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of social and demographic changes on the concentration
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North-Western Europe during the Middle Ages
(800–1200 CE)**

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An agent-based model for exploring the combined effects of social and demographic changes on the concentration and hierarchy of rural settlement patterns in North-Western Europe during the Middle Ages (800–1200 CE)

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35 **An agent-based model for exploring the combined effects of social and
demographic changes on the concentration and hierarchy of rural
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(800–1200 CE)**

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Abstract

Rural settlement patterns in North-Western Europe in 800 CE were scattered and impermanent. By 1200 they had become much more concentrated and enduring. Although this phenomenon occurred in all regions, settlement concentration and hierarchy differed widely. In this paper, we seek to
45 better understand how the processes influencing the concentration and hierarchy of rural settlement
patterns might act in different ways. To do this, we build an agent-based model entitled *SimFeodal*
that simulates their combined effects on the relocation of peasant households from 800 to 1200.
Our research objective is to determine how certain social and demographic variables interacted with
the processes modelled to produce different regional settlement patterns. We simulate a series of 15
50 scenarios with *SimFeodal* on the basis of data available for the diocese of Tours (France). The
results show that demographic growth was not the primary cause of increasing settlement hierarchy.
However, introducing demographic growth into the simulated scenarios yields simulation results
that better match the empirical data. Interestingly, the size of villages and small towns in 800, the
proportion of peasant households relocating only locally and the power of village communities do
55 not seem to influence concentration and hierarchy in the simulated patterns.

Keywords

Agent-based model; settlement hierarchy; demographic growth; intra-regional migrations; Middle
Ages

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1. Introduction

Around the year 800 CE, the Carolingian Empire reached its greatest territorial extent, covering a
large swathe of Europe from the Ebro to the Elbe. Regionally, settlement patterns were a mix of small
65 scattered villages (loose clusters of a few houses) and isolated farmsteads. Villages and farms were
impermanent and their location often shifted by a few tens of metres to several hundred metres every
one or two centuries. In this period, towns were *civitas* capitals inherited from Antiquity. Some served
a central function as episcopal sees but their economic and administrative role was minor.

By about the year 1200 CE, the piecemeal dismantling of the Carolingian Empire was complete.
70 Regional settlement patterns were by then composed of more permanent population clusters around
castles and churches. Population clusters (hamlets, villages and towns) were more numerous and more
stable than in 800 CE. The towns that had existed in 800 CE had grown much larger having developed
productive and commercial activities and new nuclei had formed around suburban monasteries. Many
small towns had emerged around castles or rural monasteries ringed by their own precinct walls
75 (Gauthiez et al. 2003).

Thus what had been a dispersed regional settlement pattern in 800 CE had become much more
concentrated and hierarchical by 1200 CE. This phenomenon occurred throughout North-Western
Europe but the degree of concentration and hierarchy differed markedly. A combination of several
processes can explain this major transition.

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- The dismantling of the Carolingian Empire and the dissipation of power induced struggles among lords and so an upsurge of violence. This produced a spate of castle-building and an increased need of protection for peasant households.
 - The militarisation of society heightened the lords' needs for both money and fighting men. This initiated the "feudal revolution" of the eleventh century, when ever lesser lords

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 - appropriated various administrative, fiscal and judicial rights for themselves and their vassals with an ensuing surge in usage fees and rents paid by peasant households to their lords.
 - Peasant households organised themselves into village communities so as to boost their productivity and counterbalance the power of their lords.
 - Religious control over society strengthened considerably, especially as a result of the

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 - Gregorian Reform. This led to the development of pastoral care, more parish churches and higher usage fees and rents paid by peasant households to the Church.

In this paper, we seek to better understand the different ways in which these processes influenced the concentration and hierarchy of rural settlement patterns. To this end, we construct an agent-based model entitled *SimFeodal* that simulates the combined effects of these processes on the relocation of

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peasant households from 800 to 1200. Using *SimFeodal*, we attempt to determine how certain social and demographic variables (e.g. the population size in 800, the intensity of demographic growth or the power of village communities) interact with the processes modelled to produce different regional settlement patterns for the period under consideration.

100 A growing body of literature shows that agent-based simulation may help archaeologists to generate possible pasts and potentially compare and contrast them with patterns observed in empirical data recovered from the material record (Cegielski & Rogers 2016; Davies & Romanowska 2018). Agent-based simulation is employed to approach various research topics such as the dynamics of complex socio-ecological systems (Kohler et al. 2012; Rogers et al. 2012; Barton et al. 2012), the

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dynamics of hominin dispersal in prehistoric times (Wren et al. 2014; Hölzchen et al. 2016), the rise of social complexity (Rouse & Weeks 2011; Crabtree et al. 2017), or even processes of cultural change (Dean et al. 2000; del Castillo et al. 2014). Crema (2018) reports that agent-based simulations can be used either to support theory building and explore the implications of one or more behavioural assumptions, or to test hypotheses in a particular historical-geographic context, with outputs that are directly comparable to observed data. Crema (2018) quoting Lake (2014) specifies that very often the two objectives coexist in the same simulation, especially in the case of empirically grounded models designed to emulate a specific historical window and from this to explore more general aspects of human behaviour such as the emergence of hierarchical societies (Kohler et al. 2012). This is precisely the case of *SimFeodal*, with the general aspects of human

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behaviour considered here being the denser criss-crossing of space with parishes and castles, and the emergence of enduring hierarchical regional settlement patterns.

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2. Description of *SimFeodal*

SimFeodal simulates the emergence of enduring population clusters around castles and churches. Over time, population clusters (hamlets, villages, small towns) become more numerous although some of them disappear; many clusters grow in population (i.e. the number of peasant households increases) but some clusters grow more than others.

120 Our simulation begins in the year 800 and ends in 1200. The latter date is not distinctive but was
chosen on the basis of two criteria. First, a simulation must make allowance for all the important
events occurring in the period under consideration (piecemeal dismantling of the Carolingian Empire,
Gregorian Reform, establishment of the feudal system, etc.). Second, the time span has to be long
enough to determine whether or not the dynamics simulated are lasting features. Each step in the
simulation represents 20 years, which corresponds more or less to an average generation in the period
125 in question. Thus our simulation comprises 18 steps.

The *SimFeodal* agent-based model has been created using the GAMA platform (Grignard et al. 2013).
In this paper, we provide an overall description of the model while a detailed description can be found
in the GitHub repository [<https://github.com/SimFeodal>].

2.1 Entities of the model

SimFeodal is designed to simulate the impact of social and political changes on regional settlement
patterns but not to simulate the changing social and political processes themselves. Consequently,
only entities playing a direct spatial role have been introduced into the model (Table 1). By contrast,
135 we omit entities with no direct influence on the spatial distribution of population (e.g. merchants) or
that are not present regionally (e.g. central authority (king or emperor) and the Holy See) during the
period. The entities modelled are abstract representations of real-world entities. Apart from the
overlords, they are all spatial in nature and so have a geometry and geographical coordinates. Agents
in *SimFeodal* are named “active entities” in Table 1.

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Table 1. Entities in the *SimFeodal* model.

Name	Categories	Activity	Level
Peasant households	Relocating locally and long distance	Active	Micro-geographic
	Relocating locally only *		
Lords	Overlords (princes, counts)	Active	Micro-geographic
	Small lords (castellans, knights, etc.)		
Tax areas	Rents	Passive	Micro-geographic
	High justice rights		
	Other rights		
Focal points	Parish churches	Active	Micro-geographic
	Castles	Passive	
	Village communities	Passive	
Population clusters		Passive	Meso-geographic
Poles		Passive	Meso-geographic

* Peasant households so dependent on their lord that they cannot leave his estates (serfs, slaves).

Each peasant household is represented by a point corresponding to the head of its agricultural holding.
145 Peasant households are an abstraction in that they are permanent throughout a simulation. Their activity consists in their potential relocation from one generation to the next.

Lords represent the functions they exercise but not the persons themselves. Secular lords and ecclesiastical lords are not differentiated. They can take on new rights (through the creation of tax areas) and build castles if powerful enough. Small lords are located within the modelled region and
150 their spatial range of action is narrow. By contrast, overlords are not located and can act (i.e. create a castle or collect taxes) in any location in the region modelled.

Tax areas are circular spatial entities held by the lord who creates them. Any of three types of fees can be collected through tax areas, one type per tax area: rents, high justice rights and other rights (usage rights).

155 Parish churches can modify the boundaries of their catchment area and initiate the building of new churches in their neighbourhood. They are abstractions because the decisions were actually taken by the secular or ecclesiastical lords who hold the parishes.

Some entities (poles and population clusters) come under a meso-geographic level as they are defined as the aggregation of micro-geographic entities. A pole is a cluster of neighbouring focal points
160 (parish churches, castles, village communities). In some cases, it can be made up of only one focal point. A population cluster is a cluster of several neighbouring peasant households and focal points. These meso-geographic entities have no capacity for action but their influence on the behaviour of micro-geographic agents (peasant households, lords and parish churches) is crucial.

165 **2.2 Modelled processes: overall description**

Peasant households can move (i.e. relocate) at each simulation step. Their moves are to a nearby pole or, less often, to a more distant location. Their successive relocations can lead to the creation or the disappearance of population clusters. Village communities can emerge in the clusters. Parish churches become more numerous and modify their catchment areas in order to serve as many peasant
170 households as possible. The number of lords also grows dramatically and their hierarchy increases, which corresponds to the elaboration and extension of the feudal system. Lords build castles and collect taxes from peasant households. Over the course of time, lords take on new rights and create new tax areas that may totally or partially overlies existing tax areas.

175 **2.3 Rules of behaviour for lords**

At the beginning of a simulation, small lords collect rents from all peasant households located within their tax area. Overlords collect rents from the peasant households located outside the tax areas of small lords. Because there are few small lords at the beginning of a simulation, most peasant households pay rent to an overlord.

180 New small lords appear in the course of a simulation. They are located within a population cluster chosen at random. Some of them get a tax area for rents in which they can collect rents from 5 to 25% only of the peasant households.

In the course of a simulation, all lords can also create tax areas for other rights. Small lords collect fees from 5 to 25% only of the peasant households in their tax areas whereas overlords collect fees
185 from all peasant households in their tax areas.

Another mechanism is the creation of tax areas for high justice rights which applies exclusively to overlords before the year 1000. From this date on, some small lords who possess a castle (i.e. castellans) can create a tax area for high justice rights around their castle.

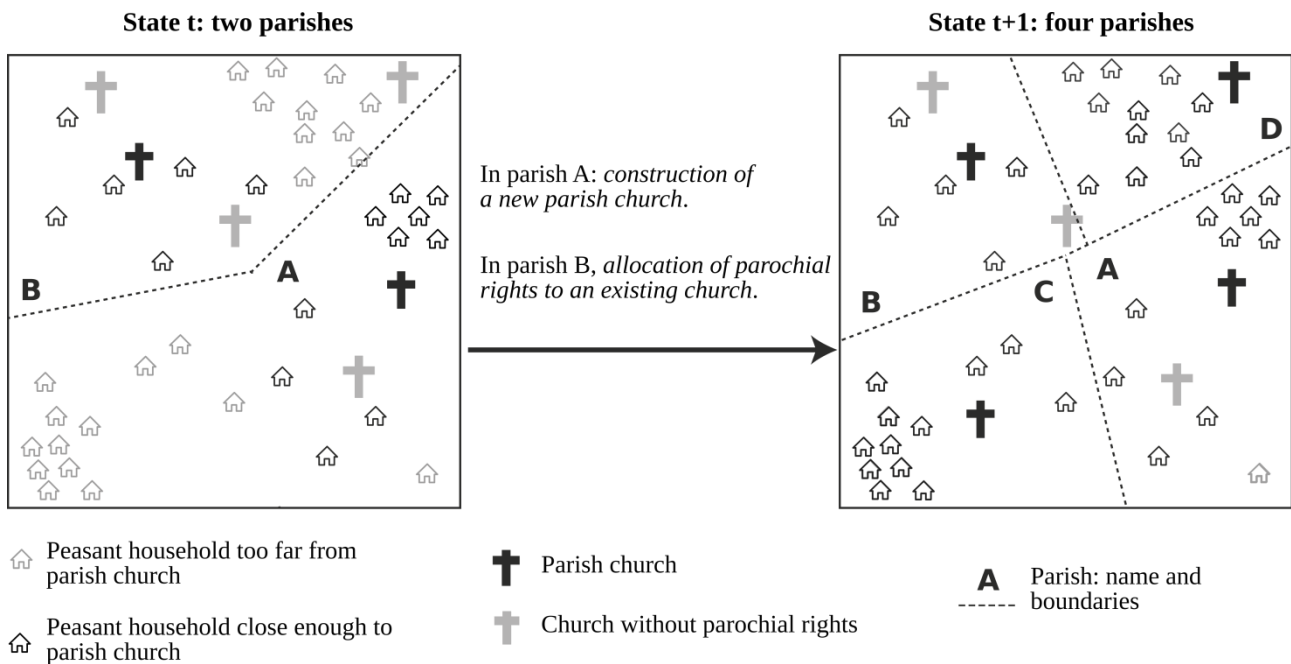
190 The amount of fees collected from peasant households by each lord determines his power which increases to varying degrees in the course of a simulation. Once a lord is powerful enough, he can build one or more castles. In the course of a simulation, overlords lose many of the rents they initially collected from peasant households located outside tax areas but they gain rents collected within tax areas linked to the castles they have built.

195 Last but not least, lords can pass on some of their rights to other lords. Similarly, a lord can pass the custody of his castle to another lord, who then becomes a castellan. Through this process of transfer of rights, some small lords can grow very powerful. Thus they may build castles and gain high justice rights. Mechanisms representing lords' gains in power in *SimFeodal* are simple. In particular, the creation of vassalage networks is not modelled.

200 2.4 Rules of behaviour for parish churches

A Voronoi tessellation is used to delimit the catchment area of each parish church. On this basis, the construction of a new parish church or the allocation of parochial rights to a single church depends locally on the number of peasant households within the catchment area of the existing parish church and the number of peasant households that are too far from the parish church (Figure 1). Each time a new parish church appears, a Voronoi tessellation is applied in order to update the catchment areas of all churches.

210 **Figure 1.** Mechanisms leading to the creation of new parishes.



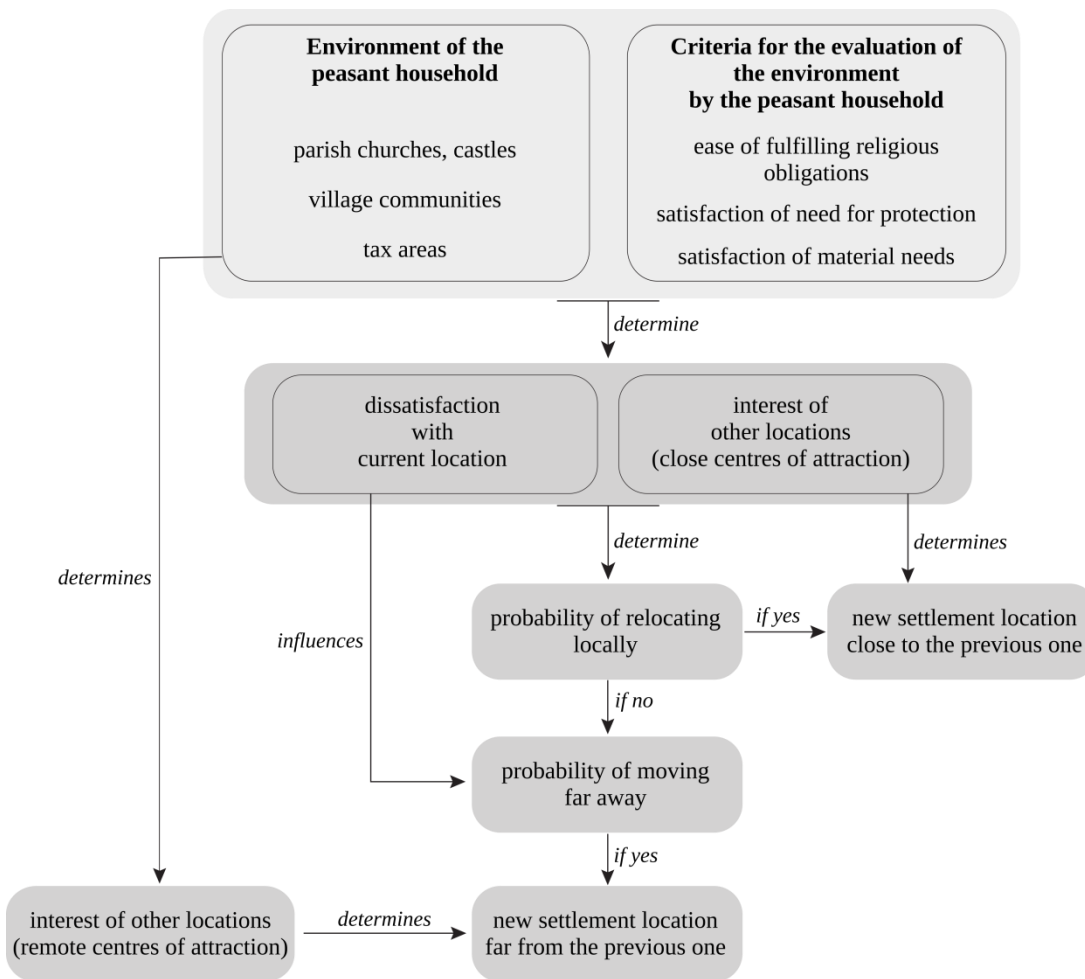
215 2.5 Rules of behaviour for peasant households

The relocation of a peasant household depends on both its dissatisfaction with respect to its current location (“push” factor) and the attractiveness of other possible locations (“pull” factor) (Figure 2). This distinction between “push” and “pull” factors is classically found in residential migration models (Ben-Akiva & de Palma 1986; Pellegrini & Fotheringham 2002). If a peasant household is satisfied with its current location, it can still move if another location is especially attractive.

220 Contrarily, if a peasant household is highly dissatisfied with its current location, it can still stay when no other location is especially attractive. Four variables are involved in the evaluation of the overall dissatisfaction level of a peasant household:

- the ease of fulfilling religious obligations, which varies with the distance to the closest parish church,
- the satisfaction of the need for protection, which varies with the distance to the closest castle and the intensity of the need for protection,
- the satisfaction of material needs, which varies with the amount of fees paid to the lords and the power of the village communities,
- the fact that a peasant household belongs to a village community or not.

230 **Figure 2.** Relocation process of a peasant household.



235 A variable number of peasant households disappear and appear in the course of simulation. Thus we represent the fact that some peasant households can enter or exit the region under study, or have no descendants. Those that appear are placed in a population cluster chosen by a probabilistic lottery weighted by the number of peasant households in each cluster.

Although possible variations in agricultural productivity between 800 and 1200 might be expected to have a significant influence on how the material needs of peasant households were met, food resources do not figure as an independent variable in the model. Among short-term variations, crop

240 failures due to bad weather were frequent, and they occurred every six or seven years in average
during the 8th and 9th centuries. They often resulted in famines, but they seem to have become rare,
or even to have disappeared, after the 9th century (Devroey 2009). Given the time span covered by
a single simulation step in *SimFeodal* (20 years) and the time span of a full simulation (400 years),
245 annual variations in agricultural productivity did not seem relevant to the model. In the long-term,
from 800 to 1200, the question of agricultural yields is difficult to address because of the scarcity of
quantifiable data during this period. The problem of agricultural intensification is closely related to
that of demographic growth, and the two are presented as alternative primary explanatory factors in
most studies of socio-economic change. While historians and archaeologists adopting a neo-
Malthusian approach consider that population growth is limited by the availability of food resources,
250 those favouring Boserupian theory believe conversely that population pressure brings about the
intensification of food production, but the two factors are difficult to disentangle for past societies
(Chamberlain 2006, 4-5). While there is no doubt that both agricultural production and population
size increased significantly between 800 and 1200, there have been many debates about the timeline
and the magnitude of this economic and demographic growth. The renewal of archaeological
255 documentation over the past 30 years and the development of environmental studies have called into
question earlier assumptions relying on the historical record. Because documentary evidence is poorly
preserved until the 11th century (Geary 1994) and because archaeological evidence for early medieval
settlements is so much less conspicuous than the material remains from Antiquity or from later Middle
Ages, it was long assumed that both population and economy were drastically downsized during the
260 Post-Roman centuries, and that this regression was followed by a dramatic surge of both during the
11th century, when there is a spectacular increase in the surviving historical records (Fossier 1982).
The development of large-scale excavations and surveys through contract archaeology revealed an
unexpected density of early medieval settlements, most of them short-lived (a few centuries,
sometimes less), some featuring commodities (fine ware, metal-work...) suggesting a well-to-do
265 population with far-reaching connections. The discovery of numerous storage-pits in these
settlements, and the increase in storage capacity in the 9th and 10th century, points to the stocking of
larger agricultural surpluses, even if it is seldom possible to give quantified estimates (Vigil-Escalera,
2013; Lauwers & Schneider 2020). These findings, together with a reconsideration of the scarce
historical record of the period, have entailed a reappraisal of the previous pessimistic view of the
270 period. Current work suggests instead that the progressive growth of medieval agricultural
productivity can be traced back as early as the 8th or 9th century (Devroey 2003; Toubert 2004; Leturcq
& Mazel 2021).

2.6 Identification of population clusters

275 A population cluster is defined as a set of at least five peasant households. It gathers peasant
households and focal points (parish churches, castles, and village communities) distant from one
another of less than 100 m. Population clusters are identified and delineated at the end of each
simulation step according to the following process. First, the convex hull of each cluster is created
and then enlarged by a given distance (100 m by default). Enlarged clusters that intersect each others
280 are then merged and the final list of population clusters is thus obtained. Peasant households that do
not belong to a population cluster are considered as being dispersed.

2.7 Comments

285 The dynamics modelled in *SimFeodal* refer to changes in the social positions of the agents (e.g.
increase in the rights held by some lords) or their spatial positions (e.g. relocations of peasant
households). Agents interact through spatial neighbourhoods. For instance, the interactions between
lords and peasant households occur through the tax areas: arrivals and departures of peasant

households in the territory controlled by a lord modify his power and, consequently, his chances of building a castle.

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Several scholars have discussed the trade-offs between the realism of models and their generality, and their implications for archaeological applications (Lake 2015). Classically, the distinction is made between KISS (*Keep It Simple Stupid*) models that simulate the emergence of stylised facts on the basis of very simple agent behaviours which may be very far removed from reality (Axelrod 1997), and KIDS (*Keep It Descriptive Stupid*) models that focus more on empirical mechanisms and represent as simply as possible agent behaviours observed in the real world (Edmonds & Moss 2005). Mechanisms in *SimFeodal* are hardly realistic because the behaviours of the agents (peasant households, lords and parishes from 800 to 1200) are not fully known. Consequently, *SimFeodal* combines both KISS and KIDS mechanisms as recommended by Edmonds & Moss (2005). The case of the catchment areas of parish churches is illustrative. Catchment areas are represented by Thiessen polygons resulting from Voronoi tessellation. Such a mechanism does not correspond to the empirical reality around 800 because peasant households might attend one or more churches once or twice a year and the churches attended could be located anywhere, close to or far from the location of the household's farm, and might or might not have parochial rights. So the Voronoi tessellation for this period is a KISS mechanism. Around 1200, by contrast, peasant households fulfilled their (numerous) religious obligations in the closest parish church. Thus Thiessen polygons provide quite a good representation of the catchment areas of parish churches that have been found empirically (Zadora-Rio 2008) and it is a KIDS mechanism.

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In agent-based modelling, it is possible to distinguish weak emergence – where the macroscopic structures resulting from microscopic behaviours can be observed by an external observer identifying a particular regularity in the process observed – from strong emergence – where the microscopic entities themselves observe the macroscopic structures they have produced and adapt their behaviours accordingly (Livet et al. 2010). In *SimFeodal*, emergence is strong because peasant households consider the drawing power of poles of attraction: when they are ready to move, they “observe” (compare) the attractiveness of poles (either locally or region-wide) in order to choose their new location. In general, social systems are characterised by strong emergence. Individuals participate in creating collective references that refer to the social group or to the place to which they belong (weak emergence). In turn, the adoption (or not) of these collective references by the group or the individual influences its behaviour (strong emergence) (Tannier et al. 2016). In *SimFeodal*, peasant household's knowledge of the drawing power of centres of attraction is a collective reference in the sense that it is the same for all peasant households in the region modelled. This collective reference influences in turn the individual behaviour of each peasant household. It evolves in the course of simulation. It does not directly influence the behaviours of the lords and the parishes but it arises from their actions, namely the creation of castles and new parishes. In turn, those creations depend on the location choices of peasant households.

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3. Setting default values for *SimFeodal* parameters on the basis of the diocese of Tours (France)

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Here we look to fix a basic set of parameter values with which simulation results approach a series of quantitative and qualitative objectives. The scenario simulated with this basic set of parameter values must represent a plausible past, which should be as realistic as possible. In no case, however, do we expect to reproduce the *real* past situation, for two main reasons. First, *SimFeodal* is a purely exploratory model: many aspects of the system being modelled are not known. Consequently, simulations should be used as an exploration of intertwined cause-and-effect processes. They

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should help to facilitate understanding of past changes but they cannot reproduce the past that really occurred. Second, even if the entities of the model correspond to real-world entities, even if the rules of behaviour for the agents are realistic, and even if the simulation results are close to the targeted objectives, this does not mean the modelled scenario is “true”; it only proves it is in principle plausible (Varenne 2010). Indeed, it is possible to simulate a given socio-spatial configuration at a macroscopic level from various sets of microscopic mechanisms, as with equifinality problems (von Bertalanffy 1968; Premo 2010). Thus the capability of a model to reproduce observed facts does not imply that this model is “true” or valid, especially in the case of agent-based models (Amblard et al. 2007), and *a fortiori* in the case of socio-spatial systems characterised by a strong under-determination between processes and morphological laws (Varenne 2016). Knowing this, the basic scenario corresponding to the default values of parameters for *SimFeodal* is considered only as a benchmark for defining other exploratory scenarios in which we vary the value of unknown parameters, especially the total number of peasant households in 800, the growth rate of this number, and the proportion of peasant households relocating only locally (serfs, slaves) (see section 4).

In order to set default values of parameters for *SimFeodal*, our reference case study is the diocese of Tours whose settlement dynamics during the Middle Ages has been the subject of historical and archaeological research over the past 30 years (Galinié & Audinet 1992; Joly 1997; Lorans 1996; Maillard 1998; Nissen Jaubert 2012; Nissen 2014; Zadora-Rio 2008, 2009, 2014). Archaeological evidence from excavations and field surveys has revealed many population clusters (hamlets, villages) in 800 which were short-lived and shifted across the landscape. They became progressively more permanent, and most of those that existed in 1200 have survived to this day. The towns that existed in 800 were enlarged by the addition of new boroughs in the 11th and 12th centuries, and small new towns emerged around castles or rural monasteries.

In order to perform relevant simulations with *SimFeodal*, the study area has to be large enough to enable us to observe the increasing coverage of space with parishes and castles from 800 to 1200. As the former diocese of Tours extended over 5508.4 km², the area of the province of Touraine in the eighteenth-nineteenth century was 7150 km², and the present-day department of Indre-et-Loire covers 6126.7 km², the chosen study area is a square with 79 km sides (6241 km²). The total width of the simulated region is 80 km because a buffer zone of 1 km is removed from the calculation in order to avoid boundary effects. The space is isotropic, without any natural features (relief, rivers, coastlines, etc.). The assumption here is that natural features only influence the spatial distribution of settlement sites in a region but not the global density of sites or their global hierarchy. In addition, no major city, namely here the city of Tours, is represented. Indeed, the attractiveness of a central city for surrounding rural areas and intra-urban location processes is not modelled in *SimFeodal*.

Distinctive characteristics of the diocese of Tours in 800 are introduced via specific values of input parameters, in particular the number of population clusters and parish churches, and the existence of two almost equally powerful overlords (namely, the Counts of Anjou and Blois) (Table 2). The number of castles is set to zero because only lineage castles are represented in *SimFeodal* (their construction begins in the mid-tenth century) but not the large collective enclosures (strongholds, *castra*) that existed in 800. The number of peasant households in each village (about 10) has been extrapolated from archaeological data available for the diocese of Tours (Nissen 2014) and other regions (Zadora-Rio 2009), but it is largely conjectural. No early medieval settlements have been entirely excavated in Touraine, and within the limits of the excavated areas, it was seldom possible to recognize more than 5 or 6 houseplots, rounded up to 10 to make allowance for the unexcavated part of the sites (Nissen 2014). It must be reminded that it is far from straightforward to infer the number of contemporary households from the number of excavated buildings within a settlement. It

is also hardly possible to determine if the remains of two settlements dated to the same general period are strictly contemporary: the trouble with archaeological evidence is that it does not allow us to know for sure whether we are dealing with a large population, or a mobile one (Bintliff & Sbonias 1999; Francovitch, Patterson & Barker 2000; Gandini, Favory & Nuninger 2012). Archaeological evidence does not produce direct information on demographic change, but only proxy-data, generally providing only qualitative or semi-quantitative information about population trends (Chapman 1999). Concerning the small towns in 800, the setting value of 30 peasant households is even more hypothetical: the existence of early medieval small towns is known both through the historical and the archaeological records, but we do not have any data about the number of households they included. Finally, with all these setting values, we assume implicitly that the proportion of dispersed population in 800 is extremely high: 95% of peasant households are located outside any village or town.

In the current state of knowledge, considering the small sample represented by the areas in which excavations and systematic surveys were carried out, and the limited use of archaeological proxies to produce demographic data, we could not rely on archaeological evidence to produce the population estimates that were needed in *SimFeodal*, and we turned instead to the historical record. In general, and in the region of Touraine in particular, demographic data are only recorded from the eighteenth century onwards. One exception is the diocese of Chartres, which borders on the diocese of Tours and for which a thirteenth-century *Pouillé* (1250–1272) provides the number of *parrochiani* (heads of households) for each parish in the diocese. On the basis of this *Pouillé*, Chédeville (1973) determined the percentage of population growth between the mid-thirteenth and early nineteenth centuries (+17%). Thus, we opted to consider the number of inhabitants in the region of Touraine in the early nineteenth century to which we applied the percentage of population growth calculated by Chédeville (1973) for the diocese of Chartres. At the beginning of the nineteenth century, the province of Touraine had 253,589 inhabitants excluding the city of Tours, which had 21,703 inhabitants (Le Mée 1989). Applying the differential percentage of -17% gives 216,743 inhabitants in the mid-thirteenth century, which corresponds to around 48,165 peasant households. The area of the province of Touraine in the eighteenth-nineteenth century was 7150 km², which is noticeably larger than the area of the simulated region (6241 km²). Adjusting for the smaller size of the diocese of Tours and assuming a similar population density reduces the estimated number of households to 41,900. Finally, we opted to round the number down to 40,000 households in 1200. By default, we did not make any assumption about demographic change between 800 and 1200, in spite of the fact that population growth is often considered as a primary explanatory factor for the increasing hierarchy of regional settlement systems in the period under consideration (Fossier 1982). The default value for the number of peasant households in 800 (Table 2) is thus the same as the estimated number in 1200, *i. e.* 40.000. This is a very strong hypothesis, supported by the lack of quantitative data (see above), and we seek to test it with *SimFeodal* in the next section of the paper.

Table 2. Default values of input parameters set for the Tours diocese in 800. ⁺: speculative estimate. *: estimate based on the sources available for the diocese of Tours (Zadora-Rio 2008).

Title	Value
Peasant households	
Number of peasant households in the modelled region	40 000 ⁺
Population clusters	
Number of Roman small towns	8*
Number of peasant households within each small town	30 ⁺
Number of villages	20 ⁺
Number of peasant households within each village	10 ⁺
Lords	
Number of overlords	2*
Relative power of the overlords (sum equal to 1)	0.5 0.5
Number of small lords	18 ⁺
Churches	
Total number of churches	150*
Number of parish churches	50*
Castles	
Number of castles	0*

430

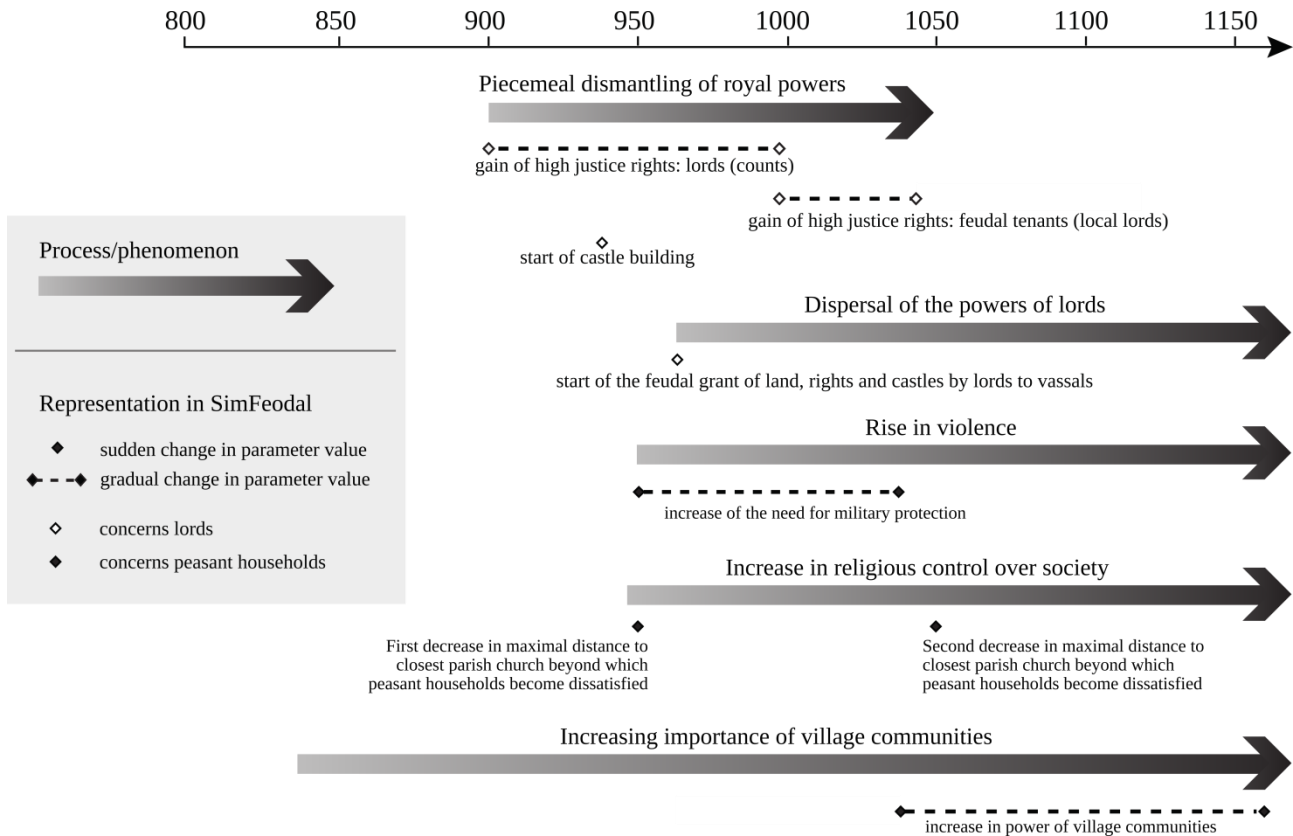
Contextual parameters corresponding to historical postulates are listed in Table 3. Many of them represent the major political and social changes during the time period in question (Figure 3). Some contextual parameters are specific to the region under study, e.g. the power of village communities, which is considered to be rather low in the diocese of Tours (Bourin & Durand 1984).

435

Table 3. Values of contextual parameters set for the diocese of Tours.

Title	Value
Peasant households	
Growth rate of the number of peasant households at each simulation step	0%
Percentage of peasant households that appear and disappear at each simulation step	0.05 (5%)
Proportion of peasant households that can only relocate locally (serfs, slaves)	0.2 (20%)
Intensity of the need of protection	0 between 800 and 940 0.2 in 960 0.4 in 980, 0.6 in 1000 0.8 in 1020 1 since 1040
Distance to the closest parish church beyond which a peasant household is not fully satisfied.	5 km before 950 3 km from 950 to 1050 1.5 km after 1050
Distance to the closest parish church beyond which a peasant household is absolutely dissatisfied.	25 km before 950 10 km from 950 to 1050 5 km after 1050
Distance to the closest castle beyond which a peasant household is not fully satisfied.	1.5 km
Distance to the closest castle beyond which a peasant household is absolutely dissatisfied.	5 km
Population clusters	
Power of village communities in the modelled region	0.2 until 1040 0.3 in 1060 and 1080 0.4 in 1100, 1120 and 1140 0.5 in 1160, 1180 and 1200
For each population cluster, probability that a village community is set up as an institution at each step of simulation	0.2
Lords	
Targeted total number of lords (overlords and other lords) at the end of a simulation	200
Probability of an overlord gaining high justice rights at each simulation step	0 before 900 0.2 between 900 and 980 1 since 1000
When a small lord builds a new castle, probability of creating a tax area for high justice rights around this castle and all his other castles (existing or future)	0 before 1000 0.2 since 1000
Date from which lords begin to pass rights on to their vassals	880
Date from which lords can give castles to their vassals	960
Castles	
Date from which castles can be built by lords	940
Time period during which castles can become major castles	from 940 to 1040 included

440 **Figure 3.** Major political and social changes between 800 and 1200 and their representation in *SimFeodal*.



Other parameters determine the agents' endogenous behaviour (see Appendices A and B). Their values are not likely to be modified for each specific regional context but they can be modified to explore their effect on the model's dynamics. Among these parameters, technical parameters are purely mechanical parameters with no empirical basis. Parameters whose empirical values are unknown are very numerous. Some can be estimated with varying degrees of precision from archaeological records and historical texts: the distance thresholds to the closest parish church and to the closest castle, the minimum distance between castles, the probability of a castle becoming a major castle when sited in or close to a pole, the maximum distance between peasant households or focal points beyond which they do not belong to the same cluster, and the minimum number of peasant households required to create a population cluster. The values of the other parameters were initially set approximately and then adjusted step by step with respect to the simulation results. A model can be calibrated against a "stylised fact" (i.e. a broad generalisation of an empirical pattern) or empirical data (Davies & Romanowska 2018). We mixed these two possibilities in calibrating *SimFeodal*. Two stylised facts are considered: the increasing coverage of space with parishes and castles, and the emergence of an enduring hierarchical settlement pattern around the castles and the parish churches. Over time, the number of population clusters should rise and their sizes should differ increasingly. Besides these qualitative objectives, we set some global quantitative objectives that should be achieved at the end of a simulation (Table 4). The targeted total number of lords at the end of the simulation was chosen to represent a proliferation: lords are 10 times more numerous in 1200 than in 800 and four times more numerous than the final number of castles (Boussard 1962; Guillot 1972). Mechanisms determining the number of lords as well as the number of castles and major castles built at each simulation step were parameterised to necessarily reach the target values. Consequently, these numbers at the end of the simulation are considered only for the internal verification of the model, i.e. checking conformity between the model specifications and the

computer program implemented (Amblard et al. 2007). Furthermore, we assessed the consistency of agents' behaviours in the course of the simulation via the observation of step-by-step changes in a series of variables: proportion of households relocating, types of migrations undertaken by peasant households (local or distant; towards a population cluster or not, etc.), number of castles built by each type of lord, etc. The objective was to detect possible contradictions in simulated behaviours (e.g. too many or too few relocations of peasant households or illogical alternation of rises and falls in the value of a variable).

Table 4. Targeted quantitative objectives set to calibrate the model.

Variable	Value expected in 1200
Number of population clusters	[200–250]
Number of castles	50*
Number of major castles	[10; 15]*
Number of parishes	[200; 300]**
Number of lords	200

* Sources: (Zadora-Rio 2014-4; Zadora-Rio 2014-5).

** Source: (Zadora-Rio 2008, p. 31).

Table 5. Values of variables in 1200 obtained by simulation with the basic parameter configuration of *SimFeodal* (parameter default values).

Variable	Mean	Median	1st quartile	3rd quartile
Number of population clusters	249	250	243	253
Number of castles	50	49	47	54
Number of major castles	16	16	16	18
Number of parishes	340	338	333	348
Number of lords	202	204	196	208

Figure 4. Change in the number of population clusters over time (mean and 1st and 3rd quartiles). Results obtained with the basic parameter configuration (parameter default values).

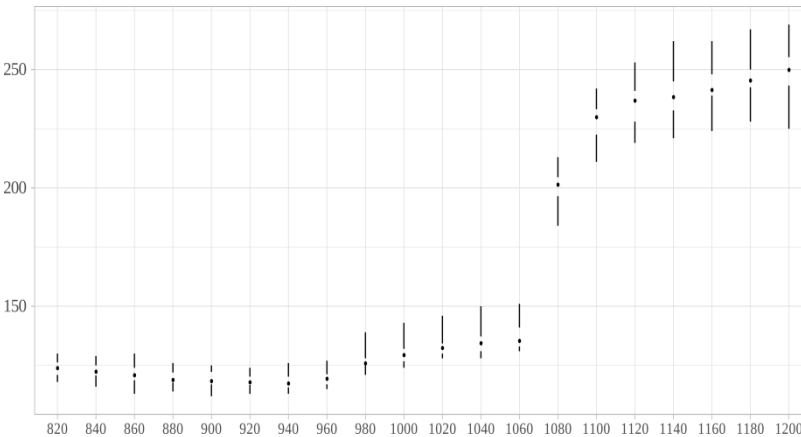
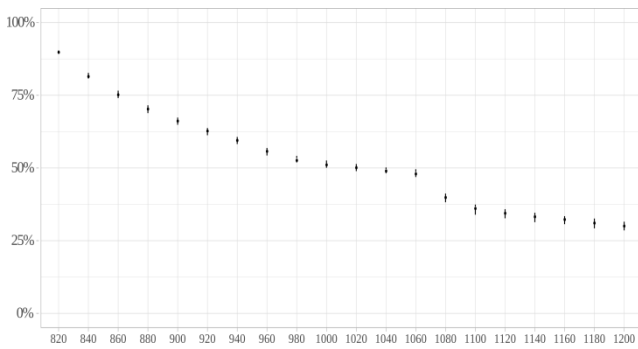
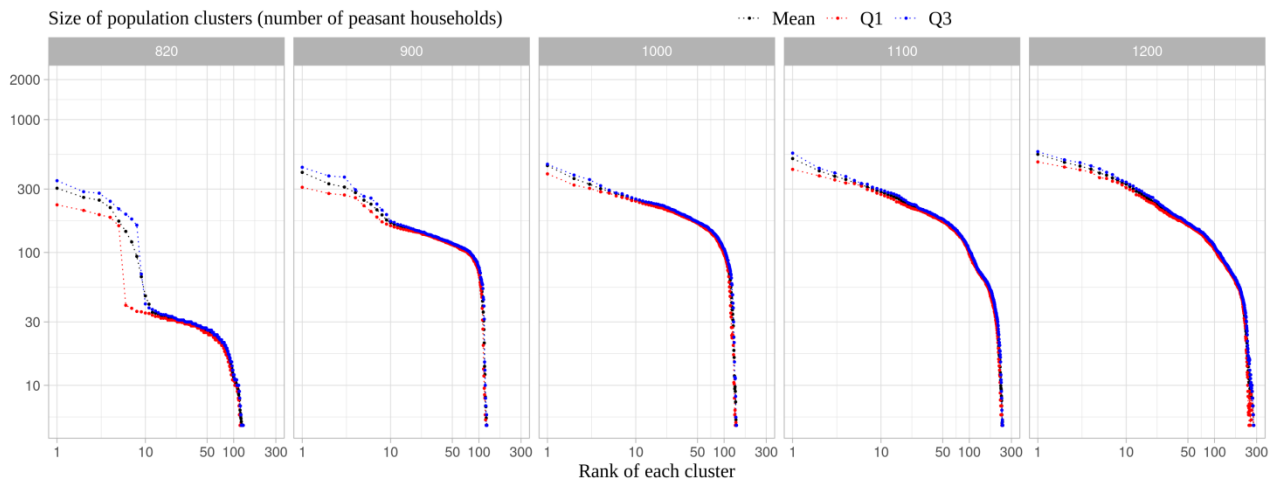


Figure 5. Change in the proportion of dispersed households over time (mean and 1st and 3rd quartiles). Results obtained with the basic parameter configuration (parameter default values).



490 **Figure 6.** Rank-size distributions of population clusters obtained with the basic parameter configuration (parameter default values) at five dates.



495 Simulation results obtained with the set of parameter default values finally chosen are presented in Table 5 and Figures 4, 5 and 6. *SimFeodal* involves a series of random draws, e.g. to determine whether a peasant household relocates locally or a long-distance away, or to determine whether a castle becomes a major castle, or even to determine whether a parish church is to be built within a population cluster. Consequently, for multiple simulations of the same scenario (i.e. a given set of parameter values), simulation results may vary. Considering this, the simulation results provided take into account 20 computation replications. Simulated values obtained in 1200 with the basic configuration of parameters (Table 5) are close to the quantitative objectives set in Table 4. Only the number of parishes is higher. The number of population clusters starts increasing from 980. Then the increase accelerates from 1080 (Figure 4). The proportion of dispersed households falls steadily over time to 30% (Figure 5). Finally, rank-size distributions of population clusters display an increasing hierarchy of the settlement pattern (Figure 6).

505 From 1080–1100, the shape of the rank-size distribution becomes convex because medium and large clusters have increased more than small clusters. From 800 to 1000, the number of clusters varies little whereas cluster size changes considerably. The smallest clusters grow slightly: ranging from 5 to 25 peasant households in 820, from 5 to 100 peasant households in 900, and from 5 to 150 peasant households in 1000. The intermediate clusters grow considerably. The biggest clusters grow slightly but regularly from around 250 peasant households in 820 to around 400 to 550 peasant households in 1200. Their size range is wider in 1200 than in 820. Besides, we confirmed visually (on the maps displayed on a graphics monitor in the *SimFeodal* software application - see Appendix C) that each of the eight small towns existing in 800 becomes a medium-sized or a large population cluster in the course of simulation.

4. Fourteen scenarios for better understanding the conditions for the emergence of enduring hierarchical settlement patterns

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This section reports on computer simulations performed to explore how varying the values of some key parameters, e. g. the number of peasant households in 800, the growth rate of this number, and the proportion of peasant households relocating only locally (serfs, slaves), can change simulated settlement patterns. The aim is to identify the factors affecting hierarchy and concentration and to understand how they act on the spatial dynamics of the settlement system. The quantitative objectives to be attained at the end of a simulation are set in Table 4. Nonetheless, we have no empirical data about the precise number of population clusters, the number of inhabitants in each cluster, and the proportion of dispersed peasant households. Considering these variables, simulation results can be for comparative purposes only but they should provide a better understanding of their explanatory factors.

525

530

We selected a series of 14 scenarios in which we varied the values of key parameters (Table 6). Each parameter is tested independently of the others knowing that the combined actions of parameters on the changes in the settlement pattern are to be explored later. As previously explained, the basic scenario corresponding to the parameter default values for *SimFeodal* is a benchmark for comparing all scenarios. From now on this basic scenario is referred to as “scenario α ”. The parameters tested were chosen on the assumption that they exert a noticeable influence on the settlement pattern. Simulation results should confirm or invalidate this. The values tested are considered plausible.

535

540

Table 6. Description of the scenarios.

	Parameter tested	Value(s) changed with respect to scenario α	Scenario title
Input parameters	Total number of peasant households in 800	30 000 50 000	A1 A2
	Number of peasant households in each village in 800	5 15	B1 B2
	Number of peasant households in each small town in 800	20 40 100	C1 C2 C3
Contextual parameters	Growth rate of the number of peasant households	3.72% starting from 20 000 peasant households in 800 12.89% starting from 4 000 peasant households in 800 14.22% starting from 4 000 peasant households in 800	D1 D2 D3
	Proportion of peasant households only relocating locally (serfs, slaves)	0% 40%	E1 E2
	Power of village communities	0.25 throughout the period	F
Mechanism parameter	Radius of the local relocation of peasant households	2.5 km from 800 to 880; 4 km from 900 to 980; 6 km from 1000	G

- For scenario A, the hypothesis is that the more peasant households there are the greater the size difference of population clusters. The values tested are within the estimated uncertainty range of the default value (i.e. 40,000 peasant households).
- 545 • For scenarios B, the hypothesis is that larger villages in 800 produce larger population clusters over the simulation period. The values tested are within the estimated uncertainty range of the default value (i.e. villages in 800 have 10 peasant households).
- For scenarios C, the hypothesis is that larger small towns in 800 make for the biggest population clusters being even larger. Two of the values tested (20 and 40 peasant households in the small towns in 800) are within the estimated uncertainty range of the default value (i.e. 10 peasant households). The third value tested (100 peasant households in the small towns in 800) represents the possibility that small towns inherited from Antiquity were much larger than supposed from archaeological sources.
- 550
- For scenarios D, the hypothesis is that demographic growth is the primary cause of the increasing hierarchy of regional settlement systems during the Middle Ages. A first scenario represents a doubling of the population from 800 to 1200: starting from 20,000 peasant households in 800, a growth rate of 3.72% yields 40,000 households in 1200 (value of scenario α). The other two scenarios begin with 4000 households in 800, a value which represents a severely downsized population. A growth rate of 12.89% was chosen so as to reach 40,000 households in 1200 (value of scenario α) and 14.22% was chosen so as to reach 50,000 households in 1200 (value of scenario A2).
- 555
- 560
- For scenarios E, the hypothesis is that the hierarchy of the settlement system is stronger when the proportion of peasant households relocating locally only is low. Indeed, if many peasant households can undertake long-distance migrations, this may favour their concentration in the largest population clusters because they are more attractive than the smallest clusters. The values tested for the proportion of peasant households relocating only locally (0% and 40%) diverge widely from the default value (20%) because the proportion of peasant households so highly dependent on their lord that they cannot leave his estate (serfs, slaves) is completely unknown and much debated (Corriol 2010; Feller 2007).
- 565
- For scenario F, the hypothesis is that the more powerful the village communities the more concentrated the settlement system. By default, the power of village communities increases over the course of simulation. In scenario F, the value remains low throughout the period under consideration.
- 570
- For scenario G, the hypothesis is that increasing the radius within which peasant households may relocate locally promotes their concentration in large population clusters. In this scenario, the largest population clusters should be even larger by 1200.
- 575

It is important to note that this experiment does not come within the scope of a sensitivity analysis, in which *all* uncertain parameter values are tested to understand their effects on the simulation results. Moreover, the parameter values tested may or may not be close to their default values. The sensitivity analysis of the *SimFeodal* model has been undertaken in the PhD thesis of Cura (2020). Since the model has numerous parameters, about 70 (see Table 3, and Appendix A and B), a factorial design study of five tested values for each parameter would require to run $5^{70} \times 20$ [replications], thus about 10^{50} simulations. Various methods have been developed to avoid such a combinatorial explosion (see e. g. Chérel et al. 2015; Montgomery 2009; Schmitt et al. 2015). All these methods require to set a few number of quantitative output assessment indexes. Yet targeted quantitative objectives set to calibrate *SimFeodal* are fuzzy (see Table 4). Moreover, other crucial output results are qualitative; many of them result from the observation of the global shape

of curves (see Figures 4, 5, and 6). For those reasons, the sensitivity analysis of the *SimFeodal* model was based on the OFAT (One Factor at A Time) protocol.

Results of the sensitivity analysis helped us to select and parameterise the 14 scenarios tested here. The simulation results are displayed in Tables 7–9 and Figures 7–13. Prior to their analysis, we checked for the number of lords, the number of castles and the number of major castles. We also confirmed that the variability of the results was weak enough by looking at the 1st and 3rd quartiles of the simulated values and their standard error for each set of 20 replications. Two variables, namely the number of population clusters and the proportion of dispersed peasant households, inform us about the concentration of the simulated settlement patterns (Table 7). The hierarchy of the simulated settlement patterns is analysed through the observation of the distribution of population clusters by class of size (Table 8 and Figure 7), the size of the four biggest population clusters (Table 9) and the rank-size distribution of population clusters (Figures 8–13). In the case of Table 9, the standard errors of the mean are often very high. Consequently, only the general trend of the results can be considered but not the precise number of peasant households in each population cluster.

We first observe that the effect of the tested changes in parameter values is negligible in the case of the size of villages and small towns in 800 (scenarios B1, B2, C1, C2, C3), the proportion of peasant households moving only locally (scenarios E1, E2), and the power of village communities (scenario F).

Table 7. Mean values (and standard error of the mean in brackets) of variables in 1200 obtained by simulation for 20 computation replications of each scenario. *: number of peasant households per km². Grey cells: variable values that differ noticeably from the values in scenario α . Note: mechanisms determining the total number of peasant households as well as the population density were parameterised to necessarily reach the target values.

	SCENARIOS														
	α	A1	A2	B1	B2	C1	C2	C3	D1	D2	D3	E1	E2	F	G
Number of population clusters	249 [2.3]	231 [2.3]	262 [3.2]	241 [2.3]	245 [2.4]	248 [2.2]	248 [2.1]	245 [2.3]	226 [2.6]	198 [1.9]	213 [1.9]	241 [1.8]	246 [2.6]	250 [2.4]	217 [2.4]
Number of parishes	348 [2.9]	302 [3.5]	374 [3.0]	340 [2.7]	336 [2.3]	337 [2.1]	334 [3.0]	338 [3.6]	307 [3.0]	252 [3.2]	277 [2.1]	336 [3.5]	331 [2.7]	345 [4.0]	333 [2.8]
Percentage of dispersed households	30 [0.2]	32 [0.2]	29 [0.2]	31 [0.2]	30 [0.2]	30 [0.2]	30 [0.2]	30 [0.2]	27 [0.2]	21 [0.2]	19 [0.2]	28 [0.2]	33 [0.3]	30 [0.2]	4 [0.1]
Population density *	6.25	4.69	7.81	6.25	6.25	6.25	6.25	6.25	6.26	6.26	7.82	6.25	6.25	6.25	6.25
Total number of peasant households	40000	30000	50000	40000	40000	40000	40000	40000	40033	40042	50028	40000	40000	40000	40000

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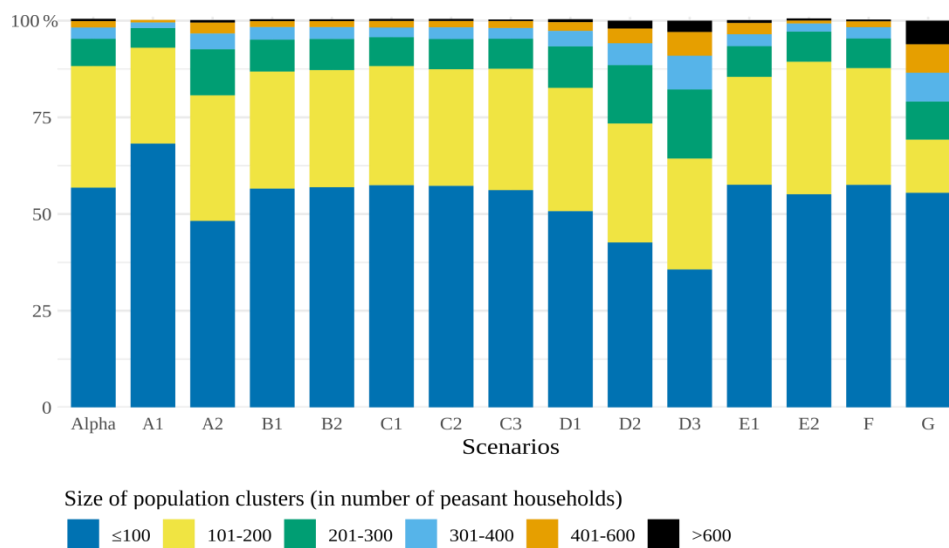
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Table 8. Mean number (and standard error of the mean in brackets) of population clusters classified by size (in number of peasant households) in 1200 for 20 computation replications of each scenario. Grey cells: variable values that differ noticeably from the values in scenario α . Small differences with the total number of population clusters displayed in Table 7 result from rounding the numbers.

	SCENARIOS														
	α	A1	A2	B1	B2	C1	C2	C3	D1	D2	D3	E1	E2	F	G
≤ 100	142 [2.6]	158 [2.7]	127 [3.5]	137 [2.5]	140 [3.0]	143 [2.8]	142 [2.4]	138 [2.7]	115 [2.6]	85 [2.0]	76 [2.5]	139 [2.0]	136 [2.9]	144 [3.4]	121 [2.7]
101-200	78 [1.8]	57 [1.1]	85 [1.7]	73 [1.5]	74 [1.7]	76 [1.4]	75 [1.5]	77 [1.5]	72 [1.3]	61 [1.8]	61 [1.5]	67 [1.7]	84 [1.4]	75 [1.8]	30 [1.6]
201-300	18 [1.0]	12 [0.7]	31 [0.8]	20 [0.7]	20 [1.0]	19 [0.8]	19 [0.7]	19 [1.0]	24 [0.9]	30 [1.0]	38 [1.3]	19 [1.0]	19 [0.8]	19 [0.9]	21 [0.9]
301-400	7 [0.5]	3 [0.2]	11 [0.5]	8 [0.5]	8 [0.6]	6 [0.6]	8 [0.5]	7 [0.6]	9 [0.7]	11 [0.6]	19 [1.0]	7 [0.5]	5 [0.4]	7 [0.5]	16 [1.2]
401-600	4 [0.3]	2 [0.2]	7 [0.4]	4 [0.4]	4 [0.3]	4 [0.3]	4 [0.4]	4 [0.3]	5 [0.3]	8 [0.4]	13 [0.6]	7 [0.6]	2 [0.2]	4 [0.4]	16 [0.9]
> 600	2 [0.3]	0 [0.0]	2 [0.2]	1 [0.3]	1 [0.2]	1 [0.2]	1 [0.3]	1 [0.0]	2 [0.3]	4 [0.3]	6 [0.5]	2 [0.2]	1 [0.3]	1 [0.1]	13 [0.6]

625

Figure 7. Mean percentage of population clusters classified by size (in number of peasant households) in 1200 for 20 computation replications of each scenario. Standard errors of the mean are comprised between zero and one percent.



630 **Table 9.** Size of the four biggest population clusters (in number of peasant households) in 1200. Mean size and standard error of the mean of 20 computation replications of each scenario. Grey cells: variable values that differ noticeably from the values in scenario α .

Scenario	Cluster rank							
	1		2		3		4	
	Mean	s.e.	Mean	s.e.	Mean	s.e.	Mean	s.e.
α	548	21	478	14	447	8	423	7
A1	441	13	382	9	345	8	322	6
A2	702	32	580	14	547	13	503	9
B1	588	25	489	18	449	16	414	10
B2	582	32	501	15	445	12	420	10
C1	586	31	510	16	446	6	417	5
C2	544	14	484	12	438	8	409	7
C3	591	33	497	12	464	11	436	9
D1	656	32	543	15	504	15	462	10
D2	884	29	768	25	670	15	611	13
D3	1137	72	894	26	813	24	734	26
E1	722	35	605	19	530	14	492	9
E2	515	21	429	18	378	5	353	5
F	564	24	492	16	444	10	411	8
G	1380	55	1156	35	1087	35	987	31

635 Simulated changes in the total number of peasant households in the study area (scenarios A1 and A2) exert a small but non-negligible effect. In scenario A1, the number of small population clusters (with fewer than 100 peasant households) in 1200 is slightly higher than in scenario α and the largest clusters are noticeably smaller (Table 8). By contrast, in scenario A2, the number of small clusters is slightly lower, the number of medium-sized clusters is slightly higher, and the largest clusters are noticeably larger. Nevertheless, the overall shape of the rank-size distributions of population clusters at five points in time is the same for the three scenarios (A1, A2 and α -
640 Figures 6, 8 and 9).

Figure 8. Rank-size distributions of population clusters obtained with scenario A1 at five dates.

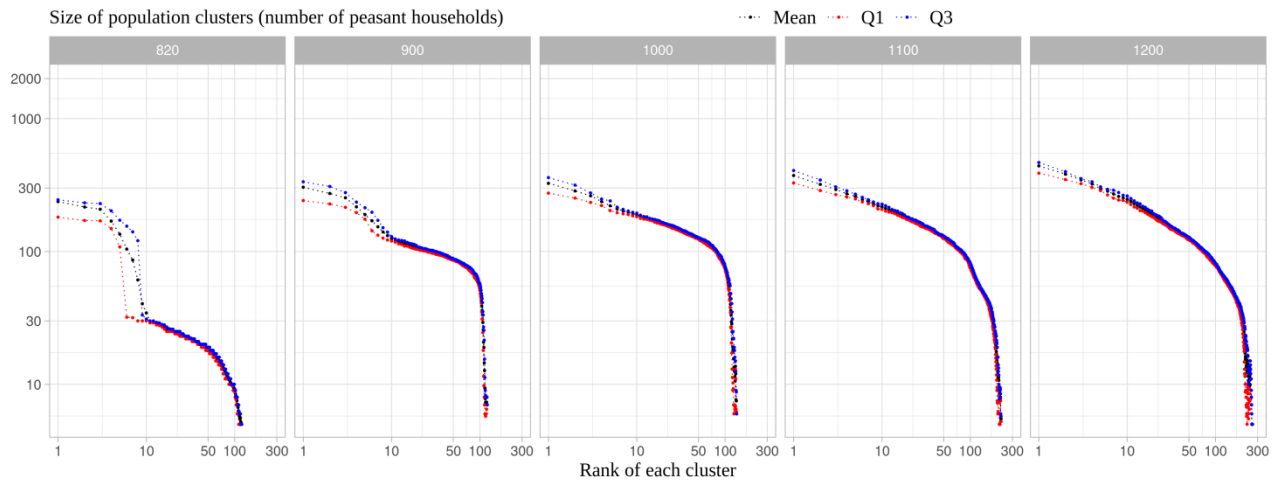
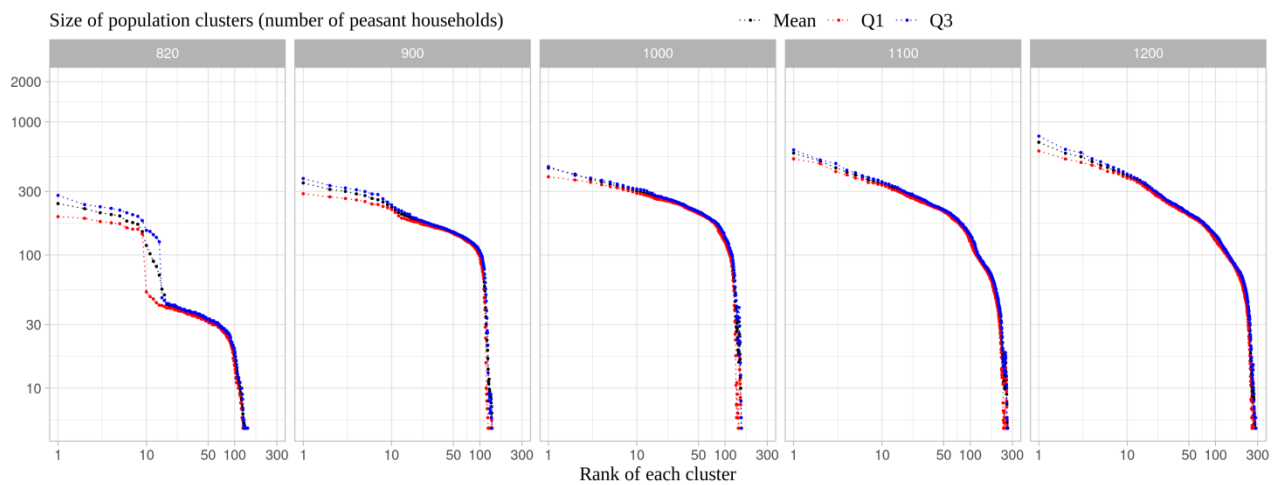
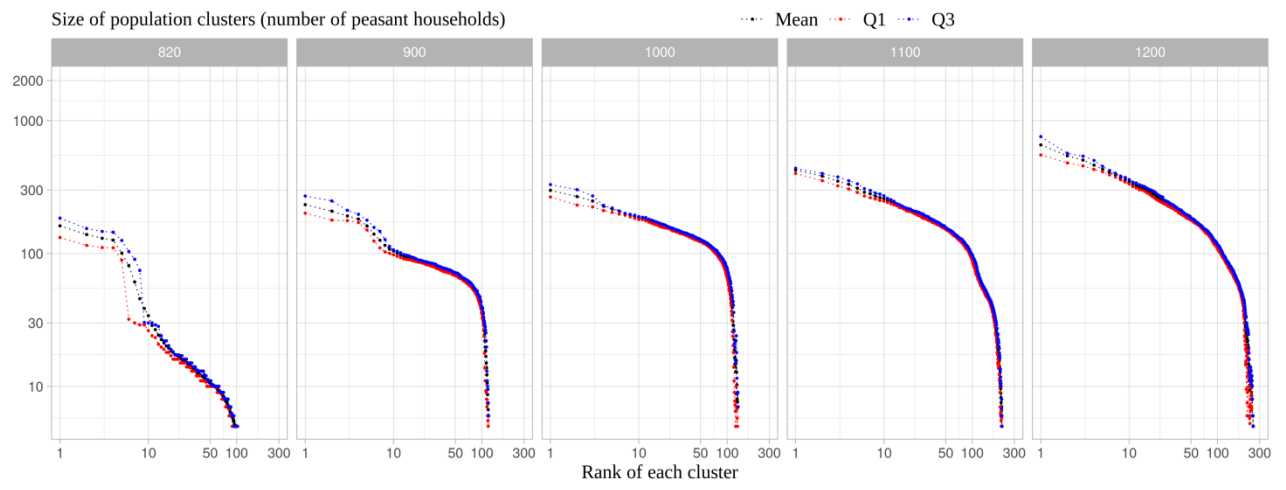


Figure 9. Rank-size distributions of population clusters obtained with scenario A2 at five dates.



645 Introducing demographic growth (scenarios D1, D2 and D3) greatly increases the concentration
 and the hierarchy of the settlement pattern over time. For these scenarios, the number of population
 clusters and the proportion of dispersed households in 1200 are lower than for scenario α .
 Moreover, settlement patterns simulated with scenarios D1 and D2 have fewer small clusters and
 more medium and large clusters in 1200 than in scenario α whereas scenario D3 has fewer small
 650 clusters and more medium and large clusters in 1200 than in scenario A2. The number of population
 clusters in 1200 depends on both the initial number of peasant households in 800 and the intensity
 of demographic growth. By contrast, the hierarchy of the simulated settlement patterns seems to
 vary with the intensity of demographic growth only. Indeed, we observe that scenario D1 has more
 small clusters and fewer medium and large clusters in 1200 than scenario D2; scenario D2 has more
 small clusters and fewer medium and large clusters in 1200 than scenario D3. We also observe that
 655 the four biggest clusters are smaller in scenario D1 than in scenario D2 and even smaller than in
 scenario D3.

Figure 10. Rank-size distributions of population clusters obtained with scenario D1 at five dates.



660

Figure 11. Rank-size distributions of population clusters obtained with scenario D2 at five dates.

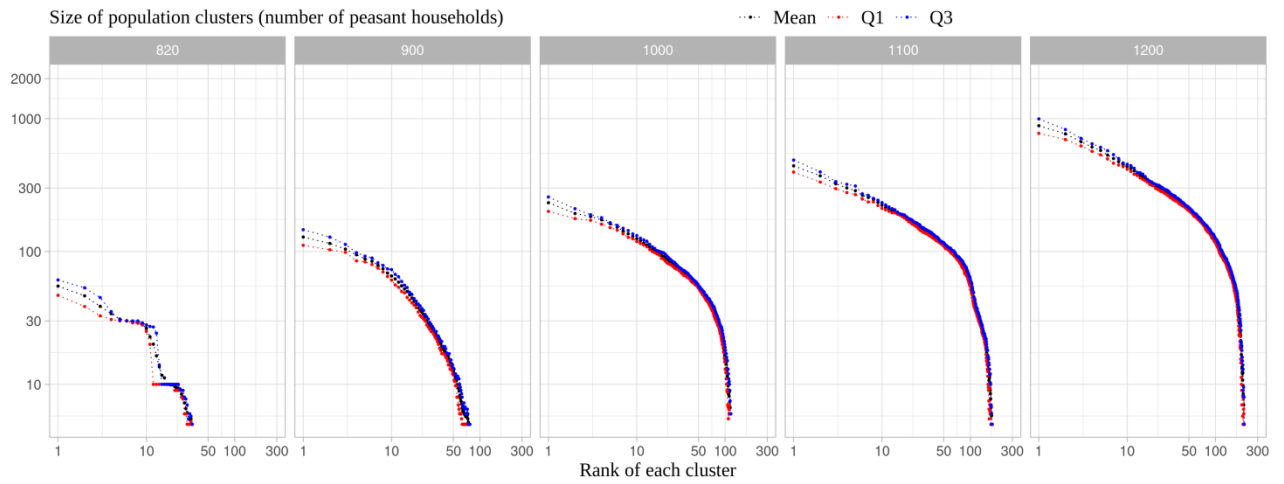
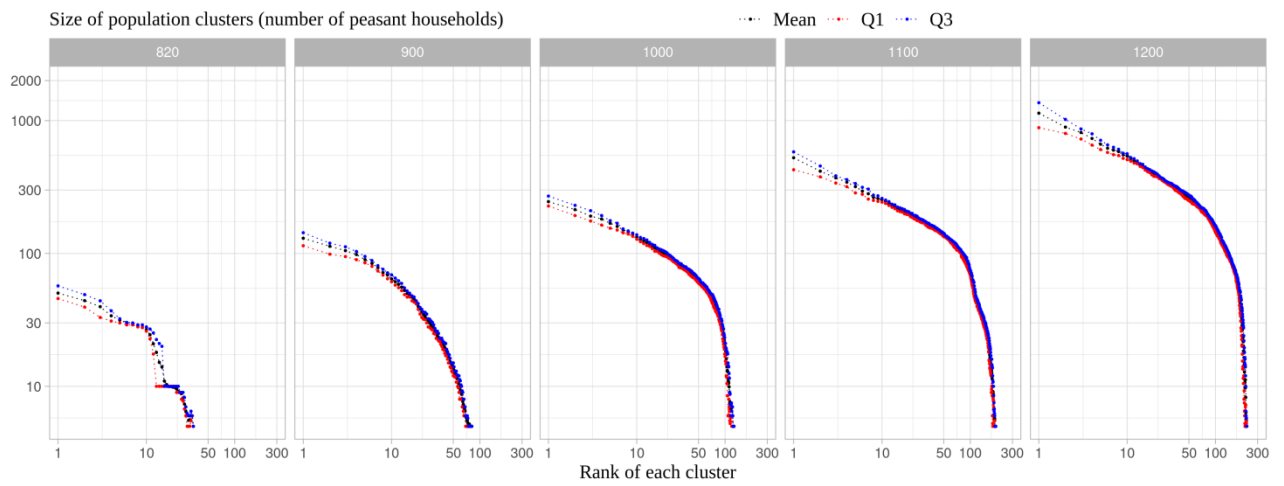
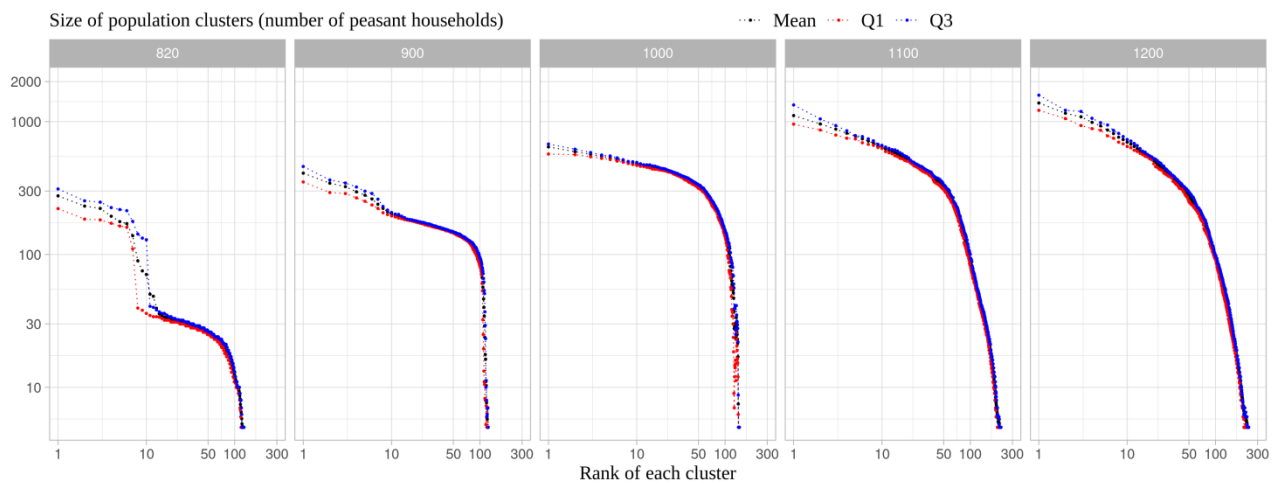


Figure 12. Rank-size distributions of population clusters obtained with scenario D3 at five dates.



665

Figure 13. Rank-size distributions of population clusters obtained with scenario G at five dates.



670 At the very beginning of the simulation, the concentration level (number of population clusters and sizes of the largest clusters) in scenario α is higher than in scenario D1 and, a fortiori, than in scenarios D2 and D3. The difference in population density may explain this phenomenon: when peasant households are closer to each other, they can cluster more easily. Incidentally, at the beginning of the simulation, the density is higher in scenario α than in scenario D1 and, a fortiori, than in D2 and D3. A consequence of this phenomenon, combined with the intensity of demographic growth, is that the settlement pattern hierarchy increases more steadily in scenarios D2 and D3 than in scenario D1 and, a fortiori, than in scenario α (see Figures 10, 11 and 12, and Figure 6).

Figure 14. Proportion of peasant households relocating at each simulation step.



680

Increasing the radius of the local relocation of peasant households strongly favours their concentration: the proportion of scattered households in 1200 is extremely low (4% compared to 30% in scenario α), the number of population clusters in 1200 is also quite low, and the four largest population clusters in 1200 are especially large compared to all other scenarios. The high concentration of peasant households simulated with scenario G is explained by the large proportion of peasant households that relocate locally at each simulation step, in particular after the year 1000 (Figure 14). Interestingly, the proportion of long-distance relocations is not changed from that in scenario α . The shapes of the rank-size distributions of population clusters are roughly similar to those in scenario A2 (Figures 9 and 13). This can be explained by the fact that the number of peasant households is higher in scenario A2 than in scenario G but, as they are more dispersed in the first case, the number of peasant households within population clusters can be equivalent. Nevertheless the distribution of clusters according to their size classes is markedly different for the two scenarios (Figure 7).

695 The number of parish churches created at each simulation step co-varies with the total number of peasant households in the study area according to the mechanisms modelled in *SimFeodal*. Thus

for instance, the number of parish churches in 1200 is almost the same in scenarios G and α . On the contrary, it is lower in scenarios D1, D2 and D3 and falls within the range of values expected from the empirical data (Table 4). Apart from the number of parish churches, their location too may differ widely between scenarios. For example, in scenario G, more parish churches are created within population clusters and fewer parish churches are created outside population clusters than in scenario α . This in turn reinforces the attraction of existing population clusters, which finally increases the concentration and the hierarchy of the simulated settlement pattern.

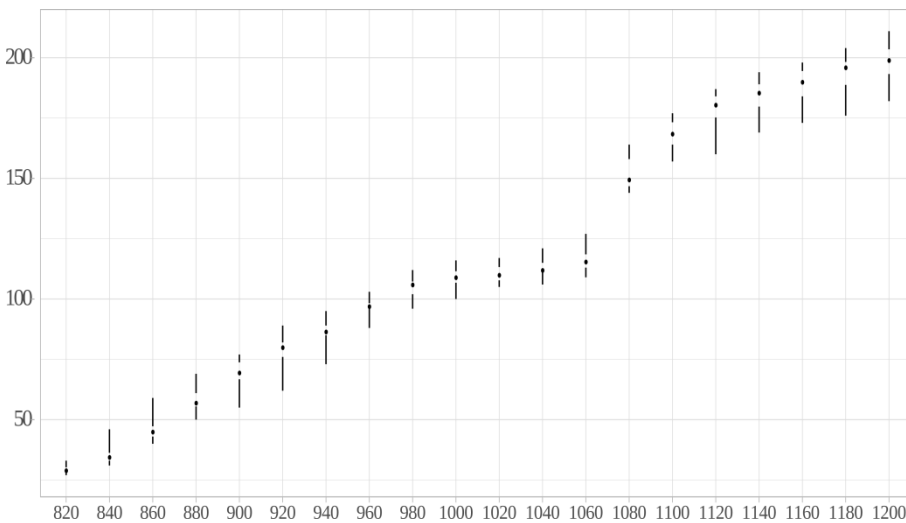
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5. Discussion

In all the simulated scenarios, with or without demographic growth, what is a scattered and non-hierarchical regional settlement pattern in 800 becomes concentrated and hierarchical by 1200. The number of population clusters and their size vary depending on the initial number of peasant households in the study area. When numerous peasant households are present in the study area from the very beginning of the simulation, some population clusters are already large from the first simulation step (year 820) (see Figures 6, 8, 9 and 13) although the rules that incite peasant households to relocate are not very constraining at this time period.

715

Figure 15. Change in the number of population clusters over time (mean and 1st and 3rd quartiles) for scenario D2.



720

When demographic growth is simulated, the settlement pattern hierarchy increases more progressively over time and the final hierarchy reached by 1200 is more regular than that produced without demographic growth. The number of population clusters also increases more steadily as shown for scenario D2 in Figure 15 compared with scenario α in Figure 4. Indeed, cumulative processes and positive feedback loops in *SimFeodal* are only fully expressed if the number of peasant households increases over time. This can be illustrated by the creation of parish churches. If many peasant households are present right from the beginning of the simulation, more churches are created early in the simulation. At this time period, the requirement to be close to a church is weak. Consequently, many churches are created outside any cluster and these creations do not increase the existing concentration and hierarchy of the settlement pattern. Conversely, if few peasant households are present at the beginning of the simulation, few churches are created early

730

on. Then, as a consequence of demographic growth, the number of churches created increases. As the requirement to be close to a church strengthens over time, most churches are created within population clusters. Thus step by step, the creation of new churches increases the existing concentration and hierarchy of the settlement pattern.

In *SimFeodal*, each mechanism does not fully determine the level of concentration and hierarchy of the simulated settlement pattern because it interacts with other mechanisms. For example, one mechanism requires that peasant households appearing in the course of the simulation are placed in a population cluster chosen according to a probabilistic lottery weighted by the number of peasant households in each cluster. In this way, the mechanism favours the concentration of population in existing clusters and peasant households have more chances of being placed in a large cluster than in a small one. This process mainly affects scenarios with demographic growth as more households appear in the course of simulation than in scenarios with no demographic growth. Nevertheless, we observe the emergence of hierarchy and concentration even without demographic growth, which shows that this mechanism is not a crucial determinant of the simulated dynamics.

5.1 Confronting the hierarchy of the simulated settlement patterns in 1200 with empirical knowledge in the field

The hierarchy of urban centres is based on the combination of a series of descriptive criteria to produce a rank-order based on cumulative functions: the presence of a command centre or administration, military facilities, religious facilities, public and private facilities (town hall, bell tower, etc.) and so on. Considering this, we can estimate that the region of Touraine had 12-15 noteworthy population clusters (small towns) in the late Middle Ages (Galinié & Audinet 1992; Joly 1997; Zadora-Rio 2014). If we consider that clusters are noteworthy when they have at least 400 peasant households, only scenario D2 has close to 12 of these biggest clusters. Scenarios D3 and G have too many large clusters and the other scenarios too few. If, however, we consider that the threshold size is 300 peasant households, then scenario α and its variants B1, B2, C1, C2, C3 and F fall in with the empirical estimation of 12 clusters.

The number of inhabitants is considered to have peaked in the thirteenth century in Northern France. Then in the mid-fourteenth century, the Great Plague produced a dramatic demographic collapse. Population growth set in again in the late seventeenth or early-eighteenth century, with the number of inhabitants recovering to the level of the thirteenth century (Biraben 1976). Knowing this, it is possible to set the simulation results against historical and archaeological data for the eighteenth century. According to Maillard (1998), almost half of the parishes in Touraine had fewer than 100 peasant households in the early eighteenth century. Settlement patterns simulated with scenarios A2, D1 and D2 correspond to this empirical situation in 1200. In scenario D3, only 35.7% of population clusters have fewer than 100 households whereas in the other scenarios, the proportion is higher (around 56%). Another point concerns the size of the biggest population clusters reached at the end of the simulation. In 1789, the three biggest towns in Touraine (excluding Tours) numbered 1456 households for Amboise, 1331 households for Chinon, and 1031 households for Loches (Maillard 1998). If we assume that the number of peasant households in each cluster in 1200 cannot be higher than it was in 1789, the largest clusters are in all probability too large in scenario G.

5.2 On the emergence of more or less hierarchical regional settlement patterns

780 A number of scholars have identified different mechanisms that can produce hierarchical site size
distributions in settlement systems. Crema (2014) and Duffy (2015) especially have provided
interesting and complementary literature reviews. The latter lists six mechanisms: seasonal
785 occupation (people use some sites for a restricted time of the year), cyclical aggregation and
dispersal of a population, fission of villages into daughter communities due to population growth,
differences in productive catchment (resource richness allows some settlements to grow larger than
others), functional specialisation of some sites, and regional political hierarchy. Of these six
mechanisms *SimFeodal* models functional specialisation alone. At the beginning of the simulation
in 800, the only focal points are the parish churches randomly distributed across the study area. At
790 this point in time, they are not very attractive: peasant households accept to travel quite long
distances to the nearest church because they do not need to attend frequently. Then, new focal points
appear, namely castles and village communities, which become increasingly attractive over time.
Finally, as the attractiveness of population clusters becomes ever more differentiated, the hierarchy
of the settlement system tends to increase. Concomitantly, the multiplication of castles and parish
churches results in the creation of new population clusters around them, which tends to reduce the
795 concentration of peasant households in a fixed set of clusters. Introducing more functional
specialisation into *SimFeodal*, especially by taking into account the presence of markets as well as
other craft and commercial activities in some places, might increase the hierarchy of simulated
settlement patterns. Yet Maillard (1998) observes that some market towns in the diocese of Tours
in the eighteenth century were smaller than big villages.

800 Besides the mechanism of functional specialisation, *SimFeodal* contains other mechanisms that also
influence the changes in the simulated settlement patterns. In particular, the push-pull relocation
process of peasant households means that not only do highly attractive places actually attract
population but also that weakly attractive places with a high level of taxation by lords are repellent.
805 On a regional scale, although no processes of competition or complementarity between centres of
attraction are modelled, the spacing between them is constrained in two ways. First, a distance
threshold ensures that a newly built castle is not too close to existing castles. Second, the size of
the catchment areas of parish churches cannot be too large (in order to avoid peasant households
travelling long distances to the nearest church) but, concomitantly, they cannot be too small as they
810 must contain a minimum number of households (in order to support the upkeep of the church and its
clergy). Last but not least, global political and social changes occurring between 800 and 1200 are
represented via contextual parameters that modify the behaviours of the lords and the peasant
households over time (see Table 3 and Figure 3).

815 With all these mechanisms and contextual parameters, *SimFeodal* takes into account both induced
and inherent spatial dependencies as defined by Fortin and Dale (2005) and discussed by Crema
(2014). Induced spatial dependencies refer to the effect of variables external to the system of interest
(e.g. contextual parameters representing global political and social changes in *SimFeodal*), while
inherent spatial dependencies refer to intrinsic properties of the generative process that can be
820 manifested in the form of forces of repulsion (e.g. territorial spacing between settlements) and
attraction (e.g. clusters of households committed to cooperative tasks). Crema (2014) suggests that
ecological, anthropological and archaeological theories of group formation have implicitly
emphasised the importance of one form of spatial dependence over another. By contrast, both forms
are present and equally important in *SimFeodal*.

825 A question you may want to ask about the *SimFeodal* model is whether it is able to produce
settlement patterns that are neither concentrated, nor hierarchical. The answer is: yes, it can, but not
with plausible values of parameters. To illustrate this, we provide here the example of a scenario in

830 which all values of parameters are the same as in scenario α except the value of the parameter
 “Maximum radius for local relocation of peasant households” set to 1000 m. instead of 2500 m. by
 default (see Appendix A). A maximum radius of 1000 m. for local relocation of peasant households
 is very narrow. With this value of parameter, the level of hierarchy of the simulated settlement
 pattern in 1200 is very low as shown by Table 10. The overwhelming majority of the population
 835 clusters are small and have about the same size. Moreover, the concentration level is also low since
 63 % of the peasant households are still scattered in 1200.

Table 10. Mean percentage of population clusters classified by size (in number of peasant households) in 1200 for 20 computation replications of each scenario.

	≤ 100	101-200	201-300	301-400	401-600	> 600
Scenario α	56.8	31.4	7.0	2.9	1.6	0.6
Tested scenario	82.6	12.4	3.4	1.0	0.7	0.4

840

6. Conclusion

We have simulated a series of 15 scenarios (including the basic scenario α) with *SimFeodal* in order
 to better understand how certain social and demographic parameters influence the level of
 concentration and hierarchy emerging in rural regional settlement patterns in North-Western Europe
 845 during the Middle Ages. According to the processes modelled in *SimFeodal*, it appears that
 demographic growth is not the primary cause of the increasing hierarchy of regional settlement
 patterns. However, introducing demographic growth into the simulated scenarios enables us to
 obtain simulation results closer to the empirical data. Moreover, both the number of population
 clusters and the hierarchy of the simulated settlement patterns increase more progressively over
 850 time than without demographic growth. Interestingly enough, the size of villages and small towns
 in 800, the proportion of peasant households moving only locally, and the power of village
 communities do not seem to influence the level of concentration and hierarchy of simulated
 settlement patterns. By contrast, increasing the radius of local relocation of peasant households has
 a strong effect but the resulting simulated patterns appear quite unrealistic when set against
 855 empirical data.

In this way, we have used agent-based modelling to facilitate our understanding of past changes
 rather than as mechanisms for simply recreating the known past (Laue 2018). As recommended by
 Crema (2018), we have paid much attention to the fit (or the lack thereof) between simulation
 860 outputs and observed data as well as the broader implications of the whole exercise instead of
 focusing exclusively on model building and description. In time, multiplying computer-based
 experiments based on explicit spatial simulations should help researchers to identify and formalise
 general laws for determining the concentration and dispersion of human settlements. This should also
 facilitate the identification of specific local features emerging in various social, cultural and political
 865 contexts.

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Appendix A. Mechanism parameters of the *SimFeodal* model.

Title	Value
Peasant households	
Maximum radius for local relocation of peasant households.	2500 m.
Potential frequency of a non-dependent peasant household relocating far away.	0.2
Population clusters	
Minimum number of peasant households for creating a population cluster.	5
Maximum distance between peasant households or focal points beyond which they do not belong to the same cluster.	100 m.
Lords	
Probability of one among all small lords building a castle at each simulation step.	0.5
When a small lord appears in the simulation, probability that he can collect rents (via the creation of a tax area).	0.1 (10%)
Probability of a small lord creating a new tax area for collecting other rights in his neighbourhood at each simulation step.	0.15 (15%)
Minimum and maximum radius of tax areas created by small lords, apart from castles.	1000 m. 5000 m.
Among all peasant households within the tax area of a small lord (apart from castles), minimum and maximum percentage of peasant households that pay fees to this lord.	0.05 (5%) 0.25 (25%)
Among all peasant households within the tax area of a castle, percentage of them that pay fees to the castellan.	1 (100%)
At each simulation step and for each tax area of a small lord independently of each other (apart from castles), probability of a small lord passing some of his rights on to another lord.	0.33 (33%)
Maximum radius of the neighbourhood within which a small lord can pass some of his rights on to other lords or build a castle.	5000 m.
When a small lord passes some rights to another lord (apart from castles), probability of the recipient of the donation being located within the neighbourhood of the giver. The maximum radius of this neighbourhood is set by the parameter exposed above.	0.8 (80 %)
At each simulation step and for each castle owned by a lord, probability of the lord passing custody of his castle to a small lord who is not already a castellan.	0.5
Castles	
Minimum and maximum radius of tax areas associated with a castle. All tax areas of a castle are of the same radius.	2000 m. 15000 m.
Minimum distance between a newly built castle and existing castles.	3000 m.

Probability of a castle being built within a population cluster.	0.5 (50%)
Probability of a castle becoming a major castle when it is located in or close to a pole containing at least one focal point in addition to the castle.	0.8
Parish churches	
Weighting (in number of peasant households) of the probability of a new parish being created within a population cluster.	2000
Minimum number of dissatisfied peasant households required for the creation of a new parish outside a population cluster.	20
Attractive centres	
Attractiveness of a small castle	0.15
Attractiveness of a major castle	0.25
Attractiveness of a parish church	0.15
Attractiveness of two parish churches	0.25
Attractiveness of three parish churches	0.50
Attractiveness of four or more parish churches	0.60
Attractiveness of a village community	0.15

Appendix B. Technical parameters of the *SimFeodal* model.

Title	Default value
Peasant households	
Maximum fees paid by a peasant household beyond which it becomes fully dissatisfied.	15
Minimum value of protection satisfaction when the distance from the peasant household to the closest castle exceeds the distance beyond which a peasant household is absolutely dissatisfied.	0.01
Population clusters	
Width of the buffer zone around the envelope of each cluster.	100 m.
Lords	
High justice rights: fees collected by the lord owner of a tax area for each subjugated peasant household.	2
High justice rights: fees received for each subjugated peasant household by the lord who has passed his rights over the tax area to another lord.	2.5
Rents: fees collected by the lord owner of a tax area for each subjugated peasant household.	1
Rents: fees received for each subjugated peasant household by the lord who has passed his rights over the tax area to another lord.	1.25
Other rights: fees collected by the lord owner of a tax area for each subjugated peasant household.	0.25
Other rights: fees received for each subjugated peasant household by the lord who has passed his rights over the tax area to another lord.	0.35
Number of successive draws of the probability of an overlord building a castle.	3
Number of successive draws of the probability of a small lord building a castle.	1

Appendix C. SimFeodal software application: Graphical User Interface. On the map, black points represent peasant households, small red disks represent castles, large disks represent tax areas.

