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An Agent-Based Model for 5G Technology Diffusion in Urban Societies: Simulating Two Development Scenarios

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Abstract: Although 5G has been deployed in several countries, stakeholders are still hesitant to adopt the technology. Massive investment and collaboration become prerequisites for this technology to be successfully implemented and bring the most benefit. This research discusses the diffusion of 5G technology to personal end-users and industries and simulates the collaboration model. The simulation analyzes key essential indicators for stakeholders, such as the number of adopters, diffusion time, and total revenue. This study follows the pragmatism philosophy and abductive approach, integrating qualitative and quantitative research, resulting in the diffusion model. The qualitative data was obtained through focus groups and semi-structured interviews with key sources, while quantitative data from 437 people were gathered through a questionnaire. The simulation resulted in a 34% improvement in diffusion time, leading to faster investment return for industry players. This study offers an alternative paradigm compared to the diffusion of innovation theory, especially for new technology distribution. Finally, this research suggests that 5G stakeholders adopt the proposed collaboration strategy to achieve better business indicators.

Keywords: 5G; agent-based modeling; diffusion of innovation; mobile network communication

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1. Introduction

In several places worldwide, fifth generation (5G) network technology has been launched as the next generation of mobile network communication. Many people have profited from this technology, which allows for super-fast internet, fixed wireless access (FWA), smart cities, industrial automation, autonomous vehicles, smart homes, and the Internet of everything [1,2]. These use cases are thought to contribute to urban sustainability by reducing electricity usage and carbon emissions [1,3]. However, despite these success stories and noble purposes, several countries have not launched 5G due to insufficient infrastructure, apprehension towards technological capability, and the 'wait-and-see' position.

Indonesia, one of the nations that have launched 5G, launched it in May 2021 at a frequency of 2.3 GHz and a bandwidth of only 20 MHz [4]. However, the government must still develop its infrastructure, such as spectrum frequency and transportation network, to meet the ITU-5G T's requirements [5]. Apart from that, due to high investment expenses, Mobile Network Operators (MNOs) are sending inconsistent signals about their profitability [6].

In this research project, we strove to support the 5G development by collaborating with relevant stakeholders and proposed a solution to overcome the aforementioned issues. Continuing the previous study, this study will utilize agent-based modeling to simulate the 5G adoption time, which can be extrapolated to GDP for government view and profitability for business firms' consideration. From a methodology standpoint, this article is unique in that it uses a quantitative survey as the foundation for model-building assumptions. The current model also incorporates additional components, such as adoption threshold, adoption score, influencing score, influencer list, buying power, adoption duration, and MNO competition, compared to the prior technology diffusion model.

Simulation is one of the most effective methods for gaining stakeholder approval for infrastructure collaboration. It explains the level of individual adopters, simulations of 5G diffusion models may provide a better understanding. Stakeholders' collaboration in infrastructure could lead to lower development cost and more effective infrastructure usage such as frequency, land, tower, and power. The 5G diffusion simulation also indicates the adoption rate by the industry or institution. These represent innovations such as autonomous electric vehicles, smart-factory, smart grid, smart government, and other 5G use cases, leading to less carbon emission, energy reservation, and use of unlimited energy sources [1,3].

2. Literature Review

The Diffusion of Innovation theory is a prominent analysis of innovation or technology dissemination for end-users at a specific time and rate. It explains why and how new ideas and technology spread at various rates to diverse groups of people. The theory also divides innovation adopters into several categories: innovators, early adopters, early majority, late majority, and laggards. The population model of technology transition forms the normal distribution, and at a certain point, the market share will be saturated [5]. The normal distribution of innovation can be seen in Figure 1.

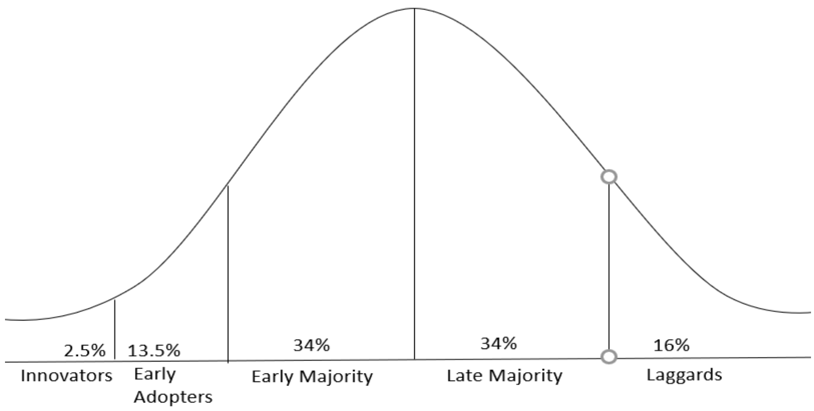

Figure 1. Diffusion of innovation [7].

Simulating technology dissemination using the agent-based modeling (ABM) technique is one way to demonstrate its ingenuity. When utilizing the ABM tool to develop a model, one can play around with various assumptions and supporting data. It is an excellent tool for determining the impact of a factor on the overall diffusion scenario [8]. Technology diffusion using ABM simulation started with the Bass model in 1969 [9]. This paradigm claims that a person's adoption of technology occurs due to marketing and word-of-mouth from their peers. Then, this model was further expanded using other scenarios such as the threshold model of collective behavior and word-of-mouth analysis of a complex system [10,11]. Since then, this has become a powerful tool used for various purposes such as economy, management, climate change, healthcare and disease, land and housing, and energy [10–17].

Further development of ABM is related to the diffusion of innovation, especially for emerging technologies such as electric vehicles and the renewable energy industry [12]. Applying the ABM model resulted in four stages of adoption for electric cars: unaware, aware, persuaded, and decided. Each stage has its threshold. If the interaction with advertising or other households as influencers adds a score above the threshold, the stage moves to the next level. Finally, fuel price, electric vehicle price, and incentives are parameters that influence the last decision-making process [13]. In a previous study on renewable energy [14], ABM provided an accurate option analysis to solve personal profitability calculation and skepticism in product performance. The model then concludes that external factors such as government incentives and promotion can significantly increase adoption. Every 10%

addition in incentive leads to a 30% adoption rate. Similarly, the study about electrical vehicle charging attitude also results in government policy as the most impacting factor [8].

Moreover, system dynamics and the ABM model were combined and studied in 5G mobile adoption in South Korea. Since the launch of 5G in April 2019, the model prediction has been necessary to discover the behavior comparison between 5G adoption and 4G adoption. The result indicates that the diffusion time of 5G is faster than 4G [15]. A similar mathematical model was also built for the 5G subscribers model based on coefficients of innovation, the coefficients of imitation, and the total number of potential subscribers for each generation [18]. In an Iranian case study, the ABM simulation was used to model the diffusion of mobile communication networks to provide telecom players an insight for strategic planning. The model uses several input parameters, for instance, adopters for 2G, 3G, and 4G. These adopters' behavior follows the distribution of adoption, namely innovators, early adopters, early majority, late majority, laggards, network topology parameter, and external factors such as advertisement and handset capability. The result shows that Iranian mobile network adoption fits the description of Watts–Strogatz's small-world network. This finding indicates that to reach an unknown person worldwide, one can use a limited number of friend networks [19]. Results also found that handset compatibility is a significant factor compared to the advertisement and the most effective scenarios of incremental 4G adoption with lowest operational steps [16].

Aligned with the Bass model, the two references' previous study [15,16] of 5G mobile adoption in South Korea and Iranian mobile network were both equipped with word of mouth, advertisement, and neighbor influence features. The 5G mobile adoption in the South Korea model has strength in combining System Dynamic and ABM to cover both macro aggregation and individual behavior. The limitation of this model is that the model only described for e-MBB 5G use cases such as mobile broadband and augmented/virtual reality (AR/VR) [15]. The Iranian mobile network model was completed with a 2G, 3G, and 4G technology generation selection. This model also provides the type of adopters from innovator, early adopter, early majority, late majority, and laggards [16]. However, this study does not include the MNO selection. Thus, the state of the art (SOTA) of this study is to include MNO selection in the diffusion model and the impact of stakeholder's collaboration in the diffusion time with additional industry as agent to cover other type of 5G use cases aside from e-MBB, such as mMTC and URLLC. The proposed model was then formulated based on the SOTA, which discusses the relationship of stakeholders' collaboration positively impacting the diffusion performance, which is diffusion time. The model provides two diffusion scenarios of two type of agents which are person and industry, representing all types of 5G use cases. Those agents could also decide the preferred MNO to create simulation close to reality.

This study refers to two prior studies on 5G adoption in South Korea and 2G, 3G, and 4G adoption in Iranian communities, particularly in terms of model construction, such as word of mouth, influence from neighbors or friends, adoption score threshold, and adopter type depending on adoption timing. This study also follows the scenario generation to have the most effective state where technology adoption (4G or 5G) is the highest. Based on the state of the art from the previous section, this research would like to answer the research question of the impact of infrastructure stakeholder collaboration such as government incentive, MNO sharing, local government participation, and co-development and co-innovation to 5G diffusion time. The hypothesis is that the infrastructure stakeholder collaboration positively influences the 5G diffusion time.

3. Model Building

As previously stated, this study builds on past qualitative research by proposing a collaborative model among 5G stakeholders for more effective and efficient development [17,20]. Focus discussion groups and semi-structured interviews were used in the qualitative study, which resulted in two scenarios for 5G development in Indonesia [21]. Next, the qualitative study was combined with a quantitative survey to build the agent-based model. A total of 437 participants with various backgrounds, occupations, ages, and areas partook in this study. The survey was conducted by sharing a link through email, social media, chat applications, or direct contact. A mixed methodology of qualitative and quantitative approaches would present substantial validation to the built model simulation. This study contributes to novelty by using the quantitative survey for model building rather than performing simulation or laboratory experiments [22,23].

The simulation was based on the findings of earlier studies in the 5G development study series, which are case studies focusing on collaboration for deploying 5G infrastructure in Indonesia. The goal of the model development is to compare and contrast two 5G development scenarios in Indonesia in terms of diffusion and economic impact. The qualitative study results are displayed in Table 1, which shows the relation of the stakeholders, proposed activities, and potential savings.

Table 1. Qualitative study results to be simulated [24].

No	Relation	Related Activities	Potential Savings
1	Regulator—MNO (Government Incentive)	MNO pays spectrum fee, Universal Service Obligation (USO), and BHP Tel (Operating Rights Fee). Governments can give incentives, such as USO for infrastructures (fiber optic projects) and frequency-sharing discounts.	10–50% Spectrum Fee
2	MNO-MNO MNO-Micro Operator MNO-Incumbent (MNO Sharing)	Inter-MNO sharing, such as passive, active, networks, and MVNO. MNO is sharing with Micro Operators. MNO/Micro Operator spectrum sharing with Incumbent.	10–40% OPEX
3	Local Government to MNO and Micro Operators (Local Government Participation)	The local government commits to fast working permits, passive support (electricity, land), and exemption from community fees. In return, MNO shall commit to building networks in non-profit remote areas. Micro Operators pay local USO to the local government instead of to the central government. The spectrum fee and BHP Tel should still be paid to the central government or regulator. This is to increase the local government's participation in network developments. The local USO can provide fiber optic, electricity, lands, and community fee subsidy.	3–4% OPEX
4	Ecosystem Development and Innovation	This includes innovative infrastructure areas with significant impacts, such as dynamic spectrum sharing (DSS) and Open Radio Access Network (Open RAN).	49% CAPEX 31% OPEX

Each construct in Table 1 is associated with a slider, namely (1) average MNO sharing, (2) average government incentive, (3) average local government cooperation, and (4) infra-co-innovation. The term average is used because the impact of each additional slider is taken from the average value of the marketing or account influencing score. Each incremental slider also correlates with each activity of collaboration, as shown in Table 2.

Our previous study [21] produced two scenarios to be simulated in this model: the wait-and-respond and the optimistic champion scenario. These are the results of the scenario planning conducted for 5G development in Indonesia. The wait-and-respond scenario represents the current condition of limited collaboration among stakeholders. Meanwhile, the desired scenario, the optimistic champion, embodies their full collaboration and cooperation, as listed in Table 2.

The first slider, MNO sharing, is determined through observation of current stakeholder collaboration. As per observation, the current condition of stakeholder collaboration for 5G development in Indonesia is constrained to several activities. MNO sharing exists and works well in passive infrastructures in several areas, while network sharing currently only involves two MNOs in several regions [25]. Thus, the scale of average-MNO-sharing for the first scenario is 1. The new omnibus law in Indonesia is just as applicable, acting as the foundation for this MNO sharing.

Table 2. Mapping of incremental sliders and activity of collaboration.

No	Name of Slider	Scale	Collaboration Activity
1	Average-MNO-sharing	1	Site Sharing (tower, rooftop)
		2	1 + Infrastructure Sharing (power, AC, antenna)
		3	1 + 2 + Telco Equipment Sharing (Radio F, TX)
		4	1 + 2 + 3 + Full Sharing
2	Average-govt-Incentive	1	USO Incentive
		2	1 + Spectrum Sharing Discount
3	Average-local-govt-cooperation	1	Quick Working Permit
		2	1 + Provide Site and Passive Infra
		3	1 + 2 + Free of Community Fee
4	Infra-co-Innovation	1	Dynamic Spectrum Sharing (DSS)
		2	1 + Open RAN (Open Radio Access Network)

The next slider is the average government incentive, which shows the central government's incentive for mobile network development. Currently, the government provides incentives for mobile network development in USO, especially in remote areas. Another form of incentive is the spectrum sharing discount, which has not been implemented. Hence, the scale for Slider 2 is also assumed as 1. This similarly happens for local government cooperation. Several local governments support telecommunication and Internet development in their areas, but unfortunately, many have not considered it a primary need [26,27]. For this reason, the scale for Slider 3 is placed at 1.

The last slider—infra-co-innovation—consists of DSS and Open RAN. DSS is an innovation that enables the existing 4G base stations to be software-upgraded to 5G using a similar spectrum frequency. This innovation can lessen capital expenditure due to its easy upgrade [28]. In contrast, the Open Radio Access Network (Open RAN) refers to the procurement separation between hardware and software entities from different suppliers. The RAN network is controlled by tech giants, such as Ericsson, Huawei, Nokia, and Samsung. With Open RAN, MNOs can purchase their software and hardware separately from any vendor, bringing highly competitive investment costs [29]. Currently, both innovations are limited in terms of applicability, so the scale for Slider 4 is 0.

From the above explanation, the wait-and-respond scenario is translated into scales of 1 for Sliders 1 to 3 and 0 for Slider 4. Hence, the sliders for the first scenario are 1-1-1-0. Similarly, since the optimistic champion scenario is the complete collaboration activities, the sliders of this scenario are placed as 4-2-3-2. The sliders and the positions can be seen in Figure 2.

In addition to these qualitative results, we also surveyed to complete the assumptions of the diffusion model for each agent. There were nine questions in total to be answered by the participants. The questionnaire, written in the Indonesian language, examined the probability of 5G adoption from respondents. The statistical behavior resulting from the survey can be used for the agent-based model simulation.

The first section of the survey inquired about 5G applications, use cases, and capabilities that the participants had anticipated. The top three answers were enhanced mobile broadband (e-MBB), fixed wireless access (FWA), and innovative city/smart grid/smart public facilities. The results of the first question can be seen in Figure 3.

Figure 2. Collaboration activity sliders in the model.

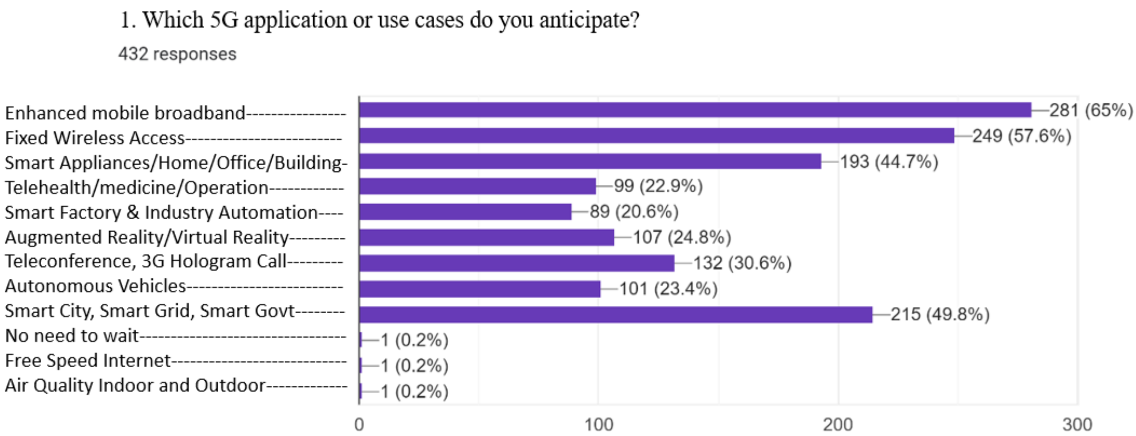

Figure 3. Anticipated 5G applications or use cases results.

The second and third questions explore the participants' willingness to adopt 5G, which can later be converted to the adoption score threshold. The second question puts the participant as a personal technology adopter[i]. In contrast, the third question puts the participant as the entrepreneur or decision-maker to adopt 5G in their company or business. These parts of the questionnaire used a Likert scale of 1–10 of the willingness to use 5G [30]. The result was then mirrored to obtain the adoption score threshold on a scale of 10–100, with '10' being the fastest to adopt and '100' being the last to adopt. Meanwhile, the adoption score threshold of a company was multiplied by 3, with assumptions that at least three persons— CEO, CTO, and CFO—are involved in deciding the technology adoption in the company.

The results show participants' massive willingness to embrace 5G both as personal and as the business owner or decision-maker, with the former being slightly higher than the latter. These results can be seen in Figures 4 and 5.

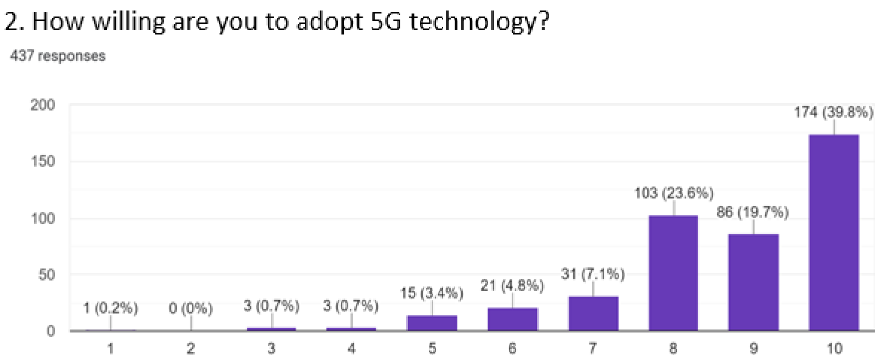

Figure 4. Participants' willingness to adopt 5G as a person.

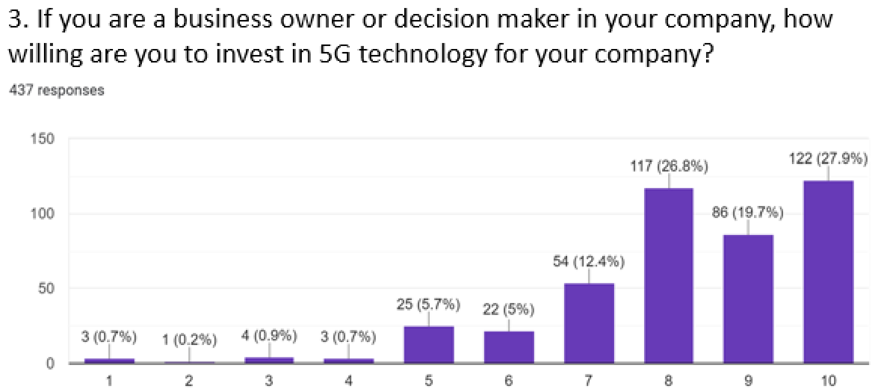

Figure 5. Participants' willingness to adopt 5G as a company or decision maker.

The distribution results of this study appear long-tailed, which is slightly different from the distribution of adopters in common—the normal distribution—between innovators, early adopters, early majority, late majority, and laggards [7]. The variance in distribution might be attributed to the participants' origin. Most participants are from big cities and are active Internet users, which might affect their eagerness to anticipate the latest technology development.

In the next section, we investigated the effect of marketing activities such as advertising (Question 4) and word-of-mouth (WoM) (Question 5). The outcomes show that the effects of both marketing and WoM in 5G adoption were not that different, with the latter being slightly higher than the former. The results can be seen in Figures 6 and 7.

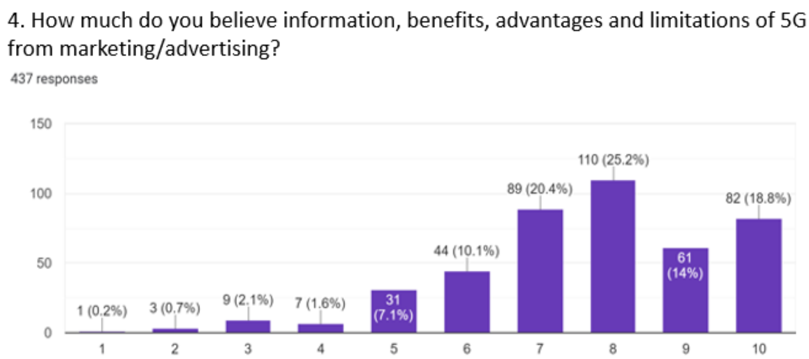

Figure 6. The impact of marketing/advertising activity towards 5G adoption.

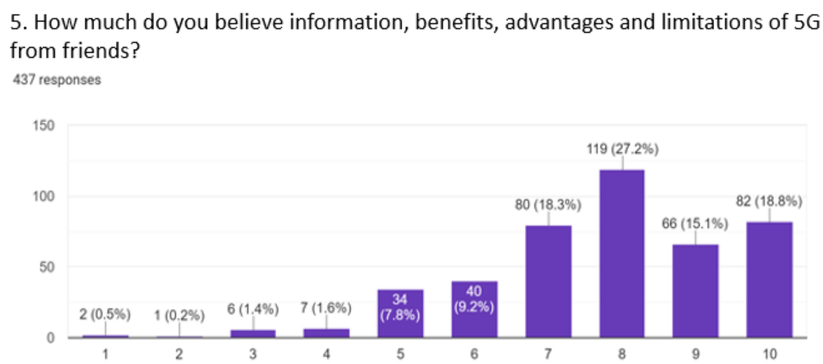

Figure 7. The impact of friends or words-of-mouth towards 5G adoption.

The influencing score was introduced as the ability of marketers and friends to affect others through WoM. The score was then distributed in the NetLogo following the random normal distribution. For a marketer, the average was 7.69 with a standard deviation of 1.8, while WoM from friends was 7.79 with 1.7 standard deviation. The solution architect had the same level of influence as the marketer but could only influence the industry. Moreover, since the assumption of industry adoption score threshold was multiplied by 3, the influence score of the solution architect was also multiplied by three from the initial marketing score, which became 23.085 with a standard deviation of 5.38. The industry influencing another industry through WoM is gained from friends' score multiplied by 3, resulting in 23.37 with a standard deviation of 5.1. The assumption is important people in certain industry will influence other important people in the same or different industry.

The next question was about the number of friends who should adopt 5G before the participant decides to do so. The result shows that the majority of people, 27.9%, do not depend on friends, 16.5% choose five friends, and 10% choose ten friends, as seen in Figure 8. This question aligns with Questions 2 and 3 about the willingness to adopt 5G, with most participants acting as pioneers or innovators. This result then becomes the base of mirroring the adoption score threshold multiplied by 10, on a scale of 10–100. Subsequently, the list of 10 influencers was injected into each agent.

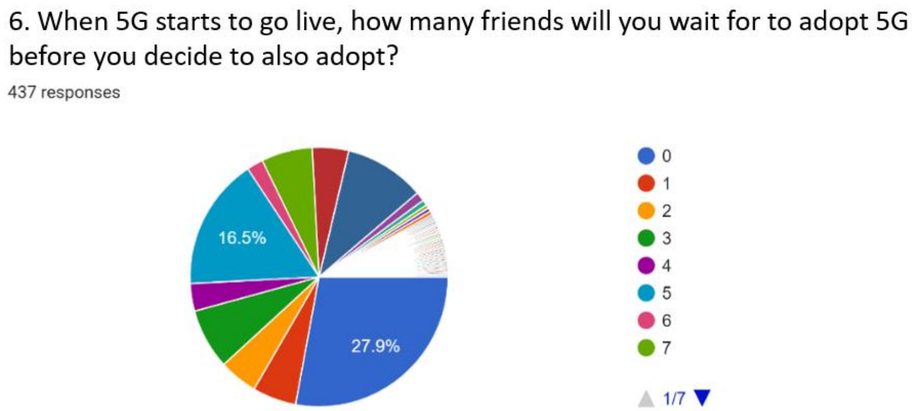

Figure 8. Number of friends to adopt 5G before participant also decides to follow suit.

The seventh question was about the type of marketing activities preferred by the participants to highlight the favorable kinds of advertisement. It showed that some types of ads (e.g., cashback, bonuses) are more expensive than others. From the results, the three highest preferable advertisements were marketing through social media (e.g., Facebook, YouTube, Instagram, TikTok), bonuses (e.g., GB data, SMS, and phone calls), and cashbacks, as can be seen in Figure 9. However, the latter two are considered uneconomical, thus requiring large capital.

The last two questions of the survey explored the buying power of participants. Question 8 examined their buying power for 5G devices (e.g., smartphone, smart watch, smart appliances, drone, VR goggles), while Question 9 was about their buying power of the Internet package. For 5G devices, most participants chose 1–9 million rupiahs, while a small number choose devices below one million rupiahs or above nine million rupiahs. Most people chose to spend 50,000–300,000 rupiahs for a data package, followed by 300,000–500,000 rupiahs. Only a few participants chose an amount less than 50,000 and above 500,000 rupiahs, as can be seen in Figures 10 and 11.

Based on both qualitative and quantitative studies, the ABM model for 5G diffusion was created with the conjunction of infrastructures strategy and economic impact. The model follows the logic flow shown in Figure 12. It also explains how an agent would adopt 5G after the adoption threshold is passed and buy 5G after sufficient buying power is attained. The adoption score would increase whenever the agent interacts with a marketer or account (or Solution Architect—SA) to represent another agent's advertisement activities. If the buying power is insufficient, the agent would be instructed to wait for a defined number of ticks before finally buying 5G.

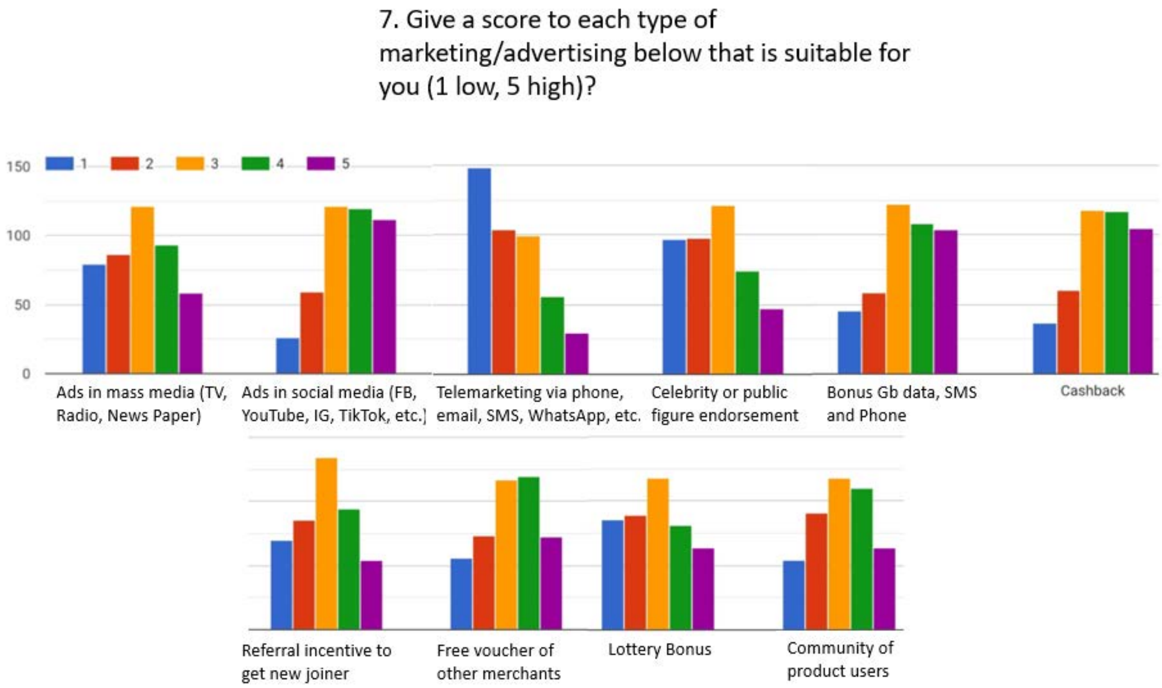

Figure 9. Preferred marketing/advertisement activities.

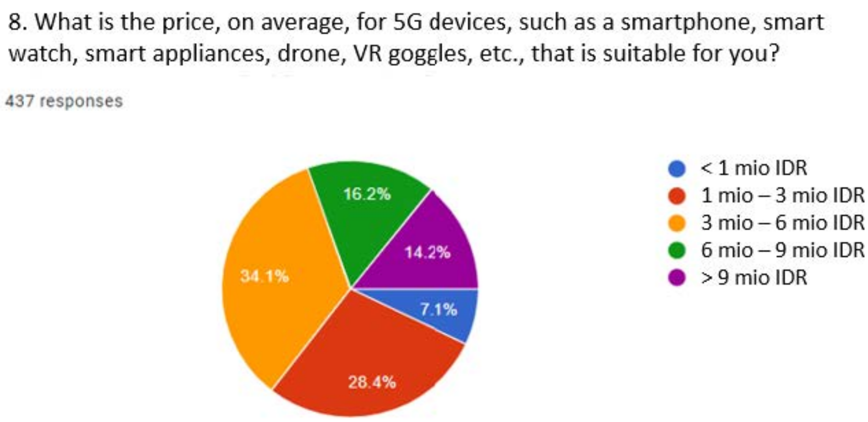

Figure 10. Buying power of the participants for 5G devices.

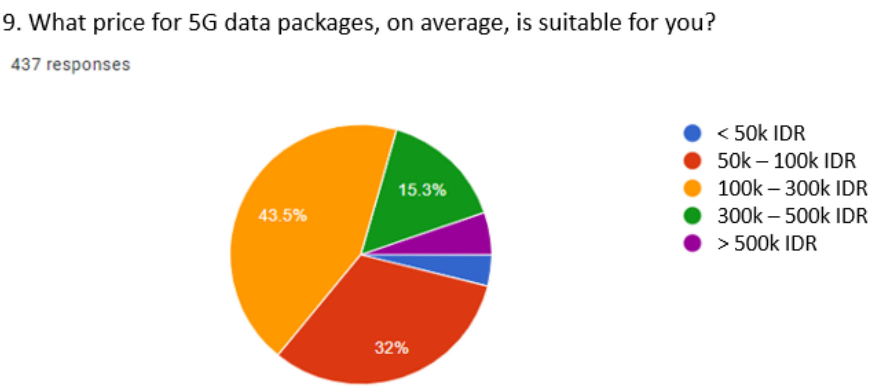

Figure 11. Buying power of the participants for 5G data packages.

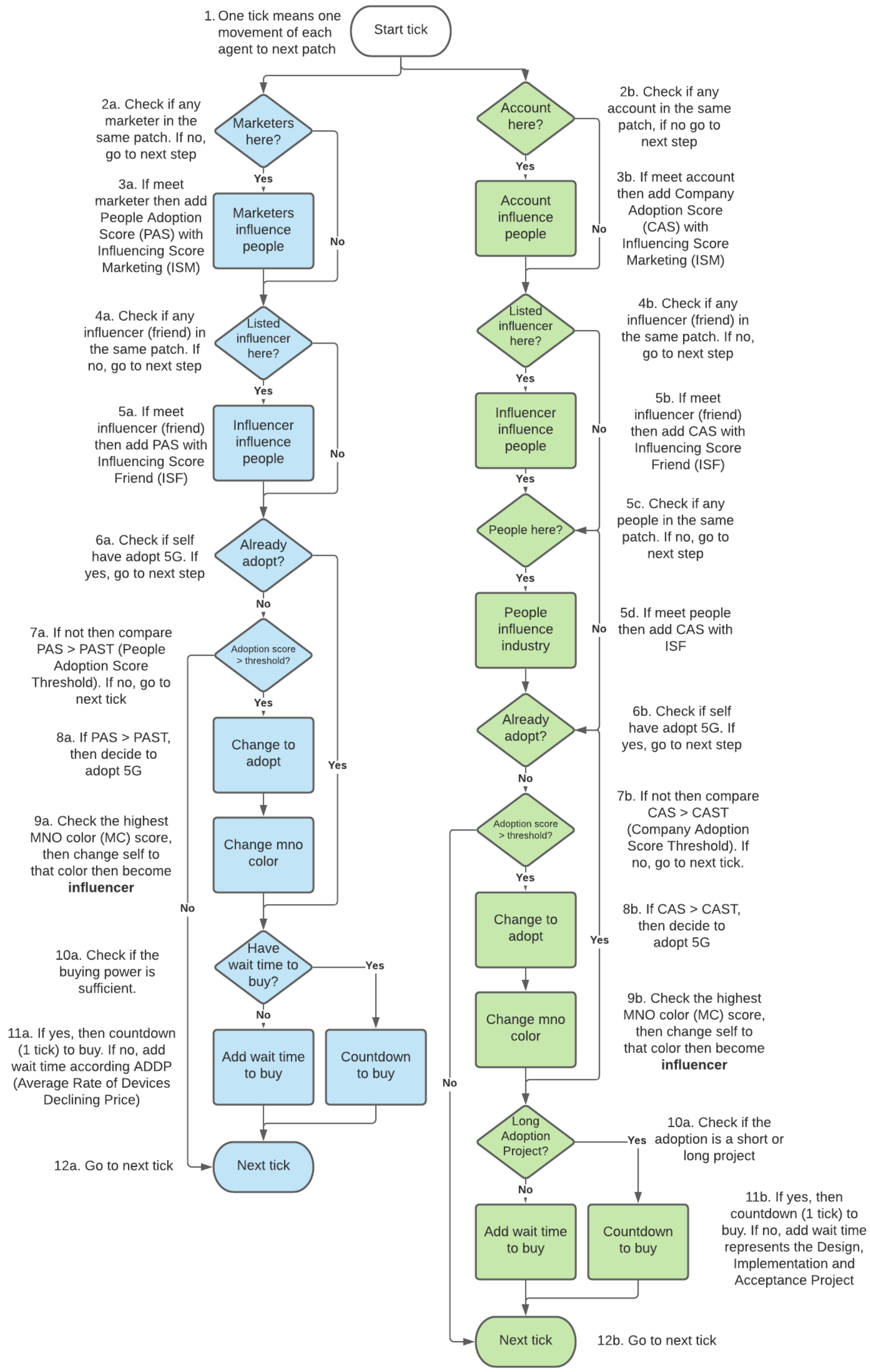

Figure 12. 5G diffusion model flowchart.

3.1. NetLogo Model

There are several agents in this model: people, industry, marketers, and account team. The ultimate goal of people and industry is to adopt 5G technology, then become influencers after adopting 5G. Meanwhile, marketers and account teams can only influence people and industry (or company), respectively. The activity of adopting and influencing is done in the small-world network and done for each tick. In each tick, those agents move from one patch to another patch. The assumption is that if two or more agents meet in a patch, an influencing activity will happen at that moment. Influencing means the People Adoption Score (PAS) or Company Adoption Score (CAS) will be added with influencing score by marketer/account (ISM) or friends (ISF).

When the simulation starts or the setup button is clicked, people and industry agents have internal properties. The properties are People/Company Adoption Score (PAS or CAS), People/Company Adoption Score Threshold (PAST or CAST), MNO Color (MC), and Buying Power (BP). PAST and CAST score distribution follows the questionnaire survey results distribution, while BP distribution follows log normal wealthy distribution. PAS/CAS and MC start from zero and are incremented based on the influencing activities in the simulation.

The person or industry interacts with the marketing or account team, listed friends (influencers), and people at a particular tick in a particular patch. In the model, it is represented by two agents who meet each other in one patch. People can only be influenced by the marketer or listed friends (influencers). If a person is not listed in the friend or influencer list, that person could not influence the agent. This follows the small-world network definition by Watts–Strogatz [19].

Meanwhile, the company or industry can only be influenced by the account team, listed influencers, and people. If influencing happens, the agent collects influencing scores (ISM/ISF) from the marketer, account team, or influencer. The process is repeated until the PAS or CAS of the agent has surpassed (become larger than) PAST or CAST. Once an agent decides to adopt 5G, then the logic continues with MNO selection. The marketer, account team, or influencer also adds MC to the agent in the influencing activity. The agent will automatically choose MNO based on the highest MC score. If there are two or more equal color counts, then the agent selects the MNO randomly. Once the agent chooses the MNO, then the agent should buy the 5G. This represents a person buying 5G devices such as 5G smartphones or tools. If the BP is sufficient, the person will wait for one tick (one week) before finally buying. If not sufficient, then the agent will need to wait until the 5G device price drops following the Average Rate of Devices Declining Price (AADP). The assumption is one million Indonesian Rupiah (IDR) per year.

For example, a people agent with the identity number '001' starts with PAST 60, PAS 0, MC 0, and BP 3. Once the simulation starts, the agent will continuously travel across the world to different random patches. With one tick, the agent will shift to one patch (horizontally, vertically, or diagonally). The agent will continue to do so until they meet the marketer of the listed influencer. Let's say in tick 62, the agent meets an MNO red marketer. Then, PAS becomes 7.6, and the MC red becomes 1. Then, the agent continues to travel in the world. Travel here represents both physical and virtual travel, which means the interaction with the marketer or influencer is valid for physical contact, virtual meeting, digital chat, or even social media posting. Let's say in tick 85, our agent 001 meets another people agent in a patch. Since this other agent is not a listed influencer, then no influencing activity is executed. In tick 100, the agent 001 meets another agent from the list of friends/influencers, then PAS becomes 15.4, MC Red 1, and MC Yellow 1. The process is continued until the PAS becomes 74 (larger than PAST 60), and MC Red 5, MC Yellow 2, and MC Blue 1. At this point, agent 001 decides to adopt 5G using MC Red. At this point, the agent starts to become an influencer on the friend list. Since agent 001's BP is sufficient (BP threshold is 3), the agent can immediately buy 5G devices. If not, the agent needs to wait until the price drops (1 per year or 52 ticks) before finally buying 5G.

Adopting corresponds to the state of mind that a person has decided to adopt 5G even though they have not bought it. An agent will not use 5G for sure before buying it, but the agent can already promote 5G to another agent. It is only a matter of time until the agent buys the 5G technology. The buying time depends on the buying power of the agent. If the buying power is high, then the waiting time is short. If the buying power is low, the waiting time is quite long following the 5G technology price reduction. However, this does not apply to the industry. The assumption is that the design, implementation, and price have been agreed upon in interaction with the sales team. Once the agent has bought the technology, it automatically becomes an influencer.

Agents (person and industry) are connected via a small-world network. The assumption is that every person has their own cluster of friends. Based on the survey data, the average number of friends who adopt (NFWA) who can influence the respondent is five persons. Those clusters of friends or influencers can only influence that person. The NFWA selection is coded such that clusters of families and friends are connected to other clusters of families and friends.

The simulation for the agent-based model runs in the NetLogo 6.2.0 application. With this application, one can show the effects of the agent in the black world and, at the same time, show several necessary plots during the running. The model consists of setup and go as the reset and start buttons. It has two principal agents—people and industry—and two influencing agents, marketers and architects. Marketers mainly influence people, while architects control the industry. Apart from that, people and industry could also be influencers once they have bought the 5G technology.

There are six sliders in the model to help the analysis. First slider is the number of people functions to determine the number of people in the world. The second slider is the proportion of people and marketers. For the choice, there should always be a higher population of people than the marketers. For architects in the industry, ratios are static in this model.

Meanwhile, the last four sliders relate to the qualitative study of this model. They are MNO sharing, government incentives, local government participation, and infrastructure co-development and innovation. Those four last sliders are potential improvements by 5G actors for technology development. Aside from that, two switches are created to regulate the influencing scenario. Memory-on means each agent has their list of influencers from the beginning, while memory-off signifies the opposite. Friend-on means all people can influence, while friends-off indicates only listed influencers can influence decision-making. The NetLogo interfaces of the 5G diffusion model can be seen in Figure 13.

Several pieces of trivia information are provided in the interface, such as the number of people, industries, marketers, and accounts. This information is retrieved from people-number and proportion-people-marketers sliders. Other information includes the number of people adopting and the number of people adopting per colored MNO. The same information is also provided for the industry. The model also indicates the ARPU (average revenue per user) per MNO, which the user can input accordingly. ARPU numbers are taken from the three biggest MNOs in Indonesia from 2020 multiplied by 34% in this simulation. As reported, 5G could contribute to higher ARPU for MNO [31].

The last part of the interface is the graphic plots, consisting of five pieces of information. The first and second plots present the number of people or industries adopting in green and gray lines. The third and fourth graphics show the number of people or industries per MNO, while the last plot displays the generated revenue. The income per MNO is indicated by the number of adopters in that MNO, multiplied by ARPU, then added with the number of industry adopters born by ARPU. Specifically, for the industry, the number of industries is multiplied by 10, which is an assumption of the average number of users in one industry. Table 3 provides the list of assumptions in building this ABM Model.

$$\text{Revenue per MNO} = (\text{Number of people adopters} \times \text{ARPU}) + (\text{Number of industry adopters} \times \text{ARPU} \times \text{average devices}).$$

$$\text{Total Revenue} = \text{Revenue MNO Red} + \text{Revenue MNO Yellow} + \text{Revenue MNO Blue}$$

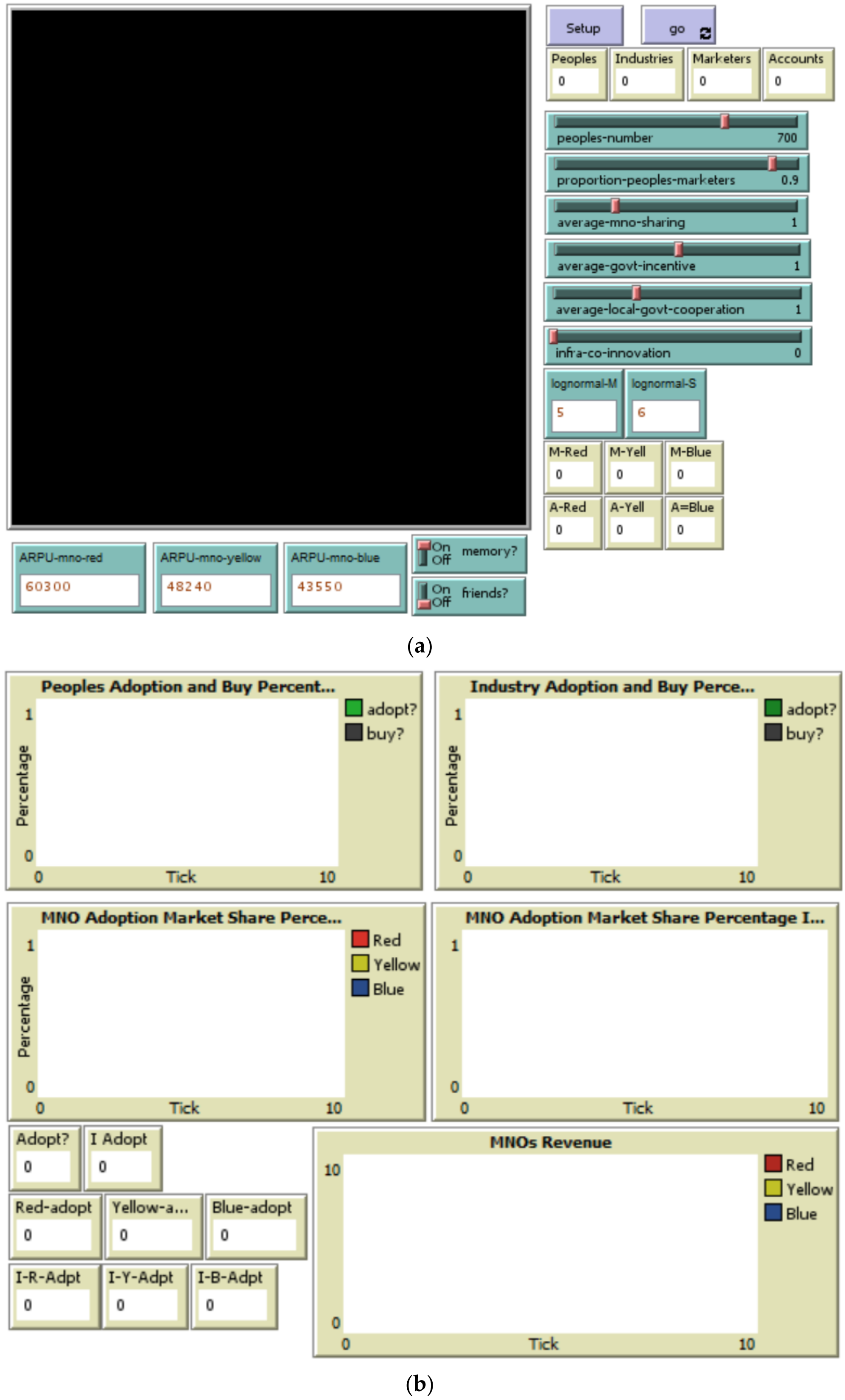

Figure 13. The 5G diffusion model interface: (**a**) input and world; (**b**) output and plot.

Table 3. List of assumptions in model building.

No	Parameters	Definition	Qualitative	Quantitative
1	Person Adoption Score Threshold (PAST)	The notion is that each person has a specific adoption score.		Empirical data from the survey (Figure 3). The distribution of PAST follows the distribution of survey results.
2	Company Adoption Score Threshold (CAST)	The notion is that each company has a specific adoption score.		Empirical data from the survey (Figure 4). The distribution of PAST follows the distribution of survey results.
3	Influencing Score Marketing (ISM)	The notion is that each marketing activity has an influencing score to a person or company.		Empirical data from the survey (Figure 5). The influencing score is the average score of survey data.
4	Influencing Score Friend (ISF)	The notion is that each word of mouth from friends has an influencing score on a person or company.		Empirical data from the survey (Figure 6). The influencing score is the average score of survey data.
5	The threshold number of friends who adopt (NFWA)	The notion is that there is a personal preference to wait for others before adopting any technology.		Empirical data from the survey (Figure 7). The result shows the listed number of friends or influencers to be injected into each person/industry, which is 10.
6	Activities to Enhance Adoption	Collaboration activities by stakeholders can enhance the adoption rate.	MNO Sharing, government incentives, local government cooperation from FGDs and interviews (Tables 1 and 2).	
7	Additional Influencing Score Marketing (AISM)	Effect of collaboration activities on the elevation of score influence. The collaboration will reduce cost, which is then used for additional marketing activities.	Discussion with marketing managers and experts about the type of marketing and cost of each activity.	Respondents were asked to score various kinds of marketing activities. Empirical data (Figure 8). AISM = (P/C)AST × Constanta
8	MNO Colors (MC)	The number of colors saved by agents to determine the MNO selection. The original colors come from marketing agents.	Analysis of real-life data observations. The assumption is that agents will adopt the most colors (brand or product), which influences them.	
9	Price of Devices (POD)	Price of 5G devices which are suitable to respondents		Direct questions of suitable prices of 5G devices (Figure 9).
10	Average Rate of Devices Declining Price (ADDP)		Data observed from the Internet. The assumption is that there is a 1 million IDR reduction that happens per year.	
11	1 tick = 1 week		Analysis of real-life data observations. The assumption is that a person will buy the device on weekends.	
12	Average subscribers/devices per industry (ASPI)		Analysis of real-life data observations. The average is 10 devices per industry user.	

3.2. Model Verification and Validation

The 5G diffusion model is based on quantitative and qualitative investigations, as previously stated. The quantitative survey aids in determining the distribution of buying power, influence score, and listed influencers. On the other hand, it aids in determining the influence of infrastructure plans on dissemination time, revenue, and MNO competition. These two methods become the foundation for this model to be as close to the reality for the 5G diffusion process. This project uses iterative modeling for model verification since a programmer is hired to code the model [32].

Monitor checking for an agent was also performed as soon as the NetLogo model was done for further explanation. The inspection began with the setup and one agent was examined. The adoption threshold, adoption-prob, wealth, current adoption score (made from 0), friend list, MNO colors (beginning from grey), friends-met, marketers-met, and peoples-met were among the parameters to be investigated. The agent was then monitored, and the ticks were tested ten times each. As expected, the current adoption score and MNO color grew every time the agent met the marketer or listed influencer (friend list). The procedure was repeated until the adoption threshold was reached, at which point the agent chose the MNO color with the highest MNO value. As shown by this monitoring effort, the model is valid.

In terms of diffusion time, the result of this model is in line with the previous 4G generation. The model shows 5–6 years diffusion time of 85% in the third year, 90% in the fourth year, and above 95% in the fifth year adopting 5G. This model aligns with the 4G diffusion time in big cities in Indonesia—e.g., Jakarta—which started in 2014 and reached around 85% in 2018 and 95% in 2020 [33–35]. Similarly, the punch of the 5G industry as users started in 2021 or three years after 5G began in the US [36]. This study also shows that the industry as 5G users is likely to grow in Year 3 after its launch.

Lastly, a trusted model for diffusion of innovation in the agent-based model area is the factual feature. One of the proofs to show this is through the S-curve produced in running the model [37]. The model of this study generates the perfect S-curve results for 5G diffusion. Even the model shows the improvement of the S-curve, as some parameters are modified as expected. The model and simulation have also been discussed in consultation with an MNO SME to confirm the results.

4. Results

The simulation results are shown in Table 4, which consists of the number of marketers and accounts per MNO and simulation. The simulation was repeated using the same input conditions. It can be concluded from Table 4 that the number of adopters—both people and industry—is influenced by marketers and accounts. Particularly with industry adopters, the number of accounts with specific influence scores can win the competition longer. This is because the marketing effort somehow escalated even more with word of mouth. If the number of marketers and accounts is equal or even close, every MNO has the chance to win.

In real-life strategy, this can be interpreted that an MNO should strategize marketers and accounts as efficiently as possible to influence people and industry despite differences in influencing capability. The accumulative influencing score of those forces can be seen in the result of adopters in the long run. However, the marketing and account teams should also be the most efficient, as abundant resources can lead to high expenditure without additional impact to adopters [37]. In the telecommunication industry, marketing, and sales account activities must include the efforts of an MNO to fix their network, as the quality of the network could somehow escalate the WoM in the real world. More applicable for the industry as consumers, the account team who sells the solution must also influence the external field, expenditure, or operational cost savings [38].

Table 4. Ten simulation results for different marketers and accounts.

Setup & Results	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5	Sim 6	Sim 7	Sim 8	Sim 9	Sim 10
Number of Red Marketers	36	32	30	27	31	36	33	30	33	29
Number of Yellow Marketers	13	15	14	14	19	7	17	15	15	18
Number of Blue Marketers	20	22	25	28	19	26	19	24	21	22
Number of Red People Adopters	280	250	231	184	243	263	302	225	260	229
Number of Yellow People Adopters	131	145	134	125	192	56	165	148	164	183
Number of Blue People Adopters	206	219	248	395	180	298	141	236	189	204
Number of Red Accounts	8	7	7	2	6	8	2	7	9	10
Number of Yellow Accounts	4	3	3	5	4	2	3	4	3	2
Number of Blue Accounts	2	4	4	7	4	4	9	3	2	2
Number of Red Industry Adopters	36	29	29	27	24	29	7	28	41	49
Number of Yellow Industry Adopters	26	17	24	14	21	6	9	18	16	12
Number of Blue Industry Adopters	8	24	17	28	25	35	54	24	13	9
Revenue of Red MNOs (mio IDR)	28.3	21.3	21	8.2	18	21.4	8.7	20.2	28.6	36.1
Revenue of Yellow MNOs (mio IDR)	14	10	13.3	13.5	12.5	3.6	6.3	10.5	9.6	7.9
Revenue of Blue MNO (mio IDR)	5.5	13	10	19	12.8	18.4	25.1	13	7.7	6.3

This study simulates 5G development scenarios in Indonesia from the previous research using scenario planning: the optimistic champion and the wait-and-respond scenarios [24]. The simulation focuses on the proposed activities in the infrastructure part for 5G development, as shown in Table 1. The wait-and-respond scenario is translated into 1-1-1-0 in the sliders, signifying MNO sharing in trim level, the government incentive merely through USO for remote areas, inadequate local government cooperation, and limited co-innovation among 5G stakeholders. Alternatively, the optimistic champion is translated into 4-2-3-2—indicating sufficient MNO sharing, the government incentive through USO and frequency sharing discount, proactive local government, and the leverage of co-infrastructure development and innovation, such as dynamic spectrum sharing and Open RAN. The simulation results are shown in Table 5 —including the KPI, tick number, the two scenarios, and remarks.

Table 5. Simulation results of the wait-and-respond and the optimistic champion scenarios.

KPI	Tick Number	The-Wait-and-Respond	The-Optimistic-Champion	Increment
Number of people adopters	156	531	593	11.7%
	208	574	607	5.7%
	260	596	620	4.0%
Number of industry adopters	156	13	25	92.3%
	208	35	48	37.1%
	260	58	65	12.1%
Total revenue all adopters (Mio IDR)	156	11.18	18.18	62.6%
	208	23.7	31	30.8%
	260	36	40.3	11.9%

It can be concluded that the results from Table 5 and Figure 14 form an S-curve, with 4-2-3-2 scenarios being more vertical compared to 1-1-1-0 scenarios. Since this model assumes a tick is one week, simulations of tick numbers 156, 208, and 256 represent three, four, and five years in real life. The simulation was run twice, and data were captured three times in ticks 156, 208, and 256 for each scenario. The results show that the optimistic champion scenario would greatly affect numbers at the beginning of diffusion years. However, there would be less improvement in the later years. As seen in the table, the increment for tick 156 is as high as 11.7, 92.3, and 62.6%—respectively for the number of people adopters, the number of industry adopters, and total revenue. The increment reduces to 5.7, 37.1, and 30.8% in tick 208 and 4.0, 21.1, and 11.9% in tick 260.

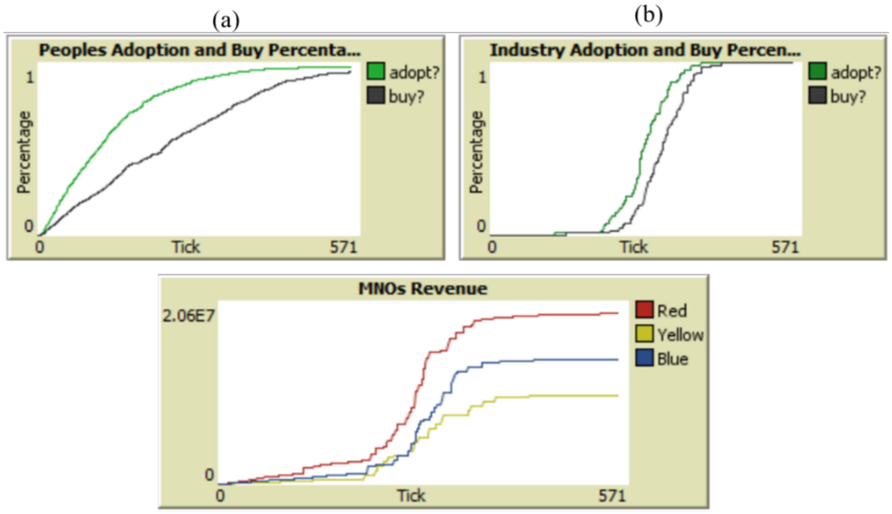

Figure 14. S-Curve for (**a**) people to adopt and buy; (**b**) industry to adopt and buy; (**c**) revenue per MNO.

When the simulation is run 30 times and ticks reach 95% of 5G adoption, the two scenarios result in a distribution of a particular standard deviation. The results clearly show the improvement of diffusion time. In the first scenario of the wait-and-respond, the time to reach 95% adoption varied between 245 and 273 ticks, with the median time reaching 258 ticks and the mean of 261 ticks with a standard deviation of 21. On the other hand, the optimistic champion scenario showed acceleration to reach 95%—around 155–187 ticks—with a median of 167 ticks and an average of 172 ticks with a standard deviation of 21.6. The average improvement of diffusion time to shift from the wait-and-respond scenario to the optimistic champion scenario was about 34% faster. The difference in diffusion time between the two scenarios can be seen in Figure 15.

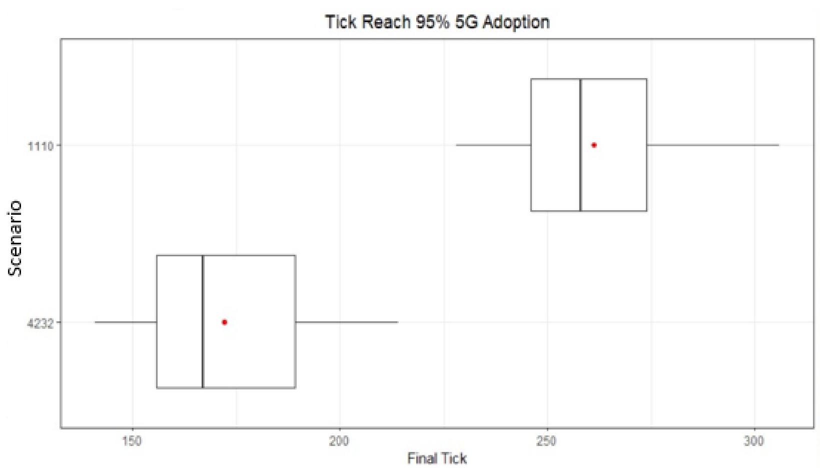

Figure 15. Two scenarios' simulation results for diffusion time.

Sensitivity analysis has been conducted to verify whether the model works as designed and to find the most impacting factor [8]. The first attempt is to assign each MNO marketer and account as 0. There is no single adopter in the simulation result with an MNO with no marketer or account. This indicates that the model is running as designed. Another sensitivity analysis is finding each qualitative slider effect: MNO sharing, government incentive, local government participation, and stakeholders' co-development and co-innovation. The results are shown in Figure 16.

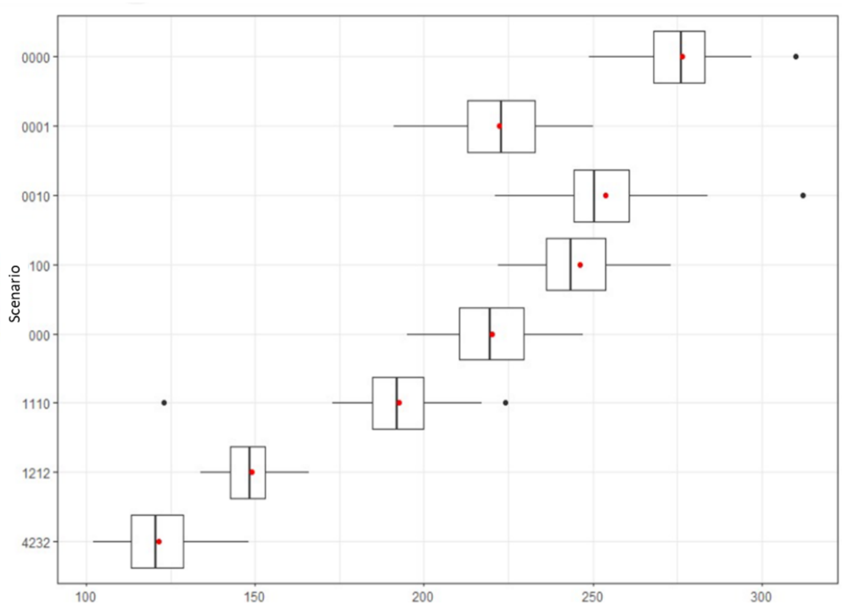

Figure 16. Sensitivity analysis for each slider.

The sensitivity analysis was run 30 times for each scenario, resulting in varied outcomes and distributions. The red dot shows the mean and the line within the white box is the median of the distribution. Each scenario has an impact in reducing diffusion time to some extent. The combination of scenarios is also manifested in the analysis—concluding that the more 5G stakeholders make an effort for MNO sharing, government incentive, local government cooperation, and co-development and co-innovation, the shorter the diffusion time and the higher the benefits received. MNO sharing and co-development and co-innovation are the two highest factors in accelerating the diffusion time.

5. Conclusions

This study contributes to the simulation collaboration model for 5G development in urban societies. The model enquires into the impact of the collaboration model on the diffusion of 5G technology among adopters. A combination of qualitative interviews, FGDs, and quantitative surveys resulted in a distinguished model. The result of this study shows an alternative paradigm from the Diffusion of Innovation theory. The empirical data and simulations indicate the distribution of 5G adoption as a log-normal distribution, differing from the normal distribution in the diffusion of innovation. The innovator in this log-normal distribution becomes the highest group number. This might be because urban people are more comfortable with technology or innovation and curious about the latest mobile network generation after experiencing 2G, 3G, and 4G. Additionally, the simulation results show that promoting a full collaboration model shortens the diffusion time by 34% compared to the current limited stakeholders' cooperation. The result also indicates that MNO sharing is the highest impact collaboration activity compared to co-innovation, government incentive, and local government cooperation.

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Data Availability Statement: The model is implemented in Netlogo 6.2.0 and the code is available online here https://www.comses.net/codebase-release/c7ad5f56-689e-459b-a7c4-618a656174a3/ (accessed on 12 November 2021).

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