Four Simple Dynamic Models to Understand Sustainability[1]

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Introduction

The term sustainability in the ecologic meaning we intend today has been coined recently, but the topic is not particularly new. Around 300 years ago, Mr Thomas Malthus approached the theme of sustainability in his book *An Essay on the Principle of Population* (Malthus 1798). He formulated a theory based on the observation that the rate of food production was less rapid than the population growth (at least at that time). So, at a certain point, not enough food will have been produced, provoking several diseases to the population, as starvation, famines and even wars. Those events would cut down the population toward a more sustainable size. Thus, to avoid such disasters, Malthus proposed 'to control' the population size regulating birth rates to be attained by means of voluntary chastity. This recommendation was and it is still criticised, also for controversial religious aspects, but beyond any ethical issues, we should recognise that the real importance of Malthus's thoughts has been the proposal 'to manage' the dynamic between food and population in a way to prevent the occurrence of disasters. Unfortunately, at the time when Malthus formulated his theory, pointing out a quantitative assessment of such complex dynamic was quite difficult: a mathematical description of the correlation between population and food production variables needed a lot of 'manual' calculations. Almost two centuries later things changed thanks to the development of Computational Science and the invention of System Dynamic modelling by Jay Forrester. The union of these two events helped and still helps a more in-depth understanding of the forerunner Malthus theory, as well

[1] This work was partially supported by the MEDEAS project, funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 691287. The opinions expressed in the present work are those of the authors' only and are not to be attributed to any organ of the European Union.

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https://doi.org/10.36250/00698_01

as of the newer theories and research in the field of sustainability management. In the present work, a set of simple dynamic models will be presented to retrace the origin of sustainability management and to highlight how this topic remains one of the main issues to solve for the modern society.

1. Methodology: modelling sustainability

System Dynamic modelling (FORRESTER 1995) allows skipping the steps of creating a model using pencils, papers and solving equations with hours of manual calculations just resorting to a software with which we can sketch and solve the same equations very fast. I use the word 'sketch' because with most of the System Dynamic programming tools math operators and variables can be represented by graphical objects. It is worth highlighting that those graphical objects often recall the shape of subjects that already have a meaning in our mind: arrows describe flows, valves describe regulators, boxes describe stocks. This new language permits 'to write mathematically' in a more intuitive way, especially for those who are not math experts. So, the method allows a substantial saving of time. This is also why System Dynamic turns out to be a very useful method to explore interdisciplinary systems, exactly as the case of sustainability management, where scientific and/or technological-related fields interface with social and economic dynamics. For this reasons, a set of 'mind sized' (BARDI 2013) System Dynamic models will be presented and discussed in the following paragraphs with the aim to individuate the archetype dynamics of sustainability.

2. Sustainability management: results and discussions

2.1. The Malthus model

According to Malthus's ideas, as they are described in his book, food grows (at best) linearly while the population would grow exponentially. The stock of food is therefore fostered by a constant inflow regulated by the constant k1. The food is consumed by the population stock, which grows proportionally to the birth rate constant k2 and to the population itself and decreases proportionally to the death rate constant k3 and to the population itself. We can see in the graphs that, initially, food is in excess, the population starts growing while the food is consumed in a smaller quantity than produced, so it also keeps growing linearly until it reaches a peak, while the population still continues to grow. This provokes the food stock level to start decreasing because now it is consumed faster and faster by the increasing population. To avoid a total depletion of food, the population should stabilise together with the level of the remaining food stock, as shown in Figure 1.

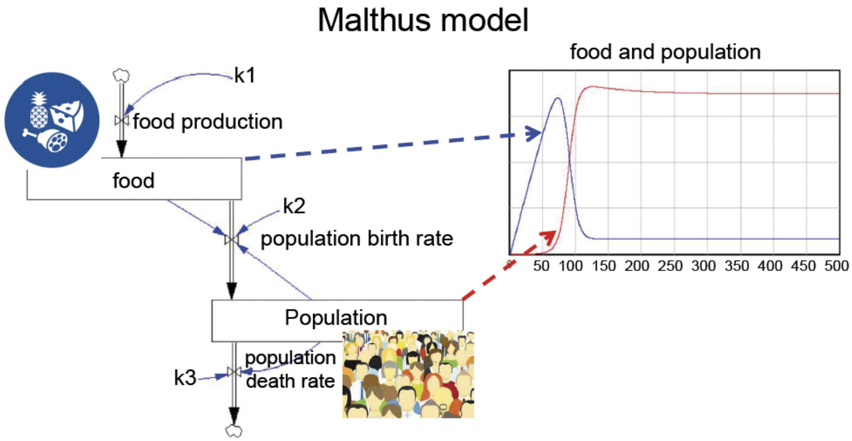

Figure 1.
The Malthus model

Source: drawn by the authors

In the above figure, the Malthus dynamic is represented by a simple dynamic model. According to Malthus's theory food grows linearly while the population grows exponentially. Here, the carrying capacity is represented by the maximum flows of food regulated by the parameter k1.

This model also contains the concept of carrying capacity elaborated by Nicholas Georgescu-Roegen in his work *The Entropy Law and the Economic Process* (GEORGESCU-ROEGEN 1971) even though the concept cannot be found in Malthus's work. How long can a given population, be it 1 million or 40 million, be maintained? Georgescu-Roegen correctly argued that Malthus was too optimistic, as he failed to recognise any upper limit to the growth of population. According to Malthus, the exponential increase in human numbers is occasionally slowed down by the difference in the slower rate of food increase in comparison to the population rate but Georgescu-Roegen widened the vision of Malthus, pointing out that some upper limit to population should be primarily bound to the existence of a limit of the total arable land and the limited amount of mineral resources Earth can provide us. In the System Dynamic Malthus model, the carrying capacity is evidently enclosed in the k1 parameter, which cannot be either infinite or constant, but it is destined to decrease considering the further Georgescu-Roegen clarification on the possibility of Recycling. Georgescu-Roegen assesses that recycling of materials and resources is possible, but only by using up some new energy resources plus an additional amount of other material resources. Energy resources, in turn, cannot be recycled at all, but are dissipated as waste heat according to the second law of thermodynamics.

2.2. The Lotka–Volterra model

Georgescu-Roegen's vision depicts a world economy that will continue growing until its inevitable and final collapse, due to resource scarcity. This hypothesis has been further recognised and assessed quantitatively by the study of Limits to Growth. Is there any other possible dynamic model that could help us in managing these situations to avoid disasters, especially in the view that renewable energy can be employed as a new source of energy?

To examine this point we need the help of Vito Volterra, who is one of the fathers of the famous Lotka–Volterra model, better known as the prey–predator model. He developed this model (independently of Mr Lotka) with the help of his son in law, the biologist Umberto D'Ancona (D'ANCONA 1942). As a difference to the Malthus model, the prey–predator model, still representable with a stock and flow diagram, has now a stabilising feedback between the stocks of prey and the predator, represented in Figure 2.

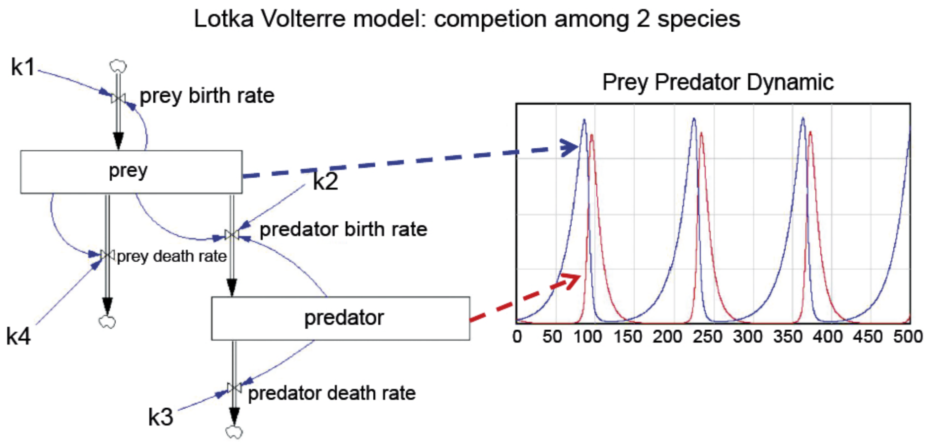

Figure 2.
The dynamic of the prey–predator model represented by the System Dynamic model
Source: drawn by the authors

It can be seen that the interaction between the prey and predator stocks provokes oscillations in the number of individuals, oscillations that, in a certain sense, represent that the system has a feature of autoregulation, at least between two populations in the prey–predator relationship: it describes a sustainable dynamic.

This model has been criticised because it can describe only very few situations in the real world, which is normally more complex than a one to one relationship of the model. Nevertheless, very recently, we found that a slightly revised version of the Lotka-Volterra model, shown in Figure 3 can fit a larger number of real systems, in particular, related to the dynamic of overexploitation of an important renewable natural resource: fish.

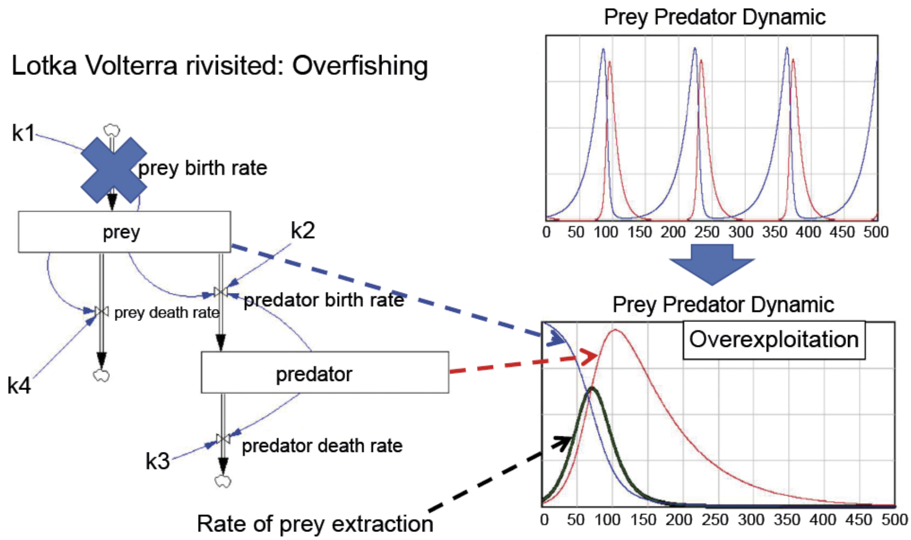

Figure 3.
Dynamic of the prey–predator interaction revisited: the case of overexploitation in fishing
Source: drawn by the authors

The model is the same as the original LV model. Here, the prey is the fish and the predator is the capital investment the fishery needs for fishing, capital that in a certain sense represents the predatory abundance. The situation is the following: due to the fact that the capital investment in fisheries tend to increase even at the moment when fish becomes scarce, in order to try to sustain the market demand, the fisheries tend to invest more effort in fishing, so that the fish is extracted from the sea faster than it can reproduce. This dynamic transforms the fish into a non-renewable resource, so the oscillation just happens once, with no possibility to recover the prey. This model has been tested and validated on a set of several statistics data on the collapse of fisheries (Perissi et al. 2017), as for the case of right and sperm whale fisheries in the United States during the 1800s, the Californian Sardines during the 1950s and the Japanese fishery decline. These tests revealed that also in cases of regulated fishing, the fish quotas are still insufficient in most cases. We can conclude that the saying "Give a man a fish, he eats for a day, teach a man to fish, he eats for a lifetime" is now changed in "Give a man a fish, he eats for a day, overfishes, and soon no one eats". Thus, even if a resource is renewable, such as fish, the economic system relying on it is destined to collapse. This is mainly due to a lack of common sense in revisiting the present economic approach making a real connection with the environment rhythms and the exploitation of the natural resources.

2.3. The Seneca cliff

Today, speaking of sustainability does not only imply the management of the predator's behaviours of the human being, as the Malthus and Volterra models teach, but there is a third actor on the stocks' scene that aggravates the situation: pollution. We may call this is 'a side effect' – although by no means negligible – of the intense exploitation of fossil fuels or the results of thermodynamic processes that transform raw materials into something very difficult to enter or to be reintegrated in the ecosystem. The rule of this third stock is well explained in the book *The Seneca Effect* of Ugo Bardi (Bardi 2017). Bardi explains that Lucius Annaeus Seneca, the Roman philosopher of the 1st century AD, qualitatively observed that in the real world some processes grow slow but collapse rapidly. This can be represented by a 3 stocks system dynamic model, as shown in Figure 4.

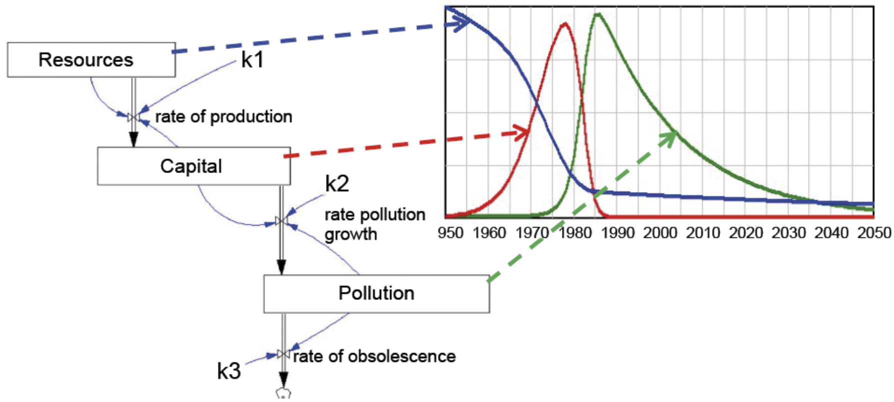

Figure 4.
Dynamic of collapse

Source: drawn by the authors

In the tentative to remove pollution, resources are dissipated further. Here again, we have no more a one to one relationship between the resources and the capital stock, the presence of a third stock (waste, pollution) to manage, to remove from society accelerates the dissipation of the capital derived by the exploitation of resources, and so, to maintain at least the same capital, resources must be depleted faster.

2.4. The Tainter model

The global pollution stock originates from a recent side effect of resources exploitations, an effect of the Industrial era. But there is a fourth stock, observed by the anthropologist Joseph Tainter that plays an important role in the sustainability dynamic: the complexity of society. Tainter, in its book *The Collapse of Complex Societies* (Tainter 1988), points out and describes, once again qualitatively, why complexity is the reason for the collapse of ancient developed civilizations, as Romans and Maya. Tainter observed that, until a certain level, complexity improves the efficiency of the transformation of resources into capital. In this way, complexity has a positive effect on the efficiency of the social organisation. Nevertheless, over a certain level, complexity absorbs resources without producing new capital or productive business: We can assimilate this situation with the presence in the society of a large number of bureaucratic activities. This is more or less the definition, in the economic term, of the diminishing returns of complexity, a term that Tainter coined to synthesise the previous concept, and that can be represented graphically by the following curve.

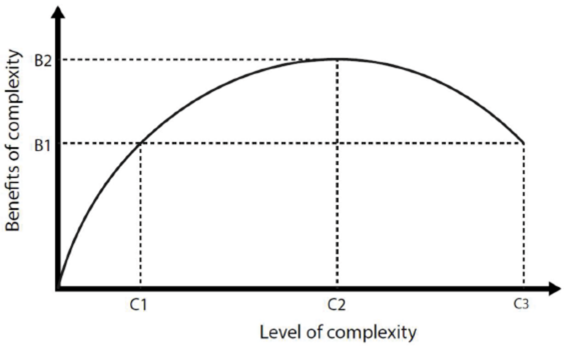

Figure 5.
Tainter's qualitative model

Source: drawn by the authors

Tainter's qualitative model represents how the increasing level of complexities can bring benefit to an organisation which has an upper level increasing further complexities and all this only contributes to creating bureaucracy.

In a certain sense, bureaucracy is a predator that lives on a lower trophic level stock. Moreover, Tainter does not speak explicitly of pollution and waste as reasons of the collapse of ancient civilizations, nevertheless, we can assess that they were and still are elements originated by complexities of a society. With a 4 stock model, we can represent Tainter's theory (Figure 6).

What we point out with this representation is that the Tainter curve of diminishing the return of complexity (production is assimilated to the benefit of complexities while complexity is identified here in terms of the level of bureaucracy) does not stop at a certain point, but it shows a hysteresis. This hysteresis represents the impossibility to go back to a simpler society, and hence, to remove part of the complexity to establish again a more efficient use of resources. This model describes the hypothesis in which the society exploits mainly resources that are not renewables, as in the case of a society based on fossil fuels or other mineral resources availability. Anyway, the system could return to a simpler configuration if it was based on renewable resources, provided that we give to resources the reform, without overexploiting them as in the case of fishing. Otherwise, the system again would behave as based on not renewable resources.

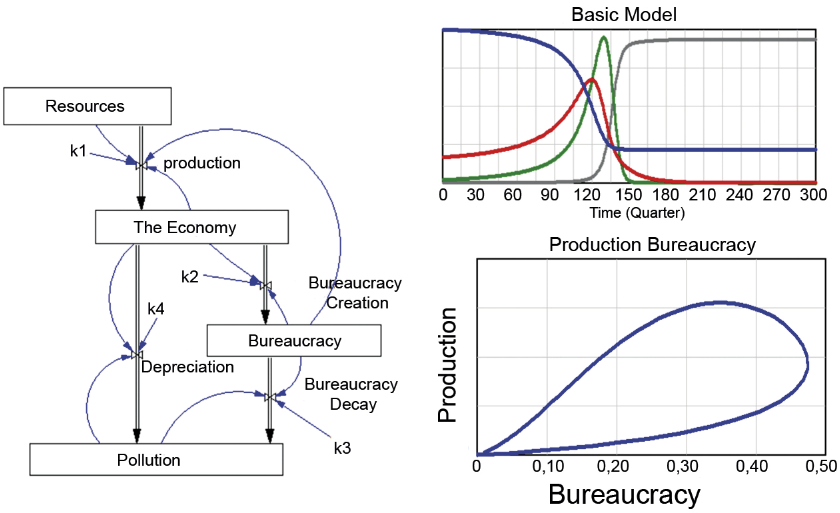

Figure 6.

Tainter's principle of 'diminishing the return of complexity' explicated with a system dynamic modelling approach

3. Conclusion

In the present paper, four 'mind sized' system dynamic models are proposed with the aim to unveil the archetype of sustainability in modern society. Each of the models is built with the aim to translate quantitatively the dynamic of fundamental theories related to the management of sustainability. The main outputs of this analysis can be summarised in a vision that aims to transform the human being activity on the planet, mainly related to economic processes and natural resources exploitation, in an activity that must harmonise with the rhythms of the ecosystem. We have the keys to a better future: dominate human actions and pursue resources limits management in a sustainable way.

4. References

BARDI, U. (2013): Mind Sized World Models. *Sustainability,* Vol. 5, No. 3. 896–911. DOI: https://doi.org/10.3390/su5030896

BARDI, U. (2017): *The Seneca Effect.* Springer International Publishing. DOI: https://doi.org/10.1007/978-3-319-57207-9

D'ANCONA, U. (1942): *La lotta per l'esistenza.* Torino, Giulio Einaudi Editore.

FORRESTER, J. (1995): The beginning of system dynamics. *McKinsey Quarterly,* November 1995. Source: www.mckinsey.com/business-functions/strategy-and-corporate-finance/our-insights/the-beginning-of-system-dynamics (Accessed: 12.02.2020.)

Georgescu-Roegen, N. (1971): *The Entropy Law and the Economic Process.* Harvard, Harvard University Press.

Malthus, Th. R. (1798): *An Essay on the Principle of Population as it Affects the Future Improvement of Society.* London, J. Johnson.

Perissi, I. – Bardi, U. – El Asmar, T. – Lavacchi, A. (2017): Dynamic patterns of overexploitation in fisheries. *Ecological Modelling,* Vol. 359. 285–292. DOI: https://doi.org/10.1016/j.ecolmodel.2017.06.009

Tainter, J. A. (1988): *The Collapse of Complex Societies.* Cambridge, Cambridge University Press.