Discover Analytics

Case Study

Developing digital twins of urban low-income communities in Sub-Saharan Africa: a case study in Ghana, West Africa

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Received: 5 June 2024 / Accepted: 18 October 2024
Published online: 04 November 2024

Abstract
Low-income urban and rural communities in Sub-Saharan Africa are habitats for more than 556 million profoundly poor people, and the United Nations and the African Union are pessimistic that sustainable development goals will be met. The number of people falling into poverty is increasing, and policy initiatives to reduce poverty have been confounded by various economic, political, social, structural, and environmental issues. Despite a wealth of natural and human assets, there is no systematic approach to sustainable development for poverty alleviation in Sub-Saharan Africa. This case study of an urban community in Ghana, West Africa, investigates the potential role of digital twins in a systematic approach to sustainable development for poverty alleviation. Aerial and community surveys of the built environment and social and economic surveys of businesses and households were compiled to inform a virtual representation of the study area. A small e-commerce business intervention was introduced, and data was recorded for studies on the impact of the intervention. A 3D interactive view, extensive video, and fixed images provided a comprehensive view of the built environment. A limited view of the social and economic environment was obtained from a small population sample. It was observed that online transactions increased in the businesses receiving the e-commerce intervention, demonstrating a willingness of businesses and their customers to engage in e-commerce when incentives are provided. A single successful community-centric initiative has little value unless it can be generalized across the broader society. This limited case study focused on developing and testing virtual and physical constructs to enhance a deeper understanding of the community, community engagement, and pathways to sustainability. The scale of the intervention was too small to conclude generalizability. Future research will focus on improving the data collection processes, fidelity of virtual representations, visualization methods, and methodologies for constructing viable virtual interventions.

Keywords Digital twins · E-commerce · Sustainable development · Sub-Saharan Africa · Urban poverty

1 Introduction

The United Nations estimates that 556 million people live in multidimensional poverty in Sub-Saharan Africa (S-SA) [78]. Despite efforts to reduce poverty, the situation in many S-SA nations is worsening due to population growth [7]. Prospects for reducing poverty across the region appear challenging because of the potential effects of climate change, armed conflict, disease, and political unrest [84].

Poverty alleviation through the sustainable development of low-income communities aims to improve social, economic, and environmental wellbeing [82]. Sustainable development is a continuum of initiatives that strive to

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sustainably maintain a balance between human needs and the preservation of the natural environment [57]. Sustainable development and sustainability are subject to variations in the composition and unique challenges of low-income communities. Initiatives that work for one community may not work well in others [45, 53]. The generalizability or external validity of a successful initiative may require a carefully nuanced approach in other communities. For low-income communities, the condition of the natural environment, such as climate change effects, deforestation, desertification, sources of water, risk of flooding, and social factors, including traditional practices, cultural values, language, and ethnicity may influence the likelihood of any initiative being successful [22]. The extent of public infrastructure, including roads and transport, electricity supply, water supply, telecommunications, and government services, may also isolate low-income communities from civic participation, especially in rural communities [22, 35].

In a review of the literature, Cordes and Marinova [29] did not discover any evidence of a systematic approach to the sustainable development of low-income communities for poverty alleviation in S-SA. The lack of funding, skilled personnel, supporting infrastructure, and market opportunities are major challenges for small to medium enterprises (SMEs) in the region. This view is partly derived from Mazambani and Mutambara [56], who stated that no performance evaluation frameworks exist that provide guidance for sustainable development to engage economic and social factors as part of a central strategy. There is no consensus on the commercial rationale for businesses to engage in sustainable development for those in poverty in S-SA [53], and developmental studies lack a cohesive approach to poverty alleviation [11, 25]. Aftab and Ismail [4] concur that there is no development theory or consensus on how development should proceed.

The sustainable development goals (SDGs) target critical areas of social, economic, and environmental development to address inequities in the livelihoods of people [82]. However, progress towards achieving SDGs in S-SA faces significant challenges due to slow economic growth, the high concentration of poverty and inequality, poor governance, corruption, and institutional weaknesses [71]. Further, numerous infrastructure deficits, climate change threats, unsustainable population growth, lack of specific sustainable development strategies, inadequate monitoring and reporting mechanisms, and funding shortfalls exacerbate progress towards meeting SDG targets [71]. The Africa Report [71] criticisms of the SDGs include the lack of target enforcement mechanisms, underfunding, complexity, inconsistencies of goals and targets, and perception that the SDGs are focused on growth at the expense of equality and preservation of the environment. According to the Institute of Security Studies (ISS) [50], S-SA will not meet the 2030 SDG target of no poverty and. estimates poverty to be 17.8% in 2043 unless significant policy and structural changes are made [50].

A community can be defined as a physical and social entity from structural, demographic, social, economic, and environmental observations [27, 48, 63, 65]. These observations contribute to the creation of an empirical data-intensive virtual representation from which dimensional, spatial, and temporal visualizations of the community can be algorithmically derived. The extent to which the physical and social entities can generate data will determine how nuanced changes in the physical and social entity can be detected [27, 63, 65]. Consequently, the data generation model of the community should include a variety of sensors, including aerial imaging, terrestrial imaging, surveys of the community infrastructure, and automated reporting from businesses, schools, clinics, weather stations, and government agencies [27].

The virtual representation of the physical and social entity can be interpreted by advanced data analytics and artificial intelligence techniques to predict outcomes and inform policymakers and investors of the progress of sustainable development initiatives such as innovations in the circular economy, local manufacturing using advanced techniques, agribusiness initiatives in aquaculture and vertical farming, pro-poor services such as eco-tourism, and participation in government initiatives to improve public infrastructure. The physical and social entity and its virtual representation exchange data and information to optimize outcomes for the community [61]. Other technologies, such as agent-based modeling, can be used to study the direction of community activities toward sustainability against perceived barriers to such goals. This aligns with and extends upon the basic concepts of digital twins in achieving sustainable development goals [48, 74].

Tzachor et al. [74] observed that, despite the potential transformative benefits of digital twins, they have not featured strongly in discussions on sustainability and the SDGs. Tzachor et al. [74] contend that digital twins can play a significant role, particularly in urban development and the built environment, and identify four benefits of digital twins that could influence SDG outcomes. These benefits include resource allocation efficiencies, the ability to extensively test the introduction of new technological innovations in a virtual environment prior to actual implementation, simulation of multiple stakeholder interactions and collaboration potential, and generation of SDG progress reports.

Hassani et al. [48] state that while digital twins have been used mainly in manufacturing, they have not uncovered any research on the application of digital twin technology in support of SDGs. Hassani et al. [48] discusses several potential opportunities for enabling digital twins to support SDGs, including urban planning, energy, manufacturing, resource

management, agriculture, health, and education. They also provide examples of opportunities within each category that could benefit from implementing digital twins. However, these examples are well-defined manufacturing or production systems for construction and agribusiness or in delivering energy, health, and education services. While these are all worthy targets for digital twins, they do not inform the effect on the built environment, human capital development, and social wellbeing in low-income communities. There is an absence of literature specifically related to the application of digital twins to poverty alleviation.

Birks et al. [23] explore the potential of digital twins in a social context to address aspects of the human condition, including poverty, crime, inequality, and poor economic prospects. Birks et al. [23] conceptualize societal twins populated by synthetic people to provide insights into the impact of potential interventions targeting crime reduction, improved transport services, and other aspects of human behavior and their interaction with physical systems. Synthetic people overcome ethical issues when dealing with human subjects when studying virtual interventions, but data from real people is required to reflect changes in the virtual representation of the physical and social entity.

Helbing and Sanchez-Vaquerizo [49] expand on the privacy concerns expressed by Birks et al. [23]. Tzachor et al. [74] address discrimination resulting from inappropriate classifications of people, which grants privileges to certain groups and not others. Social systems are complex multi-dimensional entities, and attempts to refine virtual representations with additional data may lead to misrepresentations if such data is not fact-based or verifiable [49]. This could lead to serious consequences if policy decisions are based on predictions generated from this data [49]. Further, the interactions between the physical and virtual components of the digital twins may place more emphasis on measurable aspects of social systems and control and ignore important aspects of human behavior, such as the ability to innovate and self-organize [49].

In a systematic literature review of the interrelatedness of innovation, resilience, and sustainability, Zupancic [87] observed that these three concepts have been used interchangeably, and considerable overlap exists between them. Zupancic [87] also observed that the literature variously referred to resilience as a component or trait of sustainability and that innovation was the means to achieving resilience and sustainability. Zupancic [87] concluded that while sustainability relates to performance across social, economic, and environmental domains, resilience is the ability of sustainability to continue to perform when confronted with shocks or stresses. While Zupancic [87] did not include a review of the literature on urban planning and the built environment, Horgan and Dimitrijevic [51] present several examples of how governance and the "politics of space" challenge social innovation in the built environment. In S-SA, the rate of urbanization has overwhelmed urban planners to the extent that more than 60% of the urban population lives in slums [9]. The application of digital twins in studies of sustainable development is identical to how they are utilized in aerospace and manufacturing applications. However, resilience in any context is bounded, outside of which sustainability or operational performance will collapse. Digital twins have successfully determined the range of conditions within which system performance can be maintained in aerospace and manufacturing applications [69]. They may also be helpful in determining the constraints on sustainability performance in social science.

Community engagement is essential for reporting business and household conditions [27]. A review of the literature on community-based participatory research in Ghana revealed a few studies in bio-medical research in rural areas of Ghana but none for urban areas. Appiah [12] emphasizes respect for traditional practices and cultural values when seeking community participation in research in Africa and the need to gain full support from the gatekeepers to the communities, typically chiefs or elders in rural areas. Issues related to gaining informed consent can be particularly challenging because of language barriers and literacy levels [13, 20, 44, 73]. Appiah [13] questioned the use of Western individual-based informed consent processes in "highly collectivist, low literate, and socioeconomically disadvantaged settings" in S-SA and suggested more "context-specific guidelines" were needed. Issues related to past experiences, distrust of outsiders and institutions, distrust of university research, gender of participants, and memories of colonialism are real issues confronting researchers when attempting to gain informed consent [21].

The first six SDGs are no poverty, zero hunger, good health and wellbeing, quality education, clean water, and sanitation. Data that addresses these goals can inform virtual representations of low-income communities and different sustainable development scenarios in virtual space. The outcomes are major contributors to social wellbeing and progress towards SDGs. Social wellbeing is not something that can be easily measured. However, a framework of opportunities, including jobs, education, health, affordable housing, and the natural environment, can be established and monitored in near real time to determine their effectiveness [47]. It is also possible to quantify some characteristics of the communities and their populations through observation of social and economic behaviors. Changes in household incomes, new home construction, school attendance of boys and girls, and changes in rates of healthcare clinic visits may also be markers of improved economic conditions in families [30]. Data reflecting improvements in

public infrastructure, including roads, government services, electricity supply, water supply, public amenities, and public transport, may have resulted from social innovation and the expenditure of social capital [30]. Rehabilitation of the natural environment through contributions to the circular economy may also reflect improvements in the built environment [55]. However, wellbeing also encompasses social identity, freedom of speech, belongingness, social identity, and feelings of being safe [47]. Studies of sustainable development initiatives over multiple domains with digital twins may provide insights into how these factors contribute to overall wellbeing.

This case study introduces a tentative step into the construction of digital representations of low-income communities in S-SA for studies of social, economic, and environmental innovations and their resilience to a wide range of confounding influences on their sustainability. The primary goals of this case study were to investigate challenges in gaining community-based participation, the technologies required for obtaining basic information, the processing and visualization of the data, the approach to the implementation and monitoring of an e-commerce intervention, and the construction of a social wellbeing index. The capabilities of digital twins to develop multiple scenarios at a macro level may become a powerful tool to identify optimal sustainable development initiatives and to monitor, forecast, and report performance against SDG targets.

The following sections provide an overview of digital twins and virtual constructs and a case study of a low-income urban community in Ghana, West Africa, with a small e-commerce intervention.

1.1 Digital twins and virtual constructs

1.1.1 Definitions

Boyes and Watson [26] undertook a comprehensive literature review and concluded that there was no consistent definition of a digital twin. They adopted the following definition to fit their proposed analytical framework:

> "A live digital coupling of the state of a physical asset or process to a virtual representation with a functional output."

The National Science Foundation [61] more recently stated the following more expansive definition for a digital twin:

> "A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin."

The definition of digital twins by the National Science Foundation [61] provides valuable guidance in the development of virtual constructs for sustainable development interventions and to their generalization, collaboration, and aggregation potential.

1.2 Virtual sustainable development

Figure 1 is a generalized depiction of proposed virtual constructs for the design, development, implementation, operationalization, and progress monitoring of interventions targeting sustainable development and social wellbeing in S-SA. The virtual constructs are intercoupled with the physical and social entities as an integral part of the life cycle of sustainability initiatives.

1.2.1 Physical and social entity

The physical and social entity describes the built environment of the target community and the social and economic behavior of its human inhabitants, respectively. The physical entity is characterized by the types and usage of buildings and facilities from aerial and terrestrial surveys of the community. The profile of the human inhabitants includes the total population of adults and children, a breakdown of adults and children into age groups and gender, the number of children of each gender attending school, the number of working-age adults, household incomes and expenses, asset ownership, forms of transport, types of social engagement, and other factors relating to human activities in the community.

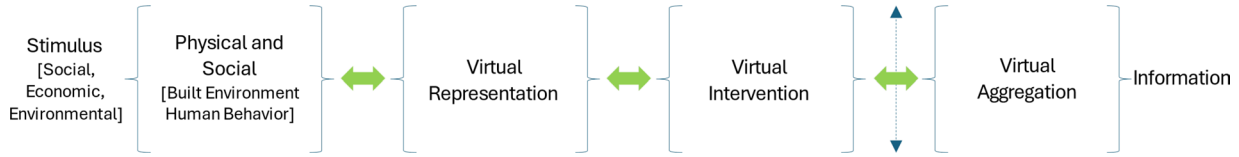


Fig. 1 Virtualization of Sustainable Development Initiatives. Attribution: Authors

This data is collected from household and business surveys using a combination of manual and automated electronic techniques. The virtual elements of Fig. 1 interact with the physical and social entity in mutually reinforcing ways.

1.2.2 Virtual representation

The virtual representation or digital twin is what we can observe and interpret from the data [61]. Various tools can assist in these observations so that ideas can be formulated into actions targeting specific aspects of the community, such as improved road access, the construction of a school, flood mitigation strategies, or some economic stimulus to create better-paying jobs or business opportunities. The quality and timeliness of data collection enhance the quality of policy or investment decisions.

1.2.3 Virtual intervention

The virtual intervention is the virtual construct of a potential future physical intervention. It derives inputs from the virtual representation of resources and capabilities within the community and from external sources to simulate an intervention that optimizes economic, social, and environmental benefits for the community. External sources of data may include business plans, market forecasts, and policy initiatives. Social innovations in sustainability and circular economy initiatives may also contribute to the virtual intervention modeling.

1.2.4 Virtual aggregation

Virtual aggregation combines outcomes of multiple virtual representations and virtual interventions to provide perspectives of proposed sustainable development initiatives across spatial, cultural, environmental, and temporal domains. It can also produce macro-economic assessments and views of sustainable development initiatives across regions and countries.

1.3 Information flow

Figure 2 identifies the core elements of Fig. 1 and illustrates the flow of information that defines the physical and social entity within the virtual space. The physical and social entity is depicted as the combination of a physical entity and a social entity.

This separation is maintained throughout the virtualization process to delineate interventions in the built environment from the social entity that exploits it. For example, the virtual representation of the physical entity may have detected that there is no school in the community. This may then invoke quite separate actions in the virtual modeling of the physical entity from actions in the virtual modeling of the social entity. The virtual modeling of the built environment would focus on location, land acquisition, type of construction, size, road access requirements, the provision of water, electricity, waste management, costs, and other needs. The virtual modeling of the social entity would focus on the resourcing requirements to achieve specific educational goals such as types of educational programs, delivery methods, technology, teacher qualifications, educational materials, and costs. Other examples include new road construction, improved access to quality water, construction of public toilets, and higher performing telecommunications services. It is expected that all social, economic, and environmental interventions will result in improvements to the built environment directly or indirectly over time.

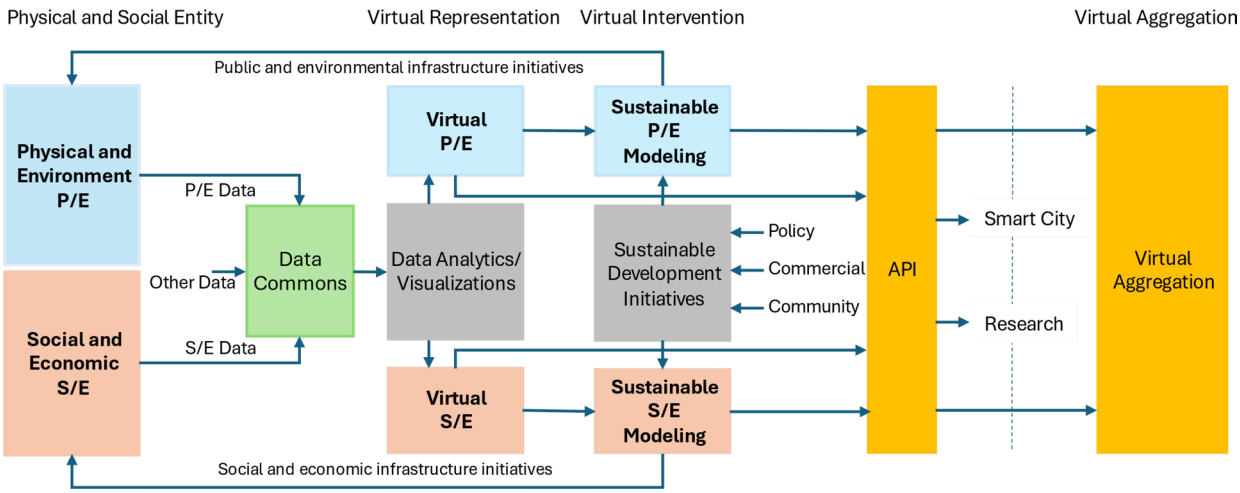


Fig. 2 Virtual Constructs and Information Flow. Attribution: Authors

1.4 Information reporting

The presence of an applications program interface (API) in Fig. 2 provides a semantically consistent digital interface to the sustainable development initiative. The API provides access to various levels of data and virtual modeling of the communities. Some examples include metadata for smart city initiatives, virtual representation data for other researchers, and a wide range of metrics required for the study of the aggregation effects of multiple communities on macroeconomic performance and progress towards achieving SDGs. Figure 2 also recognizes potential policy, commercial, and community-inspired decisions on community wellbeing. These decisions may be supportive of sustainable development goals. Examples of supportive decisions may include actions by governments to address improvements in public infrastructure, commercial obligations to improve community services and to create job opportunities as part of compensatory packages for the exploitation of natural resources, and community initiatives to build better accommodations arising from greater prosperity. However, each of these actions has downside implications for communities and the attainment of SDGs [38]. In either case the virtual physical and social intervention models provide valuable guidance for advocacy and community representation in future directions for their communities [1, 38].

1.5 Digital twins and poverty alleviation

Digital twins can be powerful tools for poverty alleviation by providing detailed simulations and real-time data analysis to inform and optimize interventions. Digital twins can model urban and rural environments to identify areas lacking essential services like clean water, sanitation, and healthcare. This helps in planning and prioritizing infrastructure development to improve living conditions and the optimal delivery of food, medical supplies, and educational materials. Digital twins provide real-time monitoring of poverty alleviation programs, such as the problematic livelihood empowerment against poverty (LEAP) program in Ghana [67], with continuous evaluation and adjustment. This helps identify what works and what does not, leading to more effective interventions. They also help to visualize the impact of poverty alleviation efforts, making it easier for communities to understand and engage with these initiatives, which fosters greater participation, trust, and community support.

1.6 Digital twins and the environment

Digital twins can transform sustainable development and climate change adaptation studies by providing detailed, real-time simulations and data analysis [34]. Digital twins can simulate urban or rural low-income communities and provide insights into their growth and built environment development [65]. They can also be used to simulate

developmental scenarios to optimize resource allocations, traffic management plans, and mechanisms to minimize pollution. For instance, data on water, energy, and waste systems may be integrated to optimize resource allocations and minimize environmental impacts.

Digital twins can simulate the impact of climate change on low-income communities, including vulnerability to flooding, increased desertification, water and electricity supply shortages, and public health issues [34]. They can provide evidence-based support and guidance for policy and investment decisions and planning for climate change adaptation strategies [15]. Digital twins then provide ongoing monitoring of changes to the environment and evaluation of adaptation initiatives. Further, digital twins can simulate extreme weather events and their impacts, helping communities prepare for and respond to disasters more effectively [34]. This is important for low-income communities, which are often subject to flooding. In this case study, Tetegu in Accra, Ghana, is subject to regular spillage-induced flooding from Lake Weija during intense rainfall. By leveraging the capabilities of digital twins, researchers and policymakers can gain valuable insights into sustainable development and climate change adaptation, leading to more resilient and sustainable communities [17].

1.7 Data integrity

Maintaining data integrity is crucial to the successful ongoing performance of digital twins. The structure of Fig. 2 facilitates a repository of diverse data from many sources. This presents opportunities for bad actors intent on disrupting sustainable development initiatives. In this case study, all data was aggregated into a cloud-based platform for ease of data sharing and is reliant on the cybersecurity provisions of the cloud storage provider. However, it is recognized that a framework of best practices for standardized security has not been developed [19]. Further, the data collection processes and technologies may have security vulnerabilities [19]. There are numerous other challenges to safeguarding data integrity, but there are opportunities for digital twins to test advanced cybersecurity measures [19]. Further comprehensive research in data integrity measures at all levels, including data collection, data integration, storage, and access, is required. One partial solution may include blockchain technology as an immutable database for data storage, access management, and smart contracts for data use [62].

1.8 Data commons

The physical-to-virtual environment structure depicted in Fig. 2 intrinsically creates a data commons [43]. However, the semantics of the data structures (e.g., spreadsheet formats, XML schema) and the type of database (e.g., blockchain, object-oriented database, graph database. or relational database management system) would need to be developed for sustainable development studies. The virtual intervention and virtual aggregation functions require access to the database and data could be made available under certain conditions via the API for smart city, urban development, and other research studies.

1.9 Digital twins and qualitative data

Qualitative data such as interviews, focus group feedback, and studies of daily life in communities may contribute to a better understanding of societal structures, cultural values, and social relationships in communities. These dimensions of social capital are difficult to quantify. This case study is a part of research investigating artificial intelligence (AI) and complexity theory techniques that may enhance the quality and accuracy of social wellbeing and social capital estimates.

1.10 Urbanization or decentralization

In a study of urbanization and poverty in S-SA, Ahimah-Agyakwah [5] emphasizes the importance of research on urban poverty. Ahimah-Agyakwah [5] concluded that urbanization significantly reduced poverty in 29 countries in S-SA but that urban infrastructure, including roads, water, energy, health, and education services, needed to be improved. Digital twins for urban development may play an important role in this endeavor. Alternatively, a decentralization strategy that offers improved opportunities in rural areas while slowing the rate of urbanization may

have social, environmental, and economic benefits. The World Economic Forum has called for innovation in agribusiness to rejuvenate the $1 trillion food industry in S-SA [86]. Digital twins may be useful in developing decentralization scenarios to direct policy and investment decisions that optimally address rural poverty while guiding urban development strategies.

1.11 Informal economy

The United Nations Development Programme [79] draw attention to the extent of the informal economy in S-SA and stated that 85% of employment in S-SA is informal. They also state that despite the significant impact on the overall economy, policy initiatives have focused on trying to eliminate the informal sector rather than supporting it with policy initiatives to reduce vulnerabilities and to indirectly encourage the transition to the formal sector. Aryeetey [16] previously observed that informality in S-SA was not well understood and that policy initiatives to formalize the sector have failed. Aryeetey [16] stated that policy initiatives should focus on support for the informal sector to allow for gradual inclusion over time. Digital twins could help to understand the informal sector better and to develop potential policy initiatives in virtual space. The following sections describe a case study of a business e-commerce intervention in the urban community of Tetegu in Accra, Ghana.

2 Case study

In West Africa, Ghana gained independence from Britain in 1957, becoming the first S-SA nation to do so. It is a parliamentary democracy. Gold, cocoa, and oil underpin the country's economy, contributing to its growth and development. The country has approximately 30.8 million people [40] and is home to diverse ethnic groups, including the Akan, Ewe, and Ga-Adangme. The national language is English. Accra, facing the Gulf of Guinea, is the nation's capital.

Ghana is currently administratively segmented across 16 regions and 261 districts [77]. The geographic boundaries of the regions and districts are periodically adjusted to account for population growth and other factors [14, 64]. Governance is multi-layered, with regions and districts having some autonomy under national imperatives. However, this can lead to challenges in implementing and managing national policies without transparency and accountability across all layers [14, 64, 77]. Effective resource allocation, including subsidies and financial incentives, may be contested and hence vulnerable to corruption [77]. Without uniform monitoring and reporting, the lack of transparency at each layer may indicate corruption [14]. A potential example of such corruption is the persistent failure of national initiatives to eliminate illegal gold mining, referred to as "galamsey" [10]. Ghana is the largest producer of gold in S-SA [3]. The presence of galamsey has had devastating social and environmental effects on rural communities [2]. It is estimated that as much as $3.8 billion each year is illegally mined and transported across the porous northern borders with Burkina Faso and Niger to be "laundered" elsewhere [76]. The destruction of traditional lands and the pollution of rivers has led to a national environmental disaster [10]. It is speculated that the failure to eliminate galamsey is because of the deep entrenchment of illegal practices with businesses and political agendas locally and nationally [10]. Corruption in the form of bribe-taking is endemic in the public sector, with deleterious effects on public services, especially law enforcement and health services [32].

According to the United Nations Development Programme in Ghana [77], the country has performed better than other S-SA countries in governance but concluded that overall government effectiveness is weak. Ghana has developmental challenges that restrict its full potential. Ghana has weak institutional capacity and cannot efficiently deliver public goods and services [77]. Endemic corruption at all levels of government severely impacts decentralization efforts [77]. The country's youth have limited participation in processes affecting the future of their country, and female representation in government is one of the lowest in S-SA [77]. The Brookings Institute [58] observed that the syndicated style of government leads to cronyism and influence peddling. There is corruption in the contract award procedures, and large infrastructure projects rarely get completed because of competition between the two political parties [77]. These challenges, political behaviors, and failures in law enforcement are not conducive to a supporting environment for sustainable development in Ghana and potentially across S-SA [77]. Addressing them requires the creation of a robust institutional

and policymaking environment attractive to private sector involvement in projects of strategic importance, especially in agribusiness, transport infrastructure, and manufacturing [58, 77, 86].

Digital twins can significantly enhance policymaking and decision-making in Ghana by providing detailed real-time simulations and data analysis of a wide range of scenarios, including monitoring financial management to ensure consistency across all layers of government, tracking subsidies, and fostering greater community participation in governance. Ideally, the digital twin representations should align with the regional, district, and local geographic delineations so that policy and other initiatives can be accurately monitored and reported, including progress toward SDGs and to inform international aid agencies and other stakeholders. Ghana has implemented several initiatives to address poverty alleviation. These initiatives include the livelihood empowerment against poverty (LEAP) program, a national health insurance scheme, free compulsory universal basic education, free senior high school, and the youth employment agency [66]. Economic initiatives include a private sector-led initiative with government support to promote industrialization and economic benefits at the district level, building dams in each district, subsidized seeds, fertilizers, and technical support, cultivation of export crops such as cashew, coffee, and coconut, and a national climate change policy to address building resilience in vulnerable communities and promoting sustainable development [66].

Digital twins can help Ghana improve the efficiency and effectiveness of its poverty alleviation efforts, leading to more sustainable and inclusive development, more transparency, and greater trust in government. However, there are some challenges to the effective use of digital twins, including data privacy and security, the technical expertise required to build and maintain virtual representations, and ongoing data collection.

2.1 Target community

The Tetegu research area is in the Weija Gbawe Municipal District in the Greater Accra Region. Based on the 2021 census data, multidimensional poverty in the Weija Gbawe Municipal District is 8.2% compared with 11.7% for the Greater Accra Region, which includes the Gbawe Municipal region, and 24.3% for Ghana overall [39]. With a lower number indicating less poverty, the Weija Gbawe Municipal District is placed eighth out of 261 districts in Ghana and 6th out of the 21 districts that comprise the Greater Accra Region [39]. The multidimensional poverty incidence is determined by 13 indicators [39]. However, this does not represent the Tetegu research area, which is vulnerable to environmental shocks, limited economic opportunities, and political indifference.

2.1.1 Research community

The research community in this case study included a nominal 150 households plus businesses and community services. It is a persistently poor urban community with entrenched consumer and business practices from decades of subsistence. The community delineation for this and other research studies in Ghana was initially meant to align with the enumeration areas designated for the 2021 Ghana census. However, the Ghana Statistical Service was unresponsive to numerous requests for shapefiles that described the geographic boundaries of the census enumeration areas. The Tetegu population was difficult to estimate because of the likelihood of overcrowding in poorly constructed and maintained buildings. It is a small enclave of the 213,674 Weija Gbawe Municipal Assembly 2021 population [40]. Based on aerial inspection, it was estimated that the portion of the Tetegu township of interest for the proposed research study was about 600–800 people. The subsequent community survey revealed that the population of the designated research area was closer to 1000 inhabitants living in cramped conditions.

The community has no public school, toilets, clinic, or hospital. A hospital was under construction for over 8 years, but the project has since been abandoned. The main occupation is fishing, which has depleted the Densu River of fish. Tetegu faces serious life-threatening issues. The Tetegu research community lies close to a branch of the Densu River. It is an area subject to intentional "spillage-induced flooding" from Lake Weija by the Ghana Water Authority (GWA) to maintain safe water levels in the lake [17]. The GWA will release large quantities of water into the Densu River during heavy rain periods with severe flooding consequences for surrounding communities [17]. These releases result in significant disruption in livelihoods, substantial property loss for the flood victims, and loss of human life [17].

Approximately 90% of the population of Tetegu are Ewe people connected to the main concentration of Ewes in the Volta Region [33] in southeast Ghana. Ewe, Ga, Twi, and English are the main languages in this community, with the majority speaking Ewe and Ga.

2.1.2 Sample size

The initial goal was to sample 50 households and 30% of the businesses. The target statistical process was the difference-in-differences design requiring a treatment and control community. The community survey identified the target households and businesses in each community. However, costs limited the sample size to ten households and ten businesses, and the difference-in-differences approach was deferred to future studies. Households purposively selected to participate in this case study had four or more occupants with heads of households deemed capable of understanding the purpose, scope, and detailed requirements of the data collection process.

2.2 Community engagement and informed consent

The cooperation of low-income communities in comprehensive data collection is essential for thoroughly understanding these communities and implementing sustainable development interventions. The literature on community access and informed consent in Ghana refers to biomedical research in rural communities [13, 20, 44, 73]. Researchers must first gain support from the traditional chief before approaching community members [12]. Respect for traditional practices and cultural values is mandatory [13, 73]. Support from the gatekeepers in these often collectivist communities is required for informed consent from community members. Access to the Tetegu urban community in Accra required a similar approach. Support was first obtained from the assemblyman having jurisdiction over the community. The assemblyman then nominated a well-known person in the community who could speak all languages and communicate the research objectives. Clark [28] reported that individuals may be reluctant to participate in further research because of feelings of exhaustion from being over-researched. Ashley [18] encountered similar reluctance and added that research fatigue can negatively impact participants' wellbeing. Ashley [18] also noted that research fatigue could materially impact research outcomes because of potential selection bias. The households and businesses within the Tetegu research community had previously engaged in multiple research endeavors and many inhabitants displayed considerable reticence in participating in further studies. Furthermore, this case study required long-term participation, and researchers had difficulty gaining enthusiasm for "yet another study."

Bain et al. [21] noted that mistrust of researchers and the nature of the research could influence community engagement. Bain et al. [21] stated that mistrust may stem from previous negative experiences with academic researchers. Bain et al. [21] also noted that the failure of research programs to deliver promises was at the core of resentment, especially toward government research [21]. Language barriers and literacy levels present significant challenges when seeking informed consent from individuals [21]. Individual autonomy may not apply in collectivist societies [13]. In this case study for Tetegu, information statements and consent documentation prepared in English were interpreted by the researchers to obtain consent. However, the barriers of distrust, resentment, and indifference had to be first overcome. Consent was recorded electronically with a purpose-built application on a computer tablet.

Community engagement is crucial for achieving the SDGs to ensure they are tailored to local needs and that all community members have a voice in planning and implementing SDG initiatives. These objectives must be supported by education programs and collaborative forums for all stakeholders. This will contribute to social capital and social innovation and the successful implementation of sustainable development interventions. However, these objectives are likely resource-constrained, and cultural barriers pose challenges to inclusive engagement. Sustainability is a continuum of activities required to maintain a balance between human needs and the preservation of the natural environment [75]. This represents a challenge that can only be met by community-led initiatives with continuous innovation and adaptation. It is an ideal that is obvious but unlikely to be achieved in S-SA without innovations in sustainable development, relevant education programs, focused collaborative public/private sector research, private sector participation, and youth activation and engagement. There are opportunities for large-scale private participation in achieving SDGs in S-SA. However, without fundamental structural changes in governance, trade, currency normalization, institutional strength, and uniform legal frameworks, foreign direct investment will languish largely in the realm of neocolonialist self-interest focused on extractive industries.

The approach in this case study was to engage with a community member who was well-known to the community and could speak all dialects and English. The community member interpreted information statements and consent documentation prepared in English to inform individuals from whom informed consent verbally was being sought. This proved arduous because the barriers of distrust, resentment, and indifference had to be first overcome.

2.3 Data collection methodology

All data was collected with electronic forms designed for this study and shown in pseudo format in Appendix A. Several commercial applications, such as Google Forms, KoboToolbox, FastField, Fluix, Ninja, Gravity, WPForms, and JotForm were considered for data collection. These applications are either cloud-based, like Google Forms and Jotform, or embedded in a purpose-built website, like Ninja and WPForms. Each had a user-friendly form-builder and conditional logic capabilities, but it was decided to use a cloud-based platform because they are a managed service with data backup, multiple data download options, privacy compliance, security, and other features that would be time-consuming to implement on a purpose-built platform. Jotform was chosen because it offered an extensive library of templates and widgets (geolocation, data tables, and survey forms) [52]. Jotform has a simple implementation of forms apps (iPhone and Android), easily deployable to field researchers using a quick response (QR) code. Other cloud-based services may be just as good or better, but they were not extensively researched.

The field researcher used a combination of an iPhone and a Samsung A8 computer tablet. All self-reporting entities were issued with Samsung A9 computer tablets with the relevant application(s) (app) installed. All form data, including streamed videos and images, were automatically uploaded to Jotform, when Internet access was available, where the submissions were collated, tabulated, and made available for downloading in various formats. Data tables were downloaded from Jotform to a local server, where data cleansing was performed manually and with software tools to detect anomalies such as outliers, repeats, spelling errors, and miscoding errors. The cleansed files were analyzed using Excel to derive descriptive statistics and visualizations presented in this case study. They were also uploaded to Amazon Web Services [8] for more intensive analysis using programmatic techniques developed for this case study. A Phantom 4 Pro V2 unmanned aerial vehicle was used for aerial surveys. The aerial surveys were used to develop a 3D image and to precisely geolocate all structures of the Tetegu research area. The fixed image and full-motion video from aerial and terrestrial surveys represent a visual snapshot in time of the Tetegu research area for future analysis and for comparison with future surveys to monitor the progression of sustainable development initiatives.

The quality of Internet access in S-SA can be highly variable, and while Jotform can operate offline, it cannot upload streaming data without access to the Internet. This is a problem when capturing videos of the environment, interviews, and automated data streams. The future availability of high-speed satellite Internet services may obviate this problem.

Data self-reporting is subject to deliberate or mistaken data entry errors. There is no single measure that can be employed to maintain accurate self-reporting. In this case study, several methods were employed, including pre-study training, careful design of the self-reporting app to ensure data types and ranges of data were kept within defined bounds, and cross-checking transactions recorded on the app with the telecommunications company records for mobile money date stamps and transaction values. The app was designed to simplify field entries with dropdown lists and multiple and single-choice selection buttons. Additional methods included regular reviews of data entries to observe outliers, patterns, and trends. This process was manual, but future studies will trial AI techniques to monitor transactional behavior. Additional cyber security measures will be implemented.

2.4 Virtual representations

There are two contributions to the creation of the virtual representation or digital twin of the Tetegu community.

- Physical and Environmental—is the physical or built environment of businesses, homes, recreation, social, cultural, public amenities, schools, clinics, and supporting infrastructure including roads, electricity supply, water, telecommunications, and transport. Environmental issues include vulnerability to climate change, flooding, desertification, air quality, groundwater pollution, and other features.
- Social and Economic—the income-earning activities of the human inhabitants, demographic profiles, social engagement, and cultural activities.

The following describes the actions taken to obtain information about the Tetegu community to create a virtual representation of that community.

Fig. 3 3D Image of Tetegu. Attribution: Authors

Fig. 4 Sample Images of Built Structures and Surrounds. Attribution: Authors

2.5 Physical and environmental entity

The physical and environmental representation of the Tetegu community was captured using a combination of low-altitude aerial surveys and terrestrial surveys as per Table A2, Appendix A:

- Aerial surveys—aerial images of Tetegu were taken using a low-altitude unmanned aerial vehicle. These images were combined with terrestrial data using photogrammetric techniques to create a 3D digital twin of the built environment, Fig. 3. The aerial images were overlaid onto Google maps to update geo-locations of the built environment of the Tetegu community.
- Terrestrial survey—a walk-through of the Tetegu community identified the purpose and geolocations of each building and the number of human occupants in each residence. Images, including full-motion video, were captured and uploaded to cloud storage, Fig. 4. The aerial map was updated to record the purpose and geolocations of structures within the boundaries of the research study, Fig. 5.

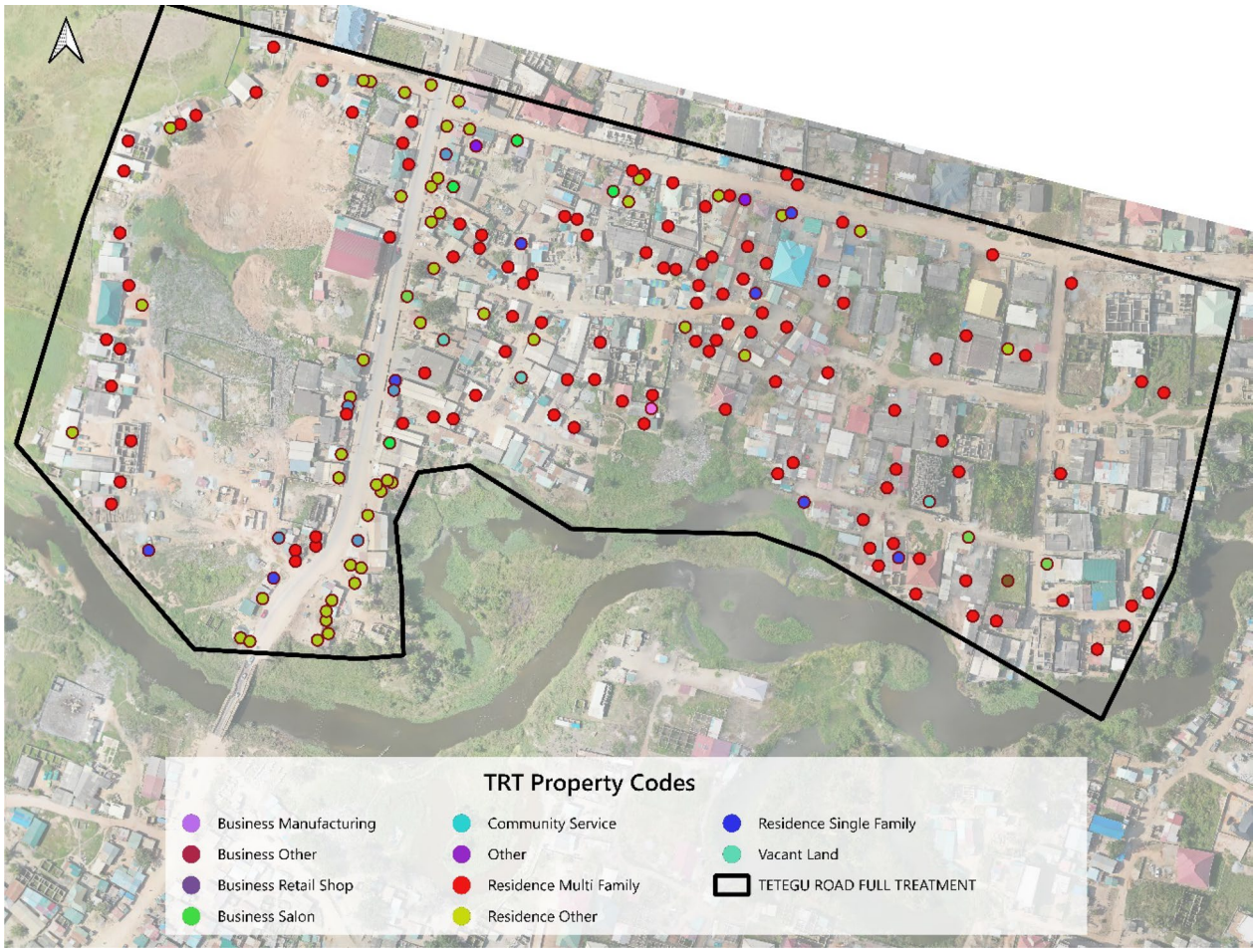


Fig. 5 Aerial Mapping of Tetegu Structures. Attribution: Authors

Referring to Figs. B1 and B2 of Appendix B, of the 207 structures identified in the terrestrial survey and mapped in Fig. 5:

- 139 were family residences comprised of 129 multi-family homes, 9 single-family homes, and one other residence.
- 61 were businesses, of which 47 were small retail operations selling various foods and drinks, 10 were small retailers of clothing and footwear, 5 were hair and beauty salons, 4 were building materials and construction businesses, and 2 were vehicle repairs and servicing businesses. 18 other buildings were identified as having a business function but could not be classified. They may have been storage units or serve some other ancillary purpose.
- 3 community service buildings, including 2 religious and one building of unidentified use.
- 3 other buildings were of unidentifiable use, and there was one lot of vacant land.
- The total human occupants of 139 residents were 1,079 people averaging 7.76 people per residence. However, as Figure B1 illustrates, the range of occupants was from a minimum of 1 person to a maximum of 21 people in a residence. Using the Ghana Statistical Service Census 2021 results [40] as a guide, at least 35% of the Tetegu surveyed population of 1079 people were children under the age of 14 years. It is estimated that there are 377 children in Tetegu. There is no school, health care clinic, or public toilets. Residents practiced open defecation, and the community was littered with decomposing trash. The community is subject to spillage-induced flooding by the Ghana Water Authority from Lake Weija [17]. Large stagnant pools of water in the community are breeding grounds for mosquitos, elevating the spread of malaria [31].

2.6 Social and economic entity

For the social and economic representation, a sample of 12 businesses from the population of 61 identified businesses and 10 households from the population of 139 households were selected to provide basic information on business activities and household demographics, economic status, and other metrics, respectively. Information was obtained from online surveys as detailed in Appendix A and summarized below. The information solicited from business owners included:

- Consent—identification of the business owner, education level, agreement to participate in the research study, and consent to use information, Table A1.
- Economic—business incomes and expenses with several questions relating to electronic payments, Table A3 and Table A4.
- Supporting infrastructure – transport and perceptions of public infrastructure, including water, electricity, and telecommunications, Table A4.

The information solicited from heads of households included:

- Consent—identification of the head of the household, education level, agreement to participate in the research study, and consent to use information, Table A1.
- Economic—household income and expenses, sources of income, and breakdown of the use of e-commerce for receipts and payments, Table A5.
- Demographics—age and gender profiles of each household, children by gender attending school, and school attendance, Table A6.
- Household assets—including home ownership and transportation, Table A7.
- Social—types of social engagement and use of smartphones with social media applications, Table A7.
- Supporting Infrastructure—perceptions of the quality of public infrastructure for health, education, electricity, and telecommunications, Table A7.

The following focuses exclusively on the economic conditions of businesses and households in Tetegu to illustrate the concepts of virtual constructs. The appearance of mobile money payments in the results is a marker of e-commerce activity. Figure C1 of Appendix C summarizes key economic metrics from the business surveys:

- The average monthly income in Ghana Cedis (GHS) for the sample of 12 businesses was GHS5,292 (USD392), with approximately 20% of the income received through mobile money.
- Average monthly expenses were approximately GHS2,082 (USD154), with an average of 26% paid using mobile money, mainly in the services sector, including construction, repairs, and other services.

Figure C2 of Appendix C summarizes key economic metrics from the household surveys. Household surveys were not conducted contemporaneously with the business surveys and were for a much shorter period:

- Household incomes averaged approximately GHS150 (USD11) per day, with only about 1% received through mobile money payments. The household surveys solicited disclosure on the sources of income, including full or part-time employment, commissions from the sale of goods (street sales on behalf of distributors), and remittances from family or friends overseas. Most income was derived from commissions or from the sale of goods and services.
- However, with an average daily expenditure of GHS132 (USD10) approximately 16% of this was paid using mobile money. Some expenses, such as mobile phone airtime top-ups and electricity, were reported to being paid by mobile money. Also, several households operated as small retailers and the purchase of goods for resale was occasionally paid for by mobile money.
- Average household occupancy in the household survey was 4 persons resulting in approximately GHS37.50 (USD2.75) income per day per person. This is marginally above the poverty line of USD2.15 as defined by the World Bank [85].

2.7 Limitations of the virtual representation

The virtual representation provides a reasonable assessment of the economic status of the Tetegu community. Aerial and terrestrial images and videos of the community convey strong qualitative impressions of the human habitat. The next stage of the evolution of this research is to bring together the large database of fixed images and videos of the community from both aerial and terrestrial perspectives to provide a compellingly concise 3D view of the community. While the physical representation was processed with 3D photogrammetric techniques, the views of the community are primarily 2D. 3D representations of virtual interventions and their aggregating effects in the broader community are required. The virtual representation reports what is observable at the physical, social, economic, and environmental levels. The missing features include topological data, propensity for flooding or desertification, air quality, crime rates, birth rates, climate type and vulnerability to climate change, and societal context (cultural, safety, disease, political, and external threats).

Topological data would provide information related to transportation and access issues, including emergency services, flood risk assessment, urban planning challenges, and the provision of essential services (water, sewerage, and electricity) [72]. Tetegu is subject to regular spillage-induced flooding from Lake Weija, which has a devastating impact on the safety and livelihoods of the population [17]. In this instance, topological data would help engineers and policymakers decide on appropriate mitigation measures. Urban low-income settlements often occupy land that is not desirable for redevelopment due to proximity to polluting industrial activities, municipal waste landfills, and polluted groundwater [9, 72]. Disputes over land ownership and the rights of persons undertaking construction are common [70]. This case study observed cultural issues, including language, traditional practices, and cultural values, and a tentative assessment was included in the model for social wellbeing. However, the methods for inclusion in the virtual representation and visualization of their importance are part of future research. Birth rates, health, safety, and vulnerability to terrorism, disease, and other threats were not thoroughly investigated. Detailed knowledge of these issues will enhance the fitness-for-purpose of the virtual representation of the target community and contribute to policy and investment decisions.

Further, non-observed features such as the availability and quality of water, electricity, telecommunications, waste management, sanitation, health, education, and other public infrastructure were not addressed in sufficient detail. This case study did obtain high-level perceptions from the community on these issues. However, more detailed investigations are needed to determine how services are provided and how they are accessed. For instance, is water delivered to a community access point or directly to homes, and how is it metered? The same applies to electricity. What waste management processes are in place, and how are they managed? It was observed from the community survey for this study that community services for health clinics, schools, and public toilets did not exist. Roads were not made and maintained, stagnant ponds were not filled or treated to stop the spread of disease, and household waste littered the community. It was initially expected that the Ghana Statistical Service would provide information on many of these issues from the 2021 census. However, despite numerous formal and informal requests, they remained steadfastly unresponsive. The framework created for the visual representation allows for a return to the field or to access other datasets that could materially improve the fidelity of the virtual representation.

3 Sustainable development intervention

A small-scale e-commerce intervention was conducted in two businesses selected from the results of the virtual representation of the Tetegu community. There were two phases to this intervention study. The first phase was a virtual intervention in which the e-commerce intervention was applied to the virtual representations of the businesses and some rudimentary assumptions were made on how this may realize benefits to the businesses. The second phase was the actual implementation of the intervention in each of the businesses and data was collected for each business to determine how well the virtual intervention was able to demonstrate the effectiveness of the intervention. To enhance conclusions about the causal effect, if any, data from two control businesses in similar business sectors were collected. The following describes the scope of the e-commerce intervention, the outcomes of the virtual intervention, and the results of the performance of each business after receiving the intervention. The limitations and implications for possible future research directions then follows.

3.1 Defining E-commerce

E-commerce may be defined as the electronic transfers that occur for the exchange of value such as the payments for goods and services received [46]. This definition implies the presence of supporting infrastructure including working capital, logistics, Internet access, an online storefront, social media for promotion of the business, and technological knowledge. This infrastructure is unlikely to exist in low-income communities in S-SA. A more realistic package for an e-commerce intervention for small business adaptation comprises a small amount of working capital, a computer tablet with basic business functionality installed, a data bundle for Internet access, and training.

3.2 Virtual E-commerce intervention

Data was collected from 12 businesses that consented to participate in the e-commerce study for approximately 6 months prior to the implementation of the e-commerce intervention. Two treatment businesses were chosen based on their approach, commitment to the study, and reliability in providing daily data during the pre-intervention study. Also, the two businesses needed to be important service providers to the community. Business A was a retail business operating as a cold store selling frozen food items and cold beverages within the Tetegu community. Business B was a retail operation selling cosmetics, toiletries, hair styling, and other personal grooming products within the Tetegu community. The virtual representations of these businesses shown in Figure D1 and Figure D2 of Appendix D provide insights to the pre-intervention business models for each business.

3.2.1 Virtual intervention design parameters

To determine the likelihood of any effect on these businesses by the e-commerce intervention the following factors were considered:

- Digital divide—is a combination of several factors. Reliable access to the Internet is a commonly known issue in low-income communities in S-SA [42]. However, the digital divide also extends to Internet-edge devices, including smartphones, computer tablets, and other mobility devices. These devices are expensive. Further, there are costs for internet access and the use of mobile money services. These costs include the purchase of data bundles and fees associated with handling mobile money transactions by the telecommunications provider. These equipment costs and service fees effectively eliminate most people in poverty from participating in the online economy [6].
- Knowledge divide—is probably the most critical issue for people in poverty. A considerable knowledge gap renders the worldwide web inaccessible to most poor people [41]. This can be partially overcome with community-based role models, practical workshops, and mentoring.
- Working capital—micro to small businesses in low-income regions have limited access to finance [68].
- Mobile money—is a service from major telecommunications companies to facilitate the interchange of small amounts at low cost. Subscribers with a phone are automatically registered to receive and make payments. However, it requires a phone, the purchase of an allocation of data from a telecommunications provider, and reliable access to the Internet via the telecommunications provider. Merchant mobile money accounts for businesses attract fees and a long wait time for approval. Merchant accounts are hence not currently viable in the e-commerce intervention package [6].
- Consumer purchasing habits—purchases are typically low-cost items paid for in cash. Consumers are likely to receive income in cash and there is little incentive to "bank" this income in their mobile money accounts just to see a portion of it consumed in service fees.
- Business purchasing habits—purchases are made from various vendors to stock shelves, or to buy materials or components for manufacturing or service provision. This is where the e-commerce intervention may have the most effect. The cash component of the intervention could help improve inventory levels. The mobile money payments could result in lowering the cost of goods sold and greater efficiency in the payment of services such as electricity, water, and rents.

3.2.2 Virtual e-commerce intervention

In consideration of the above factors for Business A and Business B:

- Digital divide—to close the digital divide, each target and control business received computer tablets with business apps installed and funding for Internet access from the telecommunications provider.
- Knowledge divide—the field researcher provided training and mentoring.
- Working capital—each business received GHS3,000 (USD220). It was expected this money would be used to increase inventory levels.
- Mobile money—the target businesses were instructed on how to use mobile money services and to record business transactions on their tablet computers.
- Consumer purchasing habits—were not expected to change under the e-commerce intervention because it was considered too expensive.
- Business purchasing habits—a modest increase in the use of mobile money payments to vendors and service providers of 20% above pre-intervention levels was predicted. No change was expected in sales volume or the total cost of goods.

The following describes the outcomes of the physical e-commerce intervention for each of Business A and Business B.

3.3 Physical E-commerce intervention

For control purposes, Business A was matched with Business A1, a similar retail cold store business, and Business B was matched with Business B1, a similar personal care retail business. Figs. E1 and E2 of Appendix E summarize the income and expense outcomes for each of Business A and Business B, respectively, following the implementation of the e-commerce intervention. Table 1 summarizes the key metrics of sales and expenses for Business A pre- and post-intervention, Business B pre- and post-intervention, Business A1 pre- and post-intervention, and Business B1 pre-and post-intervention. The Table 1 comparison of the pre-and post-intervention performance of Business A, Business A1, and the virtual intervention show:

- Business A sales increased by 4% from pre- to post-intervention. This is consistent with virtual intervention modeling. Business A1 sales increased by 28% from pre- to post-intervention. This could be because of changes in business operating hours or inconsistencies in reporting daily sales.
- Business A sales receipts by mobile money increased significantly from 4 to 41% of average sales. This was not expected in the virtual intervention. Business A1 sales receipts paid by mobile money increased slightly from 2 to 8% of average sales. This is not significant.
- Business A expenses increased by 33% from pre- to post-intervention. This could be explained by increases in stocking levels because of the microloan. Business A1 expenses increased by 23%.

Table 1 Pre- and Post-Intervention Comparisons

Daily Metrics (₵)	Business A	Business A	Business B	Business B	Business A1	Business A1	Business B1	Business B1
	pre	post	pre	post	pre	Post	pre	post
Average Sales	930	980 (4%)	262	435 (66%)	355	457 (28%)	54	226 (420%)
MoMo Receipts	40 (4%)	403 (41%)	9 (3%)	96 (22%)	7 (2%)	36 (8%)	9 (16%)	64 (28%)
Cash Receipts	891 (96%)	577 (59%)	253 (97%)	340 (78%)	348 (98%)	421 (92%)	45 (84%)	162 (72%)
Average Expenses	1011	1,344 (33%)	7	214 (3000%)	528	652 (23%)	17	70 (411%)
MoMo Paid	60 (6%)	1,246 (93%)	0 (0%)	93 (43%)	37 (7%)	188 (29%)	1 (8%)	10 (14%)
Cash Paid	951 (94%)	98 (7%)	7 (100%)	121 (57%)	491 (93%)	464 (71%)	16 (92%)	60 (86%)

₵ means Ghana cedis currency (₵1.00 is approximately USD0.08). MoMo means Mobile Money. Percentages (%) reflect relative changes from pre- to post-intervention sales and expense performance and absolute changes relative to sales and expenses for mobile money and cash payments, e.g., Business A increased sales by 4% post-intervention over pre-intervention sales. Mobile money receipts for Business A increased from 4 to 41%, and cash receipts declined from 96 to 59% of pre- to post-intervention sales, respectively—the same reasoning for expenses. Attribution: Authors.

- Business A expense payments by mobile money increased significantly from 6 to 93% of average expenses. This exceeded expectations in the virtual intervention. Business A1 mobile money payments increased from 7 to 29%. This, too, was not expected.

The Table 1 comparison of the pre-and post-intervention performance of Business B, Business B1, and the virtual intervention show:

- Business B sales increased by 66% from pre- to post-intervention. This was not expected in intervention modeling. Business B1 sales increased by 420% from pre- to post-intervention. This increase was from a small pre-intervention base and was not unexpected.
- Business B sales receipts by mobile money increased significantly from 3 to 22% of average sales This was not expected in the virtual intervention. Business B1 sales receipts paid by mobile money increased from 16 to 28% of average sales.
- Business B expenses increased by 3,000% from pre- to post-intervention. Business B1 expenses increased by 411%. This was not expected.
- Business B expense payments by mobile money increased significantly from 0 to 43% of average expenses. This exceeded expectations in the virtual intervention. Business B1 mobile money payments increased from 8 to 14%. This was not expected.

3.4 Observations

The visual representations of each treatment business indicate increased use of mobile money, but not quite in the manner anticipated from the virtual intervention. The willingness to use mobile money is encouraging and as more research is undertaken business behavior will be better understood. However, there were more surprising outcomes from the intervention:

- Both businesses started to implement better cash management processes of their own volition.
- Both businesses expressed excitement over the benefits of carrying inventory resulting in fewer trips to the market to buy products, more time in their shops, and the ability to meet customer demand. One business owner was excited because she could stock products at a certain price and enjoy more profit as the retail price of the product increased periodically. She exclaimed that it was the first time in her business life that she was able to hold inventory and operate her retail business more efficiently and profitably.
- Both businesses requested faster payback for their microloans. It was a requirement that the microloans be repaid in equal monthly instalments over two years. They both requested a one-year loan period so that they could qualify earlier for additional loans in the future for expansion of their business.
- The guidance of the field researcher was highly valued.

The Business A1 and Business B1 outcomes may be explained, in part, by the effects of the partial implementation of the intervention. Both control businesses received a tablet computer and were also required to electronically report sales and expenses using the business application. This may have prompted or enabled the control businesses to use mobile money more frequently. Future research will introduce more rigor into the data reporting processes. The use of the computer tablet with the business application was highly successful and is encouraging for broader self-reporting in the future, including qualifying households.

The e-commerce outcomes from this study reveal an enthusiastic approach to e-commerce and the development of better business practices. Business owners have become advocates for the adoption of e-commerce, and hence the generalizability of the intervention within the community. This is a significant achievement because it paves the way for broader community participation in the research in readiness for large-scale interventions aimed at enhancing the social wellbeing of the community.

3.5 Limitations of the E-commerce intervention

The e-commerce intervention was a very small-scale approach to test a virtual intervention against an actual physical result. The small number of businesses engaged in the e-commerce intervention and their outcomes may not represent the broader business environment. Further, there may have been some selection bias. However, this study was primarily

focused on the mechanics of the application of the digital twins, the supporting technologies, and the level of community participation rather than on the actual outcomes of the intervention. The intervention was internal to the Tetegu community and did not attract external revenues to the community or have the effect of creating more diverse economic opportunities within the community, such as job creation. The encouraging outcomes represented a step towards more comprehensive engagement in the online economy. A substantial intervention that draws on community resources to support a commercial initiative with local, regional, and national sales could transform the community. This requires a significant investment and is the subject of future research. No assumptions can be drawn from the outcomes of this study in other communities.

4 Social wellbeing

The conceptual construct of a social wellbeing index introduced by Cordes and Morrison [30] was further developed for this case study to generate a viable reference model for sustainable interventions and the study of social wellbeing. Table 2 contains a mixture of qualitative and quantitative assessments of the built environment, including aerial and terrestrial views, perceptions of public infrastructure from a sample of businesses and households, business and household social and economic data, and other data.

Table 2 Measure of Social Wellbeing Index

#	Dimensions	Category	Primary Sources of Data and Measurement Metrics				
1	Public		Community Survey: Business and Household Surveys				
		Roads	Paved	Maintained	Street lighting	Signage	Accessible
		Telecommunication	Provider	Coverage	Reliable	Performance	Affordable
		Water supply	Source	Quality	Delivery	Sustainable	Affordable
		Electricity supply	Source	Reliable	Delivery	Accessible	Affordable
		Public transport	Road	Rail	Air	Sea	Affordable
2	Social		Community Survey				
		Education	Levels	Transport	Equality	Incentives	Affordable
		Health	Clinics	Hospital	Insurance	Information	Affordable
		Socializing	Outdoor space	Indoor space	Social media	Travel	Mental health
		Recreational	Sport	Leisure	Playgrounds	Youth Programs	Funding
		Cultural and religious	Cultural	Religious	Communication	Aid programs	Libraries
3	Environment		Community Survey				
		Sanitation	Toilets	Maintained	Waste handling	Education	Funding
		Waste management	Collection	Recycling	Pollution control	Information	Funding
		Flooding/desertification	Risk level	Mitigation	Adaptation	Response	Recovery
		Climate change	Risk level	Mitigation	Adaptation	Response	Recovery
		Weather monitoring	Providers	Data types	Analysis	Utilization	Risk assessment
4	Economic		Business and Household Surveys				
		Employment	Jobs	Skills Training	Equality	Technology	Incentives
		Household	Income	Source	Assets	Sources of food	Loans
		Business	Income	Sector	Assets	Markets	Loans
		Production capacity	Scalability	Labor	Technology	Marketing	Subsidies/grants
		Logistics support	Market access	Transport modes	Warehousing	Technology	Subsidies/grants
5	Social Capital		Informed Consent Interviews and Data				
		Societal structure	Networks	Leadership	Political	Collaboration	Advocacy
		Cultural values	Language	Religion	Origins	Family	Community
		Social relationships	Trust	Reciprocity	Social norms	Collaboration	Marriage
		Community engagement	Forums	Consent	Research	Data Collection	Information
		Social innovation	Economic	Environment	Social	Cultural	Funding

Attribution: Adapted from Cordes and Morrison [30]

In Table 2, the five dimensions of social wellbeing are public, social, environment, economic, and social capital are the major markers of social wellbeing. There are five categories within each of these dimensions. Each category is defined by five metrics, each of which may also include sub-metrics. Each metric is a specific data type, including binary, numeric with a range of negative and positive values, text, and image formats. The scale of each dimension is from zero to one (0 – 1), and a perfect score for social wellbeing is five (5) across all dimensions. Hence, each dimension is limited to 20% of the social wellbeing score. The Table 2 framework is comprehensive but does not have to be fully populated to obtain a fitness-for-purpose. Computational techniques can isolate features or categories for focused analysis.

Public infrastructure comprises public sector services, including roads, telecommunications, water supply, electricity, and public transport. Social infrastructure includes education, health, socialization, recreational, cultural, and religious facilities. The environmental dimension addresses sanitation, waste management, potential flooding or desertification risk and mitigation, climate change risk and mitigation, and weather monitoring. The economic condition of the community is expressed in terms of employment and job opportunities for each gender, training to develop skills, technology, and incentives. A thorough understanding of household and business income and wealth accumulation is developed. Production capacity and logistics are important so that small businesses can be scaled to meet market demand and stay competitive. Social capital is defined in multiple ways in the literature [24]. In this case study, social capital comprises societal structures, cultural values, social relationships, community engagement in participatory research, and social innovation that collectively play an important role in community-focused sustainable development initiatives.

Most of the data required for the wellbeing computation is available from the formal and informal surveys of the target community described in this case study. Future studies will expand on the data collection to comprehensively contribute to the Table 2 matrix. The challenge is to develop computational techniques that adequately derive insights into the impact of sustainable interventions on social wellbeing so that reliable comparative studies can be made across multiple domains, spatially and temporally. This is the realm of computational social science and includes data analytics, machine learning, agent-based modeling, and other techniques. For the purposes of this study, a simplified programmatic analysis was implemented with Python coding to test the viability of the proposed model. All data was coded and manually entered in spreadsheet formats with identifying data types. No interrelationship analysis was performed between dimensions.

The assessed score of 0.3/5 is a reasonable measure of wellbeing in the Tetegu community. Future assessments will be made algorithmically using various artificial intelligence and other methods to describe conditions of social wellbeing more consistently over time. Social well-being will be useful as a comparative indicator of the progress toward sustainability and reporting against SDGs.

4.1 Comparative analysis of the social wellbeing index

There are no known similar studies in S-SA that focus on the social wellbeing of low-income communities at this level of granularity and reporting for households and businesses. In this case study, only partial economic data is reported to illustrate the capabilities of a small e-commerce intervention. Figure F1 and Figure F2 of Appendix F illustrate other economic data for businesses and households along with demographic and social data that contribute to the social wellbeing index for the community. While the social wellbeing index in this study is specific for the target community, it can be compared with broader country-wide indices such as the Human Development Index (HDI) [81] and the Multidimensional Poverty Index (MPI) [80]. These comparisons are important for assessing the performance of community sustainable development initiatives against national averages using different dimensions and indicators of performance. Digital twins enable longitudinal studies of social wellbeing and comparisons with HDI, MPI, and other indices over time. The following measures may be useful as benchmark indicators of social wellbeing:

- The Ghana Statistical Service reports are based on census data and household income and expenditure surveys. The Tetegu research area is in the Weija Gbawe Municipal District. Multidimensional poverty, as a composite of 13 indicators, for the Weija Gbawe Municipal District is 8.2% compared with 11.7% for the Greater Accra Region, which includes the Ga South municipal region, and 24.3% for Ghana overall [39].
- The UNDP Human Development Index (HDI) [81] reports a country-level average of three dimensions of human development: life expectancy and health, knowledge, and standard of living. It does not include poverty, inequality, empowerment, or safety indicators.
- The UNDP Multi-level Poverty Indicator (MPI) [80] reports a country-level average of ten indicators of deprivation.

4.2 Tracking movements in social capital

A concise definition of social capital is elusive. Engbers et al. [37] draw upon Woolcock [83], who describes social capital within micro and macro dimensions of "embeddedness and autonomy." At the micro level, social capital refers to the cohesiveness within the community, reflecting the level of embeddedness, or to extra-community networks, reflecting autonomy [37]. At the macro level, social capital refers to community embeddedness with the government, or the institutional capacity of the community, reflecting autonomy [37]. Social capital comprises four categories: social trust, memberships and group activities, altruism, and "informal interactions among individuals" [37]. This framework can be constructed with digital twins and populated with qualitative and quantitative data as it becomes available. Visualizing social capital in economic terms (capital) may be possible if each of the four categories of social capital described by Engbers et al. [37] can be measured systematically and consistently. However, an accurate assessment of social capital may not be achieved unless there is comprehensive community engagement in the data collection process. Community participatory engagement in the data collection process contributes to social capital. Social innovation may also be a marker of the presence of social capital when applied, for example, to community circular economy projects. In this case study, the indicators of social capital in low-income communities are societal structure, cultural values, social relationships, community engagement in research, and social innovation. These indicators can be reported individually using digital twins or as a single economic unit derived from an algorithmic integration of all data types. The advantage of digital twins is that various scenarios can be conceived and tested in virtual space where the scope of the data requirements can be more accurately defined. The essential interactions between the physical and virtual representations of digital twins generate near real-time tracking of social capital movements and how social capital is distributed in communities. This leads to more informed decisions by policymakers when designing social capital interventions.

5 Conclusions

This case study is a tentative step into the data-defining virtual space that offers enticing opportunities to advance sustainable development goals. The virtual representation or digital twin of the real physical and social space enables detailed analyses and forecasts at an unprecedented level. It defines a community with high precision and can respond to data of any type and level of relevance. The virtual representation informs the virtual intervention and potential sustainable development interventions draw upon industry experience to precisely define every aspect of the eventual physical implementation. Virtual aggregation advances studies of decentralization and collaborative initiatives in spatial and temporal domains.

The case study for Tetegu showed that despite initial resistance to more research, strong community support was possible for the surveys and ongoing business monitoring. By first engaging with businesses, business owners became community advocates for the research agenda. Aerial and terrestrial mapping of the physical and social entities was obtained, and the e-commerce trial increased mobile money transactions. Additional spinoff benefits included improvements in business accounting practices, expanded inventories, and accelerated microloan repayments.

This case study is a beginning, but it faces significant confounding challenges from the dynamism of local, regional, and global regimes, markets, climate change effects, political stability, and conflicts. These challenges can be met within a dynamic digital twin framework that captures and processes information to precisely guide real-world instantiations of projects directly addressing sustainable development goals.

5.1 Contributions to theory

This case study is one of ten similar studies of small low-income communities currently being conducted in rural and urban regions of Ghana. The combined body of knowledge will contribute to developing fact-based empirical models to inform potential sustainable development interventions, investment decisions, policy support decisions, and collaborative interactions between communities and other stakeholders. These studies do not make a conscious separation between rural and urban areas. They are communities that face similar social, economic, and environmental challenges to wellbeing. Further, these communities face similar public infrastructure challenges and the way they interact with the environment within which they are embedded. Successful agribusiness innovations in low-income rural communities may influence agribusiness practices in multiple domains. Similarly, successful innovations in low-income urban communities can stimulate and guide redevelopment strategies in cities. The use of digital twins to create virtual representations of

these communities and to then study social, economic, and environmental strategies in virtual space is fundamentally interdisciplinary. They embody technological processes for data collection and processing with advanced AI and other techniques. They provide the necessary linkages between community planning, the design and implementation of community infrastructure to support human activities, and the study of sustainability within natural ecosystems.

This case study contributes to the understanding of a specific low-income urban community in Ghana, West Africa. It introduces a framework within which virtual constructs interact with the physical and social realities of the low-income community to develop a data-driven model for interventions that address poverty alleviation strategies. It draws upon the success of digital virtualizations in manufacturing and aerospace industries and insights from emerging studies in social sciences in urban planning, health care, poverty, smart cities, low-income housing, and other areas [27, 48, 63, 65] to construct a virtual framework that addresses any scale of sustainable development in any environment under any budget. The contribution of this case study and associated case studies may lead to transformational changes in agribusiness and smart city development with decentralization rather than urbanization as a strategy for poverty alleviation [5, 36].

5.2 Future research

Future research will focus on the development of the virtualization phases shown in Fig. 1 and Fig. 2. Research into improved data collection with emphasis on automated reporting, strong community participation, and smart applications will help to improve the fidelity of the virtual processes. Computational tools and techniques to provide greater analytical, predictive, and prescriptive capabilities at each virtualization stage in Fig. 1 need to be researched and developed. The research goal is to transition the Fig. 1 framework into a data-intensive numerical model that can generate highly nuanced insights into local, regional, and national initiatives for sustainable development and poverty alleviation.

5.2.1 Fidelity of future virtual representations

This study is part of a knowledge-building program involving research in multiple rural and urban communities. The fidelity of the virtual representation is determined by data accuracy, resolution, relevance, timeliness, and costs [54, 60]. Data collection techniques involve automated and manual methods. The design of automated techniques and technological platforms can precisely collect and transmit data within specific constraints. For example, weather stations can accurately report temperature, humidity, wind speed, and air quality for a fixed location. Manual techniques are problematic, and steps need to be taken to minimize the potential for deliberate or accidental data entry and to monitor and correct for irregularities.

The integrity of human-entered data can be improved if participants are directly interested in the research and development programs, i.e., the programs contribute to their well-being. Regular reviews, training, and financial incentives may motivate more rigorous attention to data collection. Data accuracy relates to the accuracy of the measuring instrument, human or technological. Both can make mistakes, but human observations are more likely to be variable, especially on matters of judgment. Data resolution refers to sampling rates and is a function of design and the required purpose. For instance, the sampling rate for weather monitoring parameters once per week may miss significant weather events between samples. Data relevance goes to the impact a particular data set may have on the objectives of the model. For example, economic data for salaried employees has little value in modeling incomes in the informal sector. The timeliness of the data is also important. Census data taken every ten years may be useful in reporting and forecasting population growth, housing trends, and migratory trends. However, information related to livelihoods needs to be reported more frequently, especially when monitoring the effects of policy decisions and reporting progress on SDGs.

The structure of the digital twins allows for additional data sets to be included to study different scenarios of SDG interventions. They allow for the virtual modeling of interventions and the subsequent monitoring of the physical intervention. One example might be a study of the impact of free meals on primary school attendance. Another example is the monitoring of households receiving financial support under the Ghana LEAP program. Other examples include studies of the impact of specific stakeholder engagements with aid organizations, collaboration agreements, and private sector investors. However, these initiatives can be challenging because of different data types, ethical concerns, risks arising from more complex data analytics, and reporting requirements [49].

5.2.2 Longitudinal studies

This case study reported on a very simple e-commerce intervention, largely to gauge the degree of community business willingness to engage in the online economy and the barriers to implementation. It was not expected to result in any

significant impact on the economic conditions within the community. The following summarizes future longitudinal studies envisaged for this and other research communities in Ghana:

- Free Community Wi-Fi and Training Center. This facility will provide community members with free Internet access and free training at a purpose-built training facility. The purpose is to facilitate engagement with online services and communities by providing guidance on searching for items of interest, education and development programs, participating in social forums, and entertainment. Data on engagement (login requests), usage (traffic measurements), and attendance at training events will populate the virtual representation to help guide decision-making on future strategies to bridge the digital and knowledge divides [59].
- Business E-Commerce. This is an extension of the e-commerce intervention of this case study to all small businesses in the community and to enable mobile money merchant accounts, social media services, and a community e-commerce web portal for the purchase and sale of goods. All businesses will report income and expenses as per the current intervention and other metrics as a prelude to a community-wide intervention to increase sales, provide jobs, attract funding, and engage in markets external to the community. The goal is to engage all businesses in the online economy.
- Household E-Commerce. Like business e-commerce, this endeavor will provide incentives to join the online community and interact with resources and opportunities locally, nationally, and internationally. The goal is to engage each household in the online economy and illuminate the world of possibilities for everyone.
- Major Intervention. This entails implementing a commercial entity that engages in business with community-wide social, economic, and environmental benefits. Prior to implementation, this intervention will be modeled and optimized in virtual space and then continuously monitored to report progress in social wellbeing and SDGs.

Digital twins are anticipated to continuously fulfill design, monitoring, and reporting roles. Data collection and transmission technologies need to be developed to automate the update of the virtual representation.

5.2.3 Modelling and theory

In the absence of focused theoretical models for sustainable development and poverty alleviation, future research aims to develop a data-centric numerical model from which data analytics and AI techniques can draw insights to guide decision-making on sustainable development strategies [61]. However, future research will be sensitive to theories that contribute to a better understanding of the causes of poverty, practical policy frameworks for sustainable development, public and private sector participation, the role of technology, and the importance of traditional practices and cultural values when implementing sustainable development interventions. Future research will investigate the role of digital twins in developing or complementing structural theories aimed at poverty alleviation, as discussed by Bonga [25].

Author contributions D.C. wrote the initial draft, P.S. performed all data collection, and D.M. reviewed the final document. All authors read and approved the final manuscript.

Funding No funding was received for conducting this study.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Code availability The code developed for this case study is not available.

Declarations

Ethics approval and consent to participate. The research study was conducted in accordance with ethics approval HRE-2020–0646 from Curtin University.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

Appendix A

Data collection forms

See Tables 3, 4, 5, 6, 7, 8, 9 here.

Table 3 Consent and Registration

Consent	Details
Consent terms	I have received information regarding this research and have had an opportunity to ask questions. I understand the purpose, extent, and possible risks of my involvement in this project, and I voluntarily consent to take part
	I consent to the use of data I provided before withdrawing from the study
	I consent to the storage and use of my information in future ethically approved research projects
	I consent to being contacted about future research projects that are related to this project
	I consent to being photographed
	I consent to being video recorded
	I consent to being audio-recorded
Registration	
Name, contact details, and identification	Includes name, gender, date of birth, physical address, digital address, phone number, WhatsApp address, email address(es), passport or other government issued identification
Education level	Select from list of levels, e.g., no schooling, some primary schooling, some senior high schooling, high school certificate, vocational training, bachelor, master, or doctorate
Research role	Select from list of roles, e.g., CAPM, research assistant, data collection team member, head of household, business owner, or other
CAP location	Select from list of approved locations
Identification images required	Face and government issued identification

Table 4 Community survey

Aerial Survey	Details
UAV Imaging	Low altitude fly-over of nominal community to provide aerial videos and location mapping
Terrestrial survey	Details
Name of person conducting survey	Select from list of approved and consenting team member for the selected community
Name of the community	Select from list of approved locations
Date	Date of survey
Digital address	If available
Type of building/property	Select from a list of building types, e.g., residence, business, community service, vacant land, or other
Property use	If household—number of household occupants
	If business—select from list of products and services, e.g., arts and crafts, agribusiness, building materials and construction, or other
	If community service—select type from list, e.g., church, mosque, education, school, government office, health, social or leisure, or sport
	If vacant land—estimate of plot size
Images	Images and/or video of location, building and surrounds
Geolocation	Latitude and longitude of location

Table 5 Daily business report

Dailly report	Details
Name of person submitting report	Select from approved list of consenting participants
Due date of report	Select the due date of the report (Monday)
Business name	Enter name of business
Business owner name	Enter name of consenting business owner
Consent	Confirm consent
Phone number of business owner	Enter phone number
Location code	Enter pre-assigned location code for the business
Self-reporting	Select Yes or No
	If No – Query willingness to self-report with Yes/No
Daily Business Income	
Total business income yesterday from all business activities	Enter amount
Sources of business income	Select all from list provided, e.g., agribusiness, child-care, computer, or mobile phone repairs, or other
How much of the total business income received yesterday was received through mobile money or other electronic payment system?	Enter amount
Daily Business Expenses	
Total amount paid out for business expenses yesterday	Enter amount
How much of the total business expenses was paid out yesterday using mobile money or other electronic payment system?	Enter amount
How much was paid out yesterday for mobile phone airtime top-ups?	Enter amount
How much was paid out yesterday for electricity top-ups?	Enter amount
Number of employees	Enter number
How much did you pay employees yesterday?	Enter amount
How much did you pay employees using mobile money or other electronic payment systems yesterday?	Enter amount

Table 6 Weekly business report

Weekly report	Details
Name of person submitting report	Select from approved list of consenting participants
Due date of report	Select the due date of the report (Monday)
Business name	Enter name of business
Business owner name	Enter name of consenting business owner
Consent	Confirm consent
Phone number of business owner	Enter phone number
Location code	Enter pre-assigned location code for the business
Self-reporting	Select Yes or No
	If No – Query willingness to self-report with Yes/No
General Business Questions Weekly	
Type of transport mostly used by your business	Select from provided list, e.g., public/private transport, own bicycle, motorbike, car, or other
Quality and affordability of electricity service	Select from list of provided responses, e.g., very good, good, average, below average, or needs considerable improvement
Quality and affordability of telecommunications services	Select from list of provided responses, e.g., very good, good, average, below average, or needs considerable improvement
Images	Photos and videos of the business, surrounding neighbourhood, and anything else of special interest

Table 7 Household Daily Report

Daily report	Details
Name of person submitting report	Select from approved list of consenting participants
Due date of report	Select the due date of the report (Monday)
Head of household name	Enter name of consenting head of household
Consent	Confirm consent
Phone number of head of household	Enter phone number
Location code	Enter pre-assigned location code for the household
Total Household Income	
Total household income yesterday from fulltime and part time work by all working adults	Enter amount
Type of employment activities of household members	Select all from list provided, e.g., agribusiness, childcare, computer or mobile phone repairs, or other categories
How much of the total household income received yesterday from full or part time employment was through mobile money or other electronic payment system (such as gift card, prepaid debit card, bank transfer, etc.)?	Enter amount
Total household income yesterday from commissions and sales of goods?	Enter amount
Types of activities of household members from which commissions were earned	Select all from list provided, e.g., agribusiness, childcare, computer or mobile phone repairs, or other categories
How much of the total household income received yesterday from commissions and sales was through mobile money or other electronic payment system (such as gift card, prepaid debit card, bank transfer, etc.)?	Enter amount
Total household income yesterday from money borrowed or gifted to the household	Enter amount
How much of the total household income received yesterday from money borrowed or gifted was through mobile money or other electronic payment system (such as gift card, prepaid debit card, or bank transfer)?	Enter amount
Household Expenses	
Total amount paid out for household expenses yesterday	Enter amount
How much of the total household expenses was paid yesterday with mobile money or other electronic payment system?	Enter amount
How much was paid out yesterday for mobile phone airtime top-ups?	Enter amount
How much was paid out yesterday for electricity top-ups?	Enter amount

Table 8 Household Weekly Report

Weekly report	Details
Name of person submitting report	Select from approved list of consenting participants
Due date of report	Select the due date of the report (Monday)
Head of household name	Enter name of consenting head of household
Consent	Confirm consent
Phone number of head of household	Enter phone number
Location code	Enter pre-assigned location code for the household
Household Demographics and Employment Status of Adults	
Total number of people of all ages in the household	Enter number
Total number of males of all ages in household	Enter number
Total number of males older than 18 years in household	Enter number
Total number of males older than 18 years in household who work full or part time last week	Enter number
Total number of females of all ages in your household	Enter number
Total number of females older than 18 years in household	Enter number
Total number of females older than 18 years in household who worked full or part time last week	Enter number
Total number of people (males and females) older than 45 years in household who worked full or part time last week	Enter number
Total number of people (males and females) older than 18 years in household who worked full or part time last week	Enter number
Household Demographics of Children and Schooling	
What is the highest level of schooling that is practically available to the household children?	Select from list provided, e.g., nursery or kindergarten through tertiary
Total number of children less than 18 years of age in the household?	Enter number of children
Total number of boys less than 18 years of age in the household?	Enter number of boys
Total number of boys of school going age in the household?	Enter number of boys
Total number of days boys missed school last week?	Enter number of days
Total number of girls less than 18 years of age in the household?	Enter number of girls
Total number of girls of school going age in the household?	Enter number of girls
Total number of days girls missed school last week?	Enter number of days
General Household Questions	
Sources of household food last week	Select from provided list, e.g., home grown produce, street vendor produce, fast food, large multi-vendor markets, supermarkets, or other sources
Was there sufficient household food last week?	Select Yes or No
Did your household have health insurance coverage last week?	Select Yes or No
How many smartphones are there in the household?	Enter number
Images	Photos and videos of home, surrounding neighbourhood, and anything else of special interest

Table 9 Household Monthly Report

Monthly report	Details
Name of person submitting report	Select from approved list of consenting participants
Due date of report	Select the due date of the report (Monday)
Head of household name	Enter name of consenting head of household
Consent	Confirm consent
Phone number of head of household	Enter phone number
Location code	Enter pre-assigned location code for the household
Type of housing	Select from list provided, i.e., rent, own, or other
Type of transport	Select all that apply from list provided, e.g., public/private transport, own bicycle, motorbike, car, or other
Social engagement	Select all that apply from list provided, e.g., social media, phone, get together in family home, get together outside family home, no social contact, or other
Quality and affordability of education services	Select from list of provided responses, e.g., very good, good, average, below average, or needs considerable improvement
Quality and affordability of health services	Select from list of provided responses, e.g., very good, good, average, below average, or needs considerable improvement
Quality and affordability of electricity service	Select from list of provided responses, e.g., very good, good, average, below average, or needs considerable improvement
Quality and affordability of telecommunication services	Select from list of provided responses, e.g., very good, good, average, below average, or needs considerable improvement
Quality of life wellbeing rating	Out of 10-star rating, e.g., one star is poor, ten stars is great
Images	Photos and videos of home, surrounding neighbourhood, and anything else of special interest

Appendix B

Key metrics of the physical entity

See Figs. 6, 7 here.

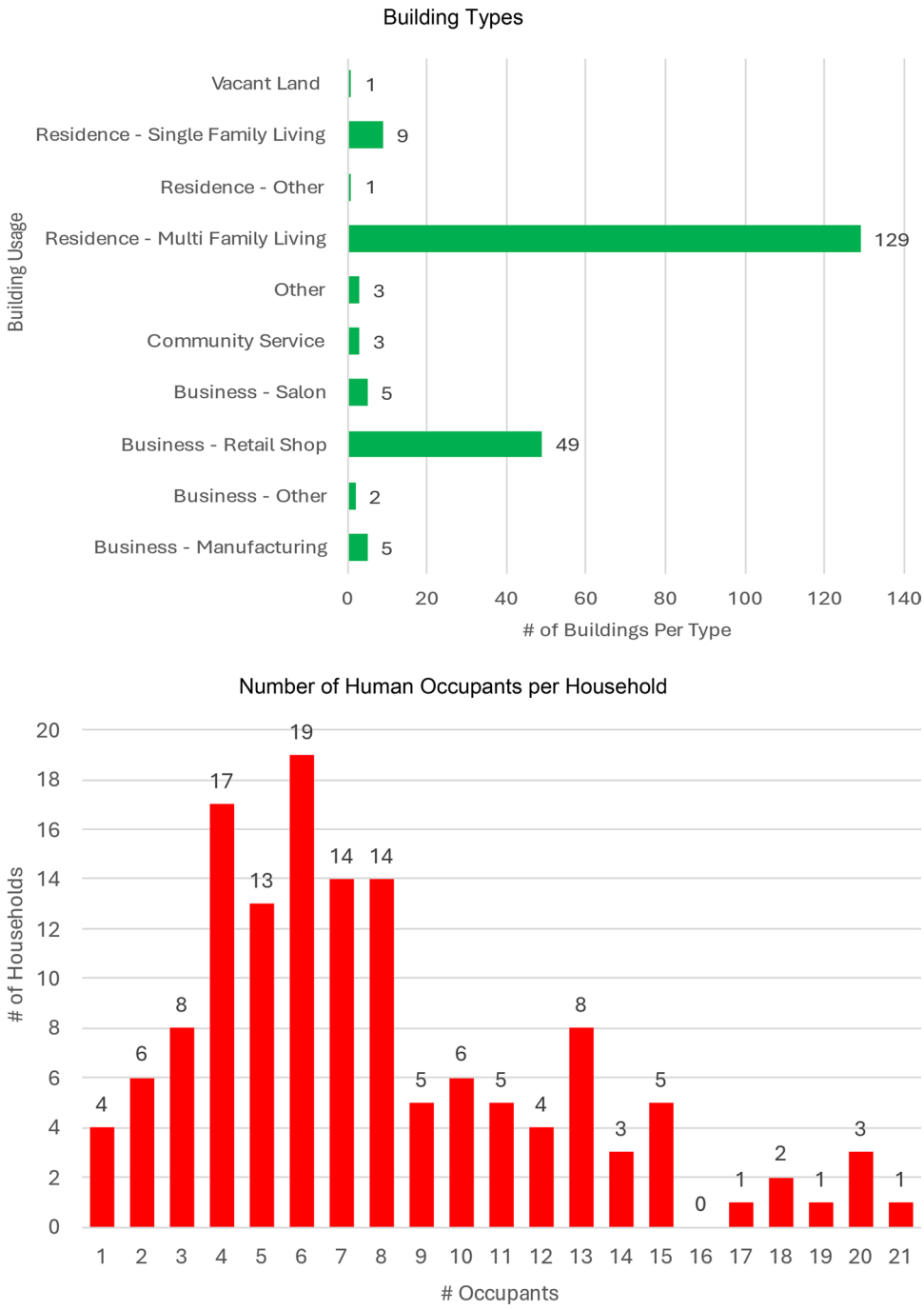


Fig. 6 Key Metrics of the Physical Entity. Attribution: Authors

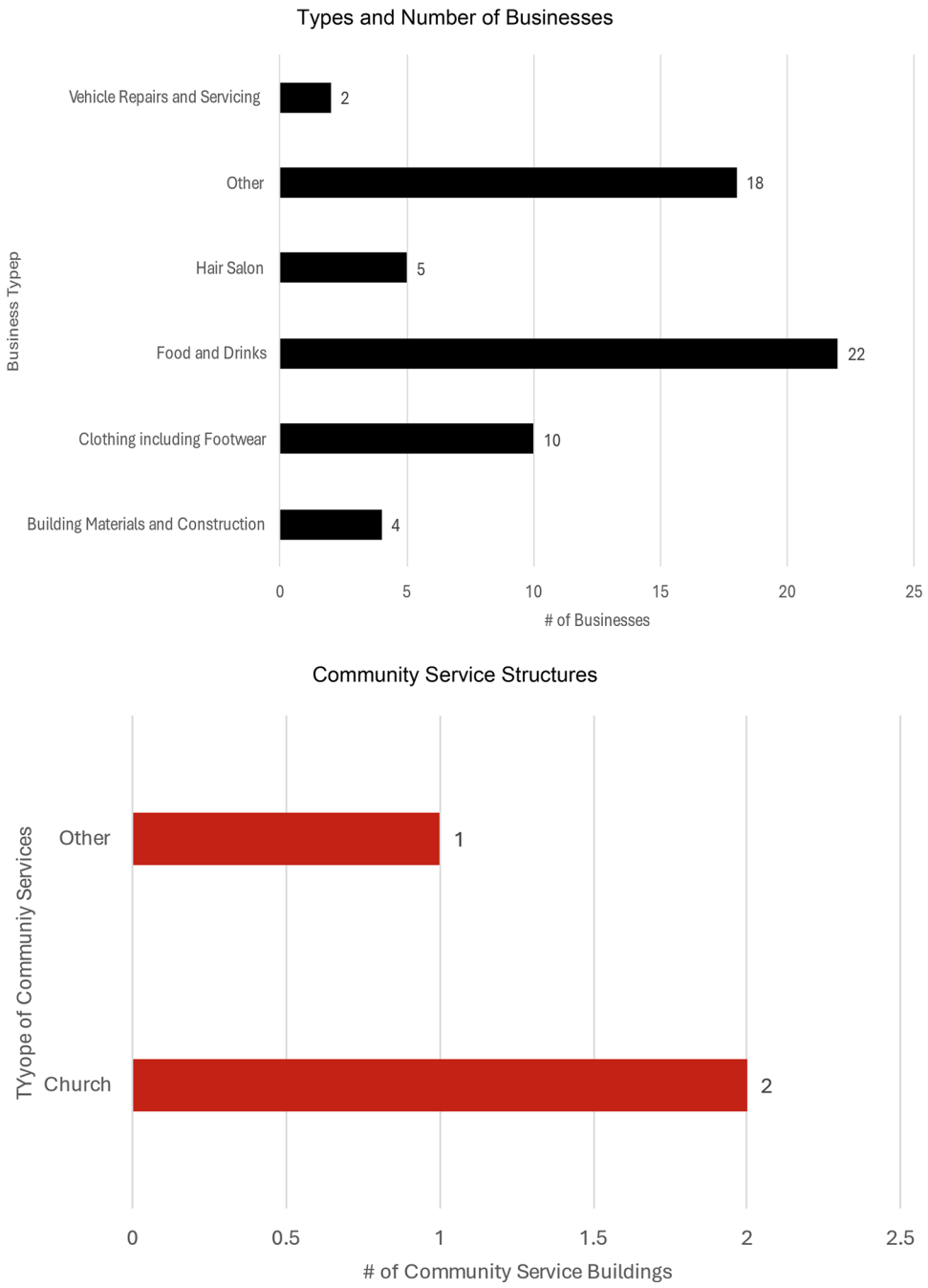


Fig. 7 Key Metrics of the Physical Entity. Attribution: Authors

Appendix C

Key metrics of the social entity

See Figs. 8, 9 here.

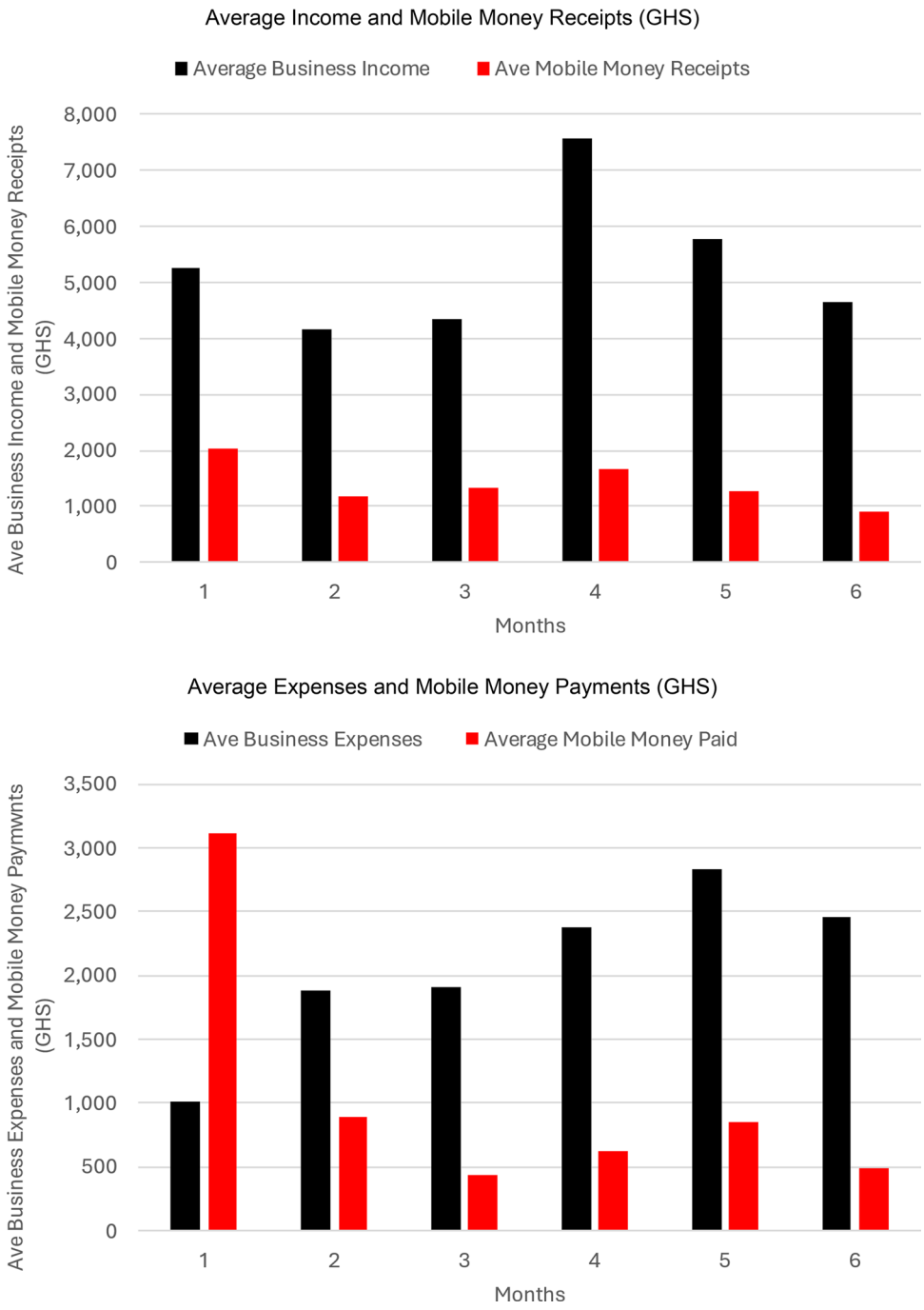


Fig. 8 Average Monthly Business Incomes and Expenditures. Attribution: Authors

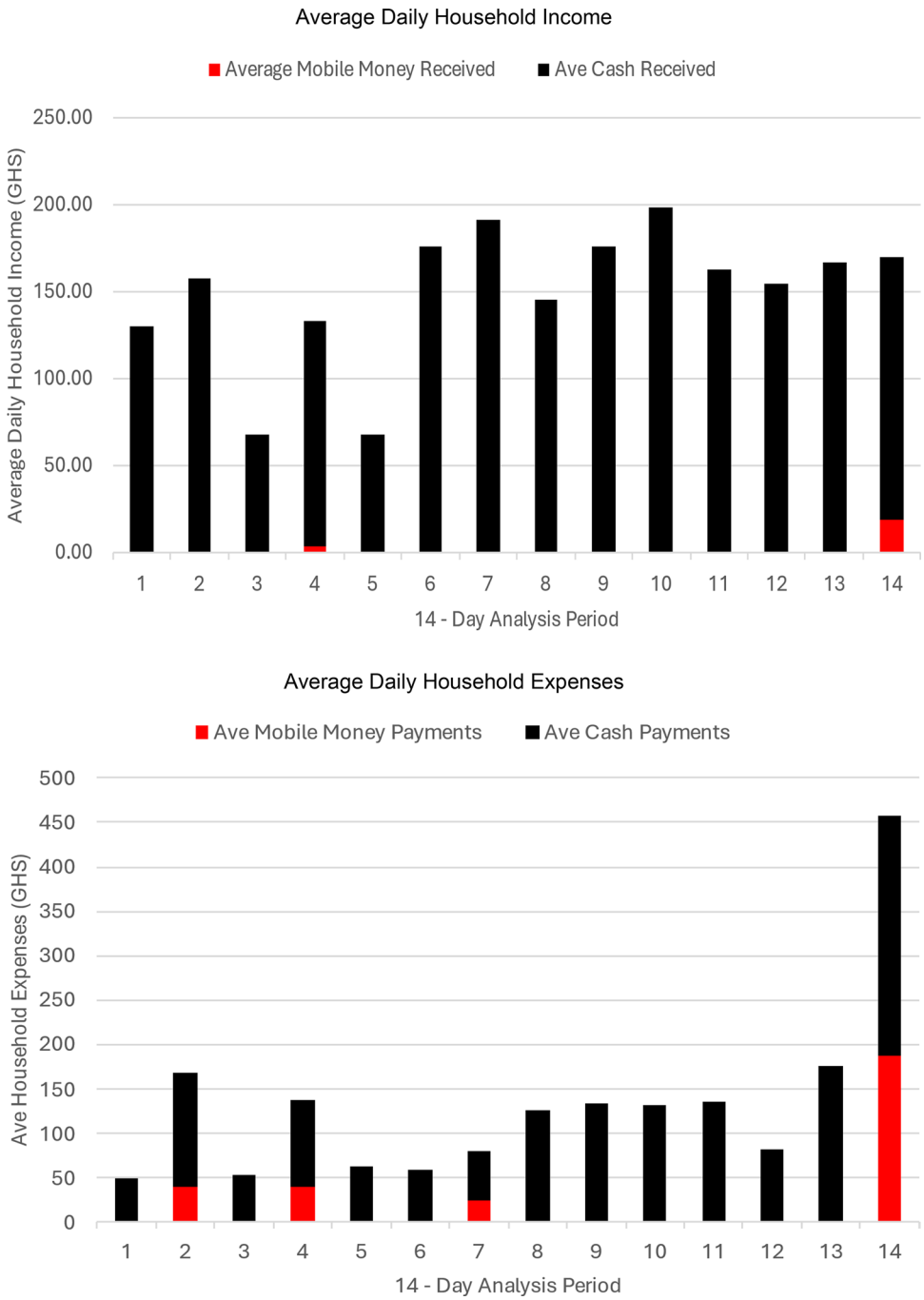


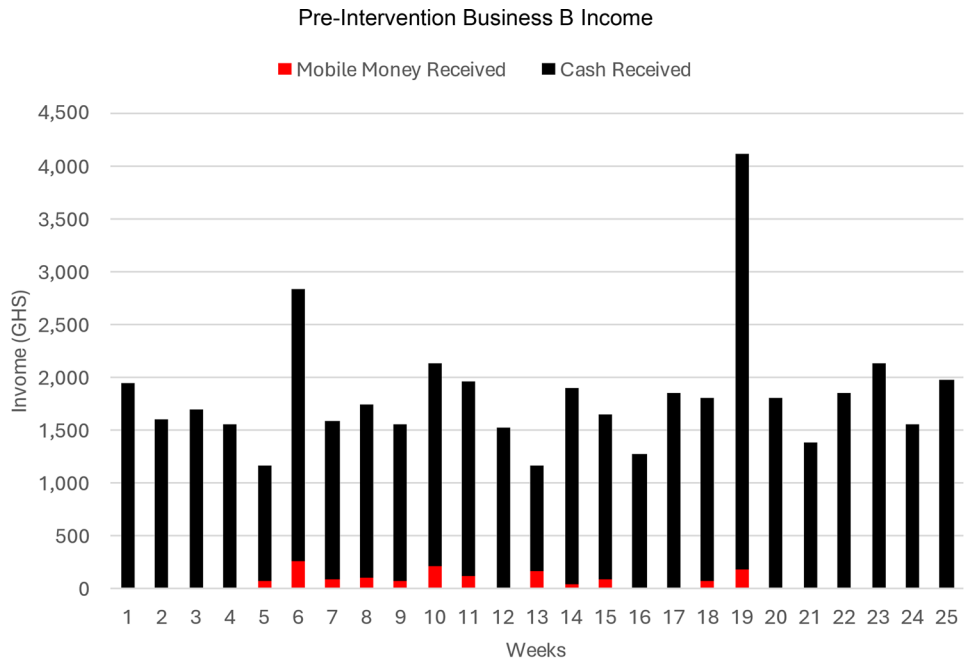
Fig. 9 Average Daily Household Incomes and Expenditures. Attribution: Authors

Appendix D

Pre-Intervention income and expense business A and business B

See Figs. 10, 11 here.

Fig. 10 Pre-Intervention Measured Business A Performance. Attribution: Authors



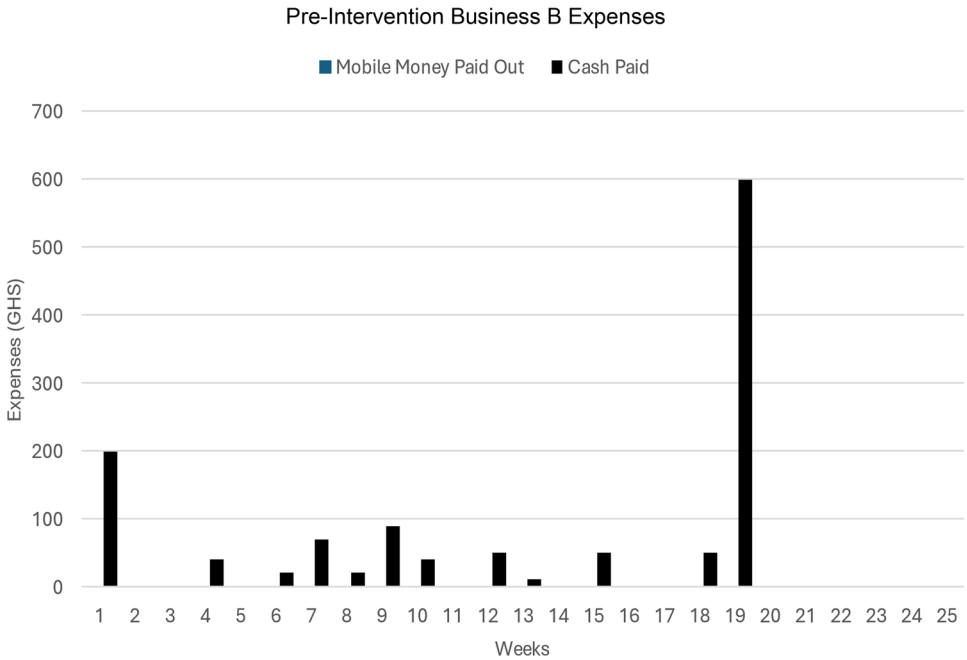
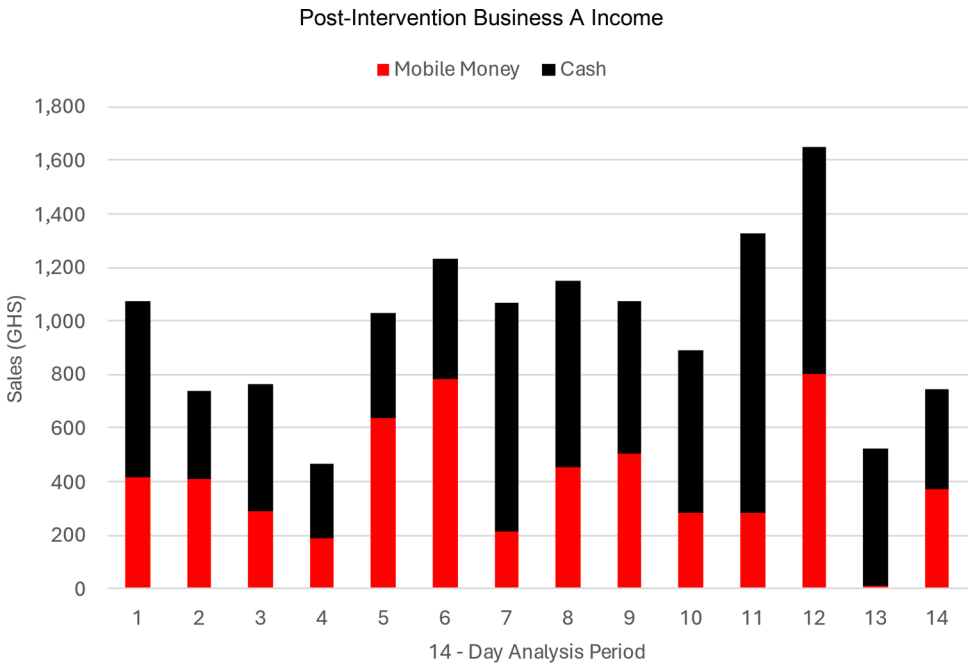


Fig. 11 Pre-Intervention Measured Business B Performance. Attribution: Authors

Appendix E

Post-Intervention income and expenses business A and business B

See Figs. 12, 13 here.



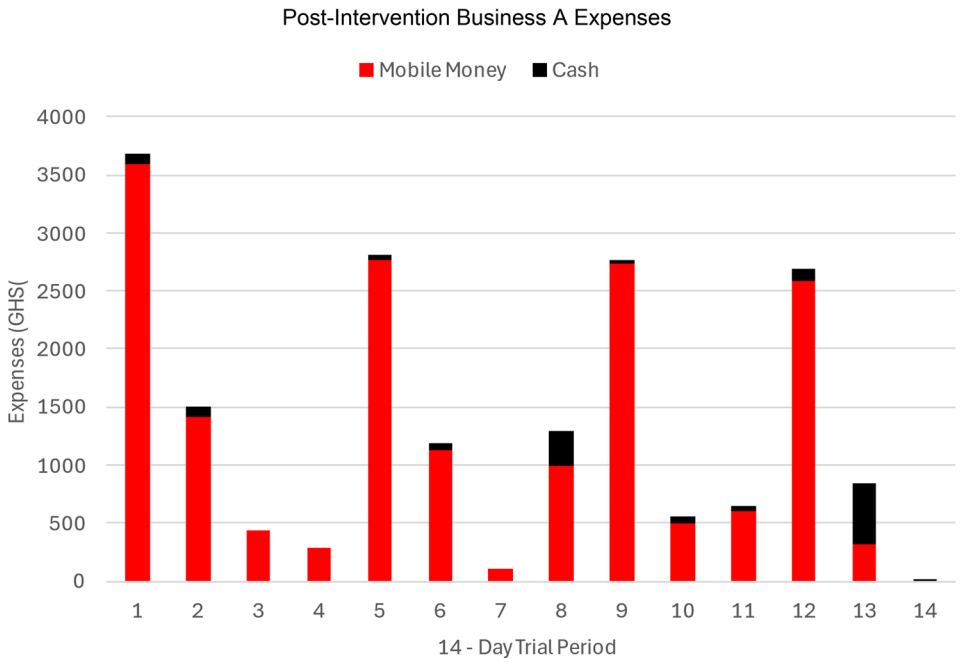


Fig. 12 Post-Intervention Business A Performance. Attribution: Authors

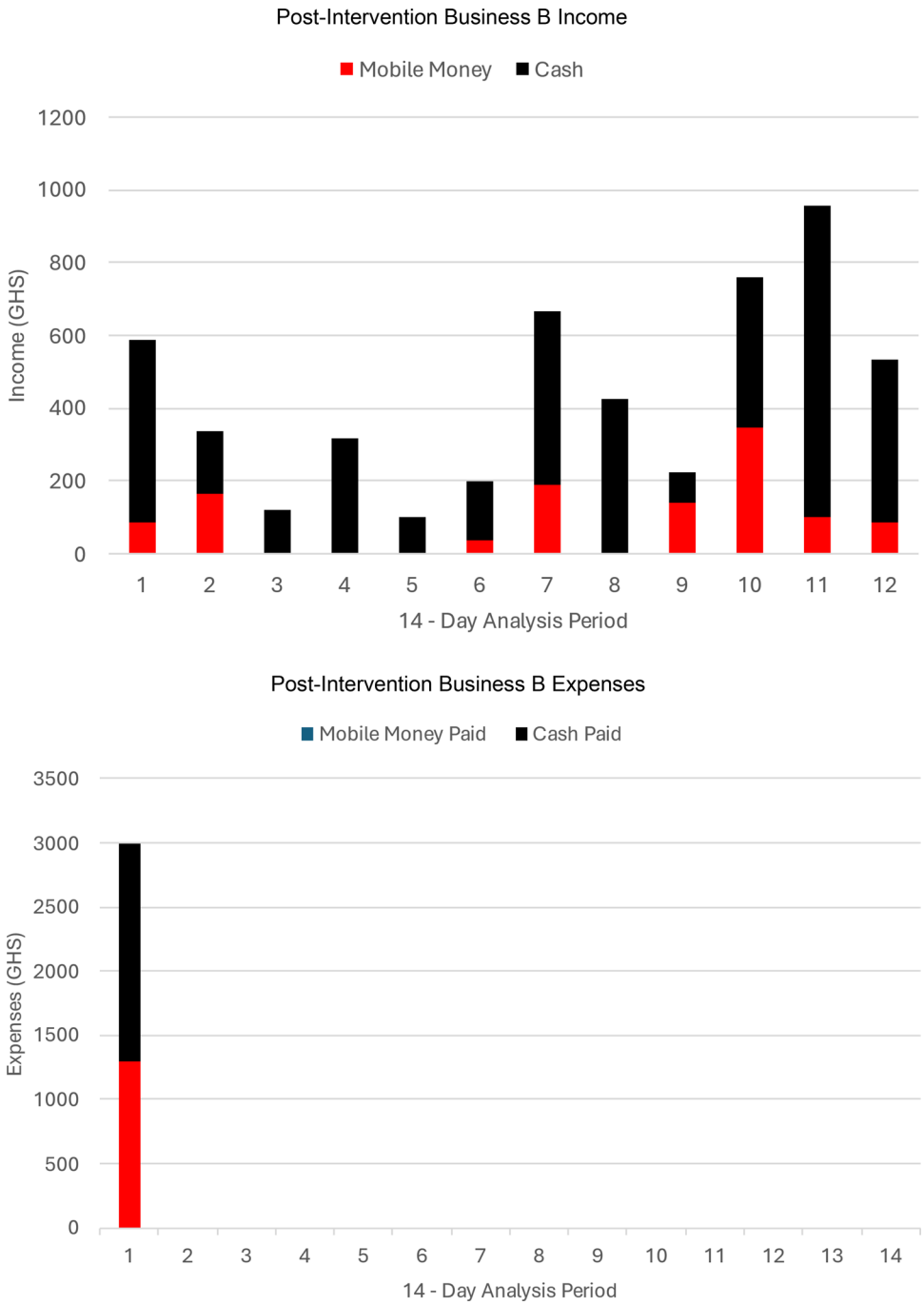


Fig. 13 Post-Intervention Business B Performance. Attribution: Authors

Appendix F

Other metrics

See Figs. 14, 15 here.

Fig. 14 Sample of Household Demographics. Attribution: Authors

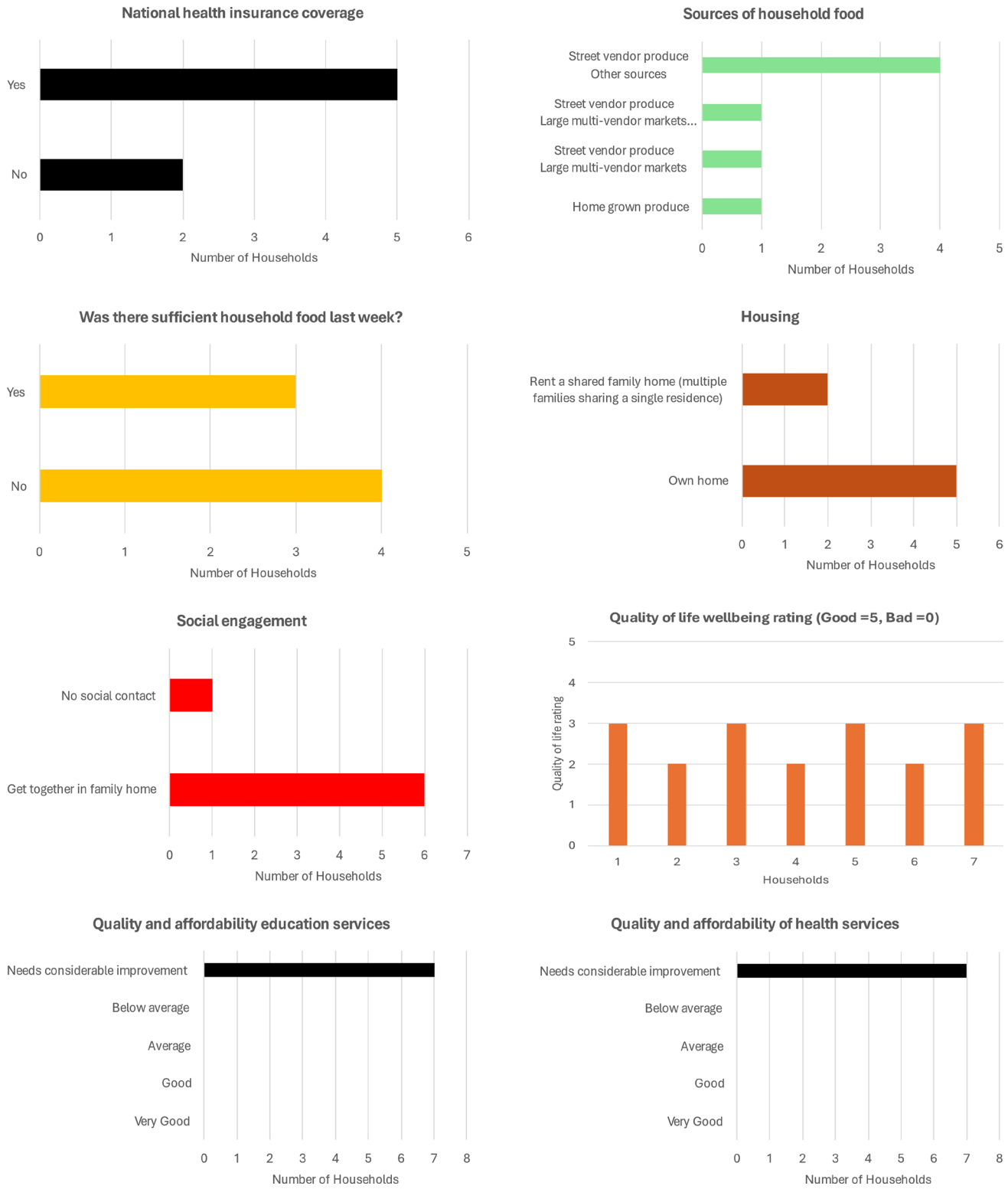


Fig. 15 Sample of Other Household Metrics. Attribution: Authors

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