

# Data Science Research Project

## Agent-based Modelling for Market Diffusion Research

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### ABSTRACT

This study based on Bass diffusion theory, combined with Agent-based modeling and complex network theory, to explore the diffusion dynamics of innovative products in the market. The research focuses on the impact of individual behavior, social network structure, and market composition on the diffusion process, aiming to provide deeper insights than traditional aggregation models. We construct a flexible simulation framework that integrates key factors such as innovation coefficient, imitation coefficient, proportion of consumer types, and different social network structures. Through systematic parameter adjustments and multiple simulations, the study reveals how these factors influence the diffusion process individually and interactively. Results show that the ratio of innovators to influential individuals has a significant impact on early adoption rates, while social network structure moderates the speed and scope of information dissemination. We also discovered “critical points” for certain parameter combinations, beyond which the diffusion rate increases dramatically. Furthermore, research highlights the importance of considering consumer heterogeneity and network effects in accurately predicting market dynamics.

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# 1 Introduction and Research Question

## 1.1 Introduction

## 1.2 Research Background

In today's rapidly changing market environment, understanding the diffusion process of new products and innovative ideas is crucial for companies and policymakers. Traditional diffusion models, such as the Bass model, provide us with valuable insights at the macro level, but often fail to capture the complexity and diversity of individual behaviors at the micro level. With the increasing popularity and influence of social networks, the interaction and information dissemination between consumers have become more complex and dynamic. In this context, combining traditional diffusion theory with modern computational methods, especially using agent-based models (ABM) to simulate market diffusion processes, has become a very promising research direction.

## 1.3 Research Objectives

This study aims to build an innovative market diffusion simulation framework that integrates the theoretical foundation of the Bass diffusion model and the micro-simulation capabilities of ABM. This integrated approach allows us to simulate the behavior and interactions of individual consumers more finely, while considering both external influences and internal influences. Our model specifically introduces the key attribute of "influencers" to improve the representation of agent heterogeneity and to be closer to the role distribution in real social networks. In addition, this study embeds agents in different types of network structures, aiming to deeply explore the impact of social network topology on the innovation diffusion process.

## 1.4 Research Significance

This research is of great significance at both theoretical and practical levels:

- Theoretical level: This study provides a new analytical framework for innovation diffusion research by integrating traditional diffusion theory and modern computational methods. This not only helps bridge the gap between macroscopic diffusion models and microscopic individual behavior, but also provides a new perspective for our understanding of emergent behavior in complex systems.
- Practical level: For businesses and policymakers, more accurately predicting and understanding the innovation diffusion process can bring significant economic and social benefits. The results of this study can help companies optimize their market strategies and more effectively identify and utilize key influencers, thereby accelerating the market penetration of new products. For policymakers, these insights can guide them to formulate more targeted innovation policies and promote technological progress and economic development of the entire society.

## 1.5 Research Questions

This study aims to explore the following key issues: the relationship between the probability distribution of individual acceptance in the market and the product diffusion rate; the role of innovators and opinion leaders in product diffusion; the impact of consumer group heterogeneity on product diffusion; the interaction of multiple factors (such as innovation coefficient, imitation coefficient, proportion of innovators, proportion of influencers) on product diffusion; and the impact of social network structure

on product diffusion dynamics. By studying these issues, we hope to fully understand the innovation diffusion process in a complex market environment and provide valuable insights for theoretical research and practical applications.

## 1.6 Structure of the Report

This research report is structured as follows:

- Literature Review (Section 2): This section provides a comprehensive review of the literature on innovation diffusion theory, the Bass model, agent-based modeling, and network diffusion. It also discusses the limitations of the Bass model and the advantages and challenges of ABM.
- Methodology (Section 3): This section introduces the model framework, agent attributes, social network structure, and diffusion mechanism of the ABM model for market diffusion research. It also presents the simulation plan design and the implementation of the ABM model using the Mesa framework.
- Simulation Results (Section 4): This section presents the simulation results of the ABM model for market diffusion research, including the impact of individual behavior, social network structure, and market composition on the diffusion process. It also discusses the interactive effects of multiple factors on product diffusion dynamics.
- Discussion (Section 5): This section analyzes the simulation results, interprets the findings, and discusses the implications for innovation diffusion research and practical applications. It also highlights the research contributions and limitations.

# 2 Literature Review

This section presents the literature review part of the report and serves as the theoretical foundation for all subsequent research. In Section 2.1, we introduce the Bass model and discuss its limitations. Following this, we explore agent-based modeling and its applications in complex systems and social science research in Section 2.2. Section 2.3 focuses on network structure and the role of influencers in innovation diffusion. We then examine the application of ABM methods to the Bass model in Section 2.4. Finally, Section 2.5 summarizes the literature review, leading to the research questions proposed in Section 2.6.

## 2.1 Diffusion of Innovation and Bass Model

### 2.1.1 Innovation Diffusion Theory

According to innovation diffusion theory, proposed by Rogers (Rogers, 1976), the process of people accepting a new product usually follows the product life cycle theory and can be divided into several stages: introduction, growth, maturity and decline. In the introduction stage, only a few innovators (about 2.5% of the population) and early adopters (about 13.5%) will try the new product. As time goes by, the product enters the growth stage and more early majority (about 34%) begin to adopt it. In the maturity stage, most potential users (late majority about 34%) have adopted the product and the market tends to be saturated. Finally, it enters the decline stage, with only a few laggards (about 16%) still adopting it (Chesbrough & Crowther, 2006). The adoption process at the individual level includes stages such as cognition, interest, evaluation, trial and final adoption (Everett, 2003). Different types of consumers have different adoption times and can be divided into groups such as innovators, early adopters, early majority, late majority and laggards (Diederer et al., 2003).

### 2.1.2 Bass Diffusion Model

Innovation diffusion models are used to describe and predict the process by which new products or technologies are gradually accepted and popularized in society. The most famous and widely used

model is the Bass diffusion model (Bass, 2004). Since Frank Bass proposed the new product diffusion model in 1969, the Bass model has had a profound impact on the research of new product adoption and technology diffusion.

In Bass's diffusion model, p (innovation coefficient) and q (imitation coefficient) are two basic parameters. P is the probability that a potential user will adopt the innovation independently, reflecting external influences (such as advertising) and early adopter behavior, and is usually small (0.01-0.03). And q is the probability that a potential user will adopt the innovation under the influence of existing users, reflecting internal influences (such as word of mouth) and copycat behavior, and is usually large (0.3-0.5).

The model describes the diffusion process of new products through a simple differential equation (Equation 1):

$$\frac{dF(t)}{dt} = (p + qF(t))(1 - F(t)) \quad (1)$$

where F(t) represents the cumulative adopter ratio, and p and q represent the innovation and imitation coefficients, respectively.

The solution of the Bass model is (Equation 2):

$$F(t) = 1 - \frac{\exp(-(p+q)t)}{1 + \frac{q}{p} \exp(-(p+q)t)} \quad (2)$$

The sales volume S(t) can be expressed as (Equation 3):

$$S(t) = m \frac{dF(t)}{dt} \quad (3)$$

The core assumption of the Bass model is that the launch of new products is the result of innovation and imitation, and the probability of launch is linearly related to the number of adopters. (Boswijk & Franses, 2005).

The literature shows that the main advantage of the Bass model is that it can accurately predict the S-shaped curve and sales peak of new product sales, and the model parameters have a clear market interpretation. Although originally developed for durable consumer goods, subsequent studies have confirmed that the model is applicable to a wide range of product and service categories, including technology products and B2B market (Massiani & Gohs, 2015).

The following figure uses pure Python to simulate the acceptance process of a product by 1000 potential users ( $p = 0.03$ ,  $q = 0.38$ ) and visualize the results using Matplotlib (Figure 1):

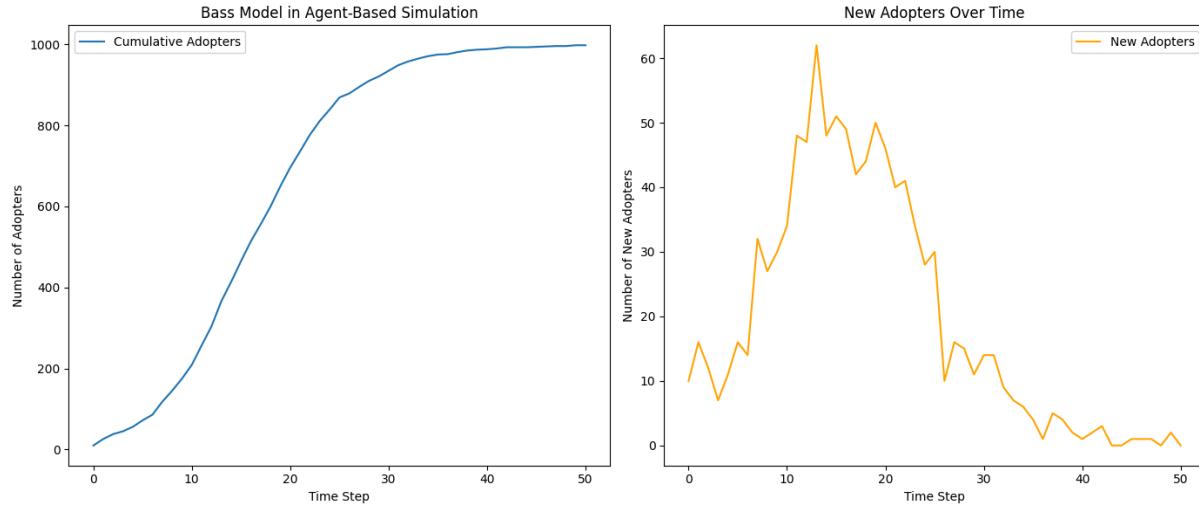


Figure 1: Visualization of Bass Model Simulation with Python [\[Code\]](#)

The influence of the Bass model is reflected in the fact that it has become the basis of many extended models. For example, the intergenerational diffusion model and the generalized Bass model developed by Bass are important developments based on the original model (Kim & Hong, 2015). These extensions further improve the scope of application and predictive power of the model.

### 2.1.3 Limitations of the Bass Model

Although the Bass model proposes a good equation to describe market diffusion, it still has some obvious limitations. First, the model is based on the assumption of homogeneity, treating all potential adopters equally and ignoring the diversity of individual decisions in the actual market. Second, the Bass model assumes that the population is fully mixed and each individual can influence others equally, thus ignoring the complex structure of real social networks. In addition, because the model operates at the aggregate level, it cannot capture the decision-making process and dynamics at the individual level. Finally, the Bass model oversimplifies the adoption process and does not reflect the many complex factors that affect the diffusion of innovation in the real world (Kumar et al., 2015). These limitations make the traditional Bass model potentially challenging in explaining and predicting certain market phenomena, especially when individual differences, social network structures, and complex adoption decisions need to be considered.

## 2.2 Agent-based Modelling and Simulation

### 2.2.1 Definition and Concept of Agent-Based Modelling

Agent-Based Modeling (ABM) is an innovative and powerful modeling and simulation approach used to study and understand the dynamic behavior of complex systems (Macal & North, 2005). The core concept of ABM is to evaluate the impact on an entire system by simulating the behavior and interactions of numerous autonomous individuals within it, known as agents. The fundamental premise of ABM is that even complex phenomena can be understood and simulated through a series of autonomous agents following specific interaction rules (Zheng, 2013).

Unlike traditional equation-based modeling methods, ABM employs a rule-based approach to construct models (Dorri, 2018), making it particularly suitable for simulating complex dynamic systems. In ABM, each agent is endowed with the ability to make autonomous decisions (Macal & North, 2009), acting based on its own state, surrounding environment, and interactions with other agents (Macal,

2016). These agents not only influence their physical and social environment but are also influenced by it, forming an intricate network of interactions.

A key feature of ABM is its capacity to capture heterogeneity within a system, allowing for the simulation of agents with diverse characteristics and behaviors, thus more accurately reflecting the diversity of the real world. Through ABM, researchers can observe and analyze how complex behaviors and patterns at the system level emerge from simple rules at the individual level. This “bottom-up” modeling approach makes ABM a powerful tool for studying emergent phenomena, adaptive behaviors, and the evolution of complex systems.

In ABM, agents are core elements with multiple characteristics, including autonomy, heterogeneity, proactivity, and reactivity. They can make independent decisions, interact with each other, learn and adapt, perceive their environment, and act according to specific rules (Davidsson, 2000). Agents typically possess bounded rationality, goal-oriented behavior, and variable internal states. These features enable ABM to effectively simulate individual behaviors and overall dynamics in complex systems.

The ABM models contains three main components: agents, environment, and interaction rules.

ABM Components	Description
Agents	Autonomous individuals with specific attributes and behavioral rules
Environment	The context in which agents operate
Interaction Rules	Governing agent-to-agent and agent-environment interactions

Table 1: Main Components of ABM

In the ABM modeling process, the setting of interaction rules, the selection of key parameters and the verification of results are the core links. The interaction rules are usually implemented by setting the behavior and topology of the agent, including the “soup” model, cellular automaton, Euclidean space, GIS and network topology (Macal & North, 2009). The key parameters cover the personal characteristics and environmental factors of the agent (Conte & Paolucci, 2014), and sometimes also include specific belief parameters (Sarvapali, 2004).

There are various methods for verifying the results: ABM simulation results can be compared with classical models or empirical data, multi-level verification methods can be used (calibrating parameters at the micro level and observing the authenticity of macro behavior) (Conte & Paolucci, 2014), or social network analysis and participatory simulation can be used to obtain agent behavior and interaction information.

However, the complexity of ABM models makes verification and calibration still a major challenge. The lack of standardized methods also increases the difficulty of result interpretation and analysis. These issues still need to be further explored and resolved by researchers.

### 2.2.2 Pros and Cons of ABM and its Applications

The main advantage of ABM is its powerful ability to simulate complex systems. It can capture complex interactions between heterogeneous agents, observe macro-emergent phenomena generated by micro-behavior (Conte & Paolucci, 2014), and provide an intuitive and realistic description of the system. The flexibility of ABM enables it to easily adapt to different scenarios and simulate the learning and adaptive behavior of agents (Dorri, 2018). It supports multi-level modeling that simultaneously considers dynamics at the individual, organizational and system levels. ABM is also spatially explicit, able to simulate the movement and interaction of agents in specific environments (Davidsson, 2000).

In addition, it provides generative explanations, can improve efficiency through parallel computing, and can be integrated with other modeling methods to enhance overall modeling capabilities.

However, ABM also faces some significant challenges and limitations. The most important of these is the difficulty of validation (Zheng, 2013). Due to the complexity of the model, it is difficult to fully verify the accuracy of the results. ABM usually requires powerful computing resources, especially for large-scale or complex models (Conte & Paolucci, 2014). In addition, calibration and validation require a large amount of detailed process data, which makes data collection difficult. The complexity of parameter calibration and the high technical requirements of the model are also important limitations. In addition, the complex interactions and emergent behaviors produced by ABM can be difficult to interpret, and there is a risk of creating arbitrary and inconsistent models. The high computational cost, the lack of unified modeling standards, and the possibility of overfitting are important aspects to consider when using ABM. Despite these challenges, ABM remains a powerful tool for studying complex systems, but its use requires careful weighing of these advantages and disadvantages.

ABM has been widely used in multiple disciplines, demonstrating its strong potential as an interdisciplinary research tool and its applicability in systems of different scales and complexities, providing researchers with a powerful tool to understand and predict complex social, economic, and natural phenomena (Macal & North, 2005).

### **2.2.3 Application of ABM in complex systems and social science research**

With the improvement of computing power, ABM is increasingly used in social sciences. Rand proposed a guiding framework for the rigorous use of ABM, covering key steps such as model selection, applicability assessment, design construction and verification (Rand & Rust, 2011).

ABM has shown unique advantages in the study of complex systems and can effectively reflect the complexity and adaptability of the system (Zheng, 2013). Through simple local rules, ABM can generate complex system behaviors, such as the collective behavior exhibited by the “Game of Life” and “Bird Flock” models (Macal & North, 2009). It can not only simulate multi-level systems and capture complex interactions between individuals and between individuals and the environment, but also allow agents to adjust decisions over time (Badham, 2018). ABM can also simulate the characteristics of complex adaptive systems (CAS), including nonlinearity, fluidity and diversity, as well as feedback mechanisms in the system (Macal & North, 2005).

In social science research, ABM provides an innovative way to integrate theory and computational methods. It applies social science decision theory (such as the BDI model) to the decision rules of agents (Zheng, 2013), and creates the emerging field of computational social science by combining data mining and complex system modeling. ABM can transform behavioral theories into computable models and calibrate them using multi-source data. It integrates multidisciplinary theoretical foundations such as complexity science, system science, and management science. Through models such as Sugarscape, ABM successfully simulates complex social processes (Macal & North, 2009). The application of ABM in areas such as trust models demonstrates its ability to integrate sociological concepts with computational models. This interdisciplinary approach not only promotes the development of social science theories, but also provides new perspectives and tools for the study of complex social systems.

### **2.2.4 Tools and Platforms for ABM Development**

UML enhances Agent-Based Modeling by providing higher abstraction, improved readability, and better modularity. It facilitates communication, documentation, and design pattern application while being language-independent. UML captures dynamic behaviors, promotes efficient modeling, and encourages professional practices, ultimately improving ABM quality and maintainability (Bersini, 2012).

ABM tools encompass a diverse range, including specialized platforms (e.g., NetLogo, GAMA), large-scale development environments (e.g., Repast, MASON), commercial software (e.g., AnyLogic), and frameworks based on general-purpose programming languages (e.g., Mesa for Python). The choice of tool depends on the user's programming experience, project complexity, and specific requirements. Pure ABM builders might find intuitive specialized tools like NetLogo more suitable, while experienced programmers may prefer tools integrated with their familiar languages. For projects requiring GIS integration or large-scale simulations, tools such as GAMA or MASON might be more appropriate. If scientific computing and graph theory related content are needed in the modeling process, it is more appropriate to use the MESA package.

## 2.3 Network Structure, Diffusion and Influencers

### 2.3.1 Network topological structure

Several studies have shown that different network topologies have a significant impact on information dissemination. By comparing the information diffusion effect of priority connection network, random network, small world network and lattice network in ABM simulation. It was found that structural characteristics such as average degree, clustering coefficient and average path length of the network are closely related to the speed and scope of information propagation. For example, small-world networks tend to exhibit faster information propagation speeds due to their high clustering and short average path lengths (Bohlmann et al., 2010).

Chen further explored the selection strategies of early adopters (seed nodes) under different network structures (Chen, 2019). The study found that the most effective early adopter identification methods may be different in different network structures. For example, the degree discount algorithm performs well in most networks, while the greedy algorithm works better in grid networks.

### 2.3.2 Influencers and Opinion Leaders in Diffusion

Influencers or opinion leaders are nodes in social networks that have a particularly important influence on the spread of information. They usually account for about 10% of network users, have a high degree of connectivity in the network, and play a key role in the widespread dissemination of information (Turnbull & Meenaghan, 1980). Studies have found that the probability of dissemination ( $p_{op}$ ) of opinion leaders is often a key factor in successfully simulating the spread of real-world information (Feder & Savastano, 2006). Ideally, early adopters are also opinion leaders, so that information can be spread most effectively. In general, influencers are widely connected and influential nodes in social networks, and play a disproportionately important role in the widespread dissemination of information (Li et al., 2021).

### 2.3.3 Node Heterogeneity and Opinion Leaders

Smith and Burow emphasize the importance of considering node heterogeneity for accurately modeling information propagation. They proposed an extended Bass diffusion model that divided nodes into different connectivity categories and took into account the correlation between nodes (Smith & Burow, 2020). Research shows that highly connected nodes (so-called "opinion leaders") play a key role in information dissemination, especially in the early stages of information dissemination.

Xue used ABM to study the spread of immunization policies in social networks. Their model considered the influence of opinion leaders and found that targeted publicity targeting opinion leaders can significantly improve the efficiency of information dissemination (Xue et al., 2016).

## 2.4 Apply ABM methods into the Bass model

#### 2.4.1 Existing research

ABMs offer significant advantages for modeling innovation diffusion compared to traditional aggregate approaches. As illustrated in the reviewed papers, ABMs can capture heterogeneity among agents, such as different consumer types in electric vehicle adoption models (Mehdizadeh et al., 2022) or varying farmer characteristics in agricultural innovation studies (Kiesling et al., 2012). They explicitly model interactions and social networks, like word-of-mouth effects in movie-going behavior (Ratna, n.d.) or peer influence in solar panel adoption (Rand & Stummer, 2021). ABMs reveal emergent phenomena from micro-level behaviors, as seen in the diffusion of organic farming practices. They provide flexibility to incorporate various decision rules, spatial effects, and qualitative factors, exemplified by models integrating psychological theories like the Theory of Planned Behavior. By enabling analysis at both individual and aggregate levels, ABMs facilitate policy experimentation, as demonstrated in studies on energy technology adoption (Nägeli, 2020) and electric vehicle diffusion (Zhang & Vorobeychik, 2016). This approach allows for more realistic representation of complex social dynamics in innovation diffusion, providing valuable insights for both theoretical understanding and practical decision support.

#### 2.4.2 Research Gap

Although there have been some cases of using ABM to study innovation diffusion, these studies still have limitations in simulating social network structure and individual heterogeneity. Many existing studies use fully connected networks or relatively simplified network models to describe the relationships between agents. For example, some studies use Moore's neighborhood network (that is, each node is connected to 8 surrounding nodes in a two-dimensional space and establishes connections with other random nodes) to simulate the innovation diffusion process (Holanda et al., n.d.). Although this simplification is computationally more convenient, it may not fully reflect the complexity of real social networks.

In addition, descriptions of node heterogeneity are often too simplistic, mainly dividing individuals into two categories: innovators and imitators. This binary classification ignores the key role of influencers in social networks. Influencers usually have extensive social connections and play an important role in information dissemination and innovation diffusion. In the real world, these highly connected individuals have a significant impact on the innovation diffusion process, but have not received sufficient attention in existing ABM research.

This simplified treatment of network structure complexity and individual heterogeneity may result in the model being unable to accurately capture innovation diffusion dynamics in actual markets. Therefore, it is necessary to develop more sophisticated and realistic ABM models to better understand and predict the innovation diffusion process.

### 2.5 Conclusion of Literature Review

By collating the literature review, the following ideas inspired our research report:

- ABM is a powerful tool for simulating complex systems and social phenomena, providing a bottom-up approach to understanding emergent behaviors.
- The Bass diffusion model is widely used in innovation diffusion research, and ABMs offer advantages for modeling innovation diffusion compared to traditional aggregate approaches.
- Influencers and opinion leaders play a key role in information dissemination, and network structure and node heterogeneity significantly impact diffusion processes. Influencers mean they have more connections in the social network.
- Network topological structure, node heterogeneity, and opinion leaders are important factors in information diffusion, and ABMs can capture these dynamics effectively.

- The main limitation of ABM is that its modeling process requires strong theoretical support and model verification is often challenging. In contrast, although the Bass diffusion model can effectively describe macro market changes, it is difficult to capture the heterogeneity and micro dynamics of individual behavior.

## 2.6 Statement of research objectives

This study aims to build an innovative market diffusion simulation framework that integrates the theoretical foundation of the Bass diffusion model and the micro-simulation capabilities of Agent-Based Modeling (ABM). This integrated approach allows us to simulate the behaviors and interactions of individual consumers more finely while considering both external and internal influences. Our model specifically introduces the key attribute of “influencer” to improve the representation of agent heterogeneity and more closely resemble the role distribution in real social networks. In addition, this study embeds agents in different types of network structures, aiming to deeply explore the impact of social network topology on the innovation diffusion process. Through this multi-dimensional modeling approach, we expect to be able to more comprehensively understand and predict the innovation diffusion dynamics in complex market environments.

And the following are our research proposals:

1. Study on the relationship between the probability distribution of individual acceptance of new products in the market and the product diffusion rate: Explore the impact of different acceptance probability distributions on the overall market diffusion process.
2. Analysis of the role of innovators and opinion leaders in product diffusion: Study how the proportion of innovators and influential opinion leaders who spontaneously accept new products affects the market penetration and diffusion speed of products.
3. Research on the impact of consumer group heterogeneity on product diffusion: Analyze the impact of the proportion of different types of consumer groups in the market on the diffusion of product acceptance, and explore the potential impact of the absence of a specific type of consumer group on the diffusion process.
4. Investigation of the interactive effects of multiple factors on product diffusion: Explore the combined impact on the product diffusion process when multiple key parameters - such as innovation coefficient, imitation coefficient, proportion of innovators, or proportion of influencers - vary simultaneously. Analyze potential synergistic or counteracting effects among these factors and how they collectively shape diffusion dynamics.
5. Analysis of the impact of social network structure on product diffusion dynamics: Study how different types of social network structures (such as small-world networks, random networks, etc.) affect the spread and adoption speed of product information, as well as the relationship between these network characteristics and key indicators of the diffusion process (such as diffusion rate, peak time, saturation level, etc.).

## 3 Methodology

In this section, we will introduce the model framework (Section 3.1), agent attributes (Section 3.2), social network structure (Section 3.3), and diffusion mechanism of the ABM model for market diffusion research (Section 3.2.2). The model is designed to simulate the diffusion process of new products in the market, taking into account the influence of individual characteristics, social network structure, and market composition on the diffusion dynamics. After that, we designed simulation experiments for the research questions (Section 3.4.2) and ran ABM using the Mesa framework (Section 3.5).

### 3.1 Model framework introduction

#### 3.1.1 Model Assumption

To address the research questions raised in Section 2.6, we built a model framework for ABM market diffusion research. It is based on the following key assumptions:

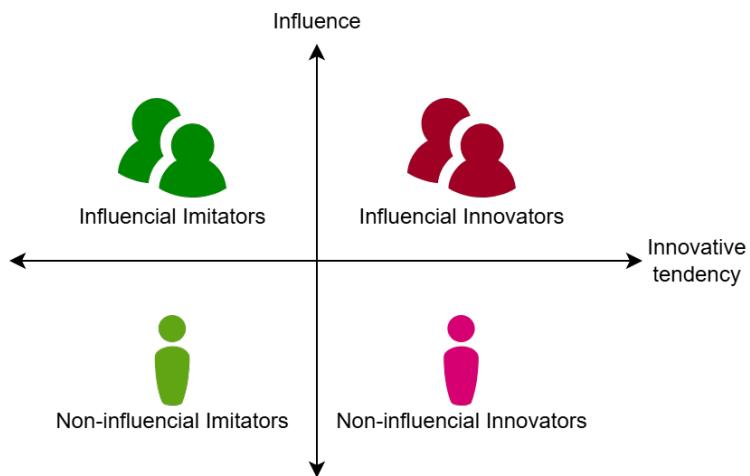


Figure 2: Market Composition of the ABM Model

- Agent heterogeneity: Agents are divided into two main types: innovators and imitators, which are further divided into influential and non-influential individuals (Figure 2). Each agent has unique attributes, including consumer type and whether it is influenced. The transition from “non-adopted” to “adopted” for the adoption status of a new product is irreversible.
- Social network structure: Product information is spread through network connections, and the relationship between agents is constructed through small-world networks and random networks. On this basis, influential agents will add more connections to simulate the role of opinion leaders or key nodes in the diffusion process.
- Diffusion mechanism: The adoption of new products is affected by two main factors: external influence (innovation effect) and internal influence (imitation effect). Innovators adopt products independently, while imitators are influenced by the adoption behavior of other consumers in the social network. The adoption probability of each agent is determined by the parameters of the innovator and imitator.
- Market composition: Assuming a closed market, a fixed number of potential adopters ( $N$ ), the total potential market size remains constant during the diffusion process, and the market consists of four types of agents: influential innovators, influential imitators, non-influential innovators, and non-influential imitators.

The market diffusion research model established based on these assumptions becomes a powerful platform for simulating and analyzing complex product diffusion processes by integrating agent heterogeneity, social network dynamics and market structure.

#### 3.1.2 Model structure

Modeling plays a crucial role in scientific research, with diverse purposes including prediction, explanation, and description. Edmonds emphasize the importance of clarifying model purposes, as this influences modeling and validation strategies (Edmonds et al., 2019). In terms of modeling strategies, KISS (Keep It Simple, Stupid) and KIDS (Keep It Descriptive, Stupid) represent two distinct approaches

(Edmonds & Moss, 2005). KISS aims to simplify models by focusing on essential elements and relationships, so in our model we choose KISS principle. We will focus on the core factors that affect the diffusion process, such as agent types, social network structure, and diffusion mechanisms.

Regarding the many ABM modeling frameworks mentioned in Section 2.2.4, considering that our model requires some support for complex networks and statistics on the agent status at each moment, We finally chose to develop with MESA<sup>1</sup>, using object-oriented programming, and consists of two main classes: BassModel and BassAgent. The BassModel class defines the overall model structure, including the network environment, agent creation, and data collection. The BassAgent class defines the properties and behaviors of individual agents.

The following UML shows the overview class diagram of the ABM model (Figure 3):

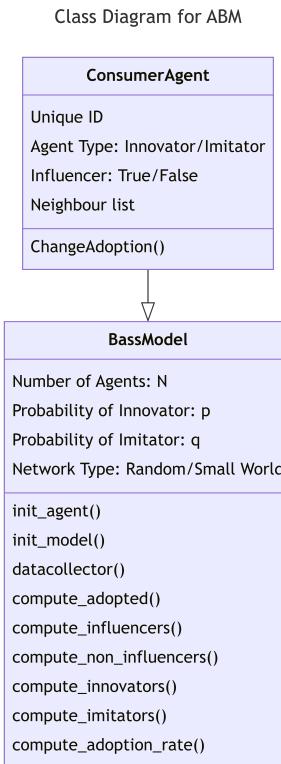


Figure 3: Class Diagram of the ABM Model

We used a bottom-up approach to design the customer (agent) and the market environment (BassModel). Bottom-up ABM starts from the micro-level, defining agents' attributes, behavioral rules, and interactions to simulate complex system dynamics (Rixon et al., 2005). This approach allows macro-level phenomena to emerge naturally from micro-level interactions, capturing the heterogeneity and adaptivity of the system (Nägeli, 2020). By constructing models from the individual level, ABM provides a unique perspective for understanding and explaining complex systems, demonstrating the advantages of bottom-up modeling approaches. The characteristics (such as the type of the consumers, the probability of accepting the product, etc.) of the user will be introduced in detail in Section 3.2, and the simulation of the market environment (like the social network type, the market scale and the proportion of different kinds of consumer, etc.) will be presented in Section 3.3.

---

<sup>1</sup>Mesa allows users to quickly create agent-based models using built-in core components (such as spatial grids and agent schedulers) or customized implementations; visualize them using a browser-based interface; and analyze their results using Python's data analysis tools. Website: <https://mesa.readthedocs.io/en/stable/>

## 3.2 Agent Attributes

### 3.2.1 Parameters for Agent Level

Each agent represents a potential consumer in the market and has the following key attributes:

- Basic attributes:
  - Unique identifier (unique\_id): used to distinguish different agents.
  - Adoption status (adopted): Boolean value, indicating whether the agent has adopted the product
- Type Attributes:
  - Consumer type (agent\_type): divided into “Innovator” or “Imitator”
    - Innovators: tend to adopt new products independently, and the adoption probability is determined by parameter p
    - Imitator: The adoption decision is influenced by others in the social network, and the adoption probability is determined by the parameter q and the proportion of neighbors that have adopted.
  - Influencer: Boolean value, divided into influential (influencer) and non-influencer (non-influencer)
    - Influential agents have more connections in the network, representing opinion leaders or key nodes in the diffusion process.
    - Non-influential agents represent ordinary consumers.
- Social network characteristics: Neighbors: A list of other agents that an agent is directly connected to in the social network.

### 3.2.2 Diffusion mechanism

We hypothesize that new product adoption is influenced by two main factors:

- External influence (innovation effect): from external information sources such as advertising and media.
- Internal influence (imitation effect): from the adoption behavior of other consumers in the social network.

So in each time step, the adoption probability of an agent is determined by:

- For innovators  $p$ : Agents independently adopt products with fixed probability p.
- For imitators  $q$ : Agents are influenced by the adoption behavior of their neighbors, and the adoption probability is determined by the proportion of neighbors who have adopted the product. The equation is ( $N$  means neighbors):

$$p_{\text{adopt}} = q \times \frac{N_{\text{Adopted}}}{N_{\text{Total}}} \quad (4)$$

## 3.3 Social Network Structure

The network structure in our ABM model is based on small-world networks and random networks. On top of these two basic network structures, We further introduced the key attribute of influencers. Influencers have more connections in the network. This design is intended to simulate the role of opinion leaders or key nodes in real society. There are three steps to build such a network:

Initialize a base network (Section 3.3.1 and Section 3.3.2) → Put agents on the network → Add connections for influencers (Section 3.3.3)

As shown in the Figure 4 below:

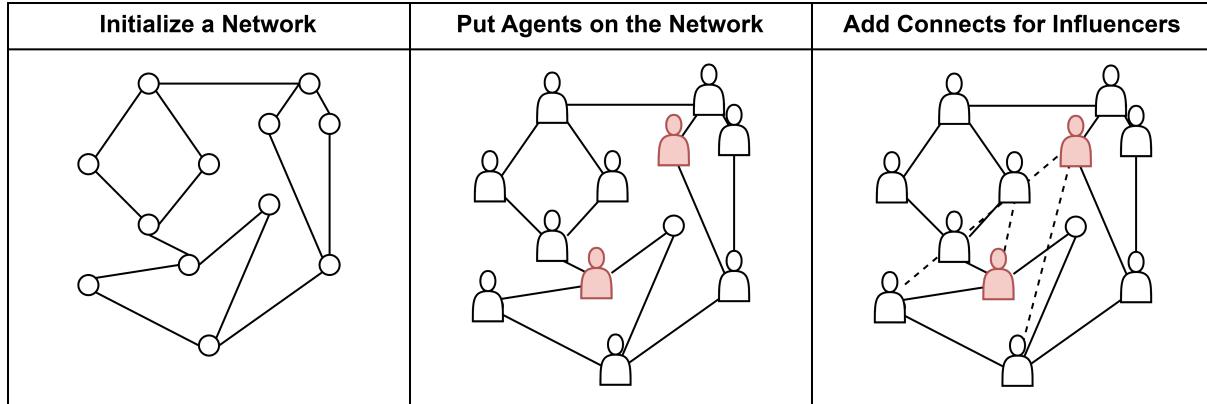


Figure 4: Initialization of the ABM Model Network

### 3.3.1 Base Network Structure

This model simulates the interconnection and influence between consumers through different social network structures. The network structure has an important impact on the information dissemination and product adoption process. The model supports 2 typical network types (small world and random network). The use the Python NetworkX library<sup>2</sup> to create the initial network structure.

The following table summarizes the key characteristics of the two network:

Characteristics	Random Network	Small-World Network
Implementation Method	Erdős-Rényi model	Watts-Strogatz model
Function	<code>nx.erdos_renyi_graph</code>	<code>nx.watts_strogatz_graph</code>
Features	Fixed probability $p$ of connection between each pair of nodes	High clustering coefficient and low average path length, simulating “six degrees of separation”
Parameters	<ul style="list-style-type: none"> <li><math>n</math>: number of nodes</li> <li><math>p</math>: connection probability (0.05 in this model)</li> </ul>	<ul style="list-style-type: none"> <li><math>n</math>: number of nodes</li> <li><math>k</math>: number of neighbors for each node (4 in this model)</li> <li><math>p</math>: rewiring probability (0.1 in this model)</li> </ul>
Potential Impact	Simulates completely random social relationships, may lead to relatively uniform information diffusion	May result in rapid local diffusion and relatively fast global information spread
Mathematical Expression	<ul style="list-style-type: none"> <li><math>P(\text{edge}) = p</math> for any two nodes</li> <li>Average degree = <math>p(n - 1)</math></li> <li>Graph is almost certainly connected when <math>p &gt; \frac{\ln(n)}{n}</math></li> </ul>	<ul style="list-style-type: none"> <li><math>C \approx \frac{3(k-2)}{4(k-1)}</math></li> <li><math>L \propto \frac{\log(n)}{\log(k)}</math></li> <li>Maintains high clustering coefficient while reducing average path length through long-distance connections</li> </ul>

Table 2: Comparison of Random and Small-World Network Models

<sup>2</sup>NetworkX is a package for complex networks. Official website: <https://networkx.org/>

The figure shows the network structure of a small-world network with 100 nodes (agents), we can see that the random network has a higher clustering coefficient and a shorter average path length compared to the small world network:

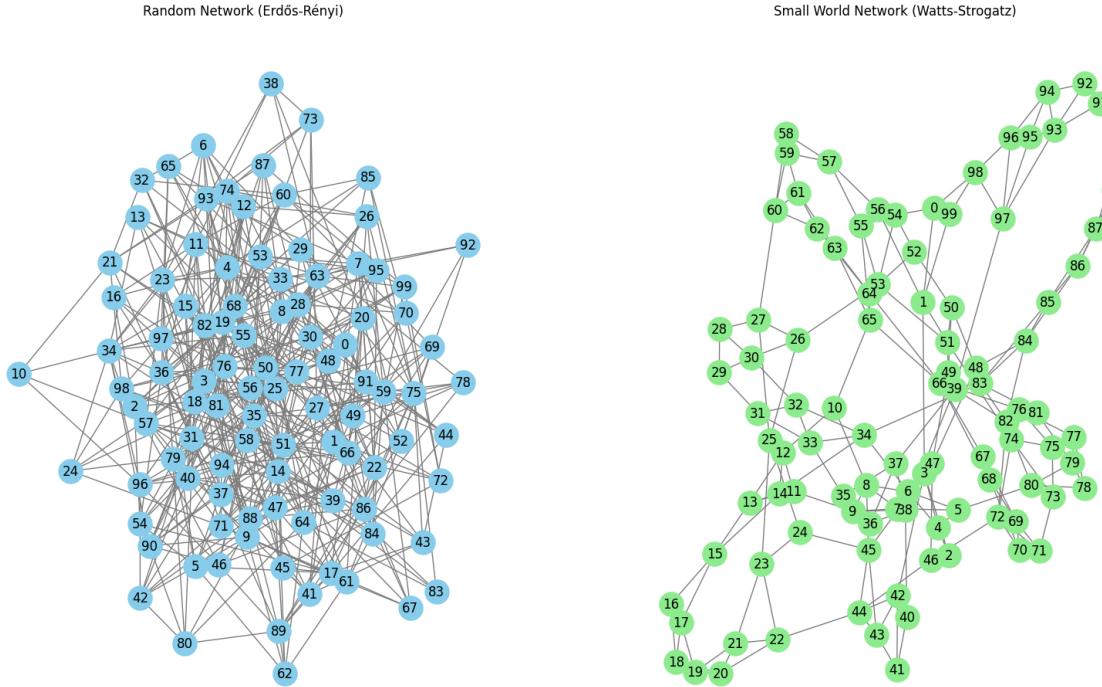


Figure 5: Random and Small-World Network Structures [Code]

### 3.3.2 Network Edge Equalization

We hope to compare market diffusion in Erdős-Rényi random graphs and Watts-Strogatz small-world networks. To ensure comparability, We use a controlled variable approach, maintaining identical node counts ( $N$ ) and total edge numbers across both network types.

We achieve two different networks in which each node has the same number of connections with other nodes by adjusting the connection probability  $p$  in the random network model and the initial neighbor count  $k$  in the small world model to achieve the same number of edges:

- For Erdős-Rényi graphs, the expected number of edges is:

$$E(\text{edges}) = \frac{1}{2} \times p \times N(N - 1) \quad (5)$$

- For Watts-Strogatz graphs, the number of edges is fixed at:

$$\text{edges} = \frac{1}{2} \times N \times k \quad (6)$$

By setting these two values equal, we can derive:

$$p = \frac{k}{N - 1} \quad (7)$$

For example, in our simulation, we set  $N = 1000$ ,  $k = 4$  in the small world network, so we can calculate  $p \approx 0.004004$  for random network.

This approach constructs network models with identical node counts and edge numbers but differing topological structures, providing an ideal platform for studying the impact of network structure on information diffusion. This way, each agent can have a similar number of neighbors before adding more links to the Influencial agent. This can be demonstrated in Section 4.1.

### 3.3.3 Add More Edges for Influencers

In social network structure research, influencers are usually defined as nodes with more connections. Here we add additional connections to influencers. This can simulate the influencer's extensive influence in the social network.

Here is the logic to implement adding more neighbors to an influencer (G means the network graph, achieved by Section 3.3.2):

<b>Algorithm 1: Rules for adding more neighbors to Influencer</b>
---

```

1: function ENHANCE-INFLUENCERS-CONNECTIONS(G, agents)
2:   for each agent in agents do
3:     if agent is influencer then
4:       Get current neighbors of agent
5:       Identify potential new neighbors (nodes not currently connected and not self)
6:       Additional Edges = min(int(25*random.random())+30, len(potential_neighbors)))
7:       Calculate number of additional edges (random between 30 to 54 ↑)
8:       Randomly select new neighbors from potential neighbors
9:       for each new neighbor do
10:        if edge doesn't exist between agent and new neighbor then
11:          Add edge between agent and new neighbor

```

Table 3: Algorithm for Enhancing Influencers' Connections

## 3.4 Model Input and Simulation Design

### 3.4.1 Model Parameters

This Model contains several key parameters that together define the behavior and characteristics of the model. The following is a detailed description of these parameters:

Parameter	Description	Impact
<b>Basic Parameters</b>		
N	Total number of agents (consumers)	Determines market size, affects network complexity and computation time
p	Innovation coefficient (0.01 to 0.03)	Higher values accelerate innovators adoption
q	Imitation coefficient (0.3 to 0.5)	Higher values accelerate imitators adoption
<b>Agent Type Distribution</b>		
agent_proportion	List of four values representing proportions of: 1. Influential innovators 2. Influential imitators	Determines market composition, affecting overall diffusion dynamics

Parameter	Description	Impact
	3. Non-influential innovators 4. Non-influential imitators	
<b>Network Structure</b>		
network_type	Options: “random”, “small_world”	Different structures lead to varied information spread patterns
p_random	Connection probability for random networks (default: 0.05)	Affects connectivity in random networks
k	Number of neighbors per node for small-world networks (default: 4)	Influences local clustering in small-world networks
p_rewire	Rewiring probability for small-world networks (default: 0.1)	Affects “small-world-ness” of the network
<b>Influence Parameter</b>		
Extra connections	Additional connections for influential agents	Simulates the broad influence of opinion leaders

Table 4: Model Parameters for Agent-Based Bass Diffusion Model

### 3.4.2 Design of the Simulation Experiment

Experimental design is a core component of methodology, which directly determines how to test research hypotheses and answer research questions. Our experimental design systematically covers changes in multiple key parameters (such as innovation coefficient p, imitation coefficient q, network type, influencer ratio, etc.) and considers their interactions to ensure the comprehensiveness and rigor of the research. Each set of experiments is iterated 5 or 25 times, and such a design captures the randomness of the model and the stability of the results. Through this systematic and comprehensive experimental design, the foundation for the analysis and discussion of the results is laid.

We designed a series of simulation experiments to explore the impact of different parameters on the product diffusion process. These experiments are divided into two categories, each containing 6 sets of experiments, conducted in small-world networks and random networks respectively. All experiments are based on a network of 1,000 agents with multiple iterations to eliminate the randomness of the simulation. Each set of experiments uses the same parameter settings in both network structures in order to directly compare the impact of the network structure. The following is a detailed description of the experimental design:

- Network Type: Small-world network experiments (simulations 1-6) and random network experiments (simulations 7-12)
- Effect of the innovation coefficient (p) on diffusion:
  - Simulations 1 and 7: Adjust the p coefficient (0.01 to 0.03), keeping other parameters unchanged.
  - Purpose: To understand how the innovator adoption probability affects the diffusion speed and pattern in different network structures.
- Effect of imitation coefficient (q) on diffusion:
  - Simulations 2 and 8: Adjust the q coefficient (0.3 to 0.5) and keep other parameters unchanged.
  - Purpose: To explore the effect of imitator adoption probability on the diffusion process in different network structures.
- Effect of influencer ratio on innovator diffusion:

- ▶ Simulations 3, 4 and 9, 10: Adjust the ratio of influencers to innovators (0 to 0.01), keeping the total innovator ratio constant.
- ▶ Purpose: To study how the proportion of influencers in the innovator group affects the diffusion dynamics of different network structures.
- Effect of the ratio of influencers to innovators on diffusion:
  - ▶ Simulations 3 and 9: Adjust the ratio of influential innovators (0 to 0.01), keeping the ratio of total innovators constant (0.01).
  - ▶ Simulations 4 and 10: Adjust the ratio of influential innovators (0 to 0.01), keeping the ratio of total influencers constant.
  - ▶ Purpose: To study how the ratio of influencers in the group of innovators affects the diffusion dynamics of different network structures. In particular, we want to study what happens when the number of influential innovators is zero.
- Interaction between innovation coefficient and proportion of innovators:
  - ▶ Simulations 5 and 11: Adjust p coefficient (0.01 to 0.05) and proportion of innovators (0.01 to 0.07) simultaneously.
  - ▶ Purpose: To explore how the interaction between innovation coefficient and proportion of innovators affects the diffusion process in different network structures.
- Interaction of innovator and influencer proportions:
  - ▶ Simulations 6 and 12: Simultaneously adjust the innovator proportion (0.01 to 0.07) and the influencer proportion (0 to 0.6).
  - ▶ Purpose: To investigate how the distribution of innovators and influencers in different network structures jointly influences diffusion dynamics.

## 3.5 Run the ABM Model

### 3.5.1 Initialize the Model

The following pseudocode outlines the core initialization process for our Agent-Based Model (ABM) of product diffusion. This initialization sets up the fundamental structures and parameters necessary for simulating the Bass diffusion model in a network context. The code demonstrates how we establish the agent population, create the social network, and prepare the model for simulation runs.

<b>Algorithm 2: Final Initialization for Market Diffusion Simulation Model</b>
--

```

1: function INITIALIZE-MODEL( $N$ ,  $p$ ,  $q$ , agent_proportion, network_type)
2:   ▷ Initialize core parameters and structures
3:   total_agents  $\leftarrow N$ 
4:   innovation_coefficient  $\leftarrow p$ 
5:   imitation_coefficient  $\leftarrow q$ 
6:   Create social network based on network_type
7:   Generate agent distribution list
8:
9:   ▷ Create and place agents
10:  for  $i = 0, N - 1$  do
11:    Create new BassAgent with properties from distribution list
12:    Add agent to network and scheduler
13:
14:   ▷ Enhance network for influential agents
15:   for each influential agent do

```

```

16:      Add extra connections
17:
18:      ▷ Initialize tracking variables
19:      steps_to_key_percentages ← None
20:      running ← True
21:
22:      return Initialized model

```

Table 5: Summary of the Model Initialization Process

### 3.5.2 Scheduler and Batch Running with MESA

Schedulers play a key role in Agent-Based Models. We chose to use the RandomActivation scheduler provided by Mesa. The main reason for using a scheduler is to manage and control the order in which agents in the model are activated. At each simulation step, the RandomActivation scheduler randomly decides the order in which to activate agents. This randomness is important because it helps avoid systematic biases that may be introduced by a fixed activation order. The Table 6 shows the difference between the five agents at each time step when using random activation and when not using random activation. In the real-world product diffusion process, the order in which consumers make decisions is often not fixed, and using random activations can better simulate this uncertainty. In addition, the scheduler simplifies the time management of the model, allowing us to easily iterate over all agents at each time step, update their states, and collect relevant data. By creating a scheduler instance at model initialization and calling `self.schedule.step()` to activate all agents at each time step, we ensure that the model runs consistently and controllably. This approach is particularly suitable for simulating social processes that do not have a fixed order, such as our product diffusion model, allowing us to more accurately capture complex market dynamics.

Time Step	Without Random Activation	With Random Activation
0	1 → 2 → 3 → 4 → 5	1 → 2 → 3 → 4 → 5
1	1 → 2 → 3 → 4 → 5	3 → 1 → 5 → 2 → 4
2	1 → 2 → 3 → 4 → 5	5 → 4 → 2 → 1 → 3
...	1 → 2 → 3 → 4 → 5	2 → 3 → 1 → 5 → 4
n	1 → 2 → 3 → 4 → 5	4 → 1 → 3 → 5 → 2

Table 6: Agent Activation: Sequential vs. Random Scheduling

Batch execution is an effective way to execute different parameter combinations in a single simulation script. With Mesa's BatchRunner, we can systematically study the impact of different parameter combinations on product diffusion. The method allows us to define parameter ranges (such as innovation coefficients and imitation coefficients), perform multiple repeated simulations, and automatically collect data. With batch execution, we can perform sensitivity analysis to understand how different market conditions affect product adoption, identify key parameters and critical points, and predict diffusion trends under different scenarios. At the same time, repeating experiments for the same parameter combination takes a lot of time. CPU multiprocessors can solve this problem when implementing batch execution capabilities to speed up the simulation process.

### 3.5.3 Data Collection

Data collection is essential for analyzing both individual agent behaviors and overall system dynamics. We employ Mesa's `DataCollector()`, a tool that enables systematic gathering of both agent-level and

model-level data. This dual-level approach allows us to track individual agent decisions and characteristics while also monitoring system-wide trends. The DataCollector efficiently gathers time-series data throughout the simulation, providing insights into the temporal dynamics of the diffusion process. This comprehensive data collection facilitates model validation, sensitivity analysis, and the exploration of emergent phenomena in product adoption patterns, enhancing our understanding of the complex diffusion process.

Level	Data Collected	Description
<b>Agent-level</b>	Adopted	Whether each agent has adopted the product
	Influencer	Whether each agent is an influential individual
	Agent_Type	Innovator or Imitator
	Neighbors	List of neighbors for each agent
	Neighbors_number	Number of neighbors for each agent
<b>Model-level</b>	Adopted_Count	Total number of agents who have adopted the product
	Influencer_Count	Number of influential agents who have adopted the product
	Non_Influencer_Count	Number of non-influential agents who have adopted the product
	Innovator_Count	Number of innovators who have adopted the product
	Imitator_Count	Number of imitators who have adopted the product
	Steps_to_X_percent	Time steps required to reach 25%, 50%, and 75% adoption rates

Table 7: Data Collection in the Agent-Based Bass Diffusion Model

## 4 Simulation and Results Analysis

In this section, we will present the simulation results of our market diffusion ABM in detail and conduct an in-depth analysis of these results. First, we will present detailed statistics of a single simulation (Section 4.2), including adoption curves and network evolution visualizations, to intuitively demonstrate the diffusion process. Next, we will explore in depth the impact of different parameters on the diffusion process with sensitivity analysis, including the role of innovation coefficients (Section 4.3.1) and imitation coefficients (Section 4.3.2), the importance of the proportion of influencers (Section 4.4), the impact of network structure, etc. We will also analyze multi-factor interactions to reveal how parameter combinations jointly shape the diffusion dynamics (Section 4.5, Section 4.6).

### 4.1 Table of Neighbors between Influencers and Non-Influencers

Before doing any ABM analysis, we first need to verify the similarity of the number of connections between different networks mentioned and add more neighbors to the influencers in Section 3.3. Statistically analyze whether the influencers and non-influencers are the same in different networks. This is the premise for the following series of comparisons.

The tables below shows the average, maximum, and minimum values of the number of influencer and non-influencer neighbors in the first five simulations. The number of neighbors of an influencer is approximately 4 to 6 times that of a flying influencer (Table 8).

RunId	Inf Mean	INF Max	Inf Min	Non-inf Mean	Non-inf Max	Non-inf Min
0	49.09	62	37	8.132222	17	3
1	49.83	69	36	8.152222	15	3
2	50.24	65	35	8.215556	16	3
3	50.83	64	36	8.283333	17	3
4	49.87	65	37	8.11	17	3

Table 8: Run Data for Agent-Based Model [Code]

The Figure 6 is a statistical analysis of the number of neighbors of all agents in simulation 1 (visualizations of simulations 2-16 are similar). The gray-green points in the figure represent influencers and he brown points represent non-influencers. From Figure 6, we can see that the number of non-influencer neighbors in the small-world network (8.205) and the random network (8.208), as well as the mean number of influencer neighbors (50.044 in random network and 50.077 in small world network), are basically the same. We can also see that the number of influencer neighbors is much higher than that of non-influencers.



Figure 6: Neighbor statistics for Influencers and Non-Influencers [Code]

In summary, the statistics in this section verify that the number of neighbors of influencers is much higher than that of non-influencers. It also proves that the network equilibrium achieved in Section 3.3.2 makes the two networks comparable.

## 4.2 Single Run Simulation Results Statistics

### 4.2.1 Statistics of Consumer's Adoption for single simulation

This Figure 7 shows one of the market diffusion simulations, showing a classic S-shaped adoption curve. The simulation set 1% innovators and 10% influencers, with an innovation coefficient  $p$  of 0.01 and an imitation coefficient  $q$  of 0.3. The results show that a small number of innovators took the lead in adopting the product in the early stage (0-25 steps), followed by rapid diffusion between 25-50 steps,

which may be due to the network effect driven by influencers. Influential agents showed higher adoption rates, but overall imitators constituted the vast majority of adopters. The whole process reached market saturation after about 50 steps, and the final adoption rate was close to 100%.

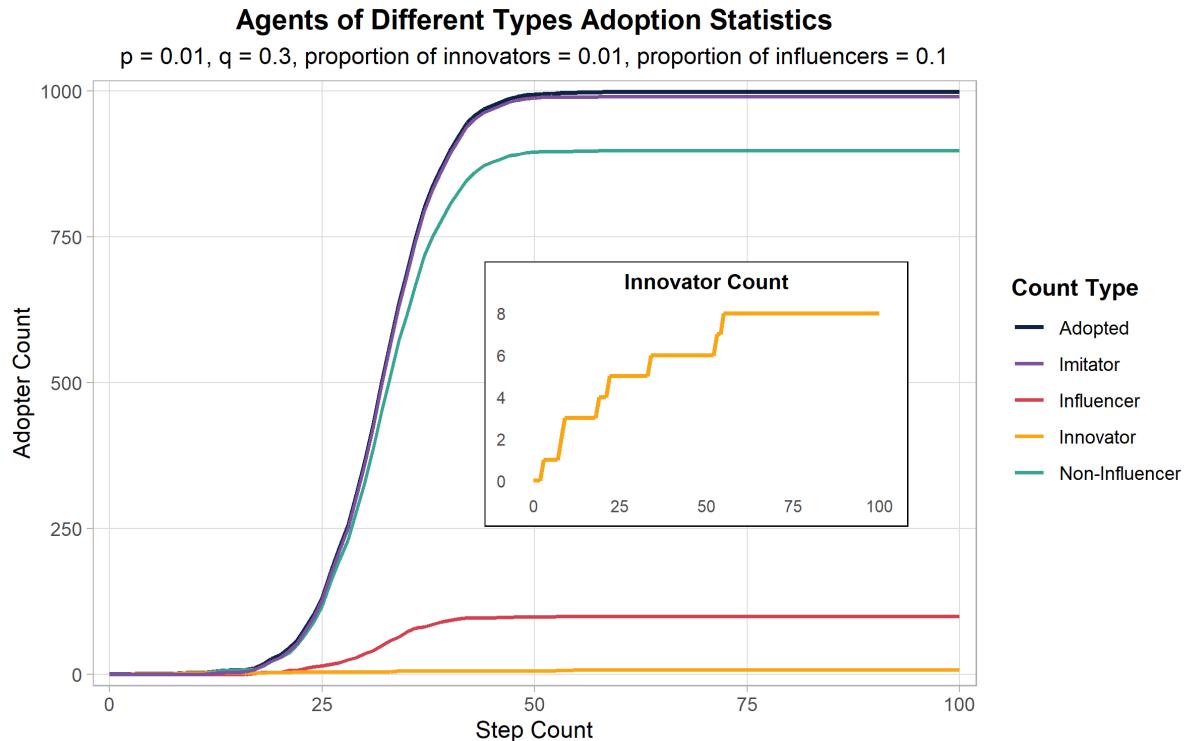


Figure 7: Adoption Statistics for a Single Simulation Run [\[Code\]](#)

It is worth noting that this simulation result (simulating the decision of every potential consumer in the market at the micro level) is highly consistent with the pattern predicted by the traditional Bass diffusion model (describing the entire market at the macro level). This consistency can be regarded as a pattern matching, which provides strong support for the effectiveness of the ABM model test. Among them, due to the relatively small number of innovators, the observation is not obvious, but in the statistics of the three groups of influencers, non-influencers and imitators, an obvious S-shaped growth curve can also be observed.

#### 4.2.2 Visualization of Network Evolution

To gain a more intuitive understanding of the process of product adoption spreading in social networks, we created a series of network graphs to visualize the time evolution of agent activations. These networks (Figure 8) were generated by the NetworkX library and visualized with igraph. In these graphs, nodes represent individual agents and edges represent social connections between them. Red nodes represent agents that have adopted the product, while blue nodes represent agents that have not yet adopted. The size of the node represents the influence of the agent, with larger nodes representing influential individuals.

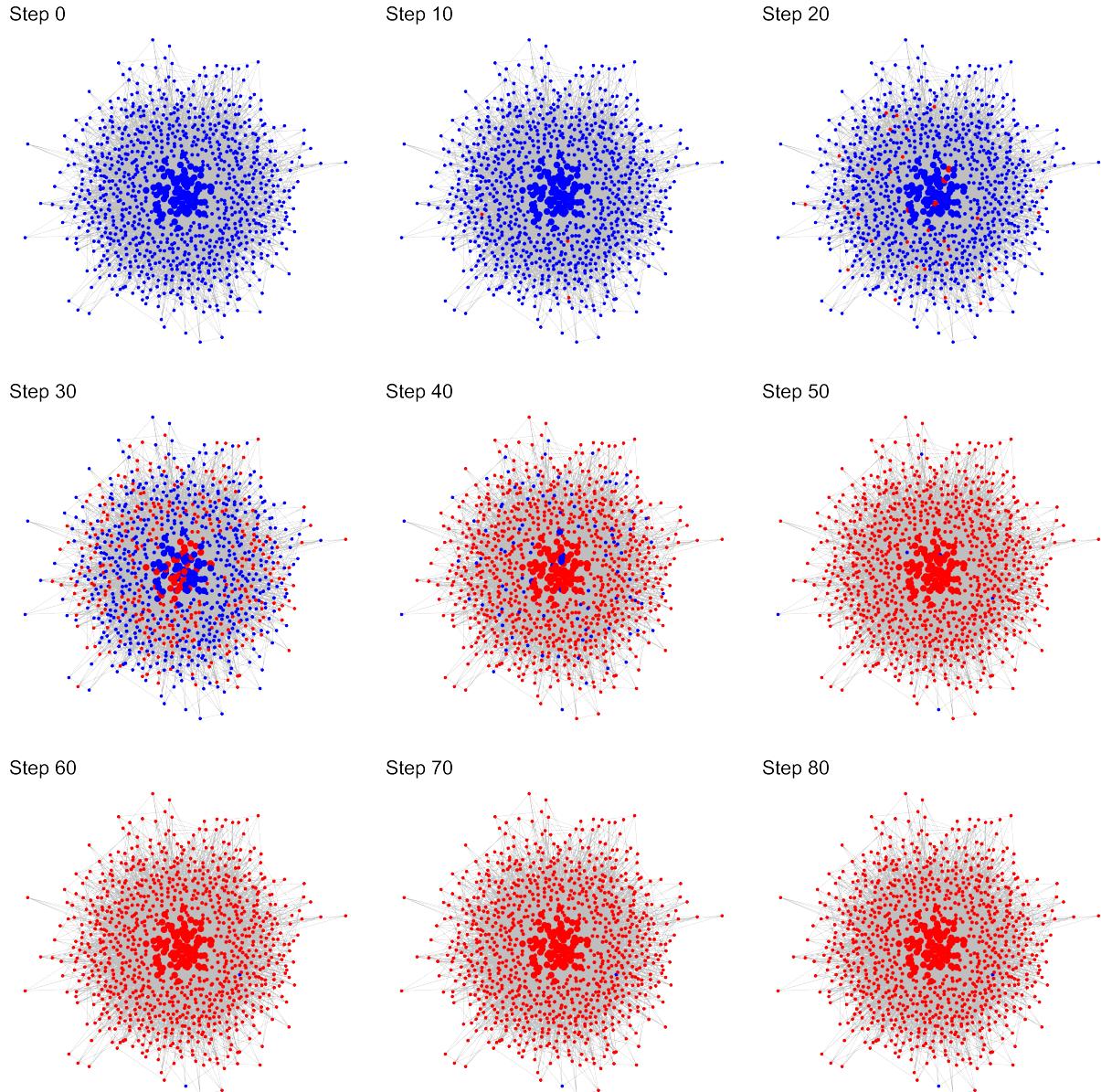


Figure 8: Network Evolution over Time from Step 0 to Step 80 [Code]

Market diffusion shows obvious characteristics of evolution over time. In the initial stage (Step 0-20), the network is predominantly blue, and only a few nodes (most likely innovators) begin to adopt the product. As time goes by to Step 30-40, we observe a significant increase in the number of red nodes, especially in the core area of the network, indicating that the product begins to spread widely among influential agents. Entering Step 50-60, the red nodes quickly spread throughout the network, marking the rapid growth stage of product adoption. Finally, at Step 70-80, the network is almost completely covered by red nodes, indicating that product adoption is close to saturation.

### 4.3 Research on Different Probability of Adoption

#### 4.3.1 Research on Innovation Coefficient ( $p$ )

The innovation coefficient represents the tendency of consumers to independently adopt new products. In simulation 1 and 7, we used the control variable method to change only the value of the innovation coefficient  $p$  (ranging from 0.01 to 0.03), while keeping all other parameters unchanged, including

the imitation coefficient ( $q$ ), network structure ( $q=0.3$ , proportion of innovators=0.01, proportion of influencers=0.1,  $N=1000$ ), overall market size, etc. For each  $p$  coefficient, multiple simulations were performed to ensure the stability and reliability of the results.

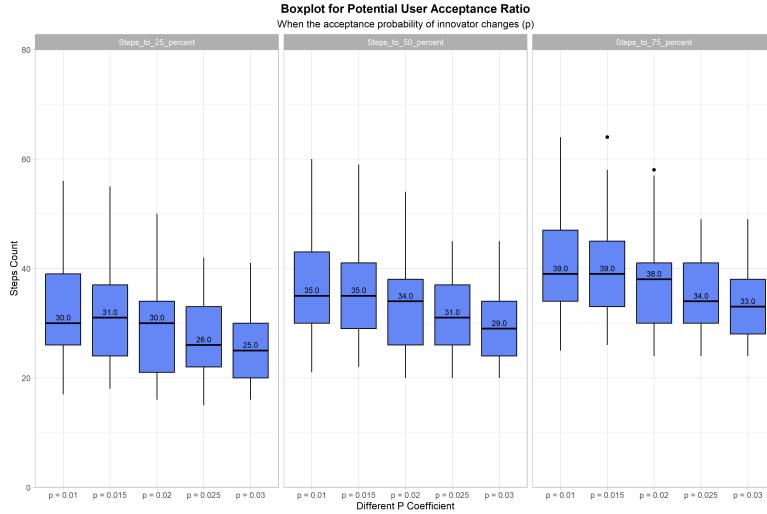


Figure 9: Innovator Adoption in Small-World Networks [Code]

This box plot (Figure 9) is made by adjusting the  $p$  coefficient from 0.01 to 0.03 while keeping other parameters unchanged in small world network. In general, as the  $p$  coefficient increases, the time required to reach 25%, 50%, and 75% adoption rates is significantly shortened, like in the early stages. For example, the median number of steps to reach a 25% adoption rate dropped from about 30 to 25. This effect weakened but still existed in the later stages (75% adoption rate). At the same time, the increase in  $p$  coefficient also led to a decrease in the variability of the results, indicating that the adoption process under high innovation coefficients is more stable and predictable. These findings emphasize the importance of increasing the innovation coefficient (such as through effective marketing) to accelerate product adoption, especially in the early stages of market penetration.

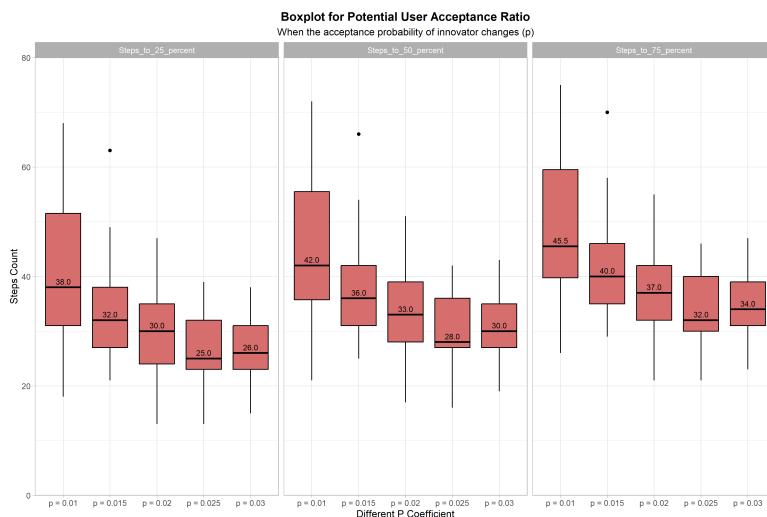


Figure 10: Innovator Adoption in Random Networks [Code]

When comparing the product adoption process in random networks and small-world networks, we can observe an interesting phenomenon: when the innovation coefficient ( $p$ ) is small, the adoption

process in the random network (Figure 10) exhibits greater variability, especially when  $p = 0.01$ , the whiskers and outliers of its box plot are wider.

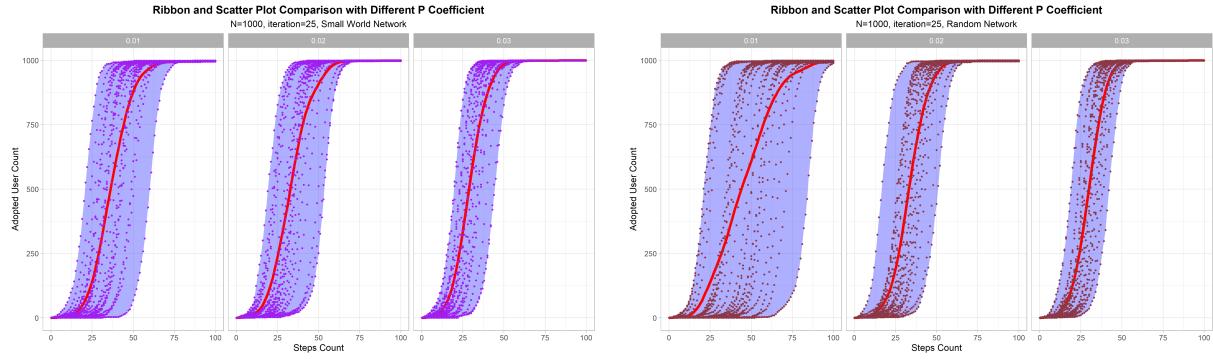


Figure 11: Comparing Innovator Adoption Across Networks [Code]

The left side of the Figure 11 shows what different  $p$  look like in a small-world network, and the right side shows what it looks like in a random network. Each data point represents a specific simulation result, the blue shaded area indicates the distribution range of the simulation results, and the red line represents the average number of steps at each  $p$  coefficient.

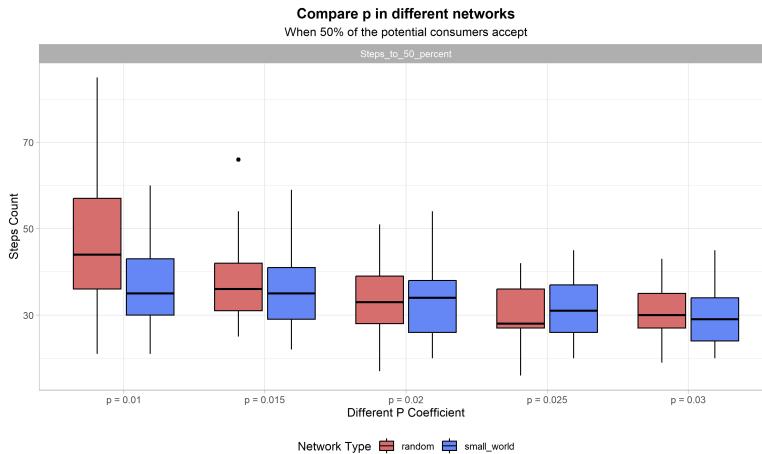


Figure 12:  $p$  Coefficient Impact at 50% Adoption [Code]

It can be seen that when  $p$  coefficient is relatively large (Figure 12), the results of the two networks are more similar. However, when  $P$  is relatively small, the coverage interval after random network simulation is larger.

We think this result may be caused by the fact that small-world networks have the characteristics of high clustering coefficient and short average path length, which may lead to rapid local propagation of information and rapid reach to other parts of the network. In contrast, the connections of random networks are more evenly distributed, but lack strong local clustering. At the same time, when the  $p$  coefficient is small, product adoption mainly depends on social propagation in the network (imitation effect) rather than independent adoption by individuals. In this case, the characteristics of the network structure become more important.

#### 4.3.2 Research on Imitation Coefficient ( $q$ )

Similar to the method of studying the innovation coefficient, in the study of the imitation coefficient  $q$  (simulation 2 and 8), other parameters are fixed ( $p=0.02$ , proportion of innovators=0.01, proportion of influencers=0.1,  $N=1000$ ), only the value of  $q$  is changed (0.3 to 0.5), and the simulation is repeated

many times. This study selects  $p=0.02$  as the baseline innovation coefficient instead of 0.01, which is based on the observation in previous experiments that the two network types showed huge differences at  $p=0.01$  (in Section 4.3.1 when  $p=0.01$  in random network, the box plot shows the results varied more than the small world network). This choice aims to reduce the interference of differences in network structure on the analysis of the impact of imitation coefficients, thereby obtaining a purer  $q$  coefficient effect. The following (Figure 13) are the simulation results when 25%, 50%, and 75% of the users are accepted in two different networks:

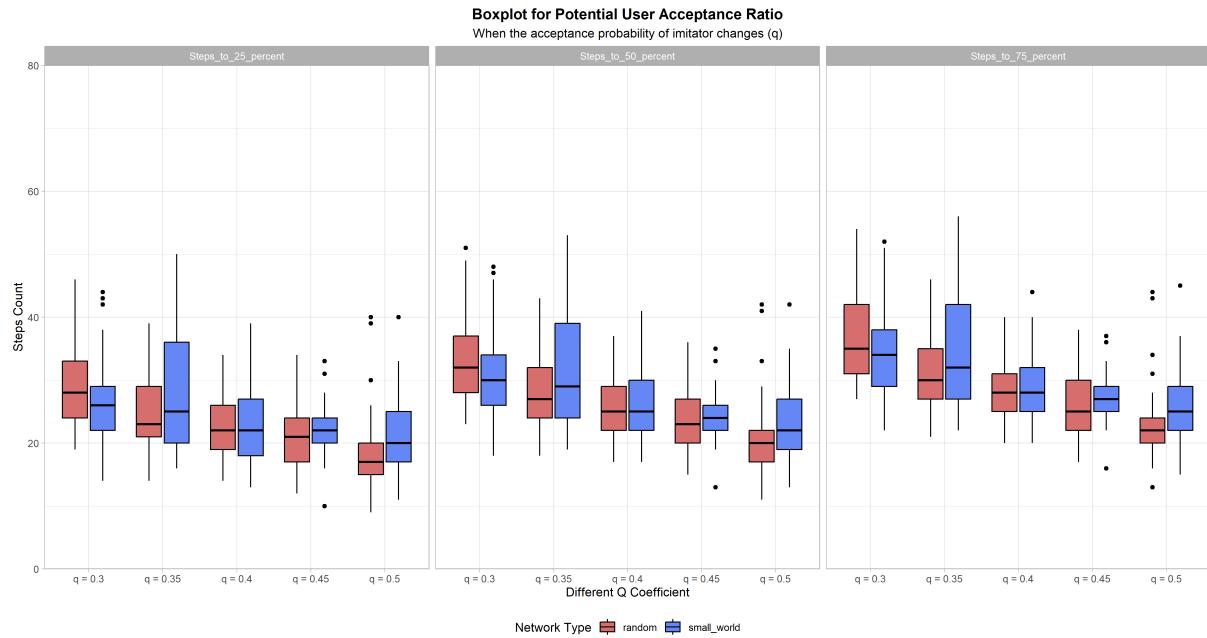


Figure 13: Imitation Coefficient Effects Across Networks [Code]

The results show that as the imitation coefficient  $q$  increases from 0.3 to 0.5, the speed of product diffusion generally shows an accelerated trend. Especially in random networks, the variability of results is significantly reduced, indicating that the propagation process under high imitation coefficients becomes more stable and predictable in random networks. However, small-world networks do not show the same clear trend of decreasing variability. Although small-world networks still exhibit slightly faster propagation speeds at lower  $q$  values, the performance gap between the two network types gradually narrows as  $q$  values increase.

It is worth noting that compared with the growth effect of the innovation coefficient  $p$  (from 0.01 to 0.02), the growth of the imitation coefficient  $q$  has a relatively limited impact on accelerating network diffusion. This finding highlights that in the product adoption process, increasing the imitation coefficient may not be as effective as increasing the innovation coefficient, especially when pursuing significantly accelerated diffusion.

#### 4.4 Research on the proportion of Influential Innovators

This section will focus on the impact of the proportion of influential innovators on the product diffusion process (Figure 14), especially when the proportion of Influencial Innovators = 0. We will study this issue through two different experimental settings: First, we will study how the change in the proportion of influential innovators affects the product diffusion process when the total influencer proportion is fixed (simulation 3 and 9). Second, we will study how the change in the proportion of influential

innovators affects the product diffusion process when the innovator proportion is fixed (simulation 4 and 10).

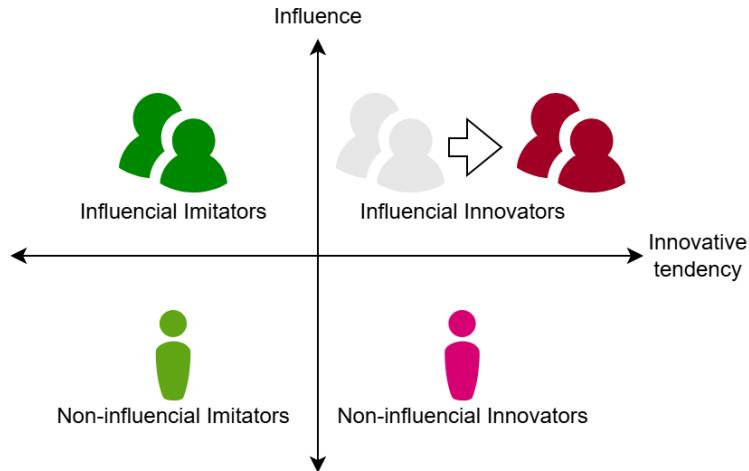


Figure 14: Research on the proportion of influential innovators

#### 4.4.1 Fixed proportion of Innovators

The Figure 15 analyzes the impact of changes in the proportion of influential innovators on the product diffusion process when the total proportion of innovators is fixed at 1% ( $p=0.01$ ,  $q=0.03$ ,  $N=1000$ ):

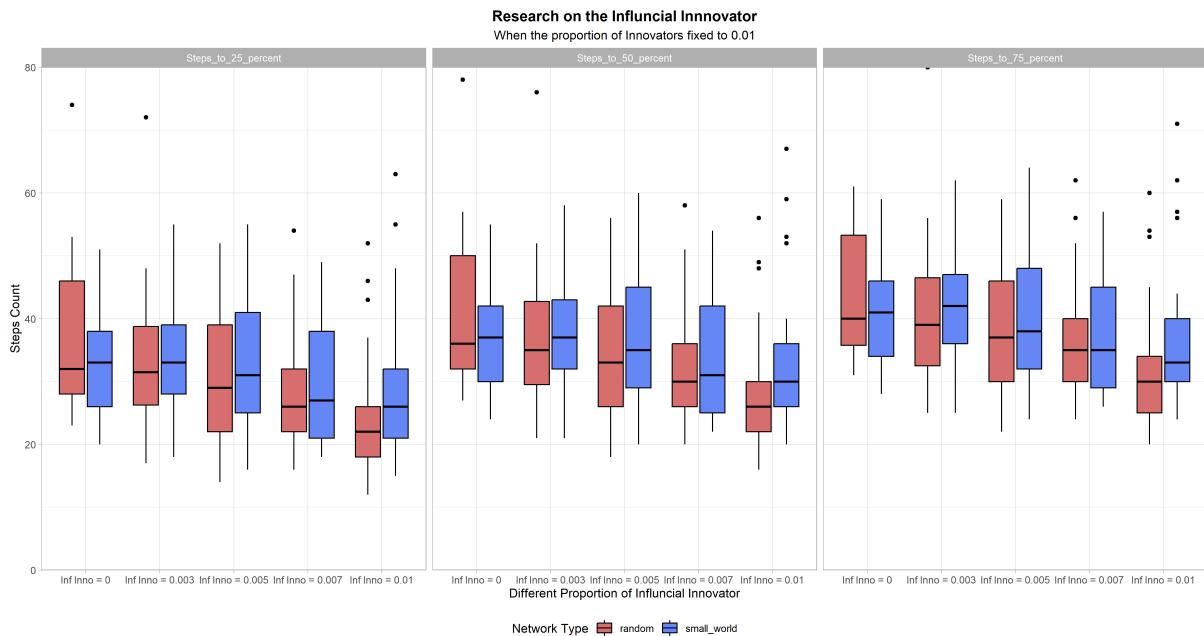


Figure 15: Scenario: Constant Innovator Percentage [Code]

From the figure, we can analyze that when the total proportion of innovators is fixed, increasing the proportion of influential innovators can only slightly accelerate the product diffusion process. Random networks and small-world networks show similar characteristics at different stages, and the overall propagation speed of random networks is slightly faster than that of small-world networks. This shows that increasing the proportion of influential innovators has limited effect on accelerating product diffusion, especially when the total proportion of innovators is low. At the same time, similar to the sim-

ulation results of the lower innovation coefficient  $p$ , a low proportion of innovators will cause greater variability in results.

#### 4.4.2 Fixed proportion of Influencers

The Figure 16 shows the effect of changing the proportion of influential innovators on the product diffusion process, while fixing the total proportion of influencers at 10% ( $p=0.01$ ,  $q=0.03$ ,  $N=1000$ ):

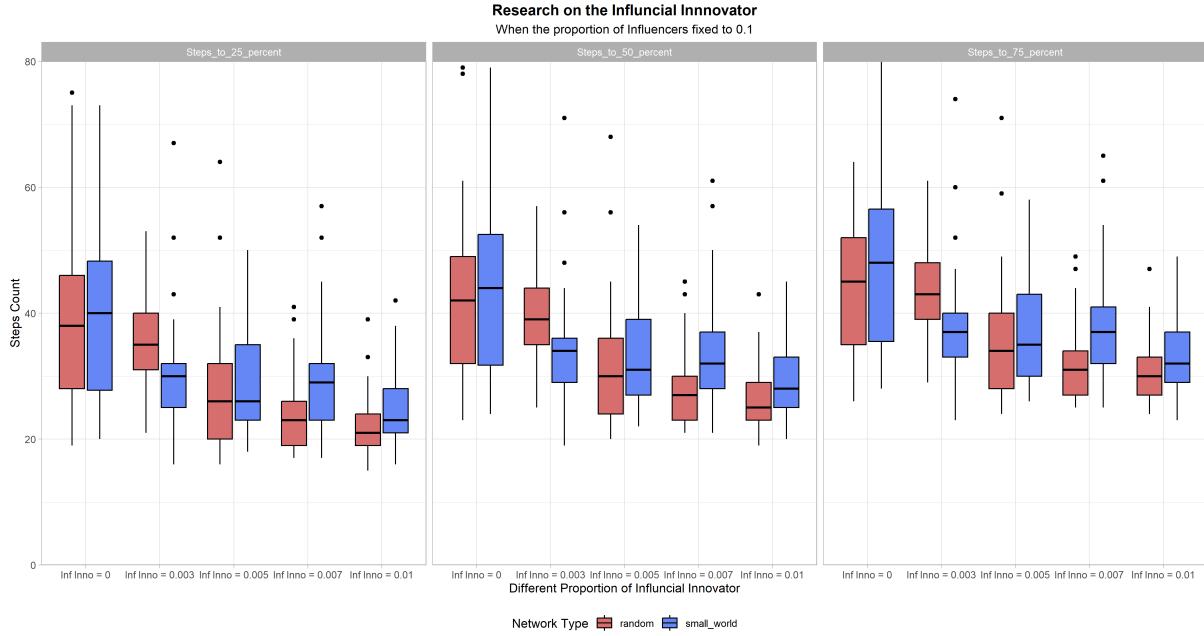


Figure 16: Scenario: Constant Influencer Percentage [Code]

It can be clearly seen from this figure that compared with the scenario where the proportion of total innovators remains constant, when the proportion of total influencers is fixed, increasing the proportion of influential innovators can significantly accelerate the product diffusion process. At the same time, as the proportion of influential innovators increases (from 0 to 0.003), the variability of the results significantly decreases.

Compared with the previous figure (Figure 15), it can be concluded that the diffusion rate of random networks is slightly higher than that of small-world networks. With the proportion of total influencers fixed, increasing the proportion of influential innovators has a more significant positive impact on product diffusion speed, while significantly reducing the variability of results, making the diffusion process more predictable. In this case, continuously increasing the proportion of influential innovators seems to continuously improve the diffusion effect. In contrast, when the total proportion of innovators is fixed, increasing the proportion of influential innovators has a small impact on the diffusion speed, the reduction in the variability of the results is not obvious, and the improvement effect is more limited. This suggests that overall market structure (especially the overall proportion of influencers) has an important impact on product diffusion dynamics when considering the role of influential innovators.

#### 4.5 Change on the Innovation Coefficient and Innovator proportion

In market diffusion research, we often need to consider the impact of multiple factors on the product adoption process at the same time. In order to intuitively show how the two key variables, the innovation coefficient ( $p$ ) and the proportion of innovators, jointly affect the product diffusion rate, I designed this set of heat maps (Figure 17). Heat maps can effectively show the interaction between two

variables and their impact on the outcome variable. In this study, each cell in the heat map represents the average number of time steps required for the product to reach a specific adoption rate (25%, 50% and 75%) under a specific combination of innovation coefficient and innovator proportion. Each value shown in the figure is the average result of five independent simulations with the same parameter settings.

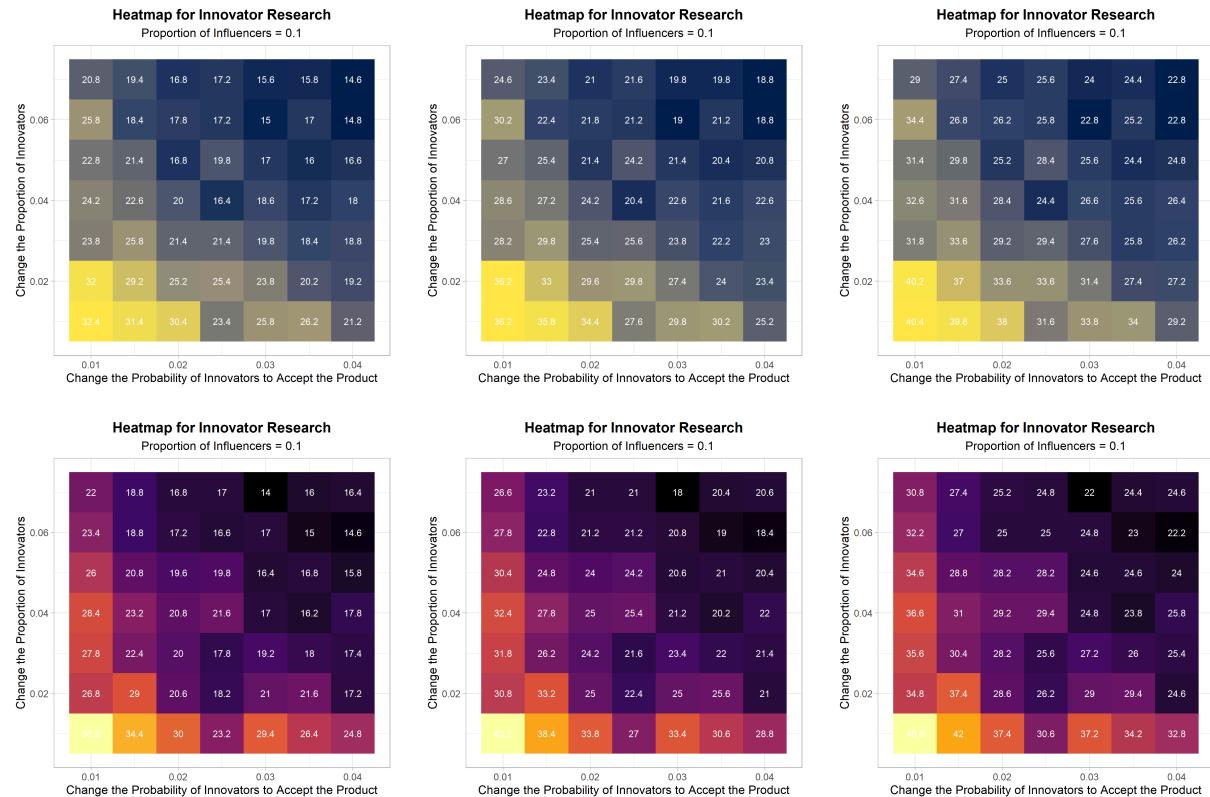


Figure 17: Innovator Analysis: Small-World vs. Random Networks

These heat maps (Figure 17) illustrate how the probability of product acceptance by an innovator and the proportion of innovators jointly affect the rate of product diffusion. The overall trend shows that as these two factors increase, diffusion speeds up (the heat map becomes darker and the values decrease). However, this relationship is nonlinear, the changes are more significant in low-value areas, and there are obvious interactive effects.

The two network structures (small-world and random networks) exhibit similar overall patterns but differ in details, especially in regions of low innovation parameters. It is worth noting that a saturation effect appears in the high-value area, indicating that there is an optimal point beyond which the marginal benefits of continuing to increase innovation input are diminishing.

These findings have important implications for formulating market strategies: when resources are limited, a trade-off needs to be made between increasing the probability of innovator acceptance and increasing the proportion of innovators; in the early stage, more emphasis may be placed on increasing the probability of acceptance; different network structures may require different Optimization strategy.

## 4.6 Change on Proportion of Influencers and Innovators

In order to gain a deeper understanding of the interaction between these two key factors, a heat map is also used here, as in Section 4.5. The Figure 18 shows how the proportion of innovators and the proportion of influencers jointly affect the speed of product diffusion under a fixed innovation coefficient

( $p=0.01$ ) and imitation coefficient ( $q=0.3$ ). Each cell in these heat maps represents the average number of time steps required for a product to reach a specific adoption rate under a specific combination of parameters.

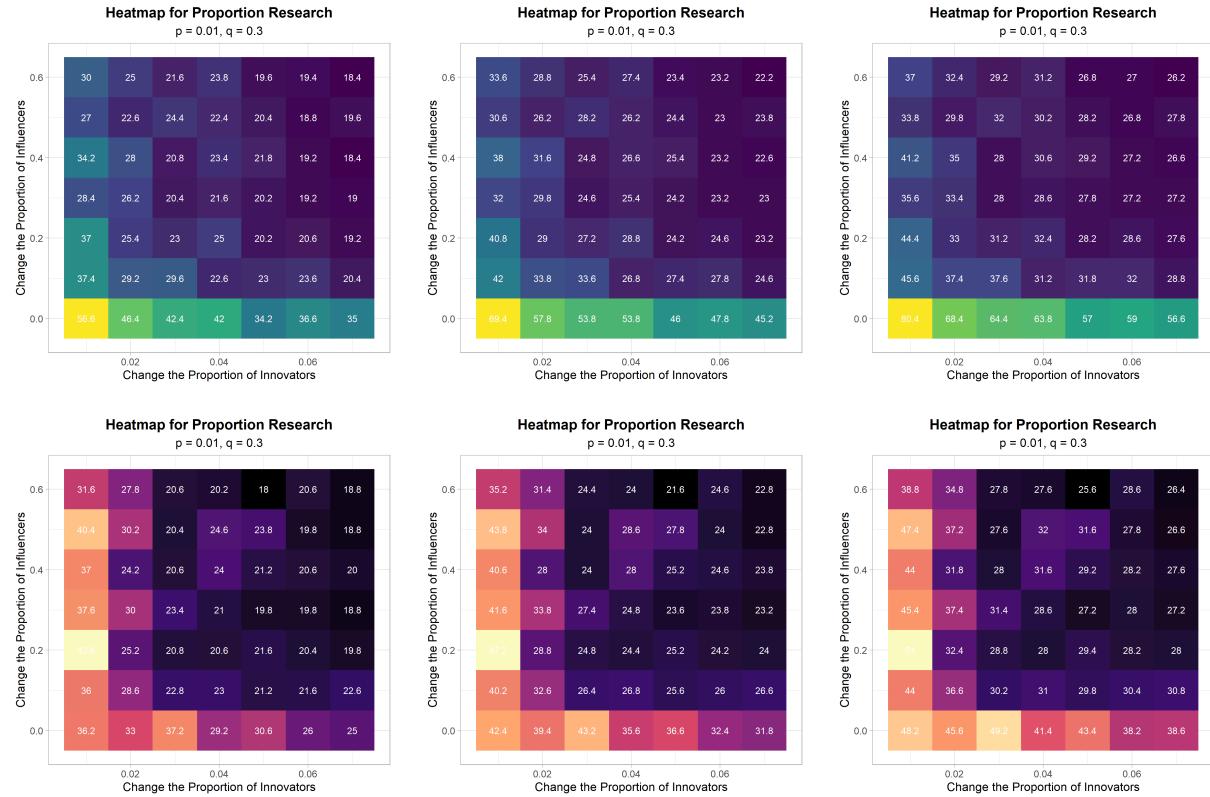


Figure 18: Proportion Analysis: Small-World vs. Random Networks

It can be analyzed from the figure that as the proportion of innovators increases from 0.01 to 0.07, and the proportion of influencers increases from 0 to 0.6, we observe an overall acceleration of the diffusion speed, but this effect is not linear. The impact of the innovator ratio is more significant at low values, while the marginal benefit of the influencer ratio shows a decreasing trend. The interactive effect between the two is most obvious in the lower left corner (both ratios are low) and the upper right corner (both ratios are high), which correspond to the slowest and fastest diffusion speeds respectively.

Comparing the heat maps of small-world networks and random networks, we find that although the overall trends are similar, random networks exhibit slower diffusion speeds at low innovator and low influencer ratios, again indicating that network structure has an important impact on innovation diffusion. In addition, color “jumps” in the heat map suggest possible critical points beyond which the marginal benefit of increased diffusion speed decreases.

## 5 Discussion

## 5.1 Summary of Findings

In today's rapidly changing market environment, understanding the diffusion process of new products and innovative ideas is crucial for companies and policymakers. By integrating the theoretical foundations of Bass diffusion model and complex networks, as well as the micro-simulation capabilities of ABM, we are able to capture the subtle dynamics and complex interactions that are difficult to reveal in traditional aggregate models. We believe that through a series of well-designed simulation

experiments and comprehensive results analysis, we have not only successfully answered key research questions, but also revealed some thought-provoking new insights.

### 5.1.1 Model effectiveness

Our market diffusion model demonstrates high validity and reliability. It is based on the widely recognized Bass diffusion model and social network theory, and innovatively combines the ABM method to better capture individual behaviors and interactions in complex systems. The model is comprehensively designed, taking into account multiple key factors, including innovation coefficient, imitation coefficient, network structure, and consumer type. The model demonstrates its stability and explanatory power through the S-shaped adoption curve of single simulation results (Figure 7), neighbor statistics (Figure 6), detailed sensitivity analysis, network structure comparison, and intuitive visual verification. The findings are highly consistent with real-world observations and existing research, further confirming the validity of the model. In addition, the scalability of the model provides a good foundation for future research, allowing for the further addition of more consumer characteristics or complex decision rules.

### 5.1.2 Response to Research Questions

Here we briefly review the research questions and come up the answers obtained through simulation analysis.

1. The relationship between individual adoption probability and market diffusion rate: How do different innovation coefficients ( $p$ ) and imitation coefficients ( $q$ ) affect the overall market diffusion process?

Research on Different Probability of Adoption (Section 4.3) reveals how these parameters affect the overall market diffusion process by adjusting the innovation coefficient ( $p$ ) and the imitation coefficient ( $q$ ) in the Bass model (Simulation: 1, 2, 7 and 8).

- First, regarding the impact of the innovation coefficient ( $p$ ): high  $p$  coefficients not only accelerate initial adoption, but also reduce the uncertainty of the results. This may reflect the importance of strong innovation marketing strategies (such as advertising, product demonstrations, etc.) in promoting early adoption and building market momentum. However, the marginal benefits brought by the increase in  $p$  coefficient shows a decreasing trend, especially when reaching a higher adoption rate. This phenomenon suggests that overinvestment in improving innovation adoption may not always be the most effective strategy, especially in the later stages of the product life cycle.
- Second, the impact pattern of the imitation coefficient  $q$  is different from that of  $p$ , reflecting the unique role of social influence and network effects in the diffusion process. The increase in  $q$  coefficient mainly accelerates the diffusion in the middle and late stages, which is consistent with the phenomenon that word-of-mouth effects and social network influence increase over time in reality. Another interesting finding is the moderating effect of network structure on the impact of  $q$ . In random networks, the increased stability brought by high  $q$  coefficient may reflect a more uniform flow of information. In contrast, the slightly faster diffusion speed exhibited by the small-world network at low  $q$  coefficient may stem from its characteristics of high clustering coefficient and short average path length, which are conducive to local rapid diffusion.

2. Influence of innovators and opinion leaders: How does the ratio of innovators and influential individuals affect the market penetration and diffusion rate of products?

Innovators and opinion leaders play a key role in the product diffusion process, especially in today's age of social media. Our study further explores the impact of these key individuals on the speed of market penetration and diffusion by adjusting the proportion of influential innovators in the model (Simulation 3, 4, 9 and 10). These findings revealed several key insights:

- The importance of influential innovators: Our results strongly support the importance of identifying and engaging influential innovators. When these key individuals occupy a larger proportion of the innovator population, they can significantly accelerate the overall diffusion process. This may be because they not only have a propensity to adopt innovations but also to quickly spread innovation information through their extensive social networks.
- The importance of overall market structure: Interestingly, increasing the proportion of influential innovators has different effects across different market structures. When the overall proportion of influencers is fixed, increasing the proportion of influential innovators has the most significant effect. This suggests that simply increasing the number of innovators may not be enough to accelerate diffusion; the key lies in whether these innovators have widespread influence.
- Amplification of network effects: Influential innovators appear to be able to amplify network effects. While keeping the proportion of total influencers constant, increasing the proportion of influential innovators not only speeds up diffusion but also significantly reduces the variability of the results. This means that their presence makes the diffusion process more stable and predictable.
- Effect of network structure: Although random networks show slightly faster diffusion speeds, the role patterns of influential innovators are similar under both network structures.

3. The role of consumer group heterogeneity: How does the proportion of different types of consumers (e.g., innovators, imitators, influential and non-influential individuals) affect product diffusion?

By segmenting consumer types (innovators or not and influencers or not), the study analyzes how the proportions of these different groups jointly shape the market penetration and diffusion rate of a product. Our analysis revealed the following key findings:

- Network structure plays an important regulatory role in the innovation diffusion process. In small-world networks, the role of influencers is more prominent, especially when the proportion of innovators is low. In contrast, random networks show greater sensitivity to the proportion of innovators. This suggests that different social network structures may influence the dynamic process of innovation diffusion.
- While imitators make up the majority of consumers, their behavior is strongly influenced by innovators and influencers. Changes in the proportion of mainly affect the speed of diffusion in the middle and late stages. This highlights the interaction and role between different types of consumers in the innovation diffusion process.

4. Multi-factor interactions: How do the interactions of key parameters (e.g., innovation coefficient, imitation coefficient, proportion of innovators, proportion of influencers) jointly affect diffusion dynamics?

- The interaction between the proportion of innovators and influencers shows a complex “substitution-complementary” relationship. When the proportion of innovators is low (less than 2%), increasing the proportion of influencers can significantly accelerate the diffusion process. However, when the proportion of innovators is high (bigger than 5%), an increase in the proportion of influencers has a relatively small effect on diffusion speed. This illustrates a dynamic interplay between innovators and influencers in different contexts.
  - We observe that there is a certain “tipping point”, when the ratio of innovators and influencers reaches a certain level at the same time, the rate of diffusion increases sharply. This critical point is roughly located in the area where the proportion of innovators is 3-4% and the proportion of influencers is 15-20%. Once this critical point is exceeded, the rate of diffusion of innovation will increase significantly.
5. The impact of social network structure: How do different network structures (such as small-world networks and random networks) affect the spread and adoption speed of product information?

In our simulation experiments, we observed quite different results in different networks using the same parameter combination. The key findings are as follows:

- Overall diffusion speed difference: In the case of small parameters, the diffusion speed of random networks is significantly faster than that of small-world networks; in the case of large parameters, the diffusion speeds of the two networks are almost the same.
- Differences in simulation results: The results of random networks are more average, less variable, and will slowly aggregate as the parameters increase. The results of small-world networks will also be more concentrated, but the regularity is not strong.

## 5.2 Comparison with Existing Research

### 5.2.1 Similarities and differences with bass model

When using Agent-Based Modeling (ABM) to conduct simulation research on market diffusion, the conclusions obtained were consistent with the parameter analysis results of the traditional Bass model. That is, in the Bass innovation diffusion model, the size and relative relationship of the p and q parameters have a significant impact on the diffusion model. A larger p coefficient represents strong innovation or external influence, leading to early and rapid diffusion; a larger q coefficient represents strong imitation or internal influence, forming a typical S-shaped curve (Orbach, 2016).

However, ABM simulations require significantly longer time steps than traditional Bass models. Through Equation 2, we can calculate the time steps required when the customer acceptance rate reaches 25%, 50%, and 75% respectively. For example, when  $p=0.01$  and  $q=0.3$ , ABM simulation (Simulation 1, proportion of influencers = 10%, proportion of innovators = 1%, random network) shows that it takes 30, 35, and 39 time steps for the customer acceptance rate to reach 25%, 50%, and 75% respectively. This is a significantly longer time step compared to the results of the traditional Bass model (25%: 7.83, 50%: 11.18, 75%: 14.66). This research finding is consistent with some other results on the comparison of ABM between fully connected networks and Moore networks (Holanda, Gerolamo, Franco, Martins, & Bazzan, n.d.).

This difference mainly stems from the differences in the inter-individual connection assumptions between the two models. The traditional Bass model adopts the “global knowledge” assumption, that is, each agent is affected by all other agents, which is equivalent to all agents in the market being connected to each other. Our ABM model considers more complex individual behaviors and network structures, and uses random networks and small-world networks that are closer to reality. This more

detailed simulation, while increasing computational time, more accurately reflects diffusion dynamics in real markets.

### 5.2.2 Similarities and differences with network diffusion

Similar to many innovation diffusion studies based on ABM, this study also confirmed that different network structures have a significant impact on the diffusion process. In particular, the maximum degree in the network (i.e., the number of connections owned by the most connected node in the network) has a significant impact on the diffusion time (Di Lucchio & Modanese, 2024). As shown in Figure 6, the maximum degree of random networks is usually higher than that of small-world networks. Our model simulations are consistent with this, showing that random networks do indeed have higher diffusion rates than small-world networks.

In addition, our research extends further and introduces the key role of the “influencer”. Through extensive experimental comparisons, we found that a higher proportion of influencers can significantly accelerate the diffusion of a product. This phenomenon is reflected in both small-world networks and random networks, and also reduces the difference in diffusion speed between the two networks.

There are several reasons for this: first, the efficiency of information dissemination has become higher. Influencers usually have more social connections and can spread information more quickly and widely. In any network structure, more influencers mean that information can reach every corner of the network faster; second, the existence of influencers may make up for the differences between different network structures. For example, in a small-world network, influencers can act as a “bridge” to connect different social groups, thereby accelerating the spread of information.

## 5.3 Contributions and Implications

### 5.3.1 Contributions

This study provides a more comprehensive understanding of the market diffusion process by innovatively integrating the Bass diffusion model, complex network theory, and ABM methods. It not only explores the behaviors and interactions at the individual level, but also analyzes in detail the impact of different social network structures, key individuals (such as influencers and innovators), and multi-factor interactions on the diffusion process. This multidimensional analytical approach bridges the gap between theoretical models and actual market conditions, providing valuable insights for academics and practitioners.

More importantly, this study establishes a flexible and scalable market diffusion research platform. This platform allows researchers to explore the impact of various parameter combinations, such as different sizes of potential customer groups ( $N$ ), different numbers of agents (Agent), and simultaneous changes in the innovation coefficient ( $p$ ) and the imitation coefficient ( $q$ ). This approach also provides a powerful tool for future researchers to further explore the complex dynamics of market diffusion.

### 5.3.2 Practical significance

Our research provides marketers with a comprehensive set of strategic guidelines, highlighting the importance of adopting dynamic and differentiated strategies based on product lifecycles and market characteristics. In the early stages of product launch, companies should focus resources on improving the innovation coefficient ( $p$  coefficient), such as increasing advertising investment and providing trial opportunities. Over time, the strategic focus should gradually shift to improving the imitation coefficient ( $q$  coefficient), such as encouraging users to share and build communities. This phased strategy not only optimizes resource allocation, but also effectively responds to market dynamics.

The key is to identify and cultivate influential innovators, who play a vital role in accelerating product diffusion. Companies should consider adopting a phased product launch strategy, first targeting these key individuals and attracting them through influencer marketing or KOL (key opinion leader) strategies. With limited resources, focusing resources on a small number of high-impact innovators may be more effective than trying to increase the overall number of innovators. In the long run, cultivating lasting relationships with these innovators, or even building “innovator communities” or “influencer networks,” can become a continuous product development and promotion resource.

Market segmentation and differentiation of network strategies is another key consideration. Different types of consumers play different roles in the diffusion process and require targeted strategies. Companies should adjust their marketing approach based on the network characteristics of the target market (closer to random networks or small-world networks). For example, in markets with obvious small-world network characteristics (such as close communities or professional fields), it may be more appropriate to adopt viral marketing or word-of-mouth marketing strategies and focus on improving the imitation coefficient. In contrast, in markets that are closer to random networks (such as mass consumer goods markets), a wider marketing coverage and a greater focus on improving the innovation coefficient may be required. This differentiation strategy also applies to the selection and use of social media platforms.

Finally, our research emphasizes the importance of comprehensive optimization and dynamic adjustment. Companies should seek a balance between multiple factors rather than overinvesting in a single aspect. Identifying and exploiting the “critical point” of parameter combinations may be the key to accelerating market penetration. At the same time, companies need to be wary of the diminishing marginal benefits brought about by overinvestment. By building a more accurate market diffusion prediction model, companies can make more informed decisions and optimize resource allocation. This comprehensive approach is not only applicable to corporate strategies, but also has important implications for innovation policy making, which helps to create a balanced innovation ecosystem and accelerate the diffusion of technology or products on a wider scale.

## 5.4 Limitations and Future Research

### 5.4.1 Limitations of the Model

Although this study has made significant progress in market diffusion modeling, it still has some limitations. First, the heterogeneity of agents is mainly reflected in two dimensions: whether they are innovators and whether they are influencers, which may oversimplify the complexity of consumers in reality. Secondly, the innovation coefficient ( $p$ ) and imitation coefficient ( $q$ ) in the model remain unchanged throughout the diffusion process and cannot reflect the dynamic changes in the market, especially the possible cyclical fluctuations in innovation effects. For example, the innovation effect of some products may show cyclical changes due to the influence of seasons, advertising cycles or economic cycles. Furthermore, the network structure is determined at the beginning of the simulation, without taking into account the dynamic evolution characteristics of social networks. And  $q$  may change as well. Furthermore, despite using small-world networks and random networks, this may still not fully capture the more complex social network structure in the real world. Finally, the accuracy and generalization ability of the model may be limited due to the lack of validation with actual market data.

### 5.4.2 Future Research Directions

Based on the limitations of the current study, future research can be expanded in several aspects. First, the heterogeneity of agents can be increased, for example, innovators can be further subdivided into

high-probability adopters and relatively low-probability adopters to better reflect the diversity of consumer groups. Second, dynamically changing innovation coefficients and imitation coefficients can be introduced, especially considering the cyclical changes of the innovation coefficient. For example, the following model can be used to describe the cyclical changes of the innovation coefficient:

$$p = p_{\text{base}} + A \sin(\omega t + \varphi) \quad (8)$$

Where  $p_{\text{base}}$  is the basic innovation coefficient,  $A$  is the amplitude,  $\omega$  is the angular frequency,  $\varphi$  is the phase, and  $t$  is the time. This model can better reflect the cyclical fluctuations in the real market, such as the impact of seasonal effects, advertising cycles or economic cycles on innovation adoption.

For the imitation coefficient  $q(t)$ , we can keep the original growth-and-decay model, or design it to change periodically according to the specific situation:

$$q(t) = q_{\max} (1 - \exp(-\mu t)) \exp(-vt) \quad (9)$$

Furthermore, future models can incorporate dynamic changes in network structure, consider the birth or death of connections between nodes, and more accurately simulate the evolution of social networks. In addition, research can explore more complex network topologies, such as multi-layer networks or networks built based on actual social media data. Finally, future work should focus on collecting actual market data for model verification and calibration to improve the practicality and reliability of the model. These directions can not only improve current models, but also provide new perspectives and insights for innovation diffusion research, helping us better understand and predict the innovation diffusion process in complex market environments.

## 6 Conclusion

This study provides a more comprehensive understanding of the market diffusion process by innovatively integrating the Bass diffusion model, complex network theory, and agent-based model (ABM) methods. We deeply explore the impact of factors such as innovation coefficient, imitation coefficient, influencer ratio, consumer group heterogeneity, and social network structure on product diffusion, revealing the complex interactions between them. These findings enrich the traditional innovation diffusion theory.

Although this study has some limitations in terms of agent heterogeneity and network dynamics, it has built a flexible and scalable platform for future research. We hope to have a deeper understanding of the innovation diffusion process based on the conclusions of this study, provide stronger support for corporate decision-making and policy making, and ultimately promote the rapid and effective dissemination of innovation on a wider range.

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## Appendix A: Model Code

Code Repository: <https://github.com/QianZeHao123/MDS-Research-Project>

The latest code package for building the ABM model are available on the GitHub: <https://github.com/QianZeHao123/MDS-Research-Project/tree/main/ABM%20version%200.7>

R code for ABM result visualization: <https://github.com/QianZeHao123/MDS-Research-Project/tree/main/ABM%20result%20visualization/model%20version%207%20visualization>

## Appendix B: Simulation Results

All the simulation results have been uploaded to the Durham University Data Onedrive and can be accessed through the following link: [https://durhamuniversity-my.sharepoint.com/:f/g/personal/bjsn39\\_durham\\_ac\\_uk/EupzzfgNaWhOsKlx1eNQG8kBSLIYDcKitluXy2zI3DQm5w?e=B2zcZB](https://durhamuniversity-my.sharepoint.com/:f/g/personal/bjsn39_durham_ac_uk/EupzzfgNaWhOsKlx1eNQG8kBSLIYDcKitluXy2zI3DQm5w?e=B2zcZB)

The simulation data files are very large, and the SHA256 hash values are provided. Every one can get the same visualization results by using the same data files. Check the SHA256 hash values to ensure the integrity of the data files.

Index	File Size	SHA256	Index	File Size	SHA256
Simulation 1	2.15 GB	119d6a9402e0f.....	Simulation 2	2.16 GB	7d6939744ecc5.....
Simulation 3	2.14 GB	ba6baf54977e4.....	Simulation 4	2.12 GB	ae1012e2fb9d6.....
Simulation 5	4.24 GB	847f82a683097.....	Simulation 6	6.08 GB	6212be09019da.....
Simulation 7	2.09 GB	469fb7afe337b.....	Simulation 8	2.11 GB	9af3c3c57ba3c.....
Simulation 9	2.08 GB	377a86228b6df.....	Simulation 10	2.07 GB	6c5345b8e3f7f.....
Simulation 11	4.13 GB	f679d8e1b0051.....	Simulation 12	5.97 GB	378940c2e9aea.....

## Appendix C: Words Count

The report is written in Typst. In this document, there are 13128 words all up (counted by [wordometer](#)).