"We are left in the hands of the generations which, having heard of microbes…suddenly concluded that the whole art of healing could be summed up in the formula: Find the microbe and kill it."

George Bernard Shaw 1906

As we consider the design of future cities, the current pandemic has brought microbes and health back to the forefront of scientific and political minds. It has also put the microscopic world back at the top of the public fear list. Yet before the pandemic, medical understanding of microbes and their relationship with health had been shifting with important implications for the way we design future cities. Not all microbes are bad, many are benign and some are essential for our health. Contemporary medical knowledge of the microbiome offers an ecological model of the human; a multi species body comprising a multitude of human and non - human cells. Different from the modernist perception of the human as a discreet body, the ecological model of the human is one that cannot be separated from the non-human microbial milieu that surrounds us, physically or philosophically.

Urbanisation, indoor lifestyles and engrained antibiotic mentalities are resulting in the decline of, and exposure to diverse environmental microbes from our daily lives. Unlike previous instances, whereby threats of infection and pandemic have been understood in relation to the presence or abundance of pathogenic microbes, the emergence of new, 21st century pathologies appear be linked not to the presence of, but to the absence of microbes from our bodies and the environments we inhabit. Evidence suggests that the separation of the human from the non-human has gone too far. It appears that in order to design healthy buildings and resilient cities we need more microbes, not less.

The aim of this research was to develop a novel approach towards heathy buildings in line with contemporary understanding of the microbiome and the essential role that exposure to microbial diversity plays towards heath. It questions how design can drive the [re]introduction of missing microbes in to buildings and proposes a new direction for architecture that rejects the modernist assumption that fewer microbes = healthier spaces. Instead it develops a more nuanced approach analogous to a kind of immune system for buildings. A living microbial layer which can limit the persistence and spread of harmful microbes but which also allows for the presence of good microbes in buildings.

The work explores the three main vectors of microbes in buildings - air, water and surfaces and questions how these can be manipulated through design to become both a source and sink of beneficial microbes. The work started with the development of novel, hybrid living materials that contain living colonies of good bacteria. The research asked how such living materials could be designed and fabricated and how the living agency could be sustained over long periods of time without the need for ongoing maintenance or expensive systems. It tested their to inhibit the growth of pathogens on building surfaces and finally it questioned how such materials could be designed and integrated in to buildings.

The work integrated a multidisciplinary team of architects, microbiologists, infectious disease experts and environmental engineers within UCL from The Bartlett School of Architecture, The Eastman

Dental Institute and Civil and Geomatic Engineering. The research was undertaken at three interrelated scales beginning at the micro-scale of the material-microbe interface, the meso-scale of the material-human interface and at the macro-scale of the building.

The first stage was funded by the AHRC project NOTBAD, which explored novel approaches towards limiting the spread of antimicrobial resistance (AMR) in the built environment. Novel ceramic and concrete materials inoculated with *Bacillus subtilis* bacterium were developed as new probiotic materials for use in buildings that are benign to humans but that can inhibit the growth of harmful microbes. A mix of design and microbiological methodologies were used to ensure biocompatibility between the material and the bacteria and long term survival in indoor environments. Finally the ability of the probiotic material to inhibit the growth of AMR superbug MRSA was demonstrated.

The meso-stage of the work involved the design and fabrication of probiotic surfaces that considered the relationship between material, microbes and human agency. Building upon the condition of fomites; (surfaces that can become contaminated with infectious agents and transferred to humans), this approach instead looks to design surfaces containing beneficial bacteria which can then be transferred to occupants and other parts of the building. Surface features and geometries were fabricated and tested both in their ability to inhibit pathogens but also to act as a source of beneficial microbes to building users via mechanisms of touch and resuspension.

Probiotic surfaces were then made as a series of wall tiles installed in to an office space to measure their influence the indoor microbiome. Driven by CFD simulations of natural and mechanical air movement, the tiles were geometrically modelled and sited in order to capture and shed beneficial microbes to other surfaces within the space. The indoor microbiome was monitored in a controlled study using a before, during and after installation approach using both plating and DNA sequencing techniques. Results demonstrated a measurable effect on the microbiome of the space following installation which is driving ongoing, longer term testing. The group are also undertaking new work to develop living surfaces with similar bacteria that are able to inhibit SARS type viruses to reduce the risk of surface transmission in the built environment.

There is a risk that the current pandemic exacerbates our preference to further separate ourselves from the microbial world which could result in unintended, longer term public health problems. This experimental work offers an initial framework for a living material and spatial based approach towards designing healthier buildings in relation to the indoor microbiome. The author calls this approach Probiotic Architecture. As we learn more about the indoor microbiome, and what exactly constitutes healthy microbes, architects will need to work with experts from non-traditional fields including microbiologists, virologists and environmental engineers towards creating healthy and resilient buildings.

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