Investigating the impact of architectural planning and functional program on the indoor microbiome. A health concern

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SUMMARY
This paper reports findings for an innovative architectural methodology in spatial analytics, for application in characterising microbial load and distribution to spatial planning and functional use in inhibiting health care acquired infections (HAI); *(including airborne and surfaces).* The spatial analytical findings represent a 1st stage pilot investigation on the microbiome of two hospitals sites in South Africa. The investigation conducted observational analyses modelled in ArcGIS software, and spatial integration modelling of CAD floor plans in Depthmap Space Syntax software. The data was overlaid and analysed. A strong correlation between high occupancy rooms and high occupancy flow zones was found in all cases. Mitchells Plein (MP) hospital presented unintelligible spatial data with low integration of space implying high core clustering. Khayelitsha District Hospital (KDH) reported high levels of correlation between the potential social interaction and observed social interaction. The static and personal monitoring of temperature, humidity and CO2 *(CO2 rebreathe air as infection risk parameter - a parallel study funded by the Fogarty Research Grant)* indicated low CO2 levels throughout, but a statistical significance indicated that both sampling methods are required for characterisation of the indoor environment (IE).

PRACTICAL IMPLICATIONS
Provides an analytical spatial assessment methodology for architectural planning, to identify potential health contamination risks by HAI in built form indoor environment planning.

KEYWORDS
Architecture, Spatial planning, Healthcare Acquired Infection (HAI), Indoor microbiome,

1 INTRODUCTION
Healthcare settings are prone to HAI (Durlach et al. 2012) Mendell (2002) reports on the immense cost burden to Governments. In South Africa 1 in 7 patients are at risk of HAI (Brink et al. 2006) with a 9.8% prevalence rate (Durlach et al. 2012), yet this may be grossly under reported as it is estimated that developing world countries have HAI rates of 15.5 for every 100 patients (Alvarez-Moreno et al. 2014). In South Africa, *Tuberculosis* (TB) is an epidemic, commonly acquired in Health Care settings. The obligate aerobe nature of *Mycobacterium Tuberculosis* (Mtb) transmitted by airborne is difficult to control, therefore environmental controls are critical to reduce and manage airborne contagion (Yates, Tanser & Abubakar 2016). These facts point to alarming risk exposure in hospital environments, especially to healthcare workers. According to 2013 statistics, Western Cape has a population of 5.82 million, and Cape Town has a TB prevalence rate of 663 per 100 000. However in Khyalitsha and Mitchel's plain (the study sites) the TB cases are far in excess of Cape Town's average with 1165 cases per 100 000 people (City of Cape Town 2014).
It is therefore of critical importance that built environment solutions are investigated to reduce disease spread and improve indoor environmental quality (IEQ) and indoor air quality (IAQ).

Contamination occurs by airborne, droplet and touch, it is accepted that 'the spread of infectious bacteria, fungi, viruses and single cell organisms (prokaryotic & eukaryotic) specifically in hospitals are first by human contamination (Hospodsky et al. 2012) and secondly dependent on environmental conditions (Basu. et al. 2007); (Nice and Vosloo 2015). Investigating potential social interactions of spatial configurations to improve spatial planning with associated microbial characterisation could lead to potential basis for evidence based design decision making in infection control. The built environment in South Africa lacks microbial characterisation, the data resource of this investigation will contribute to understanding the ecology of the South African built environment and resources for the BEC (built environment community) in spatial planning.

In furtherance of current research on the microbiome and architectural spatial configuration impact, conducted by Author Nice, J. we refer to a previous paper hypothesis for background: 'Our research hypotheses postulate that the microbial load and diversity of the indoor biome bears a strong relationship to the functional use planning and functional program and that potential amplified microbial load and organism diversity can be correlated to occupancy, functional program and the environmental conditions' (Nice and Vosloo 2015). The doctorate research investigation contains three stages:

1. Pilot study investigation of spatial observation and syntactical modelling.
2. Winter site microbial sampling and observation analysis (from stage one).
3. Summer site microbial sampling and observation analysis (from stage one).

Findings from Rintala et al. (2008) indicated seasonal variation of organisms, informing the need for a multi-season study design.

This investigation presents stage one pilot findings and investigations. The hypothesis:

1. A common spatial planning configuration can be modelled using Real-time social observations and theoretical modelling using space syntax methodology.
2. Comparable correlation equivalents to the common spatial planning configuration indicate strong relationship between the design and functional program.
3. High level of activity zones correspond to high level spatial integration zones and present most potential social interaction leading to higher risk environments.
4. A high correlation of global relation of space and local relation of space infers greater potential for social interaction and higher risk environments.

The objectives of this investigation:

1. Compare real-time observation spatial data with a theoretical spatial planning configuration to determine application value for predictive modelling for health risk.
2. Develop a theoretical modelling methodology that could be utilized to analise space for the use in risk analysis (consider potential high impact social spaces) and associated microbial sampling data to the rooms and zones for risk profiling.
3. Correlate personal CO_2 data with the static monitor data, *(CO_2 rebreathe air as infection risk parameter - parallel study funded by the Fogarty Research Grant)* to determine the need and value for one or both methods of sampling as part of the risk profiling methodology.
4. Investigate potential for incorporating environmental data, spatial analytics in preparation for stage two microbial sampling data integration.

2 MATERIALS/METHODS

Study design

The study investigates two hospital environments in the Western Cape, South Africa. Real-time occupancy and flow were observed and a theoretical spatial analysis was performed to understand and predict potential social interactions and space use by empirical means. These analyses combined with environmental data (CO_2, temperature and humidity) were used for baseline modelling in preparation of microbial sampling data for interrelationship correlations (July & December 2016). This will be used to determine health risk profiles (Nice and Vosloo 2015). The study areas included medical wards and Accident and Emergency (A&E) departments of two Public Hospitals in the Cape flats over a period of 5 days in August 2015 (winter). The study collected real-time observation data of occupancy and flow in each facility, environmental data through both static loggers placed in rooms of the same function and personal loggers carried by the nursing staff. Flow and occupancy data was analysed in GIS, and special analytics of the as-built floorplans as well as statistical analysis was conducted in Depthmap and Microsoft Excel.

Equipment, material and procedures

Static monitors manufactured by CO2Meter, Inc. Ormond Beach Florida United States (CM-0018AA) collected CO_2, Temperature and relative humidity data. These were either surface (approximately 900mm height) or wall mounted (approximately 1500mm height) in 10 locations at each facility. Seven loggers per A&E, and three per ward, collecting a total of 120hours of Indoor Environment (IE) data. GasLab®, proprietor software, was used.

Personal monitors *(A parallel study funded by the Fogarty Research Grant)* developed by UCT, Desmund Tutu HIV Centre research unit: 'portable carbon dioxide detection devices (EasyView 80 CO_2 analyzer, Extech Instruments, Waltham, MA) and custom monitors (based on COZIR Ambient sensors, Gas Sensing Solutions Ltd., Glasgow, UK)' were assigned to 5 staff members at each facility on a daily basis before their eight hour shift. Co2, temperature and humidity were collected daily.

A weather station was procured and installed, however the data could not be extracted, weather files are being sourced from the Cape Town International Airport.

Observation data was collected on five consecutive days (Friday through Tuesday) representing peak and off-peak days. The observation methodology was based on University College London (UCL) Architecture Department, Space Syntax Software manuals (Al_Sayed et al. 2014). A two task observation protocol was followed, once hourly over a nursing shift.

Task 1: "Mental snap shot" A route map was determined and marked on plan. The route was determined by the high use zones and exclusion of utility spaces. Furniture and divisional changes were indicated on the plan. The route was covered hourly with 3-4 minutes observation per zone and people (Dr, Nurse, Other, Patient) and actions (seated, standing, walking) were coded. Task 2: "Movement tracer" Similar to task 1 the routes (within, through, away, towards) taken by people (Dr, Nurse, Other, Patient) was documented.

Computer Aided modelling software: DepthmapX v0.5b, ArcGIS 10.3, and AutoCAD, 2015

Spatial modelling methodology

Nichersu and Iacoboaea, (2011) defines spatial planning as: 'the change of the distribution of activities in space and the change of the links between them by converting forms of land use and property'. Spatial planning is as relevant at building scale as at urban scale. Hillier and Hansen, (1984) describes the social logic of space, and argues that a building is seen as artifact or object but is in fact the collection of space imbedded with function and social meaning; 'the ordering of space is really about the ordering of relations between people'. Spatial analytics considers the interrelationship of space, measuring configurational properties of a layout: floor plan, urban plan etc. 'Space Syntax starts with defining movement and occupation as the fundamental functions of a layout, where permeability of all spaces is the priority' (Al_Sayed et al. 2014). The level of spatial connectivity and integration with neighbouring spaces, termed spatial intelligibility (SI), provides insight into potential social interactions. The functional use of spaces impacts the required level of integration and connectivity. Clustering of core functional spaces theoretically provides a high level of connectivity and correlates strongly with spatial integration.

Real-time observation data was captured in ArcGIS and was displayed according to activity and person type. Zonal occupancy levels is equivalent to spatial density which suggests potential high and low risk environments. Movement patterns indicate the number of actions that occur within zones. The zones were graded according to the number of actions and the potential integration and connectivity of the zones was determined (tables 3-5). The graded occupancy data and movement patterns, which considers social encounters and implies the functional use of space are represented in tables 1&2.

Table 1. Functional zones, most occupied spaces

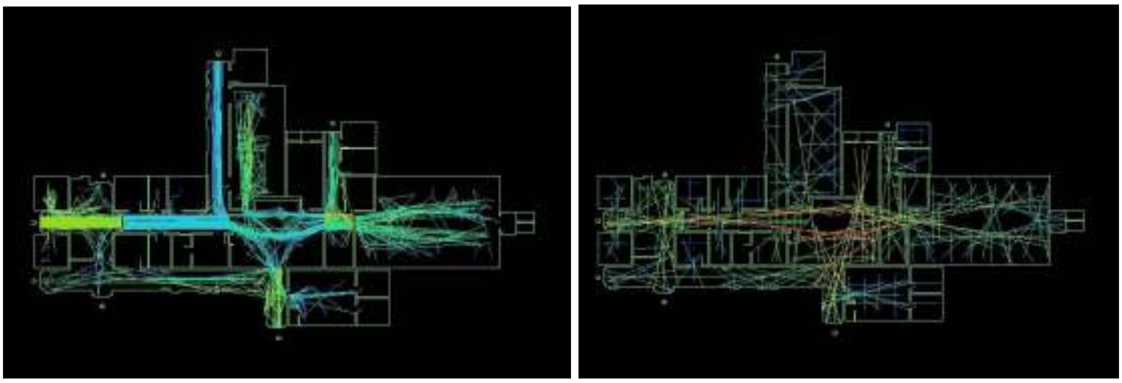
Occupancy grade	KDH Ward	MP Ward	MP A&E
1	Ward (6 Bed 3)	Ward (6 Bed 1)	Trolley Area
2	Ward (6 Bed 2)	Ward (6 Bed 2)	Waiting area (Sub Wait 1)
3	Ward (6 Bed 1)	Ward (6 Bed 4)	Resus room
4	Ward (6 Bed 4)	Ward (6 Bed 3)	Passage/Nurse Station
5	Passage/Nurse Station	Passage/Nurse Station	Public Waiting
6	Ward (2 Bed 2)	Ward (2 Bed 2)	Waiting area (Sub wait 2)
7	Ward (2 Bed 1)	Ward (2 Bed 1)	Nebulisation Room
8	Ward (1 Bed 2)	Ward (1 Bed 2)	Passage/Emergency Entrance Foyer
9	Passage/Entrance Foyer	Ward (1 Bed 1)	Triage room (Triage 1)
10	Ward (1 Bed 1)	Passage/Entrance Foyer	Passage/Nurse Administration
11	N/A	Passage	Triage room (Triage 2)
12	N/A		Procedure Room

Table 2. Functional zones, highest flow rate

Flow grade	KDH Ward	MP Ward	MP A&E
1	Passage/Nurse Station	Passage/Nurse Station	Passage/Nurse Station
2	Passage/Entrance Foyer	Ward (4 Bed 1)	Waiting area (Sub Wait 1)
3	Ward (4 Bed 1)	Passage/Entrance Foyer	Passage/Emergency Entrance Foyer
4	Ward (4 Bed 2)	Ward (4 Bed 3)	Passage/Nurse Administration
5	Ward (4 Bed 3)	Passage	Trolley Area
6	Ward (4 Bed 4)	Ward (4 Bed 4)	Waiting area (Sub wait 2)
7	Ward (2 Bed 2)	Ward (4 Bed 2)	Resus room
8	Ward (1 Bed 2)	Passage	Nebulisation Room
9	Ward (2 Bed 1)	Ward (2 Bed 1)	Triage room (Triage 1)
10	Ward (1 Bed 1)	Ward (2 Bed 2)	Triage room (Triage 2)
11	N/A	Ward (1 Bed 1)	Procedure Room
12	N/A	Ward (1 Bed 2)	Procedure Room

Total user load through all zones and activities per day were correlated against theoretical mapping to determine its viability as a social interaction mapping methodology. Activity information was not analysed in this study. CO_2 was averaged for the facility to indicate CO_2 surrogate risk as seen in figure 2. The CO_2 data was linked to the occupancy of zones. In

future, environmental data will be associated with the microbial environmental factors gathered for microbial input. Correlations between CO_2 data collected from the personal monitors and the static monitors indicates that both types of units are required to adequately characterize the C02 shared air experience in an environment.
The Space Syntax analysis axial plan does not consider function of space, but merely layout and mathematical spatial relationship. This provides insight into the most visual integrated spaces; which is relevant for hospital environments for the purpose of nurse care and medical supervision of patients, as well as way finding. Spatial analysis was conducted on the as-built floor plans as designed by the architect (Axial mapping) as seen in figure 1. A variation in the methodology of axial mapping was used as argued by by Sailer (2010) regarding a ‘more relevant representation of spatial relationship’ by considering the known social relationship of a given environment (hospital).



a) b)
Figure 1. Axial map. a) MP as-built planning, b) MP observational flow.

Previously captured observation data will in future be used for predictive modelling (Agent based modelling – Depthmap) for microbial association and potential risk environment identification. Applying microbial data with spatial analytics will assist in determining relationships of microorganisms to the movement patterns distribution.

Research Application
1) A methodology for grading zones according to actions and movement patterns to enable better clustering of functional rooms and zones. 2)A methodology to analyse to what extent designed spaces have been successful or if functional re-arrangements for optimum nursing are required. 3)A methodology for determining global and local connections, for both real-time and designed spaces to quantify social interactions.4) Level of action (flow) and occupancy count relates to the functional use of the space.
When one views risk and contamination the increased requirement of large numbers of people to planned non-integrated spaces has the potential of fueling infection, it also makes it very difficult to restrict contamination and or implement a focused plan. When one adds environmental and microorganism prevalence data to these spaces the potential host environments become apparent and the level of risk becomes more evident. The final layer of microbial characterization of each of these zones should shed light on the relationship of spatial integration and movement pattern density to the microbial load.

3 RESULTS
Space syntax allows for parametric analyses: choice, connectivity, integration and integration/connectivity etc. Due to the variation in clinical services provided over the period of a day the analysis considers a full day’s flow data for both wards and A&E departments.

Table 1 indicates zones with highest occupancy over the study period; indicating the most functionally used spaces. A high correlation was found between zone grading and movement pattern grading, indicating most functional environments are integrated with the highest flow/connectivity roots and potential cross contamination/risk could exist. When spatial integration was compared (Table 3), a strong relationship was found between "most occupied" rooms and the integration core. The SI for designed space is normatively accepted at correlations of 50%+. Table 5 shows the design spaces reflect high levels of SI. Only KDH Ward is acceptably SI, however it is still only 64% of the design potential. The MP spaces are associated as spatially unintelligible (SunI) where SI is a function of integration and connectivity and an accepted representation for potential social interaction. What is of interest is the variation of SI values on different days; this could be attributed to variations in clinical programs and corresponding zone function.

Table 3. Levels of spatial integration

	KDH Ward		MP A&E		MP Ward	
	Design	Observ	Design	Observ	Design	Observ
Avg vari	**100%**		**65%**		**46%**	
(5d) total	2.27	3.53	2.86	2.03	2.49	1.81
Day 1	2.27	1.97	2.86	2.68	2.49	1.44
Day 2	2.27	2.67	2.86	1.79	2.49	0.99
Day 3	2.27	2.15	2.86	1.66	2.49	0.95
Day 4	2.27	2.68	2.86	1.57	2.49	1.33
Day 5	2.27	1.95	2.86	1.60	2.49	1.18

Table 4. Levels of spatial connectivity

	KDH Ward		MP A&E		MP Ward	
	Design	Observ	Design	Observ	Design	Observ
Avg vari	**200%**		**79%**		**48%**	
(5d) total	7.36	57.58	16.15	48.58	10.98	21.50
Day 1	7.36	9.47	16.15	16.01	10.98	5.58
Day 2	7.36	15.40	16.15	11.08	10.98	3.84
Day 3	7.36	15.25	16.15	12.46	10.98	4.50
Day 4	7.36	26.53	16.15	14.75	10.98	6.13
Day 5	7.36	9.43	16.15	10.13	10.98	6.72

Table 5. Intelligibility correlation (integration/connectivity)

	KDH Ward		MP A&E		MP Ward	
	Design	Observ	Design	Observ	Design	Observ
Avg vari	**64%**		**24%**		**46%**	
(5d) total	**r0.84**	**r0.56**	r0.79	**r0.19**	**r0.78**	**r0.39**
Day 1	r0.84	r0.54	r0.79	r0.43	r0.78	r0.45
Day 2	r0.84	r0.58	r0.79	r0.16	r0.78	r0.34
Day 3	r0.84	r0.51	r0.79	r0.06	r0.78	r0.29
Day 4	r0.84	r0.51	r0.79	r0.10	r0.78	r0.36
Day 5	r0.84	r0.57	r0.79	r0.23	r0.78	r0.37

The movement patterns indicate the level of connectivity between zones. For this paper the number of connections between movement patterns indicates the potential number of function relations and utilised zones. Table 4 indicate that the potential design connectivity is higher than the utilised value for MP zones (48% and 79%) however for KDH the inverse is apparent with an average connectivity of 200%. The level of integration (potential to connect globally within the entire network of spaces not just immediate connections) for the MP Ward and

A&E observation is less than that of the as-built design (46% and 65% respectively), whereas KDH Ward observation is 100% correlated. In both MP Ward and A&E the observation value is less than the designed value indicating there's a functional variation and a resulting 46%-65% reduction in social interaction. Conversely, for KDH Ward 100% real time social interaction occurs. In Figure 2 the total average CO2 levels are shown for both hospitals, the data indicates very low average values (less than 500ppm). It is critical to view this in relation to occupancy which was not done in this study.

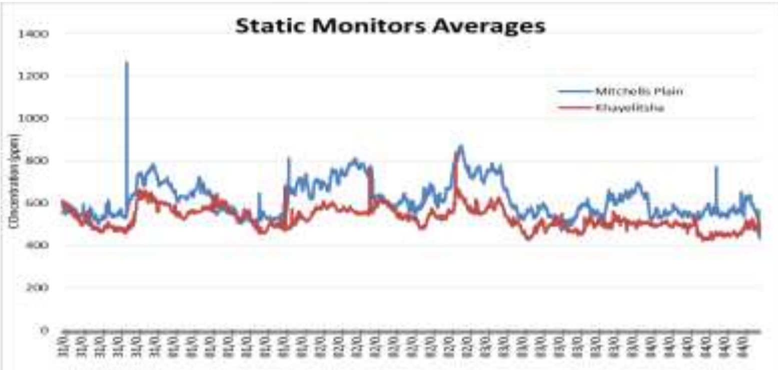


Figure 2. Static monitors combined Co2 levels for both Hospitals.

4 DISCUSSION

The spatial analysis indicates that real time social interaction varies from the designed spatial planning for all departments in MP but not for KDH. A great variance in integration was observed between the two different ward typologies (46% for MP ward to 100% for KDH ward). This variation can be attributed, but not limited to, functional layout of each department. When considering the MP data a only 24%-46% social interaction was observed as opposed to design potential. This could be attributed to variation in clinical functions, purpose for fit rooms, clinical timetables and social process knowledge not available. The data provided accurate definition to the most functional spaces and a strong relationship to the most integrated spaces. The CO2 values found for all environments on average were notably low in relation to known high risk CO2 surrogate estimates.

This research presents a new novel methodology to assess the potential social interaction in a spatial configuration for the purpose of infection control. HAI source by touch, airborne and droplet have strong correlation to human social interaction. This methodology provides potential analytical means to predict these interactions and grade room environments.

Further studies are required and the researchers plan to utilize agent based modelling as a 'next step' in validation of observed environments to test room functional variations.

5 CONCLUSIONS

Space syntax spatial analysis and GIS modelling provides a novel opportunity to introduce architectural spatial analysis to risk determination in existing environments and new design planning configurations. Characterizing the built environment microbiome through the social logic imbedded in space through syntax analysis potentially facilitates BEC in designing low risk environments. It is the view of this paper, based on the data, that an increased level of integration and connection at KDH should present higher levels of microbial spread in relation to MP. The data suggests that due to the lack of connection and integration observed, heightened levels of microbiota should be present in the core cluster areas of MP. Clustering of high activity functional zones (such as MP data suggest) will reduce integration but increase densification and could enable more environmental control and allow for more focused risk intervention for airborne or surface spread intervention.

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