Virtual Neanderthals : a study in agent-based modelling Late Pleistocene hominins in western Europe

Scherjon, F.

13. CONCLUSIONS

A model is no more than a rough simplification describing real world aspects and events. The purpose of a simulation model is to allow exploration of questions and ideas in order to identify the mechanisms that could provide a possible explanation of the observed phenomena. The outputs of a simulation derive from the interactions of the modelled parts, through a process referred to as emergence. To obtain a most parsimonious model and the most optimal fit with the data, model parameters can be manipulated to focus the comparison results. More focus increases trust in the proposed model elements and selected values.

HomininSpace was designed to contribute to the discussion of existing ideas about mobility of past hominins. In the process of implementation many parameters were identified that play a role in a model that takes subsistence requirements and translates those into motivations to move through a landscape. This final section of the thesis will start in a bottom-up fashion with suggestions for improvement of those parameters, through a more elaborate simulation structure and finally a wider application of this simulation environment.

Underlying the HomininSpace simulation system is a minimal model that describes population structure, subsistence, demographics and social interaction. Sixteen model parameters can be manipulated to create new model instances with different characteristics. Parameter values are modified with a Genetic Algorithm, an Artificial Intelligence method aiming to find good performing models through optimization techniques inspired by evolution. In a case study focussing on Middle Pleistocene hominins in western Europe, several questions that remain unresolved in the current debate on Neanderthals were explored. These include questions on the usage of coastal resources, the usability and maximal extent of a foraging range, the ability to cross large open water systems, the presence of population core areas, the distribution of energy in the environment, the use of absence data, and the character of the mobility when groups of Neanderthals explore the landscape.

In HomininSpace, a fitness value is computed based on comparison with archaeology to allow ranking of alternative models and thus exploration of hypotheses. To summarize some quick results: coastal resources make life easier for past hominins, especially for female individuals; a large foraging range allows hominin groups to cope with setbacks;

there are no better simulation scores when hominins are able to cross water bodies; population core areas facilitate certain model configurations but are by no means essential; energy in the landscape can be described using habitat types or with a continuous energy distribution but for Neanderthals this made no difference; the introduction and enforcement of absence data points in England steers the system towards unrealistic model configurations illustrating the difficulty the model has with staying out of England; and finally the mobility character of past hominins, static or dynamic, made no difference in the match with the archaeology at all.

To understand the simulation results, it is important to realize that the fitness value is constructed by matching *presence* data in the archaeological record. These data points are spread through the simulation area, both in space and time. The theoretical best match would be attained by a hominin that is present everywhere all the time (!). Such a hominin cannot be sustained by the limited amount of resources produced by the environment. So the system, implemented in a GA, searches for sub-optimal solutions. One of these is a family of solutions that represents a hominin type which is not, as such, recognized in the literature. This is a hominin that constantly travels through the landscape in very small groups (5-15 individuals), hardly interacts with other groups, and with a very high birth-rate that is close to the physical limit a female modern human body would be able to sustain (see for instance the results from Energy-B).

Because unexpected solutions that perform well are constructed it can be concluded that the implemented Genetic Algorithm works. It improves upon results from randomly constructed (unbiased) parameter values and falsifies previous research (Scherjon 2015a) that suggested that the evolved Dynamic Neanderthals have an equal or better fit than all evolved or manually constructed Static ones. The search for optimal solutions is generic, systematic and produces better results than informed manual selection of parameter values (Scherjon 2016). The character of the parameter value development for the set of most optimal solutions confirms the statistical analysis on the significance of certain parameters on the fitness value. This information can be used in future parameter reduction efforts on the model, but care must be taken: some of these parameters which are unimportant in some scenarios are important in others and vice versa (for examples see the discussion about the Temperature_Tolerance and mortality rates for the post-fertile cohort in subsection 12.3.1).

13.1 Developing HomininSpace – a tool for modelling hominin mobility

One of the aims when building the HomininSpace simulation system was the development of a tool that would be able to simulate modelled hominins in a realistic, reconstructed environment without relying on model parameter value choice by the user. Instead, the system should construct values by comparing simulation results with archaeological data and using an optimization algorithm to modify model parameter value sets in order to produce an optimal fit when used in simulations. The building of such a system is challenging, and finding a balance between what is possible, the level of realism (and the amount of details) that is to be implemented, and what can be realised given the computational capabilities and other resources requires an open mind at every step and careful consideration of alternatives and a focus on the research aims.

One of the most important lessons learned from this project is that the communication of the model is of utmost importance throughout the development process. An implemented model not only consists of model parameters and formulas, but also the structure in which those are embedded (the source code that implements the model and the runtime environment where the model is simulated). When implementing a model numerous assumptions remain hidden in the implemented classes and transmitted data between objects, in functions, in data stores, in input files, etc. Those assumptions form an integral element of a model, and must be clearly communicated. The use of an ODD is instrumental in this since the ultimate aim of an ODD is not the documentation of a model, but to provide all information needed to recreate the simulations. This means that all underlying assumptions in a simulation system must be stated in the ODD. The model developed in this study is extensive and a re-implementation is not easily done, and the review of the ODD and the reimplementation of parts of the model within the framework of this study can only address parts of the model, not the complete system.

Reproduction of simulation results has been shown to be an essential part of modelling efforts. Using community developed best practices and standards can improve reproducibility of any research (Freedman *et al.* 2015). An ODD and even a re-implementation cannot prove that a model is correct, but by making sure that in the design and in the implementation all effort is given towards proper building of the model, one can make plausible that a correct model has been created. Further analysis must make sure that the model is verified and validated. To allow proper replication by other researchers complete replication files should be publicly available (Dafoe 2014; Marwick 2017). Therefore the model of HomininSpace, including source code, data files and documentation is made available through open access at OpenABM.

Code review is the systematic examination of computer source code by third party researchers and has been shown to be very effective in eliminating errors, finding inconsistencies and improving the quality of the reviewed work early in the development cycle (Ackerman *et al.* 1989; Fagan 1976; Kemerer and Paulk 2009). Peer reviews may also address readability, consistency in coding style and purpose, potential performance issues, simplicity of programming efforts (Whitner and Balci 1989) or evolvability defects (interesting for projects with expected long life cycles, see Mäntylä and Lassenius (2009)).

The model and source code of HomininSpace has been reviewed by Iza Romanowska, a computer programmer and modeller with experience in Palaeolithic archaeology (Romanowska *et al.* 2017). In the formal code inspection model reviewers must consider the effects of proposed changes, discuss these with the developers and follow a checklist when reviewing the code (Fagan 1976). In modern, light weight reviewing procedures such strict review criteria are released (Rigby and Storey 2011) with the risk of neglecting the overall design features (Bacchelli and Bird 2013). In the current study, by positioning the code review in a replication effort, such dangers are averted even though the review itself was informally organised. Code inspection is also used to detect underlying assumptions and instrumental in completely understanding the implemented system.

13.1.1 Usability of the tool

Since a model is always a simplification of reality, modelling efforts are never an end product. Instead modelling results will be integrated into larger research projects, to be used as additional argumentation material and hypotheses exploration. A good Neanderthal model depends on the cooperation of scholars capable of writing software that implements an explicit model and executes the simulations and other scholars with a profound knowledge of and access to Neanderthal materials and data defining a useful model. An ABM is a very useful complex systems modelling tool that can link individual behaviours to population level patterns that archaeologists seek to understand. It is a modelling tool that is able to simulate change through time and capable of modelling the interactions between individuals and the environment in a decentralised, bottom-up manner. Modelled Neanderthals implement parameters to explore a range of conditions that cannot be observed first hand and do not form analogies with today but are used as blocks for systematic theory building.

Modelling appears to hold a reputation of objectivity but in general it is ultimately the designer of the system who decides what to include in a model, and which values are assigned to the model parameters. To avoid such non-neutral input HomininSpace has been designed to find values for model parameters in an unbiased and objective manner, using Genetic Algorithms. A Genetic Algorithm (GA) has been implemented to systematically explore the parameter space that results from the chosen range of parameter values in the underlying model. Simulation results are compared against an archaeological record of actual presence data, resulting in a quantitative fitness value per simulation.

It is shown that the implemented GA is capable of finding optimal fitting parameter value combinations that result in a higher fitness value than informed manually selected parameter values. It performs a directed systematic search of the parameter value space. With GA researchers' expectations and biases are overcome and a better understanding of the parameter impact on modelling results is possible. As such, a genetic algorithm or a similar systematic technique improves the results of a large scale (in simulation time, number of model parameters and/or parameter value spaces) modelling system.

Genetic Algorithm techniques applied in HomininSpace are, unfortunately, computationally expensive, since the calculation of the fitness value is the actual simulation run with the evolved parameter set. Therefore the following elements must be considered carefully when constructing a GA for an archaeological ABM: the total computational costs, stochasticity in the genetic algorithm, choice of GA operators, the stop criterion and the chosen fitness function. As with all stochastic modelling, obtaining a good or the best model is never guaranteed. And note that due to the nature of the GA improvement process the best scores tend to represent individuals from a few successful lineages only.

When applied to the research question on Neanderthal mobility alternatives, it must be concluded that the scores for Dynamic and Static strategies are very comparable. The fitness values for improved individuals are within the same order of magnitude, and there is no statistically significant difference between Static and Dynamic hominins (contrasting previous research). However, it is noteworthy that the best matching simulations were always those which, albeit by a narrow (and insignificant) margin, have hominins that are implementing a Dynamic mobility strategy.

A simulation is scored by matching the relevant archaeological data. In this research each radiometrically obtained data point is used as an interval around the calculated point in time, min and max delimited by the standard deviation. Dating results from the same layer are combined. A total of 83 checkpoints is created, illustrating the deficiency in accurate chronological information for the simulation area and period to match against. A match is a simulated presence at an absolute point in time, where one point is added to the simulation score for the matched presence itself. Up to one more point can be gained depending on how many more visits occur during the interval (as a percentage with a maximum possible score of 100%). Visits outside an interval do not count, neither as bonus points nor as minus points.

The scoring mechanism does justice to the fact that having at least one visit is most important, since we cannot be sure how much archaeology any visit produces (often one visit could theoretically have created the site in question). And there is logic in the assumption that more visits mean more archaeology to match. Visits outside the intervals cannot be interpreted as violations, since it is not sure that there are no visits if no archaeology is found (visits could have produced no archaeology to test against, the archaeology might not have been retrieved yet, more precise dating results are not available, or visits could have been made to the next cave).

Critically reviewing the model and simulation one might conclude that there is a lack of heterogeneity and that only energy requirements rigorously steer Neanderthals. Such critiques and others match some of the things said previously about equation-based models (Brughmans and Poblome 2017) and ABM has gained popularity just because it can be used to address such issues. Agents in HomininSpace are homogeneous in one simulation but vary between simulations. They are similar in character but vary in size throughout any simulation. And parameters related to the metabolic budget are amongst the least important ones in all simulations. With HomininSpace a virtual laboratory is created where hominins evolve and where the best adapted individuals are allowed to create offspring that maybe even better matches the archaeology.

13.1.2 Who were those Neanderthals?

Quite telling is the fact that the HomininSpace system is able to find good performing Neanderthals in most circumstances, suggestive of the flexibility in the implemented model. The characteristics of these Neanderthals differ per scenario, aiding in interpretation and assessment of the implemented hypotheses and answering the questions that this study aims to explore. There appears to be no difference between the continuous energy reconstruction and a delimited habitat area reconstruction. Modelled Neanderthal hominins were irrespective of the manner of energy distribution capable of using the environment to their benefit. And the comparison between dynamic and static hominins failed to identify a best strategy. Both implementations allowed the hominins to cope with the challenging environment.

Introduction of random movement made no difference in some cases (for instance in combination with static hominins) but could also result in very ineffective models (see below). Adding coastal resources to the model seems to make no difference at first glance (same simulation scores) but when model parameters are inspected these additional resources allow a more relaxed demographic sub-model with more realistic values with less physical stress for female Neanderthals (e.g. birth rates below 40%). Adding the ability to cross open water does not influence the simulation scores, but allowed hominins to reach England earlier.

Absence data states that hominins were *not* in an area for a given time period. It is very difficult to define proper temporary and geographical boundaries for absence data, and as such, only a suggested absence of England is included in the different scenarios. Striking is that the absence condition leads the system into producing relatively “strange” hominins, often stretching the boundaries of realism and the model. With the flexibility to adjust the model into many different configurations that generally score well, the model appears to have difficulty staying out of England. Introduction of model element like random movement only makes matters worse. And where limiting the foraging range does not seem to hinder foraging hominins in other scenarios (in the sense that other model parameters can be adjusted to mitigate the limiting effects), in combination with the absence condition it is actively used by the model to restrict hominin presence to the north. Especially when a population pump in the form of the core areas is activated ensuring constant supply of hominins the system can create groups that have no chance of survival for any prolonged period of time.

Very short lived and fast reproducing Neanderthals score well with the archaeological data while being unable to reach England. But in general the scenarios that have absence conditions imposed score relatively low, with Scenario Energy-CR as an ultimate example with a maximum score below 4000 points. This apparent struggle and the sometimes unexpected turns that the system takes indicate that the model cannot easily match the absence of archaeological data for this period and area. This could indicate that there were other mechanisms that kept Neanderthals out of England, or that there is archaeology still to be found or properly dated (Gibbard 1988).

In general, absence data is considered vital to avoid the perverse drive of producing as much offspring as possible in order to create an optimal match with the presence in the real world. But that is now replaced by a similar perverse system of sufficient reproduction to score but with model parameters that ensure *non* viability. Note that any other absence locations in the simulation area would have resulted in similar effects but even lower scores, since these would lack the potential absence causing mechanisms of flooded land bridges or latitudes that sport very cold climates warding off hominins. It can be concluded that absence data is a potentially very useful asset to create more realistic simulation models, but that those models must include very explicit and potentially effective mechanisms to cause that absence in order to avoid even more perverse models.

The basic hominin model as implemented is generally very capable of adjusting to different circumstances while still producing good simulation results. The HomininSpace simulation system will automatically substantiate which model under what hypothesis best represents in all likelihood past hominin behaviour in the landscape and will thus lend some empirical credibility to the effects of the included interpretive hypotheses. It will also fill in model parameter values that reflect the effect of environment, other hominins and settings in exploring possible behaviours in the past. In this manner answers can be given for specific questions, after translating the questions into hypotheses that were implemented as elements of the model.

The system prefers certain parameter value combinations for answering each question, but some trends can be identified. High birth and low mortality rates for the (pre) fertile cohorts were evident. Very clear is also that the system does not care for hominins of post-fertile conditions. Mortality rates here are generally very high, especially when compared to fertile cohort numbers. These numbers are sometimes accompanied by increased subsistence needs for elderly, often even surpassing the needs of the fertile cohort, made possible by the limited number of surviving individuals.

The subsistence requirements vary widely but whatever value is chosen it can be compensated by an unlimited or very large foraging range. The same is true for the amount of calories extracted from a kilogram of edible meat, including proteins and fat. Even when resources are scarce large foraging ranges enable hominins to gather sufficient foods allowing survival albeit in very low numbers. These very large ranges ward of competition but also paradoxically reduce score potential since checkpoints that are located within foraging range are not necessarily visited every year. Randomly moving through the landscape appears not necessarily detrimental for survival or for a good simulation score (but can be for population densities).

Tolerance for colder temperatures is not essential for getting high scores. Normally, values where hominins tolerate around -20°C as the coldest temperature of the year do well. Combined with the absence condition the value can be surprisingly high (around -10°C), contributing to early death in the north. Finally, the variables that steer group dynamics vary widely. Especially the years before group maturity and the group size before split can take values from a wide range, varying within and between scenarios. Group size and group size of the fertile cohort before merge also vary, although from a much smaller range. Occasionally the functionality these variables implement is turned off completely by the system assigning zero to them.

The power of this model to overcome different circumstances, to recover quickly after setbacks and the ability to cover large distances enables the modelled hominins to generate substantial matches with the given archaeology. That is independent of the usage of coastal resources, the ability to cross larger water bodies, the apparent non-importance of subsistence quantifications in some combinations, etc. On the other hand, it must be pointed out that there probably was not a set template for a Neanderthal individual. There was no standardized Neanderthal. True realism is more divers than a set of parameters can capture.

13.2 Implications of this study

In the literature there are constant attempts to improve demographic parameter values in Neanderthal models. The energy needs for age groups are refined and many chosen values (especially for pre- and post-fertile age groups) are supported in the literature. Implementation of the basic concept of refugia is modelled ever more realistically. The contributions of this study however suggest that variation within a basic hominin model that includes some essential demographic parameters is sufficiently capable of exploiting limited resources. Allowing parameter value variation to optimally adjust to specific circumstances creates good matches with the real world data.

Essential for a good modelling performance is the implementation of a flexible way of assigning model parameter values, allowing the system to create that combination of parameter values that produces the most optimal match with the archaeological data. In other words, the flexibility observed in the anthropological literature regarding the variation in modern humans would allow earlier hominins to be very adaptive and capable of creating the archaeological data sets as we know today. I see no reason to assume that such flexibility is lacking from, let say, the basic model of the Neanderthal species.

This study also illustrates the importance of well-chosen variables to include or exclude from the model and simulated environment. More important, it is made very clear that biased value assignment to model parameters is unnecessarily limiting the power of the model, compared to flexible value selection between given boundaries. Even a limited, very basic hominin model is then capable of matching archaeological presence data optimally, excluding the need for implementing unwarranted ideas about either environment or behaviour.

Variation within the basic hominin model allows individuals to very effectively exploit the environment negating the effects of explicit handicaps like a lacking ability to exploit coastal resources, the inability to cross larger water bodies or the behavioural limitations from having core areas. When that flexibility is removed and biased parameter values are selected the most optimal models are avoided leading to circular reasoning and self-fulfilling prophecies.

This research acknowledges what Kelly (1995) has shown in his well-wrought book '*The foraging spectrum*': that modern day as well as historical hunter-gatherers can be extremely different from each other and therefore most likely also differ from prehistoric foragers as well. There is a wide variety in almost all aspects of the hunter-gatherer life (White 2013). It is thus not possible to speak of *the* hunter-gatherer. Nor of *the* Neanderthal since there is no reason to assume less variety in pre-modern humans.

The implementation of the genetic algorithm as an essential part of the HomininSpace modelling system is warranted by the need for an effective parameter value space searching mechanism. This is a contribution to the study of agent-based modelling methodology and simulation techniques itself.

13.3 Avenues for further research

The output of the HomininSpace tool is varied and diverse. This thesis has only explored some of the simulation results, mainly aimed at answering the underlying research questions. But the emerging patterns can offer insight into many characteristics of hominin behaviour and the reconstructed environment. Graphs of the matches through time with bars for each period with the predicted amount of hits and the registered hits could better identify matching archaeology. Analysis of the matches within each checkpoint would aid in this aspect as well.

Some social aspects of hominin behaviour have not been included in the model to limit variability. But some are not difficult to implement. For instance, territoriality in many difference variants can be implemented. The different origins of the hominin group (from the different refugia for instance) could play a role here, both in sharing resources as well as social interaction (exchange of individuals, cultural transmission of ideas/technology, merging of groups). A genetic profile for each individual or group could help to illustrate and analyse the effects of such social behaviour. Extending HomininSpace with social aspects would enhance the usefulness as a tool to test hypotheses.

Where the main conclusion regarding the behavioural mobility of the past hominins in the Middle Pleistocene is that they could have included at least partly a static aspect of mobility in the way they utilize the landscape around them, a natural step further would be to investigate further the nature of that mobility. Questions regarding territoriality, group identification, cultural diversity or genetic profile distribution can be answered with only small adaptations to the existing system. For instance allowing other groups to move through a foraging range can be based on cultural type, relative group size, etc. A genetic footprint can be attached to groups, and density maps based on these profiles can be produced. Implementing some social interactions, which could include avoidance of other groups based on intrinsic group characteristics, would add significantly to the utility value of HomininSpace.

The multi-dimensional variable space created by implementing the many but essential model parameters within HomininSpace (as well as for the modelled hominins, the modelled environment and the topography) has hardly been explored, due to limited resources (time and computing power). A few promising directions have already been identified with the variation in values for cold resistance and simulations with mixed types of hominins. It would be revealing to analyse what kind of combination between static and dynamic groups produces the best matches with the archaeology. A systematic exploration of the different variables would allow the exact mapping of the influence of each parameter on the behaviour and thus the archaeology of the modelled hominins. Such an endeavour is possible using the automated parameterization feature of the Repast modelling system, possibly assisted by an automatic collection of results. This is also very useful for regression tests when further developing the software, ensuring that new functionality does not compromise earlier results. Based on the promising results of the research presented in this thesis I would highly recommend that such an exploration is undertaken.

The use of HomininSpace allows users a thorough understanding of effect of a wide range of parameters on hominin behaviour. Not only does the tool illustrate the effects of these parameters, but the ability to manipulate the variables and see the actual consequences of chosen values will animate otherwise purely theoretical concepts. The simulation period is easily adjusted, making it possible to focus on specific periods in the past. With a little more effort the simulation area can be changed since model data is basically available for any chosen locality. The model is sufficiently generic that with minor adjustments it can be applied in modelling any top predator. The possibility of actually implementing old and new theories will allow students of any level to answer questions and test hypotheses on a wide range of concepts and will aid to conceptualize ideas from the literature.

13.3.1 Recommendations when reconstructing past environments

Environmental reconstructions of the past are today created in more and more detail. This study illustrates that such reconstructions can be very helpful, and that more detail is needed to allow a more thorough analysis of past behaviour of hominins. Many options for improvement have been identified. Adding additional information to improve habitat reconstruction is a recommendable option. From actual observations it appears that soil data holds information that improves predictive models (Wisiol 1984, 474; Prentice *et al.* 1992). Accordingly, including soil information in the simulation and environment reconstruction is one way of creating a more reliable habitat reconstruction. Information about the modern geographic distribution of soils is available in the Zobler Soil Database, to be downloaded from the Oak Ridge National Laboratory Distributed Active Archive Center Oak Ridge Tennessee, USA (Zobler 1986). The Zobler soil dataset consists of latitude and longitude coordinates (1° x1° grid) for all the identified soil types under the FAO Soil Classification System (26 soil types).

This study is an attempt to use temperature and precipitation as the proximal predictors on resource gradients (as described by Guisan and Zimmermann 2000). Other resources besides energy might steer hominin movement through the landscape. One possibility is lithic availability (Fernandes *et al.* 2008). Flint, the main and preferred raw material for making tools, is mined from carbonate rocks. Flint bearing rock is distributed throughout the world (Ford and Williams 2007) and can be used to attract hominins. A digital version of the world map of carbonate rocks is available from http://web.env.auckland.ac.nz/our_research/karst/, accessed 17 September 2013.

From the simulations in this research energy, although essential in itself, appears to be less differentiating as expected. Other resources can be implemented as attractors inducing movement through the landscape and could include lithics like flint or minerals like ochre and manganese oxides. Research further suggests that specifically presence of many herbivores maintained the Mammoth steppe, and extended this habitat into a wider diversity of climates (from Spain to Siberia) than those in which it would occur naturally (Zimov *et al.* 2012). As such it is more insensitive to climate variation and thus climatic parameters alone are insufficient to predict the prevalence of this steppe. The specific conditions that allowed the Mammoth steppe to exist no longer prevail, with the possible exception at the Pleistocene Park, an artificially created and maintained area aimed to represent that steppe environment (Zimov 2005). HomininSpace models the environment using climate parameters only and as such cannot include the Mammoth Steppe as reconstructed habitat, where this is suggested to be very productive in edible resources.

13.3.2 Suggestions for simulating hominins

Palaeolithic archaeology is a fascinating research discipline. New methods and techniques are implemented rapidly and can gain wide acceptance (for instance the palaeoproteomic analysis described in Welker *et al.* 2016). This study has shown that agent-based modelling can contribute to understanding parts of the deep past. And although not a new method in itself, I argue that simulation can and should be used more often to explore the unknown elements of our origin, if only because it forces the researcher to explicitly state his or her ideas about the past in a formal and testable manner.

Elements of HomininSpace can be improved upon. Most questions about Neanderthal behaviour in the landscape were only touched upon in this work and would deserve a dedicated study with the single aim to further our knowledge focussing on a single question. In such a study the results from this research can be used as a basic data set, a starting point from which the modelled aspects can be tailored into a more extensive explicit model. Characterizing proper absence is very important (e.g. Bertran *et al.* 2013). Defining high resolution presence intervals, surrounded by assumed absence might provide a good selection mechanism. There is more data available about areas in eastern European. Core areas are now implemented by producing new hominin groups according to local circumstances, and they could vary their output and implement a variable absorption protocol (now in the form of open or closed borders, irrespective of climate, population density or other modelled attributes).

In HomininSpace, hominins are assumed to extract their main energy from mammalian resources. It is not unlikely that much if not all food consumed consisted of plant materials. The problem is how to quantify this over the landscape. Data exists on secondary biomass in a variety of habitats, but what is needed when Neanderthals are assumed vegetarians would be a quantification of edible materials for the different reconstructed habitats or energy levels.

Influencing the habitat they live in is something modern humans are very good at. Fire use in the landscape is a tool that would have allowed Neanderthals to do likewise (Scherjon *et al.* 2015). Increasing resources in a number of ways is one of the known side effects of repeated burning. We have seen that adding coastal resources relaxes pressure on some model parameters. Creating additional resources inland, appearing where Neanderthals are might have similar or additional effects which would be interesting to explore.

The capability to run the development environment on Windows, Linux and on high performance computers ensures availability of the tool on many platforms and in almost any computing environment. The intuitive source structure invites students to implement new functionality. A limited foraging range or social interaction with other groups as examples have been shown easy to implement. The use of Java as a development environment allows a large degree of freedom in the use of additional libraries and existing software. The performance of the tool allows fast development tracts in assessing effects for certain traits or in the implementation of new functionality. With the execution of multiple time steps per second, depending on chosen computer hardware and environment size, the effects of new functionality or variation in parameter values are immediately visible.

I hope that by implementing an explicit model of Neanderthals and via showing the usefulness of simulations to address questions the potential power of computational modelling will inspire other researchers to apply these methods in their own research. And that this research illustrates that the inherent flexibility in a basic hominin model which is sufficient to avoid imposing unwarranted handicaps and self-fulfilling prophecies.

13.4 Last words

With the implementation of HomininSpace a new tool has become available to answer questions and test hypotheses on behaviour of hominins in large, realistic landscapes. The implementation of Neanderthal mobility in roughly the area currently known as France illustrates the complexity of answering such questions, the possibilities and limitations of the available data, and the feasibility of implementing and simulating widely spread but thinly distributed societies over a prolonged period of time. I hope that the experience gained from this development as put down in this thesis can offer guidance to other researchers pursuing their research objectives with modelling and simulation. And that with HomininSpace a new and powerful tool to explain archaeological patterns and to answer new and old questions is added to the toolset of archaeologists and paleoanthropologists.