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Decision Making within the Built Environment as a Strategy for Mitigating the Risk of Malaria and other Vector-Borne Diseases

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Abstract

Although significant efforts have been made to combat the spread of vector-borne diseases (VBDs), they still account for more than 17% of all infectious diseases. According to the World Health Organization (WHO), there were 216 million estimated cases in 2016, which is a 9.3% decrease from the estimated cases reported one decade earlier. It is known that the built environment, through features such as openings, can propagate the spread of malaria. There have been some significant efforts directed at addressing this risk. This notwithstanding, there are some knowledge gaps that have resulted in a missed opportunity for synergistically tackling the problem of vectors through leveraging design decisions made by built environment professionals. This work assesses the extent to which design decisions in the built environment can have a positive impact on the efforts directed at mitigating the risk of malaria based on selected cases from East Africa. Secondary data derived from relevant urban health journals as well as repositories curated by leading health agencies such as WHO were synthesized and analyzed using a web of causation approach. The outcome of the analysis is a schema of primary and secondary source (risk) factors. The use of the web of causation approach revealed the existing factor-to-factor interactions that could have a reinforcing effect. This information was used to identify the critical linkages and interdependencies across different factors. The outcome of the analysis was mapped against risk factors that can be linked to decisions made during the six primary phases of the construction life cycle: preliminary phase, conceptual design, detailed design, construction, facilities management, and end of life/disuse. The findings of the research

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have established that 1) there is, in fact, a built environment–related opportunity that can be leveraged to advance the impact of malaria mitigation effort; 2) cross-disciplinary synergies are critical to managing the interdependencies and complexity of malaria risk factors that have a reinforcing effect; and 3) a knowledge-management framework that serves as a decision support tool would be valuable for sharing data under a push-and-pull mechanism, in which data shared in real time can address the timeliness of mitigating the spread of malaria at the earliest stages for the greatest impact. Based on the findings, a conceptual architecture for a decision support framework has been proposed. This will be developed into a knowledge-management platform in subsequent efforts.

Contextual Background

The overarching goal for this research is to assess the extent to which design decisions in the built environment can have a positive impact on the efforts directed at mitigating the risk of malaria, based on selected cases from East Africa. Key findings show the presence of interactions among risk factors that could have a reinforcing effect. These risk factors could propagate the prevalence of malaria during the construction life cycle. There is an interest in designing a conceptual architecture for a decision support framework to combat the increased costs and infections related to the disease. This tool incorporates features that would bridge professionals together to prevent malaria cases and decrease costs during the construction life cycle.

In 2016, there were an estimated 216 million cases of malaria in 91 countries (World Health Organization), which surpasses the prevalence of other tropical or neglected diseases such as HIV/AIDS and dengue fever (see Table 1).

Table 1: Infectious Disease Cases
(WHO 2016)

Tropical Disease	Number of People Infected in 2016
Malaria	**216 million**
HIV/AIDS	36.7 million
Tuberculosis	10.4 million
Dengue	3.2 million
Leprosy	200,000
Ebola	28,600

Around 445,000 deaths occurred in 2016 as a result of this disease. The World Health Organization (WHO) Global Malaria Program, in collaboration with governments from endemic countries and regulatory authorities, has factored in safety and surveillance, drug efficacy, and financial burden in their efforts directed at accelerating progress towards malaria elimination (Global Technical Strategy for Malaria, 2015). According to the WHO 2016 World Malaria Report, there was a 9.3 % decrease in the number of reported cases between 2006 and 2016. The Global Fund, one of the largest malaria prevention organizations, disbursed over USD 9.1 billion in 2016, a 90% increase from the funding that was provided a decade earlier (Global Fund, 2017). The opposing trends of decreasing estimated cases per year and increasing costs for malaria prevention (see Figure 1) underscore the need for new strategies for mitigating of the transmission of malaria.

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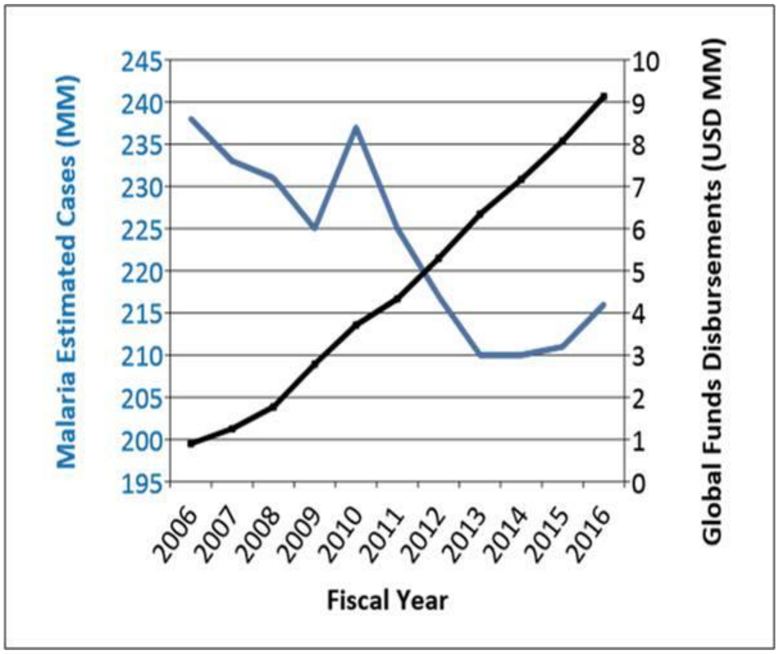

Figure 1: Relationship between Global Spending Trends and Estimated Cases of Malaria (WHO World Malaria Report, 2010 and 2017; Global Fund Malaria Financials, 2017)

Regions of South America, South and South-east Asia, and Sub-Saharan Africa had a stable prevalence of malaria in 2009, as shown in Figure 2. Regions closer to the equator had higher prevalence, and regions farther away were either formerly malarious or never malarious. Seven years later, the larger number of deaths from malaria was concentrated in sub-Saharan Africa, as shown in Figure 3. Based on this report, although the number of cases may have decreased in some developed nations, malaria is still severe in countries that are in low and emerging economies. Currently, international agencies such as the USAID, WHO, Wellcome Trust, Roll Back Malaria Group, and the Presidential Malaria Initiative (PMI) have invested millions of dollars to prevent and decrease the spread of malaria in sub-Saharan Africa. Professionals in medicine, entomology, epidemiology, the built environment, and public health policy have contributed towards the development of international programs and scientific research to address the crisis.

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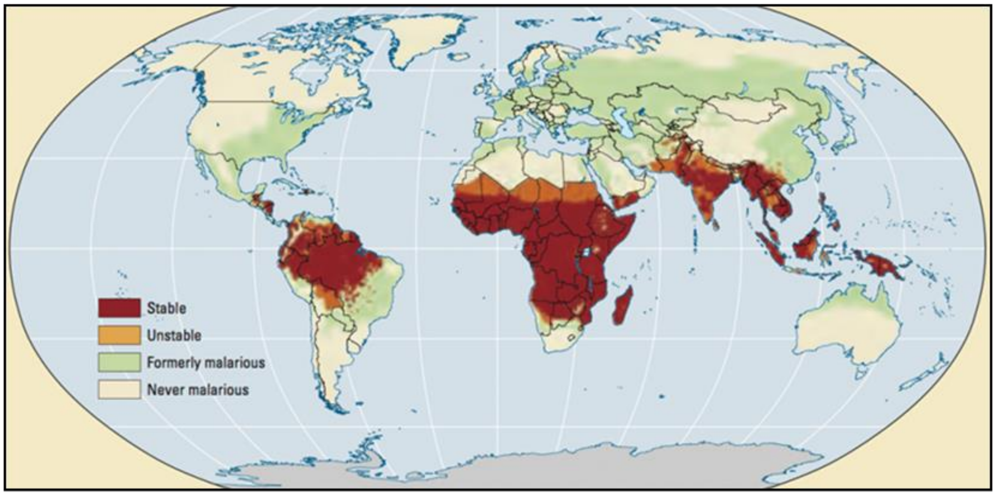

Figure 2: Severity of Malaria Prevalence in 2009
(World Bank, 2016)

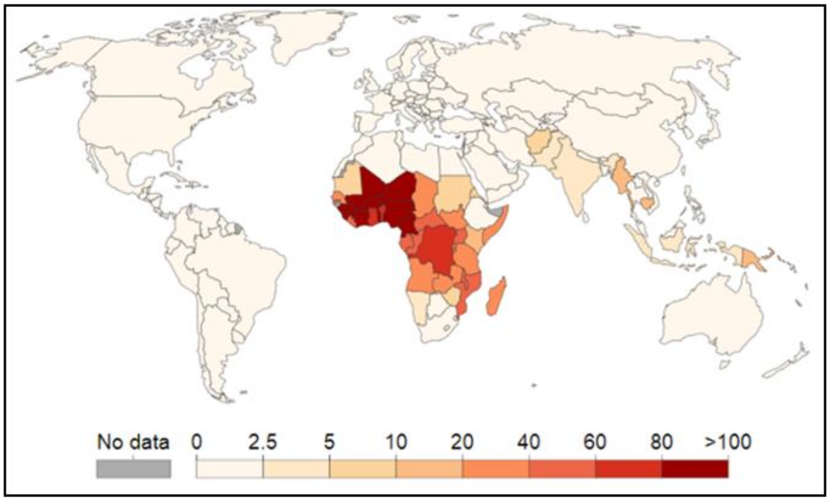

Figure 3: Malaria Death Rates per 100,000
(World Bank, 2016)

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Theoretical Background

It is known that effective design and construction of buildings and other assets can help combat the spread of vector-borne diseases (Tusting et al., 2015; Menger et al., 2014; Marshall and De Silva, 2012; Gamage-Mendis, 1991). This is evident from the malaria intervention program that was implemented during the construction of the Panama Canal. According to the Centers for Disease Control and Prevention (CDC), built environment–related strategies such as pool drainage near homes, bush cutting, and building screening resulted in a decrease in the percentage of the workforce hospitalized because of malaria from 9.6 % to 1.6 % between 1905 and 1909 (CDC, 2016).

There are several interventions that have leveraged lessons learned from the Panama Canal project. Examples include modification of building envelopes through reducing the size and/or number of openings such as windows (Ogoma et al., 2009). These reduce the ease with which mosquitoes gain access to a building. Other efforts focus on material selection given that there is a positive correlation between the use of traditional building materials and techniques, and the prevalence of malaria (Tusting et al., 2015). There is also evidence of a relationship between management of existing drainage systems and larval control (Tizifa et al., 2018), in which poor drainage can provide ideal conditions for breeding the malaria-causing mosquito. Although these types of intervention programs have resulted in some positive effects with respect to malaria prevention, the authors contend that their impact is limited because they are largely driven from a public health perspective.

A comprehensive review of published literature did not reveal any evidence of built environment professionals responsible for critical decision-making responsibilities featuring prominently in the existing malaria intervention efforts (see examples in Table 2). It appears that the overlap between the public health champions of housing modification for the control of malaria and the built environment stops at the level of construction trades.

Table 2: Categorization of Literature Reviewed

	Research Focus	
Motivation	**Outcomes assessment and impact evaluation**	**Spatial Analysis of the spread of Malaria**
Promoting Public Health from a Global Perspective	Mgone, 2010; Marshall et al., 2010; Atkinson, 2011; Wang et al., 2006; Marshall and De Silva, 2012; Qiuyin, 2012; Tizifa, et al., 2018)	Hausmann-Muela, Susanna and Julian Eckl, 2015; Ocampo et al., 2013; Tatem, 2014
The link between Climate Change and the occurrence of Malaria	Reiter, 2008; Klinkenberg et al., 2008; Hay et al., 2002; Adefemi et al., 2015.	Zhou et al., 2007; Lindblade, 2000; Tonnang, 2010; Edlund et al., 2012
Opportunities for Built Environment-related mitigation	Lindsay et al., 2002; Menger et al., 2014; Gamage-Mendis, 1991; Lindsay SW et al., 2003, Harrysone et al., 2009; Tusting et al., 2015; Tusting et al., 2016; Marshall and De Silva, 2012	Marshall and De Silva, 2012; Waite, et al 2016.; Tusting et al., 2017

There is evidence of cross-disciplinary collaboration in efforts focusing on investigating: 1) clinician-versus-patient perception of malaria diagnosis (Chandler et al., 2008); 2) impact of different public health models on policymaker and developer decisions (Nunes et al., 2013); 3) the role of bioinformatics modeling techniques (Suhanic, 2009); 4) the role that social entrepreneur and community sector organizations can play in improving both the diagnosis of malaria and the implementation of interventions (Allen et al., 2010); and 4) the development of strategic partnerships between the public and private sectors (Njau et al., 2009). There have been some positive outcomes arising from such efforts. However, there is still a need for more work to be done to fully leverage the existing opportunity to increase the impact of mitigating the risk of malaria through focusing on built environment-related factors. According to a meta-analysis and systematic assessment conducted by Tusting et al. (2015), housing, in particular, presents as a

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significant risk factor for malaria. There is, therefore, a critical need to generate actionable insights on both the magnitude and complexity of this problem.

The nature of the problem involves a public health aspect, built environment aspect, and a bridge between both fields. In particular, climate change is expected to create environmental conditions that have adverse effects on the incidence of VBDs (see Figure 4). For example, abiotic factors such as wind pattern, precipitation pattern, and relative humidity can influence vector migration, seasonal population density, and genetic composition of vector populations (Climate Nexus, 2016).

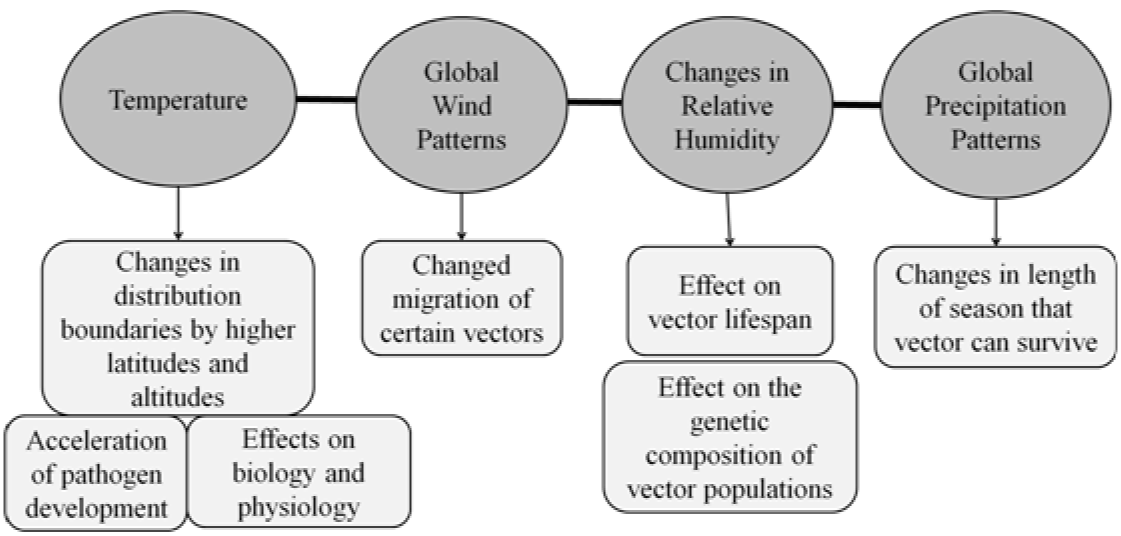

Figure 4: Direct Effects of Climate Change on Disease Vectors

Adapted from (Columbia Earth Institute Climate Nexus, 2015)

Themes that may share an indirect link towards built environment health may also factor into increased risk of malaria propagation. Such examples include social determinants of health, mental health, government advocacy, safety practices, urban planning, public–private

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partnerships, and healthcare access. For instance, one socio-cultural factor that influences the prevalence of malaria, particularly in children, is the hierarchical structure of families among communities with social stratification in parts of Nigeria (Adefemi et al., 2015). Children under five years of age have a greater need than adults for nutritiously balanced meals because they do not have a strong built-in immunity. In areas where food is scarce, fathers hold the right to the best meal, and children are often left with food that does not permit adequate growth and development for their age (Adefemi et al., 2015). Additionally, some barriers to effective intervention strategies that involve a cross-disciplinary consideration include access to public health information and level of spirituality. Some communities may have limited access to information in print or electronic media. Adefemi et al. (2015) noted that the presence of malaria under the compass of ill-health is often related to the presence of demons or evil spirits, which require herbal and spiritual remedies or behavioral changes.

The Built Environment Opportunity

Mitigating the risk of VBDs should be one of the design objectives for buildings in countries with a high incidence of malaria. An existing built environment–driven, healthy building movement that can provide the starting point for the proposed approach (Dodge Data and Analytics, 2016). Common issues explored in such initiatives include indoor pollutants, particularly those that arise from the use of toxic chemicals in paint and other building finishes (SmartMarket Report, 2016). Some efforts focus on investigating the risk of respiratory illness that can be linked to moisture-related problems such as mold. It is worth noting that the existing healthy building initiatives are championed by stakeholders in western countries. The focus, therefore, is largely on diseases and health problems that occur in countries such as the U.S., Canada, the U.K., and Australia that do not have a big problem with respect to VBDs. There are also some significant opportunities for education with respect to the different types of diseases that have a built environment-related contributing factor. In its comprehensive study of the interface between buildings and health, Dodge Analytics (2016) specifically underscored the need for more research and data on how to improve building health impacts and more public awareness campaigns on the significance of this interface. In addition, the economic constraints associated with generating public awareness should be noted. Proper economic measures, such as having the resources necessary to create an environment protective against malaria, are key factors towards enhancing the impact of public awareness on malaria mitigation.

There is a critical need to increase awareness of the different ways through which the main activities undertaken throughout the life cycle of a construction project can propagate the spread of malaria. Design professionals are either directly responsible for or uniquely positioned to influence decision making in each of these phases. The missed opportunities for them to contribute to the risk of malaria is outlined below:

1) *Preliminary Phase:* Selection of a site near an open surface water body may increase the number of breeding sites for the malaria vector.
2) *Conceptual Design:* The placement and size of openings as well as the orientation of the building envelopes affects the vector accessibility both into and out of the building.
3) *Detailed Design:* Certain types of material on housing features such as mud walls, thatched roofs, and earth, sand, dung, and stone flooring increase vector attraction into the site (Wanzirah, 2015).
4) *Construction:* Excavation work results in opportunities for several pools of stagnant water to form — these pools are ideal breeding grounds for mosquitoes.

5) *Facilities Management:* Drains and ditches are common habitats for mosquitoes to breed (Mattah, 2017). Poorly installed pipes and drain blockage can lead to poor sanitation or reduced water flow. The accumulated stagnant water can become a favorable habitat.

6) *End of Life/Disuse:* Construction and demolition waste contributes to the environmental problem of landfills.

As shown in Figure 5, the largest window of opportunity for making an impact in an effective and efficient manner is during the conceptual design phase. There is a cost associated with changes made in subsequent phases that increases with time. Therefore, it is economically more beneficial to engage with professionals responsible for making critical design decisions during the formative stage of a project.

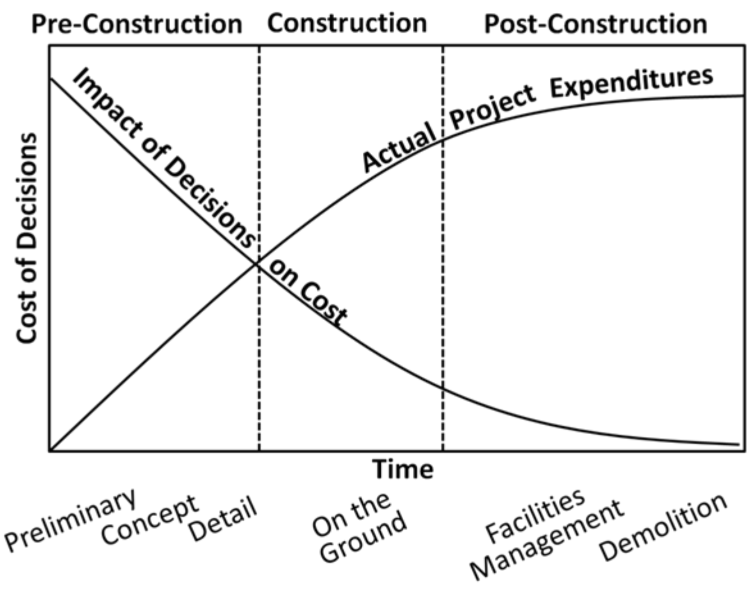

Figure 5: Cost-Benefit Curve — Early Decision Making in Construction Life Cycle
Adapted from (American Institute of Steel Construction, 2018)

There is a sense of urgency with respect to addressing the missed opportunity to leverage design decisions because of rapid urbanization rates. Half of humanity, 3.5 billion people, live in cities (United Nations, 2018), and it is estimated that by 2030, almost 60 percent of the global population will live in urban areas. According to UN population projections (2018), the parts of

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the world that are more adversely affected by malaria are going to experience the highest urbanization rates in the next several decades. In fact, there is a strong, positive correlation between increased urbanization and increased number of malaria infections (Donnelly et. al 2005). This is also apparent from the reported trends for malaria-prone regions in urban Kenya and Tanzania. Based on UN projections, Tanzania's population is expected to grow by 22% between 2014 and 2050, peaking at an estimated 68.5 million people (World Bank, 2018). During the same timeframe, Kenya's urbanized population is expected to grow by 19%, resulting in an estimated 42.6 million urban inhabitants. Rapid urbanization comes with increased construction activities because of growing demands for housing.

There is a growing urban slum population in both Kenya and Tanzania that is expected to increase seeing that the demand for housing is significantly much higher than the formal construction sector can supply. This is exemplified by the situation in Tanzania where the housing deficit is as high as 3 million (Kimani, 2017). There is a positive correlation between inadequate housing and the risk of malaria. Slum conditions such as poorly monitored land use and urban agricultural practices result in higher mosquito biting rates (Patz et al., 2004). Areas of low socioeconomic status, often at the periphery of cities, are more likely to have poor quality housing, unpaved roads, and reduced access to healthcare. These factors, combined with rapid urban expansion and ever-increasing city boundaries, result in increased transmission of malaria that town planners are unable to keep up with (De Silva and Marshall, 2012). Without considering the lessons learned from the development of the Panama Canal, the economic, medical, and social costs are expected to persist in the future. There is evidence of an opportunity for built environment professionals to create measures to control the spread of malaria, as an

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effective decision support tool could utilize the knowledge of both public health and design and construction collaboratively.

The extent to which built environment-related factors can be used to mitigate the spread of malaria during the construction life cycle requires a deeper understanding of several risk factors present during the entire construction life cycle. Changes in global wind pattern and increased rainfall are examples of risk factors that propagate the spread of the disease. The risk of malaria infection is higher at night, given that the *Anopheles* mosquitoes in Sub-Saharan Africa mainly bite between 10 p.m. and 4 a.m. when most people are indoors (Tusting et al., 2016). Weather-related factors such as increased precipitation, relative humidity, and temperature conditions can also create a more suitable habitat for the malaria vector (Climate Nexus, 2015). A study focusing on land use and malaria transmission in Uganda found that for every 1 °C increase in average minimum temperature, there was a 77% increase in *Anopheles gambiae* per each model house (Lindblade, 2000). When such favorable conditions coincide with the construction phase of a project, the breeding potential for malaria-causing mosquitoes also increases significantly. The construction phase is characterized by pools of stagnant water developing in areas of intense excavation (Reiter, 2008) and work areas with earth removal work (Lipscomb, 2006). The sources of the water can be leakages from temporary water supply points and storm water that is not drained promptly (Yhdego and Majura, 1988).

Some of the ways through which the built environment contributes to the risk of malaria transmission become more apparent during the facility use phase. Malaria-causing mosquitoes access the building through the inlets and outlets included in the design of the building envelope to allow air exchanges between the exterior and the interior. The malaria mitigation initiatives are directed at minimizing the ease with which mosquitoes access the interior of the buildings by focusing on reducing the size and number of openings (Sternberg, 2016). It is critical to engage built environment design professionals to ensure that the desired building modifications do not result in undesirable effects. Because indoor air quality (IAQ) and comfort of the occupants predicates directly on having optimal air exchanges, changes to the openings can result in unfavorable conditions for humans (Huizenga et al., 2006). Building occupants in malaria-prone areas rely on natural ventilation to attain optimal IAQ. Reducing air exchanges has a direct impact on thermal comfort of the occupants encouraging them to spend more time outdoors, particularly in evenings, where they have a much higher risk of being bitten by a malaria-causing mosquitoes. It is also known that poor IAQ can increase the risk of respiratory diseases (Ezzati and Kammen, 2002). Having the right IAQ is also important for managing air-borne pathogens. Therefore, it is important to align all decisions that affect the size, exact location, and number of openings with the principles of building physics. Ensuring that optimal ventilation rates are attained requires an in-depth understanding of the building as a system of system. Mitigating the risk of malaria from a built environment perspective is, therefore, a complex undertaking. Each decision has many associated linkages and interdependencies. Outside of working in a synergistic manner with the experts in the design and construction of buildings, any building-related intervention will be based on a partial view of what constitutes a healthy building.

The complexity of mitigating the risk of malaria transmission through managing built environment–related factors is evident from the exemplary scenario depicted in Figure 6.

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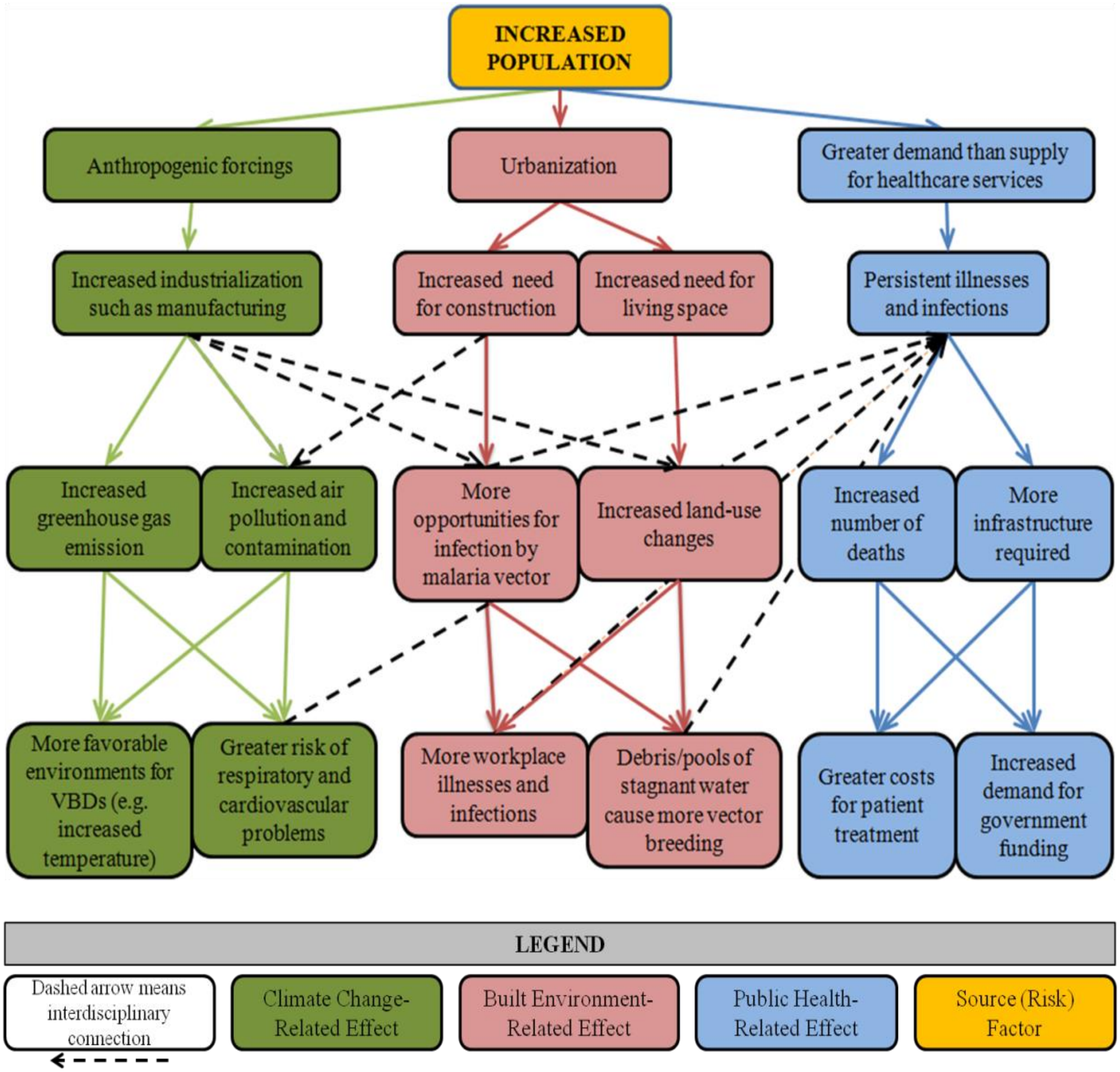

Figure 6: Source Factor Propagation Scenario

Rapid increase in population results in increased demand for the Earth's energy budget. Human activities such as agriculture and transportation technology serve as factors that increase greenhouse gas emissions and contaminate the atmosphere with pollutants. These risks increase the number and severity of human health complications such as respiratory and cardiovascular illnesses. Air contamination also causes factors such as temperature, rainfall, and precipitation to increase beyond expected patterns. These climate change-related factors provide more breeding

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sites and faster maturation times for mosquito larvae (Nabi and Qader, 2009). The effect of weather-related factors are thus compounded by climate change. Population increase will continue to propagate the spread of malaria due to its association with climate change-related risk factors.

Rapid population growth results in increased demand for housing. Given that the population is growing more rapidly in the already congested urban areas, the population density is also increasing rapidly. The rapid growth in population ultimately results in land use changes with previously forested areas being cleared to make room for human habitation. More events in the construction life cycle create more opportunities for vector–human interaction. This association, propagated by factors like debris and stagnant water pools, can cause more illness as more land is used for construction. As population in villages and towns and the building of dams increases, humans will get closer to mosquito breeding grounds (Nabi and Qader, 2009). This increase in infection will persist because of the relationship between the built environment and malaria.

An increase in population results in more health problems due to increased human–human contact and human–environment contact. Greater demand for healthcare services puts additional pressure on the health care system in malarious regions that are already resource-constrained. The increase in population contributes to an increase in the number of reported VBD-related illnesses and deaths. There is also an increases in the cost of healthcare that can be attributed to rapid population growth rates. This could partially explain the escalating expenses associated with malaria prevention that were discussed in the introductory chapter.

The complexity of the mitigation of malaria is captured by the interdisciplinary nature of risk factor propagation throughout different disciplines. Anthropogenic activities traditionally associated with climate change such as coal mining and energy consumption from transportation and trade affect the built environment. This is due to deforestation and changes in land use, which are influential components of the primary stage of the construction life cycle. Increased construction creates greater opportunities for workplace illnesses that can increase the demand for public health resources. This reinforces the cause and effect relationships that persist under the public health context described above. Each risk factor propagates within and across disciplines in unique pathways. Cross-sectoral collaboration is an effective tool for understanding the complexity of these system-in-system interactions.

As previously stated, there has been a significant increase in the amount of money spent in mitigating the risk of contracting malaria with, for example, Global Fund spending as much as USD 9.1 billion in 2016, a 90% increase from the funding that was provided from 2006 to 2016 (Global Fund Malaria Financials, 2017). During this period, the population of world grew from 6.60 billion to 7.44 billion. For Kenya and Tanzania, the population grew from 36 to 48 million and 39 to 55 million, respectively (World Bank, 2018). The resulting increased exposure to the *Anopheles* vector increases the pressure on healthcare resources through expenses such as hospital utilities, medical supplies, and government spending for research funding, which has a direct bearing on the development timeline for new antimalarial drugs that combat antibiotic resistance.

Population growth is one of many source factors that can trigger consecutively larger impact at scale across sectors. The wide range of risk factors involved require a similarly wide framework for successful intervention. The use of a decision network tool can address these major causative factors in a systemic manner through encouraging professionals in overlapping

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industries to discuss the pertinent issues in a way that mutually reinforces what each discipline is uniquely positioned to do both efficiently and effectively.

Discussion and Recommendations

Because the built environment is a complex system of systems, there are some significant opportunities for education regarding malaria mitigation efforts that need to be addressed before interventions such as building envelope modification can have impact at scale in a sustainable manner. Bridging the existing knowledge gaps requires collaboration across several disciplines. One of the initial priority action items has to be identifying and dissemination information on the specific areas where working in disciplinary silos has resulted in missed opportunities for synergistic action. The work presented in this thesis is directed at doing just that. There is also a need for characterization of the nature of relationships that exists across the known source factors. To the best of the authors' knowledge, this is the first study that has examined the sources factors from the perspective of built environment-related design decisions with the goal of mapping existing interlinkages and interdependencies. This can be achieved using the metaphor and model of the web of causation, which is an approach that has been used by epidemiologists in health studies to map primary and secondary factors as well as existing factor-to-factor interactions that may have a reinforcing effect. The authors applied this approach to the built environment–related factors that contribute to the propagation of malaria. The outcome of this endeavor is summarized in Table 3.

Table 3: Opportunities for Collaboration with Leaders from Diverse Areas

Thematic Area	Decision Team Members
Urbanization and Environmental Sustainability	Urban Planners and Designers
Climate Change	Researchers and Advocates
Formal and Informal Safety Practices	Health and Environmental Services

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Land Use and Development	Architects and Engineers
Repairs and Retrofits	Engineers, Designers, and Builders
New and Emerging Technologies	Innovators and Humanitarian Entrepreneurs
Leading Global Organizations	WHO, PMI, Global Fund, USAID
Permit Requirements	Code Approvers
Healthy Placemaking	Public Health Scientists
Social Determinants of Health	Social Epidemiologists
Scientific and Medical Research	Clinical Professionals
Government Advocacy and Policy Funding	Budget Planners

The analysis done as part of this research revealed a number of thematic area-specific opportunities for informed design decision making within interdisciplinary teams of overlapping industries. Examples of specific opportunities include collaboration with policy professionals, urban planners, research scientists, and epidemiologists. Table 3 also highlights areas in which built environment specialists are uniquely positioned to make an impactful contribution. For example, public health professionals who specialize in healthy placemaking can champion the exchange of knowledge with built environment professionals by participating in the now commonly run pre-project planning workshop. This would encourage the entire design team to prioritize on the selection of project sites for construction that reduce the risk of malaria propagation.

The analysis also established that there was a need for a knowledge sharing and dissemination platform promoting the kind of cross-disciplinary deliberations that can promote synergy in malaria prevention efforts. The envisioned platform would promote cross-disciplinary collaboration in knowledge creation, while also increasing opportunities through which relevant information could be pushed and/or pulled into a decision support tool for built environment professional at the senior management level.

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The information on specific ways through which the built environment can make a positive contribution to malaria prevention should be made available during the conceptual design phase. The impact with respect to cost savings is higher during this phase. There are still other ways through in which a more intentional emphasis on making mitigating the risk of VBDs a priority for design professionals can translate to cost savings in subsequent stages of the construction process. The design of a built asset is often based on some assumptions being made because of unknown variables. There is an expectation that some changes will be made throughout the entire construction phases as more information becomes available (Motawa et al., 2007). This results in requests for revisions to the contract documents that are communicated to the design team through change orders. Information on ways through which design decisions can be leveraged for impact in the fight against malaria can be customized to match the opportunities within the specific construction phase associated with a requested change order.

Clearly, there is a need for knowledge to be shared across different disciplines. The authors contend that this need can be addressed through developing a knowledge management framework with the features depicted in Figure 7. This conceptual architecture for what will be used as knowledge management platform once fully developed, is based on the exemplary sources factors for the risk of VBDs that can be linked to decision making during the design and construction of buildings. These factors are discussed in the subsequent paragraphs.

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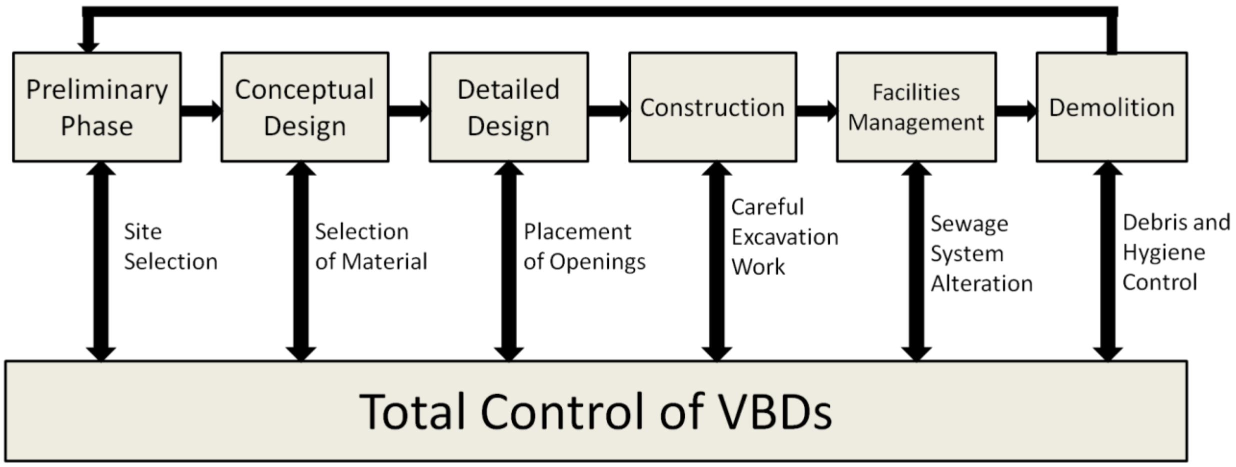

Figure 7: A Knowledge Management Framework for Professionals with Influence in Exchanging Information about VBD Risk Mitigation

Site selection is an important course factor that can be leveraged in malaria mitigation efforts. Project sites that have close proximity to dams, buildings that are dilapidated, and swamps increase disease prevalence. Creating a systematic procedure and checklist to capture all source factors can encourage the design team and building owners to consider the surroundings of potential project sites before any decision that cannot be easily reversed is made.

The appropriate selection of material can address the observed problem of buildings having been constructed using traditional materials and becoming more susceptible to mosquito intrusion. It is worth noting that traditional material are considered to be more sustainable, considering their carbon footprint. The authors recommend that rather than encouraging their disuse, efforts should be invested in researching ways through which material science can be used to address the reasons why mosquitoes prefer buildings that have been constructed using traditional materials.

The existing knowledge on specific ways through which openings can increase ease with which mosquitoes can access a home should inform what is largely a natural ventilation-driven optimization strategy used to specify the size and location of windows, doors and vents in new building envelopes.

The development of a strategy for managing pools of stagnant water that form in excavated areas will increase number of favorable sites for mosquito larvae to mature. Having a robust strategy for promptly draining stagnant pools can be factored into existing dewatering strategies. Foundation work usually has a budget for pumping out water during excavation to allow for the construction of foundation elements following heavy rains.

Retrofits, repairs, and building modifications focused on malaria mitigation should consider the impact of indoor air quality and human comfort on the risk of malaria. The facilities management phase also models successful VBD control when material of construction and surrounding moisture are considerations. A knowledge management framework would provide value by sharing proper techniques for installation and appropriate materials for piping in order to ensure long lifespan and minimal need for repair.

The impact of the demolition of a building on the risk of VBD can vary significantly depending on whether or not there is an interest in salvaging some of the material. In general, construction and demolition waste often ends up in landfills, which presents several environmental problems including the creation of favorable breeding conditions for mosquitoes. There is growing interest in shifting the construction industry to a more circular economy through encouraging both recycling and upcycling. The proposed knowledge management platform can leverage this interest to promote awareness on the link between how demolition waste is managed and the risk of VBDs.

Because malaria is a complex problem, it must be addressed through both a bottom-up and top-down approach. In addition to working directly with the built environment professionals

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as outlined in the preceding paragraphs, there will be a need for the proposed knowledge management platform to have linkages to portals where professionals working in institutions and organizations that have a regional, national and global influence exchange information. These include: 1) Public health forums such as those managed by WHO, PMI, and USAID, which provide worldwide funding and support for actionable intervention methods like SETs, ITNs, and IRSs; 2) Government programs in, for example, the Ministry of Health initiatives that have a presence at both the national and regional level; 3) Professional organizations such as the Architectural Association of Kenya, which have convening power required to disseminate information at scale through conferences, workshops and continued professional educational programs; and 4) Donor organizations and funding agencies such as the Bill and Melinda Gates Foundation, which are increasingly advocating for cross-disciplinary synergies in the fight against malaria.

While the presented study is important, this paper does not address the cultural ideas of the built environment. Each culture understands and perceives the suggested recommendations differently, so it is crucial to bridge the empirical, historical knowledge that exists within social experience and ecological structures of the locations under study with the knowledge gained from literature to generate the most sustainable form of impact.

Our study recognizes economic constraints have a domino effect in making a sustainable social development and vector-borne free built environment. Therefore, the proposed built environment strategy will be more successful if performed in conjunction with risk mitigation efforts such as poverty addressing initiatives, educational campaigns, sustainable public health policies.

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