fuel consumption; a 30 % increase in resistance due to moderate biological contamination of a 100,000 dead weight tonnage tanker hull will increase the ship’s fuel consumption by up to 12 tons/day (Smith and Colvin, 2014; Song and Cui, 2020). The price of hull cleaning is dependent on whether a diver or a remotely operated underwater vehicle is used, in addition to the vessel size. However, it has been estimated that the total cost of cleaning a ship hull will be in the range of US$5,000 to $50,000 (Glomeep, 2022). In addition, the number of times that a vessel is cleaned can influence the cost. For example, most vessels perform a coating update per 3–5 years (Hua et al. 2018), whereas the US Navy carry out hull cleaning three times per year (Cioanta and McGhin, 2017; Song and Cui, 2020).

The turnover and employment numbers associated with cleaning and decontamination are rarely fully appreciated. The UK Cleaning Products Industry Association reported sales of £ 4.5 billion in 2021, directly employing 10,000 people, many in small and medium enterprises. Global cleaning product manufacturers such as Diversey reported sales of approximately $2.6 billion in 2017. The US domestic cleaning industry alone has been forecasted to earn over US$46B in 2020, and grow 10 % p.a. by 2026 (Franchise Help, 2018; 2020). 1.7 million people were employed in the cleaning industry in the USA, and this is forecasted to experience 6 % year-on-year growth in employee numbers because of the increase in demand.

Cleaning also generates waste streams and for some applications involving hazardous materials the waste streams are also hazardous: cleaning then involves relocation of the material in a safe and controlled fashion. The environmental impact of cleaning wastes can be a significant factor in the selection and management of the cleaning operation, and a matter of growing concern to authorities and the general population.

Cleaning therefore has a direct impact on the sustainability (financial, operating and resource) of any food or drink manufacturing site, and represents an important demonstration of the water-energy-food nexus (Simpson and Jewitt, 2019). Sinner’s circle (and the Extended Sinner’s Circle, Fig. 1(*a*)) is often used to represent the relationships between components of CIP system design in the food and pharmaceutical sectors, where the contribution of each resource can be manipulated between feasible limits to achieve a given degree of cleaning. Fig. 1(*b*) shows how this information can translate into sustainability impacts, borrowing some of the concepts from the cleaning map of Fryer and Asteriadou (2009).

Quantification of sustainability impacts into cleaning system operation, management and design has been reported by several groups (*e.g.* Wilson et al., 2015; Springmann et al., 2018) with metrics ranging from efficiencies focusing on particular factors to overall impact (*e.g.* life cycle analysis, LCA). When one moves away from time to clean as the sole measure for assessing cleaning performance to include important business and operability drivers, a web of inter-related factors are involved. Fig. 2 shows the result, which could be described as the Sinner’s Circles of Saturn. *Chemical Hazards* relate to the materials imported to the system to achieve cleaning, whereas *Wastes* relate to the streams and materials generated by cleaning operations. *Staff Risks* include the health and wellbeing of those working at or near the site. *Access* refers to the mode by which materials are transported and transferred. *Control* includes validation, monitoring and sensors (both availability and performance thereof), while *Microbiology* relates to all aspects of hygienic operation and control.

These factors, and methods such as life cycle analysis, extend the control volume to be considered beyond the surfaces and devices in contact with the food product to the whole manufacturing plant, its boundaries, and the surrounding environment. At this point there is considerable overlap with cleaning practices and challenges in other sectors.

2. Cleaning – A universal challenge

Cleaning impacts people, places and production processes (Maxwell et al., 2018). Cleaning operations can be strongly localized, as in factories, or widespread and unevenly distributed when related to populations (*e.g.* hospitals, urban environments). Table 1 lists some of the sectors in the UK where cleaning and decontamination play a critical role in everyday operation, and some of the associated scientific

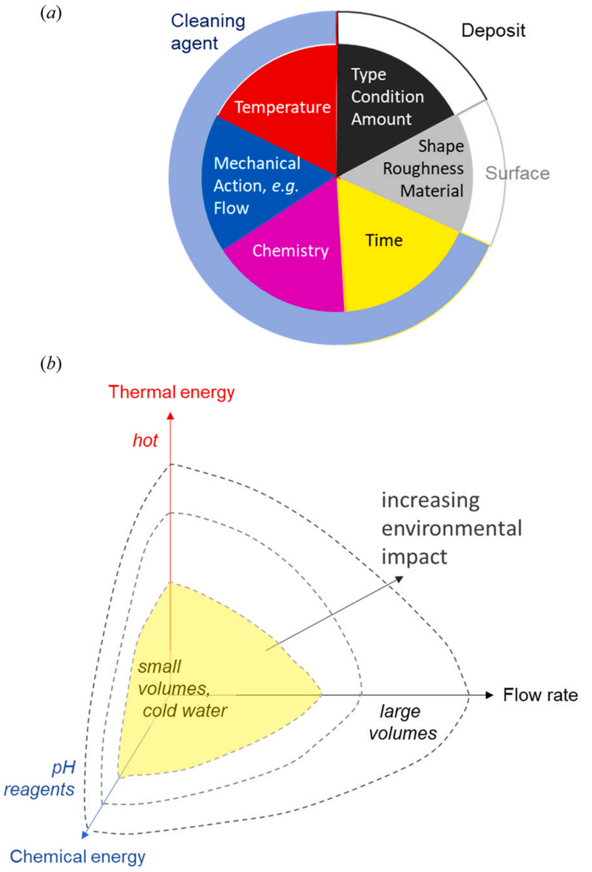

Fig. 1 – Schematics of cleaning: (a) detailed interactions (Extended Sinner's Circle, after Wildbrett, 2006) determining cleaning mechanisms and performance; (b) schematic of sustainability impacts, showing contours of equivalent environmental impact. A process consuming small volumes of water at ambient temperature has the least environmental impact.

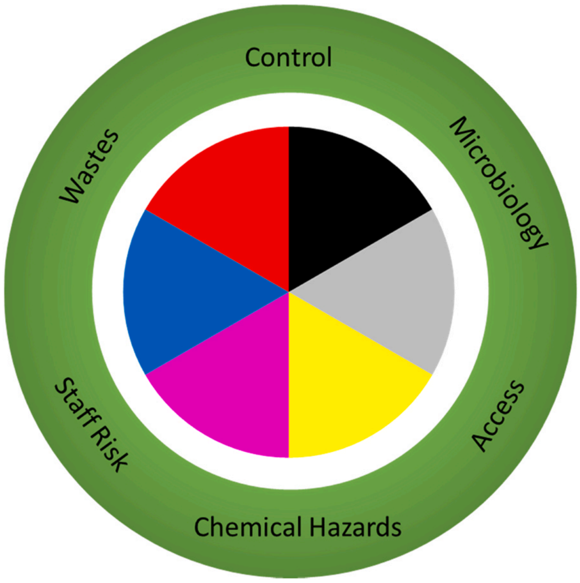

Fig. 2 – Schematic of considerations in cleaning life cycles – the 'Sinner's circles of Saturn', based on the concept presented by Taylour, (2021) at the ModCaD Workshop.

challenges. Fig. 3 summarises the challenges involved in designing, delivering and measuring cleaning across these sectors.

Cleaning is ubiquitous: it can be seen from Fig. 3 that many challenges are common to several sectors, and there is scope for the technical, management and organisational solutions to be applied across different sectors (subject to particular considerations).

Underpinning many of the solutions are quantitative models, which can be classified as

(i) Empirical (correlations based on experimental data and/or scientific principles),
(ii) Phenomenological (written in terms of basic principles, with adjustable terms), and
(iii) Simulation (based on fundamental governing equations).

Quantitative models are essential for

(1)Selection and design of cleaning operations, particularly for new scenarios: *e.g.* determining how much a new scenario will cost and how much better it will work.

(2)Optimisation of existing processes, and adjusting these for different tasks or products.

(3) Predicting how new products can be cleaned on existing process lines.

(3)Transferring the results from one application to another, particularly when experimental validation tests require large amounts of resources.

(4)Quantifying resource consumption, waste generation and operating costs.

(5)Supporting management decisions involving resource allocation and risk.

(6)LCA and sustainability studies.

(7)Conforming to industry standards, regulations and legislation frameworks.

The level of detail required for each scenario varies, and different types of models are appropriate for different outcomes. The risk assessment tools required for management decisions are often statistical in nature, and require different data inputs as well as detailed processing simulations.

3. The ModCaD meetings

This paper summarises the findings of a UK Engineering and Physical Sciences Research Council funded roadmapping exercise conducted in 2021 to determine the state of the art in quantitative models for cleaning and decontamination (aka ModCaD) and develop a strategy for building core expertise. Two meetings were held: a 3-day virtual conference, in April 2021, followed by a 1-day hybrid workshop, in September 2021. The workshop was attended by 84 delegates, with 16 from government departments and government agencies, 16 from industry, and the remainder being academic researchers (27 from engineering disciplines, 12 from mathematics, and the balance from sciences and medicine). Many of the presentations and materials, as well as the Roadmapping report, are available at the ModCaD website.

A review of the state of the art was led by keynote presentations listed in Table 2, and extended through technical presentations and group discussions.

It was evident that there are wide ranges of;

Length scales: The dimensions involved in cleaning and decontamination are very diverse. These vary in terms of mechanistic detail from the machine scale (m-scale) to the nano-scale of an organism or molecule on a surface, and in

Table 1 – – Examples of major UK sectors with intensive cleaning activity (in alphabetical order).

Sectors	*Examples of critical cleaning operations*	*Scientific challenges*
Agriculture	Decontaminating animal houses; combatting disease, *e.g.* wilt, avian flu; cleaning product for market	Distribution of cleaning agents; accessing infected areas; minimal processing
Energy	Gas scrubbing, pollutant removal; solar panel, wind turbine cleaning	CO_2 removal; fine particulates; cleaning in arid regions
Environment	Groundwater contamination, oil spills, aquifer contamination, air pollution, pollution in rivers, lakes and oceans, space debris	Multiphase flow in porous media; washout, large volumes
Food and Drink	Product changeover; removing fouling deposits; avoiding cross-contamination	Variability in products, complex rheologies and biologies
Healthcare/public health	Cleaning to deactivate/neutralize or remove pathogens from surfaces, e.g. Covid	Large areas, wide range of contaminants, uncertainty of effectiveness; complex surfaces
Hospitality	Laundry, kitchens, rooms	Complex soils
Military/public health	Decontamination of surfaces contacted with toxic agents	Identifying best cleaning method; limited resources; hazardous substances; complex environment
Nuclear	Decommissioning of reactors and fuel processing units	Hazardous materials, complex environment – strict inventory control, and waste compatibility challenges.
Personal care products	Switch-over between products	Complex fluids – don't flow easily
Pharmaceuticals	Avoiding cross-contamination between products and batches	Complex chemistries – ensuring validation
Shipping	Hull cleaning to reduce drag	Non-toxic adhesion reduction; *in situ* removal
Water	Clearing blocked supply lines	Complex biofilms, hygiene

spatial area from a single tool or container to a hospital or city.

Timescales: Cleaning operations can be very quick, lasting milliseconds with high energy cleaning flows (jetting, spraying, high-pressure flow through pipes), or very long, lasting hours when soaking, low reactivity or diffusion times are involved, and up to decades in the case of slow flow through porous media (*e.g.* soil remediation). The time scales depend on both the methods used to clean, as well as the size and type of the region requiring cleaning.

These aspects can be incorporated concisely in mathematical formulations, so that once the dominant mechanistic step(s) are identified and the key parameters then established, a model can be used to tackle problems in different physical applications which are related by the same underlying physical phenomena.

In the food sector, notable progress has been made in the dairy industry on understanding and modelling fouling and cleaning in milk pasteurisers (Wilson, 2018). Quantitative mechanistic models for deposition (*e.g.* Darko et al., 2021)

Fig. 3 – Sectors where cleaning and decontamination problems are important, and the related challenges: brown- Industry; yellow - Domestic; blue - Water; red - Medical; green - Environmental; grey- Malicious Acts; lilac – issues common to all sectors.

Table 2 – Keynote presentations at the ModCaD workshop, April 2021. Most of the presentations are available at www.modcad.org.

Speaker	*Affiliation*	Topic
Julien Landel	*Mathematics, University of Manchester*	Fluid mechanics of cleaning and decontamination
Omar Matar	*Chemical Engineering, Imperial College London*	Numerical simulations of multiphase flows in the presence of surfactants
Luís Melo	*Faculty of Engineering, University of Porto*	Biofilms disinfection and cleaning – an overview
Worth Calfee	*US Environmental Protection Agency*	Development of capabilities to support large-scale biological incident response operations
Peter Fryer	*Formulation Engineering, University of Birmingham*	Scaling up (and scaling down) cleaning
Conor Collins	*GSK*	Cleaning of manufacturing equipment in pharma – current approaches & challenges
Alex Jenkins	*Sellafield Ltd*	Decontamination for the nuclear industry
Samuel Collins	*Public Health England*	Decontaminating people
Dennis Heldman	*Food Science & Technology, Ohio State University*	Current research on cleaning and sanitation in food manufacturing facilities
Martin Seed	*NHS Manchester*	Respiratory hazards in healthcare cleaning
Jim Taylour	*Chemical Consulting Solutions Ltd*	What suppliers and cleaners need. How do we get cleaning right?
Allister Theobald	*Lubrizol Corporation*	The business angle

and removal have been developed, which have been combined with simulations of plate heat exchanger performance to provide integrated tools for process design and management (*e.g.* Sharma and Macchietto, 2021). This has yet to be achieved in other applications and practice because:

(a) **Core science insight** is required to identify the key mechanisms, for example if cleaning is controlled by physical methods, such as fluid shear, or chemistry, where reaction is needed to dissolve material or convert it to a removable form. Cleaning and decontamination problems are viciously multiscale and multidisciplinary. The unwanted materials are often complex in nature, and nonuniform (Fryer and Asteriadou, 2009). Biological materials, for instance, often evolve *in situ* (Whitehead and Verran, 2015), and the models thus need to be tuned for the system under consideration, whilst some fundamental processes are still poorly understood.

(b) **These are not simple calculations**. The problems are mathematically complex because they are inherently dynamic and the underlying equations are often non-linear and involve moving fronts (Landel and Wilson, 2021). The problems are often described as *messy* because there are frequently several key factors involved, each of which influences the outcome in a complex interplay which can be hard to compute, even numerically, and so calculations have to be done for subsets of factors and for a limited number of regimes. For example, there can be many dimensionless groups involved in a complex fluid mechanics problem, with different families of solutions for some combinations of, for example, Reynolds (describing flow); Peclet (heat and mass transport); Damköhler (reaction) and Capillary (interfaces) numbers.

(c) **The material to be cleaned** , whether a soiling layer, a fouling deposit or biofilm, is **rarely well understood**. The values of the parameters involved in the models are often not known accurately enough, or are difficult to measure. Modern scientific instruments are usually designed to work at finer scales, which is suitable for decontamination. However, cleaning of micro- and macro-scale soiling material – which needs to be done before the decontamination stage – involves thicker, often composite layers which need to be studied *in situ* and in real time.

Considerable progress has been made in recent years on developing bespoke tools for making lab scale measurements during cleaning measurements. Examples include atomic force microscopy (*e.g.* Dey and Naughton, 2017); QCM (Quartz crystal microbalance, *e.g.* Avila-Sierra et al., 2021), optical profilometry (*e.g.* Barton et al., 2008), micromanipulation (Liu et al., 2002); millimanipulation (Tsai et al., 2020); fluid dynamic gauging (Chew et al., 2002); chemical mapping (Fourier transform infrared spectroscopy, energy dispersive X-ray spectroscopy, *e.g.* Whitehead et al., 2011); or for microbial fouling and biofilms, differential staining (*e.g.* Evans et al., 2021). These techniques need to be accompanied by methods to extract intrinsic data from the studies for use in quantitative models.

(d) **Robust methods** are needed. Models are usually developed under ideal situations, for example considering one

Table 3 – Levels of cleanliness, grouped by length scale.

Length scale	*Cleanliness criterion*	*Detection method*
m-km	Room/area free of contaminants	Sparse sampling, mobile sensors
mm-m	Process performance restored	Operating data, visual, on-line sensors
10 s of microns	No visible biofilms	Visual, staining *in situ*, on-line sensors,
	Residual coatings removed	Coupons (tested *in-situ* and *ex-situ*)
5–10 µm	Bacterial cells removed	Swabbing (tested *ex-situ*)
		Staining + visualization *in situ*
1 µm	No spores	Swabbing
Sub-micron	Optically clean	Coupons (tested *ex-situ*), light reflection
Nanometre	Chemically clean	Electron microscopies, ellipsometry, QCM

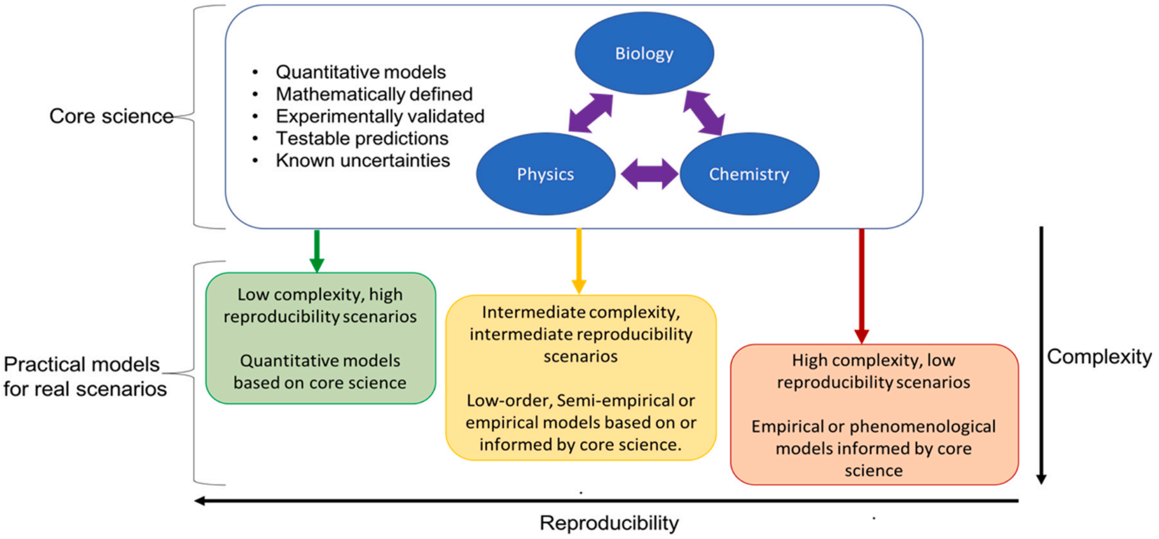

Fig. 4 – Schematic illustrating the hierarchy of practical models, based on core science, for different cleaning and decontamination scenarios. Axes indicate level of complexity and reproducibility.

reaction in a process under well-defined conditions, whilst in practice conditions are less well defined and the composition of materials varies, leading to changes in physical and kinetic properties and thus variability in cleaning rates. Uncertainty in physical property parameters and process rate constants means that the calculations are likely to need to be repeated in order to determine the sensitivity of the results to variation in these inputs.

(e) **Defining 'clean' can be difficult**. The end point of cleaning (*i.e.* when is it clean enough?) may be the most difficult part of the process to predict and is also the most difficult part to validate in practice. In some cases the target is set by the measurement methods available (see Table 3) and when a new method is developed or instrumentation sensitivity is increased, the threshold for acceptable levels of cleaning needs to be re-examined.

This analysis will often be based on *risk*: in short, the time to clean will depend on the impact of getting it wrong. Facets to consider will include.

(i) the accuracy of the measurement technique and its capacity to capture the distribution of contamination over a surface;.

(ii) the impact of the measured or modelled distribution on the product, consumer, or process;.

(iii) the reliability of the cleaning method to deliver a given level of removal;.

(iv) the acceptability of a known level of contamination to personnel and the public.

Facets (i) to (iii) are statistical in nature and require different modelling techniques to those used to calculate removal rates, but the latter must be framed so that their results can be linked to such tools. In the limit where complete decontamination is required, where the soil has such high toxicity that removal must be confirmed at the molecular level, the ability to map the surface *in situ*, reliably, will dominate (*e.g.* Butera et al., 2021). Facet (iv) requires more qualitative considerations and will draw on similar considerations as those presented by Maxwell et al. (2018) for environmental clean-up.

(f) **A hierarchy of models**. In practice, due to the variety of cleaning and decontamination scenarios, the type of models and their accuracy may vary. Nevertheless, as shown schematically in Fig. 4, all models can be rooted in the fundamental *core science* (see (a) above) underpinning all the physical, chemical and biological processes, and their interplay. The core scientific models are generally formulated mathematically as coupled systems of partial differential equations and algebraic equations describing the temporal and spatial evolution of all the components involved, such as the concentration, velocity, temperature of the different phases and their properties (Landel and Wilson, 2021). The models are validated by laboratory experiments and the uncertainties of their predictions are quantified. At the practical level, as mentioned in (b), solving the full mathematical model of a particular scenario is usually impossible. Instead, a hierarchy of models is necessary, depending typically on the complexity of the scenarios (vertical axis in Fig. 4, increasing from top to bottom) and their level of reproducibility (horizontal axis, increasing from right to left). For illustrative purposes, three scenarios are described below, two at the extreme ranges of the scales and an intermediate scenario. However, we note that a particular scenario could sit anywhere along these two scales.

(i) Low complexity, high reproducibility: such 'uncommon' scenarios may be typically found in highly controlled environment, such as in some industrial cleaning processes. The parameter space is limited and well defined, and the core science is fully known. A quantitative model can be directly extracted from the relevant core science, and solved either in advance, or in real time for the simplest scenarios. Model predictions to achieve a required level of cleanliness (see (e) above) are quantitative predictions, with a known low-level of uncertainty.

(ii) Intermediate complexity, intermediate reproducibility: this is where most scenarios sit. The parameter space is large, with the core science partially known (*e.g.* (c) above). These scenarios cannot be modelled by fully quantitative models. Instead, low-order models, semi-empirical or empirical models based on or informed by the known core science are used. Model predictions to achieve a required level of cleanliness are quantitative or qualitative, depending on the ability to test them. As the reproducibility level decreases, the difficulty to test the model increases, and the uncertainty increases.

(iii) High complexity, low reproducibility: scenarios at this extreme range of the scales are typically one-off or rare uncontrolled events, such as accidents or terrorist attacks in complex environments, or new events such as the spread of a new pathogen (*e.g.* SARS-CoV-2). The parameter space is loosely-defined and very large. The core science is mostly unknown. Mathematical models are often poorly relevant and instead flow-chart types of models, informed by the core science, are used to describe the phenomenology quantitatively. Model predictions to achieve a required level of cleanliness are qualitative, with large uncertainties.

Future research at fundamental and practical levels will not modify the complexity nor the reproducibility of a particular scenario. However, it will expand core scientific knowledge and enable practical models to be more quantitative with lower levels of uncertainties.

4. Needs and challenges

There are still underlying fundamental scientific and mathematical challenges involved in understanding cleaning and decontamination mechanisms, which need to be addressed to build robust models (Landel and Wilson, 2021). For example, many cleaning processes are inherently dynamic, involve moving fronts or contact lines, free surfaces and multiphase materials. These are areas of ongoing fundamental research. Implementing new and existing scientific learning in process and management cleaning tools also presents the following needs and associated challenges, all of which apply to the food processing sector and other sectors:

4.1. *Sustainability*

Environmental sustainability considerations and prioritisation of limited resources means that the choice of methods and chemicals that can be used in cleaning will narrow in future (Romero-Hernandez, 2004). In addition, in terms of sustainability, it has been suggested that 46 % of consumers prefer services that use environmentally friendly products (Franchise Help, 2020). In the short term, cleaning technologies that make better use of existing resources, including the recycling of cleaning agents, need to be developed and implemented. This will require models for use in optimisation tools as well as sensors to report the status of devices to control systems. In the mid-term, more systems and devices will need to be designed to be cleaned rather than retrofitted for cleaning. This aspect is already embedded in many equipment items developed for the food sector, following hygienic design principles, and is more relevant for equipment not primarily designed for food and pharmaceutical applications. For example, the ‘total cost of ownership’ concept has been included in recent hygienic equipment design guidelines (EHEDG, 2022).

4.2. *Risk – How clean is clean?*

This question arises in **all** cleaning and decontamination operations. The critical cleaning attribute(s) have to be based on assessments of impact and acceptable response, rather than simply the ability to detect the material. Systematic ways of processing data and deciding performance based on measurement patterns, cleaning efficacy and sensible detection criteria are needed. This requires understanding of the consequences of different levels of performance, together with quantitative risk analysis, training and communication of the results to all stakeholders.

Moreover, the calculation of risk and its consequences, and communication of the findings in appropriate ways, is important for developing trust between stakeholders. The COVID-19 pandemic has highlighted this challenge in the age of social media. These topics are not currently taught in most scientific programmes, and requires input from behavioural scientists to identify suitable strategies and tools to equip workers to change the narrative in these areas.

4.3. *Diversity*

There is a strong need to establish and communicate what has already been done in other fields, to avoid duplication, and to support advances in new fields by building on existing effort. An example is the application of models developed for polymer photoresist dissolution (*e.g.* Hunek and Cussler, 2002) to elucidate dairy cleaning (Xin et al., 2005). This needs to be systematic, so it can be built on and developed. As in all interdisciplinary activities, there are issues with communication and language. A common taxonomy needs to be developed to allow researchers and users to share information and concepts efficiently. For example, a physical scientist may refer to the surface on which an organism attaches as the ‘substrate’, whereas a microbiologist may use the term for the material that the organism consumes (eats)! There are parallel challenges in communication between researchers/users and public bodies, regulatory bodies, and the general public.

4.4. *Training*

Cleaning and decontamination are inherently interdisciplinary. Although within the food industry there is a number of structured or graded nationally accredited training supplied by chemical manufacturers and awarding organisations (*e.g.* Highfield, Holchem, Christeyns in the UK), there is no systematic training programme available which provides the multidisciplinary facets required to equip new practitioners and researchers with the necessary expertise to function effectively in this area. The 2018 Salisbury Novichok poisoning episode in the UK (Vale et al., 2018), the development and transmission of antimicrobial-resistant bacteria (*e.g.* methicillin resistant *Staphylococcus aureus* - MRSA) and the COVID-19 pandemic have demonstrated that new thinking is needed to bring together the fundamental understanding in the different fields in order to identify and implement effective new methods quickly. There is scope for web-based training programmes to be developed for researchers and practitioners alike.

4.5. *Sensors*

Many cleaning operations rely on old measurement methods and sensor technologies. There is a widespread need to develop sensor techniques which are versatile, reliable, scaleable and which eliminate the variability inherent in human testing (Watson et al., 2021). Both portable sensors as well as in-line sensors are required. This is challenging as the sensor data needs to represent the region around it rather than the conditions local to the sensor. There are opportunities for machine learning, artificial intelligence and uncertainty quantification in data interrogation and data fusion. There is a similar need for robust devices to make measurements *in situ*, in real time and under realistic conditions, for studying soil layers or deposits which cannot be transferred to laboratory devices such as those mentioned above. The smartphone, which makes high fidelity imaging and data transfer ubiquitous, is an obvious platform to build on.

5. A Roadmap

The ModCaD roadmapping exercise generated a report covering much of the material presented here which is available at the ModCaD website. A proposal for future activity is outlined there for the UK, with four main strands, open to non-UK participants.

1. *Community*. Networking events and conferences such as the FCFP 2022 conference are essential for sharing information between different stakeholders in specific sectors, and it is important to build and strengthen links between actors in different sectors. Tools such as LinkedIn will be used to facilitate such interactions, and researchers will be encouraged to lead focused technical sessions in national and international conferences such as EuFFoST, ICEF *etc*.
2. *Training*. Materials need to be developed covering areas such as risk management, life cycle analysis, validation *etc*. for those conducting research in the field, to provide contextual tools to accompany findings.
3. *Communication*. To assist and augment the above strands, a website (www.modcad.org) has been developed to share much of the material presented at the ModCaD meetings. It will also contain an annotated community-generated database of research related to quantitative modelling of cleaning and decontamination, to facilitate transfer of expertise between sectors.
4. *Science base*. Future progress requires the profile of cleaning and decontamination operations and the challenges involved therein to be raised, both amongst funding agencies and prospective researchers. The technical challenges are very real, but suffer from poor perception amongst ‘pure’ scientists. Those working in the field of cleaning and decontamination, both in research and delivery, are encouraged to highlight the scientific challenges by publication in international journals (*e.g. Food & Bioproducts Processing* has a topic area on hygienic processing), mainstream and social media.

In the UK, we anticipate that the Roadmap will be taken forward by academic researchers in the relevant scientific disciplines (*e.g.* biology, chemistry, engineering, food science and mathematics). Key to its implementation will be close involvement of industrial and government, as well as stakeholders and practitioners.

6. Conclusions

The roadmapping exercise looking at the quantitative modelling of cleaning and decontamination held in 2021 identified a number of factors as common to cleaning and decontamination across many sectors. These operations are complex in terms of underlying science, but common themes exist which need to be addressed in order to make them sustainable and allow prompt responses to new challenges. The themes included the understanding and communication of risk as applied to cleaning and decontamination operations; the need to construct models of cleaning performance to resource availability and decision-making processes; the advances and gaps in sensors and data technology; and the need to develop a common taxonomy that will facilitate transfer of expertise between sectors. Tackling new challenges such as the food-water-energy nexus and the wider sustainability agenda means that Sinner’s circle, often used to frame discussions of cleaning in the food sector, needs an upgrade.

Rights Retention Statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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