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Artificial Intelligence and Public Service Delivery in Africa

Duve Nakolisa

Abstract

Artificial intelligence (AI) is one of humanity's most outstanding inventions but one of the least understood and utilized in Africa. While other governments have shown practical interest in harnessing the benefits of AI for their populace, African governments appear to be lagging behind in this area of innovation that has the capacity to enhance and boost its delivery of public services to the people. Although some African countries have developed helpful policies on Artificial Intelligence and have also witnessed AI deployments in some sectors of their polity, knowledge of what this technology can contribute to social development remains minimal among the citizenry. This paper provides basic information about artificial intelligence with the goal of stimulating interest in AI-focused knowledge acquisition, research, development and deployment across the African continent. The paper uses the latest (2022) UNIDO Government AI Readiness Index to gauge the degree to which African governments have responded to fast-expanding opportunities presented by Artificial Intelligence.

Keywords: artificial intelligence, AI Readiness Index, public service delivery, African governments, UNIDO

Introduction

Africa is in dire need of infrastructural expansion, efficient and easily accessible medical care, public transport system, educational advancement, and innovations in public service delivery systems. All of these can be greatly enhanced through the creative application of artificial intelligence (AI) technology. AI increases the capacity of governments to deliver well-organized public utilities to the people because an AI machine can achieve within a given period what would take hundreds of human employees to do. And it is not all about quantity of output; AI-enabled public facilities can also leverage the technology's deep knowledge and efficiency to ensure the establishment and sustenance of uniform processes that generate quality products and services. The speed inherent in AI-enabled service-delivery systems orients them to serve a great number of people, thereby increasing capacity-utilization levels. Africa stands to benefit immensely from the utilization of AI machines in its drive to improve the social well-being of its largely impoverished and less-privileged population. Utilizing information and images obtained from electronic sources, written texts, articles from periodicals, corporate reports and books, this paper explores basic aspects of AI and some of its applications that point at how the technology can be employed to reinvigorate and improve public service delivery in Africa.

What is Artificial Intelligence?

Artificial intelligence has been described in different ways by different persons and groups all of whom agree that it involves the utilization of computer systems to make machines perform tasks and solve problems with the capacity and flexibility associated with human beings. According to one of the industries engaged in AI technologies, "artificial intelligence is a field, which combines computer science and robust datasets, to enable problem-solving. It also encompasses sub-fields of machine learning and deep learning, which are frequently mentioned in conjunction with artificial intelligence" (IBM). "These disciplines," IBM further notes, "are comprised of AI algorithms which seek to create expert systems which make predictions or classifications based on input data."

Other organisations incorporate the crucial element of autonomy seen in AI operations in their definition of AI. The Organisation for Economic Co-operation and Development (OECD) sees AI as "a machine-based system that can, for a given set of human-defined objectives, make predictions, recommendations, or decisions influencing real or virtual environments. AI systems are designed to operate with varying levels of autonomy" (OECD, 2019b, p. 7, as quoted in Gwagwa et al., 2020).

The European Commission emphasizes the foremost feature of AI – intelligence – in its definition; in Gwagwa et al, it describes AI as "systems that display intelligent behaviour by analysing their environment and taking actions—with some degree of autonomy—to achieve specific goals" (EC, 2018). AI systems are, therefore, "autonomous and intelligent systems (A/IS)" that display, according to Copeland (2023),

> the ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings. The term is frequently applied to the project of developing systems endowed with the intellectual processes characteristic of humans, such as the ability to reason, discover meaning, generalize, or learn from past experience. Since the development of the digital computer in the 1940s, it has been demonstrated that computers can be programmed to carry out very complex tasks—such as discovering proofs for mathematical theorems or playing chess—with great proficiency.

Source: theworld.org

The ability of an AI device to master the game of chess was demonstrated when "Deep Blue", an AI machine developed by IBM, beat chess Grandmaster Garry Kasparov in 1997 (Joshi, 2019). AI has been put into more uses in the social and technological sphere, and we will identify some of these applications in a subsequent section of this paper.

Aspects of Intelligence Utilized by AI

What is intelligence, and what aspects of it are utilized by AI machines? Intelligence has been defined as "...the resultant of the process of acquiring, storing in memory, retrieving, combining, comparing, and using in new contexts information and conceptual skills" (Humphreys, 1979). In the view of Sharma (2008), intelligence involves, among other elements, reasoning, learning ability, understanding, abstract and critical thinking, self-awareness, emotional awareness, creativity, and problem-solving, particularly when these are applied as knowledge within a given context or setting. Copeland (2023) notes that intelligence must incorporate "the ability to adapt to new circumstances".

As it pertains to AI, "Intelligence measures an agent's ability to achieve goals in a wide range of environments" (Legg & Hutter, 2007). To enable an AI agent to do this, some features of human intelligence identified above are employed by AI technologists; they include the learning, reasoning, perception, formulative and problem-solving features. While an AI device is capable of rote learning, generalizing what it learnt in the past and adapting it to new situations is a more challenging task for most AI agents. Making AI machines to reason is equally challenging, if "To reason is to draw inferences appropriate to the situation" (Copeland, 2023). While computers have been trained to draw inferences, making AI draw inferences "appropriate to (a given or new) situation" remains a daunting problem. Regarding perception and problem-solving features, AI has made appreciable progress, some notable examples of which are briefly discussed below.

Benefits of Artificial Intelligence

Artificial intelligence is currently transforming the way people live, work, and communicate with other people and with non-human entities. Already in the United States, Europe and Asia, the positive impacts of AI are felt in business, education, transportation and healthcare.

In many businesses, AI is used in the areas of data analysis and customer service delivery; it enhances the processing of large volumes of data and the delivery of quick personalized service to numerous customers. In industries, machines are used to automate repetitious acts and processes that characterize many production lines. Employees who could have been engaged in undertaking or managing those processes are thereby freed to take on other business-relevant activities that require human capabilities.

Health is another sector where AI impact has been felt. On the specific contributions of AI in the medical field, Ask.com notes:

> AI-powered medical imaging systems are helping doctors diagnose diseases more accurately and quickly. AI-based chatbots are providing patients with personalized health advice and support. And AI-powered robots are assisting surgeons with complex procedures. All of these advances are making healthcare more efficient and accessible, improving patient outcomes and saving lives.

AI automation is also helpful in carrying out day-to-day tasks such as data-entry, maintenance of medical records and scan analysis.

In transportation, AI's major contribution is in the development of autonomous cars – self-driving vehicles that hopefully will eliminate human errors and guarantee greater safety for passengers. Traffic jam is a problem common to many cities of the world, and AI is currently providing a workable solution in many countries. As reported by PTV, AI is being used in "traffic management systems to optimize traffic flow and reduce congestion. By analyzing real-time traffic data, AI algorithms can adjust traffic signals and reroute vehicles to less congested roads, reducing travel time and fuel consumption." PTV cites "cities like Taichung, Vienna, York, or Rome" as those currently executing "real-time solution which combines machine learning techniques with dynamic traffic modeling".

Regarding AI benefits in the area of education, the Berlin School of Business and Innovation (BSBI), which is in the forefront of AI engagement in this field, states that

> AI is revolutionising education and changing the way we learn, teach, and organise educational institutions. One of the most important benefits of using AI in education lies in its capacity to tailor the learning experience to the specific needs of each student. Conventional classroom environments frequently struggle to accommodate the distinctive learning styles and requirements of individual students, but with AI, each learning experience can be adapted to suit a variety of students' needs.

BSBI noted that AI impact in education also covers intelligent assessment of students and empowering of educators. The latter involves "AI-driven tools that assist in administrative tasks, such as managing schedules, grading, and organising course materials. This streamlines administrative work, allowing teachers to focus more on instructing and mentoring students" (BSBI, 2023).

Apart from the above areas, AI has been used in natural language processing, computer vision, computer games, and mathematical proof formulations.

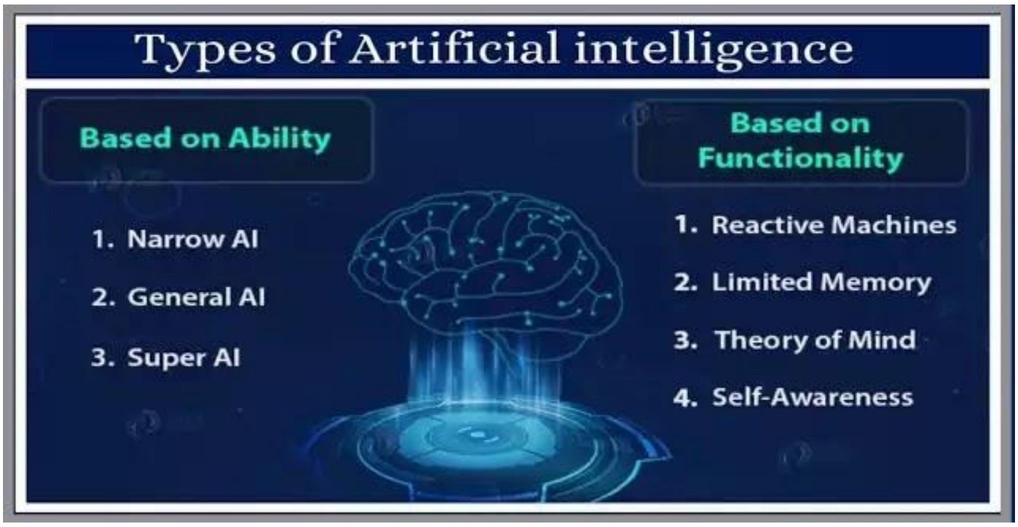
Types of Artificial Intelligence

There are two sets of classifications of AI systems. The first set of classification is based on AI's "likeness to the human mind, and their ability to 'think' and perhaps even 'fee' like humans" (Joshi, 2019). The four classes of this set are as follows:

- Reactive Machines,
- Limited Memory Machines,
- Theory of Mind, and
- Self-Aware AI.

Another set of classification, based on the intelligence capabilities of AI machines, groups them into

- Artificial Narrow Intelligence (ANI),
- Artificial General Intelligence (AGI), and
- Artificial Super Intelligence (ASI).



Source: atlearner.com

Reactive machines are first-generation AI machines that respond to a set of inputs but have no memory or learning capabilities. In order words, they cannot be relied upon to perform a new task based on lessons learnt from their past experiences. They can only perform specific input-driven functions.

Limited memory machines are distinguished from reactive machines by the data stored in their memory as reference information or experience-based datasets utilized in working out a solution to future problems. Virtual assistants and self-driving cars, among many others, are powered by limited memory AI.

In psychology, theory of mind refers to the fact that people have feelings, emotions and thoughts that affect their behaviour. Theory of mind AI is an AI that understands these vital variable layers of the human person to enable it understand, predict and interact with them. For example, a self-driving car will need some level of theory of mind capabilities to enable it relate safely with human-driven vehicles. Because of its complex nature, little progress has been made in this type of AI technology.

Self-awareness is one of the highest manifestations of intelligence. Theoretically, a self-aware AI will be an AI that exhibits the complexity and flexibility of the human brain. It is an AI that can think, feel and show emotions as well as understand the thoughts, feelings and emotions of individual human beings. This type of AI may only be fully realized in the future.

Artificial narrow intelligence (ANI) encompasses all AI systems that autonomously utilize human-like capacities to carry out specific functions. They are narrow in the sense that they can only perform what they are programmed to do, and nothing more. Reactive and limited memory AI systems fall under ANI.

Artificial General Intelligence (AGI) is an AI system that has the ability to perform exactly like real human beings, an AI that can think, learn, understand and draw conclusions like a human being – an AI that has the general and adaptive intelligence of a human being.

Artificial Super Intelligence (ASI) will hypothetically have super-human abilities as well as the competencies of human beings, thereby being superior to human beings in terms of intelligence, speed, decision-making and problem-solving abilities, among others. Many people are apprehensive that AGI and ASI AI systems, whenever they are realized, will threaten human civilization, as we currently know it.

African Governments' Level of AI Readiness

From the foregoing, it is clear that in various areas – mass education, healthcare-delivery, public transport and traffic management systems, and mass communication, among others – African governments can take advantage of the fast-growing AI phenomenon to fast-track their delivery of public utilities and services to their long-suffering populations. Currently, African government's level of artificial intelligence utilization outside the narrow sector of internal security surveillance is very low.

According to the African Development Bank, the institution behind African Public Service Delivery Index (PSDI), "Public service delivery is at the centre of economic and social progress everywhere". Gafar (2017) elaborates:

> It is instructive to note that, the existence of any government is presumed on its ability to fulfill the basic necessity of lives of its citizens. Put differently, the existence of government is justifiable on the basis that it supplies crucial services such as security of lives and properties, maintaining orderliness, providing social amenities and infrastructure, and offer legal framework for conflicts prevention and resolution and acceptable system of justice. The conventional wisdom deduced here is that, the government fulfillment of its own part of social contract agreement with its citizen will automatically confer legitimacy on government, its activities and strengthen its institutions.

African governments can take advantage of AI capabilities to transform public-service delivery in their respective countries, hence our interest in UNIDO's Government AI Readiness Index 2022, the latest of such index published by the organisation. UNIDO, through the index, wants to stimulate governments, including African governments, to do more to harness the benefits of AI for their teeming populations. According to the Government AI Readiness Index 2022, from where thenceforth I will be quoting (unless otherwise stated):

> The pace of change in AI capabilities has not been matched by the

> response of governments… We need governments to rapidly roll out responsive regulatory regimes… We need governments to build their own technological capability so that these tools can be used to improve the services used by all. Public services can and should be delivered to a high standard, with the human experience in mind. It is a government's responsibility to ensure the benefits are felt by all, not just a select few… Doing more starts with officials keeping up with global developments and learning what their peers are working on (Government AI Readiness Index 2022).

In order "to score governments on their readiness to implement AI in the delivery of public services", the Government AI Readiness Index 2022 ranked 181 countries according to "39 indicators across 10 dimensions, which make up 3 pillars". The pillars are:

- The Government pillar (which looks out for "a strategic vision for how it develops and manages AI, supported by appropriate regulation and attention to ethical problems");
- The Technology Sector pillar (which examines how government "depends on a good supply of AI tools from the country's technology sector, which needs to be mature enough to supply the government… Good levels of human capital—the skills and education of the people working in this sector—are also crucial");
- The Data & Infrastructure pillar (which focuses on data availability, representativeness and infrastructure).

The global Government Artificial Intelligence Readiness Index 2022 indicates that no African country is ranked among the first 64 countries. Below is a list of the first ten African countries showing their global ranking in the Government AI Readiness Index 2022 and their scores or degree of readiness in terms of the three pillars mentioned above.

Degree of AI Readiness of First 10 African Countries*

African Country	African Position	Global Position	Sectoral Scores		
			Government Pillar	Technology Sector Pillar	Data and Infrastructure Pillar
Egypt	1	65	63.46	36.07	48.72
South Africa	2	68	37.90	37.60	67.73
Tunisia	3	70	48.63	36.92	54.87
Morocco	4	87	34.81	34.00	55.13
Kenya	5	90	40.36	28.76	51.95
Rwanda	6	93	53.28	28.14	39.19
Nigeria	7	97	44.91	23.08	49.31
Botswana	8	98	33.42	26.61	55.05
Ghana	9	104	47.22	22.82	39.65
Benin	10	108	48.40	22.99	36.12

* Table prepared by the author based on data sourced from *Government AI Readiness Index 2022*

The above table shows that Egypt, which ranks 1st among African countries, is placed 65th in the world. Sadder than the implication of that ranking for AI-enabled public-service delivery in Africa is the fact that apart from Kiribati, Haiti, Yemen, Syria and Afghanistan, African countries make up the last 30 countries on the 181-country Government AI Readiness Index of 2022.

Conclusion

AI-enabled systems are improving the quality of life and service delivery in many parts of the world and African countries need not be comfortable with lagging behind in the acquisition and utilization of this critical and speedily expanding technology. African governments should put the right policies in place, stimulate and support their technological sectors as well as inspire and demonstrate interest in AI capabilities by incorporating artificial intelligence in their public-service delivery systems.

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Author's Brief Data

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Burden of diarrhea and antibiotic use among children in low-resource settings preventable by Shigella vaccination: A simulation study*

Stephanie A. Brennhofer, James A. Platts-Mills, Joseph A. Lewnard, Jie Liu, Eric R. Houpt & Elizabeth T. Rogawski McQuade

Abstract

Background

Shigella is a leading cause of diarrhea and dysentery in children in low-resource settings, which is frequently treated with antibiotics. The primary goal of a *Shigella* vaccine would be to reduce mortality and morbidity associated with *Shigella* diarrhea. However, ancillary benefits could include reducing antibiotic use and antibiotic exposures for bystander pathogens carried at the time of treatment, specifically for fluoroquinolones and macrolides (F/M), which are the recommended drug classes to treat dysentery. The aim of the study was to quantify the reduction in *Shigella* attributable diarrhea, all diarrhea, and antibiotic use in the first 2 years of life that could be prevented by a *Shigella* vaccine.

Methods and findings

We used data from the Etiology, Risk Factors, and Interactions of Enteric Infections and Malnutrition and the Consequences for Child Health and Development (MAL-ED) study, a birth cohort study that followed 1,715 children with twice weekly surveillance for enteric infections, illnesses, and antibiotic use for the first 2 years of life from November 2009 to February 2014 at 8 sites. We estimated the impact of 2 one-dose (6 or 9 months) and 3 two-dose (6 and 9 months, 9 and 12 months, and 12 and 15 months) *Shigella* vaccines on diarrheal episodes, overall antibiotic use, and F/M use. Further, we considered additional protection through indirect and boosting effects. We used Monte Carlo simulations to estimate the absolute and relative reductions in the incidence of diarrhea and antibiotic use comparing each vaccination scenario to no vaccination. We analyzed 9,392 diarrhea episodes and 15,697 antibiotic courses among 1,715 children in the MAL-ED birth cohort study. There were 273.8 diarrhea episodes, 30.6 shigellosis episodes, and 457.6 antibiotic courses per 100 child-years. A *Shigella* vaccine with a mean vaccine efficacy of 60% against severe disease given at 9 and 12 months prevented 10.6 (95% CI [9.5, 11.5]) *Shigella* diarrhea episodes of any severity per 100 child-years (relative 34.5% reduction), 3.0 (95% CI [2.5, 3.5]) F/M courses for *Shigella* treatment per 100 child-years (relative 35.8% reduction), and 5.6 (95% CI [5.0, 6.3]) antibiotic courses of any drug class for *Shigella* treatment per 100 child-years (relative 34.5% reduction). This

translated to a relative 3.8% reduction in all diarrhea, a relative 2.8% reduction in all F/M courses, a relative 3.1% reduction in F/M exposures to bystander pathogens, and a relative 0.9% reduction in all antibiotic courses. These results reflect *Shigella* incidence and antibiotic use patterns at the 8 MAL-ED sites and may not be generalizable to all low-resource settings.

Conclusions

Our simulation results suggest that a *Shigella* vaccine meeting WHO targets for efficacy could prevent about a third of *Shigella* diarrhea episodes, antibiotic use to treat shigellosis, and bystander exposures due to shigellosis treatment. However, the reductions in overall diarrhea episodes and antibiotic use are expected to be modest (<5%).

Author summary

Why was this study done?

- *Shigella* is a leading cause of diarrhea and dysentery among children under 5 years of age in low- and middle- income countries (LMICS).
- There are several *Shigella* vaccines in the pipeline poised to reduce mortality and moderate-to-severe diarrhea episodes.
- The World Health Organization (WHO) has specified that a preferred *Shigella* vaccine would have a minimum of 60% vaccine efficacy against moderate-to-severe diarrhea, be 1 to 2 doses, and the series would be completed before 12 months of age.
- WHO has encouraged estimating antibiotic use as a secondary endpoint in *Shigella* vaccine trials.

What did the researchers do and find?

- We performed Monte Carlo simulations using data from 1,715 children in the Etiology, Risk Factors, and Interactions of Enteric Infections and Malnutrition and the Consequences for Child Health and Development (MAL-ED) birth cohort study to estimate the expected reduction in diarrhea episodes, antibiotic use, and bystander pathogen exposure to antibiotics through the administration of 1- and 2-dose *Shigella* vaccines given at varying ages to coincide with vaccines currently administrated in the Expanded Programme on Immunization (EPI) schedule.
- Vaccine efficacy was simulated using a beta distribution with a mean vaccine efficacy of 60% or 80% for severe diarrhea.
- A 2-dose *Shigella* vaccine with 60% efficacy given at 9 and 12 months

could reduce 34.5% of *Shigella* diarrhea episodes, 34.5% of antibiotic courses to treat *Shigella*, and 33.9% of antibiotic exposures to bystander pathogens to treat shigellosis.

- A 2-dose *Shigella* vaccine with 60% efficacy given at 9 and 12 months could reduce 3.8% of diarrhea episodes of any etiology, 0.9% of antibiotic courses for diarrhea overall, and 1.1% of all antibiotic exposures to bystander pathogens.

What do these findings mean?

- A *Shigella* vaccine could considerably reduce *Shigella*-associated diarrhea and antibiotic use but will likely have a modest effect on all-cause diarrhea and antibiotic use.
- The MAL-ED study sites may not reflect the expected impact of a *Shigella* vaccine in all low-resource settings.
- Future studies should account for varying vaccine efficacy by *Shigella* species and serotypes and consider waning immunity over a longer follow-up period.

Abbreviations: AMR, antimicrobial resistance; Cq, quantification cycle; EPI, Expanded Programme on Immunization; F/M, fluoroquinolone and macrolide; LMIC, low- and middle- income country; MAL-ED, Etiology, Risk Factors, and Interactions of Enteric Infections and Malnutrition and the Consequences for Child Health and Development; OR, odds ratio; PPC, preferred product characteristic; qPCR, quantitative polymerase chain reaction; TAC, TaqMan Array Card; WHO, World Health Organization

Introduction

Shigella is a leading cause of diarrhea and dysentery in children under the age of 5 in low- and middle-income countries (LMICs) [1]. In the multisite Etiology, Risk Factors, and Interactions of Enteric Infections and Malnutrition and the Consequences for Child Health and Development (MAL-ED) study, a prospective birth cohort conducted in Dhaka, Bangladesh; Fortaleza, Brazil; Vellore, India; Bhaktapur, Nepal; Naushero Feroze, Pakistan; Loreto, Peru; Venda, South Africa; and Haydom, Tanzania, the incidence of *Shigella*-attributed diarrhea was 26.1 episodes per 100 child-years in the first 2 years of life [2]. *Shigella* is the second leading cause of diarrhea mortality [3] after rotavirus and has been associated with intestinal inflammation [4] and short-term decrements in height [5,6]. A high burden of *Shigella* infections and *Shigella*-attributable diarrhea has been further associated with decrements in linear growth at age 2 [5], with effects persisting to 5 years [5] and 6 to 8 years [7].

Furthermore, previous analyses have identified *Shigella* as a leading contributor to antibiotic consumption for diarrhea among children in low-resource settings [8], which has implications for antibiotic resistance. In MAL-ED, *Shigella* was responsible for 14.8 antibiotic courses per 100 child-years, which accounts for 11.7% of all antibiotic courses for diarrhea in the first 2 years of life [9]. Approximately 20.9% (attributable incidence: 3.09 per 100 child-years; 95% CI [2.64, 3.66]) and 16.2% (attributable incidence: 4.59; 95% CI [3.92, 5.47]) of all fluoroquinolone and macrolide courses given for diarrhea, respectively, were to treat shigellosis [9]. Frequent use of antibiotics drives selection for drug-resistant pathogens [10], and drug-resistant shigellosis is of concern [11]. Azithromycin- and fluoroquinolone-resistant strains of *Shigella* are common in Asia and are growing in prevalence elsewhere [12–14].

To address the high global burden of *Shigella*, there are several *Shigella* vaccines in the pipeline, of which three are in Phase IIA and one in Phase III trials [15]. The World Health Organization (WHO) recently published preferred product characteristics (PPC) for a *Shigella* vaccine [1], and efforts are underway to define the full value proposition for such a vaccine. The primary goal of a *Shigella* vaccine is to prevent mortality and moderate-to-severe episodes of shigellosis with an efficacy target set by WHO of 60% or more. Assuming this target can be met in trials conducted in ideal settings, real-world estimates of the reduction in diarrhea episodes that would be expected after vaccine introduction are needed to predict population-level vaccine impact.

Furthermore, a *Shigella* vaccine may produce ancillary benefits that need to be quantified, specifically reductions in antibiotic exposures since diarrhea is a major cause of antibiotic use [8,9]. Vaccine impact on fluoroquinolone/ macrolide (F/M) use is of particular interest as they are the recommended treatment by WHO for dysentery [11,16], and 34% of dysentery cases (12.8 episodes per 100 child-years) in children under 2 years of age in the MAL-ED birth cohort were attributed to *Shigella*. In addition to preventing exposures to antibiotics for *Shigella*, a *Shigella* vaccine could further reduce selective pressure on asymptomatic enteric pathogens (i.e., bystander pathogens) present in the gut at the time of shigellosis treatment. Bystander pathogens are not the target of treatment but nonetheless are still exposed to antibiotics and are therefore at risk for development of antimicrobial resistance (AMR). There were more than 7 antibiotic exposures per child-year for bystander enteropathogenic bacteria in MAL-ED [8].

To inform the vaccine value proposition, we aimed to quantify the potential impact of a *Shigella* vaccine on the incidence of *Shigella* diarrhea (severe and nonsevere), all diarrhea, and antibiotic use in the first 2 years of life via various potential vaccination strategies. We simulated vaccine introduction within the high-resolution data from the MAL-ED birth cohort study, which aimed to examine the effects of enteric infections and malnutrition on the health of children living in LMICs. The outcomes of interest were directly observed in this study, such that we did not need to make assumptions about the natural history of *Shigella*, other enteric pathogens, and antibiotic use. While a prior study estimated the global impact of a *Shigella* vaccine on diarrhea and stunting outcomes [17], we uniquely estimated the impact on antibiotic use outcomes and considered different vaccine efficacies and dosing schedules. We also quantified the potential impact of indirect protection for children who were too young to be vaccinated due to vaccination of vaccine-eligible children (i.e., herd immunity) and the impact of a vaccine that performs better for children who have been previously exposed to *Shigella*.

Methods

Study design and participants

The MAL-ED study design has been previously detailed [18]. Briefly, this study was conducted at 8 sites (Dhaka, Bangladesh; Fortaleza, Brazil; Vellore, India; Bhaktapur, Nepal; Naushero Feroze, Pakistan; Loreto, Peru; Venda, South Africa; and Haydom, Tanzania) from November 2009 to February 2014. Children were enrolled within 17 days of birth and followed for 2 years. Two times per week, fieldworkers conducted home visits to collect information on daily antibiotic use and presence of illness. Stool samples were collected monthly (nondiarrheal surveillance samples) and during diarrheal episodes. Diarrhea episodes were defined as 3 or more loose stools in a 24-hour period or the presence of blood in at least 1 stool. Diarrhea severity was determined by the modified Vesikari score, previously outlined [19].

Stool testing

The QIAamp Fast DNA Stool Mini Kit (Qiagen) was used to extract total nucleic acid from the stool specimens [20]. To detect the presence of 29 enteropathogens via quantitative polymerase chain reaction (qPCR), TaqMan Array Cards (TAC) were run using AgPath One Step RT PCR kit (Thermo Fisher) [2]. The quantification cycle (Cq) to define pathogen detection was set to <35. *Shigella* spp. were detected by the *ipaH* gene, as previously outlined [2].

Modeled vaccine impacts

We simulated the impact of vaccines on the following observed outcomes in the MAL-ED data. First, *Shigella* diarrhea was defined as diarrhea episodes with an episode-specific attributable fraction for *Shigella* (AF*e*) >0.5, regardless of other pathogens detected. AF*e*s were calculated as 1—(1/OR*e*), where OR*e* was the pathogen-specific and quantity-specific odds ratio (OR) from a generalized linear mixed model associating pathogen quantity with diarrhea [2]. Second, severe *Shigella* diarrhea was defined as *Shigella* diarrhea with a modified Vesikari score >6 [19]. Third, the number of severe diarrhea episodes of any etiology was defined as diarrhea due to any cause with a modified Vesikari score >6. Fourth, diarrhea episodes overall included any etiology (including episodes in which an infectious etiology was not identified) and severity.

For vaccine impacts on antibiotic use, we focused on F/Ms as specific drug classes of interest and additionally assessed any antibiotic use. Each diarrhea episode was considered treated with antibiotics if antibiotics were taken during any day of the illness episode. Antibiotic courses overall were defined by antibiotic courses given to the child for any reason, as previously determined [8]. Antibiotic courses were separated by 2 antibiotic-free days. Antibiotic exposures to bystander pathogens (i.e., pathogens present at the time of antibiotic treatment but that did not cause the illness that was treated) were defined by linking each antibiotic course to the most recent stool sample collected in the preceding 30 days. Any bacterial pathogens (atypical enteropathogenic *Escherichiacoli* (*E.coli*), *Campylobacter*, enteroaggregative *E. coli*, enterotoxigenic *E. coli*, and typical enteropathogenic *E. coli*) detected in the linked stool were assumed to be bystander pathogens during the antibiotic course [8]. Antibiotic exposures to bystander pathogens were attributed to the treatment of *Shigella* if the antibiotic course was given during a diarrhea episode with a *Shigella* AFe >0.5.

Vaccination scenarios

The characteristics of our simulated *Shigella* vaccine were modeled after those outlined in the WHO's PPC for a *Shigella* vaccine [1] and those from vaccines currently in the pipeline [15]. We considered 1- and 2-dose *Shigella* vaccines with multiple potential vaccine dosing schedules that aligned with other existing vaccination events in the Expanded Programme on Immunizations (EPI) schedule [21]: a 1-dose vaccine with administration at 6 months or 9 months and 2-dose vaccines with administration at 6 and 9 months, 9 and 12 months, and 12 and 15 months (Table 1). Vaccine efficacy 14 days [22] after the second dose against severe *Shigella* diarrhea was simulated using a beta distribution with mean efficacy of 60% (Beta($\alpha = 6$, $\beta = 4$)) or 80% (Beta($\alpha = 6$, $\beta = 1.5$)) in separate scenarios. These beta distributions have 80% of values within an absolute 20% above and below the mean (e.g., 80% of values are between 40% and 80% for a mean vaccine efficacy of 60%), and our results were insensitive to changes to the assumed standard deviation of the beta distribution. 60% vaccine efficacy is the minimum preferred efficacy target outlined by the WHO's PPC [1], and 80% vaccine efficacy scenario represents an optimistic scenario. Efficacy against nonsevere *Shigella* episodes was the simulated efficacy multiplied by 2/3 (for 60% mean severe vaccine efficacy) or 3/4 (for 80% mean severe vaccine efficacy) to target a mean efficacy against nonsevere episodes of 40% and 60%, respectively. Vaccine efficacy between the first dose up to 14 days after the second dose was half that which was applied 14 days after the second dose (Table 1).

Table 1: *Shigella* vaccination scenarios simulated in the MAL-ED dataset, including dosing schedules, efficacies, and inclusion of indirect and boosting protection

Scenario	Dosing schedule	*Shigella* diarrhea severity	Mean VE* 14 days after first dose	Mean VE* 14 days after second dose	Indirect effect	Mean boosting effect after first dose, before second dose	Mean boosting effect after second dose
0	No vaccine	—	—	—	—	—	—
1	First: 6 months	Severe	60%	—	20%	+20% (80% VE)	—
		Non-severe	40%	—	20%	+20% (60% VE)	—
2	First: 9 months	Severe	60%	—	20%	+20% (80% VE)	—
		Non-severe	40%	—	20%	+20% (60% VE)	—
3	First: 6 months Second: 9 months	Severe	30%	60%	20%	+10% (40% VE)	+20% (80% VE)
		Non-severe	20%	40%	20%	+10% (30% VE)	+20% (60% VE)
4	First: 9 months Second: 12 months	Severe	30%	60%	20%	+10% (40% VE)	+20% (80% VE)
		Non-severe	20%	40%	20%	+10% (30% VE)	+20% (60% VE)
5	First: 12 months Second: 15 months	Severe	30%	60%	20%	+10% (40% VE)	+20% (80% VE)
		Non-severe	20%	40%	20%	+10% (30% VE)	+20% (60% VE)
6	First: 6 months	Severe	80%	—	20%	+20% (100% VE)	—
		Non-severe	60%	—	20%	+20% (80% VE)	—
7	First: 9 months	Severe	80%	—	20%	+20% (100% VE)	—
		Non-severe	60%	—	20%	20% (80% VE)	—
8	First: 6 months Second: 9 months	Severe	40%	80%	20%	+10% (50% VE)	+20% (100% VE)
		Non-severe	30%	60%	20%	+10% (40% VE)	+20% (80% VE)
9	First: 9 months Second: 12 months	Severe	40%	80%	20%	+10% (50% VE)	+20% (100% VE)
		Non-severe	30%	60%	20%	+10% (40% VE)	+20% (80% VE)
10	First: 12 months Second: 15 months	Severe	40%	80%	20%	+10% (50% VE)	+20% (100% VE)
		Non-severe	30%	60%	20%	+10% (40% VE)	+20% (80% VE)

VE, vaccine efficacy.

*60% vaccine efficacy for severe disease is the minimum preferred efficacy target outlined by the WHO's PPC [1], and 80% vaccine efficacy scenario represents an optimistic scenario. VE for severe disease was randomly sampled from a beta distribution (Beta($\alpha = 6, \beta = 4$) for 60% mean efficacy and Beta($\alpha = 6, \beta = 1.5$) for 80% mean efficacy). VE against nonsevere *Shigella* episodes was this sampled efficacy multiplied by 2/3 (for 60% mean severe VE) or 3/4 (for 80% mean severe VE) to target a mean efficacy against nonsevere episodes of 40% and 60%, respectively. VE after the first dose was half that after the second dose.

For scenarios that assumed the vaccine would produce indirect protection for vaccine-ineligible children, we randomly selected 20% of *Shigella* diarrhea episodes that occurred in children under the age of the first dose of vaccine administration to be prevented. These simulated levels of indirect protection were based on what was observed with the Vi-tetanus toxoid conjugate vaccine in Bangladesh [23]. For instance, under a scenario with vaccine doses administered at 9 and 12 months, 20% of diarrhea episodes occurring in children under the age of 9 months were randomly prevented. For scenarios that assumed the vaccine would perform better among children previously exposed to *Shigella* (i.e., boosting protection), efficacy was increased by an absolute 20% at the mean for *Shigella* diarrhea episodes that occurred in children who had a *Shigella* infection prior to administration of the first dose of the vaccine. To do this, we multiplied the sampled efficacy for severe episodes by 4/3 and for nonsevere episodes by 3/2 for the 60% mean vaccine efficacy scenario. For the 80% mean vaccine efficacy scenario, we multiplied the sampled efficacy by 5/4 and 4/3 for severe and nonsevere episodes, respectively. For example, in the 9- and 12-month dosing vaccine scenario with 60% efficacy with 20% boosting effects, if a child was infected with *Shigella* prior to 9 months of age, mean efficacy went from 60% to 80%.

Results reported primarily in the text correspond to a vaccine with 2 doses at 9 and 12 months with a mean vaccine efficacy against severe episodes of 60% since these characteristics may be the most realistic among the range of acceptable parameters outlined in the WHO's PPC [1]. Results from all other vaccination scenarios are described in the tables and figures.

Statistical analysis

To simulate vaccine introduction within the observational MAL-ED data, we performed Monte Carlo simulations using random sampling with replacement of children to a sample size of 50,000. For each simulated vaccination scenario, we randomly selected observed *Shigella* diarrhea episodes from these children to be prevented by a probability equal to vaccine efficacy (sampled using a beta distribution as described above). In a no-vaccine scenario, no episodes were selected to be prevented. We then estimated the incidence of each diarrhea and antibiotic outcome defined above in the simulated scenario as the number with the outcome/person-time at risk, excluding the outcome episodes that were randomly selected to be prevented under each vaccination scenario. *Shigella*-specific incidence estimates were multiplied by the ratio of the total number of diarrhea episodes to the total number that were validly tested for *Shigella* by qPCR to account for episodes that did not have a stool sample collected and/or tested (ratio = 1.233). Bystander exposure incidence estimates were further multiplied by the ratio of the total number of antibiotic courses to the total number that could be linked to a stool sample collected in the preceding 30 days to extrapolate to courses that could not be linked (ratio = 1.152). Estimates and confidence intervals were estimated by the median, 2.5th and 97.5th percentiles of 1,000 iterations of this procedure. To quantify the expected reductions in the outcomes listed above, we estimated the absolute difference between each vaccine scenario and the no-vaccine scenario as the incidence rate difference $(|Incidence_{vaccine\ senario} - Incidence_{no\ vaccine\ senario}|)$, the relative difference as the incidence rate ratio $\left(\frac{Incidence_{vaccine\ senario}}{Incidence_{no\ vaccine\ senario}}\right)$, and the relative percent reduction $\left(\frac{Incidence_{no\ vaccine\ senario} - Incidence_{vaccine\ senario}}{Incidence_{no\ vaccine\ senario}}\right)$.

We estimated each of these outcomes overall and by sites to investigate heterogeneity of impact by site.

All statistical analyses were performed via R software, version 4.0.2 (Foundation for Statistical Computing).

Ethics approvals

This study involves human participants. For the parent study, ethical approval was obtained from the Institutional Review Boards at the University of Virginia School of Medicine (Charlottesville, USA) (14595) and at each of the participating research sites: Ethical Review Committee, ICDDR,B (Bangladesh); Committee for Ethics in Research, Universidade Federal do Ceara; National Ethical Research Committee, Health Ministry, Council of National Health (Brazil); Institutional Review Board, Christian Medical College, Vellore; Health Ministry Screening Committee, Indian Council of Medical Research (India); Institutional Review Board, Institute of Medicine, Tribhuvan University; Ethical Review Board, Nepal Health Research Council; Institutional Review Board, Walter Reed Army Institute of Research (Nepal); Institutional Review Board, Johns Hopkins University; PRISMA Ethics Committee; Health Ministry, Loreto (Peru); Ethical Review Committee, Aga Khan University (Pakistan); Health, Safety and Research Ethics Committee, University of Venda; Department of Health and Social Development, Limpopo Provincial Government (South Africa); Medical Research Coordinating Committee, National Institute for Medical Research; Chief Medical Officer, Ministry of Health and Social Welfare (Tanzania). For the current study, we obtained ethical approval at the University of Virginia School of Medicine (Charlottesville, USA) (22398) and Emory University (Atlanta, USA) (STUDY00003285). Caregivers provided written informed consent for their child to participate in the study before taking part.

Results

These analyses included 1,715 children, of which 83% (n = 1,427) had at least 1 *Shigella* infection during their first 2 years of life (Table 2). There were 273.8 diarrhea episodes of any severity per 100 child-years (n = 9,392) and 30.6 *Shigella* diarrhea episodes per 100 child-years (n = 754). Caregivers reported 457.6 courses per 100 child-years of antibiotics (n = 15,697), among which 110.1 courses per 100 child-years (n = 3,775) were to treat diarrhea episodes of any etiology and of which 16.3 courses per 100 child-years were attributable to *Shigella* diarrhea (n = 427). Bystander pathogens had 744.1 (n =

22,161) and 31.1 (*n* = 750) exposures to antibiotics per 100 child-years resulting from any antibiotic use and resulting from the treatment of *Shigella*, respectively.

Table 2. Diarrhea episodes, antibiotic use, and bystander pathogen exposures to antibiotics among 1,715 children enrolled in the MAL-ED cohort.

	<6 months	≥6 months, <9 months	≥9 months, <12 months	≥12 months, <15 months	≥15 months
No. children with their first instance of a *Shigella* infection, n (%)[a,d]	163 (9.5)	199 (11.6)	275 (16.0)	251 (14.6)	539 (31.4)
No. severe *Shigella* diarrhea episodes, n (rate)[b,c,d]	5 (0.8)	9 (2.9)	10 (3.2)	17 (5.5)	48 (5.2)
No. severe diarrhea episodes of any etiology, n (rate)[b,c]	434 (50.6)	286 (66.7)	192 (44.8)	186 (43.4)	290 (22.5)
No. *Shigella* diarrhea episodes, n (rate)[b,c,d]	16 (2.6)	43 (14.0)	84 (27.3)	118 (38.3)	493 (53.3)
No. diarrhea episodes of any etiology, n (rate)[b,c]	2,386 (278.3)	1,498 (349.4)	1,333 (310.9)	1,236 (288.3)	2,939 (228.5)
No. antibiotic courses for severe *Shigella* diarrhea episodes, n (rate)[b,d]	6 (0.9)	6 (1.7)	12 (3.5)	12 (3.5)	32 (3.1)
No. antibiotic courses for severe diarrhea episodes of any etiology, n (rate)[b]	253 (29.5)	206 (48)	145 (33.8)	103 (24.0)	184 (14.3)
No. antibiotic courses for *Shigella* diarrhea episodes, n (rate)[b,d]	11 (1.6)	24 (6.9)	53 (15.2)	73 (21.0)	266 (25.5)
No. antibiotic courses for diarrhea episodes of any etiology, n (rate)[b]	804 (93.8)	629 (146.7)	588 (137.1)	480 (112.0)	1,274 (99.0)
No. antibiotic courses overall, n (rate)[b]	3,478 (405.6)	2,283 (532.5)	2,164 (504.7)	2,105 (491.0)	5,667 (440.6)
No. antibiotic exposures to bystander pathogens due to *Shigella* treatment, n (rate)[b,d]	25 (4.1)	39 (12.9)	102 (33.8)	133 (44.1)	451 (49.8)
No. antibiotic exposures to bystander pathogens overall, n (rate)[b]	2,736 (367.5)	3,404 (914.4)	3,641 (978.1)	3,527 (947.4)	8,853 (792.7)

[a]Denominator = 1,715 kids.
[b]Rate is per 100 child-years.
[c]Includes episodes that were and were not treated by antibiotics.
[d]Counted among infections/episodes/exposures in which stools were collected with valid qPCR test results for *Shigella*.
Rates are extrapolated to all infections/episodes/exposures.

Prevention of diarrhea

A *Shigella* vaccine given at 9 and 12 months with a mean 60% vaccine efficacy would be expected to prevent 1.2 (95% CI [0.9, 1.6]) severe *Shigella* diarrhea episodes and 10.6 (95% CI [9.5, 11.5]) *Shigella* diarrhea episodes of any severity per 100 child-years (Table 3), which corresponds to a relative 34.0% reduction in severe shigellosis episodes and a relative 34.5% reduction in shigellosis episodes of any severity (Fig 1). While the vaccine would reduce the same number of severe and all diarrhea episodes due to any etiology, the relative percent reductions would be smaller, at 2.7% for severe diarrhea episodes of any etiology and 3.8% for diarrhea episodes of any etiology (Table 3, Fig 1).

Fig 1. Relative percent reductions in diarrhea outcomes for 5 *Shigella* vaccine scenarios with 60% (A) and 80% (B) full vaccine efficacies against severe *Shigella* diarrhea and no indirect or boosting protection.

Caption: The black lines represent 95% confidence intervals.

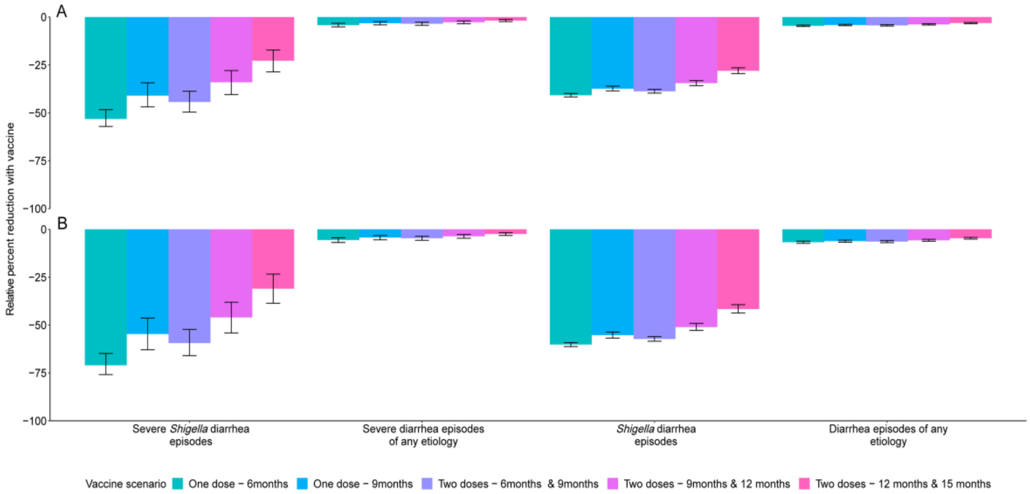


Table 3. Absolute (incidence rate differences) and relative (incidence rate ratios) differences in diarrhea outcomes for 5 *Shigella* vaccine scenarios compared to the no-vaccine scenario with 60% and 80% full vaccine efficacies against severe *Shigella* diarrhea and no indirect or boosting protection.

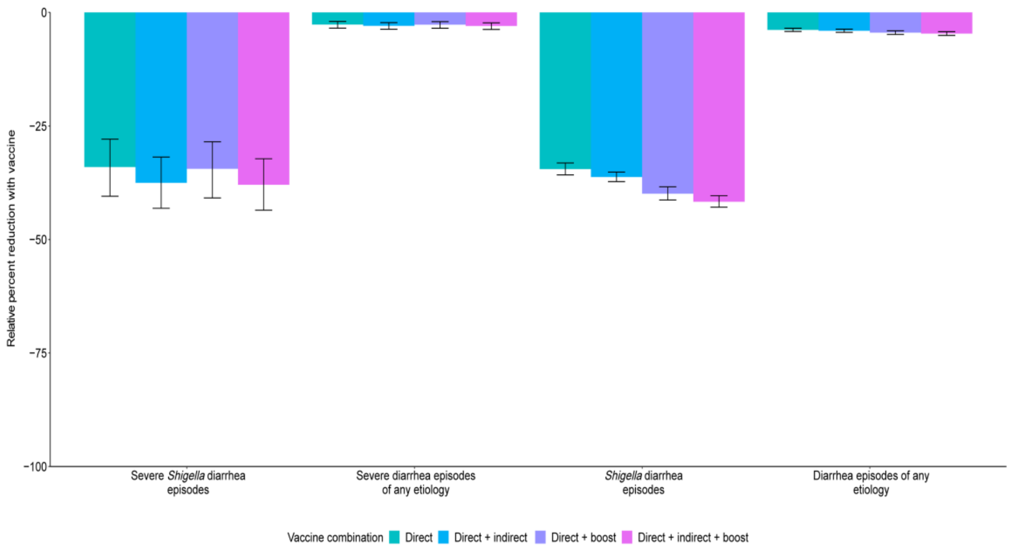
Vaccine scenario and efficacy outcome	Incidence rate difference (cases per 100 child-years)		Incidence rate ratio	
	60% VE (95% CI)	80% VE (95% CI)	60% VE (95% CI)	80% VE (95% CI)
One dose—6 months				
Severe *Shigella* diarrhea episodes	−1.9 (−2.4, −1.5)	−2.6 (−3.2, −2.0)	0.47 (0.43, 0.52)	0.29 (0.24, 0.35)
Severe diarrhea episodes of any etiology	−1.9 (−2.4, −1.5)	−2.6 (−3.2, −2.0)	0.96 (0.95, 0.97)	0.94 (0.93, 0.96)
Shigella diarrhea episodes	−12.5 (−13.6, −11.4)	−18.5 (−20.1, −16.8)	0.59 (0.58, 0.60)	0.40 (0.39, 0.41)
Diarrhea episodes of any etiology	−12.5 (−13.6, −11.4)	−18.5 (−20.1, −16.8)	0.95 (0.95, 0.96)	0.93 (0.93, 0.94)
One dose—9 months				
Severe *Shigella* diarrhea episodes	−1.5 (−1.9, −1.1)	−2.0 (−2.5, −1.5)	0.59 (0.53, 0.66)	0.45 (0.37, 0.54)
Severe diarrhea episodes of any etiology	−1.5 (−1.9, −1.1)	−2.0 (−2.5, −1.5)	0.97 (0.96, 0.98)	0.96 (0.95, 0.97)
Shigella diarrhea episodes	−11.5 (−12.5, −10.4)	−16.9 (−18.5, −15.4)	0.63 (0.61, 0.64)	0.45 (0.43, 0.46)
Diarrhea episodes of any etiology	−11.5 (−12.5, −10.4)	−16.9 (−18.5, −15.4)	0.96 (0.95, 0.96)	0.94 (0.93, 0.94)
Two doses—6 months and 9 months				
Severe *Shigella* diarrhea episodes	−1.6 (−2.0, −1.2)	−2.1 (−2.7, −1.7)	0.56 (0.50, 0.61)	0.41 (0.34, 0.48)
Severe diarrhea episodes of any etiology	−1.6 (−2.0, −1.2)	−2.1 (−2.7, −1.7)	0.97 (0.96, 0.97)	0.95 (0.94, 0.96)
Shigella diarrhea episodes	−11.9 (−12.9, −10.8)	−17.6 (−19.1, −15.9)	0.61 (0.60, 0.62)	0.43 (0.42, 0.44)
Diarrhea episodes of any etiology	−11.9 (−12.9, −10.8)	−17.6 (−19.1, −15.9)	0.96 (0.95, 0.96)	0.94 (0.93, 0.94)
Two doses—9 months and 12 months				
Severe *Shigella* diarrhea episodes	−1.2 (−1.6, −0.9)	−1.7 (−2.1, −1.2)	0.66 (0.60, 0.72)	0.54 (0.46, 0.62)
Severe diarrhea episodes of any etiology	−1.2 (−1.6, −0.9)	−1.7 (−2.1, −1.2)	0.97 (0.97, 0.98)	0.96 (0.95, 0.97)
Shigella diarrhea episodes	−10.6 (−11.5, −9.5)	−15.6 (−17.1, −14.1)	0.66 (0.64, 0.67)	0.49 (0.47, 0.51)
Diarrhea episodes of any etiology	−10.6 (−11.5, −9.5)	−15.6 (−17.1, −14.1)	0.96 (0.96, 0.97)	0.94 (0.94, 0.95)
Two doses—12 months and 15 months				
Severe *Shigella* diarrhea episodes	−0.8 (−1.1, −0.6)	−1.1 (−1.5, −0.8)	0.77 (0.71, 0.83)	0.69 (0.61, 0.77)
Severe diarrhea episodes of any etiology	−0.8 (−1.1, −0.6)	−1.1 (−1.5, −0.8)	0.98 (0.98, 0.99)	0.98 (0.97, 0.98)
Shigella diarrhea episodes	−8.6 (−9.5, −7.7)	−12.7 (−14.0, −11.4)	0.72 (0.71, 0.74)	0.58 (0.56, 0.61)
Diarrhea episodes of any etiology	−8.6 (−9.5, −7.7)	−12.7 (−14.0, −11.4)	0.97 (0.97, 0.97)	0.95 (0.95, 0.96)

CI, confidence interval; VE, vaccine efficacy.

The 10.6 (95% CI [9.5, 11.5]) prevented *Shigella* diarrhea episodes per 100 child-years increased slightly to 11.1 (95% CI [10.0, 12.1]) prevented *Shigella* diarrhea episodes per 100 child-years when analyses further allowed for 20% indirect protection. This same vaccine with 20% boosting protection and no indirect protection would prevent 12.2 (95% CI [11.0, 13.4]) *Shigella* diarrhea episodes per 100 child-years. Together, a vaccine with direct effects plus indirect and boosting protection effects would prevent 12.8 (95% CI [11.6, 14.0]) *Shigella* diarrhea episodes per 100 child-years, which equates to a relative 37.9% reduction in severe *Shigella* diarrhea episodes and a relative 41.7% reduction in *Shigella* diarrhea episodes (Fig 2).

Fig 2. Relative percent reductions in diarrhea outcomes with the addition of indirect and boosting protection for the 9- and 12-month *Shigella* vaccine dosing scenario with 60% full vaccine efficacy against severe *Shigella* diarrhea.

Caption: The black lines represent 95% confidence intervals.



Prevention of antibiotic use

A 2-dose *Shigella* vaccine given at 9 and 12 months with a mean 60% vaccine efficacy would prevent 0.3 (95% CI [0.2, 0.5]) F/M courses for severe *Shigella* diarrhea episodes (relative 35.4% reduction), 3.0 (95% CI [2.5, 3.5]) F/M courses for *Shigella* episodes (relative 35.8% reduction), and 6.1 (95% CI [5.0, 7.3]) F/M exposures to bystander pathogens due to *Shigella* treatment (relative 34.9% reduction) per 100 child-years (Table 4, Fig 3). However, this vaccine would reduce 3.0 (95% CI [2.5, 3.5]) overall F/M courses and 6.1 (95% CI [5.0, 7.3]) overall F/M exposures to bystander pathogens per 100 child-years by only 2.8% and 3.1%, respectively. The 3.0 (95% CI [2.5, 3.5]) prevented F/M courses for *Shigella* diarrhea episodes per 100 child-years increased to 3.1 (95% CI [2.6, 3.6]) prevented episodes with added indirect protection effects, to 3.5 (95% CI [2.9, 4.1]) with added boosting effects, and to 3.6 (95% CI [3.0, 4.2]) when both indirect effects and boosting effects were added to the direct effects per 100 child-years. When indirect and boosting effects were added to the direct effects, there were slight increases in relative percent reductions of all metrics: F/M courses for *Shigella* diarrhea episodes (35.8% to 43.2%), F/M courses overall (2.8% to 3.3%), F/M exposures to bystander pathogens due to *Shigella* treatment (34.9% to 42.9%), and F/M exposures to bystander pathogens overall (3.1% to 3.7%) (Fig 4).

Fig 3. Relative percent reductions in fluroquinolone and macrolide (F/M) use outcomes for 5 *Shigella* vaccine scenarios with 60% (A) and 80% (B) full vaccine efficacies against severe *Shigella* diarrhea and no indirect or boosting protection.

Caption: The black lines represent 95% confidence intervals.

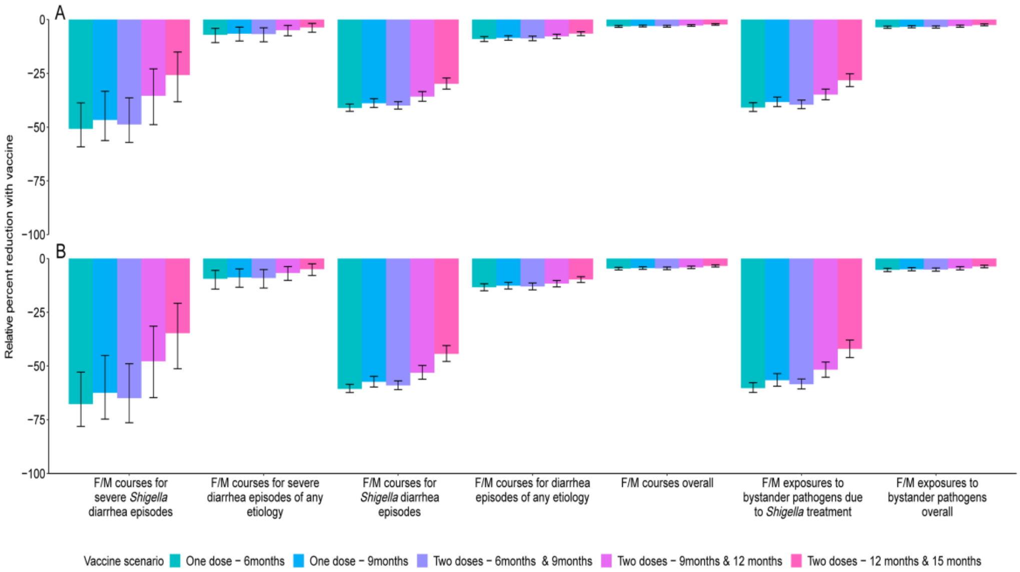


Fig 4. Relative percent reductions in fluroquinolone and macrolide (F/M) use outcomes with the addition of indirect and boosting protection for the 9- and 12-month *Shigella* vaccine dosing scenario with 60% full vaccine efficacy against severe *Shigella* diarrhea.

Caption: The black lines represent 95% confidence intervals.

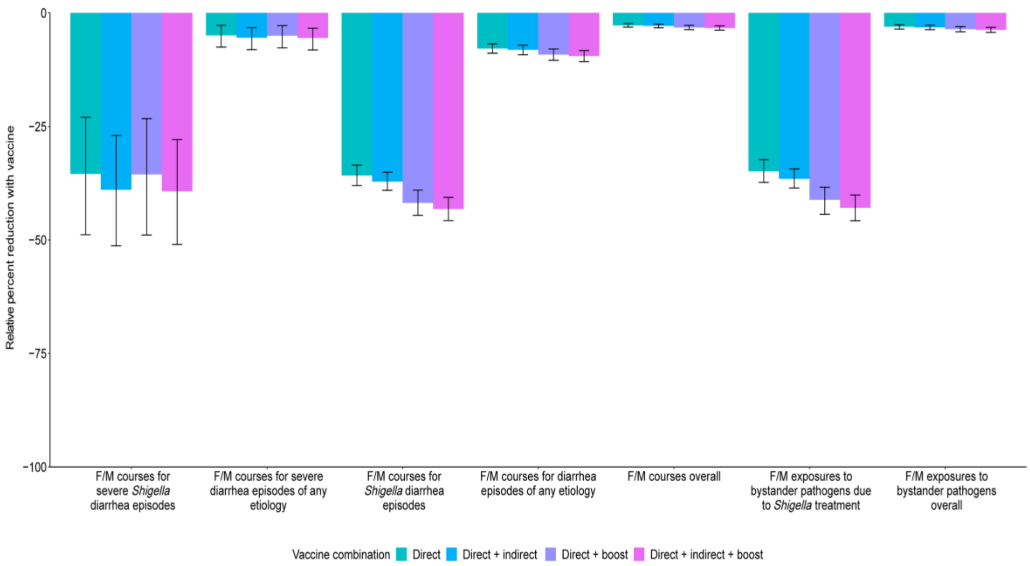


Table 4. Absolute (incidence rate differences) and relative (incidence rate ratios) differences in fluoroquinolone/macrolide (F/M) outcomes for 5 *Shigella* vaccine scenarios compared to the no-vaccine scenario with 60% and 80% full vaccine efficacies against severe *Shigella* diarrhea and no indirect or boosting protection.

Vaccine scenario and efficacy outcome	Incidence rate difference (cases per 100 child-years)		Incidence rate ratio	
	60% VE (95% CI)	80% VE (95% CI)	60% VE (95% CI)	80% VE (95% CI)
One dose—6 months				
F/M courses for severe *Shigella* diarrhea episodes	−0.5 (−0.7, −0.3)	−0.6 (−1.0, −0.4)	0.49 (0.41, 0.61)	0.32 (0.22, 0.47)
F/M courses for severe diarrhea episodes of any etiology	−0.5 (−0.7, −0.3)	−0.6 (−1.0, −0.4)	0.93 (0.89, 0.96)	0.91 (0.86, 0.94)
F/M courses for *Shigella* diarrhea episodes	−3.4 (−4.0, −2.9)	−5.0 (−5.9, −4.2)	0.59 (0.57, 0.61)	0.39 (0.38, 0.41)
F/M courses for diarrhea episodes of any etiology	−3.4 (−4.0, −2.9)	−5.0 (−5.9, −4.2)	0.91 (0.90, 0.92)	0.87 (0.85, 0.88)
F/M courses overall	−3.4 (−4.0, −2.9)	−5.0 (−5.9, −4.2)	0.97 (0.96, 0.97)	0.95 (0.95, 0.96)
F/M exposures to bystander pathogens due to *Shigella* treatment	−7.1 (−8.5, −5.9)	−10.5 (−12.5, −8.7)	0.59 (0.57, 0.61)	0.40 (0.38, 0.42)
F/M exposures to bystander pathogens overall	−7.1 (−8.5, −5.9)	−10.5 (−12.5, −8.7)	0.96 (0.96, 0.97)	0.95 (0.94, 0.95)
One dose—9 months				
F/M courses for severe *Shigella* diarrhea episodes	−0.4 (−0.7, −0.2)	−0.6 (−0.9, −0.3)	0.53 (0.44, 0.67)	0.38 (0.25, 0.55)
F/M courses for severe diarrhea episodes of any etiology	−0.4 (−0.7, −0.2)	−0.6 (−0.9, −0.3)	0.93 (0.90, 0.96)	0.91 (0.87, 0.95)
F/M courses for *Shigella* diarrhea episodes	−3.2 (−3.8, −2.7)	−4.8 (−5.6, −4.0)	0.61 (0.59, 0.63)	0.43 (0.40, 0.45)
F/M courses for diarrhea episodes of any etiology	−3.2 (−3.8, −2.7)	−4.8 (−5.6, −4.0)	0.91 (0.90, 0.92)	0.87 (0.86, 0.89)
F/M courses overall	−3.2 (−3.8, −2.7)	−4.8 (−5.6, −4.0)	0.97 (0.97, 0.97)	0.96 (0.95, 0.96)
F/M exposures to bystander pathogens due to *Shigella* treatment	−6.7 (−8.0, −5.5)	−9.9 (−11.8, −8.1)	0.62 (0.60, 0.64)	0.43 (0.41, 0.46)
F/M exposures to bystander pathogens overall	−6.7 (−8.0, −5.5)	−9.9 (−11.8, −8.1)	0.97 (0.96, 0.97)	0.95 (0.94, 0.96)

Two doses—6 months and 9 months				
F/M courses for severe *Shigella* diarrhea episodes	−0.5 (−0.7, −0.2)	−0.6 (−1.0, −0.3)	0.51 (0.43, 0.64)	0.35 (0.24, 0.51)
F/M courses for severe diarrhea episodes of any etiology	−0.5 (−0.7, −0.2)	−0.6 (−1.0, −0.3)	0.93 (0.90, 0.96)	0.91 (0.86, 0.95)
F/M courses for *Shigella* diarrhea episodes	−3.3 (−3.9, −2.8)	−4.9 (−5.8, −4.1)	0.60 (0.58, 0.62)	0.41 (0.39, 0.43)
F/M courses for diarrhea episodes of any etiology	−3.3 (−3.9, −2.8)	−4.9 (−5.8, −4.1)	0.91 (0.90, 0.92)	0.87 (0.85, 0.89)
F/M courses overall	−3.3 (−3.9, −2.8)	−4.9 (−5.8, −4.1)	0.97 (0.96, 0.97)	0.95 (0.95, 0.96)
F/M exposures to bystander pathogens due to *Shigella* treatment	−6.9 (−8.2, −5.7)	−10.2 (−12.2, −8.4)	0.60 (0.59, 0.63)	0.42 (0.39, 0.44)
F/M exposures to bystander pathogens overall	−6.9 (−8.2, −5.7)	−10.2 (−12.2, −8.4)	0.97 (0.96, 0.97)	0.95 (0.94, 0.96)
Two doses—9 months and 12 months				
F/M courses for severe *Shigella* diarrhea episodes	−0.3 (−0.5, −0.2)	−0.5 (−0.7, −0.2)	0.65 (0.51, 0.77)	0.52 (0.35, 0.69)
F/M courses for severe diarrhea episodes of any etiology	−0.3 (−0.5, −0.2)	−0.5 (−0.7, −0.2)	0.95 (0.92, 0.97)	0.93 (0.90, 0.96)
F/M courses for *Shigella* diarrhea episodes	−3.0 (−3.5, −2.5)	−4.4 (−5.2, −3.7)	0.64 (0.62, 0.67)	0.47 (0.44, 0.50)
F/M courses for diarrhea episodes of any etiology	−3.0 (−3.5, −2.5)	−4.4 (−5.2, −3.7)	0.92 (0.91, 0.93)	0.88 (0.87, 0.90)
F/M courses overall	−3.0 (−3.5, −2.5)	−4.4 (−5.2, −3.7)	0.97 (0.97, 0.98)	0.96 (0.95, 0.97)
F/M exposures to bystander pathogens due to *Shigella* treatment	−6.1 (−7.3, −5.0)	−9.1 (−10.9, −7.4)	0.65 (0.63, 0.68)	0.48 (0.45, 0.52)
F/M exposures to bystander pathogens overall	−6.1 (−7.3, −5.0)	−9.1 (−10.9, −7.4)	0.97 (0.96, 0.97)	0.95 (0.95, 0.96)
Two doses—12 months and 15 months				
F/M courses for severe *Shigella* diarrhea episodes	−0.2 (−0.4, −0.1)	−0.3 (−0.6, −0.2)	0.74 (0.62, 0.85)	0.65 (0.49, 0.79)
F/M courses for severe diarrhea episodes of any etiology	−0.2 (−0.4, −0.1)	−0.3 (−0.6, −0.2)	0.96 (0.94, 0.98)	0.95 (0.92, 0.98)
F/M courses for *Shigella* diarrhea episodes	−2.5 (−2.9, −2.0)	−3.7 (−4.4, −3.0)	0.70 (0.68, 0.73)	0.56 (0.52, 0.60)
F/M courses for diarrhea episodes of any etiology	−2.5 (−2.9, −2.0)	−3.7 (−4.4, −3.0)	0.93 (0.93, 0.94)	0.90 (0.89, 0.92)
F/M courses overall	−2.5 (−2.9, −2.0)	−3.7 (−4.4, −3.0)	0.98 (0.97, 0.98)	0.97 (0.96, 0.97)
F/M exposures to bystander pathogens due to *Shigella* treatment	−4.9 (−6.0, −3.9)	−7.4 (−8.9, −5.9)	0.72 (0.69, 0.75)	0.58 (0.54, 0.62)
F/M exposures to bystander pathogens overall	−4.9 (−6.0, −3.9)	−7.4 (−8.9, −5.9)	0.98 (0.97, 0.98)	0.96 (0.96, 0.97)

CI, confidence interval; F/M, fluoroquinolone/macrolide; VE, vaccine efficacy.

While a 2-dose *Shigella* vaccine given at 9 and 12 months with a mean 60% vaccine efficacy would prevent more instances of antibiotic use overall than of F/M specifically, the percent reductions in overall antibiotic use were smaller than what was observed with F/M use. In this scenario, 0.9 (95% CI [0.6, 1.2]) antibiotic courses for severe *Shigella* diarrhea episodes (relative 33.5% reduction), 5.6 (95% CI [5.0, 6.3]) antibiotic courses for *Shigella* diarrhea episodes (relative 34.5% reduction), and 10.9 (95% CI [9.5, 12.5]) antibiotic exposures to bystander pathogens due to *Shigella* treatment (relative 33.9% reduction) per 100 child-years were prevented. However, there was only a relative 0.9% (−5.6 antibiotic courses per 100 child-years; 95% CI [−6.3, −5.0]) and relative 1.1% (−10.9 antibiotic courses per 100 child-years; 95% CI [−12.5, −9.5]) reduction in overall antibiotic use and overall exposures to bystander pathogens, respectively. Similar to what was observed with F/M, the addition of indirect and boosting effects onto the direct effects minimally increased the number of prevented outcomes.

There was substantial variability in vaccine impact by site. The greatest absolute reductions (incidence rate differences) in diarrhea episodes and antibiotic use were observed in the Bangladesh and Peru sites, and less impact was observed in the Brazil, South Africa, and Tanzania sites due to lower burden of *Shigella* diarrhea in these sites. F/M use for *Shigella* treatment was also variable across sites resulting in little to no impact of a *Shigella* vaccine on F/M use in the Brazil, Pakistan, South Africa, and Tanzania sites. The vaccine would be expected to prevent 2.0 (95% CI [1.6, 2.4]) F/M courses per 100 child-years in Bangladesh, and 0.7 (95% CI [0.5, 0.9]), 0.1 (95% CI [0.0, 0.2]), and 0.1 (95% CI [0.1, 0.3]) F/M courses per 100-child years in Peru, India, and Nepal, respectively.

The corresponding results for the other vaccine scenarios listed in Table 1 are displayed in Figs 1 and 2, Tables 3 and 4. In general, the earlier the vaccine is given, the greater the expected reduction in diarrhea episodes and antibiotic use. Additionally, the single-dose vaccines were more efficacious than the 2-dose vaccines initiated at the same time (e.g., 1 dose at 9 months versus 2 doses at 9 and 12 months) since the full efficacy was achieved at an earlier age with the single-dose vaccines.

Discussion

A *Shigella* vaccine administered at 9 and 12 months with a mean 60% vaccine efficacy could provide a substantial reduction in severe *Shigella* diarrhea episodes, *Shigella* diarrhea episodes of any severity, and F/M courses for *Shigella* diarrhea episodes. However, given the multitude of causes of diarrhea and antibiotic use in this population, the expected reductions in all-cause diarrhea and antibiotic use overall were modest (<5%). While single-dose vaccines and vaccines given at younger ages would prevent more diarrhea and antibiotic use, none of the vaccine candidates in clinical development meet those criteria. The vaccine schedules starting later in infancy, and particularly the schedule starting at 12 months, prevent substantially less disease and antibiotic use than the earlier schedules, supporting the preference in the WHO PPC for the vaccine schedule to be completed by 12 months of age [1]. This pattern reflects the increasing incidence of *Shigella* diarrhea in the first year of life, which nearly doubled from 9 to 12 months of age compared to 6 to 9 months. Because severe disease is more common in younger children, the expected relative reductions in severe outcomes were particularly less than those for nonsevere outcomes for vaccine strategies with older ages of administration. The primary driver of differences in results across simulations was the assumed vaccine efficacy followed by the vaccine dosing schedule. Incorporation of indirect protection and boosting only slightly increased the number of diarrhea episodes and antibiotic courses expected to be preventable, suggesting that these nuances will not be major determinants of vaccine success.

Our study builds on a recent study that modeled the global impact of *Shigella* vaccines [17] by considering a broader range of vaccine assumptions and scenarios, including variations in efficacy and dosing schedules, and impacts of partial protection after a first dose and herd immunity. Despite these differences, the studies estimated similar absolute reductions in *Shigella* diarrhea episodes (approximately 7 episodes per 100 child-years [17] compared to approximately 11 episodes per 100 child-years in our study). The difference in geographic scope between the 2 analyses resulting in different *Shigella* diarrhea incidence rates is a likely major contributor to the differences between the results. Uniquely, we also estimated the effects of *Shigella* vaccines on antibiotic use.

Our simulation approach took advantage of the high-resolution data available from the MAL-ED birth cohort such that we did not need to make assumptions about the natural history of *Shigella*, other enteric pathogens, and antibiotic use. We instead only made assumptions about the potential *Shigella* vaccines (e.g., dosing schedules, efficacy) and simulated their introduction within the observed data. While this approach is likely to provide accurate estimates of vaccine impact at the MAL-ED sites, the results may have limited generalizability to settings that are not comparable. The antibiotic use results may also have limited generalizability if antibiotic use practices change substantially over time. Because the MAL-ED study was conducted in 8 diverse sites across 3 continents, we are confident that our study provides broadly generalizable inferences to similar low-resource settings.

There were several limitations to our analysis. First, our analysis assumed that vaccine efficacy varies randomly across the population. However, it may be that the level of protection is dependent on vaccine-related factors or host characteristics such as age and malnutrition status. These factors could be incorporated into future analyses once they are better characterized for the *Shigella* vaccines in development. Next, a *Shigella* vaccine will likely not be protective against all serotypes, but given the lack of serotyping data, we were unable to simulate the prevention of episodes at the serotype level. Our estimates assume 100% cross protection for subtypes not included in the vaccine and therefore may be slightly overestimated depending on the true levels of cross protection. Third, while our results estimate the upper limit of the potential benefit of a *Shigella* vaccine since we assumed 100% vaccine coverage, it is likely that vaccine coverage would be lower in a real-world setting. Finally, because we only had diagnostic testing for enteric pathogens, we were unable to estimate bystander antibiotic exposure effects on subclinically carried respiratory pathogens and the larger microbiome, which may also have implications for antimicrobial resistance.

Estimation of *Shigella* vaccine impact could be extended in several ways. First, we did not consider the potential for waning immunity since we only observed outcomes to 2 years of age. The effects of waning would likely occur more than 6 months after the last vaccine dose, which was outside of our follow-up period for most vaccine scenarios. However, if efficacy wanes substantially before 2 years of age, our expected reductions may be overestimated. Next, we did not consider a 3-dose vaccine despite there being several 3-dose *Shigella* vaccines in the development pipeline [24–27]. Our estimates of the expected reductions in outcomes would apply to a 3-dose vaccine if the full efficacy is achieved after 2 doses and may be overestimates if full efficacy is not achieved until a third dose. Finally, our predicted reductions in antibiotic use could be underestimates if suspicion of *Shigella* is the main reason for treating diarrhea regardless of etiology, such that treatment rates also decline for other diarrhea etiologies after *Shigella* incidence is known to have been substantially reduced by the vaccine. This downstream impact of a *Shigella* vaccine could also be predicted.

Given the high burden of shigellosis and antibiotic treatment of shigellosis, a *Shigella* vaccine could make a substantial impact on *Shigella* burden, in terms of absolute reduction in diarrhea episodes, and have ancillary benefits in the reduction of antibiotic use. The observed heterogeneity in vaccine impact by site suggests that local data on *Shigella* incidence will be important for policymakers' decisions about whether to introduce a *Shigella* vaccine. The absolute reductions in F/M use achieved by a *Shigella* vaccine accounted for roughly half the achievable reduction of all antibiotic use. However, there were greater relative reductions in F/M use compared to all antibiotic use since F/Ms are often targeted for diarrhea treatment and specifically for dysentery presumed to be shigellosis. F/M use has been associated with resistance in these drug classes [8,10,28], suggesting that reductions in use achievable by a *Shigella* vaccine could limit drug-resistant shigellosis as well as the development of resistance in other enteric bacteria through reductions in bystander exposure. As *Shigella* vaccines are evaluated in large Phase III trials, data on antibiotic treatment should be carefully collected such that the impact of the vaccine on antibiotic use can be measured [1,29]. To quantify this impact, it will be important for vaccine effectiveness to be estimated against less-severe disease endpoints that account for the bulk of antibiotic use.

Our estimates provide realistic expectations for the reductions in diarrhea outcomes at the population level that could be achieved by *Shigella* vaccines under real-world introduction scenarios. Uniquely, we demonstrate that *Shigella* vaccines could provide important reductions in antibiotic use for severe and nonsevere *Shigella* diarrheal episodes, and exposures to bystander pathogens due to *Shigella* treatment, which improves the value proposition for a *Shigella* vaccine. However, unless antibiotic use practices for diarrhea change more broadly as clinical suspicion of *Shigella* decreases, a *Shigella* vaccine in isolation is unlikely to make an appreciable impact on overall antibiotic use or exposures for bystander pathogens. Coadministration or combination of a *Shigella* vaccine with other vaccines for diarrheal disease may be more effective at limiting antimicrobial resistance.

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Challenges and Prospects of Real Estate Investment Funding in South East Nigeria: Way Forward on Capital Market Instruments

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Abstract

The failure of the conventional means of funding real estate development is raising serious concerns in Nigeria. This has necessitated the need for reliable alternative means of funding real estate investment. Unfortunately, extant studies have shown that capital market instruments considered to be suitable are still slow and low in their performance levels in Nigeria. This research, therefore, focuses on identifying challenges and determining prospects of funding real estate development through capital market instruments in South-East geopolitical zone of Nigeria. The population sample of study is 245; comprising of real estate developers, registered estate firm, primary mortgage and Federal mortgage banks, Nigerian Stock Exchange and Security and Exchange Commission and selected academia in estate surveying profession in the study area. The study adopted holistic sampling, with the use of Likert scale questionnaire and interview schedule. Data were presented in tables, percentages and bar charts; and analyzed with Test of Proportion using Z-approximation test. The result quantitatively identifies 7 major challenges considered to be associated with real estate investment funding in South East Nigeria and highly statistically significant 6 factors determining prospects of the capital market instruments in funding the real estate development in the study area. Based on these findings, useful recommendations are made.

Keywords: real estate, housing deficit, capital market instruments, investment funding, securitization

1. INTRODUCTION

Investment is classified into two as real estate and financial investments. While real estate investment is that made on physical assets and services like buildings, land and others; financial investment is made on financial aspect or "paper" assets like fixed interest securities, stocks and shares. Real estate investment itself, therefore, is a form of investment which is popular with investors seeking capital growth, particularly during inflation period. The principal sectors of market for this class of investment includes offices, shops, agricultural properties, factories and warehouses, special and residential properties (Udechukwu, 2006).

Real estate investment is very essential to socio-economic growth and development, yet the delivery of optimum and affordable real estate investment remains a challenge for numerous countries, particularly developing ones like Nigeria (Nebo et al., 2022). Studies have shown that in the country, several urban dwellers live in inhuman and informal conditions, while those with access to formal housing often live at exorbitant cost (Abubakar & Aina, 2019; Aina, 2018; Ewurum et al., 2020; Odenigbo & Ewurum, 2018).

There is no doubt that the provision of real estate is limited and their development requires a lot of money which is usually beyond the reach of most urban dwellers, particularly the low and middle income earners in developing countries like Nigeria. To worsen the situation, the financial security for real estate development has been exacerbated by financial institutions' stringent stance on lending to real estate developers. The Nigeria real estate developers, investors and companies traditionally raise capital through bank loans in contrast to market-oriented economy like US. Thus, the Nigerian real estate sector is highly underdeveloped. Hence, there is a dire need for innovative means of funding real estate investment in the country like capital market. Capital market which is a long term funding measure plays an important role in this scheme. The capital market is certainly the most robust institution in any economy, characterized by its capacity to mobilize the funds needed to finance long-term and productive projects (Okunev, 2000; Wijburg, 2019). The capital market manages relatively large amounts of capital and is the largest provider of long-term financing for capital projects such as real estate developments that are capital intensive. In spite of this, only a limited number of companies in Nigeria raise funds through the capital market, a model that is recognized globally for its great potential to raise huge capital (Diala et al, 2021; Okunev, 2000; Wijburg, 2019; Nebo et al, 2022).

Surprisingly, upon all the benefits derivable from the capital market, real estate developers and investors have not popularized the use of its instruments for real estate funding. In an effort to unravel this gap, this study focuses on assessing the challenges of leveraging on the prospects of capital market instruments for real estate funding.

Objectives

In assessing the challenges and prospects of real estate development funding through capital market instruments, the study was guided by the following objectives:

i. To identify the challenges of funding real estate development through capital market instruments;

ii. To determine the prospects of funding real estate development using capital market instruments in the study area;

iii. To recommend strategies for improving real estate development through capital market instruments in the study area.

II. AREA OF THE STUDY

The study area is South East, Nigeria. This is one of the six geopolitical regions in the country. It is made up of five states and their respective capitals are as follows: Abia State (Umuahia), Anambra (Awka), Ebonyi State (Abakaliki), Enugu State (Enugu), and Imo State (Owerri). The area is clearly shown in Figure 1: South East in Geospatial Map of Nigeria, verged borderline with thick black. The research used three states which were emphasized by highlighting their administrative capitals as follows:

Abia State – Umuahia, the capital is located along the rail route that lies Port Harcourt to Umuahia's south and Enugu city to its north. Umuahia has a population of 359,230 based on National Population Census (2006).

Anambra State has its capital as Awka. Most of the public estates in Anambra are located in Awka as the administrative capital while Onitsha is the commercial heartbeat of the state, and Nnewi is its industrial nerve center.

Enugu State – Enugu City, the Coal City, is the capital of the State. The State has three geopolitical zones of Enugu East, Enugu North and Enugu West with their respective identity local government area/town as Nkanu & Isi-Uzo; Nsukka; Awgu & Ezeagu. The State is cosmopolitan given its former status as the capital of Eastern Nigeria. It has an estimated land area of about 72.8 Sq. Kilometers. The population figure for Enugu urban in 2006 stands as 722,664 (NPC, 2006).

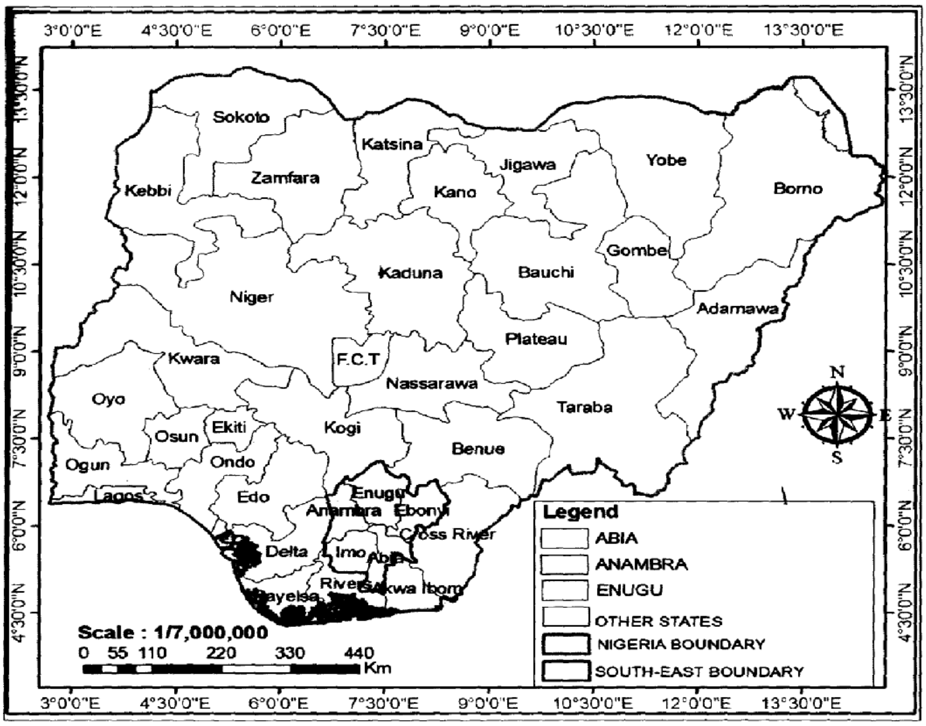

Fig. 1: Geospatial Data of Nigeria, Showing South East Geopolitical Zone, the Study Area

Source: Geographical Information System Laboratory (2021).

III. REVIEW OF RELATED LITERATURE

A skewed sectorial allocation of funds for over two decades from Federal Office of Statistics (FOS) in 2018, according to yearly budget of Central Bank of Nigeria (CBN), confirms that the real estate sector in Nigeria is being starved and needed significant injection of funds. Also, data from mortgage financing about the same period, even with increase of up to100%, indicated that housing stock column showed less commensurate increment and sometimes even negative growth as shown from International Financial Statistics and World Bank Development Indicators (IFS& WBDI). The latter heightens the worrisome state of real estate development in Nigeria and further strengthens the need to assess capital market instruments option by considering their challenges and prospects for real estate funding in the country.

A capital market may be defined as a financial market where lenders provide long-term funds in exchange for financial assets issued by borrowers or traded by holders of outstanding tradable debt instruments (Tsoukalas et al., 2017). Capital markets are known institutions that contribute to socio-economic growth and development of developing and developed economies (Onuora, 2019; Tan and Shafi, 2021). They are made popular by their outstanding role in the mediation process in these economies (Diala et al., 2021). Capital market has been recognized as a viable source of funding both in state and municipal infrastructure projects by issuance of bond. This is made clearer when one considers the level of dominance of the capital markets in real estate development within the past two decades, during which landmark government bonds were opened in 2013. Specifically, from 2010 to 2023 government bonds auctioned in the capital market are worth more than N3.36 trillion, which is equivalent to about 90.2% of the debt issued in 20 years.

There are a number of other instruments in the capital market that can be used in real estate. These include various instruments such as common stocks, real estate trust, loan and bond stocks, debentures, government development stocks, and project bonds (Nebo et al., 2022 and Ezimuo et al., 2014). It was examined and found remarkable that the utilization of these instruments hold a great potential for the resurgence of domestic real estate financing in Nigeria. In this vein, it becomes imperative that adequately assessing these potentials will go a long way towards resuscitating and advancing the real estate sector and developing the economy of the country.

In considering these likely benefits, Arunma (2010), More (2019), Raimi and Uzodinma (2020), and Nebo et al. (2023) identified them as follows:

- Existence of well-functioning money market;
- Presence of a deep, liquid government yield curve;
- Emergence of macro-economic environment;
- Tax framework which can affect the financial viability of different types of instruments and influence real estate developers' choices;
- Respect for rule of law and the framework for creditors' rights;
- Quality of regulation and supervision of capital markets can as well affect real estate developers' confidence in the market;
- Implementation of a robust insolvency system that promotes reorganization of viable enterprises and gives honest entrepreneurs a second chance of critical relevance to improve real estate developers' access to finance.

On the side of potentials, the capital market makes investments in the market very attractive and actually enhances the favourability of this market against some other alternatives. The capital market has been described by Dozie (1996) as a place where a nation's wealth is bought and sold. The market facilitates the creation of facility to raise funds for investment in long-term assets. Unfortunately, Nigeria's capital markets do not effectively play these global roles. The potentials available in Nigerian capital markets can be viewed from three different perspectives, namely, corporate finance benefits, financing options in the capital markets, and secondary market activities. Such benefits exist in form of dividends payment, stock split, capital appreciation, long-term hedge against trends (Akintola, 2018).

Securitization is another interesting aspect, and it widens the horizon of the world of commercial and mortgage real estate to the public. This results to more active real estate transactions, increasing sales, income and investment movement. Securitization obviously helps overcome the intrinsic negative perception of property as poor inefficient investment medium. According to Okolie and Anidiobu (2021), there are very significant advantages and benefits accruable from securitization, and they include the following:

- Provision of good fees to placing agents/dealers in mortgage stocks;
- Reduction of the cost of lending by financial intermediaries;
- Availability of credit due to liquidity;
- Engendering of stable financial system;
- Spread of risk through superior investment mixes and stable returns;
- Enhancement of market delivery;
- Cheaper borrowing cost due to the advantages of economies of scale;
- Low bank failure rate relative to traditional credit because of the multiple level of scrutiny that securitized credit undergo.

Challenges of accessing property development finance in Nigeria through conventional means has equally been examined and identified as having five distinct challenges in funding real estate developments: First, funds from private equity, retained earnings or profits, accumulated savings or revenue reserves are small in nature and granted on short term basis thereby making it grossly inadequate. Second, debt financing is constrained by the long-term nature of the lender’s own sources of fund. These resources are limited by regulations that dictate the proportion of total funds that can be lent for real estate development purposes. Third, there are uncertainties concerning real estate property titles as evidenced by revocation of rights of occupancy within the Federal Capital Territory, Abuja, and elsewhere within the Nigerian setting. Such experiences make certificates of occupancy (C of Os) vulnerable to litigations. Fourth, the time consuming, cumbersome and high cost of title registration processes coupled with high interest rate and high equity/debt ratio conditions demanded from the borrowers do not encourage the use of conventional sources of funds for any appreciable real estate development. Fifth, there are investments with lower risks and higher earnings within shorter periods (shares and stocks, LPO financing etc) than investments in real estate development competing for investors' funds. For this reason, these other investment vehicles often attract available loanable funds away from real estate investment opportunities.

Agbola (1998) and Diogu (2004) observed the problem of financial dependence on propensity to save as one of the challenges of real estate development finance in Nigeria. This is attributed to the fact that investment in real estate, like in any other sector, has an opportunity cost. Such cost is the return on the alternative form of investment and unless the return on property investment is commensurate with or better than investment in other sectors, there will be no significant inflow of investible funds to housing. Anota (2008) agreed that the potentials of the property sector are grossly underdeveloped in Nigeria. This is due to obvious inherent deficiencies in the property finance system. Akomolede (2007) identify the absence of thriving and sound mortgage system as a contributory factor. He opined that Nigerians, both as property developers or property buyers, do not have any other choice other than to take loans from commercial banks.

Okereke-Onyiuke (2000) posits that the cheap source of funds from the capital market remain a critical element in the sustainable development of the economy. Unfortunately, the critical quest for capital market instrument in Nigeria is slow and low level unlike in other parts of the world. Besides, extant literature has done much in terms of examining the potentials of the instruments, with most of the analyses concluding that the role of the capital market in meeting the challenges and prospects of funding real estate through capital market investment leaves much to be desired. This research, aimed at identifying the challenges and prospects of funding real estate development in South-East Nigeria through capital market instruments, fills a gap in as well as adds to the existing literature.

IV. METHODOLOGY

Data analysis method adopted in the research was that of quantitative technique. Through this approach, the questionnaire generated representative samples data that generalized the population. The questionnaire was that of Likert scale coupled with oral face to face interview.

The population of the study comprised real estate investors/developers, estate surveying valuation firms, primary and federal mortgage bank of Nigeria, Nigeria stock exchange commission, and selected academia of estate profession in south-east Nigeria.

The total population of the study was 245 distributed among the groups as indicated in Table1. The population generated from the respective directories of the respondents.

Table 1: Population Distribution of Sample Groups

S/N	Names of Group	Population of Group
1	Real Estate Investors/Developers	**70**
2	Registered Estate Firms	**55**
3	Primary and Federal Mortgage Banks	**35**
4	Nigeria Stock and Security Exchange Commission	**40**
5	Academia	**45**
	Total Population of Study	**245**

Source: Research Field Survey, 2022

Response Rate: Out of 245 copies of questionnaire distributed, 200 representing 81.6% copies were correctly filled and returned.

Respondents were given a five-point Likert rating scale (from strongly disagree to strongly agree) as shown in Table 2 below. Likert rating scale was developed in 1932 by Rensis Likert to measure attitudes (Likert, 1932). The typical Likert scale is a 5- or 7-point ordinal scale used by researchers for respondents to rate the degree to which they agree or disagree with a statement.

Table 2: Likert Scale Used in the Study

Strongly Disagree 1	2	3	4	Strongly Agree 5
○	○	○	○	○

Source: Research Field Survey, 2022

Decision Rule

The following decision rules were applied in the research:

- If p**<0.01**, Test is Highly Significant
- If p**<0.05**, Test is Significant Reject Null Hypothesis (H_O)
- If p**>0.05**, Test is NOT Significant Accept Null Hypothesis (H_O)

Where p is the level of significance.

V. DATA ANALYSES, RESULTS AND DISCUSSIONS

Research Objective 1: To identify the challenges associated with the development and application of the identified instruments in funding real estate development in the study area.

Table 3: Binomial Test of proportion using Z-approximation

Challenges associated with the development and application of the identified instruments	Category	N	Observed Proportion (p).	Test Proportion (P).	Exact Sig. (2-tailed)
Non-existence of sound macro-economic and policy framework deters the well-functioning of the capital market instrument in funding real estate development.	Agree	174	.87	.50	.000
	Disagree	26	.13		***p* <0.01 Test is Highly Significant for "Agree" option**
	Total	200	1.00		
Inadequate and inefficient market infrastructure for issuing, trading, clearing and settlement discourages the applicability of the capital market instrument.	Agree	144	.72	.50	.000
	Disagree	56	.28		***p* <0.01 Test is Highly Significant for "Agree" option**
	Total	200	1.00		
An unstable political environment and non-clarity of tax framework hinders the proper application of capital market instrument.	Agree	162	.81	.50	.000
	Disagree	38	.19		***p* <0.01 Test is Highly Significant for "Agree" option**
	Total	200	1.00		
The quality of regulation and supervision of capital market affect real estate developers confidence to participate in the market.	Agree	176	.88	.50	.000
	Disagree	24	.12		***p* <0.01 Test is Highly Significant for "Agree" option**
	Total	200	1.00		
Lack of information regarding capital market instruments, distorted government interest rate and credit allocation policy are obstacle to the use of REITs, securitization, e.t.c in the near future.	Agree	194	.97	.50	.000
	Disagree	6	.03		***p* <0.01 Test is Highly Significant for "Agree" option**
	Total	200	1.00		
High share issue cost due to government involvement in the pricing with long and miserable issuing procedure challenges the application of capital market instruments in funding real estate development.	Agree	175	.88	.50	.000
	Disagree	25	.13		***p* <0.01 Test is Highly Significant for "Agree" option**
		200	1.00		
Lack of knowledge regarding capital market instruments, distorted government interest rate and credit allocation policy are obstacle to the use of REITs, securitization, etc. in the near future.	Agree	153	.77	.50	.000
	Disagree	47	.24		***p* <0.01 Test is Highly Significant for "Agree" option**
	Total	200	1.00		

Challenges associated with the development and application of the identified instruments in funding real estate development in the study area were determined as the following:

- Non-existence of sound macro-economic and policy framework deters the well-functioning of the capital market instrument in funding real estate development; **(p= 0.87; *p*<0.01).**
- Inadequate and inefficient market infrastructure for issuing, trading, clearing and settlement discourages the applicability of the capital

market instrument; (**p= 0.72; *p*<0.01).**

- An unstable political environment and non-clarity of tax framework hinder the proper application of capital market instrument; (**p= 0.81; *p*<0.01).**
- The quality of regulation and supervision of capital market affect real estate developers' confidence to participate in the market; (**p= 0.88; *p*<0.01).**
- Lack of information regarding capital market instruments, distorted government interest rate and credit allocation policy are obstacles to the use of REITs, securitization, e.t.c in the near future; (**p= 0.97; *p*<0.01).**
- High share issue cost due to government involvement in the pricing with long and miserable issuing procedure challenges the application of capital market instruments in funding real estate development; (**p= 0.88; *p*<0.01).**
- Lack of knowledge regarding capital market instruments, distorted government interest rate and credit allocation policy are obstacle to the use of REITs, securitization, e.t.c in the near future; (**p= 0.77; *p*<0.01).**

These results suggest that the above challenges associated with the development and application of the identified instruments in funding real estate development in the study area are highly statistically significant **(*p*<0.01).** For this study, these seven (7) challenges associated with the development and application of the identified instruments can be adopted with a 99% confidence in funding real estate development in this study area. We conclude that these seven (7) factors are the major challenges associated with the development and application of the identified instruments in funding real estate development in the study area.

Table 3 above shows the proportion of respondents observed among respondents that agreed and disagreed for the challenges associated with the development and application of the identified instruments in funding real estate development in the study area. It further confirms the assertion that there was a significant difference in the proportion of respondents observed among respondents that agreed and disagreed to the various challenges associated with the development and application of the identified instruments in funding real estate development in the study area.

Research Objective 2: To determine the prospects of capital market instruments in funding real estate development.

Table 4: Binomial Test of proportion using Z- approximation

Prospects of capital market instruments	**Category**	**N**	**Observed Proportion (p).**	**Test Proportion (P).**	**Exact Sig. (2-tailed)**
Capital market enhances financial stability and reduces vulnerabilities to exchange rate stocks and sudden interruptions of capital flows.	Disagree Agree Total	14 186 200	.07 .93 1.00	.50	.000 ***p* <0.01** **Test is Highly Significant for "Agree" option**
Capital market instruments create a built in operational and creational efficiency within the financial system to ensure that resources are optimally utilized at relatively little cost.	Agree Disagree Total	191 9 200	.96 .05 1.00	.50	.000 ***p* <0.01** **Test is Highly Significant for "Agree" option**
Capital market instruments provides diversification opportunities unto all types of real estate development in various geographical locations within and outside a particular country.	Agree Disagree Total	191 9 200	.96 .05 1.00	.50	.000 ***p* <0.01** **Test is Highly Significant for "Agree" option**
Capital market instruments failure rate is low relative to traditional credit because of the multiple level of scrutiny it undergo.	Disagree Agree Total	36 164 200	.18 .82 1.00	.50	.000 ***p* <0.01** **Test is Highly Significant for "Agree" option**
Capital market instruments opens a wider range of real estate investment opportunities and enable developers to spread risk through a tax neutral vehicles.	Agree Disagree Total	197 3 200	.99 .02 1.00	.50	.000 ***p* <0.01** **Test is Highly Significant for "Agree" option**
The development of Capital market instruments will promote the creation of alternative source of funding real estate development in Nigeria.	Agree Disagree Total	178 22 200	.89 .11 1.00	.50	.000 ***p* <0.01** **Test is Highly Significant for "Agree" option**

To determine the prospects of capital market instruments in funding real estate development, a binomial Test of proportion using Z- approximation was conducted. Given data from a five point Likert scales reduced to the nominal level by combining all agree and disagree responses into two categories of "Agree" and "Disagree", a binomial Test of proportion using Z- approximation was calculated as shown in Table 4. The results of this test indicated that there was a highly statistically significant difference (***p*<0.01**) in the proportion of respondents observed among respondents that agreed and disagreed for the various prospects of capital market instruments in funding real estate development. The major prospects of capital market instruments in funding real estate development are stated below:

- Capital market enhances financial stability and reduces vulnerabilities to exchange rate stocks and sudden interruptions of capital flows; (**p=**

0.93; *p*<0.01).

- Capital market instruments create a built in operational and creational efficiency within the financial system to ensure that resources are optimally utilized at relatively little cost; (**p= 0.96; *p*<0.01).**
- Capital market instruments provide diversification opportunities unto all types of real estate development in various geographical locations within and outside a particular country; (**p= 0.96; *p*<0.01).**
- Capital market instruments failure rate is low relative to traditional credit because of the multiple level of scrutiny it undergo; (**p= 0.82; *p*<0.01).**
- Capital market instruments open a wider range of real estate investment opportunities and enable developers to spread risk through a tax neutral vehicles; (**p= 0.99; *p*<0.01).**
- The development of Capital market instruments will promote the creation of alternative source of funding real estate development in Nigeria; (**p= 0.89; *p*<0.01).**

These results suggest that the above prospects of capital market instruments in funding real estate development are highly statistically significant **(*p*<0.01).** For this study, these six (6) prospects of capital market instruments can be adopted with a 99% confidence in funding real estate development. We conclude that these six (6) factors are the major prospects of capital market instruments in funding real estate development in the study area.

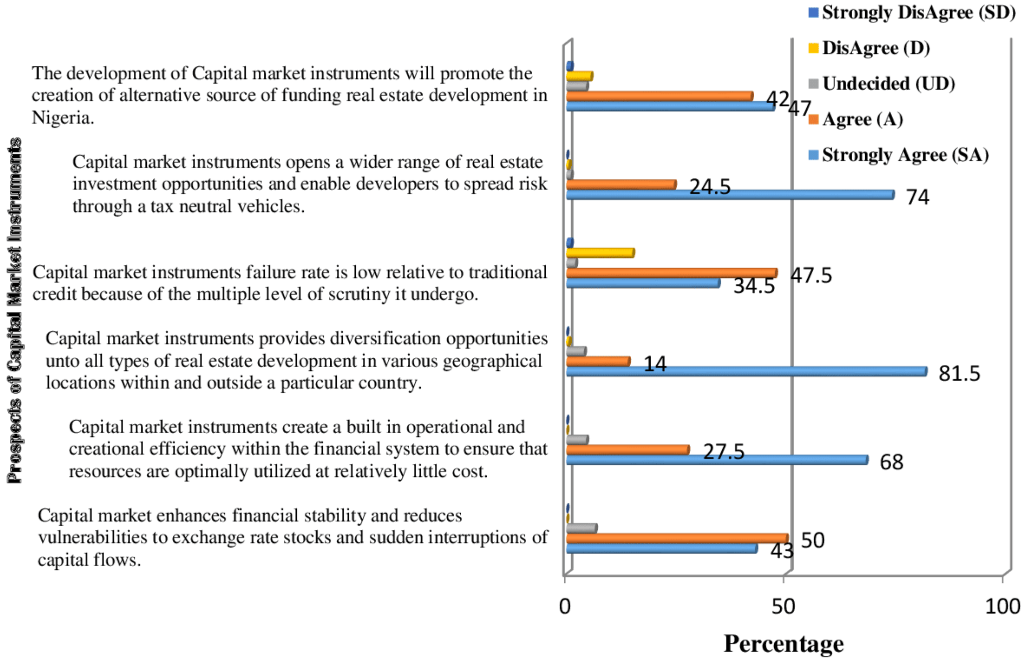

Figure 2: Prospects of Capital Market Instruments in Funding Real Estate

Source: Research Field Survey, 2022

Figure 2 above shows the proportion (%) of respondents observed among respondents that agreed and disagreed for the various prospects of capital market instruments in funding real estate development in the study area. It further confirms the assertion that there was a significant difference in the proportion of respondents observed among respondents that agreed and disagreed for the various prospects of capital market instruments in funding real estate development in the study area.

VI. CONCLUSION

The study quantitatively identifies 7 major challenges considered to be associated with the capital market instruments in funding real estate investment. The challenges notwithstanding, the research concludes that prospects of capital market instruments in funding real estate development are highly statistically significant; with 6 factors determining the prospects of capital market instruments for funding real estate development in the study area.

VII. RECOMMENDATIONS

Based on the research findings, the following are recommended:

1. Capital market instruments should be made popular and more relevant through (a) public enlightenment; (b) upgrading its overall corporate performance; and (c) review of relevant laws governing capital market instruments in Nigeria.

2. A more functional regulatory environment should be created with adequate safeguards to protect the investors and other participants.

3. Government policies on capital market investment should be flexible and liberal for real estate developers and investors.

4. Real estate developers should create alliance/synergy for their effective operation and more recognition/trust to access more fund; and to have enhanced effective property delivery in Nigeria.

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Applications of Artificial Intelligence in Civil Engineering

Leon Borf

Abstract

Artificial intelligence (AI) has made inroads into many facets of human engagements and has been used to solve problems in diverse fields of science and technology. Every AI instrument is a product of engineering that involves data computation and, often, construction of the hard devices by which the instructions inputted into the system are given operational expression. Civil engineering, being the application of scientific and physical principles required to construct and maintain physical structures like roads, bridges, dams, structural aspects of buildings, etc, requires artificial intelligence facilitation in project execution. This paper outlines some of the contributions of artificial intelligence to civil engineering operations, covering areas such as bridge construction risk assessment, predicting of building energy performance, and artificial intelligence approach to asphalt pavement pothole detection, among others.

Keywords: civil engineering, artificial intelligence, roads, bridges, houses, ANN

Introduction

Although artificial intelligence has been applied to other branches of engineering, this article is a brief examination of its application in civil engineering, a broad field that has many sub-divisions such as structural engineering, science engineering, geotechnical engineering, construction engineering, forensic engineering, earthquake engineering, and environmental engineering. In case these sound too technical, the Institution of Civil Engineers makes the relevance of civil engineers clearer for everyone by stating that "Civil engineering is everything you see that's been built around us. It's about roads and railways, schools, offices, hospitals, water and power supply, and much more" (ICE, 2023). Concerning the relevance of artificial intelligence in these and other facets of civil engineering, Dede et al. (2019) noted that "Artificial intelligence is to develop the machine elements that analyze the human's thinking system and reflect the same to reality". They pointed out that artificial intelligence uses in civil engineering include:

studies in the fields of structural engineering, construction management, hydrology, hydraulic engineering, geotechnical engineering, environmental engineering, transportation engineering, coastal and ocean engineering, and materials of construction…

Benefits of AI Applications in Civil Engineering

Artificial intelligence techniques used in civil engineering, they noted, include "ANN, fuzzy system, expert system, and swarm intelligence" (Dede et al., 2019). What are the benefits of using these and other AI techniques in civil engineering? A few case studies are presented here.

1. Risk Assessment for cable system construction of suspension bridges

Risk management is a key area where artificial intelligence has been used in civil engineering. Risk assessment is a most important aspect of any project. Safety and durability are vital guarantees in any civil engineering construction. Lu et al. (2019) did a "risk assessment method for cable system construction of suspension bridges based on the cloud model, which can combine randomness and fuzziness of risk information effectively". In their synopsis, they explained the goal of their studies thus:

> First, a multilevel evaluation index system is built by disassembling the process of cable system construction. Next, the index weights are calculated by the uncertain analytic hierarchy process (AHP). Then, according to the cloud model, a risk assessment model for cable system construction of the suspension bridge is established by realizing the mutual transformation between qualitative language and quantified data. Finally, an illustrative example concerning the risk of cable system construction of Wuhan Yang-Si-Gang Yangtze River Bridge is provided to demonstrate the feasibility and objectivity of the proposed method.

Their study covers tools such as cloud uncertainty prediction, virtual clouds and forward and reverse cloud generators but they applied only the latter two in their determination of the cloud model:

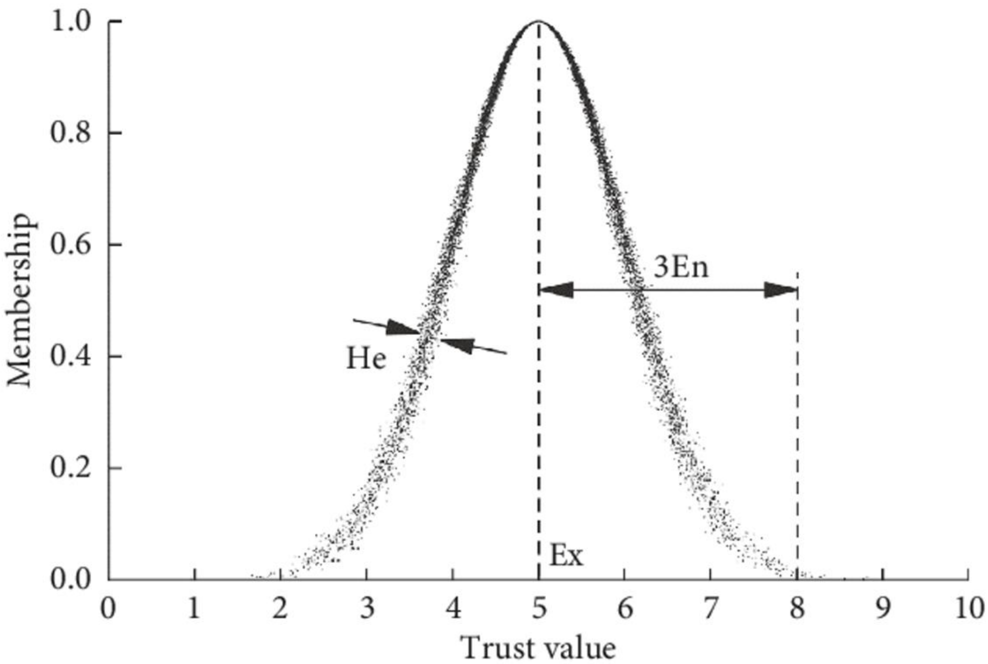
> Let U be a domain expressed by exact numerical values. For any element X in the domain, there is a stable random number Y = U(X) as the degree of concept determination of X, the distribution of X on the domain is called the cloud model or simplified as cloud, and each (X, Y) is called a cloud drop. . If the domain U is defined as an n-dimensional space, it can be extended to an n-dimensional cloud (Lu et al., 2019).

The digital characteristics of the cloud are mainly represented by Ex (expected value), En (entropy), and He (hyper entropy). Using Ex value of 5, En value of 1, and He value of 0.05, they drew a "schematic diagram of the one-dimensional cloud model" as shown in the diagram below. To better understand the diagram, in the absence of essential details of the study which we cannot provide in this summary report, the values Ex, En and He need to be further explained and Lu et al. clarified them as follows:

Ex: the value that best represents this qualitative concept, usually corresponding to the value of cloud center, reflecting the information center value of the corresponding qualitative concept.

En: the measure of the ambiguity of the qualitative concept. The number of elements that can be accepted of the qualitative concept in the domain is directly affected by the entropy value, which reflects the margin of the qualitative concept.

He: entropy of entropy, reflecting the degree of dispersion of the cloud, that is, the thickness of the cloud. The greater the thickness shows the greater the randomness of the membership.



Lu et al.'s study concluded that "the risk assessment method proposed in this study can provide safety assurance and technical support for cable system construction of long-span suspension bridge feasibly and objectively".

2. Predicting Building Energy Performance

Artificial intelligence can be used to predict building energy performance. Alvarez et al. (2018) used artificial neuronal networks (ANN) to calculate building energy efficiency. Their AI-modelled study was based on data obtained from 453 buildings located in Spain. The houses covered an area of 570,438.30 m2. A summary of their work, as abstracted by the authors, states:

Increasing the energy efficiency of buildings is a strategic objective in the European Union, and it is the main reason why numerous studies have been carried out to evaluate and reduce energy consumption in the residential sector. .e process of evaluation and qualification of the energy efficiency in existing buildings should contain an analysis of the thermal behavior of the building envelope. To determine this thermal behavior and its representative parameters, we usually have to use destructive auscultation techniques in order to determine the composition of the different layers of the envelope. In this work, we present a nondestructive, fast, and cheap technique based on artificial neural network (ANN) models that predict the energy performance of a house, given some of its characteristics. .e models were created using a dataset of buildings of different typologies and uses, located in the northern area of Spain. In this dataset, the models are able to predict the U-opaque value of a building with a correlation coefficient of 0.967 with the real U-opaque measured value for the same building.

According to the researchers, some energy-estimation problems solved with ANN are energy test bench in buildings, electric power prediction, and heating/cooling consumption prediction.

Evaluating ANN vis-à-vis traditional engineering solutions, Alvarez et al. listed the advantages of ANNs as follows:

- They can easily create models with complex relationships between data, other than linear.
- They are fast making predictions: the process of training is slow, but once trained, the predictions are usually done in milliseconds.
- They can generalize better than traditional models if they have a class example for a region: they perform well when evaluating buildings that the model has never seen, given that we trained the model with an example fairly similar to the one never seen.
- They perform well with large datasets.

According to the authors, "For the design and training of ANN, we used the software MATLAB with artificial neural networks toolbox. Using this computer tool, we can train, validate, and test an ANN". They said the result of their AI-model research indicate that "it is possible to estimate the energy efficiency of a building in a given geographic zone with a high degree of accuracy using some building characteristics, without doing an intervention in the building or using measurement devices".

3. Provision of Automatic Approach for Asphalt Pavement Pothole Detection

Road maintenance begins with detection of defects on the road. It is only after the defects are properly detected that other processes, including budgeting and gathering materials for the repairs, can then begin. Potholes are among the commonest defects on many roads, especially tarred or asphalt-surfaced roads. Potholes cause delays in transportation of passengers and goods and are sometimes the cause of ghastly accidents. Timely detecting them in the process of road maintenance and rehabilitation is, therefore, very crucial; it is what prompted Hoang (2018) to carry out a research on "An Artificial Intelligence Method for Asphalt Pavement Pothole Detection Using Least Squares Support Vector Machine and Neural Network with Steerable Filter-Based Feature Extraction".

Why is it necessary to bring AI into the routine task of pothole detection, a task usually undertaken by road inspectors? Hoang offered this explanation:

> In developing countries, the pavement pothole is often detected manually by inspectors of local transportation agencies during periodical field surveys. Although this conventional method can help to acquire accurate evaluation of potholes, it also features low productivity in both data collection and data processing. ,e reason is that one pavement inspector can only inspect less than 10 km per day. With a large number of road sections needed to be inspected routinely, the automation of the pothole detection becomes a pressing need for transportation agencies. Moreover, the productive pavement surveying process significantly leads to economic gain. It is because, if rehabilitation process is performed timely, pavement restoration cost can be saved by up to 80%.

Hoang summarized the relevance of his AI-enabled advance in asphalt pavement pothole detection thus:

> This study establishes an artificial intelligence (AI) model for detecting pothole on asphalt pavement surface. Image processing methods including Gaussian filter, steerable filter, and integral projection are utilized for extracting features from digital images. A data set consisting of 200 image samples has been collected to train and validate the predictive performance of two machine learning algorithms including the least squares support vector machine (LS-SVM) and the artificial neural network

(ANN). Experimental results obtained from a repeated subsampling process with 20 runs show that both LS-SVM and ANN are capable methods for pothole detection with classification accuracy rate larger than 85%. In addition, the LS-SVM has achieved the highest classification accuracy rate (roughly 89%) and the area under the curve (0.96). Accordingly, the proposed AI approach used with LS-SVM can be very potential to assist transportation agencies and road inspectors in the task of pavement pothole detection.

Hoang's research is well-illustrated; unfortunately, due to space constraint, we cannot show most of them here. However, below is a pictorial display of his image smoothing with the Gaussian filter:

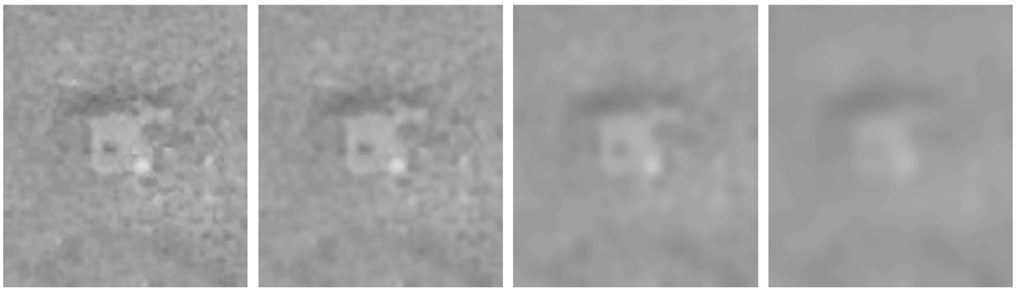


FIGURE 1: Image smoothing with the Gaussian filter.

Hoang explained that "for the task of pothole detection, Gaussian filter (GF) can be helpful to blur the asphalt background texture and facilitate further analysis of the digital image. The GF is essentially a 2D convolution operator that uses the kernel that represents the shape of a Gaussian function…σ denotes the standard deviation of the GF" (Hoang, 2018).

Conclusion

Artificial intelligence has been used to derive other civil engineering solutions. Some of the AI-derived solutions reported by Dede et al. (2019) include that of C.-Y. Kao et al. who developed a two-step computer-aided approach for pozzolanic concrete mix design. Another is that of Golnaraghi et al. who modelled labour productivity using four different ANN methods – Backpropagation Neural Network (BNN), Radial Basis Network (RBF), Generalized Regression Neural Network (GRNN), and Adaptive Neuro-Fuzzy Inference System (ANFIS). These and the few studies reviewed in this article are indicators that greater contributions to civil engineering should be expected from artificial intelligence applications.

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Author's Brief Data

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