Developing an Architectural Design Microbial Risk Model (ADMRM) for the built environment

Jako Albert Nice[1*]

[1]Smart Places Cluster, Natural Resources, Enabling Infrastructure, Professional and Public Services Division, CSIR, Pretoria, South Africa
*Corresponding email: jnice@csir.co.za

Abstract

Studies indicate that an estimate eighty five percent of our time is spent indoors, with people sited as the main contributor of bacteria, and consequently pathogenic bacteria in indoor environments. This highlights the significance of the indoor air and surface quality of buildings. To date architects and designers do not have the means to assess design and planning decisions considering potential health risk. The authors doctorate thesis research findings of an architecture and microbiome study of two South African, Western Cape hospitals (SAHM) proposes the genesis of a novel building design HAI risk model.
The study objectives were, firstly to identify factors in the built environment that are associated to architecture and planning, which impact the microbial community composition and vice versa. Secondly, applying the findings to develop the basis of a risk assessment design tool. Hospitals and, Accident and Emergency (A & E) departments are complex environments driven by function. The utilization of Space Syntax spatial analytics to model social interaction through core and global integration considering local space connectivity, provides an architectural relationship to community, organism dispersal and composition.
The investigation considered architectural spatial analysis, environment, and microbiology sampling and sequencing data. Building design dynamics such as, the fluid nature of social factors, strength of program and spatial relationships contribute to the complexities in spatial planning analysis.The findings indicated that the community composition consisted of up to sixty five percent, majority Proteobacteria followed by Firmacute Phylum. The difference made up from outdoor sources. In conclusion, the outcome provides a novel means to quantitatively determine occupancy interactions which can be applied to room grading, to determine potential health risk to occupants enabling corrective strategies. The paper presents the genesis of an ADMRM for application in healthy building design and planning.

Architecture, Built Environment Microbiology, Health, Risk assessment, Hospital

Introduction

In a recent review of MoBE studies, Adams *et al*. (2016) proposes a framework to deal with interpreting different studies, in particular studies that are interdisciplinary, considering engineering and to some extent architectural factors with those in microbiology. They postulate a “mechanistic framework that combines a material-balance approach of engineering with the ecological concept of metacommunities… Both seek to *“track the sources and sinks of a constituent in a system”.* Their framework considers tracking mass entering and leaving a system, whereas metacommunities are a set of local communities linked by the dispersal of organisms. In this the authors Adams *et al*. (2016) argue that the demographic parameters in metacommunities have direct similarities to those of the material-balance approach. The similarities in the principles are those of measurable factors entering and exiting a system that directly affect either the community (by birth, death, etc.) or the aerosol (filtration, deposition, etc.). This proposes a manner in which factorisation can occur to predict across fields within a shared framework. In the same way that the researchers identified a common challenge of factorisation, and the dissemination of field data to enable system definition or system modelling for prediction, the author Nice (2019) in his thesis considered the need for a framework in which to place architecture and the built environment (BE) and identify factors and measures within a global framework. The author postulated a mechanistic theoretical framework in which to place design, planning and architecture as a component of the system, with the end goal to develop a design tool to assist practitioners and researchers towards "bio informed" design and risk factorization with particular focus on health, healthy buildings. The interdisciplinary diversity of the MoBE research field makes this a particularly challenging task.

The author by no means suggests that the proposed framework or later version thereof is resolved or fully developed. The wire diagrams presented recommends core inputs and suggests critical paths and practical outputs that it puts forward, (refer to figure 1 and 2). The rate at which the MoBE field knowledge has grown demands a clear roadmap and framework, be this a mechanistic metacommunities-quasi-material balance approach or other. As part of venturing into the MoBE field since 2014, the author suggested a micro and macro approach, due to the scale of processes and systems. The framework referenced in Figures 1,2 and 3 provide a structure for research development and contribution to the MoBE field, but with the focus on health risk in indoor environments.

The impact that design and planning decision have on the outcome of building health and by extension the user or its client requires quantitative assessment of risk at an early design or pre design alteration phase. The absence of risk assessment in building design planning is apparent with only published research on post occupancy evaluation, with no means t integrate in pre-construction advice. Majority of research are found on epidemiology studies, event focused, this author has not found a platform that integrates these findings to offer practical tools for design application, realizing policy and best practice guidelines.

Materials and methods

The author refers to the Nice and Vosloo (2017) and Nice (2019) for the full detailed research methodology and sampling for all employed interdisciplinary fields of architecture, engineering and microbial sampling, sequencing and analysis with reference to the South African Hospital Microbiome (SAHM) study. For the purposes of this paper the author investigates the potential for developing an architectural design microbial risk model (ADMRM) deduced from the SAHM study and findings.
The investigation started in 2014 with an initial proposal, further developed towards 2019 based on various MoBE field advancements and findings over the five-year period. This and the findings of the SAHM has informed and guided the potential roadmap. Following are both the 2014 (1) and 2019 (2) model proposals.

(1) **The initial 2014 original proposed MoBE research roadmap**: At project level for research investigations, the author proposed a macro and micro

research process as a means of contributing to the MoBE research roadmap. The research roadmap (Figure 1) was initially developed to illustrate the potential relationships between parties within research fields, and geographically. It merely structures input variables in the system that either exist or are novel systems yet to be developed. It considers the four core fields of study and the set of variables in the matrix that each field contributes. It recognises the various methodologies for data collection and the central role that they would play. The framework hinges on interdisciplinary study collaboration. This is a rudimentary global study framework conceptualised to assist the author in finding context within MoBE field, and visualize and postulate the role for architecture. The MoBE research road map offers a broad, inclusive and open approach towards developing public health centred design and bio-informed design. It recognises the critical role of funding and institutional role-players. A feedback process loop is required to generate interest, build confidence, show outcomes, and inform the broader public on emerging findings. The roadmap identifies the need for interdisciplinary research collaboration amongst the disciplines of microbiology, epidemiology, medical archetypes and engineering and architecture. Each of these disciplines boasts numerous theoretical models and sample methodologies, and needs metadata studies to disseminate and identify gaps. As we know a research repository for MoBE has been established (currently done through (microBEnet). From the metadata studies a matrix of architectural and engineering, indicators and variables, can be developed. A variety of broad-based studies, both short-term and mostly longitudinal, will be required, as well as focused studies to test and develop this matrix and identify the nature of the variables. This is a cyclical approach and each study should support the matrix, which informs and develops the Architectural Design Microbial Risk Model (ADMRM). In addition, field case studies, model validation, HAI database development and constant methodology improvement and guidelines are necessary to ensure repeatability of studies that could form cross comparisons. To ensure that the findings and applications have an impact on and influence the public health domain and authorities, this roadmap envisions ecological adaptations with continental and intercontinental studies, localised climate studies, localised sub-climate studies, socio-economic diversity studies, and intra-urban and rural data sets.

The ADMRM (Figure 2) depicts the concept of a central repository of data, research and development for the MoBE research roadmap. It could become the platform for depositing and nurturing findings and data studies, expanding the field of knowledge but making it applicable and implementable. It aims to serve as practical tool to disseminate data that inform BE scientists, BE specialists, architects, engineers, IPC specialists, HCWs, hospital managers, industry, government and other policy makers. This tool aims to combine complex data sets and translate indicators into application. The goal is to provide real-time measures for designers to inform decision making before the construction of healthcare facilities. It promotes bio-informed design for healthier indoor environments. The elements discussed in the macro and micro processes are the building blocks for the tool. It is essential that the platform be building information modelling (BIM)-based to allow for computational modelling in real-time, that affords potential agent-based analysis for typology-specific environments or function-specific programs, not only in the healthcare sector, but also for public buildings, civic centres, sports halls, offices and homes, both temporary and permanent. The micro research process proposal depicted in Figure 3 presents the micro MoBE research diagram that refers to specific BE architectural and engineering components. The flow process considers “input constants” that are found universally in the built environment, i.e. room types, building typologies and building types. This is followed by built environment constants such as volume, function and spatial relationships (note the interrelationship between the macro and micro process feed).

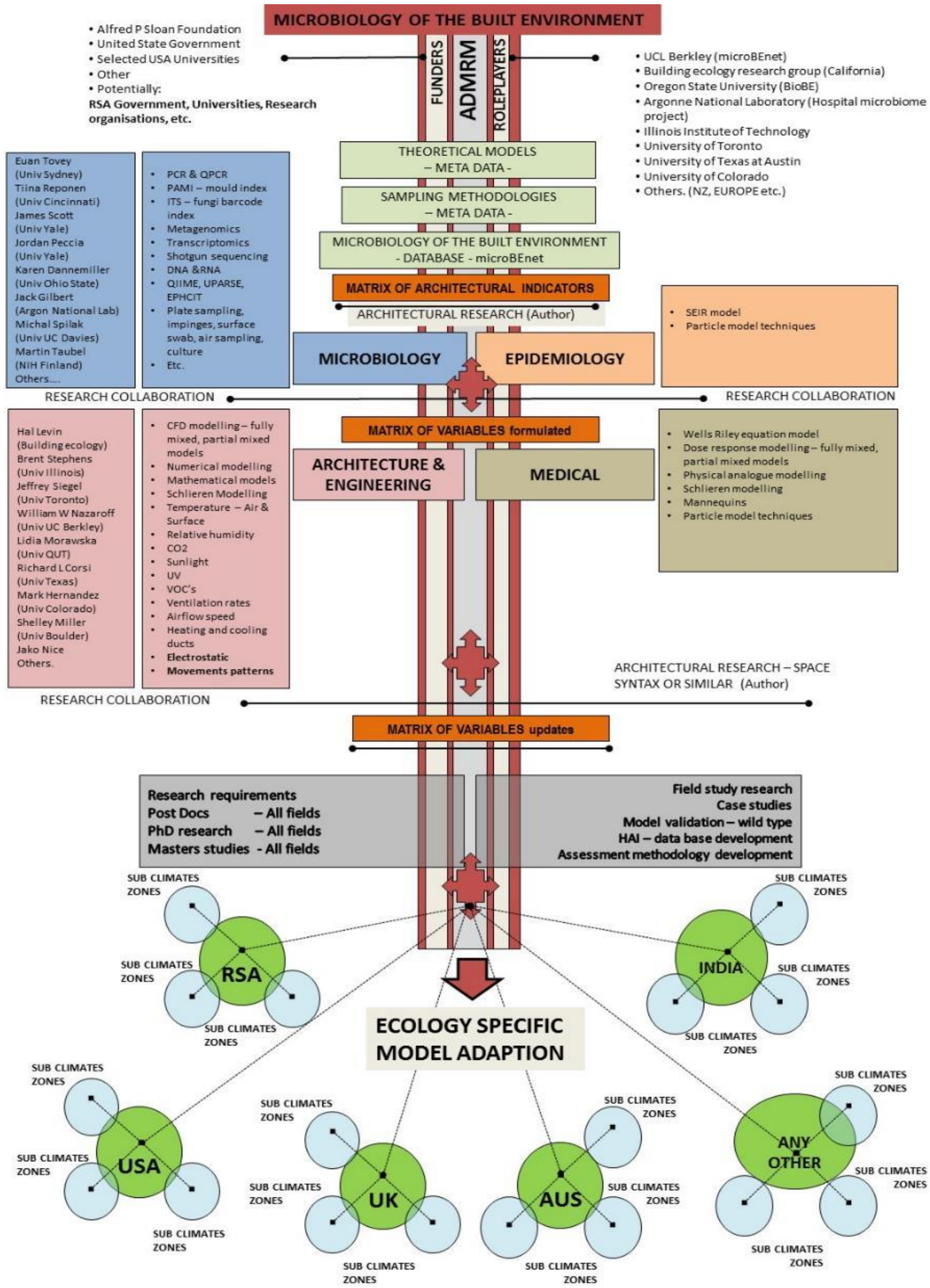

Figure **1**: ADMRM framework diagram and MoBE research road map - 2014 (Nice 2019)

These data are disseminated into architecture and engineering “built environment indicators”, i.e. temperature, RH, surface material, UV, climate and others and then combined with interdisciplinary factors (sampling methodologies and models) for microbiology, medical and epidemiology indicators. The conversion of the macro data is then applied and integrated into BIM platforms similar to the development by

Autodesk on live, in-building sensor measure and reporting as mentioned in the macro process diagram.

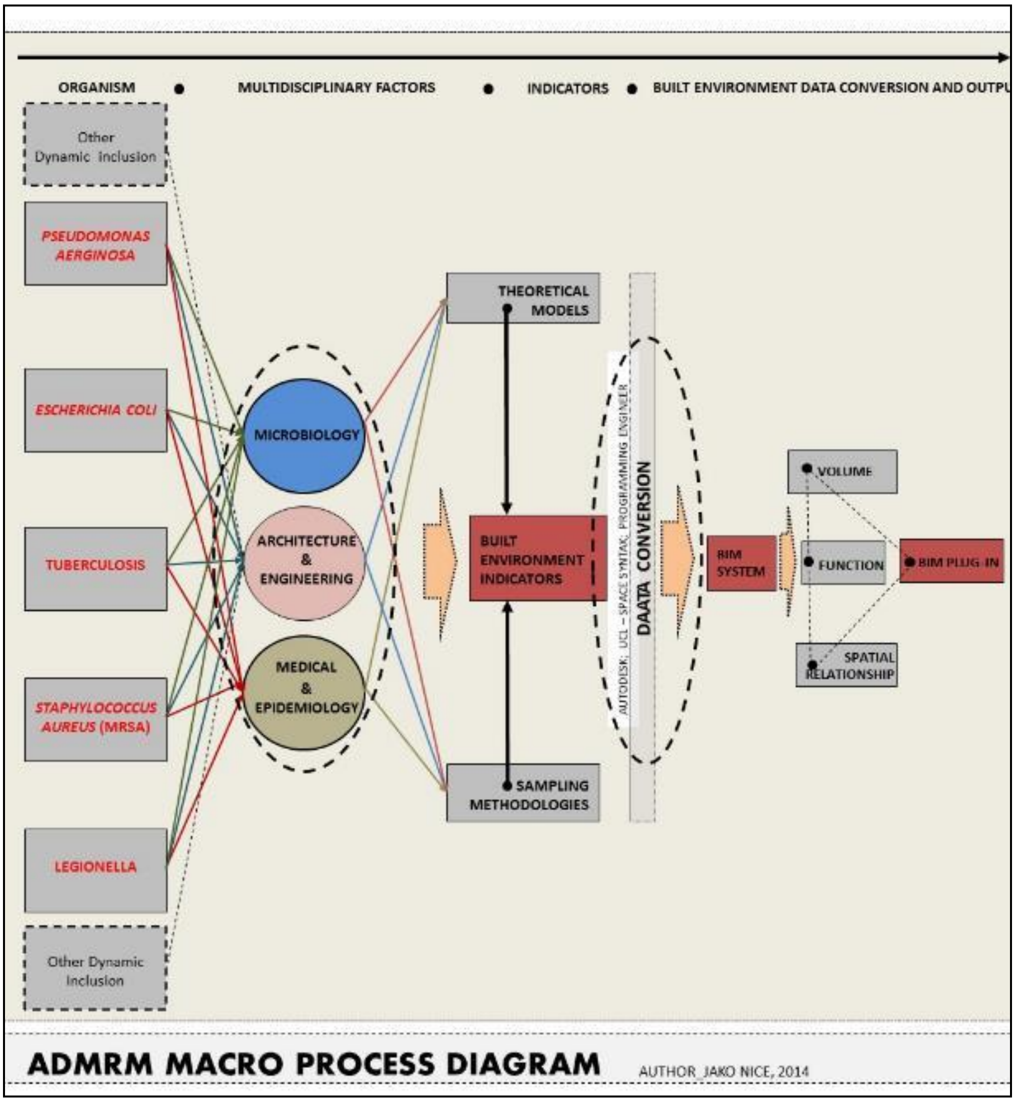

Figure **2**: ADMRM macro process diagram - 2014 (Nice, 2019)

This process is cyclical, creating fluid boundaries and allowing for novel research approaches and the inclusion of new factors. The process considers the various potential indicators or factors such as temperature, RH, surface material, equipment, CO_2, ventilation sunlight, spatial factors, etc. This micro process diagram serves as a theoretical approach to investigate building by room type data for input into BIM applications as a design tool or dissemination of information in developing data for design tools. Ramos & Stephens (2014) produced a review of applicable tools to be applied in MoBE studies, they have however identified factors applicable to built environment MoBE research. However much time and development has passed since the conceptualization of the initial tool, and hence necessitating a review and update of the proposal, the author presents the revised new research roadmap based on recent findings of the South African Hospital microbiome investigation (2014-2019) Nice (2019).

(2) **Towards a new proposed research roadmap:** This roadmap considers the ADMRM macro Figure 2 and micro Figure 3 process diagram as data generators

for the roadmap. The research findings provided critical direction for further investigation and studies required to expand the MoBE data sets of knowledge and factors influencing the built environment microbiome. The findings of the South African Hospital Microbiome (SAHM) study and those of other research studies point to a complex relationship between BE factors and microbial ecosystems. The data confirmed that biomes not only change seasonally in the built environment, but that the built environment also experiences seasonal variations. The spatial data indicated factors of spatial change in occupancy, flow patterns and functional use of spaces and the building program. The building climate factors, such as temperature, relative humidity and CO_2, showed seasonal variations. The microbial communities present in the air and on surfaces evidenced seasonal variation, and the biomes by room type indicated seasonal variation in genera and their relative abundance; thus one can infer that the complex interrelationship between a “fluid” built environment, a “fluid” spatial environment and a variable ecosystem requires more research. Sampling for the study directed a broader architectural focus by associating spatial patterns, BE factors and microbial community indicators. It is evident from the results that it was of local importance that the study be conducted, as it confirms previous international MoBE study results, as well as methodology applications. But it also indicates that a critical area of investigation is the notion of sample threshold, for both BE factors, microbial samples, and the niche role spatial metrics. The SAHMS demonstrates that focused interventional studies are required to understand the complex relationships between BE factors and the microbial environment. It is evident that BE factors do play an influential role, but the SAHM study could not determine at which scale, of which type, or how much of each type played an influential role in the composition of the indoor microbiome (excluding ventilation). Existing research data sets through the ongoing MIxS-BE data base initiative as described by Glass *et al.* (2013), informed through studies by Adams *et al.* (2013, 2014 & 2015), Brown *et al.* (2016), Koch *et al.* 2014, Kembel *et al*. (2013 & 2014) and Ramos *et al*. (2014 2015) will support the factorization and deduction. As noted by numerous researchers, a clear guidance to future studies and parameters are critical to ensure repeatable and viable data sets that can in effect produce conclusive findings.

The SAHM research indicates that the broad macro-scale investigation is critical, as found by Lax *et al.* (2017), to determine the next level of required data and data thresholds. In the context of the microbiome, the macro spatial planning network indicated spatial core and isolation flow and functional variation; however, it can be inferred from the data that the size of the microbial sample needs to be increased and dynamic temporal factors are at play as found by Nice (2019) in the SAHM. The SAHM study indicates that total hospital or building characterisation is appropriate, but a micro level of investigation should follow. The research findings suggest that one of two studies needs to follow this investigation. The first is a study repeating the same methodologies, but for two different hospitals in two different provinces and climatic zones, that will contribute to the current findings. Conversely, a more in-depth study in the same hospital environments with focused sample collection in limited rooms and with multiple daily microbial samples could provide guidance as to influential BE factors (niche based focus). The number of BE data points will always outweigh microbial data sample collection; however, it is critical to determine the critical mass of MoBE studies. The optimum extent of sample size and BE data is still undetermined. More studies, longitudinal and short-term, micro and macro, will be required to determine this threshold of influence in the indoor environment.

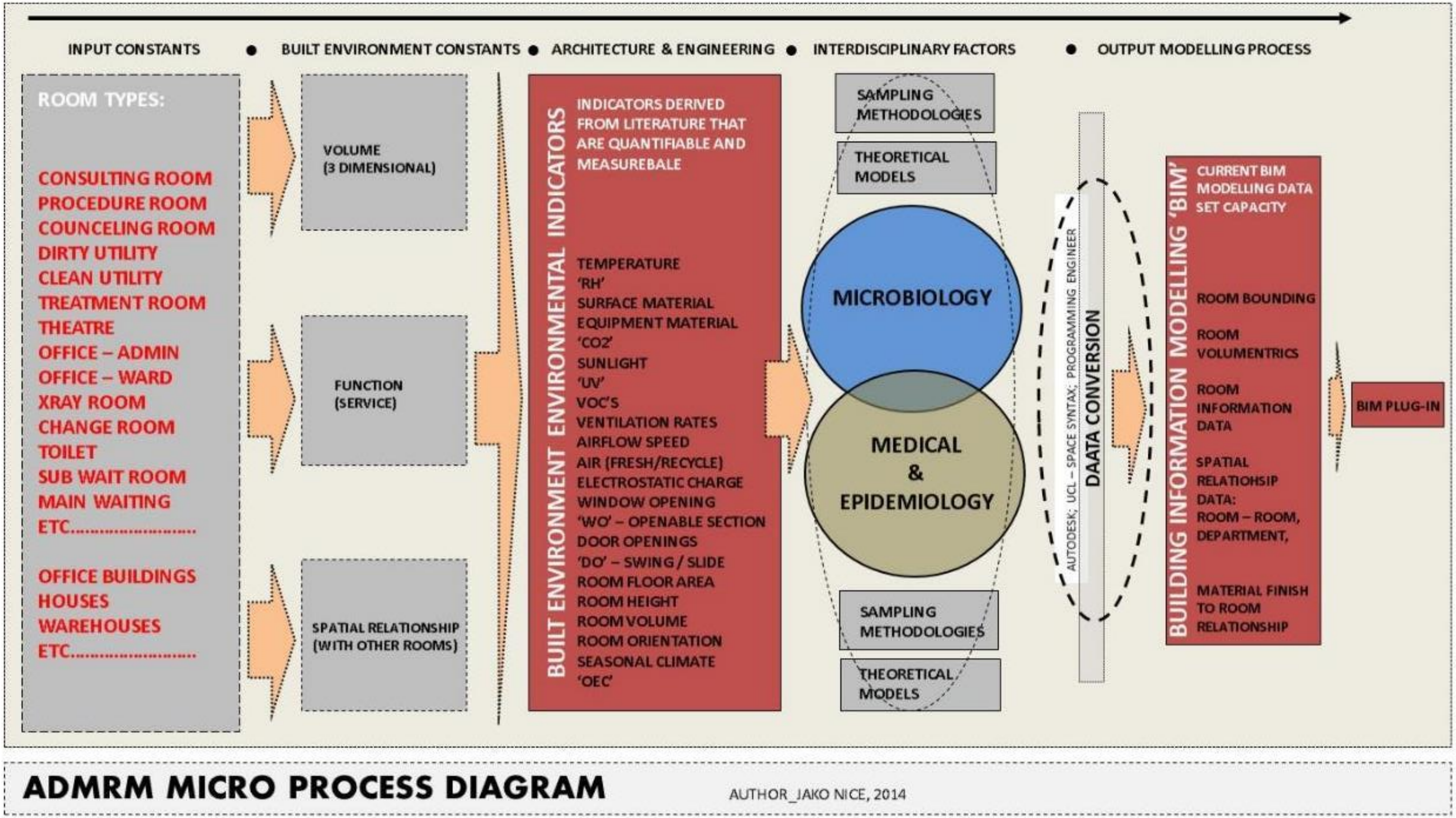

Figure **3**: ADMRM micro process diagram developed in 2014 (Nice, 2019)

Results and discussion

Apart from further developing the ADMRM tool for application in the built environment, the SAHM study presents a potential methodology for infection prevention and control (IPC) assessment that will not only inform potential designs and evaluate existing designs, operational changes and spatial reconfigurations, but also contribute to the data repository for the ADMRM tool. Numerous infection prevention control (IPC) risk assessment tools exist, developed by the Council for Scientific and Industrial Research (CSIR), Centre for Disease Control (CDC), World Health Organisation (WHO), Department of Health (DoH), National Health Laboratory Services (NHLS), National Institute for Occupational Health (NIOH), and non-government organisations (NGOs). These tools address IPC holistically and some are highly focused, such as for TB and airborne infection control; however, the element of spatial assessment is absent in the majority of assessment methodologies (only four present in all studies *(Nice, 2019 literature review and Nice and De Jager 2019 - unpublished*) and it is, if included, very rudimentary. The methodology developed in SAHM study and findings provide evidence to suggest a spatially analytical informed assessment methodology. A ***6 step +1 MoBE analysis tool*** is proposed. Derived from the authors doctorate methodology and informed by the results, the following steps constitute the basis of a framework towards developing such a tool:

1. Model the building plan in GIS and DepthMap™ or other spatial relationship syntax programs that consider the factors of integration, connectivity and mean depth, (Al Sayed *et al.* 2014)
2. Observe in real time the assessment area of the environmental study by count, beam brake, Rfid, heat sensors or other tools of identification,
3. Verify the model and note the variations of space use through analysis and observations,
4. Overlay the building data for each room within the analysis area,
5. Overlay the microbial data from each sample type collected (air and surface) noting: indicator species, OTU abundance for the room and richness of genera, and sample type (source)
6. Apply appropriate IPC methodologies based on the risk factors found to inform maintenance and operational and cleaning policies
7. Alternatively, as proposed: +1

+1) Make design changes and test these through agent-based simulation modelling, then reassign the sample data to the rooms and review the location variations for factor changes or IPC simplification in application. Space Syntax case study investigations, at both urban and building scale, over the past thirteen to twenty years have reported evidence that utilising Space Syntax to model potential human movement patterns has high correlation coefficients with actual observed flow patterns (Orellana & Al Sayed 2013; Penn & Turner 2001; Patterson 2016 etc.). In essence the principle question then: How can built environment data, microbiome data and spatial design data inform IPC processes, with the intentional focus on reducing the potential of HAI transmission?

Core finding and critical to future IPC BE planning, is the relationship of program and IPC. Previously not even a consideration. The low correlations found between the observation flow data of space use for integration of spaces, evidenced by the observed patterns, and the spatial potential at both facilities consistently R^2 of 0.4

and less opposed to R^2 0.58, (where R^2 correlation value of 0.6 is acceptable in BE) in fact supports the notion of a strong building program dominant in both of these facilities. The building program (the manner in which it is used) often overrides the assigned space function (where function determines utilisation). This complicates space related IPC approaches and provides critical insight into approaching BE design choices. Previous studies by Sailer *et al.* (2013) report on the impact of the building program. The author postulates that a stronger program will present a more temporal and dynamic microbial community not only determined by spaces but by the movement and activity between them.

Microbial sampling data indicated that both air and surface sample environments shared unique and associated genus species, implying that to effectively apply IPC interventions, both sample types are needed. When considering that HAI by touch, air and droplet has a strong correlation with human social interaction in indoor environments, as identified through various studies including Sternberg (2009); Robinson, Drossinos & Stilianakis (2013); Wargocki, Wyon & Fanger (2000); Hospodsky *et al.* (2012); Rintala *et al.* (2008); Ulrich *et al.* (2008) and Mendell *et al.* (2002). A core indicator of common organisms found in each room type and in both hospitals has been developed in the study. The data showed that both hospitals have similar biomes and thus a similar IPC approach can be followed. Whether this holds true for other health facilities in similar proximity is a worthwhile investigation towards standardisation per sub-region, and will allow for focused “attack” IPC measures. As found by Pachilova and Sailer (2013) their exists a large gap in research on spatial configuration and evidence based design. MPH Environmental measurement data revealed potential risks in various zones at both and KDH. Applying the CO_2, occupancy, Ls pp and room volume data enables one to produce a risk scale for room types for TB and other airborne pathogens relying on mass balance equations. The data indicated that Hospital KDH had lower ACH and L/s pp per room with larger volume and rooms regardless of type, whereas Hospital MPH had a 50% increase in occupancy over the winter season, combined with a higher abundance of air-associated organisms unique to the two hospitals. These findings may guide IPC measures. The data revealed core indicator species associated with room type, and culture analyses were done to determine species viability. Based on USA HAI statistics, 60% of the top five HAI associated organisms were identified in culture, and sourced from the DNA genera found with other unique pathogenic species associated locally.

The new proposed research roadmap requires a balance between focused interventional studies and broad biome studies. The micro-focused studies need to isolate factors and determine direct influences, such as investigating the Triage Consult 1 room through multi-point air sampling daily and seasonally, single area swabs with multiple swabs daily and seasonally, and multiple sensors collecting BE data and spatial use and occupancy patterns. This methodology will track localised biome variations over the course of multiple days, combined with a record of BE variations. The macro studies require completion of the same study in two different climate zones at two different hospitals, to inform seasonal variations by climate and total varied design by planning. The value of such a study will only be relevant if focused or multiple-focused intervention studies are conducted at the same hospitals.

Conclusions

The SAHM research objective was to initiate the development of analysis tools and results that could be applied to improve IPC approaches and generate functional layout changes in building design, focused on healthcare, but with the outcome for all built environment. The application of models for bio informed design as postulated by the author in this ADMRM still requires substantial data and investigation for application. However, the data and findings presented can serve as empirical guide to informed design decision making in the health sector. Spatial analytics: The methodology of modelling an existing base plan to elucidate flow patterns and focal space connectedness and levels of integration, then testing it with observational data, was shown to be highly effective. In the majority of the outcomes, the base plan analysis derived from Space Syntax methodology was correct. The observational data broaden understanding of social heuristics that develop in time and through operational and policy changes. The data shed light on both MPH and KDH rooms/zones that one would not perceive to be highly trafficked spaces and/or spatially connected with activity levels. Furthermore, the analytics elucidate the optimal planning of a hospital's central core. The findings offer insight into appropriate barriers and zone separation, and clarify the categorisation of spaces by function within a network of spaces. The data indicate potential zones of high integration and thus potential cores of interaction, providing insight into the number of people accessing spaces and moving within these spaces, when analysed within the framework of the entire system. This outcome enables BE IPC specialist to grade Zones on use, occupancy and association with risk. From integrating microbial sampling data, genus species can be associated with room types and zones, and thereby functional activities in space can be associated with the typical biome, as found. This allows for both localised IPC interventions and global network (the larger department or building) IPC interventions to reduce HAI.

Future areas of investigation should include: 1) Identifying the threshold of the microbial sample size. 2) Isolating BE factors and determining singular influence (only temperature, only RH, only surface material, etc.). 3) Extensive comparative studies on varied hospital designs (as applied in SAHM study); 4) Niche environments. 5) Hospital design studies in varying climates. 6) Diverse social demographic studies, and, 7) consistent unit/department-based studies for comparative purposes (ie. wards, accident and emergency, outpatients only).

The author, however, believes that spatial data will provide more insight into microbial distribution, as found in the ventilation outcomes and the overlay of microbial biome data per room type. The relationship between rooms will potentially provide further insight, this postulation is largly due to the limited spatial related investigation available (Nice, 2019) *literature review and spatial investigation*. The current data yielded from the SAHM do however not produce conclusive proof for this as the microbial sampling data do not show significant correlation with BE factors (environmental and spatial); however, ventilation was a strong defining BE factor finding, which could be due to the broad nature of the study design. A focused study with more localised samples from selected rooms will provide more insight. It was found that the number of BE factor samples by far outweighed the microbial samples. More microbiological samples are required to draw definitive conclusions at the micro room level. Further analysis of spatial data, observed data, BE factor data and room species indicators could provide further guidance towards this goal.

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