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The Impact of Networks on the Diffusion of Innovations: A case study using a sociological agent-based model to analyse the spread of the Bell Beaker Phenomenon in the Lower Rhine Region

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The Impact of Networks on the Diffusion of Innovations

A case study using a sociological agent-based model to analyse the spread of the Bell Beaker Phenomenon in the Lower Rhine Region

Luuk Slegers

The Impact of Networks on the Diffusion of Innovations:

A case study using a sociological agent-based model to analyse the spread of the Bell Beaker Phenomenon in the Lower Rhine Region of Europe

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Master Thesis Archaeological Science - 1084VTSY

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List of Equations

$D_i = \begin{cases} 1, & U_i \geq U_{i,\min} \text{ or } \lambda > s_i \\ 0, & \text{otherwise} \end{cases}$ (1) 40

$U_{Li} = \beta \cdot x_i + (1 - \beta) \cdot y_i$ (2) 40

$x_i = \begin{cases} 1, & A_i \geq h_i \\ 0, & \text{otherwise} \end{cases}$ (3) 41

$y_i = \begin{cases} 1, & p_i \leq q \\ 0, & \text{otherwise} \end{cases}$ (4) 41

$U_G = \frac{\overline{C}}{N}$ (5) 41

$\overline{C} = \sum_{j=1}^{n_c} \left(\frac{n_j}{N}\right) n_j, \quad n_j > 1$ (6) 41

$E(U_G) = \frac{1}{1 + e^{-\phi(U_G - M_c)}}$ (7) 42

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Chapter 1. Introduction

1.1 Diffusion of Innovations & Social Networks

In the current day and age, most of the world is connected by the internet. Newly developed technologies and ideas can be viewed in a matter of seconds and opinions are widely available. Throughout the human past ideas also spread, but at much slower rates than now. This sociological concept of the diffusion of innovations has been widely studied in many interdisciplinary settings including archaeology, for example, with the introduction of new tools or the change in material culture over time. The diffusion of innovations can be defined as the spread of new ideas over time through communication networks among people in a social system (Rogers, 1983, p. 34).

The dichotomy between the origin of diffusion in archaeology and sociology is apparent. The idea of the spread of innovations as a concept was first mentioned in sociology by Gabriel Tarde, a French judge who suggested in his book The Laws of Imitation (Tarde, 1903) that new ideas spread through imitating others. In archaeology, diffusionism became prominent around the same time. Evolutionary thinking inspired by Darwinism that all cultures gradually evolved was replaced by the idea that the complexity of ancient societies was the result of mixing different cultures (Trigger, 2006, p. 219). During the 1910s diffusionism had taken over the archaeological discipline. By the 1940s diffusionism in archaeology already had many theories, from extremes such as hyperdiffusionism (Smith, 1929) to migration being the primary means of diffusion (Petrie, 1939).

One of the first significant diffusion of innovations studies in the socioeconomic field can be considered Ryan & Gross's (1943) study of the diffusion of the innovation of hybrid corn in the United States of America. The diffusion of innovations research got its first academic footing relatively late in comparison to the archaeological paradigm, namely, in the 1960s with what is considered the most important contribution by Everett Rogers. His work *Diffusion of Innovations* can be viewed as the most fundamental study because it analyses the four elements of diffusion: (1) innovation, (2) communication channels, (3) time, and (4) social system (Rogers, 1983, p. 33). Rogers (1962) collected data from multiple studies in the United States of America (including Ryan & Gross's 1943 study) and created a theoretical and methodological framework that is now the foundation of the diffusion of innovations research.

The fourth aspect, the social system, is studied in the interdisciplinary fields of social network analysis and network science. The social system can be defined as the complete structure in which individuals engage and interact with one another (Rogers, 1983, p. 24). Network science studies the complexity and the effects of various kinds of networks on a system, examples of such networks are, computer, military, and social networks. In archaeology, social networks are studied to analyse the connection between artefacts and sites. Social networks can describe various social connections, such as, business relations, sexual relations, disease transmission, and information exchange. These networks are represented by nodes, the actors in a network, and edges, the relationship between the actors (Scott, 2017, p. 2). Social network analysis, as the name suggests, analyses these types of networks to explain social processes that happened in past societies in the case of archaeology. These can be studied by studying real-world networks (Figure 1) or using computer-generated networks (Figure 2). The latter are used in the computational modelling of social networks.

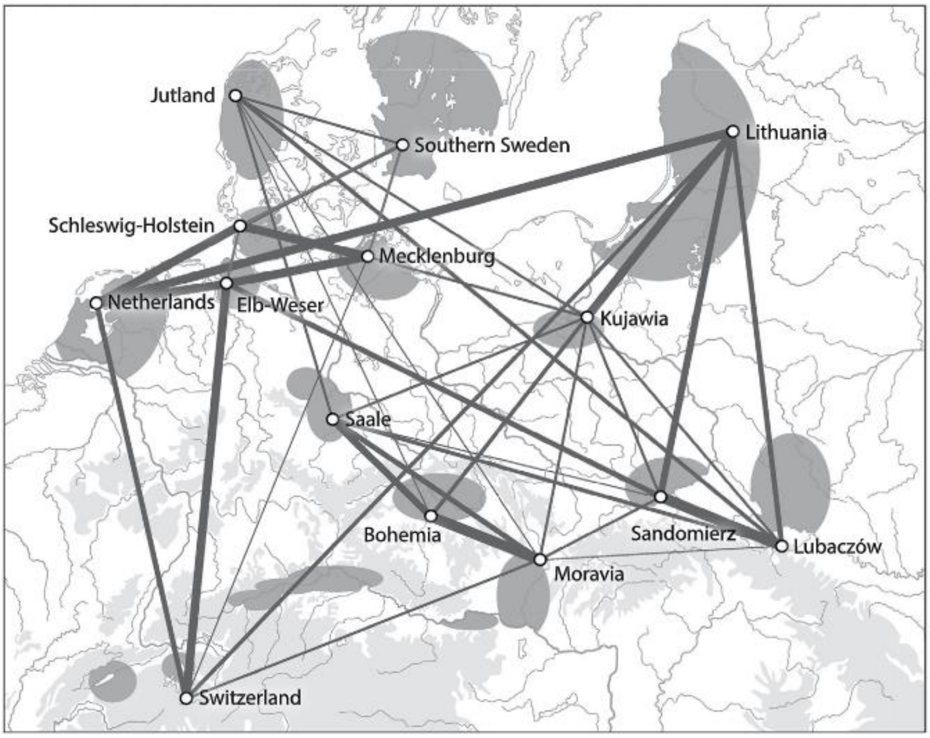


Figure 1.An example of an archaeological social network analysis. This map shows the relations based on the thickness of the edges between Corded Ware regions during the Neolithic in Europe (Furholt, 2011, p.262).

Figure 2. An example of a random-generated network (Timashev, 2019, p. 4)

In archaeological studies that involve diffusion of innovations, the focus has been on explaining archaeological distributions, for example, how farming spread (Zvelebil, 2001), how new pottery types were adopted (Bentley & Shennan, 2003), how new technologies developed (Fitzhugh, 2001), etc. This is done by studying certain processes, e.g., migration, cultural exchange, trade, etc. These distributions are analysed as a result of the processes. However, this is not completely possible. The archaeological record is reconstructed based on what is left. Connections made between individual points in a network are not always representative of the real-world networks that were in place in the past since not all of the attributes of past societies have been preserved in the ground (Sindbæk, 2013, p. 75). This means that archaeological data on its own cannot inform us about the individuals who transferred information via social networks. Archaeology can only tell us, for example, when and how pottery type A replaced or evolved into pottery type B and from what region it was influenced. Therefore, diffusion processes that happened in the past are best understood by applying sociological models that are based on present-day empirical data (Roux & Manzo, 2018, p. 968). This is because the actors in a social network can be observed and studied in the present, and they form an important part of a social system. This can be done by applying models created in sociology to archaeology. Sociological theory and methods of social networks can help understand the diffusion processes that happened in the human past. Social networks in the context of sociology and network science have been analysed by many scholars (cf., O'Malley & Marsden, 2008; Flache & Macy 2011; Snijders, 2011). While these are mostly theoretical models, they have seen some application in empirical ethnoarchaeological studies (Roux et al., 2017) but in very limited quantities.

One such model is Rogers' adoption of an innovation model, an S-Curve or Sigmoid function (see Figure 3). This model shows the rate at which new ideas are adopted within a social system. Within archaeology, this model has been used for the explanation of diffusion phenomena. For example, Fokkens et al. (2008) use the theory of Rogers' S-Curve for explaining the invisibility of early adoption of new pottery types and Kleijne (2019) for analysing the progress of innovation of new pottery over time. This framework has been employed in applied modelling in only a couple of studies. Amati et al. (2019) model the spread of dynastic rituals by analysing Mayan hieroglyphs to construct network ties. Additionally, Eerkens & Lipo (2014) analyse new pottery types that were introduced in Lake China and Death Valley, USA, and conclude that the results are comparable to Rogers' S-Curve. However, both studies use the adoption of innovations model in different ways. But they do not combine the two aspects of social networks and the adoption of innovation.

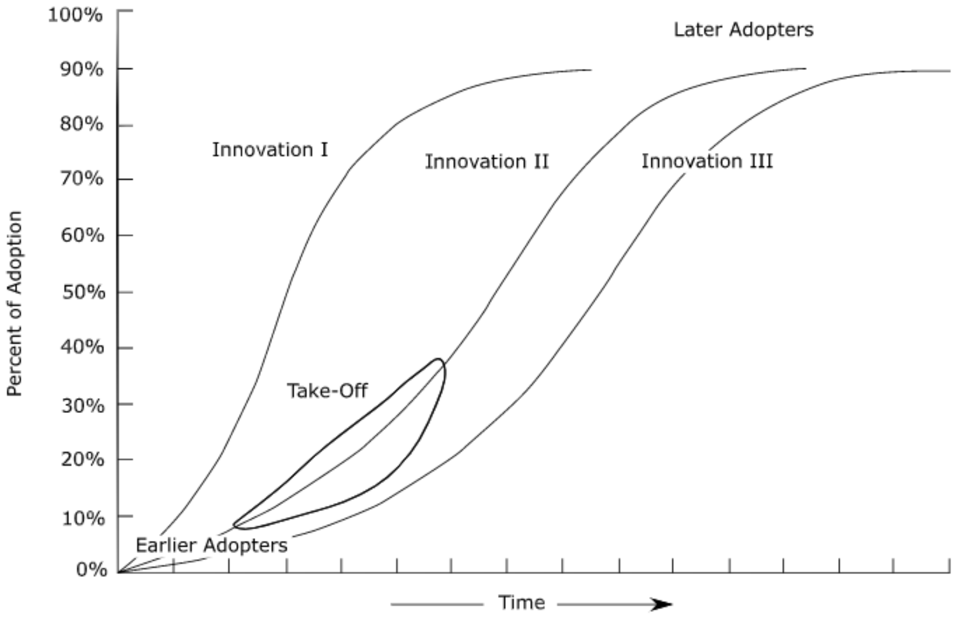


Figure 3 Visual representation of Rogers' S-Curve. The different rates of adoption are displayed for various innovations. (Rogers, 1983, p. 11)

It is crucial to evaluate if these sociological models designed are comparable to ancient societal structures. This can be done by combining the theory with data. In this thesis, I study how computer-generated network structures influence the rate of adoption of innovations. By doing this, I will show that these theoretical sociological models and network science are suitable to be applied and compared to archaeological data. The case-study to which the diffusion of innovations model will be tested is the Late Neolithic and Early Bronze Age Bell Beaker phenomenon in the Lower Rhine Region, which will be introduced in the next paragraph.

1.2 The Bell Beaker Phenomenon

The diffusion of innovations has also been studied in the Bell Beaker phenomenon. The Bell Beaker phenomenon is named after the Bell Beaker, a cup-shaped pottery vessel that was present in most of western and central Europe during the Final Neolithic and Early Bronze Age in the third millennium BC (see Figure 4). The Bell Beaker phenomenon has been one of the most discussed topics in European prehistory for over one hundred years. The main reason for this is that it can be defined as the first period in European prehistory where there was a universal material culture present that had spread in most of western and central Europe in only a couple of hundred years. However, it is now an outdated view that the Bell Beaker phenomenon was a uniform, ubiquitous culture during its existence (Turek, 2012, p. 200). This idea was suggested based on excavations of mostly burial sites studied in the last century (Kleijne, 2019, p. 16). These sites show similarities in the ritual *package* that was deposited in the graves, with some regional variations. This *package* consists usually of Bell Beakers, flint arrowheads, copper daggers, perforated amber buttons and stone wrist guards (Wentink, 2020, p. 38). Burial sites only represented a small part of the population and are therefore not representative. Looking at pottery assemblages from settlement sites shows a much more diverse picture. This type of data is more representative and directly linked to living people in the past. While settlement data used to be scarce (Fokkens, 2012, p. 29) in the last decennia more research has been put into this aspect of society mainly in the Netherlands (e.g., Fokkens et al., 2016; Kleijne, 2019), the United Kingdom and other continental European countries (Gibson, 2019).

Figure 4. (a) A typical Bell Beaker package (Wentink, 2020, p. 12) (b) Distribution map of the Bell Beaker phenomenon in dark grey (Vander Linden, 2007, p.345).

The PhD dissertation *Embracing Bell Beaker* by Jos Kleijne (2019) is a great example of a recent development in the study of the Bell Beaker phenomenon. In his dissertation, he argues that with settlement excavations over the last few decennia, the publication of older excavations, and the accessibility of large digital datasets, new light can be shed on the Bell Beaker phenomenon that is not rooted mainly in funerary practices (Kleijne, 2019, p. 20). He analyses how local communities adopted this new set of material culture across Europe, with an emphasis on the adaptation and innovation of one of the most common finds in archaeology: pottery. In parts of his PhD dissertation, he explains how new pottery types have been accepted and reinvented in some regions over time, while in other regions it was rejected in its entirety after its initial introduction (Kleijne, 2019, p. 82). Kleijne uses Rogers' (1983) S-Curve to show the adoption process of the Bell Beaker pottery type in Europe. He also uses social network analysis to create a network of communicative channels.

The Bell Beaker phenomenon has been extensively studied for more than a century. However, in this seemingly widespread phenomenon, there is still ambiguity in the diffusion processes in play during this period. Additionally, there is a need for computational modelling since studies discussing the diffusion of innovations during this period still take a theoretical approach (Kleijne, 2019; Fokkens, et al., 2008). Therefore, I want to combine the network analyses of the Bell Beaker settlements in the Lower Rhine Region by Kleijne (2019) with the theory of diffusion of innovations by Rogers (1983). This will be done by implementing a diffusion of innovations computational model by Córdoba & García-Díaz (2020a) in which the network type, and other parameters such as social influence and global influence, can be tested with the pottery settlement data of the Bell Beaker phenomenon in the Lower Rhine Region.

1.3 Research Problem, Aims, and Questions

As outlined in the previous paragraphs, the diffusion of innovations is a popular subject in research history in many academic fields. However, there is not much focus on how social networks impact the adoption of innovations. Incorporating models from sociology and network science is necessary to explain social networks in the human past. Therefore, this thesis aims to analyse how different types of networks influence the rate of adoption of the Bell Beaker phenomenon in the Lower Rhine Region. The results will be interpreted with the networks and pottery data from settlement sites created by Kleijne (2019). of the Bell Beaker phenomenon in the Lower Rhine Region. Additionally, the other parameters that are present in the diffusion of innovations model will be assessed on how they influence the rate of adoption of the Bell Beaker pottery innovations, such as social influence and global influence which will be further discussed in the next paragraph. Therefore, the main research questions of this thesis will be:

I. How do different networks influence the adoption of innovation? And how does the diffusion of innovations model by Córdoba & García-Díaz (2020a) compare to the Lower Rhine Region Bell Beaker network analysis proposed by Kleijne (2019)?
II. How can the parameters presented in the diffusion of innovations model be interpreted archaeologically?
III. How and when does rejection of innovation occur? And how can the parameters that influence these decisions be interpreted?
IV. How applicable are sociological models to archaeological complex systems?

1.4 Methodology & Data

The model that will be used is an agent-based model designed to show the adoption of innovations (Córdoba & García-Díaz, 2020b). Agent-based models study the interaction of complex systems with the use of computer simulation (Romanowska et al., 2021, p.6). Agents in such systems can be people, objects, or institutions. and have predefined attributes which make each agent have an individual decision-making process. This can be set in an abstract network or a geographically referenced model. Agent-based models can closely imitate real processes since their focus is on how individual nodes in a system interact with each other (Lake, 2014, p. 261). These models are difficult to interpret because a mathematical analysis cannot be applied. Experimental approaches are most commonly used to see how different parameters influence a system. Agent-based modelling is suited for exploring the diffusion of innovations in past societies because the interaction of agents will lead to unpredictable patterns in the system (emergence) that cannot be observed in archaeological data (Romanowska et al., 2021, p. 7).

The diffusions of innovations model by Córdoba & García-Díaz (2020a) runs on three main functions which can be tested by changing various parameters, namely, the decision of the agent (the nodes), the local influence, and the global influence. The agents in this model are represented as Bell Beaker settlement sites. The agent's decision means under what circumstances the agents will decide to adopt the innovations. This is influenced by the surrounding nodes to a certain extent (local influence) and how all the agents in the entire network engage with the innovation (global influence). The functions operate differently when testing various types of networks which subsequently will influence the social system. Additionally, values of the other parameters present in the model will be analysed on how they can be archaeologically interpreted primarily based on the data presented in the PhD dissertation by Kleijne (2019).

The data Kleijne (2019) presents relevant to this thesis comes from settlement sites in the Lower Rhine Region (see Figure 5). A large database has been composed based on older excavation publications (Kleijne, 2018). In this dataset, Bell Beaker settlement sites are listed which have data on Bell Beaker pottery frequencies and radiocarbon dates that can be attested to Bell Beaker cultural layers. The combination of these data gives an idea of how the Bell Beaker pottery was present in space and time. Using this dataset in combination with various random-generated network types can be used as a basis to apply to the diffusions of innovation model by Córdoba & García-Díaz (2020a). Additionally, Kleijne (2019) uses this data to carry out a social network analysis to reconstruct communication and exchange networks based on decorations and motifs found on Bell Beaker pottery and Common Ware. His results present a degree of connectivity within this network for the Lower Rhine Region (Kleijne, 2019, pp. 116-118). However, the direct exchange of Bell Beaker pottery was limited in the Lower Rhine Region. The composition of the clay and temper used in Bell Beaker pottery found at settlement sites indicates that these pots were mostly made locally (Salanova et al., 2016, p. 10). The limited circulation of pottery could have been sufficient for the spread of ideas. Therefore, additional network analyses by Kleijne (2019) regarding the spread of other aspects of the Bell Beaker phenomenon will be evaluated.

Comparing the results from applying networks to the diffusion of innovations model and experimenting with the values of the variables that are present in the model to the Bell Beaker network data described in this paragraph, will give answers to the research questions.

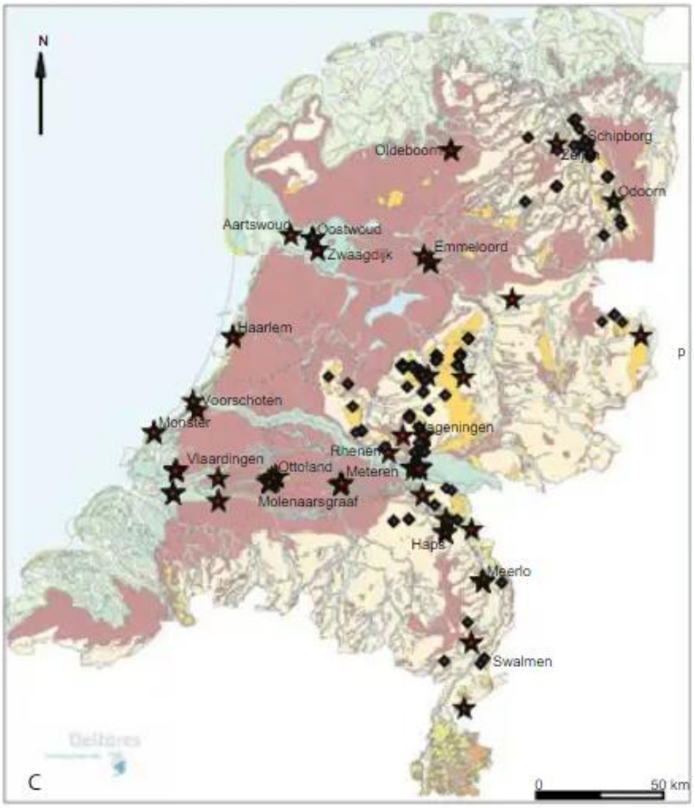


Figure 5. Bell Beaker settlement sites in the Lower Rhine Region, adapted from Fokkens et al. (2016, p.38)

1.5 Thesis Structure

In **Chapter One**, an introduction to the thesis is given. This introductory chapter includes a brief overview of the theory and the case study. Moreover, the research problem, aim, and questions are presented. In **Chapter Two**, the theory of diffusion of innovation, with emphasis on the adoption process is discussed. Additionally, relevant theory related to social network analysis in sociology and archaeology is further explained with the inclusion of graph models. Also, the background of the diffusion of the Bell Beaker phenomenon will be presented. In **Chapter Three** the archaeological data, the pottery frequencies, radiocarbon dates, and the Bayesian analysis will be evaluated. Furthermore, the diffusion of innovations model by Córdoba & García-Díaz (2020a) will be described with its additions. In **Chapter Four**, the model will be tested by using various network types. Also, the variables that are present in the model will be experimented with to see how they impact the outcome of the rate of adoption. When tested, the interpreted values for the parameters will be applied to the Bell Beaker phenomenon in the Lower Rhine Region. In **Chapter Five**, the result will be compared to the archaeological data and the use of networks in archaeology will be discussed. And finally, the research questions and the thesis will be concluded in **Chapter Six**.

Chapter 2. Theoretical Background

2.1 Diffusion of Innovation

The diffusion of innovations theory is key in understanding the later described model and the social networks. Rogers' S-Curve shows how fast an innovation will be adopted within a social system. Although, the model on its own looks straightforward many theoretical and empirical analyses have been done to explain why it is shaped as it is. Here I present the theory and research on the S-curve and how the rate of adoption can be analysed by the four main elements that influence it, namely the (1) innovation, (2) communication channels, (3) time, and (4) social system.

2.1.2 Diffusion and S-Curve

To begin, what is diffusion? Rogers (1983, p. 5) defines diffusion as 'the process by which an innovation is communicated through certain channels over time among the members of a social system'. Important is that diffusion concerns a type of two-way communication by which a new idea is transmitted and, if successful, adopted. The eventual adoption of innovations through diffusion will lead to social change in the function and structure of a social system. For example, the introduction of the Bell Beaker pottery in various regions within Europe must have led to social change, since people accepted this new technique into their social system.

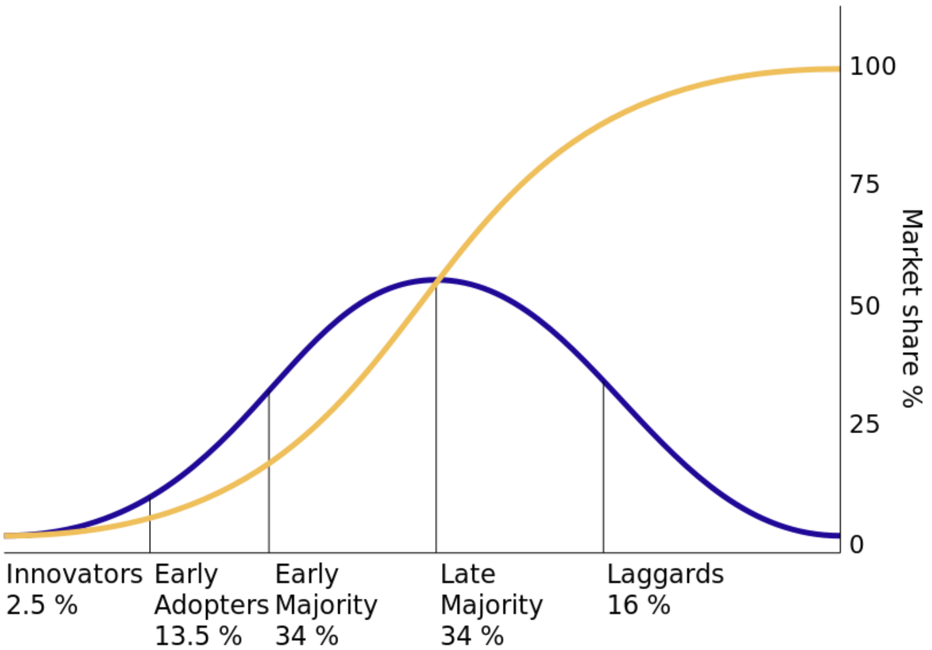


Figure 6. In yellow, the diffusion of innovations curve in cumulative of the total population as proposed by Rogers (1983). In blue, the Bass model shows the total amount of consumers for each category (Public domain).

With diffusion addressed, we can now consider the model for the rate of adoption. This S-curved model shows how innovations get adopted within a population over time. The adoption process can be theoretically explained into five phases. The introduction of innovation, the early adopters, the early majority, the late majority, and finally the laggards (Table 1 for more explanation). At the point that innovation reaches critical mass within a population, the innovation will be adopted. An additional model that follows the same terminology but displays the division of the population based on the five phases is the Bass model (see Figure 6). The Bass model is one of the first and most important base models in the innovation of diffusion discourse (Córdoba & García-Díaz, 2020b, p. 4). This model is in line with the S-Curve Rogers (1983) proposed for the percentual growth of a population in adopting an innovation. It implies that when a new trend is being adopted, the adopters of this trend will steadily increase until a critical mass is formed which results in the laggards and sceptical consumers being the only ones needing to adapt to the new trend. Both models rely on the same theory of diffusion of innovations. The Bass model and its adaptations can be and have been used for analysing market trends, which can also be translated to the S-curve by using the cumulative number of adopters (e.g., Delre et al., 2007; Córdoba & García-Díaz, 2020b). This adapted model will be discussed in Chapter 3.

Adopter type	Total population	Description
Innovators	2.5%	The small group that introduces a new technology or idea from outside of the social system. These individuals deal with the risk and uncertainty of the success of an innovation.
Early adopters	13.5%	Important opinion leaders within a system. They control the speed of the diffusion. Their role is to decrease uncertainty and convey innovation to peers in the system.
Early majority	34%	Followers of the system. They have a relatively long decision-innovation period but form important agents to interconnect with the rest of the population.
Late majority	34%	The late majority adopts the innovation out of necessity. They only adopt if most of the population has adopted the new idea and when the uncertainty is gone.
Laggards	16%	Traditionalists and conservatives. They are wary of innovations. They may already lag if even newer innovations have entered the system. They are the most isolated in the system too.

Table 1. Ideal types of adopters in the diffusion of innovations system (Rogers, 1983, pp. 248-251).

2.1.3 Applying the Diffusion of Innovations Theory to the Bell Beaker Phenomenon

The theoretical background of the S-curve and Bass model is rooted in the fields of sociology and economics. So, to ascribe the descriptions presented in Table 1 exactly to the Bell Beaker phenomenon is not entirely possible. However, translating each group to what is known about the Bell Beaker network is feasible. I try to establish how these types of adopters can be interpreted as part of the Lower Rhine Region Bell Beaker pottery network.

1. The innovators can be viewed similarly in the context of the Bell Beaker phenomenon to what Rogers (1983, p. 248) presents them as the small group of people who introduce the Bell Beaker pottery to a region.
2. The early adopters, this group depends on whether a centralised or decentralised was in place within Bell Beaker communities. These early adopters represent people that were on the move within a region, e.g., exchange networks (Vander Linden, 2007, p. 347). These people can decide if it is fruitful to use this pottery type and pass this information on when they come into contact with other people or communities.
3. The early majority, this group is part of the first adapters within families. Several Bell Beaker communities across Europe display patrilocal residency and female exogamy (Sjögren et al., 2020, p. 18). This practice results in the creation of local communities that have a father lineage as a family relation technology (see Figure 7). If individuals within the communities were to accept the new Bell Beaker pottery, it would take some time for the rest of them to embrace this new technology.
4. The late majority can refer to the ones within the community that only start using the Bell Beaker pottery when it is somewhat established. It will be difficult to distinguish between the early and late majority since archaeology cannot assess definite relations.
5. The laggards are the group that is most closely in line with Rogers' definition. These are traditionalists that do not see the need for change in their system. These can represent newly found patrilocal communities that did not accept the new pottery.

This list might seem speculative to some extent. However, this representation can also give a more engaging view of the otherwise sociological terminology. Many other factors influence Rogers' S-curve, but this thesis intends to focus on the social network aspect of the diffusion of innovations. Therefore, the four elements that are key need to be discussed first.

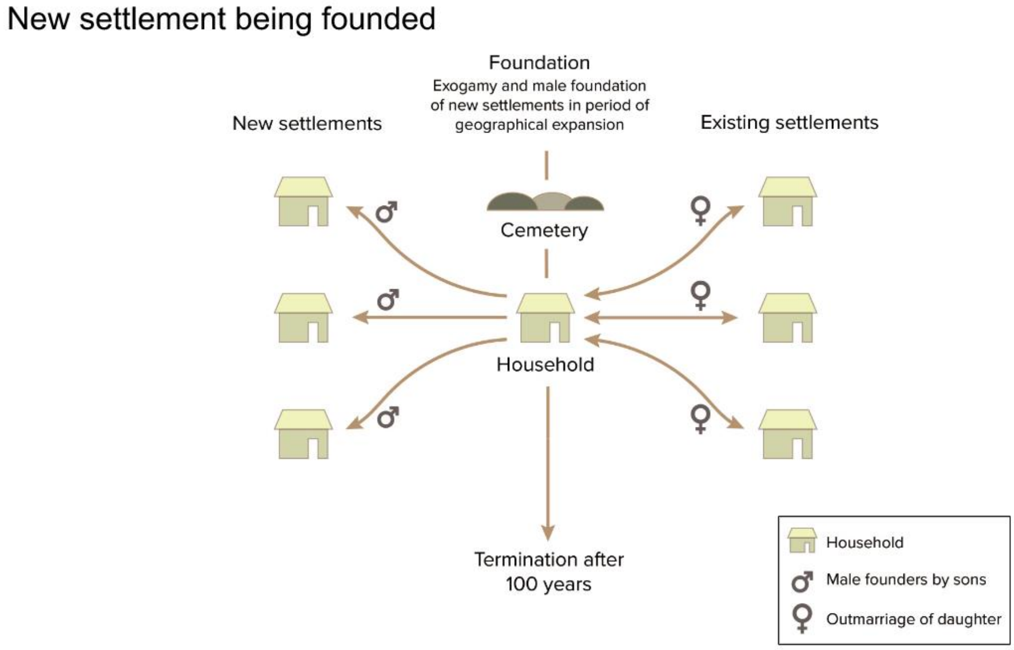


Figure 7. A system of exogamy (females come from existing settlements) and patrilocal settling (the male foundation of new settlements) (Sjögren et al. 2020, p. 19).

2.1.4 The Four Main Elements of Diffusion of Innovations

The key elements in the diffusion of innovations discourse are (1) Innovation, (2) communication channels, (3) time, and (4) social system. All these factors form the basis of every diffusion of innovations research and will therefore be explained.

2.1.4.1 Innovations

The innovation '… is an idea, practice, or object that is perceived as new by an individual' (Rogers, 1983, p. 11). The innovation can be perceived by individuals as new at each of the five phases mentioned in the former paragraph. Innovation can have two components: the hardware or software aspect. Hardware refers to the physical objects that are being created while the software indicates the information or idea behind the physical item (Rogers, 1983, p. 12). In the case of the Bell Beaker pottery, it refers to the Bell Beaker pot that has been created and the information about creating this pot. There are five characteristics of innovations:

1. The **relative advantage** refers to the degree to which an innovation is *better* than the technology or idea it replaces. This can vary for each individual and be based on relative economic, convenience, social, etc., benefits. The Bell Beaker typology must have had a significant advantage whether economic or social to be adopted across most of Europe.
2. **Compatibility** refers to how well the innovation fits in with current beliefs and values. If it does not hold up to the ideas of its time, then it will not be adopted. In regard to the Bell Beaker pottery, this can be seen as possibly social and ritualistic beliefs since this pottery type has

been excavated in a grave context. However, the Bell Beaker pot has also been associated with the spread of alcohol (Sherratt, 1987). This means that it might have been important to use this pottery type in social or even ritual drinking ceremonies (Rojo-Guerra et al., 2006).

3. **Complexity** relates to the difficulty to understand and produce innovation. Since pottery had been around for some millennia (depending on the region) one can assume that this aspect is less important. However, it could have occurred that a new technique in the making of pottery was present that people needed to learn.
4. **Trialability** refers to the ability to experiment with the innovation before adoption. If creating Bell Beaker pots or trying to copy their results is a complete failure, the rate of adoption would be much lower.
5. **Observability** indicates the accessibility and visibility of the innovation. If there is more exposure to the Bell Beaker pottery type, then it is more likely to be adopted faster.

A different aspect that can occur, is **reinvention**. This can be described as the degree to which an innovation is changed to comply with the individual's needs. The innovation does not need to fully comply with the recipient's needs, and they can change it in a manner that suits them better. The five characteristics are a basis for analysing the adoption of innovation, but it is still a simplification of reality. Individuals do not use a checklist when coming into contact with a new idea and are usually more subjective in the matter (Rogers, 1983, p. 16).

2.1.4.2 Communication channels

The second element can be simply defined as the process in which information is transmitted between two individuals (Rogers, 1983, p. 17). The information-exchange relationship determines whether or not an innovation is carried over. This can occur through mass media and interpersonal connections. The Bell Beaker phenomenon happened far before the invention of mass media. For that reason, only interpersonal connections are relevant. Interpersonal channels are between one-on-one or one-on-many interactions. This interaction can usually happen in two different ways: homophily and heterophily (see Figure 8). Homophily refers to the sameness of two individuals. If two persons share the same ideas, e.g., beliefs or interests, they are more likely to engage in positively effective communication. Hence, similar people live in the same group and community and reinforce this idea of homophily. In archaeological simulation research, this has been used for the diffusion of cultures and peoples. A well-known example is the Cultural Dissemination model, an agent-based model that presents the diffusion of cultural traits through social influence in a homophilic network (Axelrod, 1997).

The opposite is heterophily. As one can expect, this involves communication between two individuals who do not share the same beliefs, interests, status, etc. It is obvious that these types of interaction are less common, but they are needed for an innovation to spread. Some degree of heterophily needs to be present, if not, people would not respond to innovation at all since there are no differences between individuals. A different argument to this can be the idea that an innovation is communicated through the next generation which can show up in the archaeological record. This is still a form of homogenous relation so initially a heterogenous communication must have taken place.

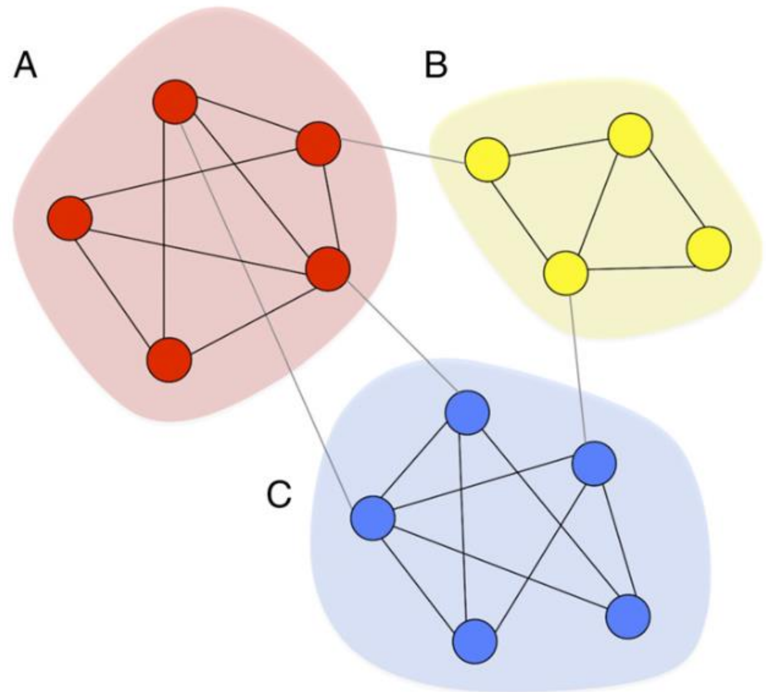


Figure 8. A schematic representation of homophily and heterophily in a network. Clusters A, B, and C have homophilic relationships. The connection between the clusters can be defined as heterophilic relationships (Barnes et al., 2016, p. 2).

2.1.4.2 Time

The third key element in the process of diffusion is time. This dimension concern all the steps that are present in the adoption of an innovation. This can be ascribed to three main processes: the innovation-decision, an individual's innovativeness, and the adoption rate.

In the innovation-decision process, time is spent on acquiring and processing the innovation. This process usually follows four steps: gaining knowledge of the innovation, weighing the benefits or usefulness of the innovation, making a decision, and finally implementing and validating the innovation (Rogers, 1983, p. 21). During this process, either the adoption or the rejection of an innovation occurs.

Innovativeness refers to when an individual decides to adopt a new idea. This can be defined by the five adopter categories discussed earlier in the former paragraph: innovators, early adopters, early majority, late majority, and laggards. Each of these categories can be described with a decrease in innovativeness in order from left to right because the innovators are the first to introduce or pick up on the innovation while the laggards are the very last to accept the innovation.

Finally, the definition of the rate of adoption is straightforward: the relative speed at which members adopt an innovation within the system (Rogers, 1983, p. 23). The cumulative rate of adoption of a population usually follows an S-curve or sigmoid function (see Figure 3). However, this may vary based on each of the four elements mentioned in this paragraph. There are generally periods of slowdown and acceleration which result in the shape of an S.

As archaeologists, we are familiar with time. Placing an object or material culture in a time period using radiocarbon dating or relative typological sequences has been used inexhaustibly. Since many attributes influence the time it takes for an innovation to spread, it is difficult to pinpoint how much time it took for the Bell Beaker pottery to be consolidated in Bell Beaker communities in the Lower Rhine Region. However, the exact timeframes are difficult to access since the archaeological record is fragmentary. Therefore, pottery sequences are difficult to place in time and even with radiocarbon dating it is still difficult to be sure because of limitations, such as a large standard deviation.

2.1.4.4 Social systems

Last but certainly not least is the social system. This is the complete structure in which individuals engage and interact with one another. As one can expect this is the most complex element in diffusion. Many aspects within a social system affect the diffusion process, such as the structure itself, the effect of norms, the agents or individuals in the system, and the innovation decisions.

The structure can be seen as a network in which patterns are established between units (Rogers, 1983, p. 24). Such networks that deal with an interpersonal exchange or where information is transmitted between individuals, can also be viewed as a social structure. In addition, there are rules or norms within a system which can aid or hold back the spread of diffusion, for example, social values and religious beliefs. These are aspects that tell us how the structure of the system is established but the individuals or agents in the system also impact the structure.

There are opinion leaders, these individuals are major influencers of the system. They are exposed to more information within the system than the average individual. Additionally, they have a central position in the information exchange of a system and have one-to-many interpersonal communication. Opinion leaders have a higher social status which makes them prominent figures in the flow of innovation. Opinion leaders are still bound by the norms and rules of the structure. If the norms do not allow for an innovation to spread, the innovation will most like be rejected. The decision the opinion leader makes can affect the rate at which an innovation spread. However, more types of decision-making processes affect the social system.

In general, four types of innovation decisions influence the system: optional, collective, authority, and contingent. Each of these decision types is related to the autonomy of the individuals in the system in decreasing steps. Optional innovation decisions refer to the individuals who are making independent decisions, collective innovation decisions refer to a group that makes a decision, authority innovation decisions refer to a governing individual who decides for larger groups of individuals, and lastly, contingent innovation decisions indicate a reassessment of a previous decision-making process. All these innovation decisions influence the system positively or negatively in an increasing fashion from optional as the least impactful to authority being the most influence.

Lastly, there are the consequences that innovation can have on the system. These consequences occur on the individual or system level. The effects that innovation can have on individuals can affect the entirety of the system. A clear example is the invention of the internet, which has had major effects on the global system, but also on each individual.

The four key elements innovation, communication channels, time, and social system, all have a great impact on the diffusion process (see Figure 9). Each element affects the process while also each of the elements affects the other. This complex system of combining all elements into one model is a major undertaking, therefore, I will focus on the social system element. To be more precise the network in the social system on which all information is spread.

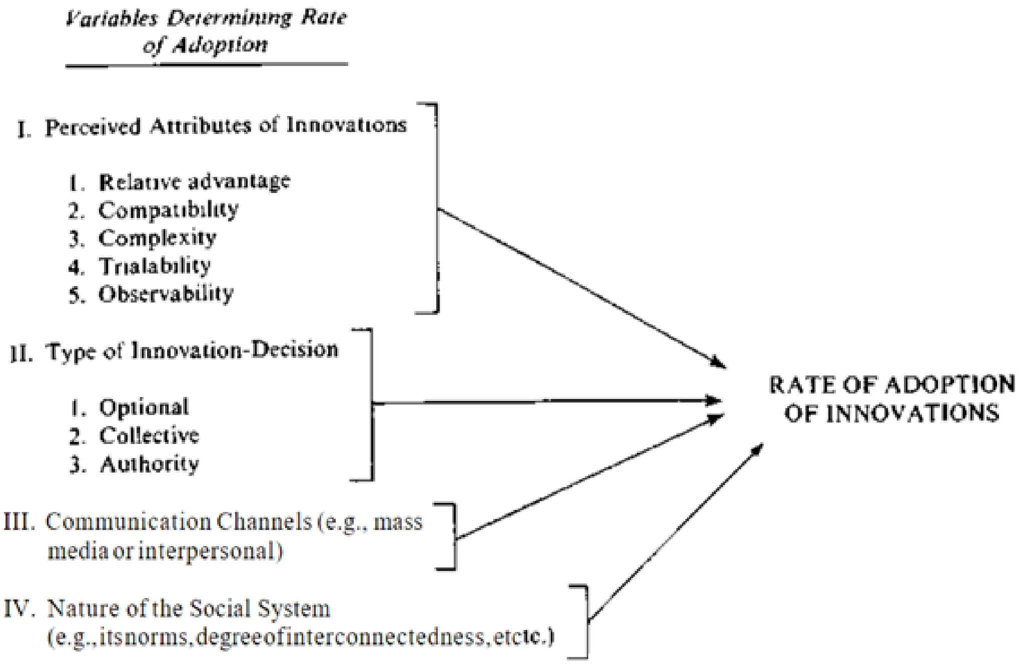


Figure 9. Schematic overview of how the four elements of diffusion influence the rate of adoption, adapted from Rogers (1983, p.233).

2.2 Social Networks Analysis (SNA)

In the previous paragraph, the social system has been described by Rogers (1983). This is a key element of the diffusion of innovations that is comparable with the definition of social networks. Additionally, it was briefly discussed what social networks are and how analysis is done in the introduction of this thesis. Here, I will look in more detail at the research background and theory of social networks and network science in sociology and archaeology concerning the diffusion of innovations. Additionally, applied graph theory will be discussed that is relevant to the model.

2.2.1 Social Network Analysis & Network Science

Social network analysis is widely studied in interdisciplinary fields such as sociology and archaeology. Some scholars refer to it as a paradigm within social sciences rather than a separate field. Therefore, many fields have had and still influence social network analysis. This has resulted in a scatter of studies that use similar principles but do not stem from the same source. The origin of social network analysis, however, can be traced back to graph theory, the study in maths concerning the relationship between nodes and their connections.

The first academically known problem was the 'Seven Bridges of Königsberg' which was solved by Euler (1736). This can be seen as the foundation of graph theory since it used the relationship between edges and nodes for the first time. The study of networks was eventually transformed by social sciences into social network analysis, which transformed graph theory from pure mathematics to applied maths. This way of thinking was adopted by sociology and used for creating models for the diffusion of innovations since the late 1960s. By then, all four components of social network analysis were set. (1) The core of social network analysis is rooted in a structure of ties connecting social agents. This is (2) based on analytical empirical data and (3) uses visualisation to portray the data, which is (4) gathered by mathematical or computational models (Freeman, 2004, pp. 3-4).

The type of models that came forward since then can be divided into three classes: macro models, spatial autocorrelation, and network models. The macro models were the first type that focussed on the speed of diffusion and rate of innovation. The Bass model (1969) is one of the first models used in diffusion research. It incorporates the percentage of adopters at points in time to measure the rate of adoption and focuses on external and internal influences in the system. Initially, this type of model did not measure how individuals were connected in a system. However, later adaptations do add this feature to the model (see Delre et al., 2007; Córdoba & García-Díaz, 2020b).

In addition to the rate of diffusion spatial autocorrelation models focus on the spatial relation between the innovation. Moran's I (1956) is an early model that uses this method. It measures the connectedness of nodes and how this deviates from the average network behaviour (see Figure 10).

The major assumption this type of modelling uses is that geographic proximity is associated with communication, while this does not have to be the case. Additionally, this type of modelling encounters estimation errors. And even though it shows the rate of diffusion at the macro level it could not show how the structure of the network influenced the outcome.

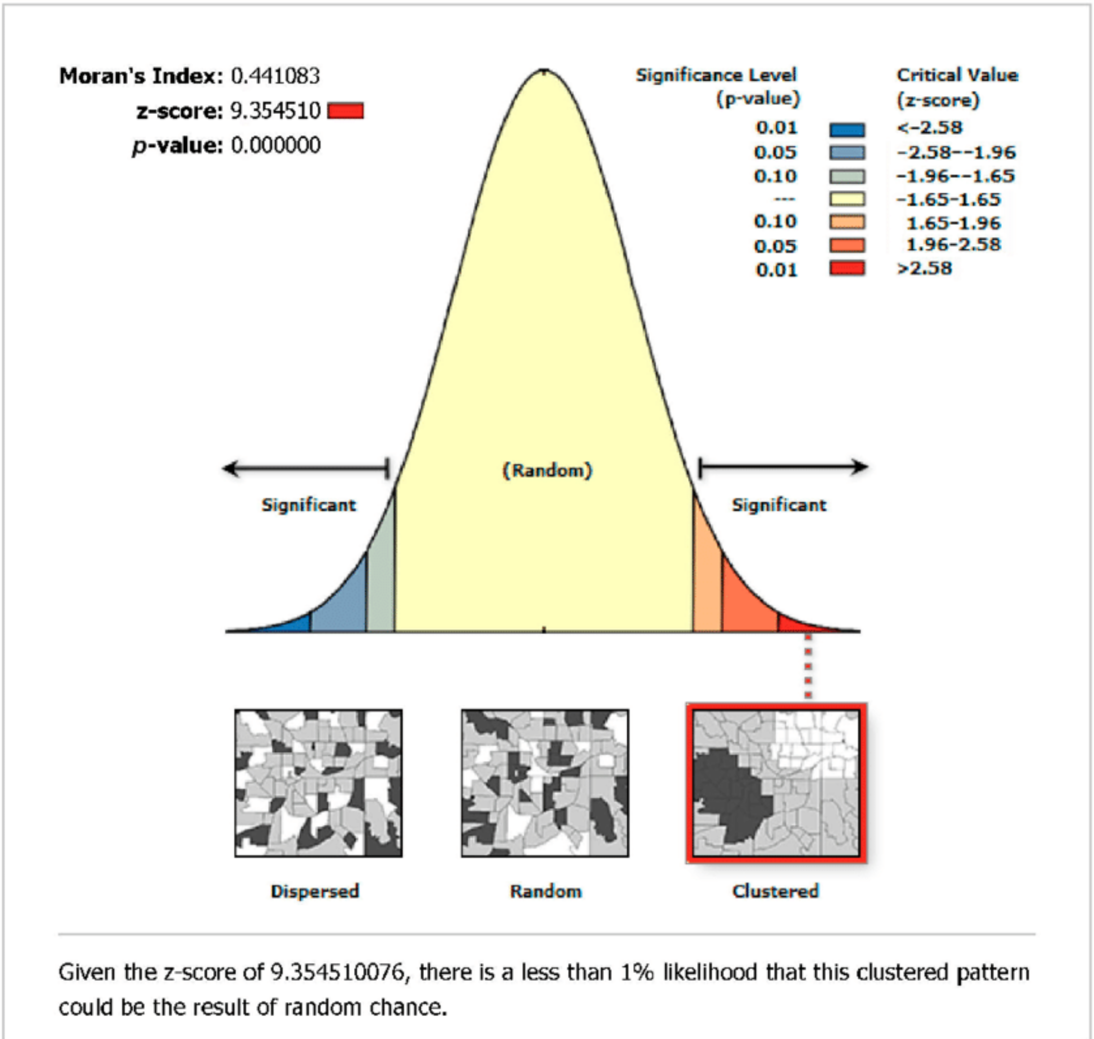


Figure 10. Example of Moran's Index. This example shows that Moran's I is positive with a low p-value, meaning that a given attribute (in this case pottery finds) shows that the spatial autocorrelation is not random, but clustered with a high degree of significance (Vojtekova et al., 2019, p.9)

The last type of modelling focuses on the influences a network has on the system. This is usually expressed in the rate of exposure to the innovation, which increases when the personal or local network has a higher percentage of adoption. This rate of exposure and adoption can be altered or tested by changing the type of network that it operates on. In essence, exposure is synonymous with the social influence which is generated through social comparison (Valente, 2005, p. 103). These social influences can be grouped into three categories of weighted connections, namely relational, positional, and central (see Figure 11).

Relational refers to how the relationship ties between the nodes are constructed, for example, how is each individual connected and how the ties influence one another in a system. Positional relates to the distance and how the similarity between the nodes can attribute to exposure. Central relates to a central point of exposure, e.g., how nodes with a high exposure rate operate in a network (opinion leader) receive a higher degree of influence. The close focus on interpersonal connections regarding weighted links gives network models an edge over autocorrelation and macro models.

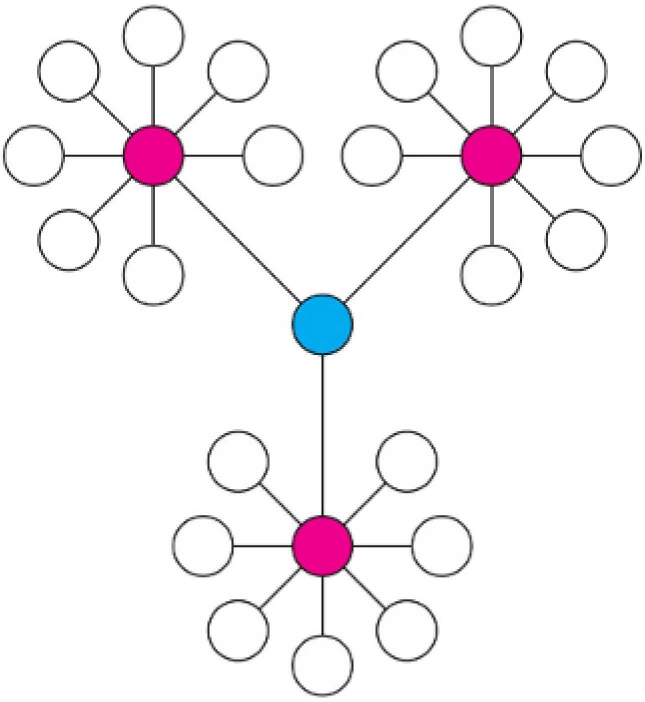


Figure 11. Example of weighted connections in a system. In this example, the red node has a high central social influence because many nodes are connected to it. The blue node position is further away from the other nodes, which affects the influence. However, the relation between the red nodes and the blue node can be significant since it connects this small network (Junker et al., 2006, p. 4).

In social network analysis, there are two approaches to studying networks: the theories on node position, and overall network structure. The former refers to how the position of a node in a network is influenced. In sociology and subsequently the diffusion of innovations, one of the most well-known models created by Granovetter (1973) called the 'Strength of Weak Ties' focuses on node position. His study is based on findings in the job market that suggest that new information is better transmitted between more distant relations (heterophily) than between close friends (homophily). Within a group of close friends, usually, the same information is shared and therefore no new ideas will manifest unless an outsource will provide this innovation. This idea of the balance between homo- and heterophily in the diffusion process is still present in many models today.

As the name suggests, theories of overall network structure focus on the whole network. In this thesis, I will analyse how the entire network functions and not the nodes individually because the aim is to see how varied network structures influence the diffusion of innovation. The network structures implemented in the diffusion of innovations model by Córdoba & García-Díaz (2020a) are generated by using code. In the next paragraph, these networks or graphs are further explained.

2.2.2 Random and Non-Random Graphs

Before exploring the diffusions of innovations model by Córdoba & García-Díaz (2020a), it is important to address how networks, or graphs, work in modelling. This is mostly done in computational modelling by generating random graphs as the structure on which the system operates. As the name suggests, a random graph is constructed by random probability in relation to the connection of nodes and edges. In addition to random graphs, there are scale-free and small-world graphs which also operate to a degree of randomness. Completely random networks do not exist in real-world situations, there is usually a degree of structure within the randomness (Chaos Theory). To create some structure in random networks, the small-world network model was created in the late 1990s (Watts & Strogatz, 1998). This model is still inherently random but operates on the idea that there is a short path between all nodes in a system. This concept is more commonly known as the *six degrees of separation,* meaning that all nodes are connected within only six links of each other. This network type can be seen in many real-world processes, such as the connection of neurons in brains and food webs. It was therefore accepted in the modelling of complex networks (Brughmans, 2013, p. 643). When used in modelling, this graph generates cliques that are linked by only a few edges (see Figure 12).

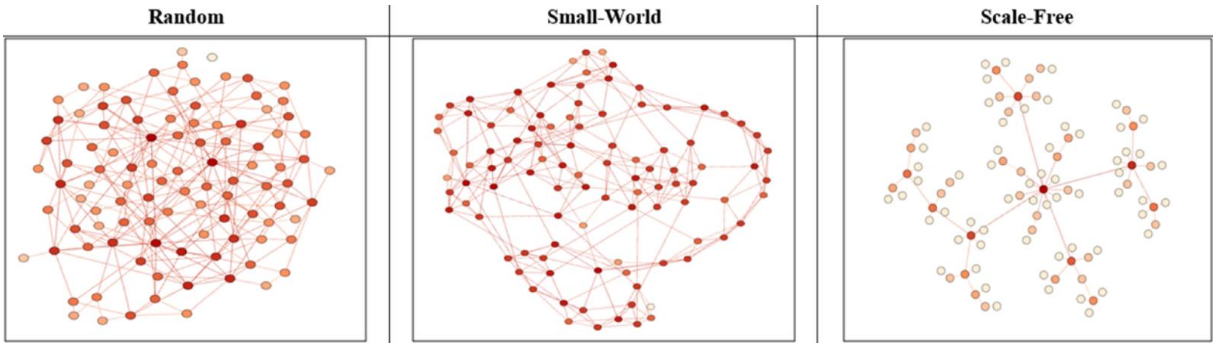


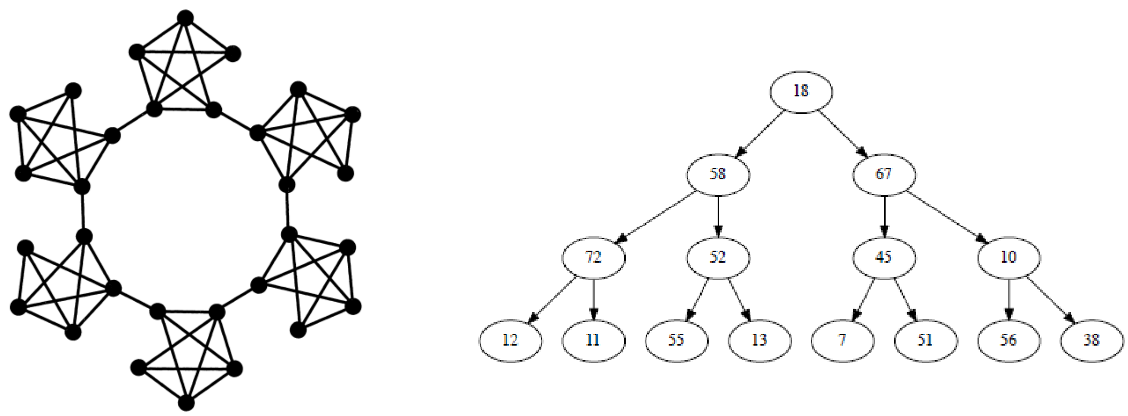
Figure 12. Three types of random networks that are commonly applied in network science (Perera et al., 2017, p.5).

The idea behind scale-free networks was created shortly after the small-worlds model was published. Scale-free graphs operate on the idea that real-world networks are created based on power law (Albert & Barabási, 2002). This means that nodes in a system are more likely to be linked to nodes that already have many edges. This is also attested to real-world processes, for example, the structure of how internet sites are connected.

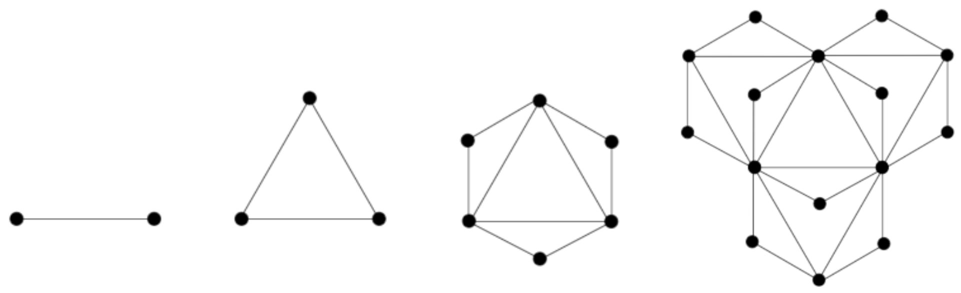
These two graph types are used in most publications since they have evidence in real-world networks. These graph types are already present in the current configuration of the model and can be altered as a variable to see how it influences the system. The implication of these graph types is the focus as presented in the research questions but in addition to these commonly used ones, other graph types will also be implemented to see how those will affect the rate of adoption in the system. These are non-random graphs, namely the balanced tree, caveman, and Dorogovtsev-Goltsev-Mendes (DGM) graphs (see Figure 13). The balanced tree and DGM graphs have been chosen because they have a hierarchical order in their structure. It is interesting to see if this hierarchy in the network will show different results. The clique formation in the caveman graph is similar to that of a small-world network. However, the non-random structure of the caveman graph is easier to assess than the small-world network, since it is more structured (see Figure 13a).

The balanced tree graphs are generated by the height and branching factor instead of probability. The branching factor connects a given number of nodes and the height determines how many times this occurs (see Figure 13b). These types of graphs can be used to analyse network routing of communications networks (Moharam & Morsy, 2017, p. 132). The caveman graph has a similar idea to a small-world network; however, it is not random. This type of graph is created by a fixed number of cliques and the size of the cliques (Watts, 1999, p. 500). All the cliques are connected by one edge. The idea is that each clique only shares one edge with other cliques and can therefore be used for network analysis. Lastly, the DGM graph is a pseudo fractal graph type that has similar properties as a scale-free network (Dorogovtsev et al., 2001, p. 3). This graph type expands with each generation adding new edges to already existing nodes (see Figure 13c). Although deterministic, the hierarchically scale-free properties will be interesting to test in the model.

In archaeology, there have been some studies which address the combination of social network analysis, graph theory, and the theory of diffusion of innovations. This will be discussed in the next paragraph.



(a) *(b)*



(c)

Figure 13. (a) DGM graph with generations 0, 1, 2, and 3 displayed from left to right (Dorogovtsev et al., 2001, p. 4). (b) A balanced tree with a height of 3 and a branching factor of 2 (Alekseev & Schäfer, 2016, p. 16). (c) A caveman graph with 6 cliques of 6 nodes (Watts, 1999, p. 501)

2.2.3 Social Network Analysis in Archaeology

Archaeology adopted the theory of social networks and their analysis late. During the 1970s there were some early adopters using graph theory and proximal point analysis for studying networks (Harary, 1969; Irwin-Williams, 1977). However, they were not using social network theory for their analysis of networks. One of the main driving factors for the addition of social network theory was the shared principle of complexity in computer sciences and archaeology. In computer sciences, many algorithms and other methods are found in complex systems and archaeology, the view of past societies is a difficult-to-assess complex concept. In the early 2000s, Geographic information systems (GIS) were already adopted into the archaeological discipline. Only in the last decade social network analysis has been more and more incorporated into archaeological theory (Mills, 2017, 381). This is also due to some other factors, such as the need to work with large data sets due to the data deluge (the abundance of data due to the digitalisation of quantitative data, such as pottery assemblages), the applications of additional computer-based methods such as GIS and agent-based models, and the necessity of tools for visualisation for especially clear data analysis and public outreach (Mills, 2017, 385).

Archaeological studies on social network analysis should have a standard. Collar et al. (2015) present some standards that follow a logical flow of reasoning. Firstly, the past phenomenon needs to be established, e.g., the relationship between individuals on how innovations are spread. Secondly, an abstraction needs to be made, such as the flow of information. Thirdly, this abstraction translates the present network data, which is the diffusion of innovations represented by a flow of information (see Figure 14). Though basic in explanation it is important to clarify what has been exactly studied.

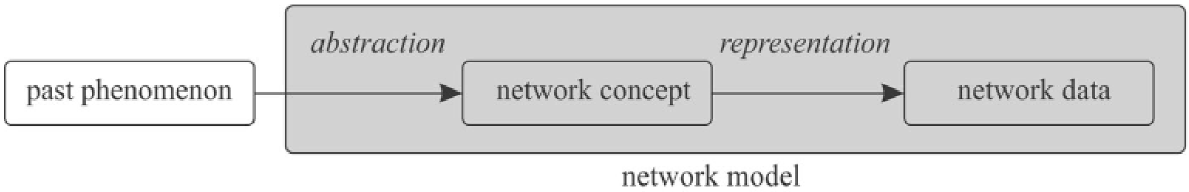


Figure 14 Abstract representation of a network model (Brandes et al. 2013)

Some archaeological studies use the diffusion of innovations concerning complex social networks. Kandler & Caccioli (2016) developed a simulation framework which analyses what occurs on the individual level to the macro level pattern in the social system. This study implies how underlying processes can influence several outcomes, such as the adoption curve. This purely theoretical study implies that processes are heavily influenced by how heterogeneous the population is in addition to the network model. A different study by Östborn & Gerding (2016) examines the diffusion process of Hellenistic and Early Roman-fired bricks in the Mediterranean based on agents with long-distance and short-distance interaction. They use a network-based model which analysed the difference in interaction. One can conclude through the results that in the later period of the Roman Empire when artisans gained more independence, the adoption of innovations was more rapid when compared to the earlier Hellenistic period. In this earlier period, elite commissioners had more influential power in the construction process but were also less likely to innovate since it was not their expertise.

There have been archaeological studies that combine social network analysis and the diffusion of innovations theory. However, these have only been present over the last decade. Rogers' (1983) theory of diffusion of innovations has been applied in some archaeological studies in combination with the systematic use of social network analysis since the publication of the book by Knappet et al. (2011). Even though diffusion has been studied within the archaeological discipline since the early twentieth century (Lemercier, 2020b), this was done by applying different methods. In the next paragraph, these methods will be described in combination with the presentation of the case study of the Bell Beaker phenomenon.

2.3 The Bell Beaker Phenomenon – Background and Diffusion

The reason why the Bell Beaker phenomenon is not named a culture is that this phenomenon is too complex and diverse to be considered one single material culture. A typical set of objects can be defined as belonging to this period in Europe, such as copper daggers, stone wrist guards, and Bell Beakers. However, a complete or identical *package* has never been found in the archaeological record (Wentink, 2020, p. 11). The Bell Beaker phenomenon is currently the accepted term in academia because it does not group all the archaeological date into a homogenous, ubiquitous culture.

Most of this research focuses on explaining the reasons and effects diffusion had on prehistoric Europe. This is done by applying research from many interdisciplinary fields, such as isotope, genetic, osteology, burial, and material studies. In this paragraph, the focus will be on the history of diffusion research in the Bell Beaker phenomenon.

2.3.1 Bell Beaker Phenomenon

The Bell Beaker period can be roughly dated between 2600-1800 BCE (Kleijne, 2019, p. 102). First appearing in either the Lower Rhine region or the Portuguese Estremadura and last in Great Britain. It is rather difficult to set a specific timeframe for the whole period itself since it does not appear everywhere at the same time. For some regions, it is solely related to the Neolithic (Denmark), while for other regions finds associated with Bell Beakers are well past the transition point into the Bronze Age (Iberia).

The first period of the identification of the Bell Beaker typology took place during the late 19th and early 20th centuries. After mostly regional studies, researchers all over Europe compared their work and concluded that similar pottery typologies and burial types were found in the regions (Kleijne, 2019, p. 16). The first theory that was proposed for this widespread Bell Beaker phenomenon was by Gordon Childe and his contemporaries. He postulated that "Beaker folk" were merchants who roamed the Atlantic coast and settled in regions where their status and wealth created a form of political and economic power which took over the local tradition (Childe, 1925; Van Giffen, 1928). The pace of the transition could only be explained by rapid migration and material conservatism. This is in line with the idea of diffusion at the time. The cultural-historic paradigm had the idea that new cultural traits or new technology were introduced by way of migration. Since Bell Beaker pottery had been found over a large area this must have meant that the population must have been replaced and succeeded by the Bell Beaker people.

During the second half of the 20th century, the *Rückstrom* hypothesis had been formed by Sangmeister (1963). He formulated that a wave of migration from the Portuguese Estremadura followed the Atlantic coast to western and central Europe, where it merged with the Corded Ware culture. Subsequently, a migration back into southern France and Britain could be noticed. This hypothesis explained the variability in local and regional material culture. Additionally, Lanting & Van Der Waals (1976) introduced a new hypothesis. The so-called *Dutch* model proposed that the origins of Bell Beaker pottery originated in the Lower Rhine region. This hypothesis is based on the typological overlap of the Corded Ware and Bell Beaker culture in this area. According to Lanting and Van Der Waals (1967), these two traditions show a large similarity and therefore they hypothesise that the Bell Beakers originated as a result of evolution from the Corded Ware. Until this day it is not clear where the Bell Beakers originated due to a calibration plateau that spans the entirety of the initial spread of the Bell Beaker phenomenon in Europe (see Figure 15) (Fokkens, 2012, p. 23). The Iberian origin hypothesis is currently favoured because the first beakers show close similarity with a preceding pottery type that is found in the initial phase and have a relatively early dating (Cardoso, 2014). This earlier timeframe has been used in recent publications analysing different aspects of Bell Beaker society (e.g., Furholt 2021). However, the sampling methods of the Iberian site have been questioned, since the dates come from an unsure single context (Kleijne, 2019, p. 102).

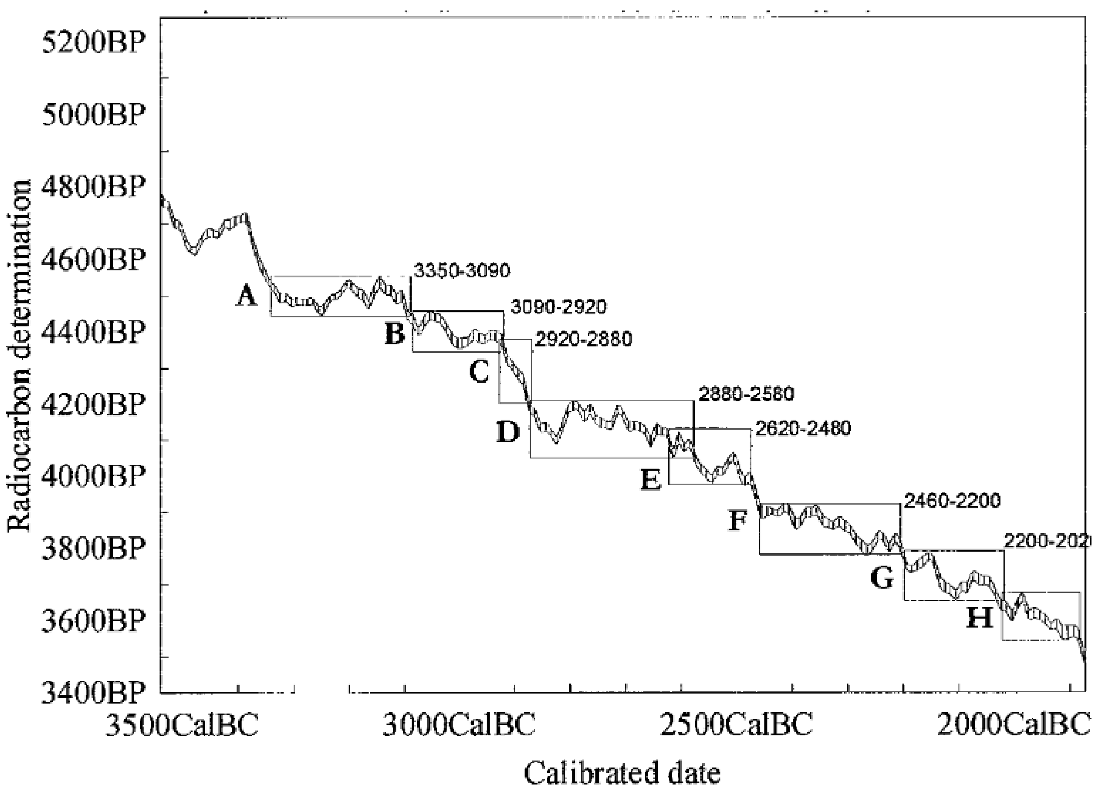


Figure 15. The calibration curve during the transition from the Neolithic to the Bronze age in Europe. The y-axis displays the uncalibrated data that intersects with the calibration curve. The Bell Beaker transition occurs during phase D. This means when calibrating radiocarbon dates during this period, a large error margin occurs spanning several hundreds of years. This makes dating the Bell Beaker period to a specific region impossible to do with radiocarbon dating, adapted from Furholt (2003, p. 15)

During the paradigm shift around the 1970s, the consensus shifted from diffusion through migration to a more social and economic viewpoint of cultural transmission (Kleijne, 2019, p. 17). Even though Lanting & Van Der Waals (1976) proposed their migration hypothesis during this period, the focus on the origin of the Bell Beakers fell into the background. During this period, the idea of the Bell Beaker *package* was proposed: Bell Beakers, flint arrowheads, copper daggers, perforated amber buttons and stone wrist guards. This *package* is associated with economic and social status, which the emerging elite strived to adapt throughout the whole of Europe (Lemercier, 2020b, p. 122). During the late 1980 and early 1990s, the idea came forward that the Bell Beaker culture is not related to a single group or culture in the various regions where Bell Beakers have been found (see Lemercier, 2020b). In the last two decades, much has changed due to the implementation of various scientific technologies from various academic fields. The idea that migration had a major impact in the third millennium BCE is being reconsidered. In recent ancient DNA studies, a large genetic change has been recorded in most of Europe stemming from the Pontic Steppe and related to the Corded Ware culture which was a contemporaneous material culture (most notably: Haak et al., 2015; Olalde et al., 2018). This genetic migration has also been visible in Bell Beaker-related sites (see Figure 16). In addition, isotopic studies can determine from which region individuals come based on the analysis of isotopes in dense bones. These studies (Price et al., 1998; Parker Pearson et al., 2016) show that Bell Beaker individuals were highly mobile in most regions. However, mainly the ancient DNA studies remain somewhat ambiguous within archaeology. There is no denying that some type of migration or mobility has impacted the diffusion of the Bell Beaker phenomenon.

To summarize, the Bell Beaker phenomenon was first considered to be a migration of people throughout most of Europe during the Cultural-Historical paradigm. From the 1970s until the late 1990s, the origin of the Bell Beakers was put into the background and the socioeconomic idea of the Bell Beaker *package* was introduced. During the last two decades, the ideas of migrations have been revised through the use of new methodologies such as isotopes and ancient DNA analysis.

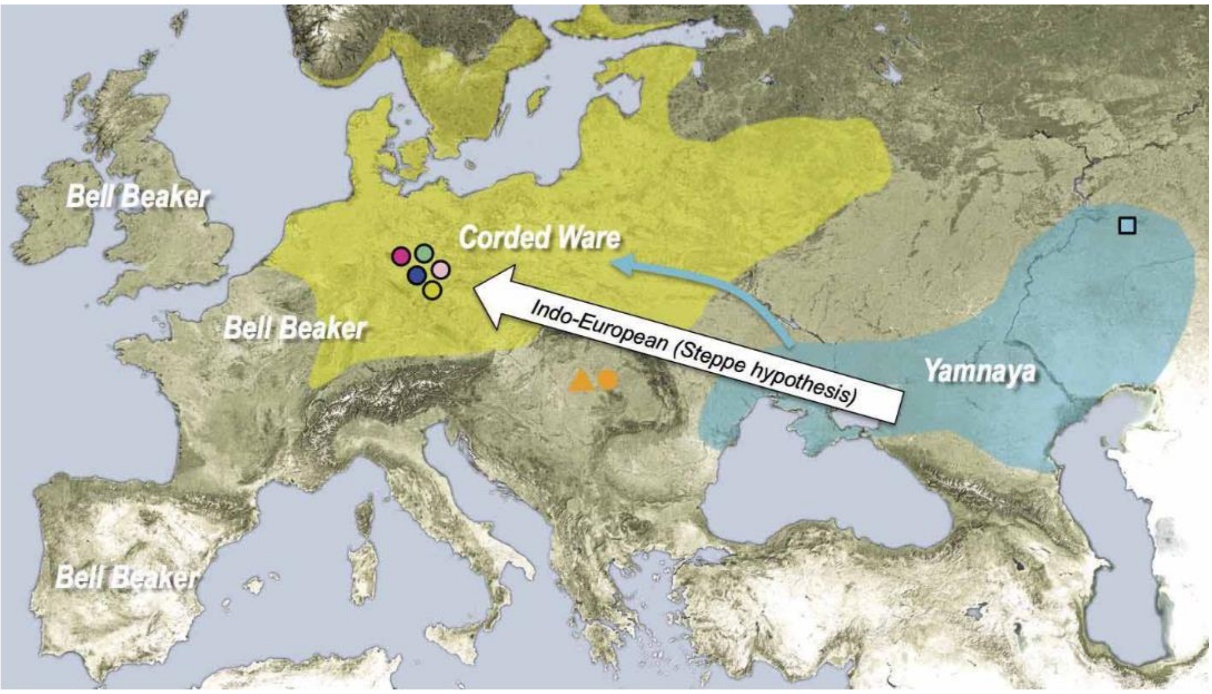


Figure 16. Genetic turnover from the Pontic Steppe to Western Europe (Haak et al., 2015).

2.4 Chapter Summary

This chapter discusses the relevant theory behind the diffusion of innovations by Rogers (1983), social network analysis, and network science. Additionally, the research background of the Bell Beaker diffusion and social network analysis has been discussed in the historical and current state.

Within archaeology, there have been some studies that address the diffusion of innovations through social network analysis. The construction of networks results in the creation of ties between archaeological data. However, no study addresses how the networks themselves can be assessed. In the next chapter, the Bell Beaker pottery and communication networks will be discussed that will be used to analyse the Bell Beaker networks in the Lower Rhine Region. These data will be used to assess the parameters in the diffusion of innovation model by Córdoba & García-Díaz (2020a).

Chapter 3. Data & Methodology

In this chapter, the data concerning the diffusion of the Bell Beaker phenomenon in the Lower Rhine Region will be discussed. This will be primarily based on the research done by Kleijne (2019). In his PhD dissertation, he describes how pottery frequencies and radiocarbon dating can inform about the diffusion of the Bell Beaker pottery in the Lower Rhine Region. Additionally, he uses social network analysis to show how these settlement sites can be connected during the Bell Beaker period.

Furthermore, the description of how the diffusion of innovations model by Córdoba & García-Díaz (2020b) works will be presented by explaining how the functions in the model operate, how the code is written and adjusted, and how the variables in the model can be archaeologically interpreted.

3.1 Bell Beaker Data

The data comes from identified Bell Beaker settlement sites in the Lower Rhine Region. This is one of the six regions (northern Germany and southern Scandinavia, the Czech Republic, the Lower Rhine region, northern France, western France, and the Portuguese Estremadura) in Europe that is presented in Kleijne's (2019) PhD dissertation (see Figure 17). All these settlement sites have been excavated and can be dated either by radiocarbon dating or by material culture found in the Bell Beaker period around 2600-1800 BCE. The definition of what can be considered a settlement site is broad, but all sites can be attributed to human activity. This includes single man-made features, structural remains, a cumulative palimpsest of several occupations etc. (Kleijne, 2019, p. 60).

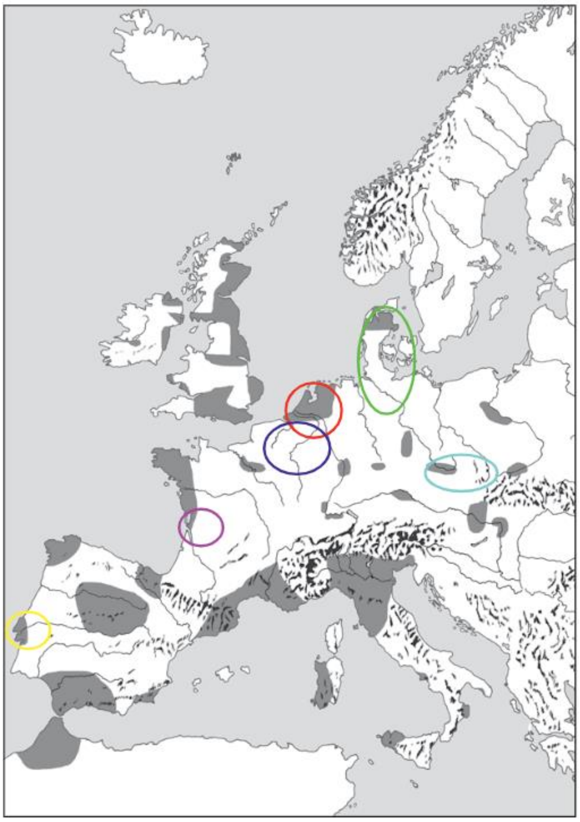


Figure 17. The distribution of the Bell Beaker phenomenon in dark grey, with the six study areas encircled in various colours, adapted from Kleijne (2019), after Vander Linden (2007).

The reason for selecting the Lower Rhine Region as the case study for this thesis is because of the quality of the data. Since the start of the *Valletta Harvest* programme in 2001, a large dataset has been compiled and published of the Late Neolithic and Early Bronze Age in the Netherlands (Fokkens et al., 2016). Additionally, the presence of a national digital repository for archaeological data (DANS) makes the data more accessible. These aspects are lacking in other regions (Kleijne, 2019, p. 65). Therefore, the Lower Rhine Region has been selected to see how the diffusion of the Bell Beaker pottery took place.

The Bell Beaker period in the Lower Rhine Area has 81 settlement sites of which 26 have no presence of Bell Beaker pottery (Kleijne, 2019, p. 68). In total, only 31 of these sites in this region have radiocarbon dates that can date the pottery chronologically (see Figure 18). This is determined by looking at complete vessels or pottery sherds of Bell Beaker pottery in comparison with other types found, e.g., Pot Beaker and Common Ware (see Figure 19). Different frequencies of pottery can be interpreted as to how important and relevant the Bell Beaker pottery was at given sites. The frequencies can be classified into low percentages (0-20%), middle percentages (21-40%, 41-60%) or high (61-80%, 81-100%) percentages (Kleijne, 2019, p. 84). The pottery frequencies show a high variability when comparing the settlement sites and plotting them against the radiocarbon dating shows that directly linking it to Rogers' S-curve is difficult to do. This is because the initial phase of a new technology or innovation is archaeologically not visible (Fokkens et al., 2008). When the critical mass has been reached there is still a high percentage of types of pottery other than Bell Beakers which leaves the question if Bell Beakers were fully consolidated into the Late Neolithic communities.

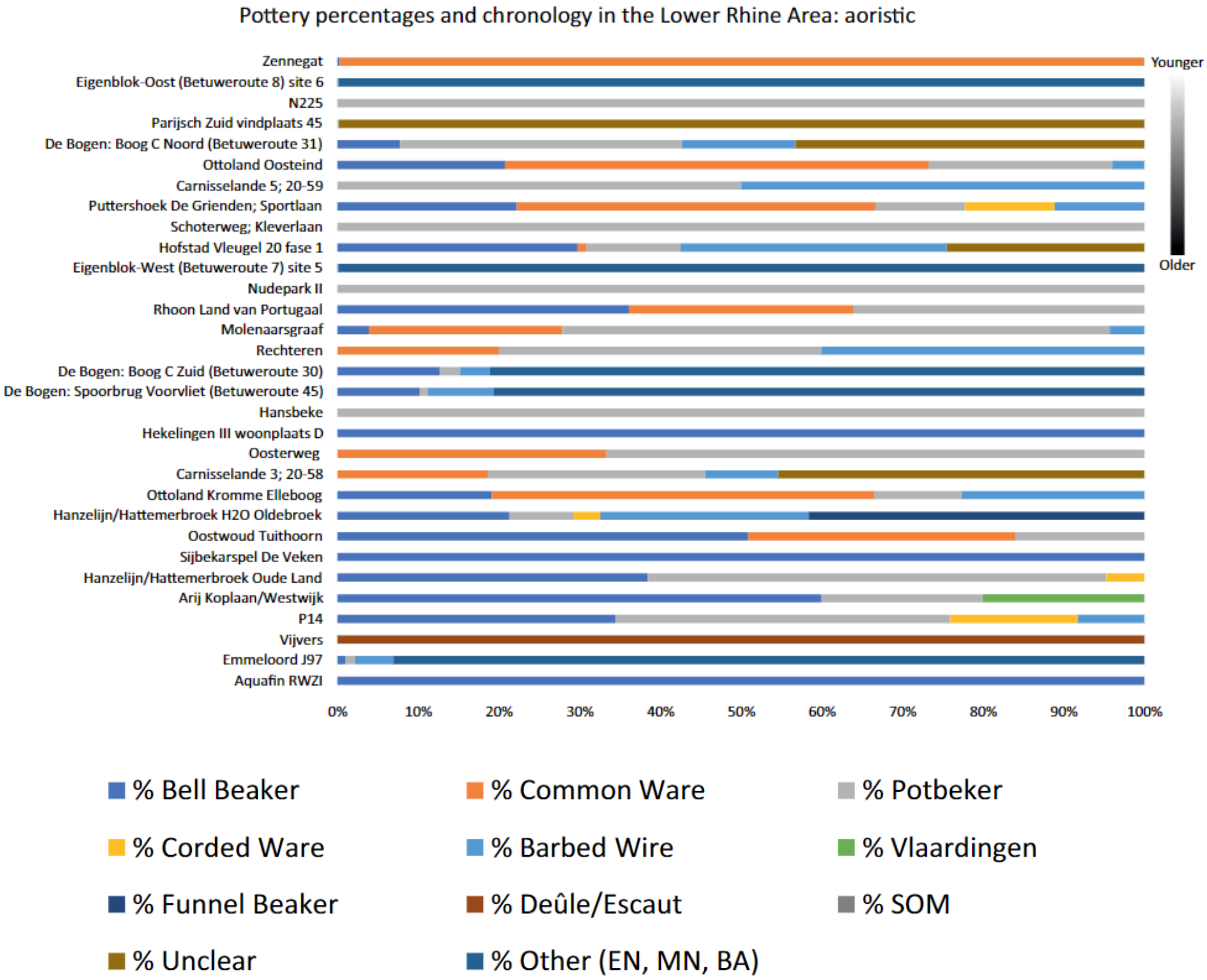
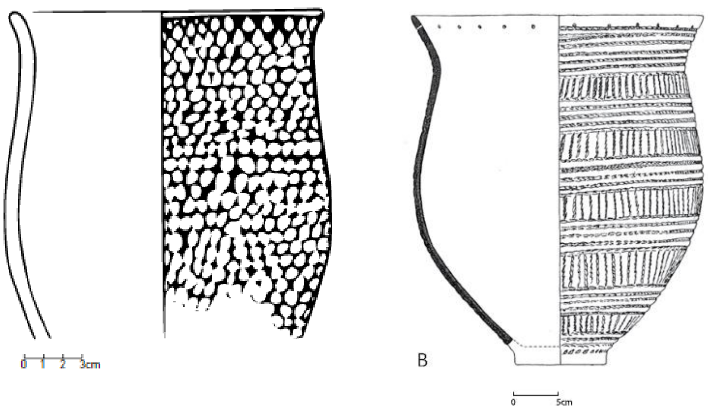


Figure 18. Pottery percentages from settlement sites in the Lower Rhine Area, displaying a chronological order from young (top) to old (bottom), adapted from Kleijne (2019, p. 79).



(a) **(b)**

Figure 19. Cross section of (a) Common Ware (Kleijne, 2019, p. 155) and (b) Pot Beaker (Kleijne, 2019, p. 157).

In the Lower Rhine Region, no evident rejection of the Bell Beaker pottery occurred. This means that Bell Beaker pottery has been found at settlement sites during the entire Bell Beaker period (2600-1800 BCE). Even though the Bell Beaker pottery type has a lower frequency at sites later on in time. It does not mean that it had a lower impact. Some of these other pottery types, such as Pot Beakers can be interpreted as reinventions of the Bell Beaker pottery (Kleijne, 2019, p. 184). The pottery percentages are used as a proxy to see the diffusion of innovations, meaning that throughout time a change in Bell Beaker pottery frequency can be seen. But this change cannot be analysed by looking at the increase or decrease in the Bell Beaker pottery type at sites alone. If we look at the origin of the pottery, meaning the clay composition, most of the pottery assemblages from the Lower Rhine Region consist of locally sourced materials (Salanova et al., 2016, p. 9). This indicates that the pots themselves were not the primary cause of the diffusion of the Bell Beaker pottery, but the spread of ideas was. The exchange in Bell Beaker pottery was limited (Salanova et al., 2016, p. 10). Therefore, the Bell Beaker network of ideas and not that of pottery should be considered when assessing the communication network of the Bell Beaker pottery.

To analyse the adoption of the Bell Beaker pottery, time is an important aspect. Not just the radiocarbon dating that is evident in some of the settlement sites, but a chronology of the Bell Beaker period needs to be established to gain insight into the process of adoption. This has been done by Bayesian analysis, where the absolute calibrated radiocarbon dates and relative archaeological artefacts can be combined to make a more accurate chronology (Kleijne, 2019, p. 97). While this is a useful tool for creating an order of events, Bayesian modelling is not always possible, such is the case of the Bell Beaker settlement chronology. The preconditions are that a sequence of reliable radiocarbon dates relative to the cultural layers dating to the beginning and the end of the Bell Beaker period needs to be present. Not only do many sites not have multiple dates, but they are also not all reliable since not all of the dating has been done on organic material that has been directly associated with human occupation (Kleijne, 2019, p. 63). Therefore, a settlement site has been taken with a reliable sequence of radiocarbon dates to calculate the period the Bell Beaker phenomenon was present. The Lower Rhine region shows a moderate rate of adoption according to the interval between the pre-Bell Beaker and the Bell Beaker phase of the settlement site of Vlaardingen Arij Koplaan (Kleijne, 2019, p. 91).

Based on the data alone, it can be determined that the Bell Beaker pottery specifically was not fully integrated. Kleijne (2019, p. 191) also notes that this method of determining the S-curve is not without its flaws. Even though the Bell Beaker pottery did not completely replace the existing pottery types, it still left an imprint in society which can be seen in the communication networks during the Bell Beaker phenomenon.

3.2 Bell Beaker Communication Networks

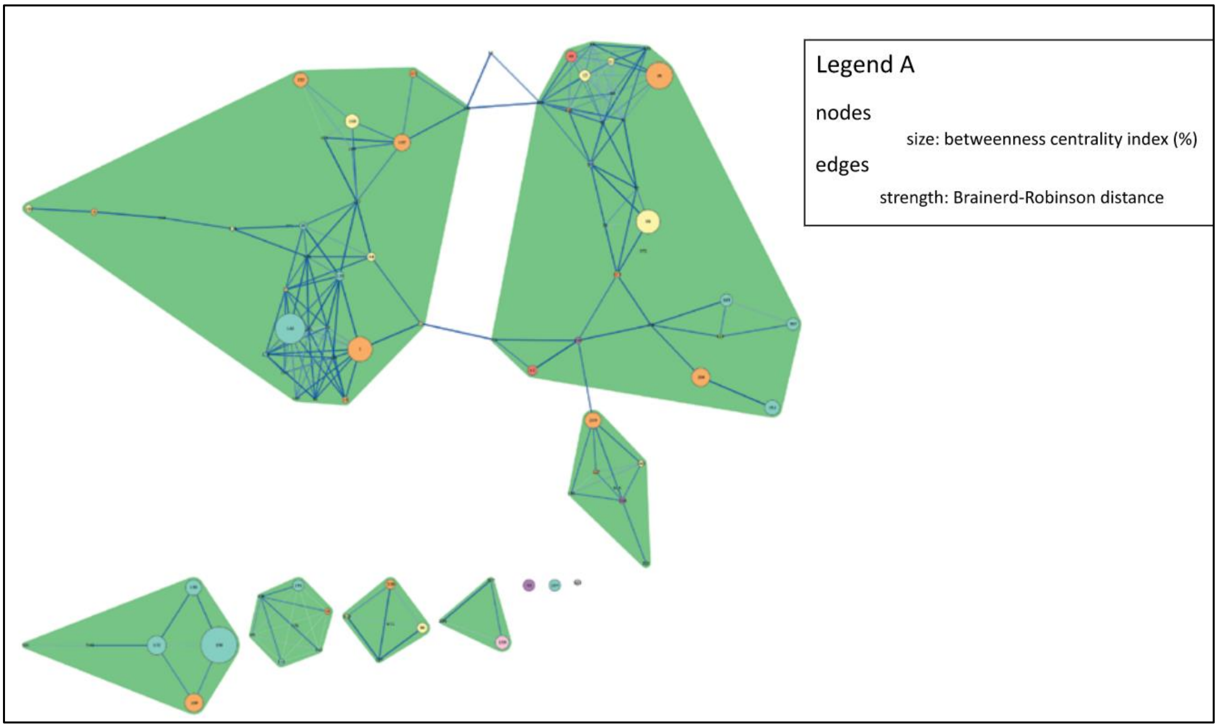
The characteristics to define the connection within the Lower Rhine Region are based on the communication networks during the Bell Beaker period. Kleijne (2019) has recreated these networks based on the decorative attributes found on pottery, stone and flint artefacts, and subsistence (Appendix A. Tables with the variables used by Kleijne (2019) for the construction of the Bell Beaker communication network). The network of decorative pottery attributes consists of the comparison of the Bell Beaker, Common Ware, and Pot Beaker (Kleijne, 2019, pp. 49-51). For the Bell Beaker pottery, spatula, *Cardium*, and cord impressions are common decoration techniques. Additionally, the all-over, geometric, zoned motifs are found on Bell Beaker pottery. Also, it was recorded if incrustation or paint was present on the beakers. Common ware and Pot Beakers share similar decoration attributes and were therefore grouped. A distinction has been made between applied and incised features on pottery. Additional characteristics that have been analysed are the presence of handles, holes below the rim, type of base, and decorations.

The data for the network of stone and flint artefacts are determined based on the comparison of frequencies of tool types at sites. Kleijne's (2019, pp. 51-53) analysis of flint and stone artefacts also includes the provenance and the state in which the artefacts have been found, meaning if the tools were complete, fragmentary, or a preform.

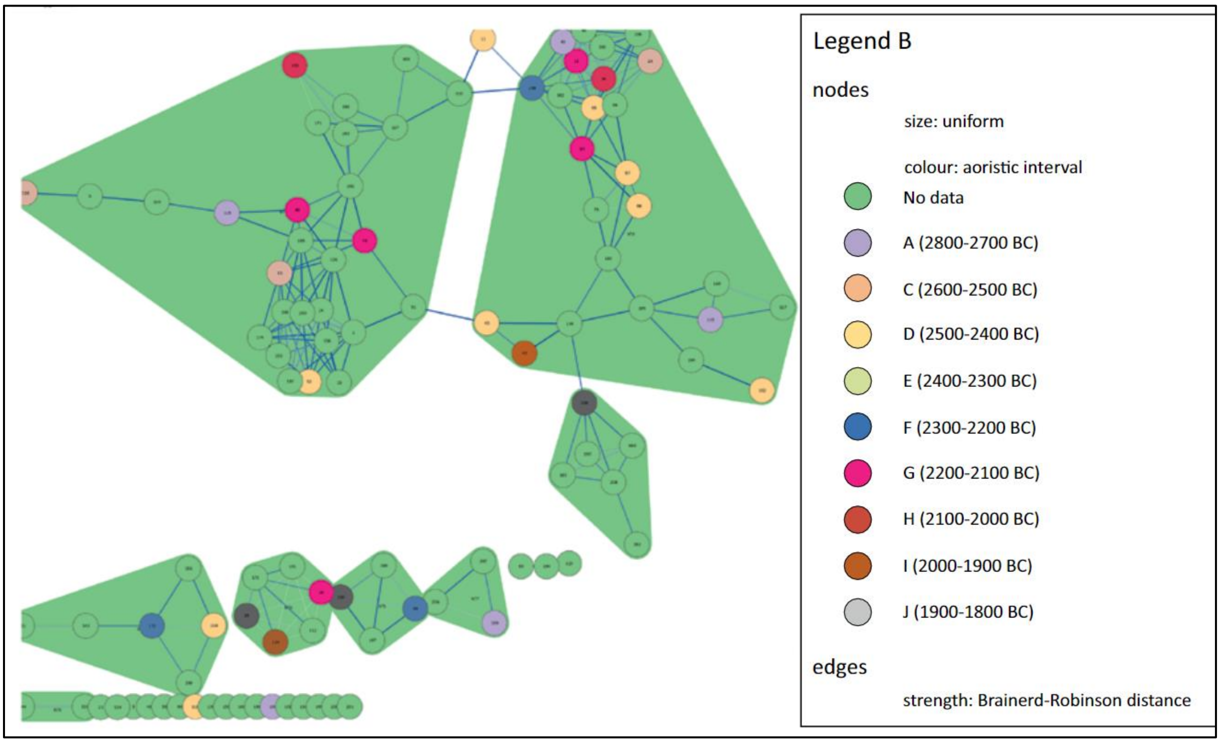
The data for the subsistence strategies that were present at the settlement sites can also indicate how ideas spread. The subsistence network analyses the difference between wild and domesticated animals, and the amount of various grain types (Kleijne, 2019, p. 53-55). The distinction of animal remains between wild and domesticated has been made since it removes the bias of geographical and ecological circumstances. This means that no distinction between species is made, e.g., fish bones are only located near coastal or river sites, so, when statistical analysis would be done on the species level, the total amount of fish bones compared to non-domesticate and domesticate bones would skew the data.

These three networks have been combined into one regional network of the Lower Rhine Area. The similarities and differences between the settlement sites are measured by using the Girvan-Newman clustering algorithm, a method for constructing communities or cliques in complex networks (Girvan & Newman, 2002), and the Brainerd-Robinson coefficient, a method to analyse the similarities between archaeological assemblages (Brainerd, 1951: Robinson, 1951). These methods show that the Lower Rhine Region has three large clusters and overall, a highly connected network (see Figure 20).

The network that has been created by Kleijne (2019), will be used for analysing the results that will be presented in the next chapter.



(a)



(b)

Figure 20. The communication networks of the Lower Rhine Region with (a) displaying sites with a high betweenness centrality based on size and (b) the chronology of the sites based on colour, adapted from Kleijne (2019, p. 124)

3.3 The Diffusions of Innovations Model

The model that will be used is an agent-based model designed to show the adoption of innovations (Córdoba & García-Díaz, 2020a). This model is based on an equation-based model related to the adoption of innovation, namely the Bass model (1969). The Bass model is a dynamical systems model, which uses mathematical equations that show change through time by quantifiable means. This type of modelling has a couple of disadvantages. Equation-based modelling is deterministic, and the system of the model is treated as an undifferentiated whole (Lake, 2014, p. 261). This is a major drawback in simulating past events since the adoption of innovation is not deterministic by nature. The results we see in the archaeological record have been influenced by many other factors than one trend. Therefore, adaptions were made by Delre et al. (2007) and subsequently by Córdoba & García-Díaz (2020b). These adaptions will be described in the upcoming paragraph.

3.3.1 Description of the Model

Delre et al. (2007) expanded the Bass model by adding two new components: agents and a social network. All agents are placed on nodes in a social network. A fraction of the agents is introduced to the new product. This subsequently follows with adopters and non-adopters interacting with one another. If an agent's utility is greater than a set minimal utility or marketing has influenced the agent, following the contact with an agent who has the adopted product, the agent will decide to adopt this product. This can be put as:

$$D_i = \begin{cases} 1, & U_i \geq U_{i,\min} \text{ or } \lambda > s_i \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

Where D_i is the decision of the *i* agent, U_i is the agent's current utility, $U_{i,\min}$ is the agent's minimal utility, s_i their susceptibility to marketing, Λ the effort of marketing. $U_{i,\min}$ and s_i are drawn from a uniform distribution *U* (0,1), with the first value being assigned to agent *i* before the simulation starts and the second one every time *i* is about to take their decision. As the explanation of the formula with words such as *product* and *marketing* indicate that the model is used in modern-day economics or social sciences. These parameters are not in line with an archaeological example, but this will be addressed later.

Continuing, U_i depends on local influence. This is determined by how useful it is to adopt based on two factors: individual preference and the rate of adoption of their closest neighbours. Which can be expressed as:

$$U_{Li} = \beta \cdot x_i + (1 - \beta) \cdot y_i \tag{2}$$

$$x_i = \begin{cases} 1, & A_i \geq h_i \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

$$y_i = \begin{cases} 1, & p_i \leq q \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

Where U_{Li} is the derived utility from this equation, where β is called the coefficient of social influence, and it weights the importance of an agent's peers on their decision; A_i is the fraction of adopters among the agent's closest neighbours; h_i is the minimal fraction of adopters among those neighbours necessary to arise the desire to adopt; p_i is their individual preference, and q is the quality of the product the agent wants to adopt. Both p_i and h_i vary uniformly between 0 and 1 which is given to each agent at the beginning of the simulation. β and q are global parameters that can be altered between values of 0 and 1.

This is the model created by Delre et al. (2007). It shows that only local influence affects the diffusion of innovations by the equations mentioned above. In addition to this model, Córdoba & García-Díaz (2020) further expanded Delre's et al. (2007) adaptation by adding reflexivity, a process that affects itself recursively (see Figure 21). This process affects the agents on the entire network (Global influence). Agents will adopt a new product when a sizable portion of the population has also adopted the new product. This can simply be put as the average size of connected components in a social network. A percentage of the total amount of adopters would not work since it would disregard the structure of the social networks used (Cordoba & Garcia-Diaz, 2020, p. 5). As this average grows, agents are more likely to join.

$$U_G = \frac{\overline{C}}{N} \quad (5)$$

$$\overline{C} = \sum_{j=1}^{n_c} \left(\frac{n_j}{N}\right) n_j, \quad n_j > 1 \quad (6)$$

The global utility is defined as U_G, where C is the average size of components of adopters, N is the total number of agents, n_c is the number of components at time t, and n_j is the number of adopters in component j. When C increases so will the global utility and will therefore eventually slowly influence the agents into the adoption of the product. The reflexivity in this model will not be added immediately after an agent becomes aware of the adoption in the system. It becomes aware of the global process when the critical mass has been reached. This process can be defined as:

$$E\left(U_G\right) = \frac{1}{1 + e^{-\phi\left(U_G - M_c\right)}}$$

(7)

Where *E* is the emergence factor which increases when U_G come close to the critical mass. M_c is the critical mass which equals the connected components in the system. ϕ is the sharpness by which agents can detect the emergent critical mass. Both M_c and ϕ are global parameters. Now that the model is explained the implementation can be discussed.

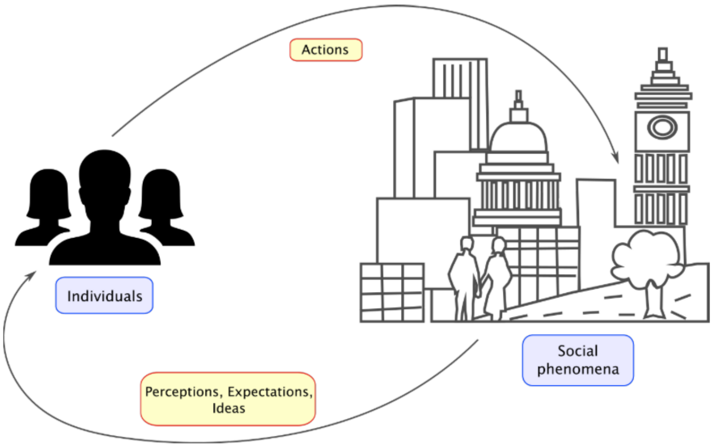


Figure 21. Schematic representation of a reflexive process (Córdoba & García-Díaz, 2020b, p. 2).

3.3.2 Running the Diffusion of Innovations Model

The Python code to model is freely available on CoMSES Net, the Network for Computational Modelling in Social and Ecological Sciences (Córdoba & García-Díaz, 2020b). This digital repository focuses on the open science principle and, therefore, the agent-based and computational models are free to download and use for the development of research (Janssen et al., 2008). The model can be downloaded in a zipped folder and contains five Python script files, a YML project file, a readme.md file which can be viewed in Notepad, and an HTML link to the model description. In the *readme* file, there is a step-by-step guide on how to run the project. However, this does not work. The reason for this is that the model, for some reason, is made in Python 2.7 which was released in 2010 and is not supported since 2020. Therefore, the problem is that some of the packages, extra tools for coding, the model uses are no longer available in the current version of Python (3.11). To fix this some additional steps were taken to resolve the issue.

The first step was to replace the existing *anaconda-project.yml* file with the self-created *environment.yml* file (see Figure 22). This step was necessary because the old file was the problem in running the code and did not work, but this resolved the issue. In this new file, the older version of Python and the packages that are used in the model are listed for the creation of the environment, which are directories in which you only use a specific version of Python and only the packages necessary.

For the code to run, first, Miniconda3 needs to be installed. This is a free downloadable small program which contains Python, a bootstrap version of Anaconda, and its dependencies. Anaconda is a user-friendly package management programme that aims at an easy way to share find access and store packages Miniconda3 also includes the Conda package and environment manager. The difference with Anaconda is that Conda can use the packages stored in Anaconda. Conda is also used for creating environments.

environment.yml

File Edit View

```
name: Innovations
channels:
  - conda-forge
  - defaults
dependencies:
  - python=2.7*
  - matplotlib=2.0*
  - seaborn=0.7.1
  - pandas=0.20.3
  - networkx=1.11
  - numpy=1.14*
  # IPyparallel and its deps
  - ipyparallel=5.2.0
  - tornado=4.5.3
  - pyzmq=16.0.3
  # For Spyder
  - spyder-kernels
```

Figure 22.YML file with the dependencies necessary to make the model run, including the channels they were extracted from.

When the new file is in place the setup of the model can begin. After installing Miniconda3, the Miniconda3 command prompt is opened to create a new environment based on the replaced YML file. This makes sure all the packages and their dependencies are in place to be able to run the analysis for the model. Following the activation of the environment, a fix to an error is run, to be able to use the five Python scripts in the folder to run the analysis for the model. When the analysis is activated, the agent-based model will produce its results after a few minutes (depending on the computational power of the device). The results of the basic configuration will then be saved and stored in a new folder. At this point, the model is ready to be used. If the Anaconda command prompt is closed when opened again simply go to the right directory and activate the previously created environment (a more detailed description is present in the attached files). In the next paragraph, the code of the agent-based model will be described.

3.3.3 The Code

Five Python scripts make the model run which can be used and altered in an integrated development environment (IDE), such as Spyder (this programme has been used for this thesis). In the first script *utilities*, the functions are composed. In this file the setup for the model is made, which means the agents are configured, the way the adopters are converted in the network, the degree of homophily, the speed of diffusion, and how the global utility works in the model. Additionally, code is written here to collect and save part of the data in the results file coming from the global utility and the adopter, such as the mean percentage of the adopters at a given point in the run, and the time reflexivity takes off in the model.

In the *parameters* file, all the variables of the model are listed, this includes the number of consumers, social influence, randomness, activation sharpness (when reflexivity is activated), level, quality, initial seed of the first adopters, at what point critical mass is defined, number of neighbours, marketing effort, graph type, and time delays. In this script, it is also possible to choose what type of plot is created for the output, e.g., the total amount or percentage of adopters. The values that can be adjusted to influence the outcome are for most variables either a whole number, such as the number of consumers, and the number of neighbours, a number between 0 and 1, such as the social influence, and the quality of the product, binary, such as the use of time delays (True or False), and finally the predefined numerical categories. The latter can only be adjusted for the graph type and there are three options to choose from: random, small-world, and scale-free networks.

In the *algorithm* file, the conditions for the simulation are presented. The utilities are imported from the first script and the graph on which the diffusion occurs is created. In addition, the attributes of the nodes are constructed, such as the time delays and the neighbour relations. Next, the algorithm will run the decision-making process of the agents, which can be repeated to a set maximum time.

The *plots* file consists of all the code for the visualisations that are being produced after the analysis is run. This includes not only graphs but also the possibility to use several graphs in one plot.

In the *analysis* file, all the data from the other scripts are imported and the code to run the analysis is created. The simulation is run, and the plots are created. Subsequently, all the output is saved in the *Results* folder that appears in the code directory which consists of graphs or CSV files, and JSON files with the stored parameters used in the visualisations.

3.3.4 Code Adjustments

A few adjustments have been made to apply more graph models to the code and to remove some of the unnecessary visualisations in the output.

In the *algorithm* file, the network generators for the balanced tree, caveman, and DGM graphs have been added. For the balanced tree and DGM graph to work properly, the initial seed of adopters needed to be configured to start at the first node (node 0). This implementation was located in the *utilities* script where the argument was added that would set the initial adopter to node 0 when the DGM and balanced tree graphs were applied if they were put in the graph type parameter.

For the visualisations, the label was changed from *reflexivity* to *diffusion*. Additionally, the *no reflexivity* curve was removed. These two changes were made because the aim of this thesis was not to analyse the difference reflexivity has on the diffusions of innovations. This was the purpose of the paper by Córdoba & García-Díaz (2020b).

3.4 Applying the Archaeological Data to the Model

According to the analysis of Kleijne (2019), pottery frequencies present at excavated settlement sites do not show signs of a completed adoption of the Bell Beaker pottery. The Lower Rhine Region does show a phase of reinvention. Even though the Bell Beakers themselves were not consolidated, the characteristics were highly impactful. Analysing the diffusion of the Bell Beaker pottery as an innovation and modelling the diffusion process of the Bell Beaker communication network separately will convey more about the Bell Beaker phenomenon in the Lower Rhine Region. Altering each of the parameters in the model will influence the output significantly. However, comparing the archaeological data to all the parameters in the model is difficult. In this paragraph, all the parameters will be listed and the ones that can be archaeologically interpreted will be further discussed in combination with the Lower Rhine Region.

Agent decision	**Local influence**	**Global influence**
D_i = Agent decision	U_{Li} = Derived utility	C = (Weighted) average size adopters
U_i = Agent utility	B = social influence coefficient - Global	N = Total number of agents
$U_{i,\,min}$ = Agent minimal utility	A_i = Fraction of adopter of neighbours	N_c = Number of components at t = Time
S_i = Market susceptibility	H_i = Minimal fraction of adopter to arise desirability	N_j = Number of adopters in component j > 1
Λ = Amount of marketing	P_i = individual preference	
U = Uniform distribution of random values	q = Quality of the product – global	

Table 2. Variables in the equations of the diffusion of innovations model by Córdoba & García-Díaz (2020b).

In paragraph 3.3.1 Description of the Model, the variables of the equation are described. As we can see from Table 2, some of the descriptions of the variable do not directly suit archaeological research. Some are difficult to alter since there is no empirical data to support these variables. However, some can be used (with assumptions). Table 3 shows what parameters are present and are changeable in the model. The nodes or agents in this model are the settlement sites.

Parameter	Value	Adjustable for application in Archaeology
Quality	Is measured from a distribution between 0 and 1	yes
Social influence	Is measured from a distribution between 0 and 1	yes
Graph type	Category of 7 choices: 1. Small-world 2. Preferential attachment 3. Power-law cluster 4. Random Graph 5. Caveman 6. Balanced 7. DGM	yes
Randomness	Is measured from a distribution between 0 and 1	possibly
Number of consumers	1 represents 1 consumer or node in the network	yes
Activation sharpness	At what step reflexivity is introduced	no
Level	The constant of an agent	no
Initial seed	Reflects the percentage of the total number of consumers, e.g., 0.001 of 1000 is 1	no
Critical mass	Is measured from a distribution between 0 and 1	possibly
Number of neighbours	The average number of neighbours a node has in the network	possibly
Marketing effort	Is measured from a distribution between 0 and 1	yes
Use of time delays	Time delays that can be implemented at steps in the simulation	yes

Table 3. The variable parameters in the model.

Firstly, the quality of the innovation can be assumed to be low for the Bell Beaker pottery itself. Not necessarily because it was of poor quality, but because pottery was already well-established in European societies during the introduction of the Neolithic. Additionally, the quality of the pot greatly depends on the potter. While the pot may have been of great quality, the adoption and reinvention took place in local settings in the Lower Rhine Area (Kleijne, 2019, p. 184). Local reinvented types, such as the Veluvian Bell Beakers (see Figure 23), show that the initial Bell Beakers were highly influential but not the quality.

Secondly, the social influence can be assumed to be high. As described in the diffusion of innovations model, this parameter looks at the rate of adoption of the neighbouring nodes. Since the spread of the Bell Beaker pottery is present in all of the settlements and highly impacted the Lower Rhine Region, the social influence must have contributed to this in combination with the overall shared idea of the Bell Beaker phenomenon. This can be seen in the initial high frequency of the Bell Beaker pottery. The quality and social influence variables are tested first since can be best interpreted archaeologically.

Third and fourthly, the graph type and the randomness of the graph will be tested. As discussed previously, there is an option for three random graph types including the random, small-world, and scale-free networks. For the application of archaeological data, it is difficult to decide which is the best to apply. Both the small-world and scale-free graph types are representative of real-world systems. The degree of randomness determines how predictable the model is, meaning if using a high degree of randomness, the graph will closely represent a random graph since it is not fixed by the rules. This variable is difficult to interpret and will be tested. The balanced tree, caveman, and DGM graph are tested to see if hierarchically structured graphs can inform about the diffusion of innovation.

Fifthly, the total number of agents is alterable (global influence). Population size has been theorised to positively influence the rate of adoption and conformity regarding complex technologies, innovation, and change over time (Eerkens et al. 2007, p. 264). Kleijne (2019, p. 85) also shows that changes in innovation over time vary within the Bell Beaker pottery assemblages in Europe. However, he does not mention population size. Others have argued that cultural change happens due to population pressures, meaning that due to small population size, certain innovations will spread over time (genetic drift; Shennan 2000). This has not been tested by using various types of networks. Córdoba & García-Díaz (2020) use different social networks in their research but do not specifically focus on population size. However, since we are using settlement sites as agents it is difficult to apply this theory. The population within settlements is not known. Even though there are various methods for analysing populations based on scarce settlement data, none are without problems (Lemercier, 2020a). Therefore, population size is difficult to assess.

In total, only 31 Bell Beaker settlements sites in the Lower Rhine Region have radiocarbon dates that can date the pottery chronologically (Kleijne, 2019, p. 80). Using 31 as the total number of consumers in the simulation is still an underestimation of all the settlements that were most likely present during the time. But since there is no other data to insist on a higher number of nodes, this number will be used. However, the number of agents will be tested to see how it influences the rate of adoption.

Sixthly and seventhly, the number of neighbours and the initial seed will be addressed. The number of neighbours refers to the average number of nodes on node has, meaning one node will have four neighbouring nodes. Increasing or decreasing this number will impact the rate of adoption. This variable has to be tested to see how it works on the various types of graphs. Additionally, the initial seed of the innovation can be altered. Increasing the initial number of agents as innovators will probably increase the rate of diffusion. However, this variable is difficult to interpret since it is impossible to detect multiple instances of diffusion due to the calibration plateau during the Bell Beaker period (see Figure 15).

Eighthly, the marketing in the agent decision equation, s_i and Λ stand out. In the equation, there is an $U_i > U_{i,min}$ or $s_i > \Lambda$ statement, which means that the marketing part could be removed, if necessary, but instead of marketing it can be replaced by an archaeological variable that expresses the same intent as marketing. It is postulated that social gatherings of some nature have taken place during the Bell Beaker period (Salanova et al., 2016, p. 10). This could have reinforced the societal pressure of adopting each other's pottery. The exchange of pottery during the Bell Beaker phenomenon is limited (Kleijne, 2019, p. 151). Most of the pottery had been made locally with some exceptions so referring to the pot that travelled is not possible. Additionally, the Bell Beaker phenomenon shows a shared idea that is most prominently present in the burial record but also in the pottery itself. Therefore, marketing can be translated to the societal pressure that was present during the Late Neolithic in Europe. Each time the model runs 1 time is passed.

The ninth and tenth parameters are the critical mass and the time delays. These two parameters are selected together since they indicate the reflexivity in the model. The critical mass can be determined by a value of 0 to 1 which represents when the adopter notices the total amount of adopters. The critical mass is also complicated to assess. The adopters were likely aware of the diffusion of the Bell Beaker phenomenon, however, to what extent? Fokkens et al. (2008, p. 18) also indicate that critical mass has had to be reached for the Bell Beaker pottery to become visible in all the regions. Time delays in this model indicate the number of time-steps a percentage of the population waits until the reflexivity is activated, meaning when the nodes are influenced by the global utility of connected components. These variables will be experimented with to analyse how they impact the diffusion rate.

Lastly, the activation sharpness and level will not be addressed. Activation sharpness indicates how fast the decision of the adopter is in response to when the given critical mass is reached. The activation sharpness is difficult to interpret archaeologically, therefore it is put in its *standard configuration* of 30. Additionally, the level parameter will not be adjusted. The level refers to the utility level of the agent which is predetermined, and it is not clear what altering his variable does in the model. Therefore, it will not be addressed.

Since many parameters can be used, it is important to specify which will be the focus. Therefore, the parameters with significant archaeological assessment will receive more attention. The parameters that will be specifically focused on are social influence, quality, number of consumers, societal pressure, and most importantly the graph type. Various combinations between these variables will be tested in the upcoming chapter. Additionally, the other, more unclear parameter will be tested to see how an increase or decrease of these variables influences the rate of adoption.

Figure 23. A highly decorated Veluvian Bell Beaker, adapted from (Wentink, 2020, p. 55).

3.5 Chapter Summary

In this chapter, the data regarding the diffusion of the Bell Beaker pottery and how these data have been used to construct a communication network of the Lower Rhine Region. The main attributes of this dataset consist of the pottery frequencies and radiocarbon dates from settlement sites. These frequencies show the impact of the Bell Beaker phenomenon in the Lower Rhine Region and can be used as a proxy for the diffusion of innovation of the Bell Beaker pottery type. The communication networks, which have been created by Kleijne (2019) show how the spread of ideas was manifested in the Lower Rhine Region. This network will be used to analyse how the results in the next chapter can be interpreted.

Additionally, the diffusion of innovations model has been explained. The agent-based model uses three main components to analyse the spread of innovations: the agent's decision, the local, and global influence. The variables that are present in the model by Córdoba & García-Díaz (2020a) show that application of the archaeological data is difficult, but the social influence, quality, and number of consumers will be specifically explored in Chapter 4.

The network structure will be the main focus of the discussion, and the six graph types that have been mentioned in paragraph 2.2.2 Random and Non-Random Graphs, will be implemented and discussed in the upcoming chapters.

Chapter 4. Results

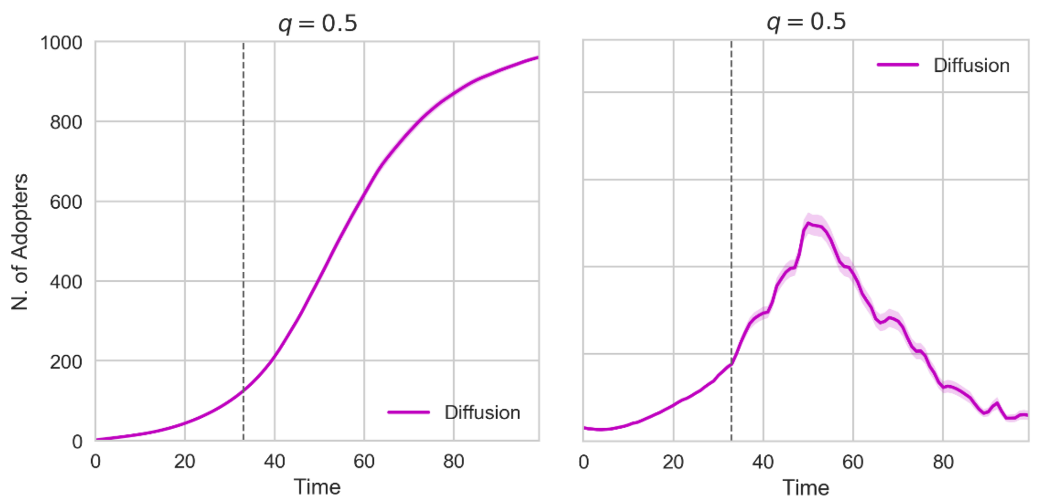
In this chapter, the results are presented which are the outcomes of the simulations run by the diffusion of innovations model by Cordoba & García-Díaz (2020a). The parameters that will be tested are explained in the previous chapter. Running and testing all parameters at once can become chaotic. Therefore, the parameters will first be tested to understand how they influence the diffusion of innovations presented by the graphs of the reflexivity function, meaning the line present in the figures. Secondly, the tested parameters that correlate with the archaeological data of the Lower Rhine Region will be assessed.

The (1) quality and social influence will be assessed first since they can be interpreted best archaeologically before applying the (2) various graph types & the number of consumers, (3) the number of neighbours & the initial seed, and lastly, the global parameters of (4) critical mass, marketing effort, and time delays. Each of these parameters is tested in combination with each other, meaning, for example, the number of neighbours is tested with the initial seed. This is done to save space (and time) since exploring each variable individually would result in redundancy. Additionally, paragraph 4.1 is to test how the model works and how each of the parameters can be interpreted.

We first start with a *standard configuration* of all the parameters. From this, the agent-based model can be built to reflect the diffusion of the Bell Beaker innovation in the Lower Rhine Region. The *standard configuration* is listed in Table 4. These parameters will gradually be adjusted across the upcoming paragraphs. The decision for most of these parameters to be listed as they are in Table 4, is because it is the mean of most of the variables (compare with Table 3). The simulation is run 1000 times to ensure that the randomness of the initial seed, network, and node properties, does not interfere with the results of the run. Additionally, the result of running the *standard configuration* shows essentially the *ideal* S-curve and the Bass model (see Figure 24). Now that the standard setup has been configured, the model can be explored.

Parameter	Variable	Standard configuration
Social influence	β	0.5
Quality	q	0.5
Graph type	*Category*	Small-world
Randomness	r	0.1
Number of consumers	N	1000
Activation sharpness	ϕ	30
Initial seed	δ	0.001
Level	L	1
Number of neighbours	k	4
Critical mass	M_c	0.5
Marketing effort	λ	0.03
Use of time delays	$f(d)$	False

Table 4. The standard configuration of the diffusion of innovations model.



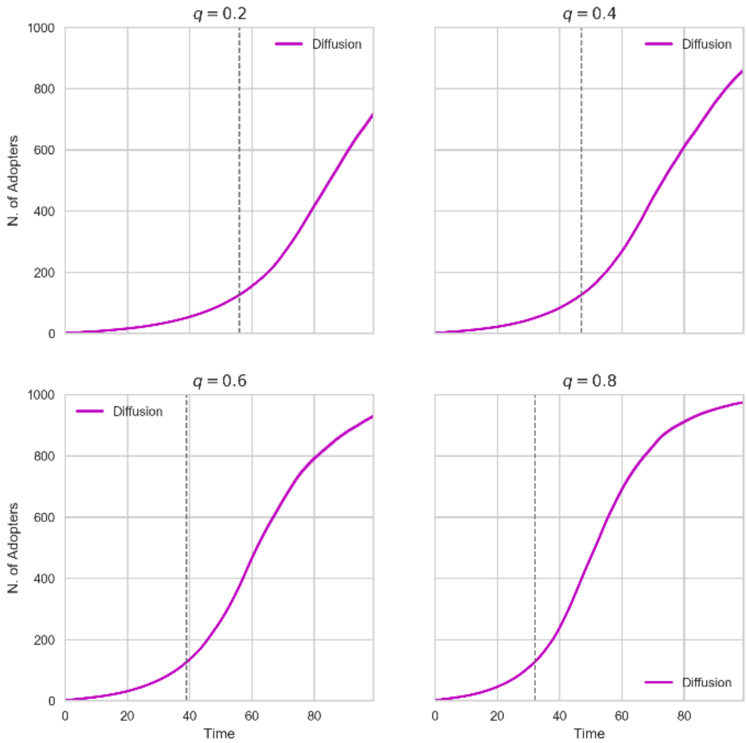
(a) *(b)*

Figure 24. The graphs from running the simulations in the standard configuration. (a) shows the cumulative number of adopters (Rogers' S-curve). (b) shows the total number of adopters at each step in the simulation (Bass model).

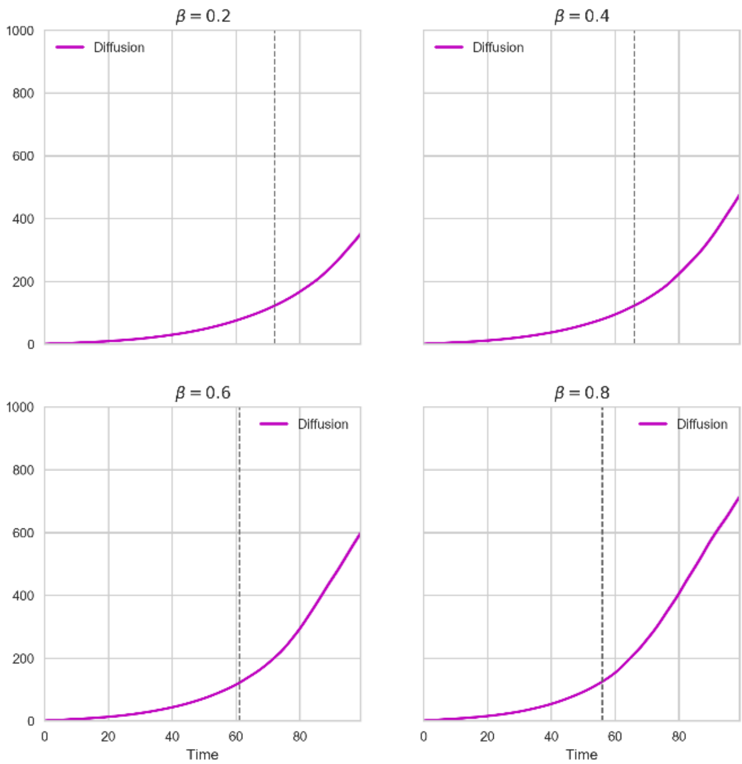
4.1 Understanding the Parameters

4.1.1 Quality & Social Influence

In the previous chapter, it is discussed how we can assess the quality and social influence in the context of the Bell Beaker pottery. These two variables are assessed first since they are the most approachable based on archaeological data. Therefore, a high social influence (0.8) and a low quality (0.2) are analysed. In this first test, the quality is plotted against the social influence. The diffusion curve is drawn with four different values of quality (0.2, 0.4, 0.6, and 0.8) and a high value of social influence (0.8) (Figure 25a). The other parameters are set in the *standard configuration* of the model. To see the reverse impact, a low value of quality (0.2) is used with four values of social influence (0.2, 0.4, 0.6, and 0.8) (Figure 25b).



(a)

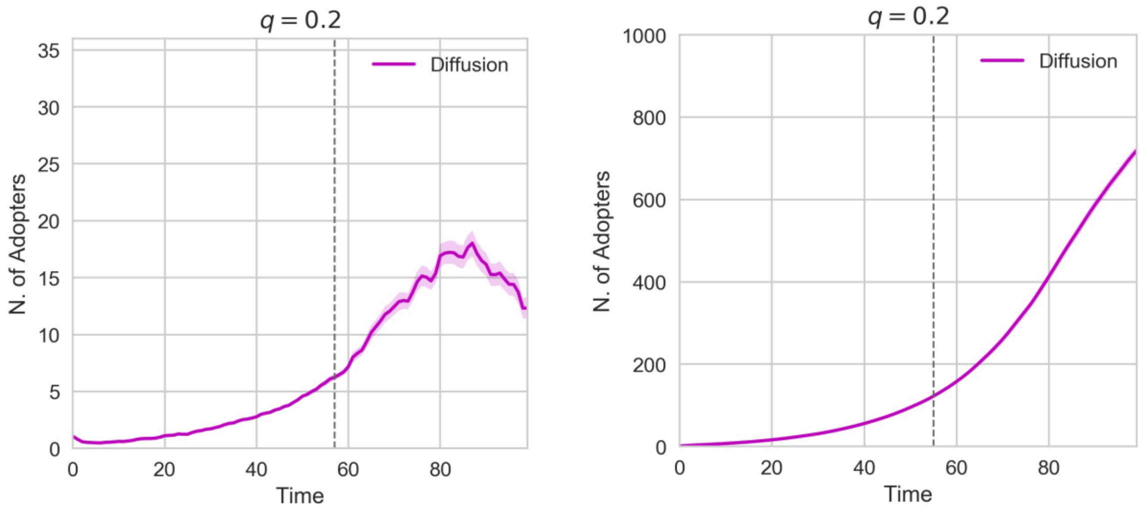


(b)

Figure 25. (a) Standard configuration with the variable values for quality. (b) Standard configuration with quality = 0.2 and variable values for social influence

In Figure 25a, it is visible that the lower the quality, the slower the innovation takes off. Remarkably, the combination of a high quality (0.8) and a high social influence (0.8) shows the *ideal* innovation curve that Rogers (1983) proposed. One would expect a more rapid take-off since both the social influence and the quality are high. The presumed value of quality (0.2) and social influence (0.8) give a slow take-off shown in the top left of Figure 25a or the bottom right of Figure 25b. In comparison with the higher quality values, this graph indicates that the innovation has not been fully accepted in the system in the same amount of time the other diffusion curves have. If more time would elapse, then the diffusion process would most likely slowly increase. Looking at the total number of adopters (Figure 26), it is visible that the innovation went over the critical mass and has been well-consolidated within the system.

The quality and social influence variables have a positive relation to the diffusion curve. However, Figure 26b is not the final curve that is accepted since the other variables will influence the process which has not been tested yet.



(a) **(b)**

Figure 26. (a) This graph shows the total number of adopters at each time-step. (b) This graph shows the cumulative number of adopters at each time-step

4.1.2 Random, Non-Random Graph Type & Number of Consumers

The graph type and the number of consumers will be tested to see how these two parameters will influence the system. In the previous paragraph, a slower adoption process was visualised to an extent. First, the network type will be tested. In the *standard configuration*, the small-world graph has been applied. Here, the random and scale-free graph will be used in combination with the altered variable q = 0.2 and β = 0.8. However, what is interesting is that the rate of diffusion rapidly increases in this scale-free and random network compared to the small-world (see Figure 27). The reason the rapid diffusion in a scale-free network is present is due to the scale-free network having a higher probability of linking new nodes to nodes that already have a high number of connections. Therefore, if such a node has a high degree of social influence, as is given in this simulation, the innovation will spread faster in the system. The increase present in the random network is due to the connectedness of all nodes, meaning that all nodes are more likely to be connected without a present structure. This results in a fast diffusion of innovations over the graph. That is also why the small-world network does not show this rapid increase in the diffusion curve because this network type has small clusters that are only connected by a few edges, making the transmission in the whole network slower. However, when running the simulation to test the social influence factor, the scale-free network only shows a minor slowdown in the diffusion process (see Figure 28). Therefore, other parameters besides social influence and quality are probably more influential in this system with a scale-free network.

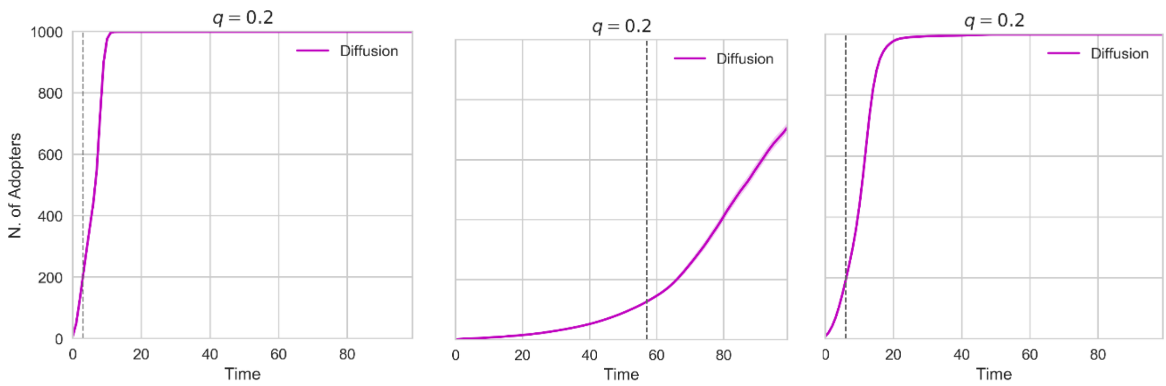


Figure 27. (a) Random network *(b) Small-world network* *(c) Scale-free network*

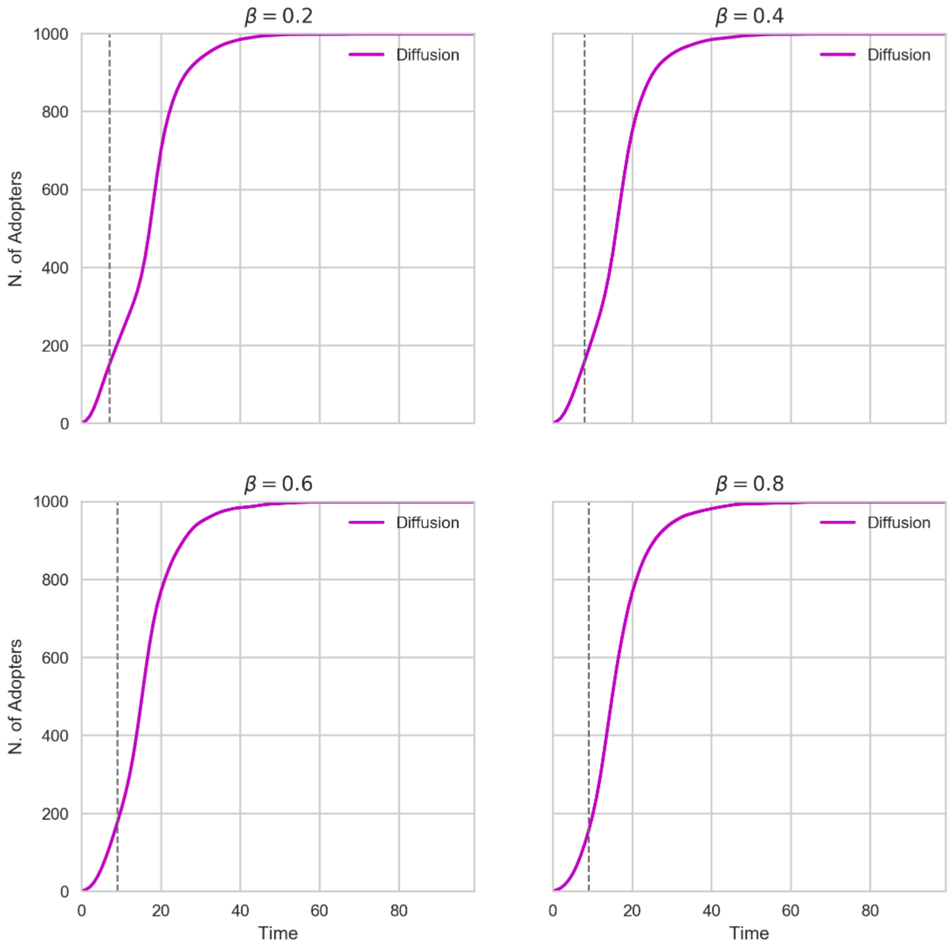


Figure 28. Increasing the social influence factor for the scale-free network does show a rapid increase in the beginning for all graphs, but for a social influence factor of 0.6 and 0.8, this happens earlier in the curve.

Reducing the total number of consumers by tenfold expectably also reduced the time before an innovation is adopted. In the configuration with the reduced number of nodes from 1000 to 100, a social influence of 0.8, and a quality of 0.2 in a small-world graph (Figure 29a) a near complete adoption is present in 100 time-steps. In the same amount of time, with the same factor of social influence, and quality but with only a difference in nodes (1000 instead of 100) the innovation curve only reached approximately 70 % of the total number of adopters (Figure 26b). It seems logical that with a fewer number of nodes, it takes less time to adopt an innovation, however, when running the simulation in the *standard configuration* with the only exception being the decrease in the total number of consumers from 1000 to 100, a decrease can be seen in the rate of adoption (compare Figure 24a with 29b). The early and late majority is reached faster, while the laggards still take a long time and do not fully adopt the innovation in the set timeframe. Even though this increase is minor, it is kept in mind that a larger population will result in a small decrease in adoption rate given the parameters used to this point.

The total number of consumers in the final configuration will be 31. This represents the total number of chronologically dated sites in the Lower Rhine Area discussed in Chapter 3.

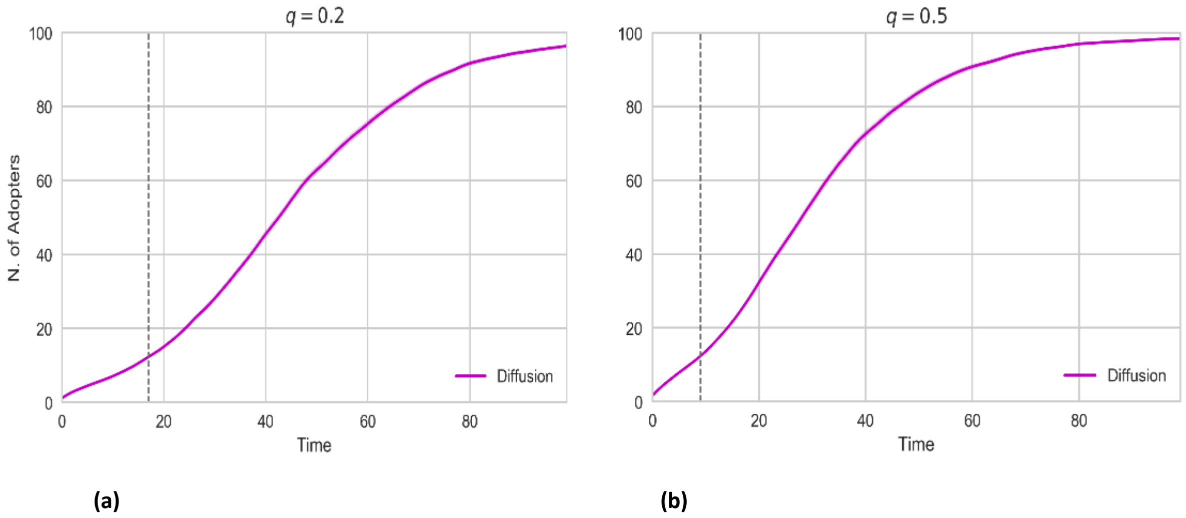


Figure 29. (a) shows an S-curve with for social influence = 0.8 and quality = 0.2. In comparison with (b), which shows the normal configuration with the exception that the total number of adopters has been reduced to 100 instead of 1000.

4.1.3 Non-Random Graphs

Three other graphs have been tested. These are the balanced tree, caveman, and DGM graphs. These graphs were not present in the original model by Cordoba & García-Díaz (2020a) but have been added to analyse how non-random graphs will influence the diffusion curve. The three graphs are not random but are all created in a set way (see paragraph 2.2.2 Random and Non-Random Graphs).

In Figure 30, the balanced tree, caveman, and DGM graphs are displayed in the *standard configuration* with a change in the total number of nodes of 31, a social influence of 0.8, and a quality of 0.2. The balanced tree graph in Figure 30*a* shows a bump in the beginning of the adoption curve which turns into a linear progression. This tree has a height of 4 and a branching factor of 2, meaning that a complete tree consists of exactly 31 nodes (see Figure 31).

For the caveman and the DGM graph, a strong increase at the beginning of the adoption cycle occurs, but this gradually decreases to nearly 0. Both graphs show a low number of total adopters at 8 and 13 respectively at time-step 100. The latter two graph types show active rejection that the other random graphs did not show in the system. This is visible in Figures 30*b* and *c*. There is an increase in adopters from time-step 0 to 30 but after that the number of adopters does not grow, meaning that the rest of the nodes in the system are not willing to adopt the innovation. However, the representability of the graph types is difficult to compare with reality. The reason that both caveman and DGM graphs show a logarithmic function is difficult to explain without delving deeper into how the function of the graph relates to the model. It is likely that some of the nodes in these graphs do not receive social or global influence or that the connection between the nodes hinders the spread of innovations. The same is present for the balanced tree graph.

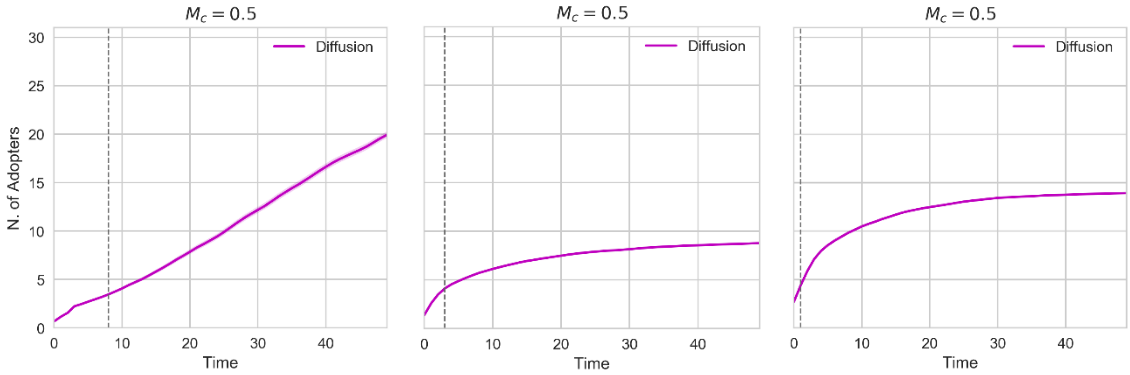


Figure 30. (a) Balanced tree, (b) caveman, and (c) DGM graphs set with the configuration in Table 5.

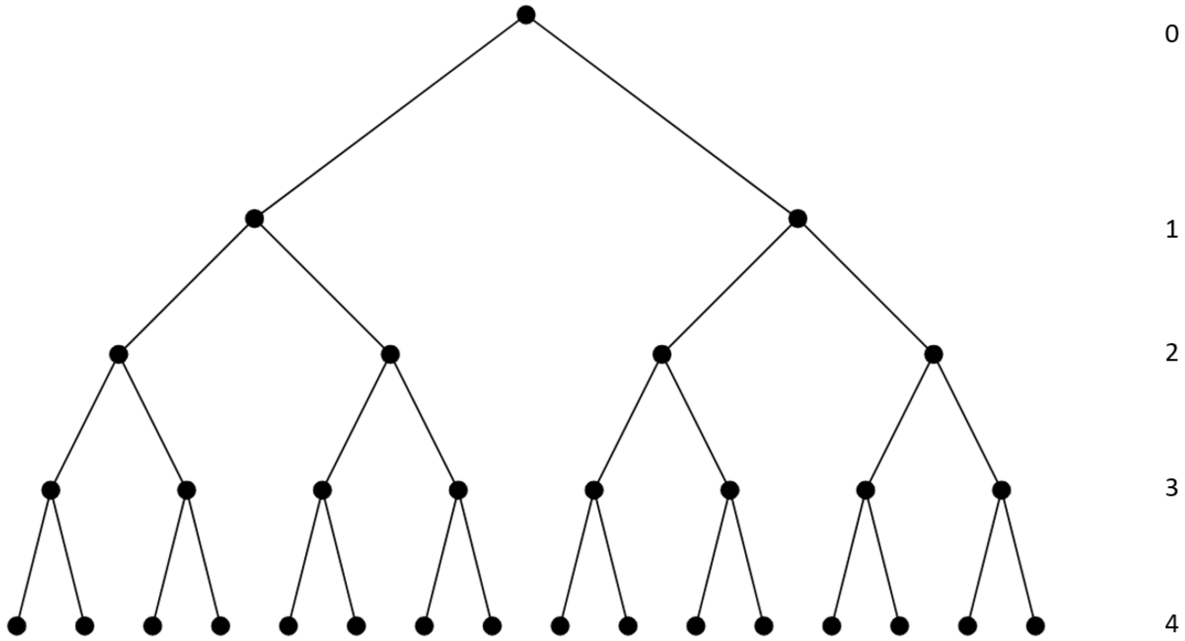


Figure 31. A balance tree graph with a height of four and a branching factor of two, adapted from Leiserson et al. (2016, p. 5)

The balanced tree graph has a structured way of connecting components. Therefore, the global and local influence will function differently than in a random graph. This different influence is difficult to assess with this graph type. Additionally, the caveman graph represents, in this case, a set group of 3 cliques with every 10 nodes. This is based on the network analysis of the Lower Rhine region, which shows two large cliques and a few loosely connected cliques (Kleijne, 2019, p. 124). The problem with using this graph type is the fixed number of cliques in relation to the nodes. Each clique has the same number of nodes, and all cliques are linked by one edge in a circle. This type of graph is more theoretically oriented and difficult to apply to empirical data. The same can be said for the DGM graph, the graph itself is a fractal and is created by implementing the generations it takes to grow. In this case, four generations are added resulting in 42 nodes (less was not possible because three generations would result in only 15 nodes). The steps the DGM graph takes are similar to a scale-free network, meaning every time a new node is created, it connects to two existing ones with a connection to the centre of the graph. This creates a central expanding system that follows a hierarchical order. However, the shape of the DGM graph cannot be logically explained with real-world data.

The way the model has been constructed is not meant to represent a directed, hierarchically ordered path or a fixed graph. While the idea of using unconventional graph types is interesting for modelling in a general sense, they are not representative of the diffusion of innovations in this particular model.

4.1.4 Number of Neighbours & Initial Seed

When analysing how the change in the number of neighbours influences the graph and the diffusion process, it is visibility drastic (see Figure 32). The influence the number of neighbours has varies greatly for a scale-free and a small-world network. For a small-worlds network, the reduction in the number of neighbours greatly stagnates the diffusion process. On the contrary, the scale-free network does show stagnation but to a much smaller degree. Only when k = 1 there is a strong decline in diffusion. The reason for this occurrence in small-world networks is that this network type connects new nodes with the number of neighbours given. The idea is that most nodes are not neighbours of each other but are connected via a short path to other nodes (neighbours of neighbours). Therefore, when the number of neighbours even only decreases by one it has a major impact on the diffusion process because fewer connections are made with other nodes that are further away. Therefore, the information about the innovation spreads slower. This is less of a problem with scale-free networks because newly created nodes in these types of networks have a high likelihood to connect to an existing node with a large number of links. Therefore, when the number of neighbours decreases the innovation still spreads relatively fast because most of the nodes will maintain a connection with a so-called hub. Only when each node has one neighbour does the diffusion rate decrease rapidly because most nodes will link up with only the central hub and another cluster that will be further away from the innovation.

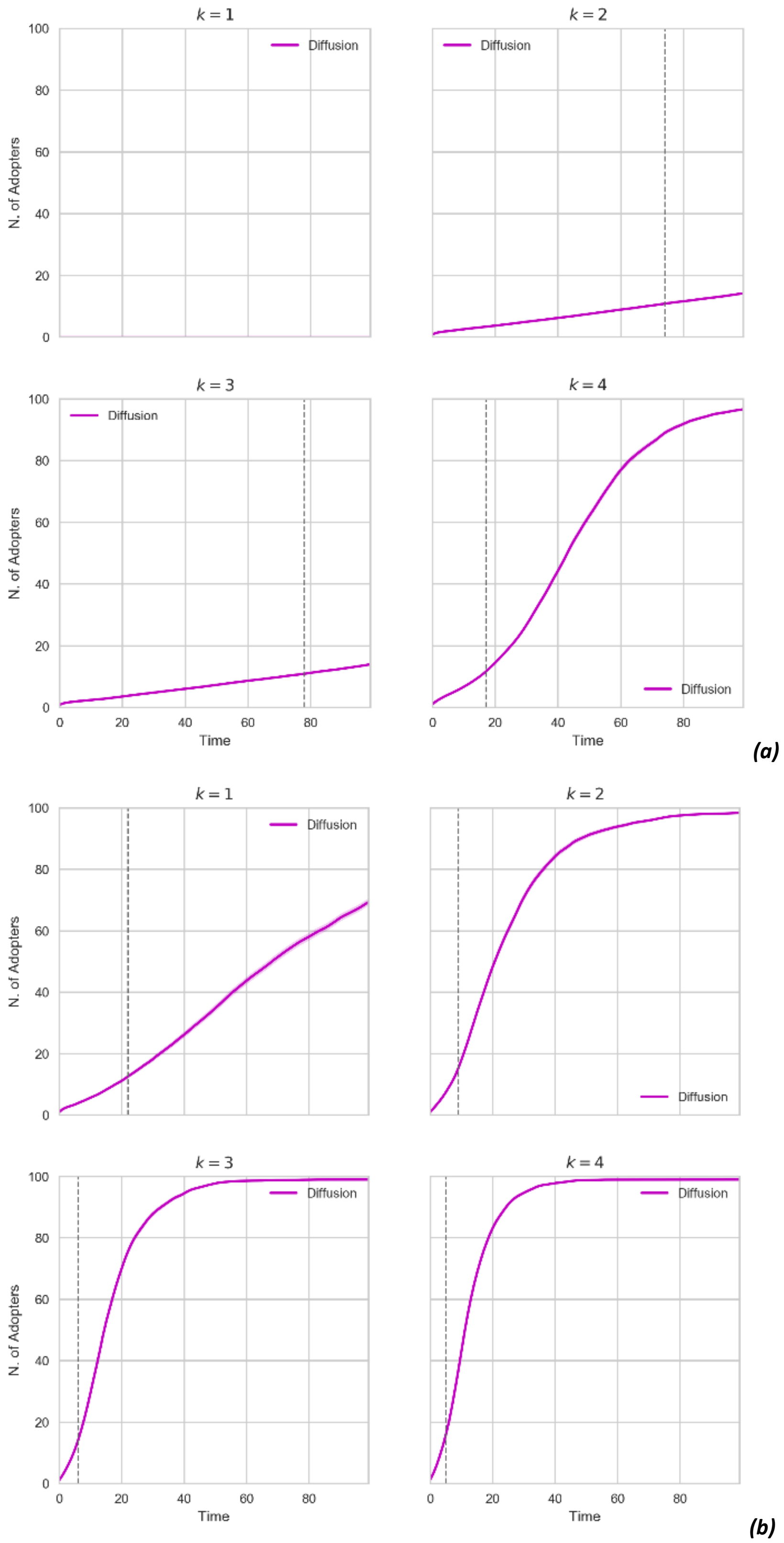
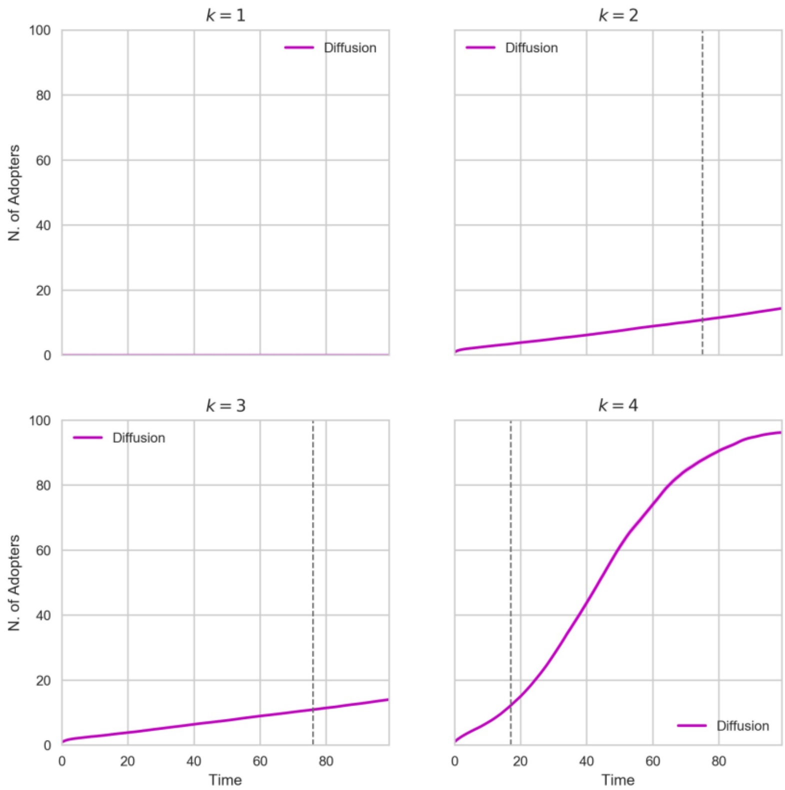


Figure 32. All graphs have a quality of 0.2 and a social influence of 0.8. (a) shows the influence the reduction of neighbours has on a small-world graph with 100 consumers. (b) shows the influence the reduction of neighbours has on a scale-free graph with 100 consumers.

The initial seed has been set to *one* node for each simulation so far. If this number is changed to three we can see an increase in comparison to the number of neighbours in the system. While this increase almost doubles the number of adopters at each step (see Figure 33). It is important to keep in mind that these initial three adopters are not linked to each other and are randomly placed in the system. It is impossible to assess how often the Bell Beaker pottery has been introduced or if this happened multiple times over a certain time span, whether days, weeks, months, or years. Therefore, this variable will not be further discussed but only shown here to note that the increase of initial adopters has an influence on the rate of diffusion in the real-world system.



(a)

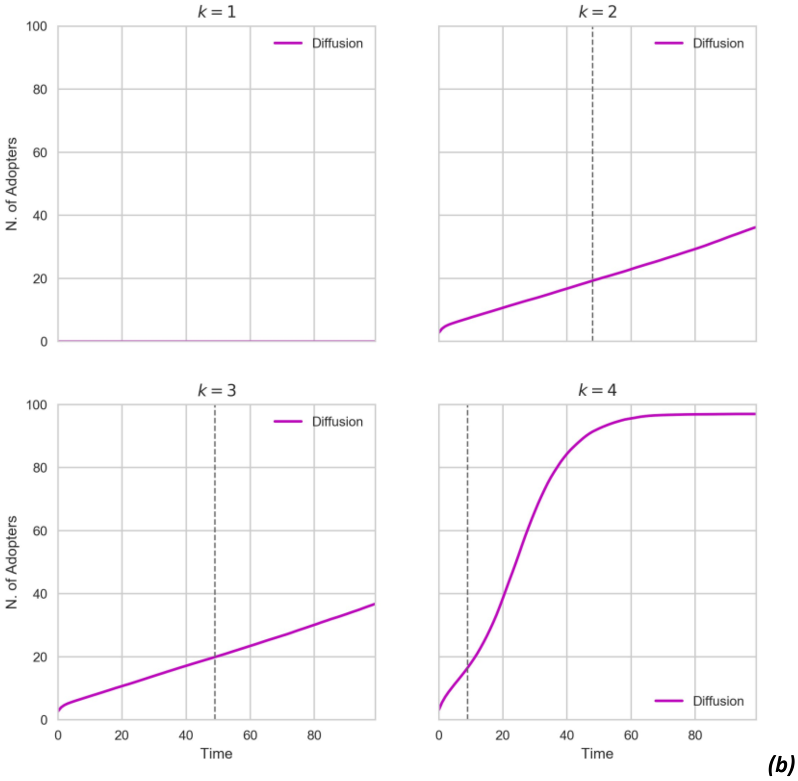
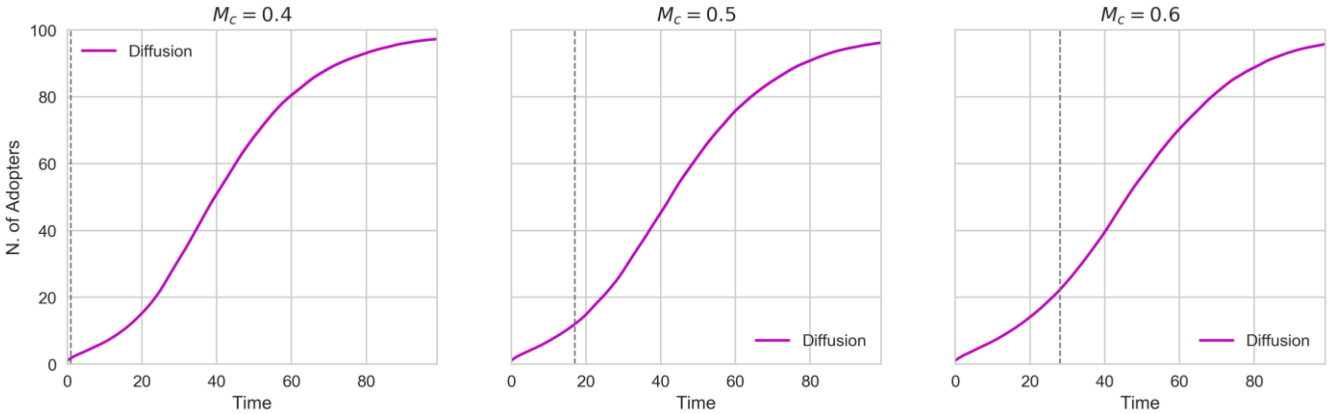


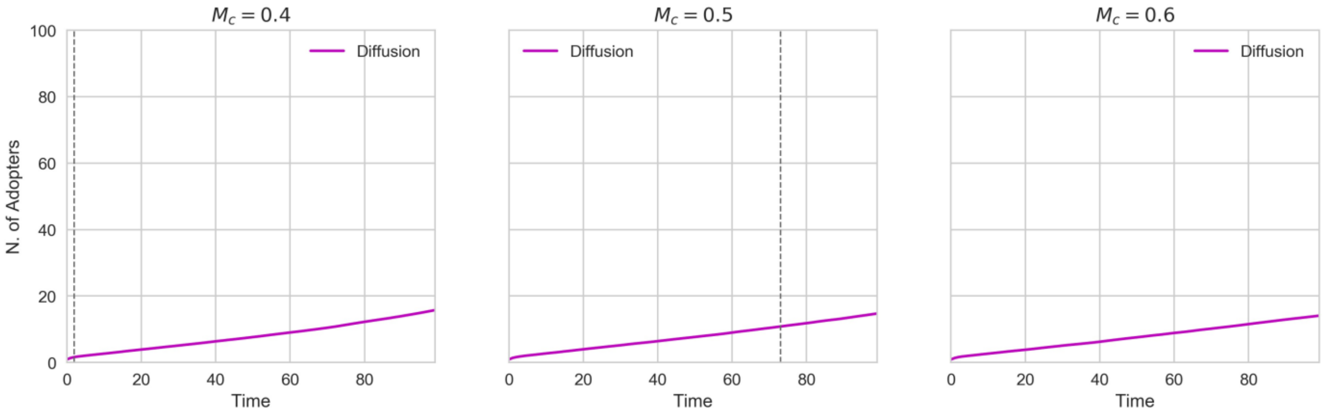
Figure 33. (a) shows the rate of adoption with 100 nodes and an initial seed of 1. (b) shows the rate of adoption with 100 nodes and an initial seed of 3.

4.1.5 Critical Mass, Marketing Effort & Time Delays

The parameters that affect the global influence are discussed here and how they influence the system. Critical mass refers to the point when the adopters notice the innovation in the system. A lower threshold of critical mass corresponds to earlier recognition of the innovation by adopters in the system, while a higher degree of critical mass facilitates the opposite. In Figures 34 and 35, it is visible that with a lower critical mass, the adoption process accelerates in comparison to the number of neighbours in a system. For both the small-world and scale-free networks an increase can be seen, even though it is not as impactful as the other variables. Determining how the critical mass was observed in Bell Beaker societies is difficult to assess. However, before an innovation becomes visible in the archaeological record the critical mass has to be reached (Fokkens et al., 2008, p. 18). Therefore, considering an earlier recognition of the critical mass in some Bell Beaker societies might make a difference in the outcome.

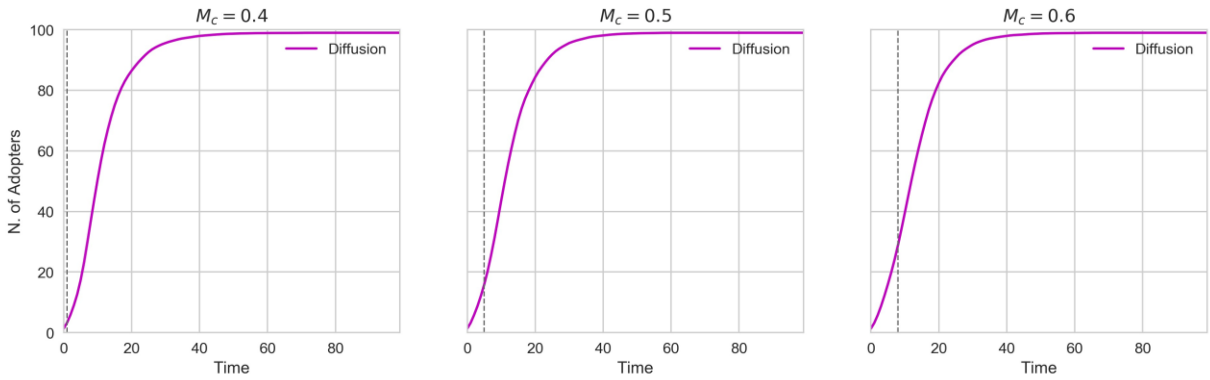


(a)

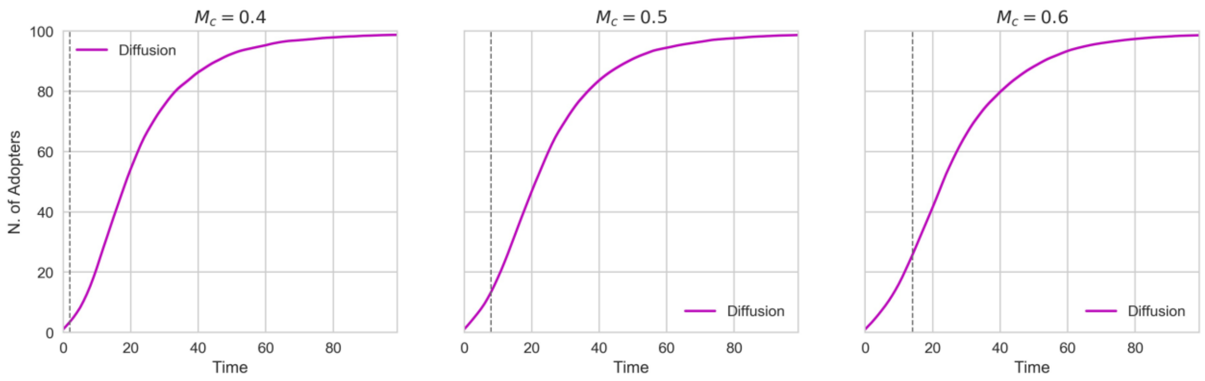


(b)

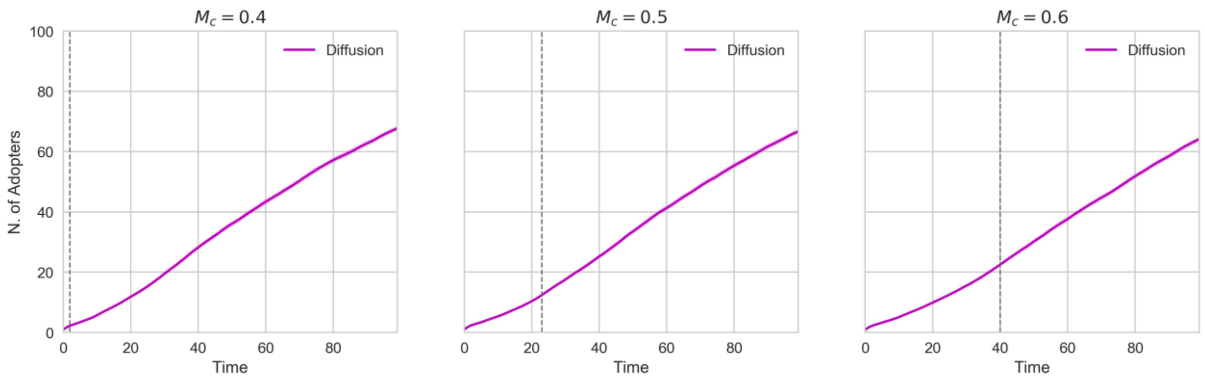
Figure 34. (a) shows the effect of the nodes in noticing the critical mass early = 0.4 or late = 0.6 with 4 neighbours in a small-world network. (b) shows the effect of the nodes in noticing the critical mass early = 0.4 or late = 0.6 with 2 neighbours in a small-world network.



(a)



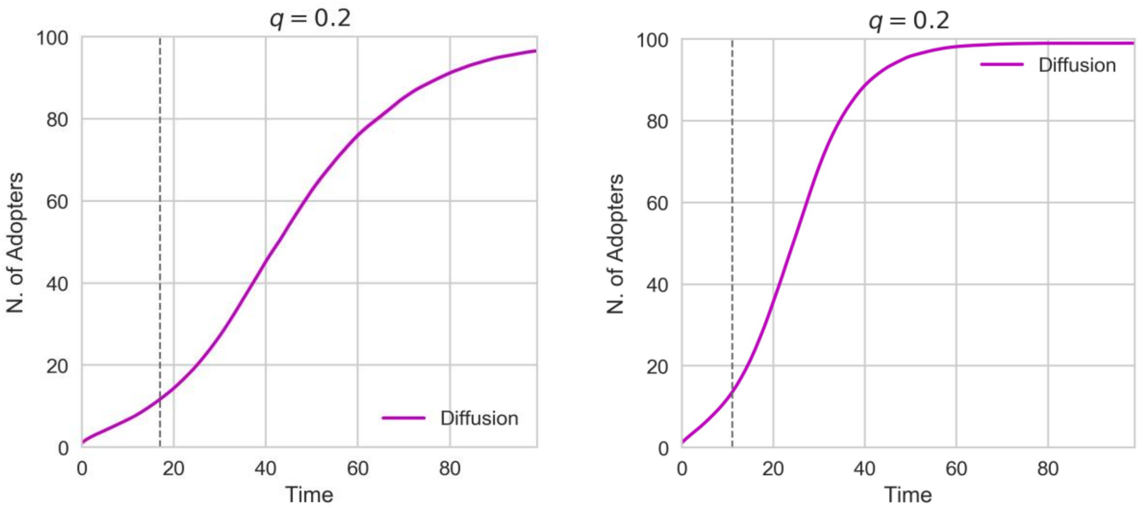
(b)



(c)

Figure 35. (a) shows the effect of the nodes in noticing the critical mass early = 0.4 or late = 0.6 with 4 neighbours in a scale-free network. (b) shows the effect of the nodes in noticing the critical mass early = 0.4 or late = 0.6 with 2 neighbours in a scale-free network. (c) shows the effect of the nodes in noticing the critical mass early = 0.4 or late = 0.6 with 1 neighbour in a scale-free network.

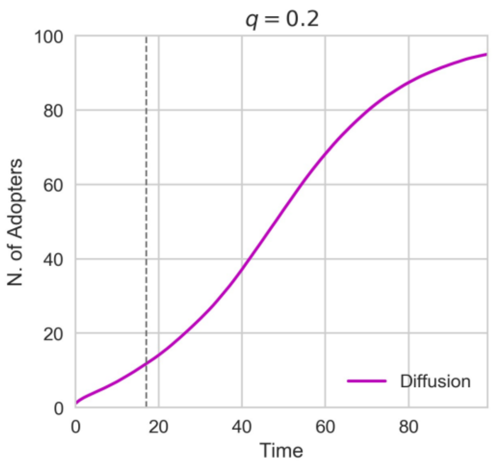
When an agent is influenced by the marketing effort or societal pressure the predetermined susceptibility of the agent is below the marketing range. When the value of societal pressure is increased more agents will be susceptible to this parameter. Therefore, a positive relation is present as is visible in Figure 36, where the marketing is displayed for small-world networks and scale-free networks. This variable is combined in the original model with time delays. This parameter is highly influenced by when the reflexivity in the system is activated (dotted line). The time delays work similarly to how a build-up of a virus affects the body. Once a node is exposed to global influence it does not immediately adopt the innovation, only after a given time delay.

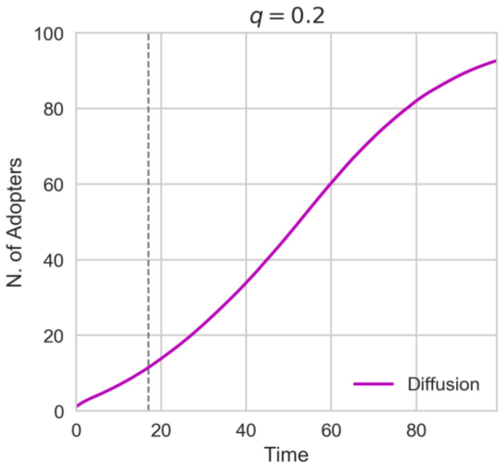


(a) **(b)**

Figure 36. Small-world networks with 100 nodes and a social influence of 0.8 and quality of 0.2, with in (a) a marketing effort of 0.03 and in (b) a marketing effort of 0.06.

As mentioned in the previous chapter, these time delays can be interpreted archaeologically as regional social gatherings that took place. However, these events were uncommon and have not been reported in the Lower Rhine Region of Europe (Salanova et al., 2016, p. 10). As can be seen in Figure 37 below, the time delay impacts the take-off phase of the diffusion curve. The values given in this example are 10 cycles in Figure 37*a* and 20 cycles in Figure 37*b* (each cycle represents a 1-time-step in the simulation). This variable can be altered based on the total population, meaning that values can be given for percentages of the total number of agents in the system, for example, 30% has to wait for 10 cycles, while 70% has to wait for 20 cycles. Since these happenings were not regular it is difficult to decide how often to implement them in the model.





(a) **(b)**

Figure 37. Small-world networks with 100 nodes, social influence of 0.8, and marketing effort of 0.03. (a) time delay is 10 cycles for the whole population. (b) time delay is 20 cycles for the whole population.

Each variable influences the diffusion curve differently. The variables that alter the rate of adoption most significantly are the graph type, followed by the number of neighbours (small-world network only), and the initial seed. The other variables influence the system less drastically.

Since the parameters are tested with some of the generalized data of the Bell Beaker phenomenon, it is time to analyse which values of the parameters are most suitable for the Lower Rhine Region. It is important to note that rate of adoption is based on the pottery percentages concerning settlement sites. However, the pottery percentages are only a proxy considering the Bell Beaker pottery was not physically being exchanged. Therefore, the pottery percentages in combination with the communication networks by Kleijne (2019) are taken into account when assessing the Lower Rhine Region.

4.2 Adoption of Bell Beakers in the Lower Rhine Region

4.2.1 Lower Rhine Region Configuration

The decision for selecting this region is that it is one of the first regions in which the Bell Beakers occurred, but also because the best quality settlement data is available (see Fokkens et al., 2016). This area has been described in the previous chapter.

The Lower Rhine Region can be characterised by a high impact of the Bell Beaker phenomenon because settlements have a high percentage of pottery during the initial phase. But when looking at the Bayesian modelling this shows a moderate rate of adoption, according to the interval between the pre-Bell Beaker and the Bell Beaker phase (Kleijne, 2019, p. 97).

Keeping the data in mind, in the previous paragraphs it has been discussed how the parameters influence the model. For the analysis of the adoption rate of the Bell Beaker pottery, the following values for the parameters have been chosen (see Table 5). The number of nodes has been set to 31, representing the settlement sites with reliable radiocarbon dating present in the Lower Rhine Area.

Parameter	Variable	Applied configuration
Number of consumers	*N*	31
Social influence	β	0.8
Randomness	*r*	0.1
Activation sharpness	ϕ	30
Quality	*q*	0.2
Initial seed	*δ*	1 node
Number of neighbours	*K*	4
Critical mass	M_c	0.5
Marketing effort	*λ*	0.03
Graph type	*Category 1 – 7*	various
Time delays	*f(d)*	False

Table 5. The configuration for the Lower Rhine Region social network

The social influence has been set to 0.8. The reason for this high value can be explained by the way the pottery spread. Most of the pottery production within the Bell Beaker phenomenon in the Lower Rhine Region was locally created. Additionally, Bell Beaker communities most likely were created by patrilocal settlement founding, meaning that the males settled in new areas while the females were married off based on ancient DNA analysis (Sjögren et al, 2020; Scorrano et al, 2021). Regarding the locality, isotopic studies found that most people during this period were confined to local or regional areas (Vander Linden, 2007).

The quality can be considered to have a low value. This is not due to the low quality of the Bell Beaker pottery. The reason for this low value can be explained by the fact that pottery was already well-established in societies. Therefore, the acceptance of the Bell Beaker pottery was not based on the vessel itself, but rather the social or ritual connotation attached to the pottery.

The randomness of the network remained at 0.1 since not much changed for the outcome of the model while testing it and it is difficult to explain randomness in an archaeological context. A similar problem is present in the activation sharpness.

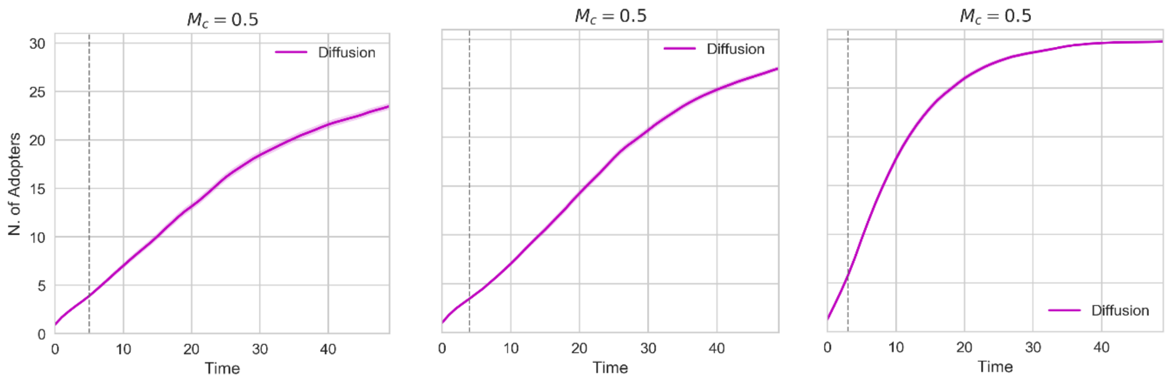
The initial seed has been set to *one* node, to simulate a single introduction. With this low number of nodes (31), increasing the initial seed would drastically impact the adoption curve. The number of neighbours has also not been changed since this would break some of the graphs implemented. The number of neighbours of four has been used from the *standard configuration*.

The marketing effort will be tested here, as mentioned before, the critical mass must have been reached for the pottery to show up in the archaeological record. Since the adoption rate can be considered moderate, we can assume that people were not fast regarding the recognition of a global phenomenon. But they were also not slow, therefore, the critical mass is set at the mean value of 0.5 for when the critical mass is recognised in the system. The marketing effort is related to societal pressure. Since the Bell Beaker phenomenon is widespread in the ideological sense, meaning the burial record is very similar continentally (Wentink, 2020) and the communication networks created by Kleijne (2019) show that the Lower Rhine Region was (mostly) connected. Therefore, this variable can be expected to be high, but that is to be assessed in the results. Regarding the time delays, there is no evidence of social gatherings in this region. Therefore, this will not be used.

The graph types that are used are the three random graph types that were present in the initial model, random, small-world, and a scale-free network. In the previous paragraph, we have seen that each graph has different results, here they will be compared with the Lower Rhine Region configuration (see Table 6) to see which graph type suits the networks presented by Kleijne (2019). The non-random graphs will not be used since their results in the previous paragraph were not deemed to be representative.

4.2.2 Testing the Variables with Archaeological Context

First, the variables are tested without the use of marketing effort. As can be seen in Figure 38, the random and the small-world network show linear growth with a slowdown at the end of the diffusion curve. The small-world graph shows a slight resemblance to a S-curve as Rogers (1983) proposed. The scale-free network on the contrary shows a rapid increase at the beginning of the curvature which also rapidly comes to a halt early on in the graph.



(a) **(b)** **(c)**

Figure 38. (a) Random network, (b) small-world network, and (c) scale-free network with the configuration described in Table 5.

When adding an increase in marketing effort (0.03 → 0.06), the rate of adoption increases substantially for all three graph types (see Figure 38). This is to be expected when the other variables remain the same. This addition results in the smoothening of the curves and the random and small-worlds graphs display a better-defined S-shaped curve in comparison with Figure 37. The scale-free graph shows a rapid upward trend reaching over 80% of the total amount of nodes in just 10 time-steps.

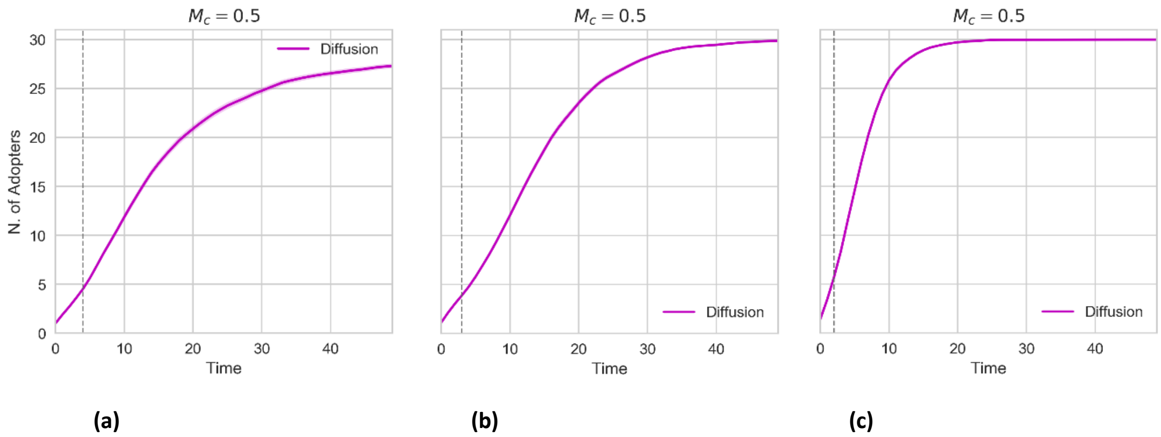
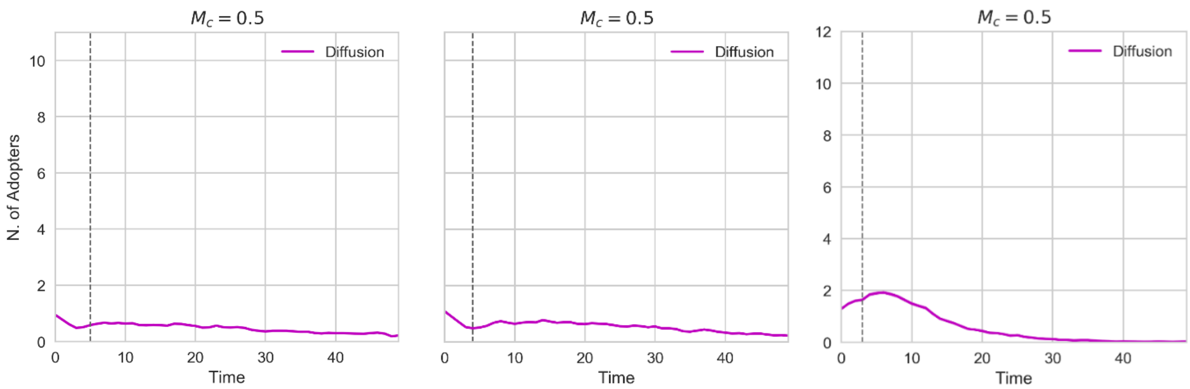


Figure 39. (a) Random network, (b) small-world network, and (c) scale-free network with the only adjustment from configuration from Table 5 being the increase in marketing effort = 0.06.

How can these graphs be interpreted in comparison to the adoption of the Bell Beaker pottery in the Lower Rhine Region? A couple of problems arise when trying to analyse the results. The main problem is that the model is built in a way that always completely, or nearly completely, adopts an innovation, at least with these types of graphs. The other problem is the time variable. Up to now, this has been set at 50 (each step in the model is 1 time). However, it is possible to change this and the other variables in such a way that at time-step 100 a similar diffusion rate would be visible. One step could be considered one generation. On average, one human generation spans approximately 26.9 years across the past 250,000 years (Wang et al., 2023). The first known Bell Beaker site in the Lower Rhine Region is Aquafin RWZI which dates to 2851-2697 calBC with 95.4% probability, the last know site Zennegat dates to 1842-1611 calBC with 94.7% probability (uncalibrated data taken from Kleijne (2018) Appendix A, and calibrated using OxCal (Ramsey, 2009)). This spans a minimum of 855 years and a maximum of 1240 years. If, for simplicity's sake, the mean number of the two is taken that will come down to 1047.5 years in total that the Bell Beaker phenomenon was present in the settlement context in the Lower Rhine Region. Dividing 1047.5 with 26.9 gives results in 38.94, meaning that rounded up 39 generations were present in the Bell Beaker timeframe. This can be deduced then to 39 steps in the model. But then the problem arises with the way some of the variables are programmed. For example, when adding a time delay of ten time-steps will indicate ten generations, which subsequently are mismatched with the marketing effort. Quantifying the delay of the Bell Beaker phenomenon as a cultural idea that is spreading in the area is difficult to access archaeologically if the 1 time-step equals 1 generation is envisioned.

Using this method to understand the timeframe in which the Bell Beaker phenomenon was present in the Lower Rhine region can only be applied to Figure 38 since no time delays or marketing efforts are present. The number of adopters for the random, small-worlds, and scale-free network results in 22, 24, and 29 adopters respectively at time 39. When looking at the pottery frequencies at sites, 28 settlements show Bell Beaker pottery in some percentage or a reinvention of the Bell Beaker, e.g., Pot Beaker (Figure 18). Nineteen settlements show some frequency in Bell Beakers ranging from a few high percentages early on and gradually decreasing over time and three have no affinity to the Bell Beakers.

The scale-free graph shows the best similarities to the data, 29 adopters compared to the 28 Bell Beaker settlements with Bell Beakers and derivatives. If compared to a higher degree of societal pressure, then the small-world graph equally suits the data. The random graph visualises the similarities with the sites that only have some degree of Bell Beakers. However, the graphs should indicate that the Bell Beaker pottery as an innovation was fully adopted in each of the settlements. This can is only the case for three settlement sites where exclusively Bell Beaker sherds and pots have been found.



(a) **(b)** **(c)**

Figure 40. (a) Random network, (b) small-world network, and (c) scale-free network with the configuration from Table 5. These graphs show the number of adopters per step in time.

In Figure 40, the aggregate number of adopters per time is displayed for the random and scale-free graphs. The random graph shows a linear slightly decreasing trend in the total number of adopters over time. The scale-free graph displays an increase in the beginning which gradually slows down over time. Again, this is in line with the high percentage of pottery during the initial phase at Bell Beaker settlement sites.

4.3 Chapter Summary

The implication of the archaeologically empirical data has been incorporated in several graph types. The results show that the diffusion curves do not show synchrony with the adoption of the specific Bell Beaker pottery. The adoption curve is more in line with the communication networks, and therefore, the spread of ideas. The number of adopters is similar to the settlements that have had Bell Beaker influences. If we consider more theoretical or structured graphs, the DGM and caveman graph types show the rejection of an innovation that is not present in the random graphs. But non-random graphs are not representative of real-world network structure.

The scale-free network has the most similarities with the given data and is the most representative of the Bell Beaker phenomenon in the Lower Rhine Region. Additionally, the high social influence and the low-quality determined in the parameters, show that the Bell Beaker pottery as a physical object was less important in the settlement context. In the next chapter, the results are discussed.

Chapter 5. Discussion

5.1 Networks and Agent-based modelling

The focus of this thesis has been on how different types of networks can influence the spread of innovations in the context of the Bell Beaker phenomenon in the Lower Rhine Region. This has been done by implementing a diffusion of innovations model in which the parameters have been altered to suit this archaeological case study. The main focus of these parameters has been the networks on which the system operates. These graphs have been explored and the results indicate that modelling based on the adoption of a pottery type is a difficult process. When testing the different graph types, the scale-free graph indicates the most accurate network type in which the Bell Beaker phenomenon has been spread in the Lower Rhine Region. There is an emphasis on the clear distinction between the pottery and the phenomenon itself. The pottery frequencies per settlement in the Lower Rhine Region were used to determine the rate of adoption over time by linking the radiocarbon dating to the frequencies per site. Kleijne (2019, p. 97) has shown that the adoption rate in this area was supposed to be moderate. However, applying the diffusion of innovations model with the archaeologically interpreted parameters shows that the introduction phase was fast and slowed down in the later phase. This can be attested in the pottery frequencies at the settlement sites for which the parameters were interpreted which indicate a high percentage at the beginning of the Bell Beaker phenomenon and a gradual decrease over time. This happened on a scale-free graph type which has the properties of a power-law distribution, meaning that the nodes, the settlements, in a network have more connection to central nodes that have the most links.

The idea that there were central sites within the Bell Beaker phenomenon is also present in the network analysis of not only pottery, but multiple factors, such as other material culture, and pottery decoration techniques and motifs. This is indicated by Kleijne (2019, pp. 124-126) betweenness centrality of the Lower Rhine Regions sites, which measures the influence a single node has in a network. Comparing the results of the thesis with the network analysis indicates similarities in network structure. There are central nodes, or settlements that have a larger influence on the spread of the Bell Beaker phenomenon. The question is how representative these central hubs are in the totality of the Bell Beaker phenomenon in the Lower Rhine Region. Especially the network analysis data operate on a deterministic basis in the creation of central hubs, meaning that the central role these sites seem to play originates from the lack of other settlement data. Settlements that have existed in the past and have either not been discovered yet or did not stand the test of time are not being incorporated into the analysis. If a new Bell Beaker settlement was to be added as a node to the network the connections withing the network could be vastly different, given that the chronological settlement data is relatively small (31 settlements). This issue has been pointed out (Brughmans, 2013, p. 648, Sindbæk, 2013).

Additionally, Kleijne (2019, p. 132) assumes that from the results of his network analysis, a communication system can be deduced based on the connections of the sites. This is, however, not possible because the similarity in material culture between sites does not directly correlate to communication. It only shows the connection between the groups that operated within the settlements (Sindbæk, 2007, p. 66). Furthermore, time-averaging influences the results of a network. Time-averaging is the process where an assemblage of cultural remains deposited over an amount of time appears to be contemporaneous (Kidwell and Behrensmeyer, 1993). This is known as a palimpsest in archaeology. The settlement sites range from 2800 to 1800 BCE and are divided into sections of 100 years in the social network analysis of the Bell Beaker phenomenon in the Lower Rhine Regions. However, this does not mean that each site has been occupied continuously for 100 years Daems et al. (2023), indicate that time-averaging effects highly influence network structures. Therefore, the effects time-averaging has on networks should be considered when analysing the network structure presented by Kleijne (2019).

The diffusions of innovations agent-based model by Córdoba & García-Díaz (2020a) is not restricted by the determinism present in the network analysis of the Bell Beaker phenomenon in the Lower Rhine Region. The fact that a random, scale-free, and small-world network has been generated regardless of the known connections and timeframe between sites makes it so that the deterministic tendencies that are present in archaeological network analysis are forfeited. While the scale-free network in this model better suits the present archaeological network, the random and the small-world graph should not be disregarded. The results between the latter two types are somewhat similar. This is because small-world have the same type of randomness in the network that is present in random graphs (Watts & Strogatz, 1998).

The rate of adoption in the Lower Rhine Area was moderate according to Kleijne (2019, p. 97). This is not reflected in the pottery frequency but in Bayesian modelling. If this moderate adoption rate was present in the past, both random and small-world networks are more suitable for interpreting the diffusion of the Bell Beaker pottery. These networks show a near-linear adoption curve that slows down at the later stages in time. However, Bayesian modelling of the radiocarbon dates was done on only one site (Vlaardingen Arij Koplaan). Therefore, the representativity of one site in comparison to an entire region is arguable.

The use of agent-based models in combination with complex networks has been applied more often in the last decade. A notable example is the MERCURY model, an agent-based model that analyses the distribution of Roman tableware through trade networks (Brughmans & Poblome, 2016). This trade network has been established by applying random and hypothesised social networks to known sites. Crabtree (2015) uses a similar approach as Brughmans & Poblome (2016) to study networks by using an agent-based model to simulate food exchange among Pueblo communities. The difference however between the two models described here and the diffusions of innovations model used in this thesis is that the former two models operate with already defined archaeological sites, leaving out the possibility of the existence of other sites that were present in the past. Watts and Ossa (2016) present this separation of network models and archaeological data. In their paper, they present how pottery exchange networks were constructed in the Sedentary-period Hohokam, a pre-Columbian material culture. They assess if open, scale-free, and spatial preferential attachment network models are comparable to the empirical data and conclude that an open network model is the best fit for the pottery exchange, meaning a model which has no restrictions only distance and price are considered (open market).

Except for this study, the comparison of abstract network models to archaeological networks is not present in other literature. Therefore, abstract agent-based modelling can infer how archaeological data can be analysed which has been shown in the diffusion of the Bell Beaker pottery and the exchange networks of the Sedentary-period Hohokam. Additionally, The implementation of the diffusions of innovations model by Córdoba & García-Díaz (2020a) has shown that a theoretical model can be applied to archaeology. Apart from this model, agent-based modelling in archaeology based on diffusions of innovation theory has only been done by Kandler & Caccioli (2016). They have created a model that focuses on how homophily and heterophily influence the adoption of innovations in the social system. Simulation models that use interdisciplinary concepts and theories can give new insights into understanding the past.

Another important aspect that has not been addressed is the fact that individuals are not aware of the larger network that they are part of. These all-encompassing random graphs do not take into account the micro-level interactions. These individual networks have not been analysed in the larger picture of the application of networks in archaeology (Brughmans, 2013, p. 643). In this thesis, the construction of smaller individual networks has been attempted. The use of a balanced tree graph has been used to explain the diffusion process. The results show a linear adoption process, this is interesting to analyse but since global factors are at play in the model that is used, this type of analysis is not suitable.

Additional theoretical graphs have been used to explain the diffusion of innovation. These are the caveman and Dorogovtsev-Goltsev-Mendes (DGM) graphs. These are non-random graphs, and both display a logarithmic curve creating a strong increase at the beginning of the adoption but a fast and stagnating process later in the diffusion curve. These graph types do not apply to real-world processes in the sense of shape and form. However, the mechanisms display a rejection of the diffusion process, something that has not been present in the previously mentioned graphs. These two graph types can tell us something about the hierarchy in a system. But the reason for the shapes of the curve cannot be explained and therefore these types of graphs do not suit this model. This black-box phenomenon, where the mechanisms of the creation of data analysis are not known, should not be ignored and therefore these graph types need further exploration.

5.2 The Bell Beaker as an Innovation Process

In Chapter 2, diffusion was defined as "*the process by which an innovation is communicated through certain channels over time among the members of a social system*" (Rogers, 1983, p. 5). The social network and the timeframe have thus far been discussed. The innovation, the Bell Beaker phenomenon, and the communication channels will now be discussed. Most of the theory is difficult to interpret in prehistoric archaeology, many factors are simply not known and can only be speculated. Therefore, when looking at the innovation in the context of the model that has been used, we can only consider the quality, social influence and societal importance.

The quality of the innovation in this model has been deemed low. This is because pottery was an innovation that was not necessary to adopt. After all, pottery had already been widely established since the introduction of the Neolithic in the Lower Rhine Region. This does not mean that the pots themselves were a phase of low-quality material wise during the introduction. But the social influence in accepting the pottery must have been more important than the pots themselves. The reason for this can be seen in the initial phase of the Bell Beaker phenomenon where sites have a high percentage of Bell Beaker pottery. Over time, the Bell Beaker pots were still in use, but they were less important in the domestic setting. That is the reason why reinvention occurs, not necessarily because the Bell Beakers were rejected but because time, social learning, and an ever-evolving society reinterpreted the pots into new morphologies, whether for functionality, e.g., Pot Beakers for making beer (Dineley, 2004) or simply generational degradation of knowledge.

The social influence parameter in the model is defined by the predefined personal preference and the rate of adoption of the closest neighbours (Córdoba & García-Díaz, 2020, p. 5). The latter attribute can correspond with patrilocal settling. This is also attested in isotopic and aDNA studies (Scorrano et al., 2021). Isotopic values of analysed individuals show a lot of local and regional mobility for both the male and female sex in different regions during the Bell Beaker period (Price et al. 1998). This can be explained by the exchange of marriage partners (Vander Linden, 2007, p. 349). The model therefore can be interpreted such that when the innovation is already present in the paternal settlement, the likelihood that the innovation will be transmitted is high and the quality variable would be less important. This is only one part of a possible diffusion of innovations since not all of the spread can be attributed to a single-family expansion. Another possibility of why the social influence was high can be contributed to the location of the settlement sites. Most of the settlement sites during the Bell Beaker periods are found near coastal, river, or floodplains (Fokkens et al., 2016, p. 292). This indicates that waterways were used for the transport of goods and ideas.

Additionally, global influence is important. This is defined in the model as the size of the connected components and the awareness of the emergence of the connected components (Córdoba & García-Díaz, 2020, p. 6). This societal influence must have been noted in the Late Neolithic societies. The shared values expressed themselves in the burial record which was similar across all the Bell Beaker communities (Kleijne, 2019, p. 193). The reason for such a prominent adoption of these values must have been the compatibility of the ideas among the Bell Beaker societies. This might also be the reason why the Bell Beaker pottery in the burial context was more important than in settlement context. There is a clear distinction present in the burial and settlement context which cannot be explained since the Bell Beaker pottery has been introduced. Fokkens et al. (2016), shows that local traditions were still in place that were present before the arrival of the Bell Beaker pottery in settlement sites in the Lower Rhine Region, but the burial practices changed. The socially shared values were more important in the ceremonial context than in settlement life. This can also be compared to Roger's (1983, p. 12) definition that innovations have hardware, the physical object, and software, the information or idea, aspects. The software aspect of innovation does not manifest in the archaeological record, but it can be noted that this must have stayed a prominent aspect in the ritual world of the Bell Beaker societies in the Lower Rhine Region. This can be due to the relative advantage, compatibility, complexity, trialability, observability, or a combination of these aspects as Rogers (1983, pp 14-16) proposes. The global influence was probably initially high which is in line with the rapid rate of adoption at the beginning of the diffusion curve of the Bell Beaker phenomenon which is visible in the scale-free network discussed earlier.

The application of a diffusion of innovations model has shown a different approach to the adoption of innovations. The implementation of this model is valuable in comparison with Bell Beaker data and network analysis. However, it is important to note that social complexity is impossible to model. A model is always a simplification of reality, while some can give insight into certain processes. Integrating theoretical sociological-based models with archaeology can lead to new approaches and ideas. The limitations this model has are evident in the quantification of qualitative archaeological data. For example, the timeframe is a main issue. In this thesis, one step in the adoption process is deemed one generation. But considering how the algorithms in the model are configured, perhaps this is not the best approach. Further research should focus on making agent-based diffusion of innovations models from other disciplines more suitable for archaeology since I have shown here that these types of models can be applied.

Additionally, creating micro-level network models can give insight into the diffusion of local systems. One such micro-level network could study the diffusion of innovation through marriage partners during the Late Neolithic. Vander Linden (2007) suggest that the diffusion of pottery spread is related to a local network of marriage exchange. A micro-level, agent-based model that is based on this idea can be combined with a directed hierarchal network, such as kinship networks (see Figure 41). Kinship networks are constructed by three principles: marriage, biological sex, and affiliation (Hamberger et al., 2013, p. 533). Therefore, they can be applied to the Late Neolithic marriage system. Kinship networks analysis is underexplored in archaeology and can be just as Rogers' diffusions of innovations be applied to archaeological data, such as the diffusion of pottery, as presented in the previous example, but it can also be applied with ancient DNA. The combination of diffusion of innovation, marriage exchange networks, and kinship networks has much potential for future research.

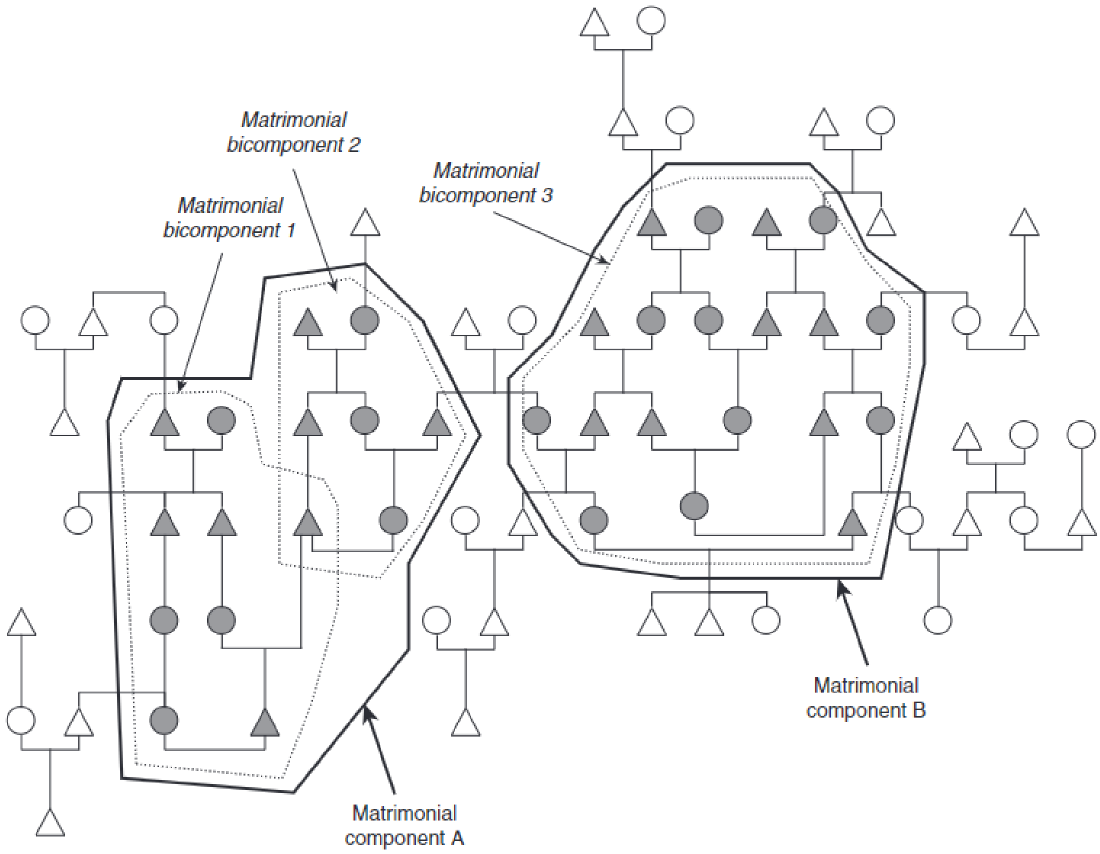


Figure 41. An example of a kinship network in which various matrimonial family clusters are displayed (Hamberger et al., 2013, p. 543).

Chapter 6. Conclusion

This thesis focused on the impact networks have on the diffusion of innovations during the Bell Beaker period and how sociological models can be applied in archaeological research. The results from the network analysis have been discussed in the previous chapter.

The **first** research question, *how do different networks influence the adoption of innovation? And how does the diffusion of innovations model by Córdoba & García-Díaz (2020) compare to the Lower Rhine Region Bell Beaker network analysis proposed by Kleijne (2019)?*, has been assessed by applying random and non-random graphs. It can be concluded from the results of the diffusion of innovations model by Córdoba & García-Díaz (2020) that a scale-free random network matches the Bell Beaker communication networks proposed by Kleijne (2019) the best. The Bell Beaker sites in the Lower Rhine Region are only a sample of the total amount of settlements present in the past. This indicates that archaeological data is deterministic, meaning that such networks cannot be assessed properly. The scale-free network shows the most accurate results in comparison to the random, and small-world network. The random and small-world network should not be disregarded. Through the agent-based model that has been used in this thesis, these deterministic data can be avoided. An agent-based modelling approach circumvents determinism since the agents generate emergent behaviour in a system.

The **second** question, *how can the parameters present in the diffusion of innovations model be interpreted archaeologically?,* could not be applied to all parameters. The values of the parameters that can be best interpreted archaeologically are quality, social influence, and societal pressure. The quality of the Bell Beaker innovation was deemed low. This is not based on the quality of the Bell Beaker pottery but on the innovation in its totality. Innovation consists of hardware, the physical object, and software, the idea or information of the object, aspect (Rogers, 1983, p. 12). The hardware component, the Bell Beaker pottery, was less important. This can be seen in the reduced frequency of the Bell Beaker pottery at settlement sites during the later stages of the Bell Beaker period. The software component, the communication of ideas, can be deemed high. While the Bell Beaker pottery was less important, the social influence was high. This can be attributed to the relatively high regional mobility within the Lower Rhine Region according to isotopic and ancient DNA studies (Price et al., 1998; Scorrano et al., 2021), the location near waterways (Fokkens et al., 2016), and the spread of pottery through marriage exchange networks (Vander Linden, 2007). These social influences reinforced the societal pressure, which is indicated by the widespread homogeny of the burial record (Wentink, 2020).

The **third** question, *how and when does rejection or reinvention of innovation occur? And how can the parameters that influence these decisions be interpreted?*, could not completely be answered.

The reason for this is the time frame and the tendencies of the algorithms in the code of the agent-based model. The time in this model is abstract, one time-step in this model does not relate to a real-world time process. One time-step has been translated to one generation, which is based on the difference between the radiocarbon dating of the earliest and latest Bell Beaker site in the Lower Rhine Region. Although this approach has been used to analyse the results the validity is arguable since one time-step includes the decision-making of an agent, which cannot be attributed to a single generation. Additionally, the algorithms are coded in a way that innovation will always be accepted, however long it will take. The timeframe can also be manipulated by changing the parameters drastically to increase or decrease the rate of adoption immensely. I have made an effort to show that rejection is possible by implementing additional non-random graphs, namely the balanced tree, caveman, and Dorogovtsev-Goltsev-Mendes (DGM) graphs. The latter two displayed rejection in the form of a logarithmic curve. However, the reason why such a curve occurred was impossible to assess and, therefore, these non-random graphs do not work in this model.

The **fourth** question, *how applicable are sociological models to archaeological complex systems?,* is more approachable. Even though there are some limitations to the model, I believe that they are applicable in investigating complex social systems. Most of the parameters can be addressed with proper archaeological reasoning. Additionally, the theoretical aspects of the diffusion of innovations fit in this archaeological context. Combining interdisciplinary methods and theories is beneficial for research in general. Even though diffusion in archaeology is a well-studied subject, this sociological conceptual view gives a different angle that has not been explored in archaeological theory.

The difficulties addressed in this thesis can be elaborated in future research. The idea of how innovations have spread on a micro-scale, by modelling local exchange or the rate of innovation when dealing with various types of graphs can give new insights. A more bottom-up approach will be a good approach for assessing the Bell Beaker phenomenon and complex systems in general. The modelling of micro-level social systems concerning the exchange of marriage partners on kinship networks could reveal new ideas on how Bell Beaker societies were constructed. Furthermore, kinship network analysis has not been explored in archaeology. This is another interdisciplinary method that could be applied to archaeological theory (in combination with the diffusion of innovations). Additionally, modelling time in future agent-based models concerning diffusion processes needs to be properly addressed. Time-averaging in archaeological networks and data is a problem. A cumulative palimpsest reflects multiple occupations of a site. Grouping them into a single period and connecting them with other sites creates a bias that the sites were contemporary.

Diverse network types have different effects on the diffusion of innovation in the Lower Rhine Region. A suitable estimation can be made on how innovations spread by archaeologically interpreting the parameters in de diffusions of innovations model. Furthermore, the use of abstract network models can provide a different approach to archaeological network analysis. The applicability of sociological models, or models from other fields should be looked at to create an interdisciplinary understanding of complex systems. Bridging two fields that have much in common on the aspect of diffusionism is beneficial for advancing the theoretical paradigm.

Abstract

Social networks are analysed to identify connections between archaeological phenomena, such as pottery assemblages, communication networks, and sites. This can be done by linking these phenomena using statistical methods or abstract network models. However, the use of abstract, computer-generated networks to study empirical datasets has been underused in archaeology. Therefore, employing computational models from other academic disciplines can benefit from this lack of abstract network analysis.

This study analyses how various computer-generated networks influence the rate of adoption of the Bell Beaker pottery in the Lower Rhine Region. The Bell Beaker pottery is a Late Neolithic and Early Bronze Age material culture that had been widespread across Western and Central Europe. For more than a century, there has been much debate on how the Bell Beaker phenomenon became prevalent in the archaeological record. The spread of the Bell Beaker pottery can be analysed in the context of the Lower Rhine Region by using the sociological concept of *diffusion of innovations*.

In this thesis, the diffusion of innovations is applied to an agent-based model in which the spread of the Bell Beaker phenomenon in the Lower Rhine Region is simulated. In this model, various computer-generated networks were tested to analyse which network type fits the Bell Beaker data the best. This data is comprised of pottery frequencies from settlement sites which were chronologically organised to show how the Bell Beaker pottery was distributed over time. The results from the simulation were compared to the communication network of the Lower Rhine Region devised by Kleijne (2019). The results of this comparison show that the diffusion of the Bell Beaker phenomenon was initially fast but stagnated later in time. The diffusion was transmitted over a network structure in which a few nodes have a central position in connecting the entire network (scale-free network).

The results indicate that using abstract, computer-generated networks is a suitable approach to assessing archaeological networks. Additionally, the application of theoretical and computational models from other academic disciplines can contribute to archaeological theory building. Further research is needed to test other types of network structures that were not applicable to the model used in this thesis.

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Appendices

Appendix A: Tables with the variables used by Kleijne (2019) for the construction of the Bell Beaker network.

Appendix B: Link to the diffusion of innovations model.

Appendix A. Tables with the variables used by Kleijne (2019) for the construction of the Bell Beaker communication network

Decoration types	Description
cardium	impression made with Cardium shell
spatula	impression made with a spatula implement
cord	impression made with a cord
incision/impression	combination of impressed and incised decoration
cord/spatula	combination of cord and spatula impression
spatula/incision	combination of spatula and incised decoration
Decoration extent	**Description**
all-over	decoration covering the whole body of the vessel
zoned	decoration covering either the whole body of the vessel or the upper half, alternating empty zones with horizontally decorated zones
geometric	decoration covering either the whole body of the vessel or the upper half, in diagonal or vertically decorated zones
Decoration extra	**Description**
incrustation	white substance (often bone) placed in the impressed or incised decorated negative surface of the vessel
paint	red or black substance partially or fully covering the vessel

Table 6. Bell Beaker pottery variables (Kleijne, 2019, pp. 49).

Decoration types applied	Description
Cordon	applied band below the rim of the vessel, horizontal
Wellenleist	applied band below the rim of the vessel, wavy line
Bands	pinched or incised horizontal relief on the body of the vessel
Rusticated	irregular lump of clay applied to the body of the vessel
Warts	pinched round or oval relief on the body of the vessel
Decoration types impressed	**Description**
Nail	impression using the tip of the fingernail
Finger	impression using the tip of the finger (tend to be deeper and coarser than nail impressions)
Cord	impression using cord
Spatula	impression using spatula
Incision/Groove	incised line, or broader groove, in any direction or motif
Round/Oval/Triangular	impression by means of any object leaving hollow round, oval or triangular traces
Barbed Wire	impression using a knotted and twisted cord, resembling the appearance of barbed wire
Pseudo-cord	impression using the tip of the fingernail in a pattern that resembles cord or barbed wire impression

Handles	Description
Holes beneath rim	the presence or absence of one or several holes (either full holes or partially impressed holes) below the rim
Horseshoehandles	applied cordons in the shape of an upside-down horseshoe
horizontal_perf	horizontal applied handles with perforation
horizontal_unperf	horizontal applied handles without perforation
knobs on/below rim	horizontal applied knobs on or below the rim
vertical	vertical applied handles
Feet	**Description**
Foot_flat	vessel with a flat to lens-shaped base
Foot_protruding	vessel with a protruding base
Foot_round	vessel with a round base
Decoration extent	**Description**
All Over	decoration covering the whole body of the vessel
Random	decoration without a regular motif, covering either the whole or upper half of the vessel
Zoned	decoration covering either the whole body of the vessel or the upper half, alternating empty zones with horizontally decorated zones
Geometric	decoration covering either the whole body of the vessel or the upper half, in diagonal or vertically decorated zones

Table 7. Common Ware and Pot Beaker variables (Kleijne, 2019, pp. 50).

Artefacts		Production waste
adze	hammer stone	blade
anvil	knife	core
arrowhead	microlith	core preparation flake
arrowshaft smoothener	microserrated tool	core rejuvination flake
axe	perforated adze	flake
axe fragment	pic	fragment
battle axe	point	hammered piece
battle axe fragment	polishing stone	notched piece
bec	punch	piece
borer	retouched blade	plate
bracer	retouched flake	potlid
burin	retouchoir	splinter
chisel	saw	splintered piece
chute de burin	scraper	truncated piece
combination tool	serrated tool	waste
cooking stone	sickle blade	
cubic stone	sinker	
cup mark stone	splitted segments	
cushion stone	strike-a-light	
dagger	vessel	
dagger fragment	wedge	
gouge	whetstone	
grinding stone		

Arrowhead	barbed
	barbed/tanged
	hollow base
	leaf
	lozenge
	mitra/miter
	tanged
	transverse
	triangular

Table 8. Stone and flint tools, various types of production waste, and types of arrowheads (Kleijne, 2019, pp. 52-53).

Stone and flint sources	
Sources	Alpine
	Ardennes
	Belgian
	Escaut
	Grand Pressigny
	Northern France
	Meuse
	Rijckholt
	Saintonge
	Scandinavian
	Southern
	Spiennes
	Wommersom
Approximations	unknown
	local
	non-local
	regional

Table 9. Stone and flint sources (Kleijne, 2019, pp. 54).

type of rock	type of stone
igneous rock	basalt
	diorite
	dolerite
	granite
	volcanic rock
	pumice (volcanic rock type)
metamorphic rock	amphibolite
	ecologite
	gneiss
	helleflint
	jadeitite
	metamorphic stone
	quartzite
	rock crystal (quartzite type)
	serpentinite
	slate
sedimentary rock	chert
	conglomerate
	flint
	limestone
	sandstone
	siltstone
	quartzitic sandstone
mineral	fibrolite
	quartz

Table 10. Raw minerals of flint and stone (Kleijne, 2019, pp. 55).

Animal remains	Wild animals	Wild mammals	
		Birds	
		Fishes	
		Amphibians/Reptiles	
		Mollusks	
	Domesticated animals		*Bos primigenius taurus* L. (Cattle)
			Sus scrofa domesticus E. (Pig)
			Ovis aries L./*Capra hircus* L. (Sheep/goat)
			Canis lupus familiaris L. (Dog)
			Equus ferus caballus L. (Horse)
Plant remains	Domesticated cereals	*Hordeum*	*Hordeum vulgare* L. (Barley)
			Hordeum vulgare L. var. *nudum* Hook. f. (Naked barley)
		Triticum	*Triticum aestivum* L. (Bread wheat)
			Triticum dicoccon (Schrank) Schübl. (Emmer wheat)
			Triticum Monococcum L. (Einkorn wheat)
			Triticum Spelta L. (Spelt wheat)
		Avena L. (Oat)	

Table 11. Subsistence data (Kleijne, 2019, pp. 56).

Appendix B. Link to the diffusion of innovations model

Link: https://drive.google.com/drive/folders/1uBuKd6CrIyMf-KUUw9tXp5m2mTtfyvoS?usp=sharing