The Exergy Footprint as a Sustainability Indicator: An Application to the Neandertal-Sapiens Competition in the Late Pleistocene

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ABSTRACT

A Thermodynamic analysis of Population Dynamics and of Sustainability provides rigor to many important issues. In this work, the "system Society" is analysed in connection with the "system Environment" using an exergy metric, and the method includes an internalization of the Externalities (Capital, Labour, Environmental effects) conducted on the basis of a "system+ environment" balance. In this perspective, this study investigates the Late Pleistocene extinction of the Homo Neandertalensis, which took place in a geologically short time and in the presence of a competing species, the Homo Sapiens. The case in study is not trivial, and its choice not casual: in those times, the only factor that could lead to an advantage of one group over the other was their respective resource use intensity. A specific indicator, the Exergy Footprint, is here applied to measure the total amount of primary resources required to produce a certain (material or immaterial) commodity, including the resources needed for the physical survival of the individuals. On the basis of the available data, the results show that the EF of the Neandertal was higher than that of the Sapiens, and that, both species sharing the same ecological niche in a time of dwindling resources, the less frugal was also more fragile in an evolutionary sense.

Keywords: EEA; Neandertal extinction; Thermodynamic population models; Sustainability; Exergy footprint

NOMENCLATURE

Symbol, units	Definition	Symbol, units	Definition
cee	Extended exergy cost, J/J	L, workhrs/day	Work flux
CO	Conversion sector	LGM	Last Glacial Maximum
D, kg/day	Discharge (waste) flux	M, kg/day	Meat flux
D-O	Damskaard-Oeshger event	N	Number of individuals
DO	Domestic sector	P, units/day	Product flux
E, W; e, J/kg	Exergy/specific exergy flux	S, kg/day	Stone material flux
E_δ, W	Exergy destruction	V, kg/day	Vegetables flux
EE, W;	Extended exergy	W, kg/day	Wood flux
ee_L, J/workhr	EE of Labour	yBP, years	Years before present
EEA	Extended Exergy Accounting	*Greek Suffixes*	
E_{sun}, W/m^2	Net exergy of solar irradiation	α	Econometric coefficient
EX	Extraction sector	β	Econometric coefficient
F, kg/day	Food flux	δ	Destruction
H	Heinrich event	ε	Exergy efficiency
HN	Homo Neandertalensis	φ	Fuel mixture ratio
IN	Production sector	ψ	Waste coefficient

1 – INTRODUCTION: THERMODYNAMICS, SUSTAINABILITY AND POPULATION DYNAMICS

The minimization of the adverse environmental effects of industrial activities while maintaining the effectiveness of the "production chain" is a complex task that must rely on models that quantify the material- and energy flows in a system [22]. Since a society is obviously composed by interacting individuals, it has been proposed to complement "industrial/ecological" models with a dynamic population model that accounts for the effects of the "production" on the numerosity of the population and vice versa. By doing so, it is possible to identify several types of interactions between the number of individuals, their needs and the resources required to satisfy them. If such a combination of different approaches can explain with reasonable accuracy some of the large-scale events of the past, thus providing a sort of experimental validation to the models, and possibly reinforcing their mutual theoretical basis, its credibility in predicting the future may be reinforced [34].

The metaphor that human (industrial) societies "evolve" in a way similar to that of other natural ecosystems is gaining credibility and, given the growing throughput of anthropic structures, its application naturally rises concerns over the unsustainability of the current state of affairs. But "sustainability" seems impervious to a rigorous and generally accepted definition[1]. It has been argued [16] that "*the classical ecosystem analogy omits aspects of human social and cultural life central to sustainability*". According to the currently prevailing paradigm, "sustainable development" is thought to be resting on three pillars: Economics, Environment and Society. In this (recently criticized) perspective, resource use is seen as a Production Factor inevitably increasing with numerosity, and the emphasis is shifted to its equitable, economical and technologically feasible allocation.

Since drastic population limitation measures are out of the question, it is easy to see that the growing metabolism of the human society is approaching a critical limit, not only with respect to the available resource inputs, but -more importantly- to the sinks for waste and emission outflows. The so-called circular economy paradigm is a convincing strategy, which aims at reducing both the input of raw materials and the output of wastes by increasing as much as possible the amount of "recycling" (in its global sense, i.e., both of energy and of materials) [24]. Though the potential for "total recycling" is immense, very little attention is placed to the fact that recycling needs energy and (some) additional materials, and that Second Law of Thermodynamics places a limit to this "circularity" [9].

As for population dynamics, it is relatively easy today for anthropologists and paleoarcheaologists to identify direct links between geologically rapid changes in the numerosity of a population and the state of the environmental niche within which the population survives. While several studies successfully describe the history of the evolution or extinction of certain vegetal of animal species [33,51] though, it is extremely difficult to concoct a comprehensive model for the human society, where the interconnections among individuals, communities and populations and between them and the environment are much more intricate.

In spite of the common idea that small (non-human) populations should be more affected by environmental change than large populations, experiments have shown that adaptability, maturity, genetics and resource use appear to be as important factors as numerosity, and in fact small populations, at least at some life stage, may perform equally well or even better than large populations. It is only when they share the same ecological niche that relative numerosity may become an essential advantage [58]. If this is true for plants and lower vertebrates, it does not seem to apply to primates [23]: but the idea that smaller human groups may over sufficiently long time succumb to larger groups with whom they compete for resources ought to be tested

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[1] In fact, already in 1996 a literature survey [14] identified almost 300 different *discursiive* definitions of sustainability and sustainable development

separating the "resource" from other more "anthropic" issues (technology, social organization, cultural habits…), which is of course impossible for the contemporary human race. Thence the choice of the topic of this paper: since the competition between Homo Neandertalensis and Homo Sapiens could not possibly be based on economics and neither on environmental preservation issues, the only possible driver must have been the use they made of the available resources, which in a specific geological era, late the Pleistocene, were very scarce.

The existence of a quantifiable link between ecological dynamics and sustainability is of substantial importance here. On this point, some scholars argue that adaptive cycles are a fundamental property of living systems and that such systems can adapt to stresses in a manner such that each generation maintains properties experience proved to be healthy. Holling [27] defined sustainability as "*the ability to create, test, and maintain adaptive capacity*", and development as "*the process of creating, testing, and <u>maintaining</u> opportunity*" (underscore added). In his argument, he uses terms such as resilience, wealth, and opportunity, to characterize an evolutionary path in which each generation retains many of the positive properties of the preceding one and possibly adds more desirable traits. He suggests that properly managed adaptive cycles constitute sustainable development, which is not at all the same "sustainable development" evoked by the familiar Brundtland definition. In spite of the merits of such an approach, I prefer using Ehrenfeld's definition: his framing of sustainability is that it is "*the possibility that human and other forms of life will flourish on the planet forever. Flourishing has great metaphorical power.*" [17]

1.1 The exergy footprint

The concept of exergy footprint (EF in the following), introduced in [47], provides a rigorous thermodynamic basis to sustainability studies: it is a measure of the total primary resource consumption of a system (in particular, of a society), measured in terms of exergy. The use of exergy in lieu of energy has some advantages, both from a theoretical and from a practical point of view, and interested readers are referred to the vast literature on the topic (see for example [10,39,53,54] and references therein)[2]: what is of importance here is that societies with different life standards can be ranked according to their respective EF, a higher value indicating a "less sustainable" and a lower a "more sustainable" lifestyle. It is clear that in modern societies the interconnection of economic, social, political and resource related issues tends to blur the simple and rather blunt conclusion that a substantial change in societal structure of most advanced economies is necessary to reduce their EF: thus, a brave scholar who wished to propose a comparative EF study between two modern societies would find it extremely difficult to separate ethical, social and in general non-thermodynamic issues from the substantial result, i.e., from the inevitable exhortation to a more cautious resource exploitation. To simplify the issue, this paper presents a comparison between two pre-historic social organizations, for which sufficient data exist to compute the respective EF: demonstrating that the method works for primitive societies may lead to its successful application, *mutatis mutandis*, to contemporary ones. Since sustainability is obviously linked to political planning, it is believed that the new approach opens new possibilities for a rational comparison between "more" and "less" sustainable societal organizations.

1.2 - Homo Neandertalensis and Homo Sapiens

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[2] The fundamental difference is that energy is conserved while exergy is not: in any physical process/transformation some exergy is destroyed by irreversibility. This confers to the primary exergy input the characteristic of a "cost" of the final exergy output. Notice that if one adopts the "final energy use" as a measure of resource consumption, the distinction between energy or matter streams of different quality (thermal- vs mechanical power, or chemical vs thermal, etc.) is completely lost.

The unusually fast disappearance of the Homo Neandertalensis has puzzled archeo-etnologists for a long time: what circumstances drove to extinction in about 20000 years a species that had survived for over 400000 years, most of which in Europe, under extremely harsh environmental conditions, and in the course of time evolved to an almost incredible degree of adaptation to such conditions? Was it by chance that this extinction took place after Neandertals and Sapiens started sharing their environmental niches? Was there a "war" between the two species? Was there some sort of epidemics to which one of the species succumbed? Did the large and frequent volcanic events of the late Pleistocene and the related strong and fast climate variations have an impact? This paper addresses the problem from a thermodynamic point of view, using well-published and accepted data to compile a reasonably accurate list of the primary resources available at that time and positing some assumptions -also extracted from reliable sources- on the final uses the two species made of the resources. Then, an Extended Exergy accounting [47,49] is applied to two groups of the two species placed in the very same ecological niche (central Europe), to compare their Exergy Footprint, i.e., the "gross resource load" they placed on the environment. The striking conclusion emerges that, in each one of the 5 examined scenarios, the Neandertal consumed a higher *pro-capite* amount of primary resources than the Sapiens, and this might have become a decisive factor when the two species came to coexist at a time of dwindling resources. It is likely that a dynamic study (i.e., one that includes in the calculations the variation in time of the climate and of the available resources) would provide some additional insight in this important issue: this topic is left for later studies. The steady-state study presented here confirms the importance of an exergy-based resource analysis method for the calculation of a new important thermodynamic sustainability indicator, the Exergy Footprint.

The origin of the Neandertal species (HN in the following) is generally placed in the North-East part of Africa (roughly, today's Ethiopia and Kenya) around 500000 years before present (yBP) [11]. Somewhat later, possibly 430000 yBP, they migrated north, reaching Europe (some Neandertal bones found in a cave in Spain date in fact back to 430000 yBP [38,39]). They definitely came into contact with the Homo Heidelbergensis, a more primitive species that appears to have preceded them to Europe about 600000 yBP[3]. Neandertals adapted very well to the Pleistocene rigid climate, lived in small groups of hunters but also knew some form of gathering [11], knew the use of fire and adopted a nomadic lifestyle. Their numerosity varied strongly with the successive glaciations, and in the relatively warm Saale/Weichel interglacial period (130000-115000 yBP (figure 1) they went through a substantial demographic growth and spread into Eastern Europe. Approximately midway through the most severe of the four Pleistocene events, known as the Weichel glaciation (115000-12000 yBP, i.e., around 50000 yBP), their number started to dwindle, and there is no known Neandertalian settlement after 15000 yBP.

The first traces of Homo Sapiens (HS in the following) were found in the Ethiopian Omo Kibish region, a little North-East than the original site of appearance of the Neandertal, and date approximately to 200-300000 yBP [25,28]. An alternative opinion [31] is that the species evolved slowly but much earlier from the South-African predecessor Homo Rhodesiensis. Be as it may, it appears that they started migrating towards Europe only much later, about 110000-70000 yBP. There is also archeological evidence of a contact between the two species around 100-60000 yBP, in what is now Syria, but in spite of some researchers' hypothesis, there is no certainty of

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[3] The HN- and the HS- migrations were not the first Homo migrations from Africa to Europe. Much earlier, different waves of Homo (Erectus, 1.9 million yBP; then Heidelbergensis, probably 600000 yBP) had profited from prolonged periods of extreme monsoon activity in north-East Africa to cross the then fertile and water-rich Sahara region [5,28].

interbreeding at that time[4] [11,26,46] Between 70- and 25000 yBP the Sapiens colonized all Europe and most of the Russian subcontinent, reaching Asia and displacing local Hominins populations, until by 15-10000 yBP they crossed the Bering strait, at that time covered by a solid ice sheet, reaching into the Americas. The Sapiens were a hunter-gatherer society, practicing some primitive form of agriculture [25,31] and herding, and were therefore less nomadic than Neandertals. They lived in larger groups (over 30 members and up to 150 [25]) and were the first species to show "fast adaptive response", i.e., the capability of modifying their utensils (weapons, tools, pottery, etc.) in a relatively quick response to changed climatic conditions.

2 – MATERIALS AND METHODS 1: THE LATE PLEISTOCENE CLIMATE[5]
2.1 – The glaciations
Paleo-climatological evidence shows that during the Pleistocene the temperatures in the Northern Hemisphere were substantially colder than today, while the now tropical and sub-tropical areas enjoyed a humid and temperate climate [29,57]. The geographical region this study applies to is the portion of the European continent spanning from the Mediterranean coast to northern Scandinavia and the westernmost part of northern Russia. The first of two extended periods of extremely rigid climate was the Saale glaciation (named after the river Saale in northern Germany) that lasted from about 380,000 to 130000 yBP. The HN survived this period, while the HS had not yet entered the scene. The second extended glaciation (Weichsel glaciation) lasted from about 115,000 to 12000 yBP: this will contain -for reasons that shall be made clear shortly- our window of observation. Its name originates from that of a river in Poland were geological remnants were first discovered. In early Weichsel the glaciers were limited to large parts of Southern Scandinavia, while northern Europe was covered by tundra and low shrubs of birch and willow. The prevailing fauna included mammoth, woolly rhinoceros, bison, reindeer, musk ox and their predators, but smaller herbivore and insectivore mammals were also present. This glaciation contained a brief but very cold period (23000-19000 yBP) known as the Last Glacial Maximum (LGM), in which the only area not covered by glaciers was that comprised between today's northern Europe and the Alps: this entire region was a large steppe devoid of natural barriers in which large ungulates and their predators were abundant [59]. Again, the coastal region of the Mediterranean Sea was somewhat warmer (average yearly temperature between -1 and 2 °C), and covered by forests of pine trees. Experimental findings confirm that Europe was continuously inhabited already 600000 yBP by the Homo Heidelbergensis, a predecessor of the Neandertal. When the latter migrated from northern Africa via the Middle East corridor, they colonized the Balcans, central, western and southern Europe and took advantage of some interglacial period to reach northern Russia (30-40000 yBP) and probably pass the Ural mountains as well.
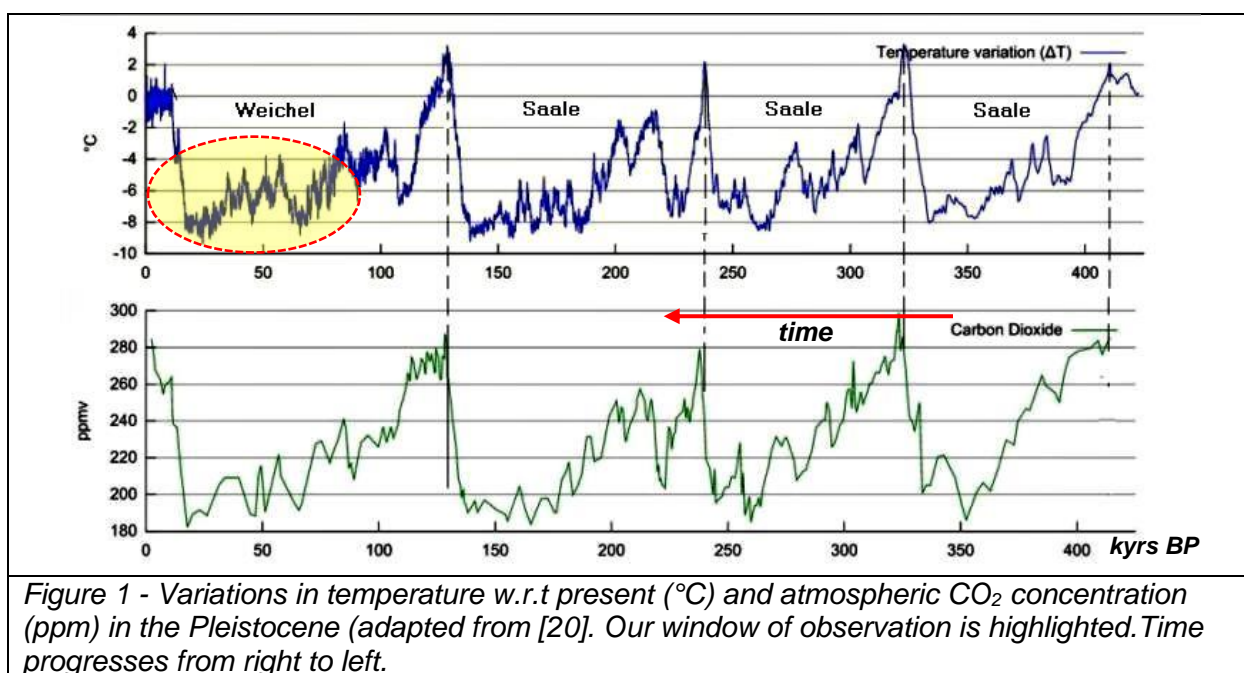
2.2 - Volcanism
Pleistocene climate was affected by impressive volcanic activity that affected both the flora and fauna at various times. Such eruptions are collectively denoted as Damskaard-Oeshger (D-O) events and their traces are still easily identifiable in the sub-surface crust layers of Eurasia. In the most recent portion of our window of observation 75000-15000 yBP) the main event was the Toba

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[4] It is certain though that the two species interbred at a later time: both archaeological findings [19,30] and DNA analysis [46] show that there was substantial interbreeding between HS males and HS females, while it seems that the HN-male/HS female matings were not fertile on genetic reasons [8,40,42]

[5] This section is necessary to better understand the development of the study, but it contains material clearly outside of my field of expertise. Therefore, I relied extensively on some excellent paleo-meteorological works, namely [2,7,20,21,28,43,44,57]. Possible inaccuracies are to be ascribed solely to my elementary understanding of climate processes.

eruption (Sumatra, 75000 yBP), the largest ever recorded on Earth, which resulted in extremely high atmospheric dust concentrations over 10000 years [2,44]. Another significant event was the almost as powerful *Campanian Ignimbrite* eruption (modern Napoli, Italy, 40000 yBP) [7,20,21] that lead to very high accumulated dust levels in the atmosphere, causing a century long "volcanic winter" and depositing millions of tons of dust over Italy and eastern Europe. These volcanic events contributed to a strong decrease in the average Earth temperature and to an equally large mortality of most of the then existing plant species, which in turn caused a strong decrease in the animal population, especially the large herbivores.

Figure 1 - Variations in temperature w.r.t present (°C) and atmospheric CO$_2$ concentration (ppm) in the Pleistocene (adapted from [20]. Our window of observation is highlighted.Time progresses from right to left.

3 – MATERIALS AND METHODS 2 : NEANDERTAL AND SAPIENS LYFESTYLES AND DEMOGRAPHICS

3.1 – Homo Neandertalensis

Fossil evidence shows that the extremely low population density (0.1 to 1 persons/km^2 [8,52,55]) and the relative abundance of prey strongly influenced Neandertals' technological and social characteristics in central and northern Europe. Small groups of HN ("family-based clans" rather than "tribes") displayed high residential mobility limited to rather short distances [11]. Their main prey were the herds of herbivores (horses, bison, reindeer and snow goats), with a smaller amount of many other smaller game species. There is evidence that some Neanderthal groups in certain areas may have had a wider diet that included plants and smaller animals, but this pattern is not very widespread. In the southernmost coastal regions, their diet only occasionally included shellfish, birds, and turtles [35]. They scavenged and hunted, and their hunting was direct and dangerous: HN followed the herds, tried to isolate an individual prey and attacked it in groups by using wood-and-stone pikes and clubs (such hunting style explains the large amount of injuries evidenced by the fossil remnants). There appears to have been no division of labor by gender between hunting and gathering, which means that both males and females (and probably younger adults) worked indifferently as hunters and gatherers. HN knew how to use fire both for cooking meat (and probably some vegetables) and for hardening the points of their pikes. Their nomadic or semi-nomadic production system, largely skewed towards hunting, was obviously affected by high incidental mortality [37,56], which is one of the factors that slowed the HN demographic

growth rate. In addition, the metabolic expense associated with this lifestyle required a high calorie diet (essentially game)[6], and this, combined with the semi-nomadic lifestyle, probably caused long birth intervals in HN females and, therefore, low fertility. There are also indications that birth was difficult for HN females [40,42], and this leads to modern estimates of 5 or less children per female. It is also possible that, like the caribou females studied by Bårdsen [3], HN females confronted with more and more rigid winters adopted low-risk strategies by allocating more resources to building their own body reserves during summer and less to reproduction.

In the longest interglacial period, the warmer climate resulted in the extension of steppe-like savannah and grassland areas in eastern Europe, and in a large increase in the density of herbivores and of their carnivorous predators: this resulted in a demographic growth of HN, and led to their relatively rapid expansion towards the Black Sea and further east in the Russian tundra. It is also likely that this migration/expansion favoured a gradual -and advantageous- genetic homogenization, thanks to increased infra-breeding among different groups and the contemporary increase in population density. But the enlarged communication did not lead to quantum jumps in the lifestyle and, on the contrary, all experimental evidence demonstrates that HN were rather "technologically conservative", because their hunting techniques did not substantially change over more than 150 kyrs: the only consequence of the growth of the locally available prey was a reduction in their mobility. This in turn reduced the required caloric input and resulted in a rise in female fertility (more frequent pregnancies). There is no proof either of a change in their cultural lifestyle: they did not produce new tools, nor changed their feeding habits. It is also unknown whether they still preferred to live in caves or natural shelters or had learned to build rough wooden huts like their predecessor, Homo Heidelbergensis. As we shall see, this prolonged Neanderthal technological stagnation was one of the major causes of their low competitiveness with respect to the more technologically advanced Sapiens.

Recently proposed models [6,26,52,55] estimate an HN numerosity ranging from 5000 to 12000 in their archaic periods (430000 yBP), growing slowly to 60-75000 individuals (115000 yBP) and then steadily declining from about 50000 yBP to their extinction around 15000 yBP.

These low numbers are better understood considering that except in few temperate niches (but semi-arid, except around the Mediterranean Sea), the vegetation was mainly cold steppe and tundra and was periodically devastated by an environmentally catastrophic alternation of warm (Dansgaard–Oeschger, DO) and cold (Heinrich, H) climate events[7] [43]. It can be thus reasonably assumed that the Neanderthal population, living in smaller groups under conditions of extreme and in geological terms rapid environmental instability, was primarily stagnant, with frequent genetic bottlenecks: random accidents (fires, floods, diseases, earthquakes, etc.) could lead to episodes of decline, possibly accelerated by occasional skirmishes with their cousins Sapiens [15].

3.2 – Homo Sapiens

It is quite apparent that, in contrast to the low rate of numerosity of the HN, there was a demographic advantage for Homo Sapiens, at least during the window of observation of the present study. Such advantage was probably the result of a higher fertility (due to a less nomadic lifestyle) and/or reduced premature mortality (thanks to a safer hunting strategies), because no proof has been found that adult longevity or other structural causes have played a role in this

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[6] Recent estimates [1,11] conclude that the metabolic cost of an adult Neanderthal was very high (3500–5000 kcal/d [0.17-0.24 kW] vs. 2000–2400 kcal/d [0.09-0.12 kW] for a modern European human adult male.
[7] In paleoclimatic terms, a Heinrich (H) event is a period of very cold climate. A Dansgaard-Oeschger (D-O) event is, on the contrary, a period of relatively warmer conditions. It is known today that such events, short in geological terms (less or about 1000 yrs), but very intense (variation of ±5-8 °C in the average yearly temperature), took place several times in the Pleistocene.

demographic transition[8]. The median life span (25-40 yrs) and the maximum longevity (over 65) are proven to be almost the same between HN and HS [52].

The societal organization of the HS was quite different from that of the HN: they lived in larger groups (30-150 individuals [25]), had domesticated some animals (notably, the wolf), were expert gatherers and hunted with spears, avoiding direct contact with the prey. There appears to have been a subdivision of tasks in the HS tribes, with "specialized" hunters, gatherers (probably, the females and youngsters) and toolmakers. This is in stark contrast with the "individualistic" HN members, who made their tools by themselves and divided their time between searching for suitable stone materials and wood for the weapons, gathering, hunting and preparing the meat. HS made and used stone tools, built mud-and-wood huts, invented a variety of conceptually complex and specialized items like composite stone tools, in later ages fishhooks and harpoons, bows and arrows, spear throwers and sewing needles. A strong hint to their lifestyle is the fact that already the first HS produced "consumers goods" like pottery (as early as 40000 yBP), or stone- and, later, ceramic figurines.

The HS diet was more varied than that of the HN, and their hunting technique less dangerous thanks to the use of projectile spears: this implies lower mortality of young adults and a higher demographic growth, favored by the higher fertility of the HS females (more than 5 and up to 10 children per female [8,52]). Sapiens lived apparently a more sedentary life than HN, and this probably favoured their cultural development, because their nomadism was likely to be seasonal rather than continuous.

3.3 – Neandertal's and Sapiens' resource basis

The resource basis of the two species was almost the same: meat (a higher quantity *pro capite* for the NH), wood for cooking and heating, stones for weapons and utensils, vegetables (a higher quantity *pro capite* for the HS). It is likely that both species camped in the immediate vicinity of water sources, to facilitate supply. Well-accepted estimates for the food intake are available: the remaining values highlighted in grey in Table 1 are likely but not certain. The solar irradiation (400 W/m^2 for both groups) was calculated on an area of 5 km^2, assumed as the "reference living domain" for both species.

Table 1 – Estimated <u>final</u> resource consumption
of Homo Neandertalensis and Homo Sapiens

Resource Type	Neandertal (*pro capite*)		Sapiens (*pro capite*)	
Meat	3.44 kg/day	20608 kJ/day	2.25kg/day	13470 kJ/day
Wood	5.34 kg/day	26700 kJ/day	3.27 kg/day	16350 kJ/day
Stone	0.86 kg/day	12900 kJ/day	0.83 kg/day	12450 kJ/day
Vegetables	0.1 kg/day	340 kJ/day	0.2 kg/day	605 kJ/day
Other (mud, water)	5 kg/day	5000 kJ/day	10 kg/day	10000 kJ/day
TOTAL, kJ/day/person	65548		52875	

Note: The kJ values in the third and fifth columns are the estimated exergy contents of the resources.

4 – MATERIALS AND METHODS 3: EXERGY ANALYSIS OF THE NEANDERTAL AND SAPIENS SOCIETIES

The main goal of this study is to quantify the resource use and consumption of the two species from a thermodynamic point of view. HN and HS were chosen because their societal organization was rather elementary, and did not include any real "economics", which make their societies a good benchmark for theories of exergetic cost. The idea is to calculate the amount of primary

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[8] Though there is no final proof of episodes of "tribal war", it is likely that, like other Primates and Hominins, whenever two groups happened to forage in the same environmental niche, some sort of direct physical confrontation may have arisen, leading to accidental deaths, mostly among youngsters and adult males.

resource consumption needed by each group to produce their tools while following their characteristic lifestyle. The Extended Exergy Accounting (EEA) method [47] was applied to "production systems" that model the Neandertal and Sapiens societies.

The goal of this study was to understand whether the exergy resource basis and the consumption patterns of the two societies may give some hint as to the reason for the stunning and "sudden" (in geological times) prevalence of the one species over the other. Previous studies on the application of EEA [10,12,13,18,48] have provided some interesting results: the criticism usually centers on the correct calculation of the econometric coefficients α and β [10,36,48], and therefore in the current model the value of α is derived from the "experimental data" generated by the model for ee_L, as if the data had been collected on the field. The steady-state analysis presented here[9] consists of two steps: for a given set of specifications that include the resource input, the numbers of the two groups, their respective allocation of the workhours, and the output ("products"), the exergy flows through each system are calculated. An "exergy cost" is thus obtained, which has a pure thermodynamic value and provides at the same time a measure of the irreversibility in each production process and a verification of the credibility of the results. On this basis, labour intensity is factored in, and an extended exergy analysis is performed. Environmental Remediation (EE_{ENV}) costs are not accounted for in the calculations, given the negligible influence of these primitive societies on the environment.

4.1 – Resource input

Although the numerical values are at best modest approximations of the real final resource use, we shall use the estimates given in Table 1 to derive the respective primary exergy consumption of the two groups. The following main model assumptions are posited:

a) The exergy content of live meat and vegetables is assumed equal to their respective average exergy content (kCal/kg), neglecting the intrinsic exergy value of the prey and of the plant;

b) The hunting, preparation and transportation of meat, vegetables, stone and wood are accounted for as equivalent primary Labour exergy;

c) The wood was gathered rather than cut, while the stone material is considered to be extracted from caves not necessarily in the vicinity of the HN or HS camps;

d) The exergy of solar irradiation is a "hidden input" into the Domestic Sector, since it maintains the biosphere whence both species extracted their resources. Its value for the reference scenario is in accordance with accepted data [29,32,57].

4.2 – Internal work division

As stated above, the labour division was one of the major differences between the two species. The members of the groups are identified as "male adults" N_M, "female adults" N_F, "young adults" N_Y, "juveniles" N_J, and "old and injured" N_{OI}. The group numerosity is $N_{tot}=N_M+N_F+N_Y+N_J+N_{OI}$, and number of working members is $N_W=N_M+N_F+N_Y$ [41], the value N_W/N_{tot} being a model parameter whose effect on the result is substantial, though no convincing experimental data are available for it. The above numbers for both species are adapted from [8,55]. Table 2 reports the values assumed in this study. The N_W assumes different values in the two societies, because while in the HN group all adults equally shared the work ($N_W=N_A$), in the HS tribe the labour tasks were differentiated and the number of injured hunters was percentagewise lower. In the following, for both groups it is assumed that females and youngsters took care of the cooking and gathering while the males prepared the weapons, and the relative percentages were extracted from [8]. As

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[9] A dynamic analysis along the lines proposed in [50] requires a substantially larger database, and is left for future studies

an additional assumption, the hunting was performed only by adults (N_M+N_F) [41]. The labour flows are calculated on the average working hours/day/person. Allowance was made for the fact that the better organization of the more numerous Sapiens society reduced their individual workload, so that besides hunting, gathering and toolmaking, the Sapiens also found time for "artistic" production: these hours are counted here as "idle" time.

**Table 2 – Estimated demographics for Homo Neandertalensis and Homo Sapiens**

	N_M	N_F	N_Y	N_J	N_{OI}	N_{tot}	N_W
Neandertal	2	4	3	2	2	13	9
Sapiens	10	20	15	10	5	60	45

4.3 – Representative products and production process

To perform an exergy analysis, it is necessary to model some production process. Considering the respective lifestyles described in section 3, we shall compare the resource consumption required by the production of two indispensable artefacts common to the two societies: a stone ax and a wood-and-stone pike (for HN) or spear (for HS), assuming different labour intensity for the two products. The respective production processes are depicted in figure 2. To normalize the production with respect to the number of members of each group, the results are presented normalized w.r.t. N_{tot} (i.e., per person per day). Allowance was made for the "leisure" activities of the HS (statuettes, ornaments, etc.) by reducing their workhour load by 1 hour per day.

The physical model is at a much more disaggregated level than EEA: this is necessary though, because the exergy budget of the set of the individual sectors (extraction, EX; conversion, CO; industrial, IN) is described in terms of the individual fluxes of material and energy they exchange. EEA shows 3 additional exergy fluxes (L_{CO}, L_{EX}, L_{IN}) that quantify the primary exergy equivalent of the workhours invested by the N_W working members of the society in each production task. The system equations are derived in the following sections. Although the use of the terms "Conversion" and "Industrial" may appear inappropriate to describe the simple activities they refer to here, the names are the same as in the general EEA nomenclature, for ease of comparison with similar works.

Figure 2 - The physical exergy flows (top) and the EEA model of the HN and HS production chains
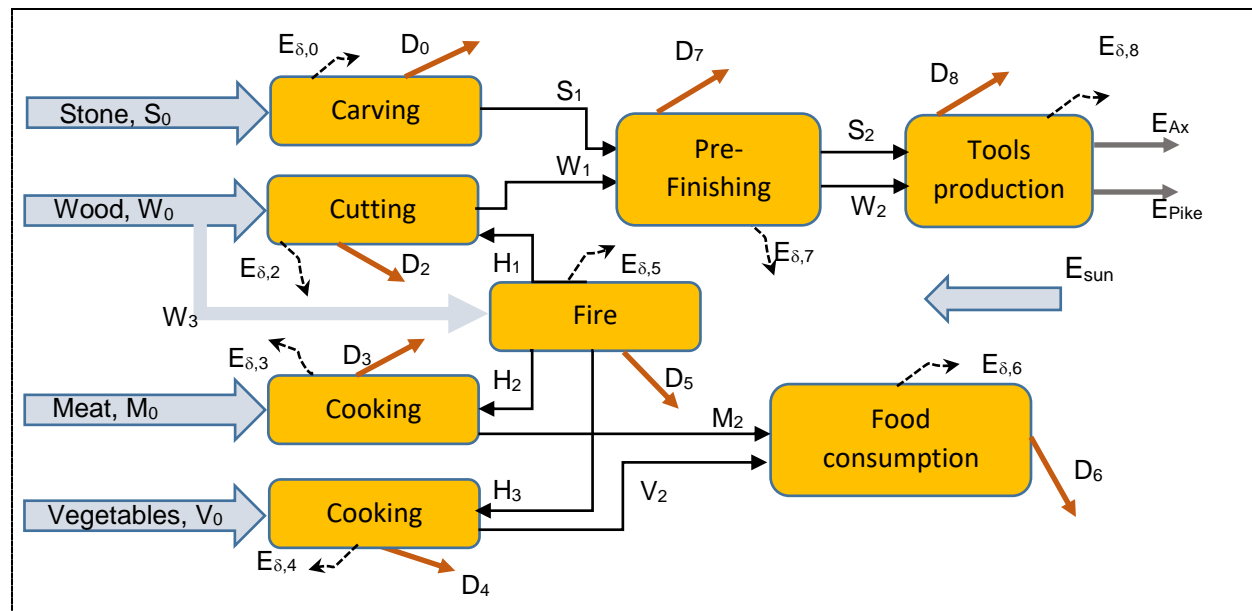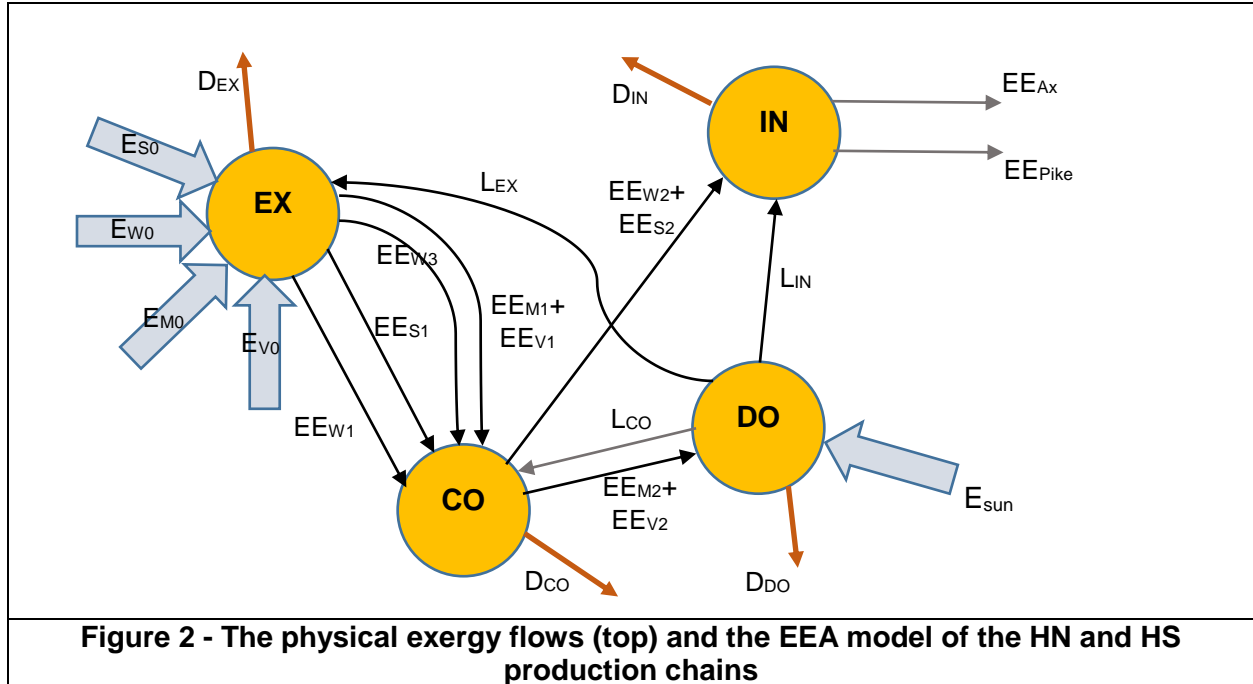
Legenda for figure 2: D=discharge; E_δ=exergy destruction; M=meat; V=vegetables; H=heat; E_{sun}= exergy of solar radiation; L=Labour; S=stone; W=wood (H, L, M, S, V, W in [kJ/s]); **CO**=conversion sector; **DO**=domestic sector; **EX**=extraction sector; **IN**=industrial sector

4.4 – Mass- and exergy balances

- *Carving*

$$\dot{m}_{S0} = \dot{m}_{S1}\Big/(1 - \psi_{0,S})$$
$$\dot{m}_{S1} = \dot{m}_{S2}\Big/(1 - \psi_{7,S})$$

$$\dot{E}_{S0} = \dot{m}_{S0}e_{S0}$$
$$\dot{E}_{S1} = \dot{m}_{S1}e_{S0}$$
$$\dot{E}_{S2} = \dot{m}_{S2}e_{S0}$$
(1)

- *Cutting*

$$\dot{m}_{W0} = (\dot{m}_{W1} + \dot{m}_{W3})\Big/(1 - \psi_{0,W})$$
$$\dot{m}_{W2} = (\dot{m}_{W1})\Big/(1 - \psi_{7,W})$$

$$\dot{E}_{W0} = \dot{m}_{W0}e_{S0}$$
$$\dot{E}_{W1} = \dot{m}_{W1}e_{W0}$$
$$\dot{E}_{W2} = \dot{m}_{W2}e_{W0}$$
(2)

- *Cooking*

$$\dot{m}_{M0} = \dot{m}_{M1}\Big/(1 - \psi_{0,M})$$
$$\dot{m}_{M1} = \dot{m}_{M2}\Big/(1 - \psi_3)$$

$$\dot{m}_{V0} = \dot{m}_{V1}\Big/(1 - \psi_{0,M})$$
$$\dot{m}_{V1} = \dot{m}_{V2}\Big/(1 - \psi_4)$$

$$\dot{E}_{M0} = \dot{m}_{M0}e_{S0}$$
$$\dot{E}_{M1} = \dot{m}_{M1}e_{S0}$$
$$\dot{E}_{M2} = \dot{m}_{M2}e_{S0}$$
$$\dot{E}_{V1} = \dot{m}_{V1}e_{V0}$$
$$\dot{E}_{V2} = \dot{m}_{V2}e_{V0}$$
(3)

- *Feeding fire*

$$\dot{m}_{W3} = (\dot{q}_1 + \dot{q}_2 + \dot{q}_3)\Big/[LHV_{fuel}(1 - \psi_5)]$$

$$\dot{E}_{W3} = \dot{m}_{W3}e_{W0}$$
$$\dot{E}_{qj} = \dot{q}_j\eta_C$$
(4)

- *Feeding*

$$\dot{m}_{M2} = \dot{m}_{M1}\Big/(1 - \psi_{6,M})$$
$$\dot{m}_{V2} = \dot{m}_{V1}\Big/(1 - \psi_{6,V})$$

$$\dot{E}_{M2} = \dot{m}_{M2}e_{M0}$$
$$\dot{E}_{V2} = \dot{m}_{V2}e_{V0}$$
(5)

- *Production*

$$\dot{m}_{Ax} = \left.(\dot{m}_{S2,ax} + \dot{m}_{W2ax})\right/(1 - \psi_{8,Ax}) \qquad \dot{m}_{pike} = \left.(\dot{m}_{S2pike} + \dot{m}_{W2pike})\right/(1 - \psi_{8,Pike}) \qquad (6)$$

$$\dot{E}_{Ax} = \dot{m}_{S2Ax}e_{S0} + \dot{m}_{W2Ax}e_{W0} \qquad \dot{E}_{Pike} = \dot{m}_{S2Pike}e_{S0} + \dot{m}_{W2Pike}e_{W0}$$

The inputs $\dot{E}x_{S2}, \dot{E}x_{W2}, \dot{E}x_{M2}, \dot{E}x_{V2}$ can be specified on the basis of the estimated weight of each weapon and of the metabolic rate of HN and HS [11,45], and thus the system (1-6) can be solved if the "material waste coefficients" ψ_j are known: in this work, the latter have been assigned by adapting the values proposed by different sources (Table 3).

The results provide the values of the primary gross resource consumption (mass- and exergy values) for the Neandertal and Sapiens society and are listed in Table 4 (the flows are identified in Figure 2). The efficiencies ε_1, ε_2…ε_7 result from the calculations.

Table 3– EEA model assumptions for the Neandertal and Sapiens societies

Homo Neandertalensis				Homo Sapiens			
φ_{fuel}	0.4	ψ_4	0.5	φ_{fuel}	0.4	ψ_4	0.5
$\psi_{0,S}$	0.3	ψ_5	0.2	$\psi_{0,S}$	0.4	ψ_5	0.2
$\psi_{0,W}$	0.2	$\psi_{6,M}$	0.2	$\psi_{0,W}$	0.2	$\psi_{6,M}$	0.2
$\psi_{0,M}$	0.25	ψ_2	0.1	$\psi_{0,M}$	0.25	ψ_2	0.1
$\psi_{0,V}$	0.2	$\psi_{6,V}$	0.2	$\psi_{0,V}$	0.2	$\psi_{6,V}$	0.2
$\psi_{1,S}$	0.2	$\psi_{7,S}$	0.2	$\psi_{1,S}$	0.2	$\psi_{7,S}$	0.2
$\psi_{1,W}$	0.1	$\psi_{7,V}$	0.2	$\psi_{1,W}$	0.2	$\psi_{7,V}$	0.2
ψ_2	0.2	$\psi_{8,Ax}$	0.2	ψ_2	0.2	$\psi_{8,Ax}$	0.4

Table 4 – <u>Primary</u> resource consumption for the Neandertal and Sapiens society
(*m* in kg/person/day; *E* in kJ/person/day)

Homo Neandertalensis					
m_{S0}	1.92	E_{S0}	28760	ε_1	0.7
m_{W0}	7.62	E_{W0}	38109	ε_2	0.8
m_{M0}	6.12	E_{M0}	36636	$\varepsilon_{(3+4)}$	0.795
m_{V0}	0.16	E_{V0}	425	ε_7	0.84
Homo Sapiens					
m_{S0}	2.16	Ex_{S0}	32444	ε_1	0.6
m_{W0}	5.82	Ex_{W0}	29109	ε_2	0.8
m_{M0}	3.75	Ex_{M0}	22450	$\varepsilon_{(3+4)}$	0.795
m_{V0}	0.28	Ex_{B0}	756	ε_7	0.8

4.5 – The EEA balance equations

There are yet additional terms that express the equivalent primary exergy of Labour and do not appear in the exergy budget. An additional set of equations, specific of EEA, must be considered. Referring the reader to [10,47,49] for a detailed description of the EEA paradigm, it suffices here

to recall that the specific equivalent Labour exergy is posited to be equal to a portion of the total incoming exergy flux:

$$\dot{e}e_L = \alpha \frac{\dot{E}_{tot,input}}{wh_{person}} \frac{N_{tot}}{N_W} \tag{7}$$

Where N_W is the number of workers and *wh* are the workhours per worker per unit time (here, per day): the rationale adopted in deriving eqtn. (7) is that the total resource input sustains the entire population, and if the work is performed by a reduced number of members, their contribution is in effect used to sustain themselves <u>and</u> the non-working part of the group. The econometric coefficient α must be obtained experimentally, which in our case is obviously impossible: to avoid circular definitions, it was calculated here by including the ee_L among the model unknowns, and then inverting (). Since Extended Exergy measures the "cost", expressed in equivalent primary resources, of the outputs of a system, it obeys a conservation equation of the type

$$\sum \dot{E}E_{products} = \sum \dot{E}E_{inputs} \tag{8}$$

By definition [47] the EE cost of generic stream *j* (regardless whether an input or an output) is obtained by summing the contributions given by the material, energy and labour contributions:

$$\dot{E}E_j = \dot{E}E_{j,M} + \dot{E}E_{j,E} + \dot{E}E_{j,L}{}^{10} \qquad \text{[kJ/s]} \tag{9}$$

Eqtn. (9) is applied to each of the four sectors EX, CO, IN and DO. Under the assumption that the exergetic cost of the waste flows is equal to zero, the extended exergy (rate) budgets [kJ/s] can be written as:

– *Extraction sector EX*

$$\dot{E}_{S0} + \dot{E}_{W0} + \dot{E}_{M0} + \dot{E}_{V0} + \dot{E}E_{L,EX} = \dot{E}E_{S1} + \dot{E}E_{W1} + \dot{E}E_{M1} + \dot{E}E_{V1} + \dot{E}E_{W3} \tag{10}$$

– *Conversion sector CO*

$$\dot{E}E_{S1} + \dot{E}E_{W1} + \dot{E}E_{M1} + \dot{E}E_{V1} + \dot{E}E_{W3} + \dot{E}E_{L,CO} = \dot{E}E_{S2} + \dot{E}E_{W2} + \dot{E}E_{M2} + \dot{E}E_{V2} \tag{11}$$

– *Industrial sector IN*

$$\dot{E}E_{S2} + \dot{E}E_{W2} + \dot{E}E_{L,IN} = \dot{E}E_{Ax} + \dot{E}E_{Pike} \tag{12}$$

– *Domestic sector DO*

$$\dot{E}_{sun} + \dot{E}E_{M2} + \dot{E}E_{V2} = \dot{E}E_{L,EX} + \dot{E}E_{L,CO} + \dot{E}E_{L,IN} \tag{13}$$

The four EEA equations can be rewritten in terms of the $c_{ee,j}$, the extended exergy costs of each flow[11]:

$$\dot{E}_{S0} + \dot{E}_{W0} + \dot{E}_{M0} + \dot{E}_{V0} + ee_L \dot{N}_{hours,EX} =$$
$$c_{ee,S1}\dot{E}_{S1} + c_{ee,W1}\dot{E}_{W1} + c_{ee,M1}\dot{E}_{M1} + c_{ee,V1}\dot{E}_{V1} + c_{ee,W3}\dot{E}_{W3} \tag{14}$$

$$c_{ee,S1}\dot{E}_{S1} + c_{ee,W1}\dot{E}_{W1} + c_{ee,M1}\dot{E}_{M1} + c_{ee,V1}\dot{E}_{V1} + c_{ee,W3}\dot{E}_{W3} + ee_L \dot{N}_{hours,CO} =$$
$$c_{ee,S2}\dot{E}_{S2} + c_{ee,W2}\dot{E}_{W2} + c_{ee,M2}\dot{E}_{M2} + c_{ee,V2}\dot{E}_{V2} \tag{15}$$

$$c_{ee,S2}\dot{E}_{S2} + c_{ee,W2}\dot{E}_{W2} + ee_L \dot{N}_{hours,IN} = c_{ee,Ax}\dot{E}_{Ax} + c_{ee,Pike}\dot{E}_{Pike} \tag{16}$$

$$\dot{E}_{sun} + c_{ee,M2}\dot{E}_{M2} + c_{ee,V2}\dot{E}_{V2} = ee_L(\dot{N}_{hours,EX} + \dot{N}_{hours,CO} + \dot{N}_{hours,IN}) \tag{17}$$

To obtain the exergy footprint of the system it suffices to sum equations (14) through (17) and obtain:

$$\dot{E}_{sun} + \dot{E}_{S0} + \dot{E}_{W0} + \dot{E}_{M0} + \dot{E}_{V0} = c_{ee,Ax}\dot{E}_{Ax} + c_{ee,Pike}\dot{E}_{Pike} \tag{18}$$

---

[10] As stated in section 4, neither the capital nor the environmental remediation EE [47] appear in this formula

[11] The extended exergy cost $ee_{c,j}$ is defined as the cumulative exergy of primary resources consumed for the production of 1 kJ of exergy of product *j*. Its units are kJ/kJ.

Where the right hand side represents the total equivalent primary exergy entering the system, i.e. the total of the biosphere resources consumed by the system for its survival: by definition, its EF. The values for the two societies are reported in Table 5.

Table 5: Exergy Footprint of each product and of the two societies

Homo Neandertalensis			Homo Sapiens		
EF, kJ/person/day	EE_{ax}, kJ/unit	EE_{pike}, kJ/unit	EF, kJ/person/day	EE_{ax}, kJ/unit	EE_{spear}, kJ/unit
117988	43435	21718	97025	38032	7226

An EEA analysis provides though much more insight than this: by solving the system (14-17) in the unknowns $c_{ee,j}$ it is possible to assess how each processing step affects the total cost.

Since there are 11 unknowns (c_{eeS1}, c_{eeS2}, c_{eeW1}, c_{eeW2}, c_{eeW3}, c_{eeM1}, c_{eeM2}, c_{eeV1}, c_{eeV2}, c_{eeAx}, c_{eePike}), we need to specify 7 auxiliary equations to close the system. These equations must represent a physical relation between the extended exergy costs. Adapting to the case in study the allocation rules of Thermo-Economics [4], we posit:

$$c_{ee,W3} = 1 \qquad \text{(unpreprocessed input)} \qquad (19)$$

$$c_{ee,S1} = c_{ee,W1} \qquad \text{(co-products)} \qquad (20$$

$$c_{ee,M1} = c_{ee,V1} \qquad \text{(co-products)} \qquad (21)$$

$$c_{ee,S1} + c_{ee,W1} + c_{ee,V1} = c_{ee,M1} \frac{hrs_{gathering}}{hrs_{hunting}} \qquad \text{(Labour intensity prevails)} \qquad (22)$$

$$c_{ee,S2} = c_{ee,W2} \qquad \text{(co-products)} \qquad (22)$$

$$c_{ee,M2} = c_{ee,V2} \qquad \text{(co-products)} \qquad (24)$$

$$c_{ee,Ax} = c_{ee,Pike} \qquad \text{(co-products)} \qquad (25)$$

And obtain the results shown in Table 6.

Table 6: Extended Exergy cost c_{ee} of the intermediate streams,

c_{ee} in kJ/kJ, ee_L in kJ/workhour

Homo Neandertalensis				Homo Sapiens			
$c_{ee,S1}$	$c_{ee,m1}$	$c_{ee,AX}$	ee_L	$c_{ee,S1}$	$c_{ee,m1}$	$c_{ee,AX}$	ee_L
2.473	3.972	5.233	32787	2.274	3.724	4.659	25732

The results agree quite well with some recent values measured in modern underdeveloped societies [47,49].

5 – RESULTS: RESOURCE-WISE, AN UNAVOIDABLE EXTINCTION

The results (Table 6) show that the amount of primary resources needed to produce their weapons (one ax and one pike or spear) was different for the two species: *the average Neandertal individual had to harvest more exergy from the environment to produce the same amount of final goods*. The reasons, thermodynamically speaking, are the above outlined different lifestyles and numerosity and the different allocation of labour inside of the group. The EEA model captures both the first difference (higher material resource consumption), and the resource intensity differential between the two production processes: notice that the both the Environmental Footprint of each artefact (EF_{Ax}, EF_{pike}, in kJ/unit) and that of the society as a whole (EF_N, EF_S, in kJ/(person*day) are higher for the Neandertals.

The above results provide a preliminary answer to the initial question: the Neandertals' individual primary resource consumption for the production of their hunting tools per person/day is substantially higher than that of their "cousins" Sapiens. This is confirmed by the EF_{ax} etc., that quantifies the primary resources per unit. At a society level, the amount of primary resources consumed by the HN to sustain themselves (EF_N) was also substantially higher than that of the HS (EF_S). The picture that emerges from these results is unequivocal: *the Neandertalian "technological production chain" was globally much less efficient than the Sapiens' one; and furthermore, the Neandertals' lifestyle placed higher requirements on the environment in terms of primary resources*. It is then clear that, in case of dwindling resources (a situation that is very likely to have occurred in the Weichsel LGM and probably even before, during the post-Toba and post-Campanian Ignimbrite volcanic events), the HN species would have been at a strong disadvantage with respect to their more efficient competitors. Paleo-archeaological evidence shows in fact that in the period spanned by our window of observation the Neandertals went through a series of "survival crises" that systematically decreased their numerosity and may have led to other fatal problems, like local genetic bottlenecks and low fertility [2,8,52,55], which sealed their extinction.

6 – CONCLUSIONS

Within the frame of a series of investigations aimed at the definition of thermodynamically-based sustainability criteria, the primary resource consumption of two primitive societies, the Neandertal and the early Sapiens, have been compared. The goal was to establish whether there were resource-related factors that placed the Neandertals at a disadvantage with respect to their competitors. Under the given assumptions, the results show that in the considered window of observation -between 115 and 15 kyBP- the resource consumptions of the two species were indeed substantially different, the Sapiens' lifestyle being more "frugal". The inevitable simplifications required by the modelling suggest and the strong dependence of the results on the initial assumptions suggest to examine these result with care, although a sensitivity analysis (not presented here) reinforces the idea that even significantly different scenarios would not have changed the Neandertal's disadvantage. The analysis has been performed at steady-state, and in view of the likely influence of time-dependent factors like genetic bottlenecks, interbreeding and possible local competition, this is a very strong limitation. It is therefore suggested that further attention to the dynamics of the exergy footprint of the two species is addressed in future studies.

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