Digitalisation of Food Materials: A key step for Industry 4.0

Manoj K Patel[a,c], Geoffrey R Mitchell[b]
[a]CSIR–Central Scientific Instruments Organisation, Chandigarh–16003, Chandigarh, India
[b]Centre for Rapid and Sustainable Product Development, Polytechnic of Leiria, 2430-080, Marinha Grande, Portugal
[c]Academy of Scientific and Innovative Research, Ghaziabad–201002, Uttar Pradesh, India

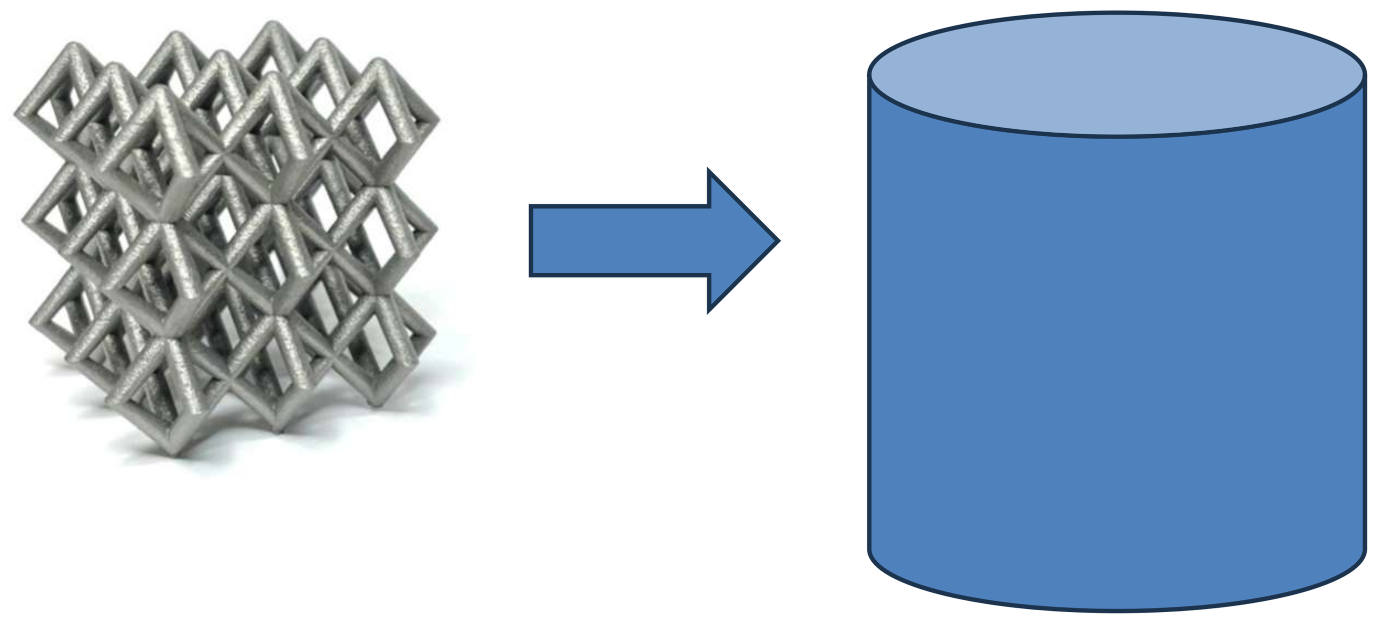
INTRODUCTION & AIM

The Food Processing 4.0 concept takes food processing into the digital era by leveraging Industry 4.0 technologies to improve the quality and safety of food and reduce waste [1]. Despite the severe environmental challenges facing the food industry (such as accounting for a significant portion of global anthropogenic GHG emissions and biodiversity loss [2]), Food Processing 4.0 offers novel pathways towards sustainable production through digital technologies (e.g., digital mixing, personalised food) — for instance, by optimising processes to reduce resource waste or by utilising precision formulations to lower carbon footprints. One of the major advantages of the digitalisation of manufacturing is the ability to optimise the workflow in terms of any objective function. Such objective functions could include greenhouse gas emissions, nutritional value, reversing obesity, and, of course, more medically formulated objective functions such as the prevention of diabetes. Another advantage of digital manufacturing is the ability to vary the properties during the fabrication process [3], thereby opening up pathways to personalisation and to graded structures in the final product. A key and necessary step in digital optimisation is to define the digital coordinate space for food materials and the method of describing properties and composition. We are looking forward to a scenario of 3D printing of food materials. This is akin to 4D printing of more technical products, in which the part printed is not the final product, but is transformed via an optical, thermal, or similar method to the final product, which, in general, will exhibit a different shape. In the case of food 3D printing, a major part of the fourth stage will be a thermal transformation to largely the same shape but with different properties and composition. This presentation introduces these concepts and lays out a roadmap of possibilities and actions.

METHOD

Digital Manufacturing proceeds in distinct stages:
Stage A: is the use of soft pliable material, including liquids, gels, and powders, to prepare 3D shapes through the use of extrusion and digital fabrication techniques.
Stage B: these shapes transform to a solid 3D shape through the process of solidification, gelation, cross-linking, and other technologies
In the case of food technology
Stage C: these solid shapes are transformed into ready-to-eat food through thermal and other process technologies

Stage A to Stage B must take place quickly to retain the shape imposed by the technology used to define it
Stage B to Stage C must take place on a time-scale required for edible food production and for an effective production rate



A

C

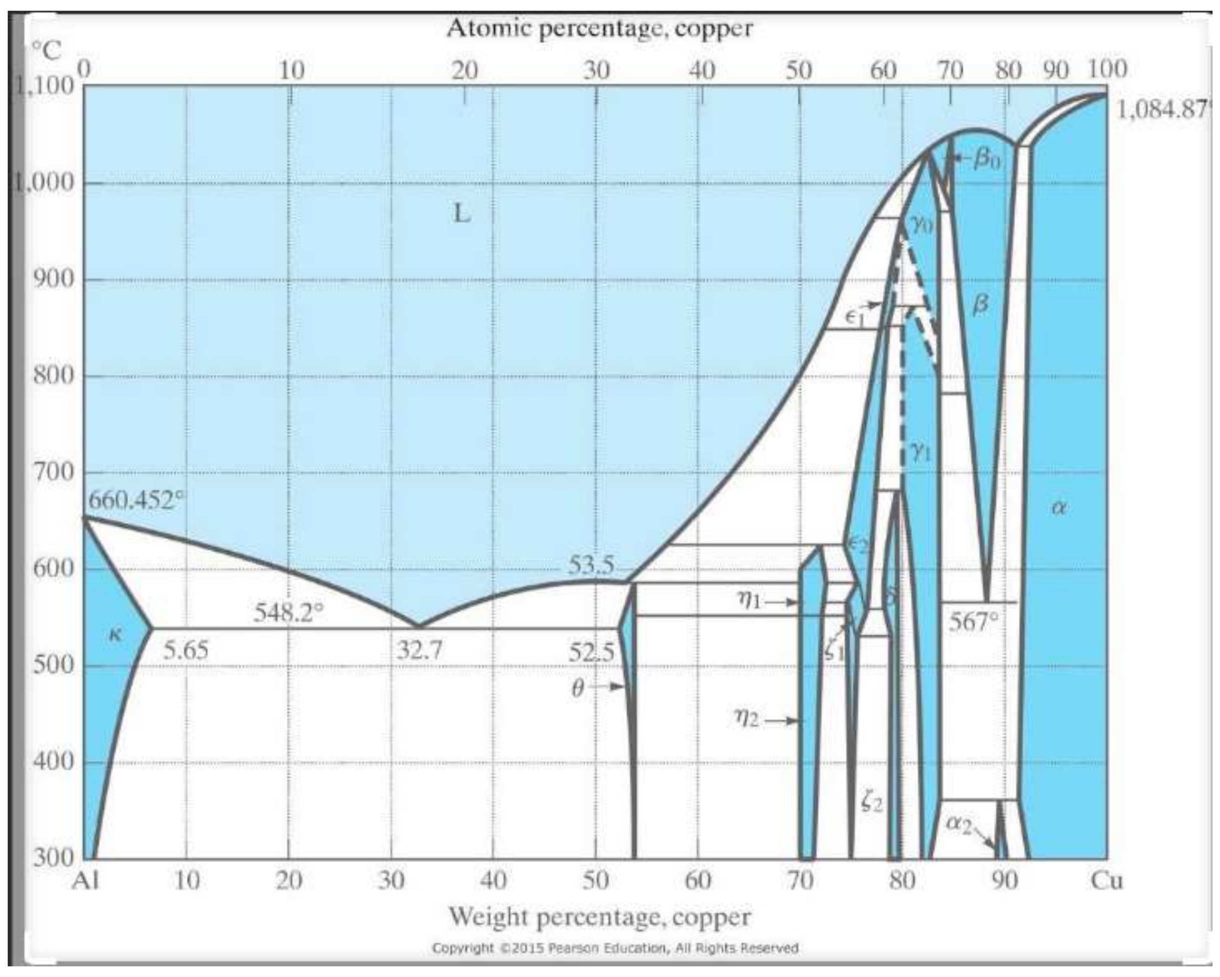
The objective here is to produce tailored and personalised food products with specific nutritional and therapeutic value at stage C with ingredients at stage A with quite different, physical, chemical and biochemical properties

For this digital manufacturing process to deliver the full value of digital fabrication, we need to identify an appropriate digital description for the materials and processing parameters so that the process of fabrication can be digitally optimised against the target nutritional and therapeutic needs of the end user.

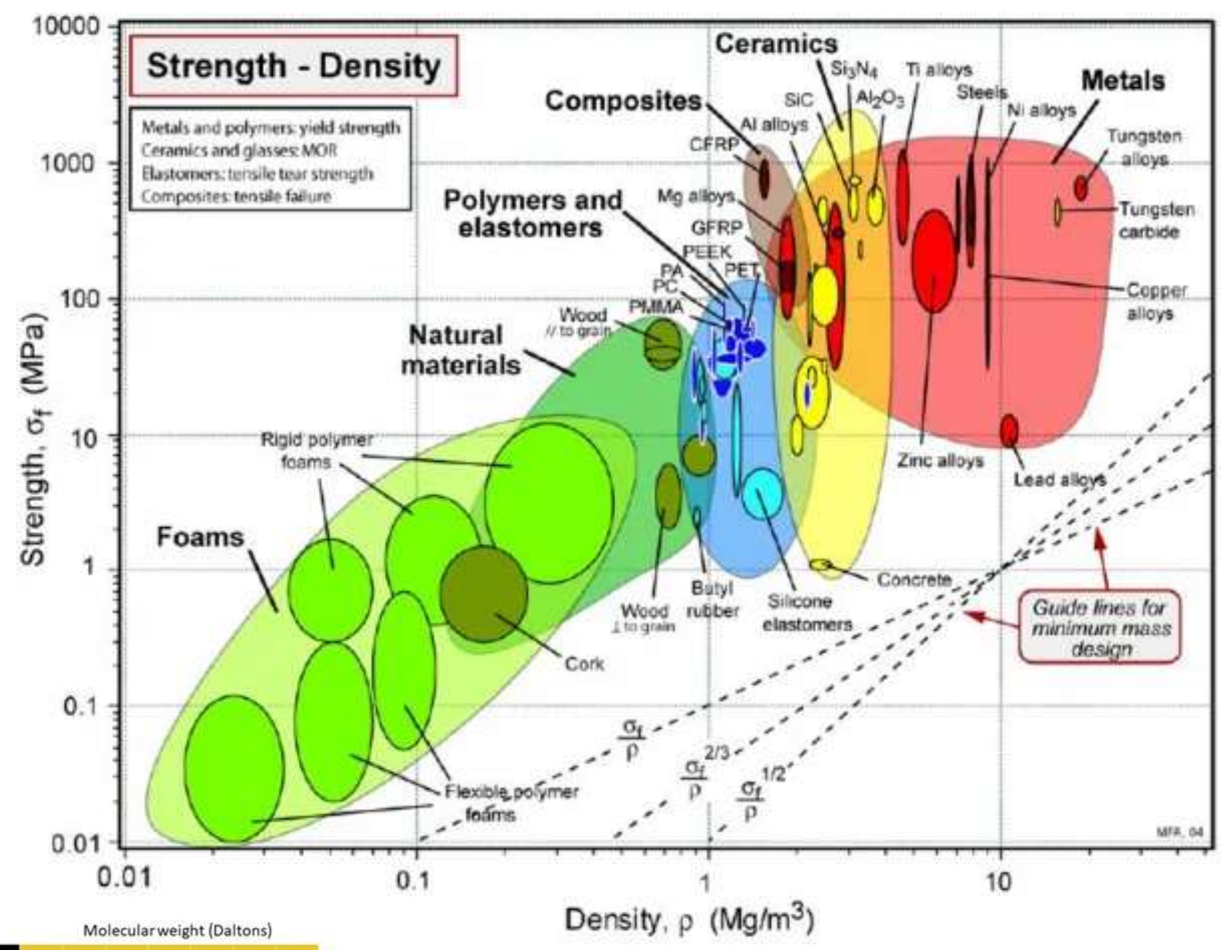
RESULTS & DISCUSSION

Digitilisation of materials is not only a challenge for food materials but for all materials in this digital era.

Let us consider as an example, metals, these are largely elemental materials so the example should be simpler. We could start by considering the digital coordinate space for a metal as the elemental composition



Here we show the phase diagram for a mixture of copper and aluminium [4]. It shows the phases that will exist under equilibrium conditions as a function of composition (horizontal axis) and Temperature (vertical axis). It shows a series of phases from α at the Cu rich end to κ at the aluminium-rich end. From a practical point of view, we know from hundreds of years of metallurgy research that the composition of the final product will be elementally similar to the start point, but from a phase point of view, it will depend critically on the time-temperature profile from the homogenous melt to the solid state, and the phase distribution will determine the properties of the product.



Another approach to the coordinate space for materials is that developed by Prof Ashby in the late 1980s [5]. He developed an approach in which material types are placed on a chart known as “Ashby plots,” usually with two axes, in the example shown here, strength and density. They are excellent in showing how the properties of materials change from foam, through polymers, ceramics, and metals. We can immediately see the advantages and the disadvantages. In terms of material selection, they are excellent but as a material coordinate system, there is no continuity and much of the space is empty.

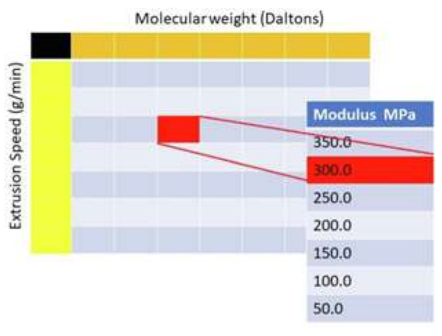


Fig. 1. An illustrative example of the mapping of properties to a multidimensionallook up table of processing parameters and material characteristics. Here we show only a 2D mappingfor simplicity but in practice there will be a much more complex mapping [3].

We adopt the methodology of Faria et al [3] in which the proposed fabrication systemis used to prepare test samples of the food product and for example the nutritional and theraputic value is evaluated and this becomes the material coordinate system and with each set of values there is a set of conditions used to manufacture the product

CONCLUSION

1. The digitilisation of materials is vital is we are to realize the full benefits of digital manufacturing allowing optimization of the complete process from synthesis through to end of life treatment.
2. Materials are a critical component of manufacturing which are challenging to digitalize and there appears no convenient generalised solution.
3. We propose a generalised approach in which the materials digital space is focused on properties in the widest sense and that each property element is mapped to a multi-dimensional space which identifies the processing parameters required to achieve that property.

FUTURE WORK / REFERENCES

[1] Hassoun, A., Aït-Kaddour, A., Abu-Mahfouz, A. M., Rathod, N. B., Bader, F., Barba, F. J., … Regenstein, J. (2022). The fourth industrial revolution in the food industry—Part I: Industry 4.0 technologies. Critical Reviews in Food Science and Nutrition, 63(23), 6547–6563. https://doi.org/10.1080/10408398.2022.2034735
[2] Bekzod Khakimov, Violetta Aru, Tomasz Pawel Czaja, Søren Balling Engelsen,” Foodomics: A lever to avoid the Darwinian boomerang of malnutrition and compromised nutritional value in the rapidly emerging green food transition,” 2025 Trends in Food Science & Technology, 159,104997, doi.org/10.1016/j.tifs.2025.104997.
[3] Pascoal-Faria, P., da Silva, D.P., Mateus, A. and Geoffrey R Mitchell, (2023) “Digitalisation of material science – Improving product design in the context of Industry 4.0”, Materials Today: Proceedings, doi.org/10.1016/j.matpr.2023.06.237.
[4] Ashby M.F. “Materials Selection in Mechanical Design” 3rd edition, by M.F. Ashby (Elsevier-Butterworth Heinemann, Oxford, 2005).
[5] Aluminium-Copper phase diagram online https://techschems.com/aluminium-copper-phase-diagram accessed 20th October 2025.