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INNOVATION IN AFRICAN-AMERICAN HIGH-TECH ENTERPRISES: A MULTI-AGENT MODELING AND SIMULATION APPROACH

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Abstract. African-American-owned high-tech enterprises and innovations are underrepresented in industry in comparison to non-African-American-owned ones. Various complex and intertwined socio-economic factors hinder the innovation capability of African-American-owned high-tech enterprises leading to underrepresentation of these businesses. Understanding the causal relationship between firm's interactions with internal and external entities and its ability to innovate can foster the efforts of a high-tech enterprise in increasing and sustaining innovation capabilities. Agent-based modeling (ABM) emerges as one of the popular approaches to the study of complex socio-technological systems. Characterizing the organizational behavior of African-American-owned high-tech enterprises through the ABM perspective may provide a better understanding of the drivers, processes, and outcomes of this industry segment. By analyzing interview data among African-American entrepreneurs, this study proposes an ABM framework to represent and analyze the innovation capabilities of African-American-owned technology enterprises in comparison to other types of ownership. The ABM model illustrates the key involved agents, their attributes, actions, and the complex interactions amongst them. Simulation results indicate that African American population is underrepresented in the high-tech industry due to two significant factors of social and economic standings implying that the simulation trajectory is in the right direction. Model calibration, verification using real data and implementation plans related to policy development discussions and factors impacting African-American enterprises are also discussed in the study.

Keywords: African-American entrepreneur; agent-based model; high-technology; innovation; NetLogo; entrepreneurship

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1. Introduction

African-American-owned enterprises and innovations are underrepresented in the high-tech industry as compared to their counterparts (Adhikari et al. 2014; DiTomaso and Farris 1992; Liu 2016; Conrad 2006; Gatchair 2013; Marcus). High-tech enterprises fuel the economy and enable economic growth (Fallah, Partridge, and Rickman 2013; Linden, Dedrick, and Kraemer 2011; Mohr, Sengupta, and Slater 2009). However, there is a lack of diversity in the high-tech industry (Commission 2016). The high-tech sector has a disproportionately higher percentage of White enterprise owners; they represented 68.5% of all high-tech enterprises in 2014. Meanwhile, African Americans only accounted for 7.4% comparing to the 14.4% overall private-sector African Americans employment rate. Furthermore, only 2% of the executives and 11% of the technicians were African Americans. Despite the technological advancements over the past decades, the lack of diversity and underrepresentation of African Americans is still apparent in the industry, with no signs of improvement (Foundation 2016; R.W. Fairlie and Chatterji 2013). This lack of representation for African-American high-tech entrepreneurship hinders wealth creation for the African-American community and society overall. It is essential to investigate the reason for the extremely low rate of African-American high-tech entrepreneurship considering its significant influence on the economy and social equality (Bradley 2016). Investigating the causes of the underrepresentation of African-American high-tech enterprises may reveal potential solutions that may enhance their representation in this industry (Simard 2009).

Technological innovation entails recognizing new technological possibilities, organizing the human and financial resources needed to transform ideas into useful products or processes. Technological innovation projects involve uncertainty in decision making and complexity in conjunction with dynamic interactions (Wu et al. 2010; Sie, Bitter-Rijpkema, and Sloep 2011; Van Zee and Spinler 2014; Aparicio, Urbano, and Gómez 2016). The relationship between actors in an innovation system is changing constantly (Junior and Lakemond 2017; Macal and North 2010; Tayaran 2011). The complex nature of the evolving innovation process makes it extremely difficult to study and analyze the problems in innovation through traditional, static statistical approaches (Hekkert et al. 2007).With the progress in computer technology development, modeling and simulation emerge as one of the best ways to solve complex problems (Gilbert and Doran 2018; Gilbert and Troitzsch 2005; Helbing 2012). Models are commonly defined to study and explain observed phenomena or to foresee future phenomena (Abar et al. 2017b). Computer modeling and simulation describes the manipulation of a computational model to increase the analysis of systems' behavior and to evaluate strategies for its functioning in the predictive or descriptive modes. An advantage of computer simulation is that it allows the system to be broken down into parts, making the study of system behavior possible (Brodsky and Tokarev 2009). The theory or model becomes more verifiable because an executed computer program can quickly identify problems, inconsistencies, and the incompleteness of the theory or model. Simulations also permit the discovery of new predictions that can be derived from theory and support the search for new empirical data to verify these predictions (Cangelosi and Parisi 2002). Computer modeling is widely used in socio-technical model studies. A significant amount of previous work has concentrated on the analyses of risk-based decision making and technological innovation processes (Ma and Nakamori 2005; Wu et al. 2010; Pyka et al. 2007; Korber 2011).

To address the low representation of African-American enterprises (AAEs) in the high-tech industry, evaluate the scenarios that lead to new products, and create entrepreneurial strategies that increase the level of representation, the study focused on the socio-economic aspects of innovation with the representation of the framework. Through qualitative data collection and analysis, the paper conceptualized an agent-based modeling (ABM) framework for the complex African-American innovation system. The proposed framework integrates the well-illustrated knowledge-driven technology innovations and computer modeling and simulation approaches (Pyka, Gilbert, and Ahrweiler 2007; Pyka, Gilbert, and Ahrweiler 2002; Korber 2011). It entails the socio-economic elements that hinder the development of African-American groups through a computer modeling framework, providing a new perspective on race equality in high-tech industries.

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In this regard, the contributions of this study are bifold. Firstly, a thorough analysis of current state of the art of high-tech African-American enterprises is provided. Based on the literature gaps identified as a result of this review, an ABM framework is also developed to construct a detailed model of the business environment of these enterprises. The ABM framework, in addition to providing a holistic view of the high-tech industry also provides a novel systematic approach that would benefit organizations which are underrepresented in highly competitive markets.

The paper is organized as follows. The complexity of technology innovation system, innovation systems, ABM, and socio-economic factors that affect African-American innovation are provided in the following section. The third section details the agents, actions, and decision-making components of an agent-based model while the fourth section illustrates agent interactions and performance measurements. The model's implementation and simulation test are presented in the fifth section, followed by the conclusion and discussion.

2. Literature Review

The literature review of this study addresses the key components of the African-American technical innovation system by detailing studies on technology innovation system theory, computer modeling and simulation technology and the socio-economic factors impacting the African-American entrepreneurship (Fig. **1**). Extensive literature review indicates that there is lack of research addressing African-American owned high-tech entrepreneurship through computer modeling and simulation. This study focuses on the intersection of these three areas to gain insight to prior research and gaps as indicated in (Figure 1).

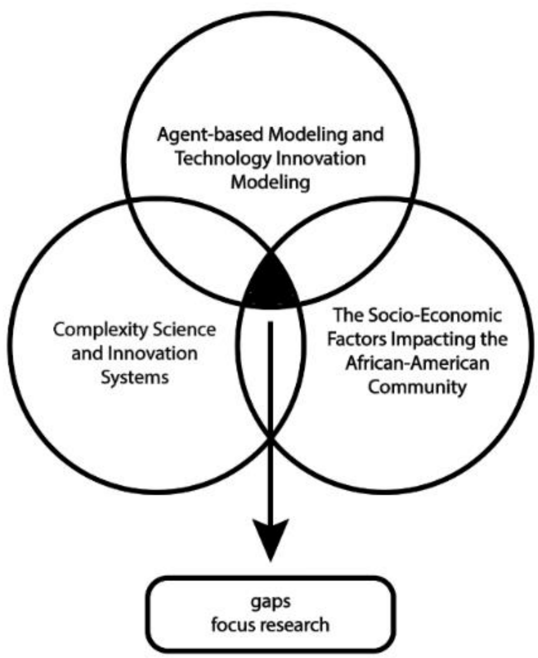

Fig. 1. Scope of literature review. Source: developed by the authors

A. Complexity Science and Innovation Systems

Complexity science is the study of complex systems that consist of several components that interact with each other to produce non-trivial phenomena that cannot be explained by analyzing the individual constituent elements (Holland 2006; N. Johnson 2009; Mitchell 2009). There are two core concepts of almost all areas of complex systems: emergence and self-organization. Emergence and self-organization each highlight the diverse characteristics of a system's behavior. Emergence includes the unexpected behavior that results from interactions among the components of an application in conjunction with the environment (Easterling and Kok 2002; C.W. Johnson 2006; De Wolf and Holvoet 2004). How the order and structures are formed in nature can be easily described by the dynamics and attractors of complex systems (Mainzer 2004). Self-organization is a dynamic and adaptive process by which systems acquire and maintain their structures without external control (De Wolf and Holvoet 2004). The essence of self-organization is adjustable behavior that autonomously acquires and preserves an increased order formed from a disordered system (Ashby 1991; De Wolf and Holvoet 2004).

The innovation process is a complex system (Muller, Héraud, and Zenker 2017; Katz 2016). Like other complex systems, it contains many components with multiple evolving interactions (Zeng et al. 2017). In the global economy, enterprises rarely innovate alone; they usually rely on partners for successful innovation (Muller, Héraud, and Zenker 2017). Enterprises and universities share knowledge and collaborate to improve innovation. Research universities are an invaluable source of intellectual capital for high-tech enterprises (Motohashi 2005; Tether and Tajar 2008). Thus, enterprises collaborate with research universities to enhance their innovative capabilities, leading to new high-tech products and methodologies (Giannopoulou, Barlatier, and Pénin 2019). However, due to the limitation of resources, enterprises must compete with other enterprises for partnerships with research institutes. Innovation enterprises often require support from the government as well to obtain a platform to enhance their technological innovations (Berteau and Swan 2018; Joshi, Inouye, and Robinson 2018; Wallsten 2000). Banks and angel investors also provide funding to many small high-tech entrepreneurs for their enterprises (Shane 2012; Colombo and Grilli 2007).

B. Agent-based Modeling and Technology Innovation Modeling

Agent-based modeling has been identified as one of the best tools to solve complex problems (Gilbert and Doran 2018; Gilbert and Troitzsch 2005; Helbing 2012). It is one of the most popular modeling and simulation tools for analyzing systems with a large number of interacting agents and emergent system properties that cannot be deduced via aggregating methods (Macal and North 2010; Axelrod and Tesfatsion 2006; Wilensky and Rand 2015; North and Macal 2007). Agent-based models comprise of a set of agents characterized by attributes that interact with each other based on a set of rules defined for a given environment. These models can be beneficial for reproducing systems related to social sciences and economics through a network-based design (Barbati, Bruno, and Genovese 2012).

With the fast development of computer technology, researchers have modeled innovation systems using ABMs in various capacities. For example, Ma and Nakamori (2005) created an agent-based model of technological innovation and described it as an evolutionary process that's both constructional and environmentally selective. Their results demonstrated that ABM and simulation are instrumental in guiding intuitions about technological innovations. Ma and Nakamori (2005); Wu et al. (2010) modeled technological innovations using the ABM framework. Pyka et al. (2007) developed the Simulating Knowledge Dynamics in Innovation Networks (SKIN) model, a knowledge-driven model; i.e., changes in the level of knowledge directly lead to product innovation. The agents consisted of innovative firms aiming to optimize their innovations by selling them to other agents and end-users. Later, Korber (2011) extended the model to simulate the biotech innovation system in Vienna. The study modeled differentiated between agents representing companies, research universities, and research organizations. In this model, all the agents had different degrees of knowledge endowments. Varying degrees of knowledge among the agents allowed for incorporating a knowledge attribute into the system. The model introduced public

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institutes and other agents into the system as well, but they were treated as innovation entities, and the impact of the agents was brought into the model externally.

C. The Socio-Economic Factors Impacting the African-American Community

Socio-economic factors like personal wealth, matriculation in physical science and engineering programs, and other historically conditioned cultural factors lead to significant shortages of African-American high-tech entrepreneurial identities, causing this community to lag behind mainstream innovation (Herring 2009; Hurtado et al. 2010; Beasley and Fischer 2012; Liu 2016; Robb, Marin Consulting, and San Rafael 2013). Although significant progress has been made over the past century, enormous gaps remain between the income, employment, occupational attainment, and poverty levels of African Americans and White Americans (Thomas et al. 2018). African-American enterprises (AAEs) still encounter many barriers to entry due to ethnic inequalities (R.W. Fairlie, Robb, and Hinson 2010; Bates 2011; Robb, Marin Consulting, and San Rafael 2013; Dorsey 2016).

The 2014 Annual Survey of Entrepreneurs reveals that African-Americans and Hispanics remain underrepresented in business ownership. Minority-owned businesses display larger support on family savings as well as personal savings as a means of startup capital. Hispanics and African-Americans did not have business bank loans as compared to Whites. African-Americans rely more of using their credit cards as a mean of financing for debt which is much higher than bank loans from financial institutions. African-Americans, in general, had inadequate capital when starting their businesses. When launching their businesses, they had less than $10,000 in financial capital, compared with Asians and Whites. The high cost of securing capital impacted their profitability, compared with White-owned businesses. Research illustrates that African-Americans, as well as Hispanics, had a higher percentage of pursuing new financing relationships utilizing a range of sources, including banks compared with their White counterparts. This likely indicates the higher rejected rates when compared with Whites (Robb and Niwot 2018; R.W. Fairlie, Robb, and Hinson 2010; R. Fairlie, Robb, and Robinson 2016).

In general, racial discrimination, cultural family background differences, and the overall socio-economic environment are contributing factors in the underrepresentation of AAEs. Therefore, the present study included interviews with AAEs to identify the socio-economic barriers they encountered during the innovation processes. The next section illustrates the methodology and summarizes the identified entities, actions, and decision-making processes in an ABM framework.

3. African-American Agent-Based Innovation Modeling Framework

To theorize the African-American innovation process, the study conducted interviews among African-American entrepreneurs, universities, government, and funding institutes and identified them as internal entities within the complex innovation system. The figure below demonstrates the process to build the framework with input from the African-American entrepreneurs validating the model (Fig. 2).

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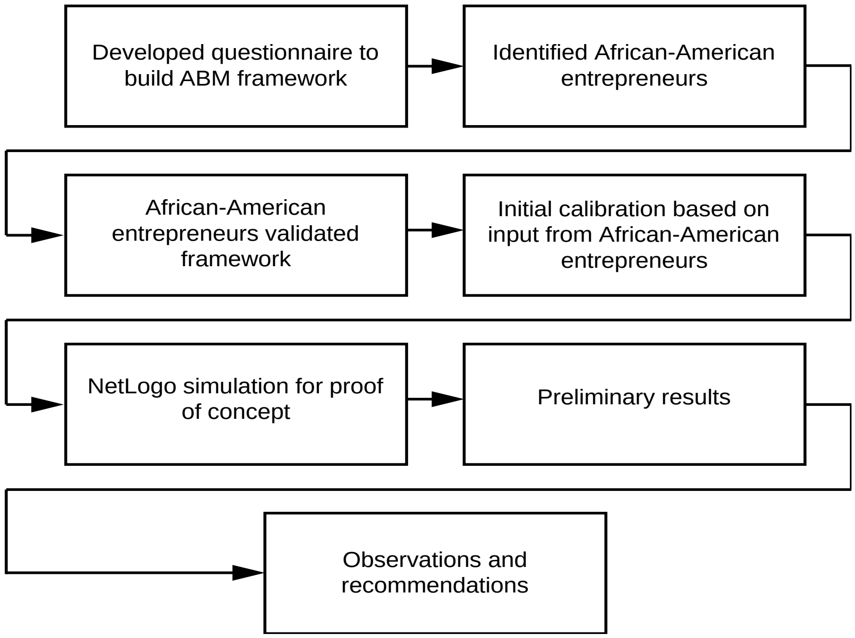

Fig. 2. Framework development methodology. Source: developed by the authors

In total, over 200 African-American enterprise executives and employees were surveyed through questionnaires and interviews in 2019. The questionnaires were sent out by using Google Form and the interviews were recorded and transcribed to text context, which was then used as inputs for NVivo thematical analysis. A selection of respondents is represented in the following Table 1.

Table 1. Selection of respondents. Source: developed by the authors

Age Range	Company Size	Sector	Respondent Profile (Background)
36 -55	Small	Aerospace Engineering (NASA)	President & CEO (Aerospace Engineering)
56 plus	Mid	Cybersecurity (Defense industry)	President & CEO (Computer Engineering)
36 -55	mid	Telecommunication	CEO (Electrical Engineering)
56 plus	mid	Software engineering (Defense industry)	CEO (Aerospace Engineering)
36-55	small	Telecommunication (Commercial)	R&D Director (Computer Engineering)
36-55	mid	Pharmaceutical (manufacturing)	CEO (Biomedical Engineering)
36-55	mid	Information Technology (Defense Industry)	CEO (Information Technology)
36-55	small	Computer systems design (Defense Industry)	President & CEO (Computer Engineering)
…	…	…	…

Five types of entities—i.e., African-American enterprise, funding institute, non-African-American enterprise, government R&D department, and university research institute were identified in the African-American innovation process (Fig. **3**). These entities take actions, interactions with each other and the built-up social network environment.

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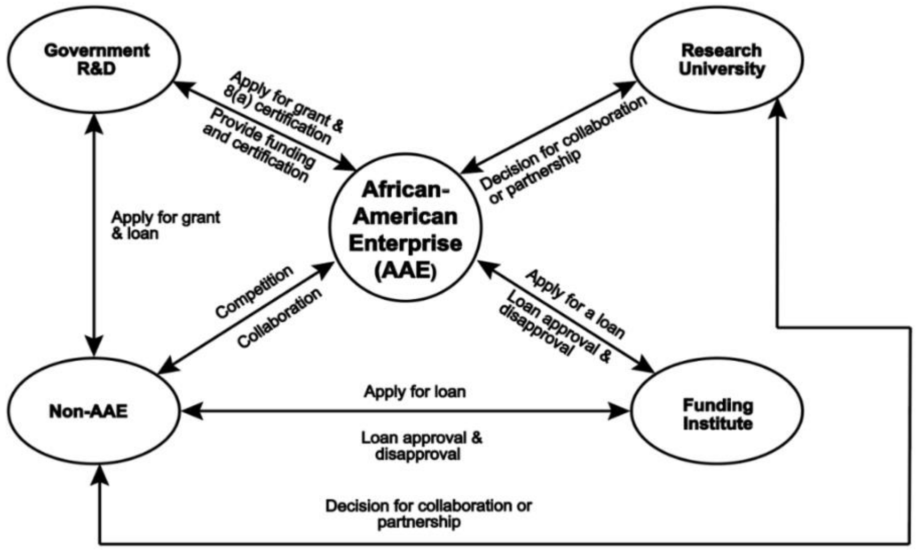

Fig. 3. Schematic representation of African-American innovation and ABM framework. Source: developed by the authors

Building on the knowledge-driven approach (Korber 2011; Pyka et al. 2007), the involved entities are treated as agents and each agent has certain attributes and skills. They can be represented by a set of kenes. A kene is defined as the knowledge based of the agents with at least three elements: capability, ability, and expertise level (Gilbert 1997). In the proposed African-American agent-based innovation model, enterprise agents are capable to perform research and development activities, and commercialize the products. Their ability would be research and development talent coupled with business acumen. And their expertise level would consist of a team of experienced developers and business leaders. The following section entails the agents and their actions obtained from the series of interviews. First, the agent attributes and kenes are illustrated in detail. Each agent's actions are then defined as functions of the identified socio-economic factors. The rules defined for each agent are presented by the agent's action pseudocode.

A. African-American Enterprises and Non-African-American Enterprise Agents

African-American enterprises (AAE) and non-African-American enterprise agents (non-AAE) represent the African-American high-tech enterprises and non-African-American (mainly White) agents, respectively. AAE and non-AAE agents are the core entities of the complex innovation system. They initiate innovations and develop products based on inputs from the knowledge base. The data analysis identified the socio-economic factors that determine the result of innovation as race, education, age, start-up, research and development (R&D) investment, risk tolerance, level of partnership, partner search strategy, minority enterprise 8(a) set-aside, product future, and product maturity level (Table 2).

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Table 2. The socio-economic factors of the African-American innovation enterprise agents*

Attribute	Definition
Age	Age of the entrepreneur when the venture was started
Education	Level or obtained degree
Personal start-up	Personal capital invested in the venture
Race	Ethnographic classification
R&D investment	Amount of money the entrepreneur has to invest in R&D (e.g., the demand for R&D and the long-run payoff for the firm's R&D investment)
Risk tolerance	Amount of tolerance for which the entrepreneur is willing to invest their time and money
Level of partnership	Whether the agent decides to pursue a go-it-alone strategy or looks for partners
Partner search strategy	Partner preference
Minority firm 8(a) set-a-side	In defense contracting, a Certified 8(a) Firm is a firm that is eligible to receive federal contracts under the Small Business Administration's 8(a) Business Development Program because it is owned and operated by socially and economically disadvantaged individuals (Zhu 2017).
Product future	Whether the product has a good future
Product maturity level	Whether the product has reached a certain maturity level and is ready to be sold in the market

* The attributes were summarized from interview results among stakeholders. Source: developed by the authors

Age is an important attribute of AAE agents. Three stages of maturity in the age attribute were identified through the conducted interviews. Innovation entrepreneurs of different age groups had different innovation strategies. For instance, recent university graduates endowed with fresh and creative ideas chose to start their own businesses upon graduation. The second stage of maturity included people who decided to pursue an opportunity after working for several years. At this stage, these entrepreneurs had already been exposed to working in a high-tech industry and were ready to embark on their innovation journeys. They were inspired by their work experiences and had accumulated social resources to turn into their first customers. The final stage of maturity included a group of people who began the innovation process after retirement. They were inspired by their work or their own life interests and usually had plenty of financial and social resources to start their own businesses.

In addition to the age factor, innovation and R&D are major components that lead to new high-tech products, methods, and services; therefore, education is vital to this process. It is a major factor related to the entrepreneur's ability to be more innovative when creating high-tech products and services.

To start their own enterprises, both AAEs and non-AAEs require investment capital to make key decisions about how to grow their businesses. Both AAEs and non-AAEs also require R&D investments (i.e., the amount of money the enterprise must invest in R&D). This includes understanding not only the demand for R&D but the long-run payoff for the enterprise's R&D undertaking.

The interviews indicated that every entrepreneur is exposed to a certain degree of risk. The proposed framework defines risk tolerance as the amount of tolerance for which the AAE/non-AAE is willing to invest their time and money. For the AAE/non-AAE to be more competitive, the agent evaluates whether to pursue joint ventures with

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other high-tech enterprises or research universities. This is called the level of partnership. The level of partnership allows the AAE/non-AAE to increase its competitive edge by leveraging the talent pool via partnering and R&D investment capital.

The interviews revealed that enterprise agents could elect to pursue a government certification that will allow them to compete for individual federal contracts. This is a disadvantaged minority certification known as the 8(a) certification under the Small Businesses Administration, which remains valid for a total of nine years. Commercialization driven by innovation is the key to product development; it is imperative to generate products that can be sold on the market.

Each innovation enterprise agent a_i (i = 1, …, N) owns a set of kenes ak_i. The kenes ak_i of a_i are elements of the following set:
$ak_i \in \{(S_i, c_i, b_i) | i = 1, \dots, N\}$ where $S_i = [r_i, g_i, u_i, t_i, d_i, y_i, v_i]$
S_i is the socio-economic factor vector of a_i, r is race, $r = 0$ represents African-American enterprises, and $r = 1$ represents non-African-American (White) enterprises. g represents the innovator's years of work experience, and v_i is the start-up initial of enterprise agent a_i. y represents the annual income, and d is the credit rating of the agent.

According to the interviewees, the core competency c of the innovation entity i is a function of the innovator's work experience (in years), annual income, credit rating, personal startup amount, and R&D investment amount.
$c_i = f(g_i, d_i, y_i, v_i)$

The business plan quality b of the innovation entity i was determined using the corresponding work experience, education, social networking with innovators, and university R&D entities. Generally, the innovation entities obtained business plan writing skills from school and previous workplaces as well as aid from other innovators.
$b_i = f(g_i, u_i, t_i)$

The AAE/non-AAE agent initiates the enterprise through startup innovation. During the innovation process, AAE agents may choose to work with other AAE or non-AAE innovation agents. Innovation agents also have opportunities to collaborate with university agents and funding institution agents to obtain support. In addition, they compete for resources such as funding and government projects. Innovation agents have the freedom to join other innovation projects as employees or university researchers. The agents' unique attributes and actions enable them to operate and make decisions accordingly.

Non-African-American enterprises compete with AAEs for funding, research university access, and small business innovation research (SBIR) grants. Non-AAE agents can also partner with AAE agents and leverage their network and talents to help AAE agents enhance the innovation process. Non-AAE agents have the same characteristics as the AAE agents; race is the only difference. Most non-AAE agents are White Americans. Therefore, the non-AAE agents in the present study represent White entrepreneurs. Race was selected as the key variable because most successful high-tech enterprises consist of only White entrepreneurs. In the proposed model, AAE and non-AAE agents compete for opportunities or decide to start a partnership and compete as a joint venture.

B. Funding Agents

The funding agent is the institution responsible for providing AAE/non-AAEs with the necessary funding to support their enterprises (e.g., angel investors and banks). The funding agent's attributes include the loan size, loan history based on race, loan history of supporting startups, and maximum loan amount the bank or venture capitalist can provide. The loan size may be small, medium or large, depending on the existing market. Different

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financial institutions have different strategies. Another attribute of the funding agent is their history of providing loans to AAEs. This is vital information to determine the likelihood of the AAEs getting loan approvals. The credit rating of a start-up is crucial for the funding agent to evaluate the start-up's ability to make the loan payment if approved. The agent considers the start-up's loan history to evaluate whether there is a history of the AAE defaulting on loan payments. There is also a maximum loan amount that this agent can provide.

Funding institute agents $f_{j,}$(j = 1, …, N) own a set of kenes fk_j. The kenes fk_j of f_j are elements of the following set:

$$fk_j \in \{(ls_{j,} lh_j, lm_j)|j = 1, \dots, N\}$$

The ls represents the maximum loan the funding institute agent f_j can provide, and lh is the loan history based on race. The lm represents the total funding limit of the institute.

The amount of money agent a_i needs to borrow from funding f_j is denoted by $al_{i,j}$. It is the total start-up amount required T_i minus the agent's initial start-up amount v_i.

$$al_{i,j} = T_i - v_i$$

The funding institute f_j makes financing decisions based on the evaluation of the applied funding $al_{i,j}$, the credit rating d_i of agent a_i, and the business plan b_i.

$$fd_{j,i} = f(al_{i,j}, d_i, b_i)$$

Agent action pseudocode:
IF loan amount <= Funding institute agent loan size/threshold
IF credit score >= credit bureau agency threshold
IF the AAE business plan meets the minimum standard of acceptable quality score
THEN approve loan amount according to company's size, small, medium, large [group history + 1, agent credit score + 1]
ELSE deny loan, [agent credit score – 1, group history – 1]

C. Government Research Agent

Government research agents represent the local to global level administration authorizations that make innovation policies and guarantee funding. As indicated in the interviews, the government institute of the U.S. government provides SBIR grants. According to the interviewees, the U.S. government R&D agents interact with the AAE and non-AAE agents to determine whether an enterprise can provide R&D expertise to support SBIRs. The government agent also provides enterprises with a small business/R&D loan. The government research agent has attributes and actions that present opportunities for the high-tech enterprises to compete for SBIRs and research funding backed by the government. The government research agent can also provide small disadvantaged business certifications to minority-owned companies. This certification allows the AAEs to compete for federal contracts that are only for certified disadvantaged enterprises. We included this type of agent in our study because the government plays a significant role in implementing policies that help AAE high-tech enterprises. In the proposed model, the government agent provides the AAE or non-AAE agents with the opportunity to compete for SBIRs as well as R&D funding backed by the government. The kene can be denoted as follows:

$$gk_l = \{(ha_l, hf_{l,} SBIR_{l,})|l = 1, \dots, N\}$$

The gk represents the government R&D agent l kenes, ha represents the government's project sponsorship history, hf represents government-guaranteed R&D funding for the AAE, and $SBIR$ represents the SBIR project. The government agent approves the funding support based on the company's 8(a) certification (ec) and project proposal (b):

$$SBIR_{l,i} = f(r_{i,} ec_i, b_i)$$

where $ec_i = \begin{cases} 1\ if\ os_i > 50\% \\ 0\ if\ os_i < 50\% \end{cases}$

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The os represents the firm agent ownership of the company.
Agent action pseudocode:
IF firm owner race = African-American
Then grant 8(a) certifications
If ownership > 50%
If business plan meets the threshold
Then award grant, business credit score + 1, experience + 1
Else denied

D. Research university agent

The research university agent is the research university or institution with which the AAE/non-AAE fosters a relationship that can lead to new opportunities and strategic locations to increase the AAE/non-AAE's recognition and knowledge base. The research university agent's primary role is to be a resource for high-tech enterprises to leverage institutions for their research expertise, talent pool, and grant opportunities. The AAE and non-AAE compete for collaboration opportunities with this agent. This agent is a vital resource for creating innovations that make AAEs more competitive.

The research university plays a vital role in increasing the innovations of high-tech enterprises. Enterprises must collaborate with research universities to increase their knowledge base and enhance their innovation capacity. Universities are often the primary source of knowledge transfers (Scandura 2016). In the proposed model, the research university is an invaluable knowledge base for high-tech enterprises seeking to collaborate and compete for university expertise. The AAE/non-AAE submit their proposal for university collaboration. The approval action for this agent is defined by the following equation:

$$rk_m = \{(hr_m, tp_m, ra_{m,i})|m = 1, \dots, N\}$$

The rk represents the research university agent's kenes, hr represents the agent's work history with AAEs, tp represents the talent pool, and ra represents the research assistance.

The approval of a collaboration with the research university agent can be expressed as follows: $ua_{m,i} = f(ra_m, hr_m, b_i)$

The $ua_{m,i}$ is the final decision of research university agent m to collaborate with applicant i, ra_m is the collaboration capacity, and b_i is the application's proposal quality.

Agent action pseudocode:
IF collaboration criteria met
Then proposal quality + 1, project experience + 1
The key agents' variables are summarized in Table 3.

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Table 3. Summary of the agents' kenes. Source: developed by the authors

Agents	Variables	Definition
AAE/non-AAE (a_i)	ak_i	Kene of AAE/non-AAE agent a_i
	S_i	Socio-economic factor vector of a_i
	c_i	Core competency of AAE/non-AAE agent a_i
	b_i	Business plan quality of AAE/non-AAE agent a_i
Funding Institute (f_j)	fk_j	Funding institute kene of f_j
	ls_j	Maximum loan size of the funding institute agent f_j
	lh_j	Loan history for the race group
	lm_j	The total funding limit of the institute
Government (g_l)	gk_l	Kene of government agent g_l
	ha_l	Government project sponsorship history
	hf_l,	Government-guaranteed R&D funding
	$SBIR_l$	SBIR project
University (r_m)	rk_m	University agent's kenes
	hr_m	History of work with AAEs
	tp_m	Talent pool
	$ra_{m,i}$	Research assistance to a_i

E. Interaction among Agents and Performance Measurement

In the proposed innovation framework, AAE agents, non-AAE agents, funding institute agents, university agents, and government agents are endowed with defined social-economic factors (Fig. 5). They can interact with each other to network and develop partnerships. The complex interactions among the agents create a virtual social environment. This allows AAE agents to share knowledge and resources that may lead to innovative ideas.

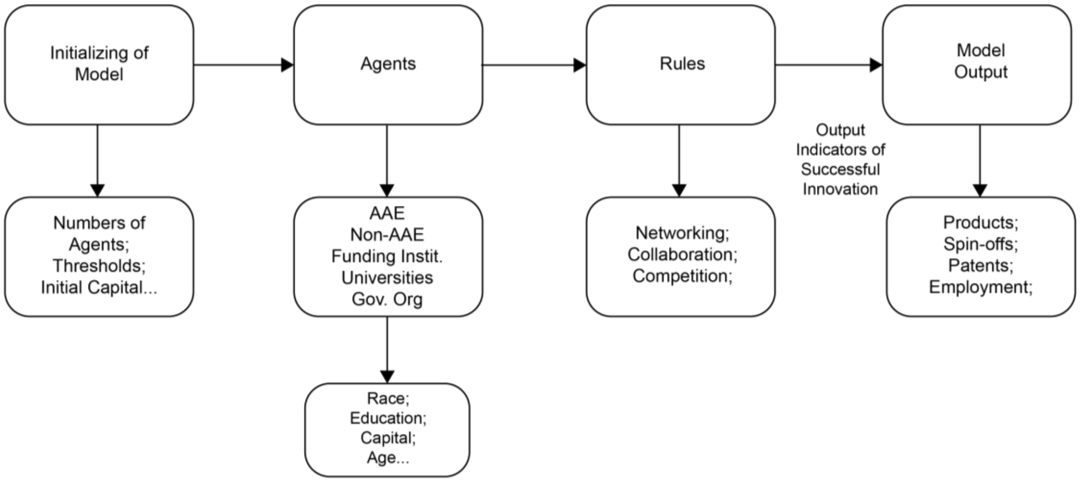

Fig. 4. African-American innovation agent-based model flow. Source: developed by the authors

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In the model, each agent has an attribute called individual power. Agents can initiate networking with other high-tech enterprises. Whenever two agents (i, j) interact, they establish a partnership that gives them the opportunity to share knowledge and resources. The model design was formulated with an on/off option to trigger networking with other innovative agents. In turn, the total sum of the links' energy represents the overall networking power. This can be denoted as follows:

$$N_t = \sum_{i,j} En_{i,j} \text{ with } i \neq j$$

N is the number of connections between the agents i and j. The agents obtain new experiences through communication and knowledge sharing. The higher the N, level of expertise, and proposal quality, the higher the AAE's level of expertise.

Innovation in research and development consists of basic and applied research to create knowledge in a product development environment. Both innovation and research enhance the knowledge base of a firm (Henard and McFadyen 2005; Herrera and Sánchez-González 2013). Basic research and development (i.e., fundamental research) focus on journal publications and patent applications that result in R&D growth (Quélin and Mothe 1997). The R&D group gets repaid through improved academic reputations or patent charging fees. Applied R&D focuses on new or improved products or processes and creations. This type of R&D gets rewarded through product sales (Quélin and Mothe 1997). A group of innovators commercialize the newly developed knowledge and build their own businesses through entrepreneurial start-ups or major organization spin-offs. Therefore, the success of R&D output O of the innovations generated by the AAE/non-AAE can be measured in various forms.

$$O_i = \begin{cases} 1 = basic\ RD: patent, journal\ publishment \\ 2 = applied\ RD: new\ product, new\ process \\ 3 = commercialized\ RD: start - up, spin - off \end{cases}$$

The primary purpose of the proposed model is to examine various scenarios for successful innovation among African-American high-tech enterprises and determine the factors that influence innovation outcomes. In the Biotech Innovation System model developed by Korber, Paier, and Fischer (2009), the spin-off companies determined a certain knowledge flow that connects academia with the industry. The university scholars held stocks in companies or became entrepreneurs themselves. In the African-American Enterprise Innovation Model (AAEIM) for African-American high-tech enterprises, spin-off companies provide a way to measure success for the AAE, thereby linking knowledge flow to collaborations with universities. There is a success threshold that triggers new spin-off enterprises based on the current level of success. The present model uses the number of spin-offs as the measure of innovation success.

4. Simulation and Scenario Comparison

The proposed agent-based enterprise innovation concept was implemented using NetLogo (Tisue and Wilensky 2004). NetLogo is a practical software environment that is easy to use and is applicable to interdisciplinary work. NetLogo consists of a variety of ready-to-use programs and libraries through which a user can focus on model design rather than complex computer programming tasks (Abar et al. 2017a; Allan 2010; Crooks and Castle 2012; Robertson 2005). NetLogo is widely recognized as the ideal software tool for creating agent-based models (Alden, Timmis, and Coles 2014). It is a powerful tool for people new to modeling or scientists with minimal software development expertise (Lytinen and Railsback 2012; Wilensky and Rand 2015).

Fig. 5 shows the interface for the African-American enterprise innovation's NetLogo model. The left side of the model interface displays a list of the initial parameter settings, including the total initial number of simulating agents, initial funding, input–output ratio, partnership strategy, and firm success thresholds. Next to them, the

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switches for research strategies and networking partnerships as well as start-up controls are provided. These are the additional functions available to test the results of different innovation environments. The view window in the middle shows the number of agents. For instance, a green-colored person symbol represents the AAE agent, a yellow-colored person symbol represents the non-AAE agent, a single house symbol represents the university agent, stacked house symbol represents the government agent, and bird symbol represents the funding institute agent. During a simulation, underperforming firms may die out while the over-performing firms have a chance to grow and produce spin-offs. The number of AAE/non-AAE agents can directly represent the results of the simulation. The plots on the right-side monitor the performance of each of the key variables.

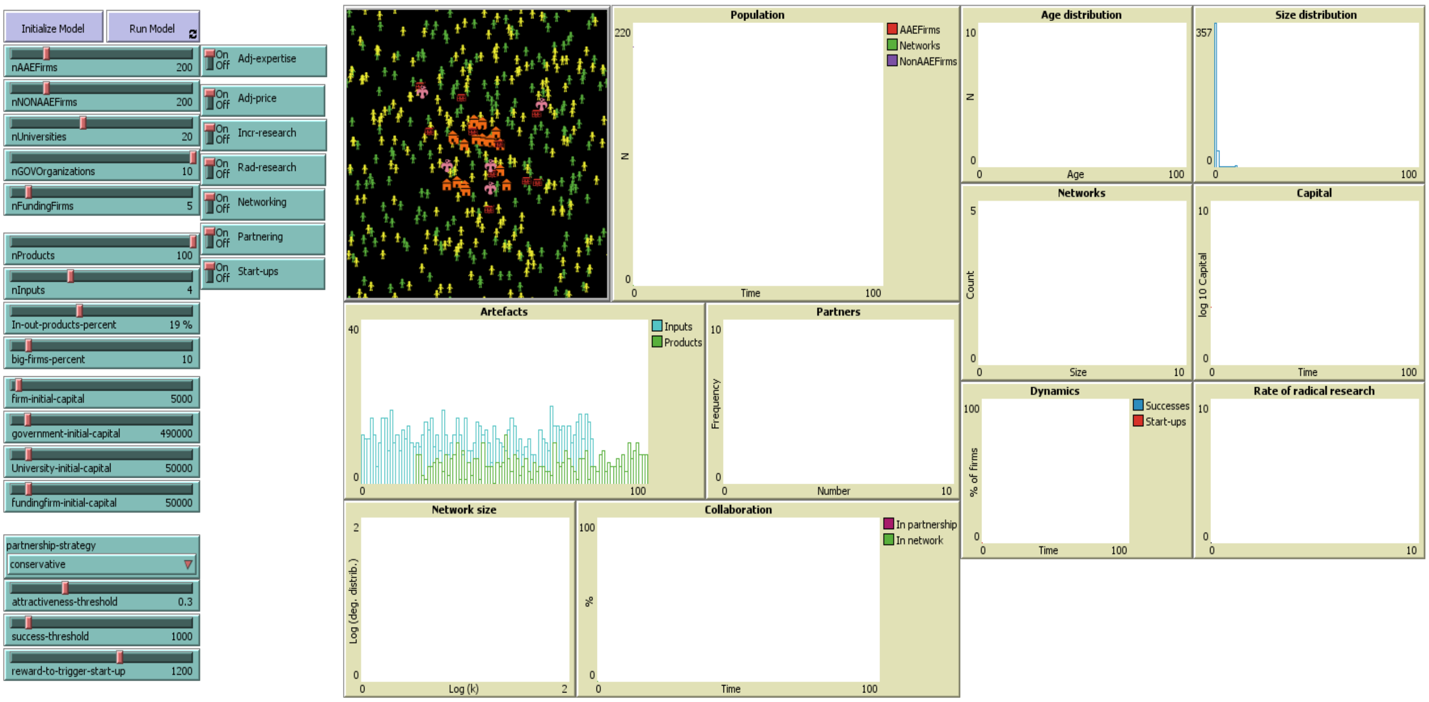

Fig. 5. The African-American Enterprise Agent-based Model on NetLogo. Source: developed by the authors

A. The Analysis of the System Performance and Simulation Results

According to the knowledge-driven approach, there is no knowledge or other creative difference between the AAE and non-AAE agents; the same innovation results would be obtained for both the agent types with the same input factors. However, our preliminary data collection and literature review suggested that African-Americans usually have less initial capital than non-African-American entrepreneurs. This study created a scenario in which the AAE and non-AAE agents had different initial capitals.

The model results depicted in Fig. **6** shows that African-American agents lag behind non-African-American agents in start-up spin-offs. As shown in the top-right line plotting window, the number of non-AAE-owned firms (purple line) consistently increased in this scenario. On the contrary, the AAE-owned firms (red line) showed a fast decline before an increase. This gap between the non-AAE and AAE agents grew over time. The "yellow person" (non-AAE agent) outgrew the "green person" (AAE agent). During the simulation period, non-African-American agents dominated the African-American agents even when they had the same initial enterprise counts.

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This corroborated the literature that suggested that African-American enterprises are underrepresented due to socio-economic factors (Lofstrom and Bates 2013).

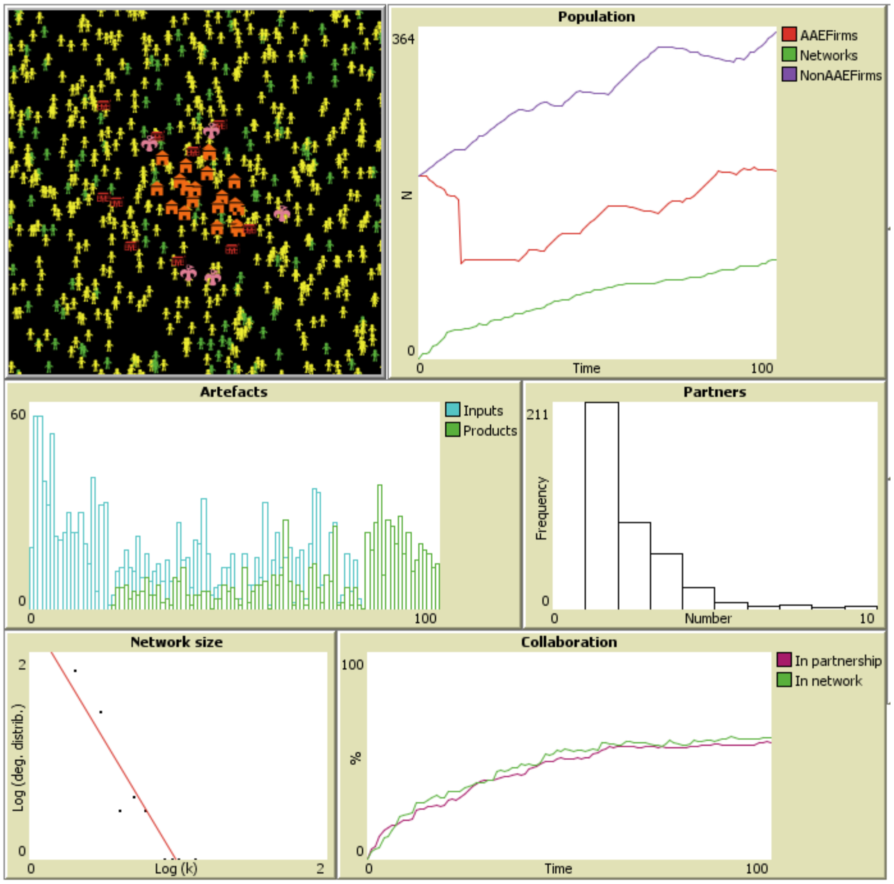

Fig. 6. Model simulation results. Source: developed by the authors

Model simulation results: In the top-left visual window, the yellow "persons" represent the non-AAE agents, and the green "persons" represent the AAE agents. Initially, there were equal numbers of yellow and green "persons." After the simulation of multiple generations', the number of yellow "persons" dominated the number of green "persons." This is shown in the top-right graph; the number of AAE firms (red line) is way lower than the non-AAE firms (purple line), while the other graphs demonstrate that all the other conditions were equal.

5. Discussion and Conclusions

This paper presented a conceptual framework of an African-American enterprise innovation model for addressing the underrepresentation of African-American high-tech enterprises based on interviews and questionnaires conducted with African-American entrepreneurs. The proposed innovation-based model consists of five autonomous agents in a dynamic, complex innovation system that employs an agent-based modeling approach. Thematic qualitative data analysis was conducted, and the attributes and actions for each type of agent were defined. The proposed framework was then implemented into a computer model on NetLogo platform. The simulation results corroborated the results from existing literature that African-Americans are underrepresented

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because of their socio-economic status (Adhikari et al. 2014; DiTomaso and Farris 1992; Liu 2016; Conrad 2006; Gatchair 2013; Marcus). It indicates that the model is successful in depicting the true characteristics of market participants.

To the best of our knowledge, this work is unique with its introduction of factors that constitute the African-American high-tech industry business environment. This approach fills literature gap on the lack of causal-relationship investigation in African-American entrepreneurship study (Gatchair 2013). The proposed framework constructs a dual virtual environment including socio-economic factors and involving entity networks. The created entrepreneur agents adopt knowledge-driven approach innovating and creating startups in the created virtual environment. Successful businesses will grow, thrive and spin off new business over time. Constrained businesses may lose competition and die out. This replicates the innovation reality.

Furthermore, the study also contributes to the literature by introducing a novel ABM approach for the systematic evaluation of this industry segment. The proposed model first introduces peer agents, non-African-American entrepreneur agents, to the framework simulating the competition/collaboration relationships among them. The performance of each ethnicity group is reflected by their numbers directly. Second, instead of treating educational, governmental and financial institutes as external forces as similar studies (2007; 2011), the proposed framework internalized these entities and treated them as parts of the complex system. The various agents compete/collaborate with each other through an evolutionary dynamic approach. Knowledge, resources and historical paths accumulate and feedback to the environment over time.

Therefore, the proposed framework not only provides a holistic model for African-American high-tech enterprises but also maps the partners in industry differentiating their internal and external collaborators. In addition, introducing a multi-layer classification of an otherwise complex system, the model also allows similar underrepresented industries to decide on the level of information technology and capital investment required to foster and grow individual relations in the marketplace. This model can be used by technology managers to determine how different scenarios can be more competitive. The technology managers can also measure the effectiveness of various innovations by using the computer simulation outcomes. Thus, technology managers initializing such models can gain higher recognition and have greater impact in research and development.

Diversity is not only a crucial element of sustainability but is also proven to be a key driver of innovation. Similarly, lack of representation of all groups that vary by gender, race, ethnicity and other status irrefutably hinders the progress of any industry. This study focuses on addressing the factors that contribute to the low representation of African-American owned high-tech enterprises. In this regard, the research significantly contributes to the related literature by providing a data-driven assessment tool to evaluate the potential success of innovation projects prior to their launch. The simulation-based model is easily applicable to other high-tech products and processes. The study further contributes to the related body of work underscoring the importance of empowering minorities and ensuring diversity in all dimensions in Science, Technology, Engineering, Math (STEM) fields. Increasing the representation of African-American high-tech enterprises would not only benefit the African-American community but society as a whole. On a broader scope, the study establishes a platform for facilitating a policy discussion regarding the unique challenges African-American high-tech entrepreneurship is facing.

Even though the simulation results demonstrated the success of the framework and modeling approach, the proposed model requires further calibration and verification before it can be used for policy analysis and formalization. Given that ABM approach allow great flexibility, the platform can easily be adjusted to industries with varying levels of agents and model components. Due to its versatile nature, additional agents can also be seamlessly integrated in to the model environment to widen the scope and the robustness of the framework.

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Additional data needs to be collected to structure the socio-economic factors for the proposed model. This study defined agent interactions as linear relationships to simplify the modeling approach. However, the causal relationships between the influencing factors and agent interactions are far more complicated. Future work might benefit from creating what-if scenarios to examine emergent behaviors and the use of sensitivity analyses to predict the probability of successful innovations. Further, incorporate real-world data inputs from questionnaires into the model would improve the performance of simulation runs and model calibration.

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