Synthesis

The study entitled “The trajectory of the Anthropocene: The Great Acceleration” [1] shows a great acceleration for socio-economic and earth system trends, starting from the post war world II. Moreover, after the 1950 there is a clear evidence that fundamental changes in the functioning of the Earth System are guided by human activities. These trends brought the research community to define a sustainable development paradigm for the Anthropocene with an integrated point of view [2,3]. The Earth’s Life Support System is seen as the higher limit that includes society, which in turn includes economy, which in turn includes the manufacturing industry. Therefore, the idea of “Absolute Sustainability” was introduced [4], as well as that of the IPAT equation to quantify the overall environmental impact of an human activity [5,6]. At the same time, the attention to the efficient use of energy and resources is grooving among the political authorities. At worldwide level, the G7 Summit Declaration of June 2015 launched the G7 Alliance on Resource Efficiency with the aim to promote Circular Economy (CE), Remanufacturing and Recycling concepts as strategic actions [7]. A report produced by Ellen MacArthur Foundation with the McKinsey Center for Business and Environment and the SUN Institute, strongly recommends the need to switch to a CE system for Europe in order to remain competitive in the manufacturing sector at global level [8]. Therefore, it is possible to notice how the CE actions are currently seen as solution to meet the requirements of our world. However, it is necessary to contextualise the CE logics with the current manufacturing paradigm. According to [9], the main characteristic of the current paradigm (i.e., the direct digital manufacturing - DDM) is that the design requirements of a product are directly created by a network of different people. The Additive Manufacturing (AM) technology is considered as one of the drivers of DDM. In fact, with AM, CAD files and open-source printer software, products can be directly manufactured close to the customer and directly derived from digital models [9,10].

This work finds its space into this panorama. More in details, it aims to answer to the following research questions:

Research Question 1 (RQ1). With a Circular Economy point of view, how to assess the remaining useful lifetime of products and how to perform a LCA study under a function-oriented analysis?

Research Question 2 (RQ2). How to evaluate the energy efficiency of a manufacturing technology at the unit process level and which can be a good methodology to achieve this goal?

The RQ1 comes from the need of LCA methodologies customised for a CE-based scenario. In fact, the available LCA methodologies applied to a linear economy scenario mainly focus on a single production of the product and do not pursue the comparison for the further lives the product may have. Moreover, the implications of the reliability property on the iterated products represent a central topic still to be addressed. The study in this work is performed considering AM processes to offer an immediate relationship with the current manufacturing paradigm [11,12], even if, the proposed methodology can be applied to other production techniques.

The RQ2 mainly comes from the need to feed the developed LCA methodologies with data that are closely related to the considered case study. In particular, the literature showed practices already available for conventional processes (e.g., machining, injection moulding). On the other hand, the study of the state-of-the-art literature regarding the AM techniques produced the need to fill different research gaps. Moreover, the boundary constrains of the current manufacturing paradigm require an investigation of the advantages and disadvantages that AM can also bring regarding the sustainability at its unit process level. For instance, AM techniques are characterised from low productivity and high energy demand, especially in comparison with bulk and subtractive techniques [13–16]. Therefore, this kind of study are particularly worth for this technology.

This thesis is articulated as follows: (a) an introduction section to better contextualise the performed work; (b) Chapter 1 for the literature review to support the RQ1 and RQ2 and to define the state-of-the-art literature gaps and the aims of this work; (c) Chapter 2 develops the LCA methodology for a CE scenario; (d) Chapter 3 investigates the energy efficiency at the unit process level of different AM technologies; finally, (e) the conclusion section summaries the results and makes considerations on the entire work.

[1] W. Steffen, W. Broadgate, L. Deutsch, O. Gaffney, C. Ludwig, The

trajectory of the Anthropocene: The Great Acceleration, The Anthropocene Review. 2 (2015) 81–98. https://doi.org/10.1177/2053019614564785.
[2] J. Rockström, Bounding the Planetary Future: Why We Need a Great Transition, (2015).
[3] W. Steffen, K. Richardson, J. Rockstrom, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. de Vries, C.A. de Wit, C. Folke, D. Gerten, J. Heinke, G.M. Mace, L.M. Persson, V. Ramanathan, B. Reyers, S. Sorlin, Planetary boundaries: Guiding human development on a changing planet, Science. 347 (2015) 1259855–1259855. https://doi.org/10.1126/science.1259855.
[4] M.Z. Hauschild, S. Kara, I. Røpke, Absolute sustainability: Challenges to life cycle engineering, CIRP Annals. 69 (2020) 533–553. https://doi.org/10.1016/j.cirp.2020.05.004.
[5] P.R. Ehrlich, J.P. Holdren, Impact of Population Growth, Science. 171 (1971) 1212–1217. https://doi.org/10.1126/science.171.3977.1212.
[6] B. Commoner, The environmental cost of economic growth, Population, Resources and the Environment. 339–363.
[7] G7, G7 Summit Declaration, (n.d.). www.consilium.europa.eu/en/meetings/international-summit/2015/06/07-08/.
[8] Ellen MacArthur Foundation, Growth within: a circular economy vision for a competitive europe, (2015). https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf.
[9] D. Chen, S. Heyer, S. Ibbotson, K. Salonitis, J.G. Steingrímsson, S. Thiede, Direct digital manufacturing: definition, evolution, and sustainability implications, Journal of Cleaner Production. 107 (2015) 615–625. https://doi.org/10.1016/j.jclepro.2015.05.009.
[10] I. Gibson, D.W. Rosen, B. Stucker, Additive Manufacturing Technologies, Springer US, Boston, MA, 2010. https://doi.org/10.1007/978-1-4419-1120-9.
[11] M. Matsumoto, S. Yang, K. Martinsen, Y. Kainuma, Trends and research challenges in remanufacturing, International Journal of Precision Engineering and Manufacturing-Green Technology. 3 (2016) 129–142. https://doi.org/10.1007/s40684-016-0016-4.
[12] M. Leino, J. Pekkarinen, R. Soukka, The Role of Laser Additive Manufacturing Methods of Metals in Repair, Refurbishment and Remanufacturing – Enabling Circular Economy, Physics Procedia. 83 (2016) 752–760. https://doi.org/10.1016/j.phpro.2016.08.077.
[13] K. Kellens, R. Mertens, D. Paraskevas, W. Dewulf, J.R. Duflou, Environmental Impact of Additive Manufacturing Processes: Does AM Contribute to a More Sustainable Way of Part Manufacturing?, in: Procedia

CIRP, The Author(s), 2017: pp. 582–587. https://doi.org/10.1016/j.procir.2016.11.153.

[14] K. Kellens, M. Baumers, T.G. Gutowski, W. Flanagan, R. Lifset, J.R. Duflou, Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental Implications, Journal of Industrial Ecology. 21 (2017) S49–S68. https://doi.org/10.1111/jiec.12629.

[15] H.-S. Yoon, J.-Y. Lee, H.-S. Kim, M.-S. Kim, E.-S. Kim, Y.-J. Shin, W.-S. Chu, S.-H. Ahn, A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study, International Journal of Precision Engineering and Manufacturing-Green Technology. 1 (2014) 261–279. https://doi.org/10.1007/s40684-014-0033-0.

[16] S. Junk, S. Côté, A practical approach to comparing energy effectiveness of rapid prototyping technologies, Proceedings of AEPR'12, 17th European Forum on Rapid Prototyping and Manufacturing. (2012).