Neanderthals on the Move: Identifying Potential Neanderthal Sites in The Iberian Peninsula and France: Using a Novel Mathematical Diffusion-Age-Structured Model for Neanderthal Remains to Identify Possible Site Locations in The Iberian Peninsula and France

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Chapter 1: Introduction

In archaeology Agent-Based Modeling is currently used to study the movement and spread of Neanderthals. This is because Agent-Based Models are good at studying complex systems. An agent is given rules and then interreacts with other agents or their environment according to these rules. Neanderthals were spread over large areas and only stayed on their sites for short-term periods of time treating them as camps (Bargalló et al., 2020, p. 14). They also adapted to the changing climate around them well and had an active lifestyle (Burke, 2012, p. 230). These rules and environment interactions can be given to the agent for an Agent-Based Model. This thesis will focus on comparing this model with a new Diffusion-Age-Structured model that was created by Dr. S.C. Hille from the Mathematical Institute of Leiden University and I that models the spread of Neanderthals in the Iberian Peninsula and France. This novel model will be run to predict where possible new neanderthal sites could be located and can be considered as a proof of concept. The Diffusion-Age-Structured Model not only models the living Neanderthal population like the Agent-Based Model does, but it is models the distribution of Neanderthal remains as well.

Neanderthal sites are very sparce and difficult to find, so any model that can provide new information on where neanderthal remains could be found would be veery valuable in learning more about this hominin. One thing this model does not consider that the Agent-Based Model does, is that it does not try to biologically understand why Neanderthals move in a specific way. Scientifically it is impossible to know that Neanderthals acted a certain way. Archaeologists can theorize how they moved but modelling that uncertainty would most likely be unhelpful in finding new sites. Instead, this model focuses on the Iberian Peninsula and France specifically because of the mountains. Using these mountain ranges as the only factor affecting the Neanderthals' movement creates a more simplified model and makes it to where there is not a huge number of assumptions involved. Simulations of the model are done using a COMSOL Multiphysics software package, capable of creating reaction diffusion systems in spatial domains. Currently there is lots of research being done into finding new hominin sites. Even though this thesis is focusing on Neanderthals because they are the youngest of hominins, the model could be applied to other types as well.

1.1 Research Questions

The main research question for this thesis is: "How does the Agent-Based Model compare to the Novel Diffusion-Age-Structured Model, and which one is more beneficial to the archaeological interpretation and why?"

The following sub-questions will also be addressed:

- "Does the Novel Diffusion-Age-Structured Model provide a proof of concept for being able to predict possible new Neanderthal sites?"
- "What are the downsides of the Agent-Based Model and the New Diffusion-Age-Structured Model when modeling with the idea of attempting to discover new sites?"

1.2 Methodology

This thesis is going to be focused on previous literature about Agent-Based models in archaeology. Most of the literature review will also focus specifically on Neanderthals and setting a timeline for when they existed. A focus is also on what climate occurred when the Neanderthals were in the Iberian Peninsula and France and their Movement and settlement patterns as well as subsistence strategies. For the Novel-Diffusion-Age-Structured Model, the data being used to run the model comes from two published articles about neanderthal sites that include the age and location of the remains.

Lastly, the model itself comes Dr. S.C. Hille from the Mathematical institute of Leiden University and me as well as the taphonomic rates from Surovell et al. (2009). The model will be run using COMSOL Multiphysics, a simulation software that can model two or three-dimensional models and is provided by Leiden University Mathematical Institute.

1.2.1 literature review

In addition, for agent-based modeling in archaeology Romanowska et al. (2019) and Kowarik et al., (2012) provide a solid introduction and definition for what Agent-Based Modeling really is. With information focused on explaining how and why this specific type of model is used. Though these publications do not focus on how it is specifically used for the distribution of Neanderthals, a case study by Coco and Lovita (2025) on modeling what path Neanderthals took to get across Eurasia to Siberia using an Agent-Based Model, sheds light on this process. This literature will be useful in supplying data on Agent-Based Modeling in archaeology.

1.3 Reading Guide

Before proceeding with describing the different models I will begin this thesis by providing some very necessary background information on Neanderthals and their daily life in Chapter 2 with specific attention paid to any aspects relevant to modeling Neanderthal movement.

Chapter 3 will then focus on describing Agent-Based Modeling in depth. Providing background information and explaining how it works. Next it will describe some pros and cons to using Agent-Based Modeling in archaeology as well as providing a case study on Neanderthal dispersion being modeled by an Agent-Based Model.

Chapter 4 begins with describing the challenges faced with creating the Diffusion-Age-Structured model made by Dr. S.C. Hille and myself. This is followed by the behavior of the model and a description of the model being made. Next, the parameters are introduced in depth and the results of the simulation are presented. Finally, this chapter ends with a discussion of advantages and disadvantages the Diffusion-Age-Structured model brings in modeling possible Neanderthal site locations.

Chapter 5 discusses the differences between the Agent-Based Model and the Diffusion-Age-Structured Model. It begins by discussing their advantages to archaeology and then their disadvantages. Next the chapter discusses how the models are useful to archaeological interpretation. Finally, the limitation of the new model is discussed as well as the limitations of both models to archaeology in general.

Chapter 6 provides a concluding summary to the thesis, discussing the findings of the novel Diffusion-Age-Structured Model as well as reflecting on both the Agent-Based Model and the Diffusion-Age-Structured model to identify which one is more useful to the archaeological interpretation.

Chapter 2: Background

2.1 Timeline and Background

Neanderthals as a species were first discovered in the early nineteenth century with a few scattered remains but recognized in 1856 when their fossils were uncovered in Neander valley in Germany (Trinkaus & Howells, 1979, p. 118). During the early twentieth century scientists believed that Neanderthals had no connection to the modern human even after it was discovered that they used stone tools and hunted large animals. Due to this they were separated from the modern *Homo sapiens* and put into their own separate species of *Homo neanderhalensis*. In the later twentieth century, after more discoveries were made, this was called into question as some scientists believed that Neanderthals evolved into modern humans. Nowadays, with fossil genetic studies and the knowledge that Neanderthals and humans existed at the same time, the belief is that Neanderthals are their own unique hominin and have a distinct evolutionary lineage that did not contribute to the modern *Homo sapiens* line (Harvati, 2010, pp. 367-368).

Now that is has been established that Neanderthals are their own unique evolutionary line and are not regarded as "early men," it is important to understand the timeline that they existed on earth. Neanderthal remains were discovered in many different locations in Western Europe and Central Asia. In Europe Neanderthals have been found in a range from Iberia to Russia and from the Mediterranean to Northern Europe. They have also been documented in the Near East and Western Asia as far as Uzbekistan and even Siberia (Harvati, 2010, p. 368). The appearance of Neanderthal-like features, but not actual Neanderthals is thought to have begun 600,000 years ago with the hominin known as *Homo heidelbergensis*, which is thought to be the possible beginning of the Neanderthal evolutionary lineage. Neanderthals themselves began appearing in the fossil record during the Late Pleistocene, between the period of around 70,000 and 30,000 years ago (Harvati, 2010, p. 368). The Late Pleistocene lasted from roughly 129,000 to 11,700 years ago and the last glacial phase of the Late Pleistocene lasted from 80,000 to roughly 10,000 years ago and was interrupted by a warm interval 35,000 years ago (Trinkaus & Howells, 1979, p. 125).

Not much is known about how exactly Neanderthals became extinct. There are many different hypotheses though as seen above it was not caused by the evolution into the *Homo sapiens* line.

Some paleoanthropologists believe it was caused by unstable climatic conditions mixed with the loss of lots of megafauna, however this hypothesis is often discarded due to the knowledge that Neanderthals had survived many prior cold fluctuations successfully. Another hypothesis is that modern humans' co-existence with Neanderthals mixed with the obvious advantages humans had over the Neanderthals and the limited resources available led to their extinction (Harvati, 2010, p. 373). While it is uncertain what caused this eventual disappearance, the species of *Homo neanderthalensis* no longer existed in the fossil record after 30,000 years ago.

2.2 Climate

Climate played a strong role in the migration patterns and movement of Neanderthals in Eurasia. As discussed above it is believed that the change of climate itself into a colder glacial period did not cause the extinction of Neanderthals, however climate change did cause the Neanderthals to move to warmer southward areas throughout the period when they occupied Europe and Asia. This final movement to warmer areas is theorized to have caused their extinction due to climate-driven intensified competition (Tzedakis et al., 2007, p. 207).

Neanderthals continuously existed in the warmer areas of southern and western Europe, but only ever existed temporarily in central Europe. This is most likely due to the harsher climate that existed in central Europe during the period of rapid climate fluctuations. This is specifically seen during the early and middle Weichselian glaciations (~115,000 - 30,000 yr BP) (Skrzypek et al., 2011, p. 481). During the Late Pleistocene period atmospheric circulation patterns resembled modern days patterns, which means that the rainfall in Europe in the past would have been like today (Skrzypek et al., 2011, p. 484). While many aspects of the climate would have affected Neanderthal movement and settlement locations the strongest one was the Mean Annual Temperature which caused them to continuously stay in the warmer southern areas and restricted the migration into northern Europe with the colder Mean Annual Temperatures (Skrzypek et al., 2011, p. 486). Though it cannot be determined if climate ultimately led to the extinction of the species *Homo Neanderthalensis* it affected their settlement patterns and migrations.

2.3 Movement and Settlement Patterns

Neanderthal sites were generally spread out over a large area and consisted of open-air and closed-air sites. These sites were only visited for short but recurrent periods of time (Navazo & Carbonell, 2014, pp. 275-276). The evidence for this short-term site settlement and occupation in

Neanderthal sites is commonly seen by the low density of archaeological remains in a reduced settlement area with the remains being found congregated around hearths. There is also low taxonomic diversity in the faunal assemblage and several tool kits found in Neanderthal sites which points to a short-term site (Bargalló et al., 2020, p. 14). These short-term sites are often referred to as "camps" as they are only resided in for a short period of time.

The camp is part of many different hunter-gatherer settlement systems and is where the Neanderthals would participate in daily activities (Vaquero, 2022, p. 208). Neanderthals were organized into hunting territories with sources for both meat and lithics for tools. They chose to camp in places that were good for fauna as they moved as whole groups according to the season of the game. Neanderthals intercepted migrating game which supports the idea of high mobility around a wide territory surrounding a single camp. Within these camps there are specific areas for different activities like butchering, cooking, etc. (Patou-Mathis, 2000, pp. 391-392). Most tasks are generally performed within these multi-functional areas with the bulk of domestic activity being centered around the hearth (Vaquero, 2022, p. 208).

While Neanderthals themselves are focused on a camp in the short-term they are not a homogenous entity and there is diversity between Neanderthal populations and their settlement and movement patterns. They had to adapt to their surrounding and during a time when there was lots of irregular and cold climate they physically adapted (Vaquero, 2022, p. 220). This physical adaption involved the changing of their post-cranial morphology, which shows an adaptation to cold climates and an active lifestyle (Burke, 2012, p. 230). This active lifestyle is seen in the movement of Neanderthals from site to site through their opportunistic strategy of resource obtaining or in other words they moved to areas where there was the game that they hunted, the stone that they needed, or the shelter, etc. that they relied on for survival. Due to Neanderthals being capable of targeting herding animals they can live in a large variety of climates. They tended to move on a regional small scale and used up local resources in large amounts before quickly moving on to their next short-term site (Burke, 2012, pp. 230-231). Neanderthals moved around smaller areas and tended to have a local pattern of social interaction (Burke, 2012, pp. 231-232). This means that they did not have any long-distance communication or trade, but rather they only communicated on a small scale.

Most Neanderthal sites are open-air camps, but many that were preserved in the archaeological record are caves or rock shelters (Vaquero, 2022, p. 210). These open-air sites have lots of irregularity and are defined by their different uses. The diversity of site types shows how Neanderthals knew how to use the local resources in the area around them according to their daily requirements (Patou-Mathis, 2000, p. 391). Ultimately Neanderthals operated using short-term camps with hunters exploring the surrounding areas for game. They travelled according to the season for hunting and were adaptable to a large scale of climates.

2.4 Subsistence

A final important aspect of Neanderthal life is their subsistence. Neanderthals had their own tool kit, known as a Mousterian tool kit, that consisted of stone tools. The largest part of their subsistence came from large prey hunting. This means that though they ate plants, seafood, and small game, most of their diet was meat (Johansson, 2014, pp. 615-616). Since large game was often the chosen thing hunted by them the prey was dismembered at the kill location and then brought back to the camp. Neanderthals often hunted species that migrated meaning that the main type of prey they hunted were herd animals. Neanderthals even set up their camps in areas where these herding animals would cross. Hunting of prey occurred in every single season and the game was selected according to the animal's age or sex (Patou-Mathis, 2000, pp. 389-390).

This characterizes Neanderthals as skilled hunters who exploited prime game, or game that is more difficult to hunt but has a higher pay off in terms of products. This includes mammoth, horse, steppe bison, ibex, and red deer. What Neanderthals hunted depended on their local habitat and not on the species of animal alone. It was also a tendency that small game was not often used as food for Neanderthals, most likely because they do not preserve as well. They also hunted fish, shellfish, and more marine animals in lesser amounts (Power, 2019, p. 2). To hunt this food Neanderthals did not use any long-range weapons like spears or bows, but instead hunted at closer range, which increased their risk of mortality and the energetic cost of hunting (Power, 2019, 3).

To process the meat Neanderthals used fire (Johansson, 2014, p. 615). They also would have utilized multiple parts of their game including fat, skin, bones, and fur. With bones being used as tools, fuel, and even large bones like mammoth bones being possibly used as dwelling frames

(Patou-Mathis, 2000, pp. 390-391). Other than meat, many plants held value to Neanderthal subsistence. They ate many different plants including charred hazelnut shells, pine nuts, diverse legumes, acorns, etc. (Power, 2019, p. 4). There was plant use during cold periods of time, but Neanderthals that lived in colder climates tended towards more meat-based diets and Neanderthals in warmer climates have more mixed diets (Power, 2019, pp. 5-6). The significant thing to note about Neanderthal subsistence is that they tended to hunt large herding game, especially in colder climates. They also were able to hunt prime game and use many parts of the prey they hunted.

Chapter 3: Agent-Based Modeling

3.1 Background and Basics

A model is a simplification of a system or structure and can be many different things including a set of equations or a computer program. Modeling is the simplified representation of a complex reality so that it can convey as clearly as possible how one believes reality operates (Kowarik et al., 2012, p. 238). A simulation runs the actual model and can be influenced to understand the system behavior. Computational modeling is important because every aspect of the model must be explicitly stated for the model to run giving an overall better understanding of the model. It also can be set up with conditions that can be changed allowing new understandings about what the model is on to be understood (Kowarik et al., 2012, p. 239).

Agent-Based Modeling (ABM) can answer many different research questions from various disciplines. Agent-Based Models are great at studying complex systems, or systems that have many parts where interactions of different parts of the system can lead to new and random behavior at the system level. Or in simpler words, cause and effect relations in the system are non-linear meaning that the system behavior is created through actions and interactions from the "bottom up." An "agent" in ABM is programmed by being given simple behavioral rules that determines how the agent interacts with other agents or with the environment. Every agent can be given individual rules and can represent different things for the model. The environment itself represents a geographical space (Kowarik et al., 2012, p. 240). ABM was introduced to archaeological science in the 1990s and was applied to many different areas of archaeology including spatial processes, social interaction, etc. (Kowarik et al., 2012, p. 241). ABMs were originally created to help researchers when applying mathematics to complex phenomena (Cegielski & Rogers, 2016, p. 284). An ABM is easy to understand if it is thought of as a hypothesis with an argument created by data collection from multiple sources. The parameters are developed through a process called abstraction or considering opponents as their own separate entities. These abstractions are then compared against real empirical data to see if they are valid using calibration (Cegielski & Rogers, 2016, p. 292). The output of the actual model is then tested against real archaeological records in a process called "validation" to see if the model can be useful to archaeology. Then after the model has been run the first time the parameters undergo sensitivity analysis, or checking to see if there is any parameter that when changed drastically does not affect the model. If this is the case some archaeological conclusions can be drawn about that entity (Cegielski & Rogers, 2016, pp. 292-293). While it is useful that is can model many different concepts and complex systems the focus of this thesis is to see how Agent-Based Modeling is useful in modeling Neanderthal movement to determine where best to find new sites. In the following sections this aspect of ABM will be investigated.

3.2 Advantages and Disadvantages of using ABM

3.2.1 Advantages to Modeling with ABMs

Agent-Based Modeling is useful for archaeology as mentioned above because it can focus on individuals and their interaction with the environment. Archaeologists have been more concerned with groups and have ignored the individual within the last few decades. Another reason why ABM is so beneficial for archaeology is because instead of using the language of equations to create the model it uses familiar entities like people, groups, etc. to create the Agent-Based Model. This allows an archaeologist with a limited knowledge of mathematics to understand what is occurring in the model (Romanowska et al., 2019, p. 4). An additional advantage to AGM is that it can be reproduced. The reproducibility of a model is important as it allows an archaeologist to validate and test their data (Cegielski & Rogers, 2016, p. 285).

The fact that Agent-Based Models are also able to cover a wide range of archaeological topics is very beneficial. These topics include historical, formation, and evolutionary processes, etc. with the topic of historical processes being important to this thesis as it focuses on the history of interactions between an agent and its environment (Cegielski & Rogers, 2016, p. 287). In this case the modelling of Neanderthals.

3.2.2 Disadvantages to Modeling with ABMs

While there are many advantages to using Agent-Based Modeling in Archaeology, there are also a few disadvantages. The first one of these is that ABMs are reductionist. Meaning that unlike in real life they cannot focus on all aspects of an environment or system at the same time. However, this is not always necessarily problematic as sometimes it is useful to study only certain aspects of a system (Cegielski & Rogers, 2016, p. 284). Another drawback to using ABMs is that to construct the complex system simulations it is necessary to have a powerful computer and software. This means that many larger complex models are unable to be run in a simulation because the lack of a powerful enough computer. This correlates with another shortcoming that is that the software needed to create an ABM is very complex (Cegielski & Rogers, 2016, p. 294). This necessity of a complex software can be difficult to understand for users, or in other words archaeologists who are not knowledgeable with running software programs or coding. When creating an Agent-Based Model it is also necessary to make basic assumptions about the model for it to perform tasks. These assumptions are a disadvantage as it is an outward influence on the model. While modeling with ABMs it is important to remember that the past is not fully known so what is being modeled is simply an idea of what might have occurred in the past and not the actual past. Even if there is a direct match with the archaeological record, it is not correct to claim that the model is accurate or can describe real processes in the past perfectly (Kowarik et al., 2012, p. 248). These disadvantages mentioned occur with many different types of models as they are simply modeling something that occurred and are not the actual thing. As archaeologists it is important to remember that the archaeological record that is accessible is limited and to not make too many assumptions about what occurred in the past.

3.3 Case Study on a Combined AB-LCP Model

3.3.1 Overview of Case Study

The authors Coco and Lovita (2025) considered a current debate in archaeology to model with a combined Agent-based least cost path (AB-LCP) approach. This debate is what path did the Neanderthals take to get across Eurasia to Siberia. They chose to use a combined approach due to normal Least cost path analysis assuming that travelers will know the complete area they are traveling in and will always choose the more cost efficient, or easier to travel path. Due to this being an unknown landscape treating a Neanderthal as an agent in ABM is a more realistic approach (p. 2).

3.3.2 Setup of Model

The authors began by simulating agent-based cost-minimizing Lévy walks of mobile agents, or in other words by creating agents that were placed on random squares in the Caucasus Mountains where at each new tick, or second of the model the agent evaluates all eight surrounding squares and chooses the one that is the least cost to move to that had not been previously occupied (Coco & Lovita, 2025, p. 3). The random starting locations were derived from the locations of Middle Paleolithic sites in the region and there was a rule added that stated that rivers greater than one kilometer were barriers (Coco & Lovita, 2025, p. 4). The authors Coco and Lovita (2025) considered being within 500 kilometers of the Altai site cluster a successful crossing into Siberia. They did 110 runs and out of all of them only three were successful (p. 5).

3.3.3 Insights from Model

After running the AB-LCP Model, the authors Coco and Lovita (2025) were able to hypothesize new things about the second Neanderthal dispersal from Western to Eastern Eurasia. They used ethnographic data about how far hunter-gatherer populations move within a year and estimated that it would have taken around 2000 years to move from the Caucasus Mountains to Altai for the Neanderthals. Their results also suggested that the Neanderthals could have dispersed using Northern routes specifically, as all three successful crossings utilized northern routes (pp. 7-8). They were also able to see where Neanderthals or the agents chose to be located during long-distance movements and discovered that the model had them often traveling along rivers (Coco & Lovita, 2025, p. 6). This could be an interesting application in archaeology.

3.3.4 Relevancy to Thesis

The model of Coco and Lovita (2025) offered a unique AB-LCP approach that allowed the movement of an agent in an unknown area while still considering energy costs. It was able to lead to the discovery of new movement dispersal paths into Siberia for Neanderthals (p. 9). One disadvantage of their model was that it included a static representation of a landscape that would have been changing during the thousands of years needed for Neanderthal migration. This stationariness makes it impossible to include any fluctuations to the environment (Coco & Lovita, 2025, p. 9). Though there were many benefits and some disadvantages to using this model, it was a great example of not applying too many assumptions to the past and using new models in archaeology. This case study showed how modeling can provide new insights into archaeology.

Chapter 4: Diffusion-Age-Structured Model

4.1 Challenges in Creating the Diffusion-Age-Structured Model

Before the math behind the model was created, first the ideas behind what was being modeled was considered. The interest is in a distribution of Neanderthal remains. This is because where there are the most remains there is the most likely location of a site. In the model the first challenge faced therefore would be the link of the living to the dead as the interest is in the actual remains and not what the living Neanderthals did. To start this prosses the model considered how individual Neanderthals would move around in the Iberian Peninsula. The model assumptions are that they would move around in tribes and as a group of hunting individuals together (Patou-Mathis, 2000, pp. 391-392). It is also assumed that the Neanderthals would have a "basecamp" where they move around in the daily as supported by archaeological discoveries of Neanderthal camps (Vaquero, 2022, p. 208). They would move this basecamp around in the long term i.e. years. When they move this basecamp long distances, they explore the surrounding areas and are likely following their game they are hunting or looking for resource abundant areas (Burke, 2012, pp. 230-231).

Another challenge in this model is modeling how many remains would still be present after thousands of years. At first this was modeled as a constant state of degradation, but eventually after some more research an archaeological paper by Surovell et al. (2009) explained that remains have a particular degradation rate that is non-constant in terms of age and how long they have been in the ground (p. 1717). This is important to incorporate because it explains a long-term preservation idea i.e. if the remains have been in the ground for a while, they will stop degrading and remain unaffected by erosion or other processes.

4.2 Behavior of the Model Explained

To more accurately model how Neanderthals dispersed throughout the Iberian Peninsula and the south of France to indicate the most promising locations to obtain new archaeological finds it is necessary to consider how they would have moved. Originally the idea of modelling with solely diffusion was considered, however the spread of Neanderthals is not each individual moving in random directions, but rather moving and living as groups, or referred to throughout the rest of this thesis as 'tribes.' These tribes were involved with foraging activates as individuals or small hunting teams in what shall be referred to as the 'basecamp' because they tend to not hunt to far from the tribe.

Moreover, modelling with only using the dispersion of living Neanderthals is not sufficient to answer the question or reach the objective of discovering possible spots of finds. To do this the model also has to consider where Neanderthal remains are expected to be deposited and how these 'decay.' For the taphonomy the calculations done shall rely on the argumentation set-up by (Surovell et al., 2009, pp. 1717-1718).

The first process of the model is that the Neanderthal tribes will move around randomly which is exactly like diffusion in physics or how Brownian pollen move around in a petri dish. Though archaeologically tribes might have had a particular migration patter, the model claims they explored the territory randomly as this hunting pattern cannot be known. The Diffusion Equation in the Diffusion-Age-Structured model is based on the Brownian motion equation as well. With diffusion an essential thing is that there is no preference of direction in which the object moves which is the simplest thing to start from for the model. Though Neanderthals may also follow the migration of game this model only considers diffusion or random movement.

The model simplifies another process as well and that is the daily exploration of individual Neanderthals in the area around the basecamp. This is only considered when considering the spread of the tribe or basecamp is in a Gaussian or Normal distribution curve. The model instead focuses on the large-scale movement of basecamps in years.

The model also assumes that mountainous regions are not accessible for the tribes to stay in for longer times due to Neanderthals avoiding colder regions and following hunted game (Johansson, 2014, pp. 615-616). Individuals can still theoretically enter the mountains, but this is not incorporated in the simulation yet, which is why the areas remain empty, or the mountain are depicted as fully impenetrable barriers. Due to this ignorance of the mountainous regions the model also leans towards modeling only open-air sites for simplicity of ignoring caves along the mountains which were imputed as barriers in the software program.

4.3 Description of Model

The following equations were created with the above ideas in mind by Dr. S.C. Hille and me. When combined the following two equations create the Diffusion-Age-Structured Model.

(R) $\partial_t R_x(a,t) = -\partial_a R_x(a,t) - \lambda(a) R_x(a,t) \; for \; a > 0, t > 0$

This equation for (R), or Remains equation above, describes the density for remains of a particular age a at time t after the start of the simulation at position x and the change in time occurs because the actual remains themselves age. All the equation terms are explained in the Appendix. The result of this is a shift that is represented by the first term or the aging term which explains that the remains age as fast as time goes which makes sense logically. The second term is the deterioration of the remains at the location x and according the Surovell paper the deterioration rate is not constant but age dependent and they give an expression for this age dependent rate or taphonomic rate with this formula:

$\lambda(a)$ = taphonomic rate

$= \frac{1.3925}{2.1764+a}$, according to Surovell et al. (2009), Eq. (2), p. 1717.

$$\lambda(a) = \frac{b}{a_{1/2} + a}$$

Where the parameter is simply taken that was used by the Surovell et al. (2009). When saying that the remains are aging, the aging is referring to the actual remains once they have been deposited in the soil at location x, they become older, but it is necessary to know how long they are already in the soil to have the right rate of degradation at time t. Every age class deteriorates at a different speed and that is why it is necessary to distinguish between ages. Important to note is also that the remains at location x of age 0 at time t are the freshly deposited remains and they are modeled by the following equation:

$R(x, 0; t) = \varepsilon \cdot \mu \cdot n(x, t)$

Which represents the depositing efficiency, which says that remains do not move substantially (on km scale), or in other words, the remains of the Neanderthals do not move very far from where the original Neanderthal died other than by animals, rivers, erosion, weathering; times the rate at which individual Neanderthals die times the number of Neanderthals that are there at the particular location at that time. This binds the two main equations together used for the Diffusion-Age-Structured Model. These two equations include the (R) Remains equation above and the following (N) Neanderthal tribe location below.

Logically as an introduction to the model it is first essential to overcome the problem that the unknown is the location of the distribution of remains, these remains are deposited and are dead Neanderthals, but these living Neanderthals are moving in tribes, as is the assumption for the model. Only the tribes move in a diffusive way on a long-term time scale, but the individuals on a daily basis stay more or less close to the basecamp. So, it is required to bridge these things, which was done by modeling the dispersion of the tribes first using the diffusion equation for that. If the distribution of tribes is known the individuals are then located according to Gaussian or Normal curve around their basecamp which is the formula for the small n, or individual Neanderthals. The dynamic for the remains is fed by the link $R(x,0;t)$ that the living Neanderthal distribution died and leaves behind remains. An essential point of the model is that the taphonomic rate relies on the age of the remains. If objects have stayed sufficiently long in the soil, then they stay there for a very long time. Which makes sense archaeologically speaking because they would be buried under lots of soil and by that point they are preserved and degradation, erosion, and weathering would not have that strong of an effect.

(N) $\partial_t N(x,t) = D(x)\Delta N(x,t) + f(N(x,t))$

$$f(N) = S(N) - \mu o N$$

This equation (N) represents the Neanderthal tribes, and it really is a spatial dispersion equation with diffusion, which is the first term, that says that they randomly move around and explore their territory without any particular direction, but with the possibility that they move differently in different regions which is why there is a spatial dependence of the D. In the Model it is represented in the Iberian Peninsula and France with different spatial dependence or in other words the Neanderthals are able to spread around the Iberian Peninsula easier than France. Then the dynamics of the tribes themselves was taken into account. The individuals will multiply, and the tribes will become larger and split up, and then the exact curve for the splitting or propagation of tribes was decided to be a Gaussian curve.

If there are hardly any tribes in a region or low density than they would not want to split up, tribes do not propagate like individuals do. The shape shows a maximal of ideal or long term of distribution or carrying capacity in a region which is determined by ecological circumstances and geography which can be different per region. If there is low density there is no region for tribes to split up. This (N) equation is saying that there are tribes that move in a random way, and they will split if they get past a certain point and any mountainous region in the map has been excluded from any tribes settling there. Even though individuals can enter the mountain ranges no basecamps, or tribes will be located there.

4.4 Parameters and Simulation Results

4.4.1 Parameters Defined

Region Dependent Parameters-

Region	Diffusion (D) [km^2/yr]	Splitting rate (So) [1/yr]	Carrying Capacity (K) [1/km^2]	Source (estimates)
Iberian Peninsula	2.5	0.1	4	Dr. S.C. Hille
France	2.5	0.1	4	Dr. S.C. Hille

Table 2 Region Dependent Parameters. Estimated parameters by Dr. S.C. Hille on the diffusion rate, splitting rate, and carrying capacity for the Diffusion-Age-Structured Model. (Table by McKayla Richardson, on the basis of S.C. Hille, personal communication, April 17, 2025.)

Region Independent Parameters-

$a_{1/2}$	2176 [yr]	Surovell et al., 2009, pp. 1717-1718
b	1.39 [unitless]	Surovell et al., 2009, pp. 1717-1718
$\bar{n}$	300 [number]	Dr. S.C. Hille (estimate)
μ $individual$	1/50 [1/yr]	Dr. A. Verpoorte (estimate)
ε	1	Dr. S.C. Hille (model assumption)

Table 3 Region independent Parameters. Estimated parameters on depositing efficiency (ε), the average number of individuals ($\bar{n}$), and the mortality rate of Neanderthals (μ individual) and known parameters for years after which the rate has halved since a = 0 ($\alpha 1/2$) , and (b) the value found in the paper for taphonimic decay rate. (Table by McKayla Richardson, on the basis of Surovell et al., 2009, S.C. Hille, personal communication, April 24, 2025, and A. Verpoorte, personal communication, April 25, 2025.)

The values of the parameters in Table 1 and Table 2 unless stated otherwise are best guesses created for the model by Dr. S.C. Hille and I both during personal meetings. Each parameter will now be described how they were derived in depth to make the simulation make a bit more sense. The first parameter from Table 1 is the diffusion constant (D). It is measured in km^2/yr and measures how fast the tribes will spread. The formula that was used to solve for the parameter D was the Mean Squared Displacement formula. It takes the average of the radius squared approximately the area over which they have spread at time t after the start in the center multiplied by four times the diffusion constant multiplied by time. The area in which the Neanderthals occupy by moving in a diffusive fashion increases linear in time so that is how diffusion works. Then the parameter is estimated on the average they cover a 10km^2 region in ten years as a tribe divided by the base camp movement. This is just a rough estimate, but with this formula and calculation the result is a diffusion constant D of about 2.5km^2 per year so that is where the value comes from. This explains how the basecamp location moves around. The tribe is settled in this basecamp and the individuals in the basecamp move to better positions.

The splitting rate (So) is measured in 1/yr. It is calculated from the shape of the Gaussian curve in Figure 1.

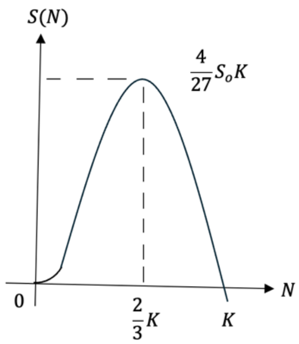

Figure 7 Gaussian Curve depicting tribe splitting. This curve shows how if there are many Neanderthals tribes they will disappear through competition for resources or fighting. (Figure by McKayla Richardson, on the basis of S.C. Hille, personal communication, April 17, 2025.)

In the splitting rate both n and k are density which causes the rate to have a dimension of density over density which makes it become dimensionless. If the splitting rate is taken as a function than the maximal level is located at time 4/27k which can be computed in a specific way. Smax as 1/100 is how S/So was computed for the other ones. If the shape of the curve is considered and then also the new function it would compute the derivative. Where the derivative is zero the n is 2/3 of k which does not change by this constant. It becomes the splitting rate per density of tribes or the Sn, so if it is divided it will result in the maximal splitting rate per year which is set to 100. Then if the 4/27Sok is divided by 2/3k the result is 81/8. This value means that once in a hundred years the tribes separate into more than one tribe. The tribes will split up at a rate of once in a hundred years to have that roughly happening in the model basic splitting rate was set to 81/8 times this maximum level which boils down to 0.1 per year. This basic splitting rate is estimated from the expression that above and thinking that the tribes split into two at most every one hundred years.

The carrying capacity (K) is measured in $1/km^2$ and refers to tribe development. It is the equilibrium long-term density of tribes that would be expected without any movement of tribes locally in a region if they do not disappear to infinity, they would stay there no more than k number of tribes square kilometer would be present there. It is set to four in the simulations per square kilometer, but it may be way too much due to the fact that it is just a number taken for the simulations and therefore it is completely unknown.

The following parameters are from Table 2 and describe the region independent parameters, The depositing efficiency (ε) describes how the remains are deposited on the surface and if they will be removed by erosion, flooding, or other natural causes. The average number of individuals ($\bar{n}$) is estimated and is 300. The mortality rate of Neanderthals or the μ individual, describes the expected lifetime of Neanderthals which is estimated around 50 years (A. Verpoorte, personal communication, April 25, 2025). This parameter is given as a unit of 1/50 in a unit of 1/yr. Both taphonomic rate parameters are from a paper by Surovell et al. (2009). It describes $\alpha 1/2$ as the age at which the taphonomic rate has reduced to half the maximal value which is 2176 yr and b as simply a calculated value that came from the paper as 1.39 (pp. 1717-1718).

4.4.2 Simulation Results

The Model has been run a few times with possible points to show what would happen if there were to be two different sites in the Iberian Peninsula and where the most likely movement of Neanderthals would occur as well as where the location of new possible find could be based on Tribe location. Specifically in the simulation ran below two actual Neanderthal site locations were used to run the model. The first was the site of Axlor located in Dima, Spain (Bailey et al., 2024, p. 1). The second site was Abrigo de la Quebrada located in Chelva, Spain (Real et al., 2019, p. 1). These site locations along with the Model equations described above and all the parameters were then put into a program called COMSOL Multiphysics.

COMSOL Multiphysics is a graphical use interface where first the geometry is described in this case the map of the Iberian Peninsula and France. Then what physics is occurring in each region is prescribed. Next, the parameter values for both regions are set and then the intricate detail of the simulation is dealt with by the program. This program has the benefit that the mathematical intricacies are taken care of by the software developers. The program has many different equation types available like heat and flow equations that are physics related, but for this thesis the diffusion/Brownian motion equation is considered only. There is an easy user interface once the model is implemented and the equations are implemented and it is easy to play around with the model as a non-expert without much knowledge of coding, it is only necessary to have knowledge of the mathematics.

The model simulation starts with tribes of Neanderthals located at the location of the two sites and then they begin to diffuse and breed as well as die and leave remains behind. This creates a dual simulation with one part showing the active diffusion of the Neanderthals and the other part showing the spreading of the remains of the dead Neanderthals as seen in Figure 2 which shows what happens after the simulation has run for 1000 years. This second part which shows the distribution of remains is very important as it shows where possible dig sites could be. If there is a denser amount of remains there is more likely to be a site that has Neanderthals, there as it considers the taphonimic decay rate.

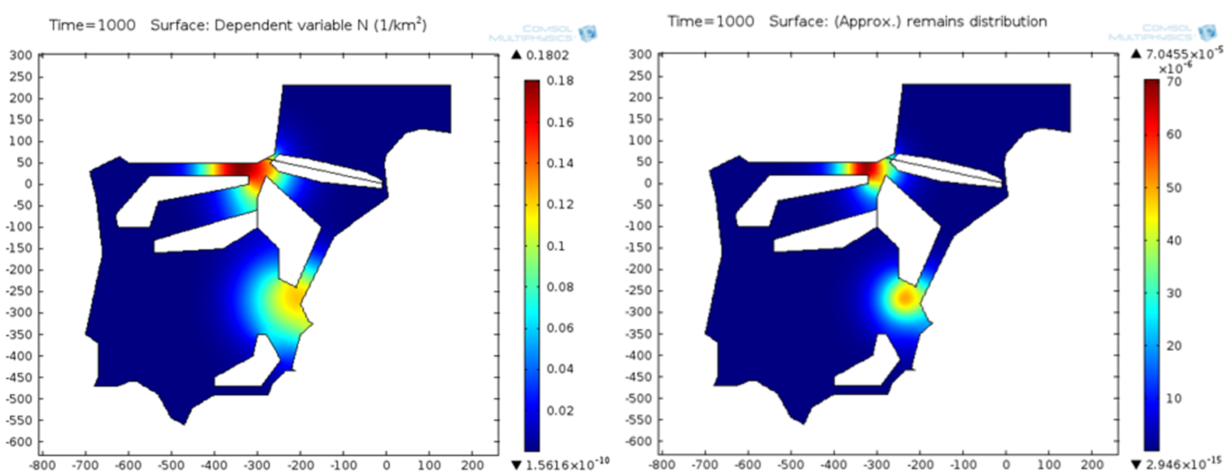

Figure 8 Map of the Iberian Peninsula and France with the Distribution of Neanderthals (left) and Neanderthal Remains (right) after 1000 years. The map was created using coordinates on the COMSOL software to represent where two sites existed in the Iberian Peninsula. This simulation shows what happens after the Neanderthals have existed for 1000 years and where they would be located (left) and where the most remains would be (right). (COMSOL Multiphysics® software v. 4.2.1.110).

After the model has run for a bit, it looks like there are no Neanderthals in France, however the scales are changing between each simulation. Figure 3 and Figure 4 show what occurs after 5000 and 10000 years respectively. There are a few Neanderthals that have entered France though it is a very low number, this is because it is difficult to cross the Pyrenees Mountains in the simulation. It is important when looking at data to evaluate what the scale is showing.

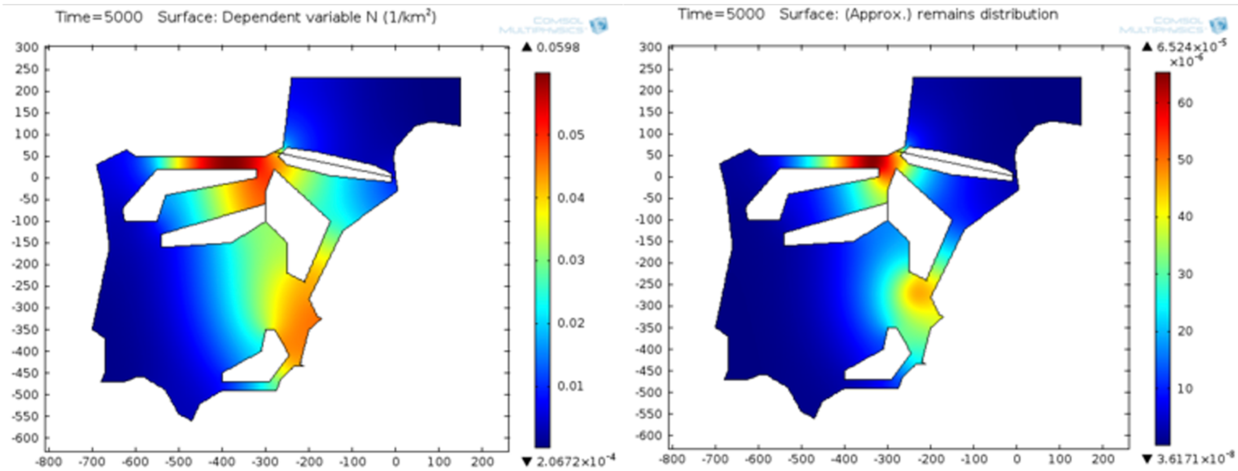

Figure 9 Map of the Iberian Peninsula and France with the Distribution of Neanderthals (left) and Neanderthal remains (right) after 5000 years. This simulation shows what happens after the two Neanderthal sites have existed for 5000 years and started diffusing and where they would move to (left) and where the most remains would be located after this time (right). (COMSOL Multiphysics® software v. 4.2.1.110).

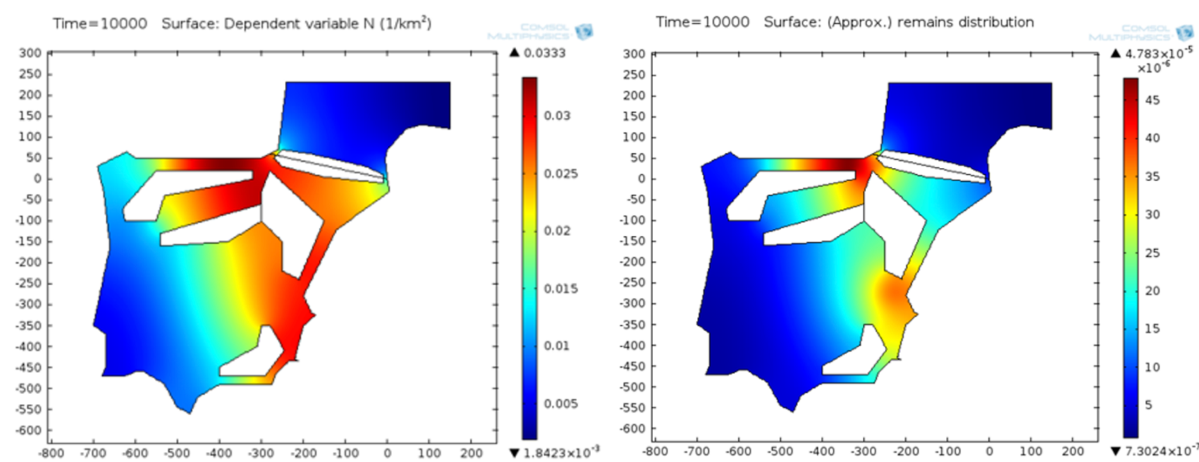

Figure 10 Map of the Distribution of Neanderthals (left) and Neanderthal remains (right) after 10000 years in the Iberian Peninsula and France. This simulation shows what happens after the Neanderthals have existed for 10000 years and how they would spread (left) and where the majority of remains would be located (right) with the barriers of the Mountain ranges. (COMSOL Multiphysics® software v. 4.2.1.110).

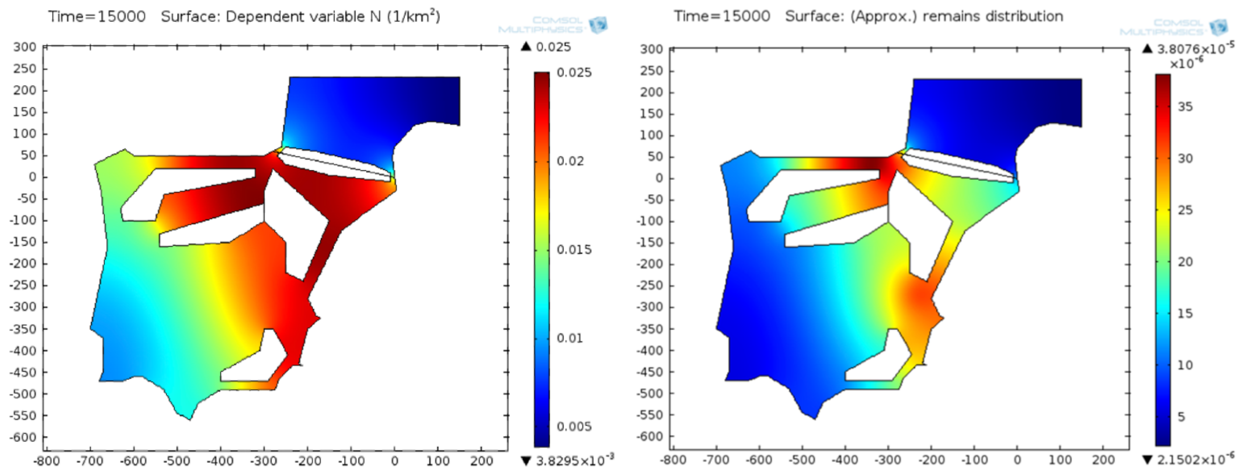

Figure 11 Map of the Iberian Peninsula and France showing the Distribution of Neanderthals (left) and Neanderthal remains (right) after 15000 years. This simulation shows what happens after the Neanderthals have existed for 15000 years and where they would be located (left) and where the remains would most likely be (right). (COMSOL Multiphysics® software v. 4.2.1.110).

Figure 5 shows what occurs after 1500 years when considering the mountains as barriers. The scale once again changes, and more Neanderthals enter France.

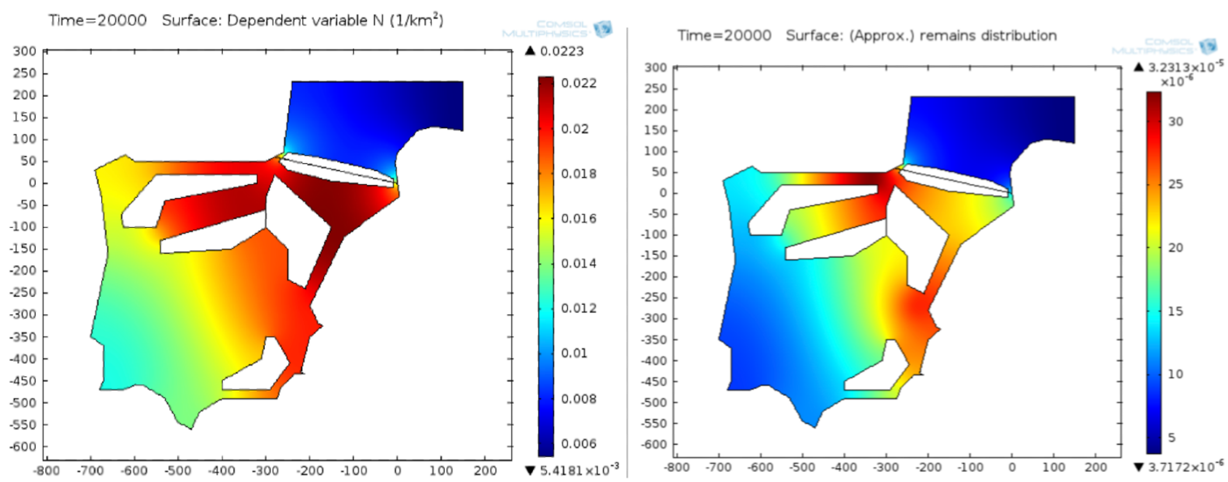

Figure 12 Map of the Distribution of Neanderthals (left) and Neanderthal remains (right) after 20000 years in the Iberian Peninsula and France. This simulation shows what happens after the Neanderthals have existed for 20000 years and how they would have spread throughout the area (left) and where the remains would most likely be found (right). (COMSOL Multiphysics® software v. 4.2.1.110).

Finally, Figure 6 shows what occurs after 20000 years which is as far as the model was coded to run. It shows that though there were two equally sized tribes there is more likely to be remains found on the northern part of the Iberian Peninsula. When looking at where the most Neanderthals would be currently existing it does not necessarily match up with the remains map simulation which is why it is important that the simulation shows both aspects and runs both model equations for the Diffusion-Age-Structured model.

4.5 Model Discussion

The Diffusion-Age-Structured Model created by Dr. S.C. Hille and I has many unique new aspects that it brings to the field of modeling in archaeology. The first is that is has the unique ability of calculating events over a large timescale. This is often difficult for other model types. The model also focuses not only on the living movement of Neanderthals in the past, but where their remains would have been located and considers the taphonomic decay rate as well as natural factors that affect remains like erosion, and more. Any sites and period can be used if the time scale is great enough as eventually all remains in the ground will have reached past the taphonomic decay rate and will simply stay preserved in the ground. In other words, this means that this model can be applied to any hominin or extinct species.

While there are many positives and new and exciting things about the model there are also some obvious disadvantages to introducing it to archaeology. These include the fact that the landscape travel cost and energy cost is not considered. Also, the largest one being that this model while not requiring a knowledge of coding requires a knowledge of advanced mathematics to implement. Though, one positive is that it would result in collaboration between archaeologists and mathematicians. Another thing the model does not consider too much is the actual landscape ignoring rivers, lakes, and things like soil acidity. These can be implemented in the future to the model, but it would take lots of time. The model is over simplified and may provide new insights into possible Neanderthal sites, but it should also be noted that it is not as easy to implement as other popular used models.

As a proof of concept, it has been shown that with more validation of parameters it could be possible to discover new Neanderthal sites using the Novel Diffusion-Age-Structured Model. However, it is necessary to make sure that more validation is done. It is also necessary to address that the past can only be interpreted and this model is only a model of how neanderthal tribes might have moved around the Iberian Peninsula and France.

Chapter 5: Discussion

5.1 Comparison of the Models

5.1.1 Advantages of the Models

Both the Agent-Based Model and the Diffusion-Age-Structured Model introduced in this paper have advantages when it comes to modeling archaeological concepts. The largest benefit of the Agent-Based Model in comparison to the Diffusion-Age-Structured Model is that it can model a multitude of archaeological concepts, while the Diffusion-Age-Structured Model can only model the spread of extinct species and their distribution of remains. Agent-Based Models also have the unique ability to focus on the individual or a group, while the Diffusion-Age-Structured Model can only focus on the movement of a group as a whole and the interactions between the individuals. Agent-Based Models also allow those with limited knowledge of mathematics to understand the model if they have a basic understanding of coding (Romanowska et al., 2019, p. 4). Conversely, if someone had no knowledge of coding, but was good at math the Diffusion-Age-Structured Model would be easier to run and understand. Both models can be reproduced which is very beneficial as it allows for the changing of a few parameters to see how it affects the model's outcomes. Another advantage that the Diffusion-Age-Structured Model has is that it has the ability to work over a very large timescale without any issues. Finally, a unique advantage of the Diffusion-Age-Structured Model is the modeling of the remains of Neanderthals with taphonomic decay taken into account. This allows for the location of where a possible site location to be identifiable.

5.1.2 Disadvantages of the Models

The models may have many benefits for archaeology, but there are some disadvantages to using them. The strongest one for both is that the past is not fully understood, so when modeling the past, it is important to remember that it is an idea of what could have existed and not what actually was there. Even if it aligns with what occurred in the archaeological record it does not mean it is a confirmation of the hypothesis. No model can even ninety percent describe a process accurately. The Agent-Based Model and the Diffusion-Age-Structured Model are reductionist which means that they both only hold some aspects of the complex system that was actually occurring in real life in the past. One disadvantage of the Agent-Based Model is that it requires a powerful computer and simulation to run the complex models, while the Diffusion-Age-Structured Model only needs to have a physics-based software package but does not need a powerful computer. The software for both systems is confusing in different ways, while the user interface is easy to understand for the Diffusion-Age-Structured Model it is necessary to know high-level mathematics, and for the Agent-Based Model the software is very complex, and coding is required. Both models make base assumptions as well which is a disadvantage. Finally, a few major shortcomings of the Diffusion-Age-Structured Model are that it does not consider too much actual landscape like rivers or soil acidity, and it is not as easy to implement as other popular archaeological models.

5.1.3 Archaeological Interpretation

While both models bring different insights into archaeology, Agent-Based Modeling is more beneficial to the archaeological interpretation. This is because it considers landscape more and can run simulations based on a multitude of complex archaeological systems and hypotheses. For the specific topic of discovering new Neanderthal sites the Novel Diffusion-Age-Structured Model definitely has some unique insights to where new sights could be discovered if it was run with more data and the parameters were calibrated further.

The Diffusion-Age-Structured Model has been shown to provide new information on where the majority of remains could be found, but it would be necessary to calibrate the model with more parameters and also take into account the landscape before it could be determined if the locations where the majority of finds are would be valid locations to look for Neanderthal remains. Though there are some drawbacks it is a step towards involving more advanced mathematics in archaeology which could lead to new avenues of discovery.

5.2 Limitations

One limitation is that the current record of Neanderthal remains is very limited, which means that what is known about Neanderthals is not very much. In order to model Neanderthals, it is necessary to know a few things about how they lived and moved, but with limited data available this is a limitation when it comes to modeling this species. Another limitation is that the Diffusion-Age-Structured Model does not consider all aspects of the landscape only the borders of the seas and mountains surrounding the Iberian Peninsula and France. Another limitation is that the Diffusion-Age-Structured Model oversimplifies how Neanderthals would have interacted with their environment by defining movement as diffusion. While this takes away the bias of assuming they moved a certain way it also removes some aspects that could help make the model even more accurate.

Chapter 6: Conclusion

This thesis has analyzed Agent-Based Modeling and the Novel Diffusion-Age-Structured Model to answer the following research question which asks what model is more useful to the archaeological interpretation and why. In archaeology finding new sites for Neanderthals is very extraordinary. It does not occur very often due to a multitude of reasons, a few of these being that remains do not last well in the archaeological record and another being that Neanderthals are from the Late Pleistocene. This thesis considered a well-known archaeological model of Agent-Based Modeling and a new Diffusion-Age-Structured Model to address how they compare, and which one is more beneficial to archaeological interpretation.

To begin with this analysis, I first created the Diffusion-Age-Structured Model with Dr. S.C. Hille from the Mathematical Institute of Leiden University, to attempt to create a model that considers the remains of Neanderthals during the modeling. During the creation of the model, it was necessary to consult with other archaeological sources, specifically Surovell et al. (2009), to determine the taphonomic decay rate so that the model can accurately determine how fast remains decay once they are in the ground. Once the actual model was created it was implemented in COMSOL Multiphysics software and two sites were selected to be used for the analysis, Axlor and Abrigo de la Quebrada.

The model was run multiple times, and the parameters were determined by Dr. S.C. Hille and me. The Diffusion-Age-Structured Model was found to provide the beginning of a proof of concept for using it to find new Neanderthal sites. However, it became understood that the model itself still needs some work with validating the parameters and applying more sites for analysis.

When it comes to trying to determine new archaeological sites of Neanderthal remains the Agent-Based Model and the New Diffusion-Age-Structured Model have some disadvantages. When interpreting archaeological concepts, it is imperative to recognize that the past can only be interpreted and there is no way to perfectly model what happened in history. Both models cannot describe the past perfectly and even if the model results align with what occurred in the archaeological record it does not mean that the model means that there is definitely Neanderthal remains in that location.

Agent-Based Modeling and the Diffusion-Age-Structured Model also only represent aspects of a complex system that was occurring in the past and cannot model the entirety of what was happening. Specifically, Agent-Based Modeling considers one agent and how it interacts with other agents, or the environment based on rules, but in order to assign these roles the archaeologist running the model is already making assumptions and leading the Neanderthal to go in a specific direction that may not have occurred in the past. The same can be said with the Diffusion-Age-Structured Model, as it is very simplified and considers Neanderthal movement to be a diffusive flow. It does not assign any traits to how Neanderthals would have moved in the past. Finally, while the Diffusion-Age-Structured model actually models the remains and their distribution unlike the Agent-Based Model, it ignores lots of aspects of the landscape, which in turn makes the interpretation of where a new site could be not as accurate.

The Agent-Based Model and the Novel Diffusion-Age-Structured Model both have many advantages when tasked with modeling archaeological complex systems and ideas. Both models can be reproduced which is a big advantage when interpreting the archaeological record. However, each model has their own advantages over the other.

The Diffusion-Age-Structured Model can run a model that involves a very large timescale as seen in the running of the simulation of 20,000 years without any issues. This model also deals with modeling the remains of Neanderthals as well as their movement. Which is helpful in discovering feasible areas for sites.

On the other hand, Agent-Based Modeling in comparison has the strength that it cannot only model the movement of Neanderthals and predict possible site locations, but many archaeological concepts including evolutionary processes, formation, and history. Agent-Based Models also can focus on the individual which is invaluable in archeology where it is often difficult to estimate how one agent would have interacted with the surrounding landscape.

Though the Diffusion-Age-Structured Model has some unique aspects for modeling possible find locations for extinct hominins, overall, Agent-Based Modeling is more beneficial to the archaeological interpretation. It not only considers the landscape but considers the interactions between the agents and the environment and the agents and each other. Being able to set rules to how the agent interacts with the environment can also lead to unique discoveries like how the case study by Coco and Lovita (2025) combined Least cost path analysis and Agent-Based

Modeling to learn more about Neanderthal dispersion routes. Agent-Based Modeling can still be applied to more things in archaeology and as technology advances how it aides in archaeological interpretation will only grow.

This research was done because it is very difficult to find new Neanderthal sites. Even though the New Diffusion-Age-Structured model is not fully accurate it can give insights into where possible new Neanderthal site locations can be found. This model can make it easier to find Neanderthal sites so archaeologists can study this hominin even more and contribute to reconstructing how they lived. This creation of the model also allowed for advanced mathematics to be applied to the field of archaeology which I hope to do more in the future.

Abstract

This thesis was written because of the lack of models that can successfully model where possible new sites can be located. At the beginning a literature review was done on a known archaeological model to better understand its advantages and disadvantages before creating my own model. The Agent-Based Model provided insight into what type of models the field of archaeology had access too. I knew I wanted to use my knowledge of mathematics to create a new model and with the help of Dr. S.C. Hille from the Mathematical Institute of Leiden University, I was able to determine what to model. The novel Diffusion-Age-Structured model uniquely modeled not only the living population Neanderthal movement, but also the distribution of their remains. This model also is able to run over a large time period and in this thesis the time scale of 20,000 years was used.

While this new model was beneficial as it approached modeling how to find new archaeological sites from a new angle, it lacked a lot of aspects that are valuable in an archaeological interpretation. The landscape was not taken into account, and neither was the individual only the group of Neanderthals in a tribe. Also, by denoting all Neanderthal tribes as flowing in a diffusive state they moved aimlessly with no direction, which is not accurate to how it would have been in the past. This new model still has a long way to go before it can fully be used to successfully find new sites, and it is not as useful to the archaeological interpretation as the Agent-Based Model. However, it is a step towards combining more advanced math with archaeology and tracking remains to discover new sites.

The Agent-Based Model with the ability to be used for multiple aspects of archaeological interpretation and focus on the individual is still the model that I would recommend archaeologists when attempting to locate a new site.

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Appendix

Table of the terms used in the equations for the Diffusion-Age-Structured Model.

This table defines the terms that were used in the equations for the Diffusion-Age-Structured Model in detail. (Table by McKayla Richardson)

∂_t	Partial derivative symbol
$R_x(a,t)$	Local density at x at time t of remains of age a (in years) [unit: number per km^2 per 'age-class' yr]
$\lambda(a)$	Taphonomic rate
$R(x,0;t)$	Expected number of deposited remains of Neanderthals at position x that died at time t
ε	Depositing efficiency
μ	Mortality rate of Neanderthals (their expected lifetime in ~50-60 years)
$n(x,t)$	Expected density of living Neanderthals at position x at time t
$N(x,t)$	Neanderthal tribes at position x at time t
$D(x)$	Diffusion constant
$f(N(x,t))$	Reaction term that models how tribes will split up at one point or disappear altogether
$S(N)$	Splitting rate
μoN	Disappearing of Neanderthals through bad luck