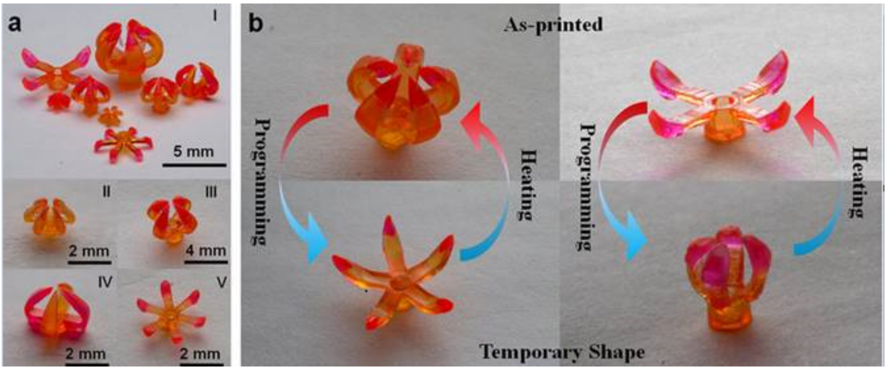
Series Editor
Jean-Charles Pomerol

4D Printing 1

Between Disruptive Research and Industrial Applications

Frédéric Demoly
Jean-Claude André

Color Section



Evidence of a 4D effect (reversible closure by thermal effect according to Ge et al. 2016)

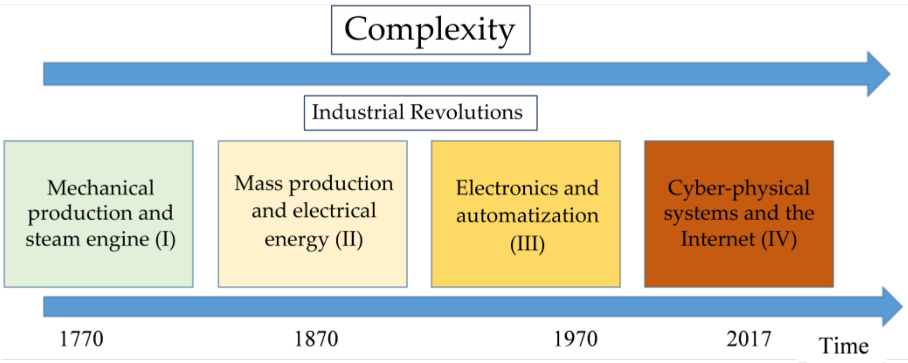


Figure P.1. *Technological change: from Industry 1.0 to 4.0*

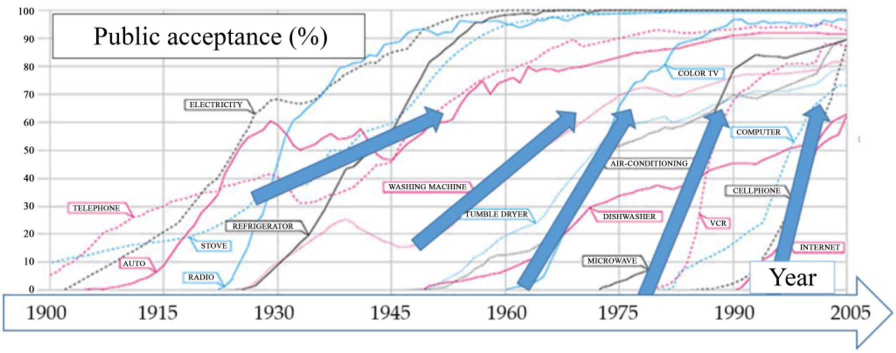


Figure P.3. *Increasingly rapid appropriation of technologies*

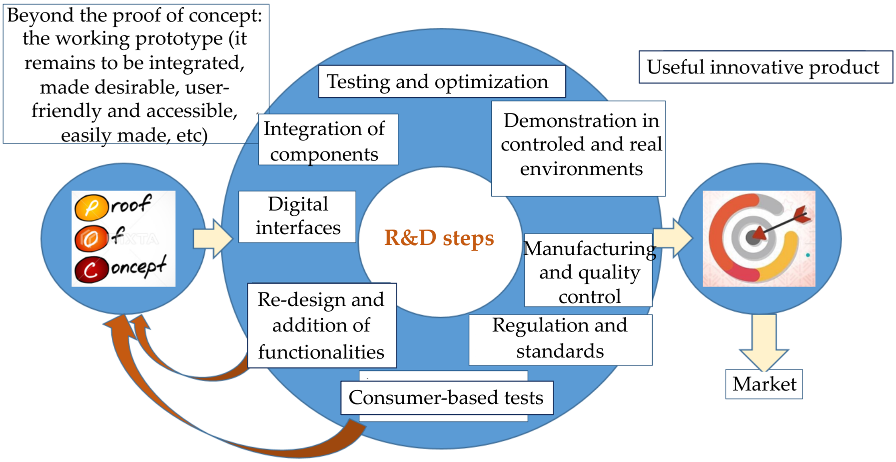


Figure P.6. *From concept to application*

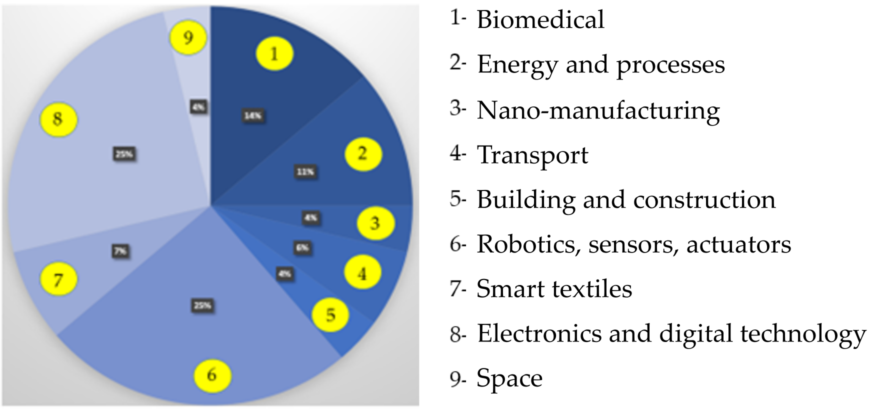


Figure P.7. *Examples of applications of 4D proposed in the literature*

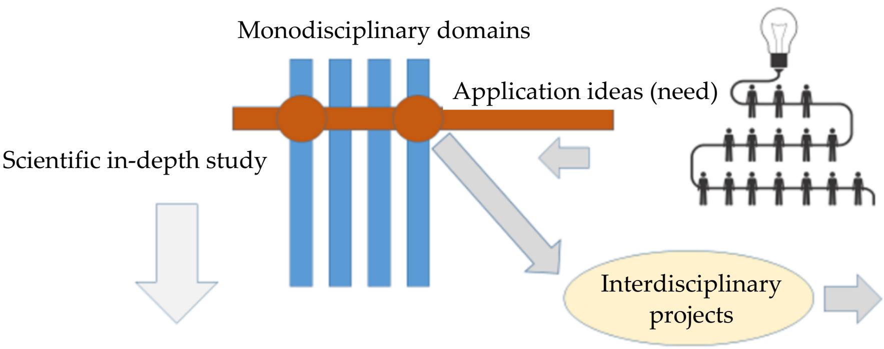


Figure P.8. *Proposed basic action plan for the development of 4D printing: crossing between top-down and bottom-up approaches*

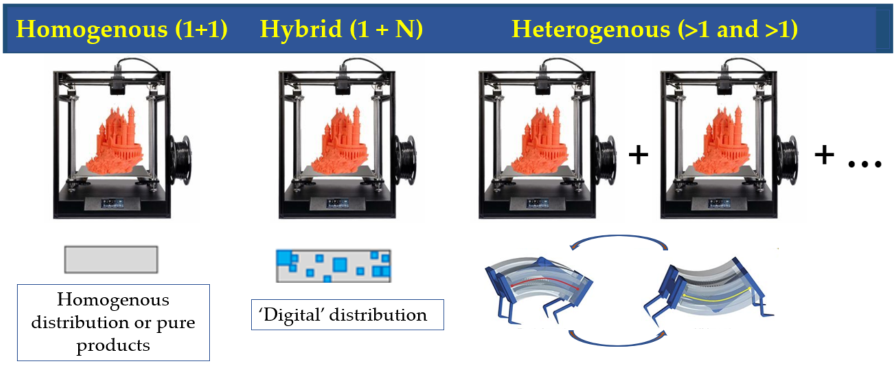


Figure I.2. *The different forms of 4D printing (e.g. it is possible to do hybrid 3D printing with a multi-material machine and heterogeneous 3D printing when we couple different processes)*

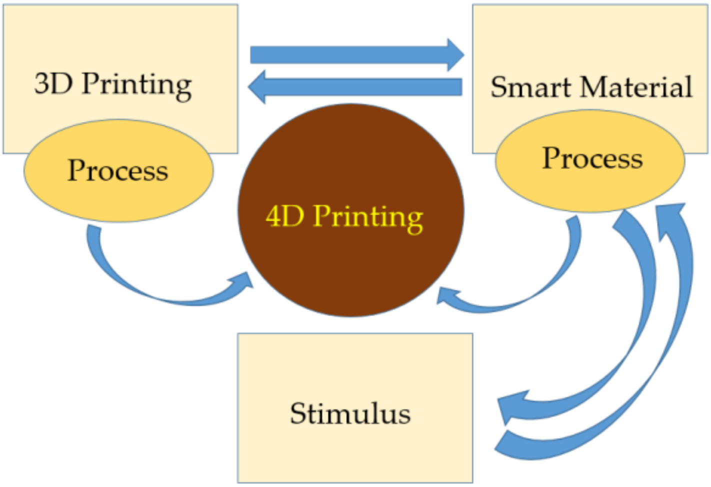


Figure I.4. *Process-material coupling in 4D printing*

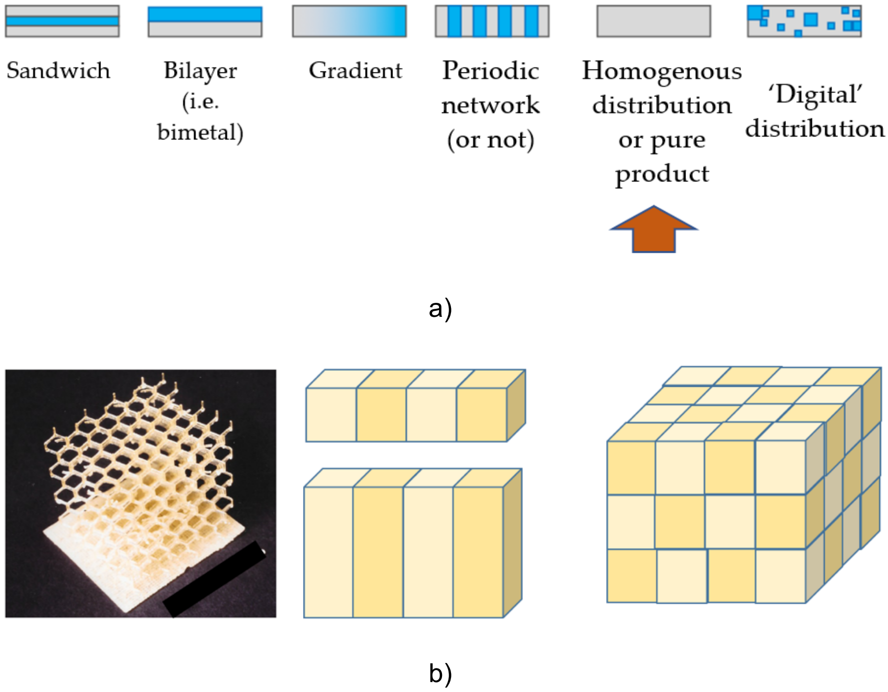


Figure I.5. *How to change the spatial properties of a structure over time: a) 2D system; b) 3D system according to Castles et al. (2016)*

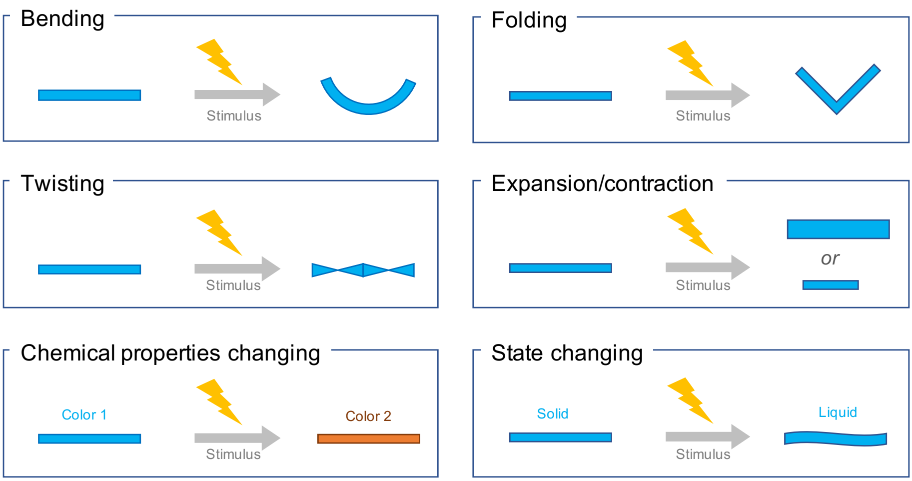


Figure I.6. *Change opportunities of pure and/or associated materials that can be exploited in 4D printing (from Dimassi et al. (2021))*

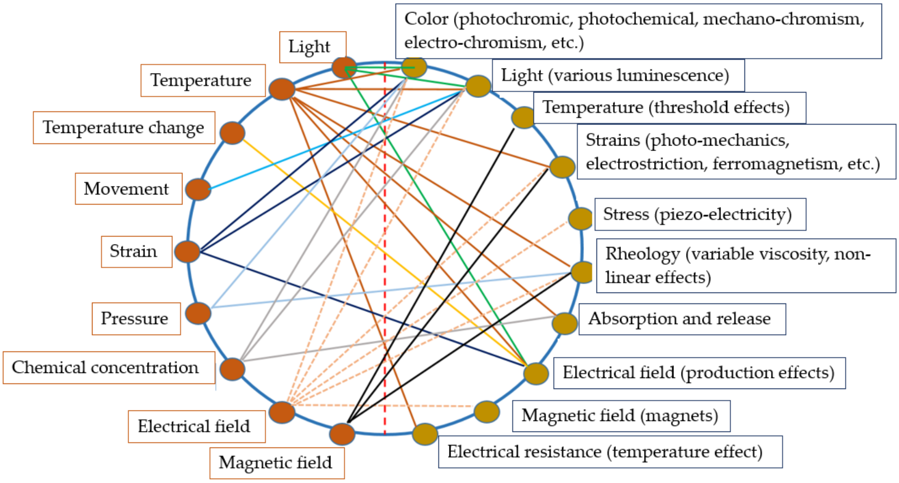


Figure 1.1. *Examples of cause-effect relationships in 4D printing*

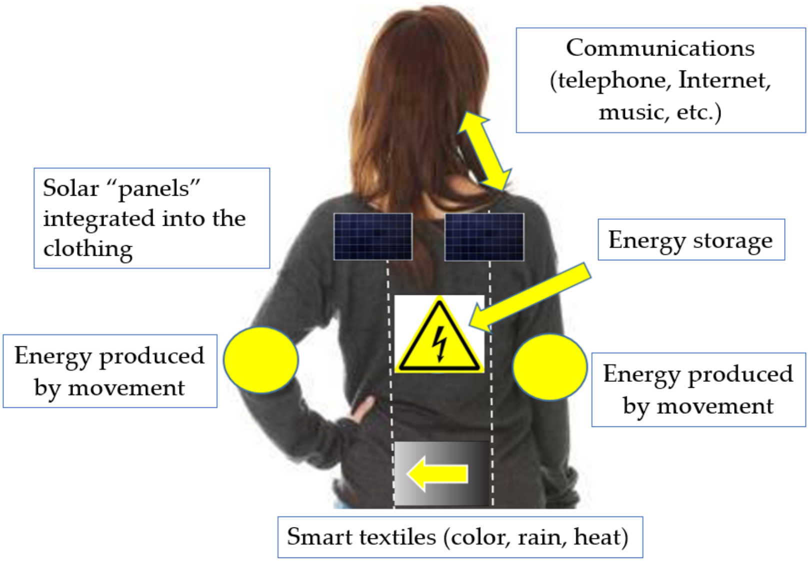


Figure 1.2. *Integrations enabled by 4D printing; the example of smart clothing*

Figure 1.3. *Peter Breughel's The Blind Leading the Blind*

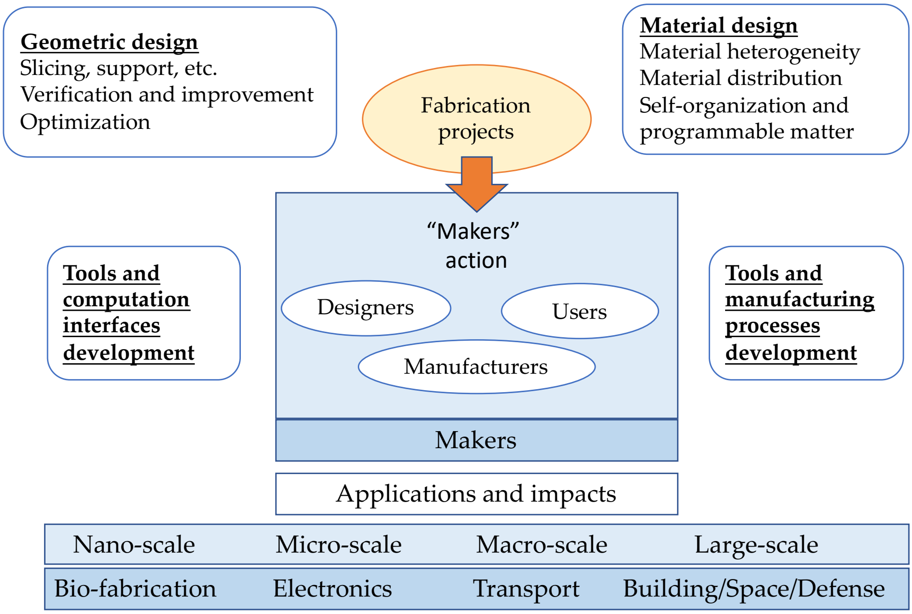


Figure 1.5. *Offerings resulting from the mastery of 3D technologies*

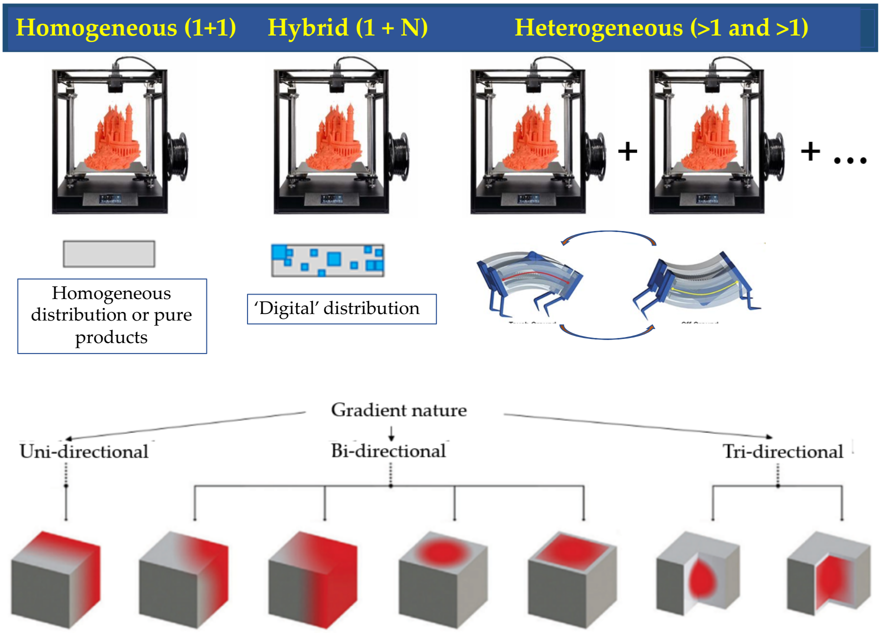


Figure 1.6. *The different forms of 4D printing*

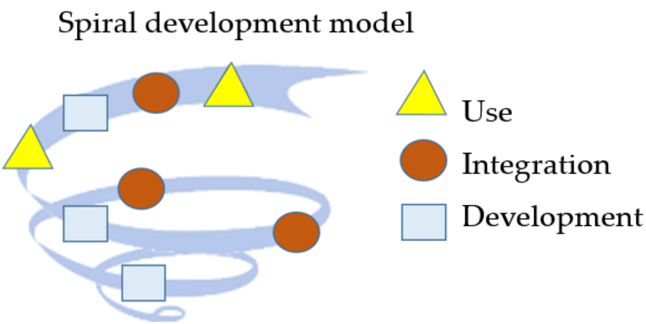


Figure 1.7. *Spiral development process and stages involved in the system design lifecycle*

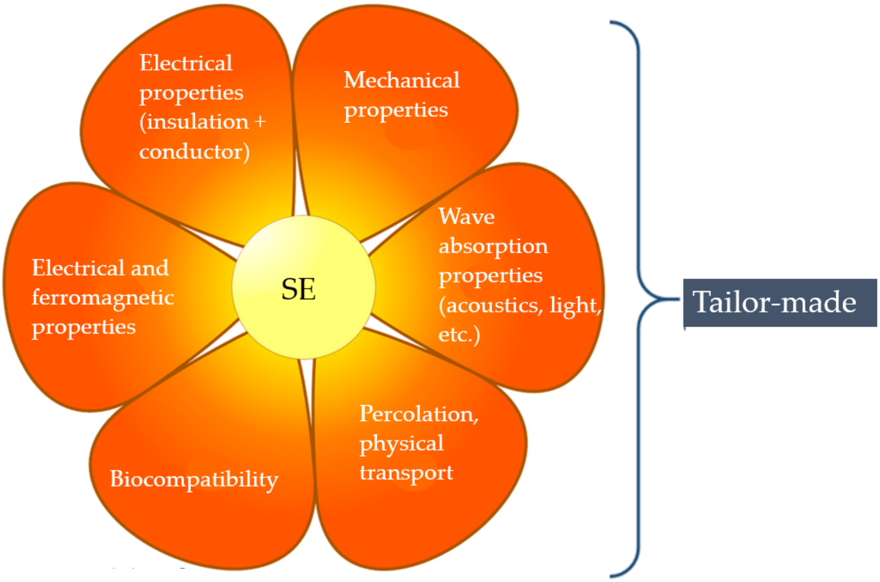


Figure 1.8. *Properties sought in structural electronics (SE)*

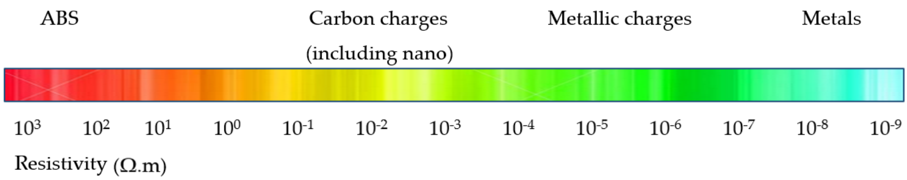


Figure 1.9. *Resistivity of conductive/insulating materials used in 4D printing (illustrating the interest of hybrid manufacturing)*

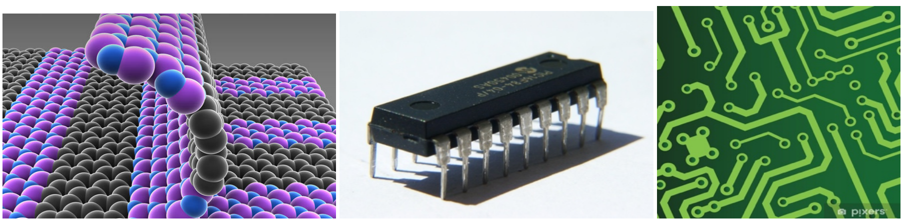


Figure 1.10. *Scaling in electronics*

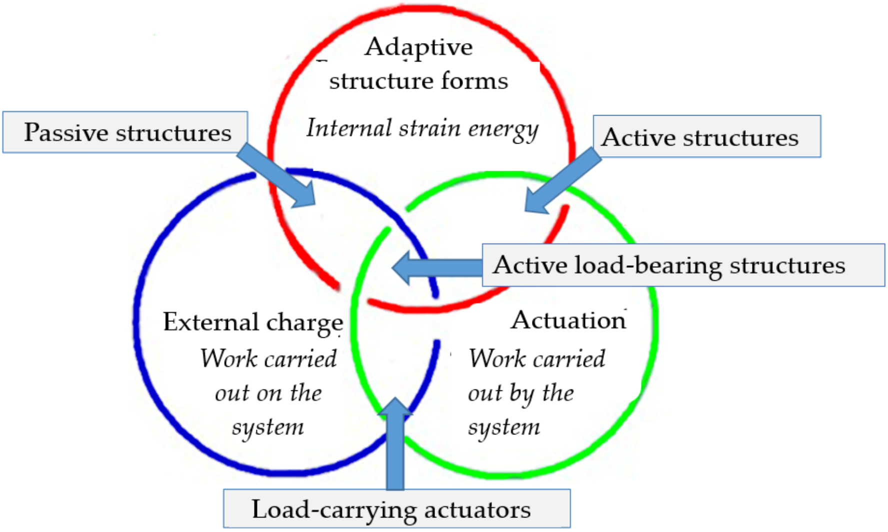


Figure 1.11. *Interdependencies between passive structures and active structures*

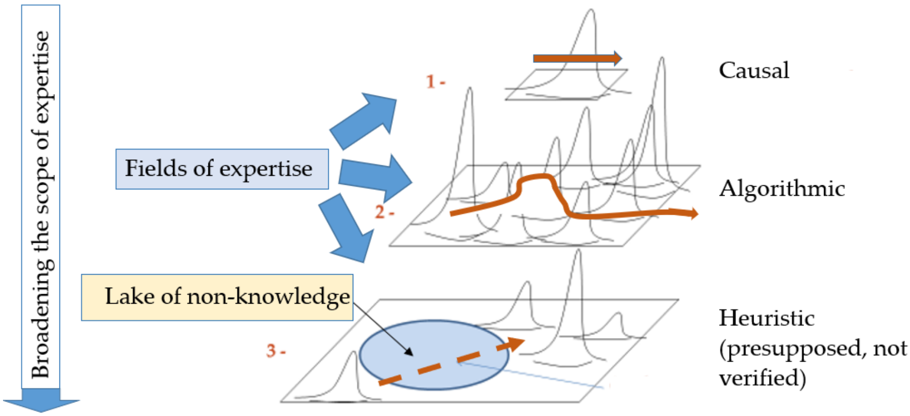


Figure 1.12. *Fields of expertise (the approximate Gaussian lines represent the scientific achievements from previous research work; depending on the form of expertise, the field is covered (causal, algorithmic) or partially covered (heuristic))*

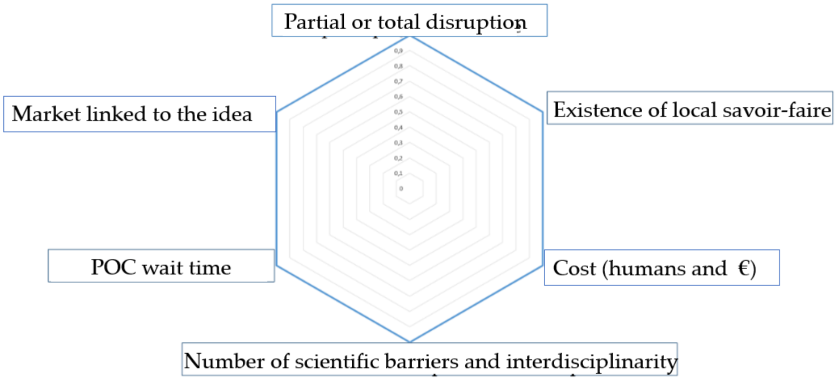


Figure 1.13. *Basis for "strategic" project evaluation*

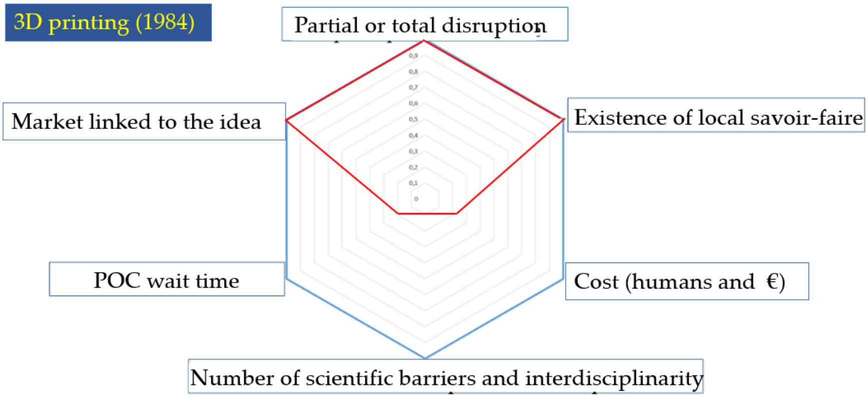


Figure 1.14. *Example of 3D printing (applicable to 4D printing)*

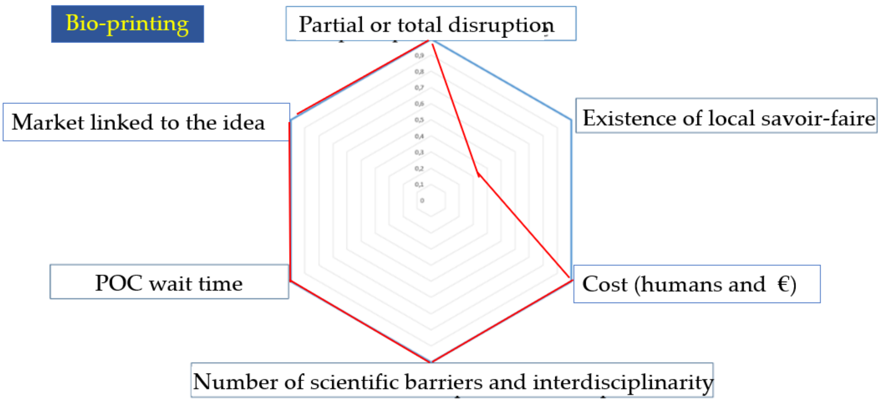


Figure 1.15. *Example of bio-printing*

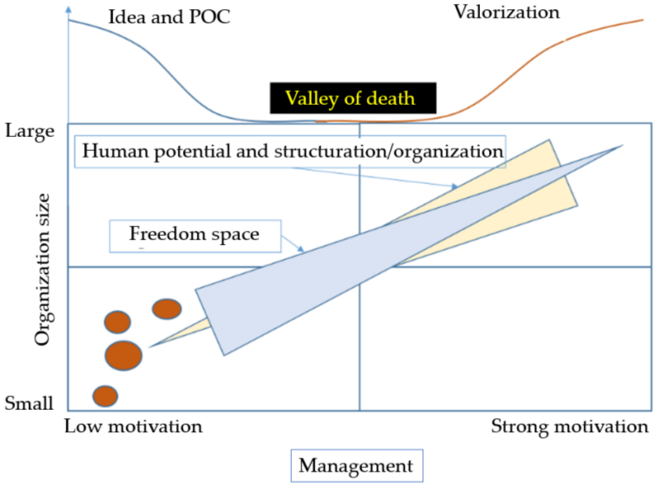


Figure 1.16. *From idea to application*

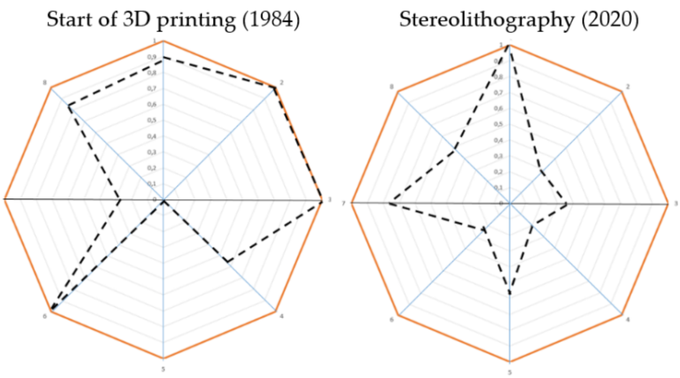


Figure 1.17. *Evolution of the mapping of scientific evolution*

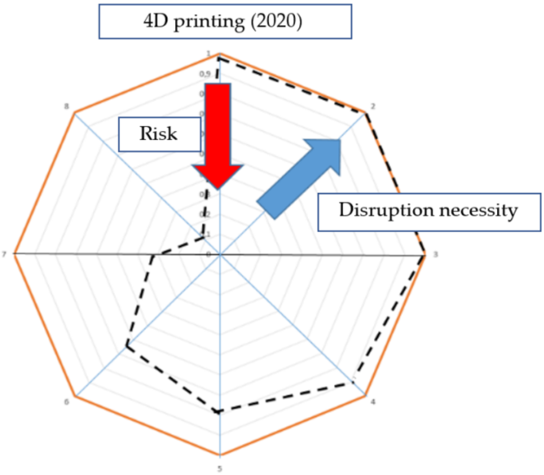
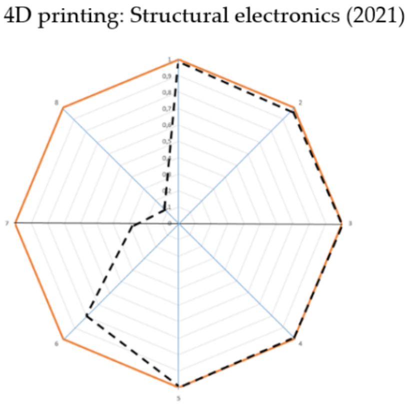


Figure 1.18. *Mapping of scientific evolution for 4D printing*



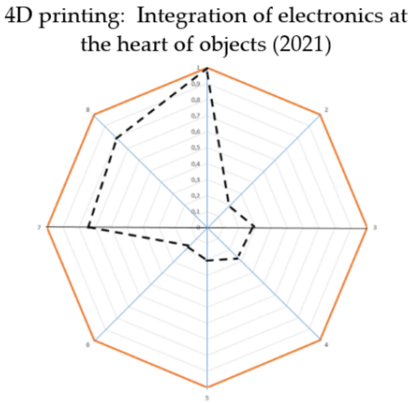


Figure 1.19. *Comparison between two situations. Left: electronics in the core of objects; right: absorption of acoustic waves*

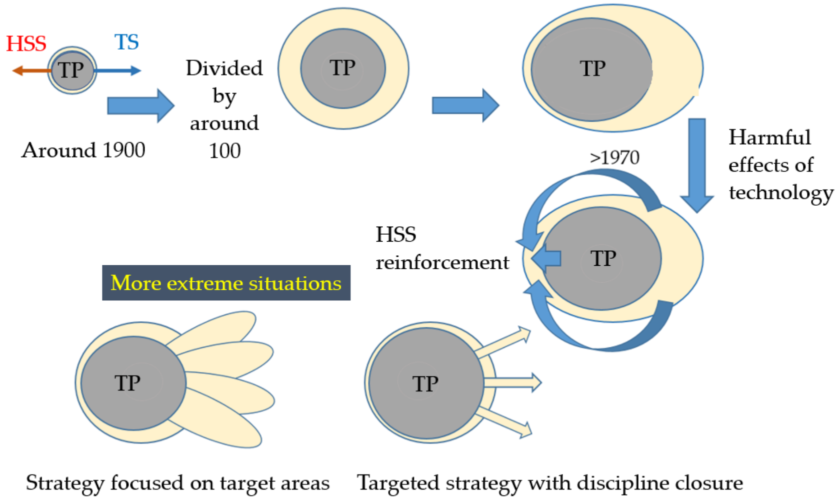


Figure 1.21. *Relationships between technological progress (TP) and strategic research policy (HSS: human and social sciences, associated with environmental sciences and hazard and risk management sciences; TS: technosciences and "hard" sciences)*

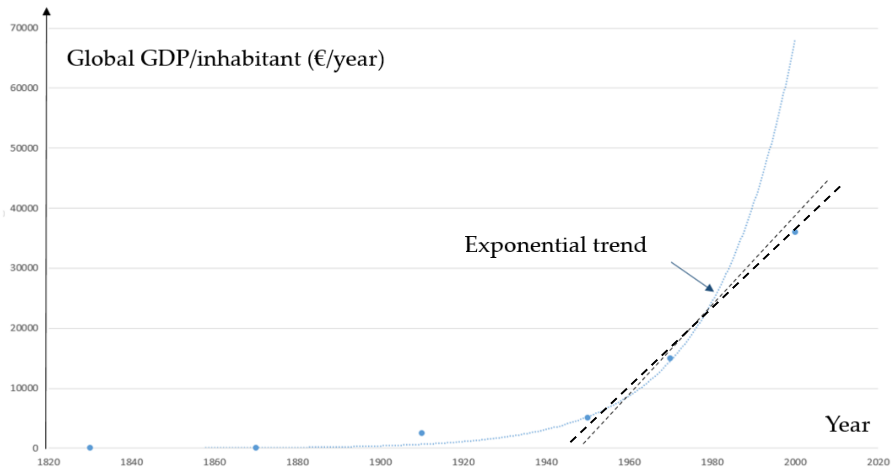


Figure 1.22. *Evolution of world GDP (black dotted line, linear evolution)*

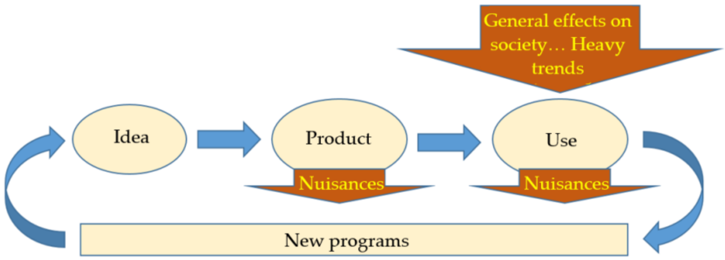


Figure 1.23. *Continuous improvement process associated with technological advancement*

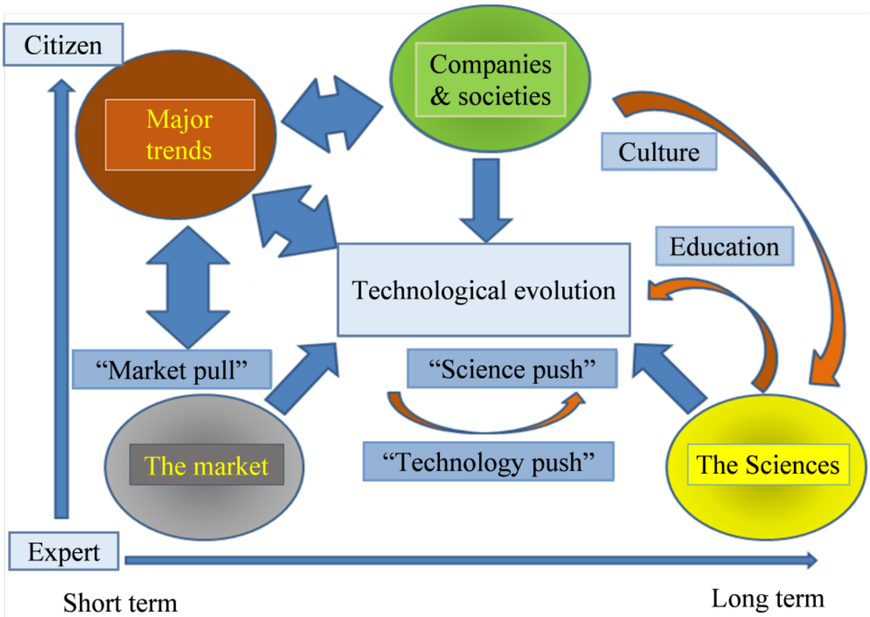


Figure 1.24. *A vision of linkages to be considered in techno-scientific foresight*

Figure 2.1. *Spectacular example of a 4D object made with heat sensitive polymers, validation for additive manufacturing according to Ge et al. (2016)*

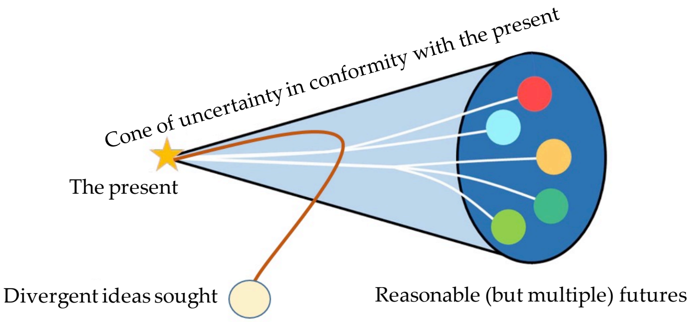


Figure 2.2. *Between compliance and divergence in the survey*

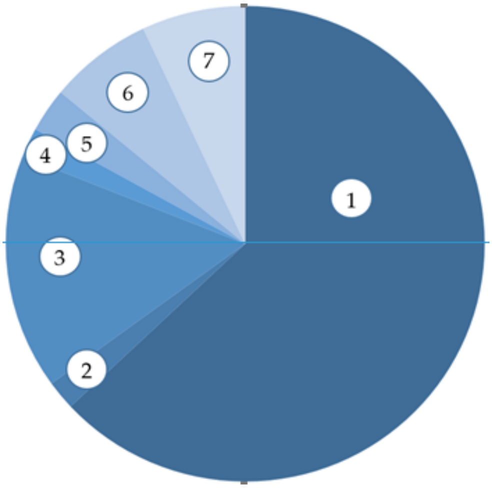


Figure 2.4. *Topics covered in publications on 4D printing (1. Organic materials and their stimuli: 63%; 2. Inorganic materials and their stimuli: 2%; 3. Review articles: 16%; 4. Modeling: 2%; 5. Miscellaneous: 3%; 6. Applications: 7%; 7. Processes (including 4D origami): 7%)*

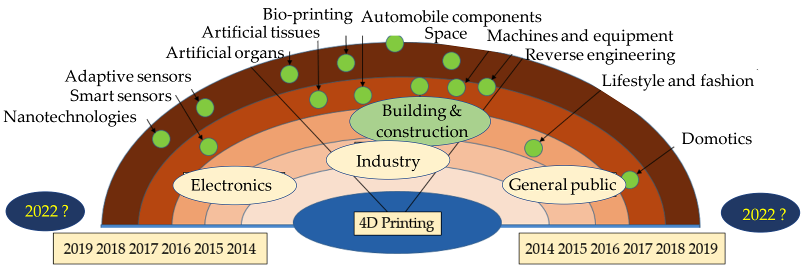


Figure 2.5. *Possible (potentially optimistic) anticipated applications of 4D printing methods*

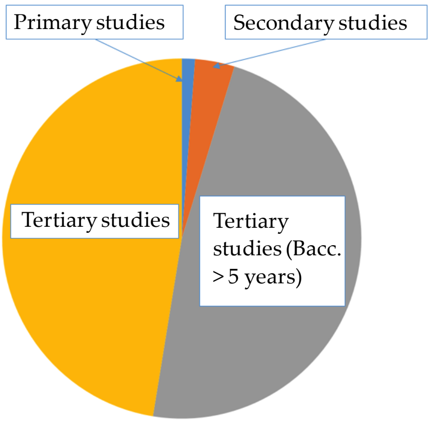


Figure 2.6. *Educational attainment of respondents (to compare with OECD data)*

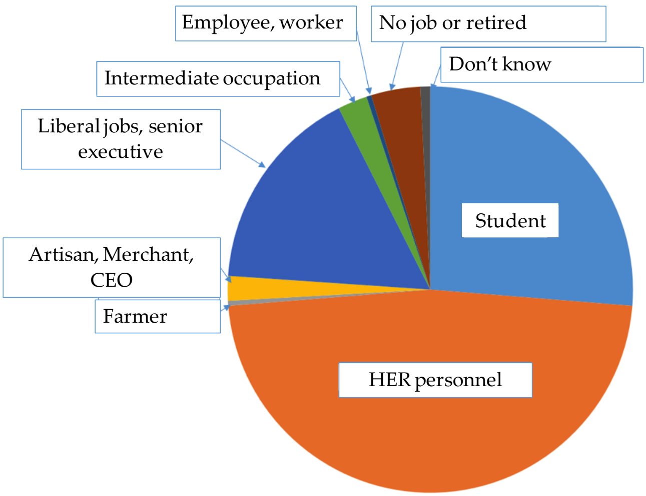


Figure 2.7. *Distribution of respondents by activity (HER for Higher Education and Research)*

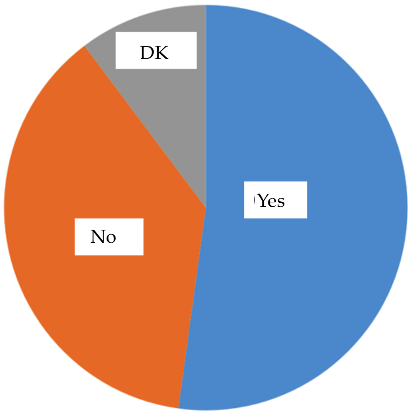


Figure 2.8. *Usefulness of 4D printing for respondents in the future (DK: Don't know)*

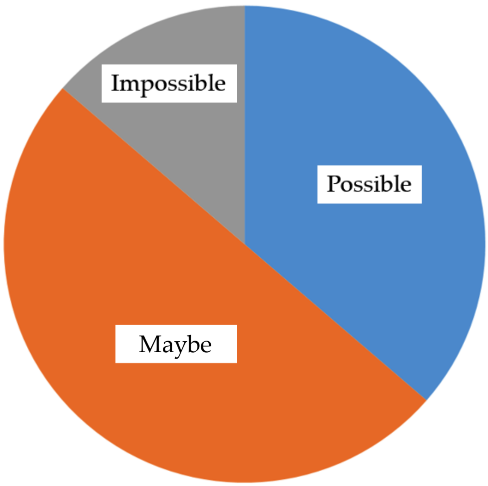
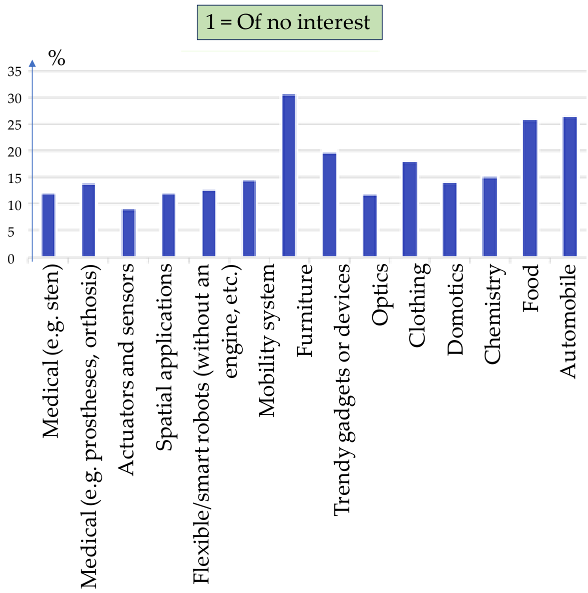


Figure 2.9. *Distribution of spontaneous responses according to their current feasibility*



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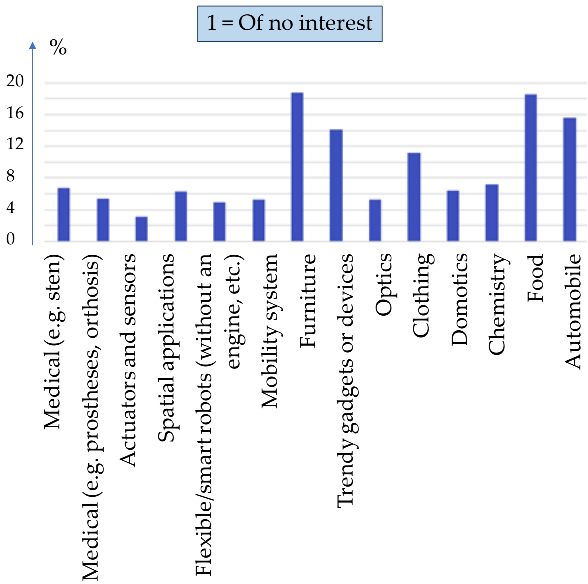
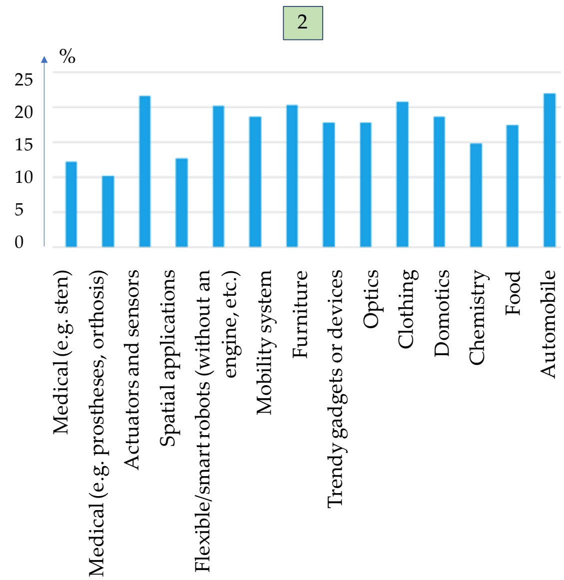


b)

Figure 2.12. *Responses by category (1: not interested – A: now; B: future)*



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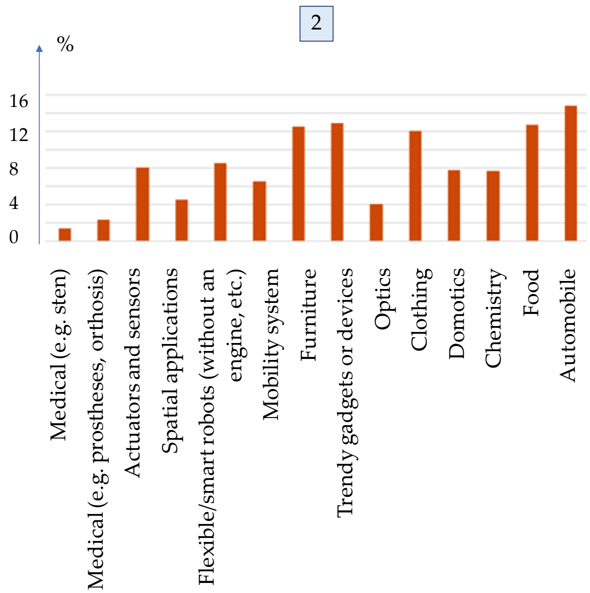

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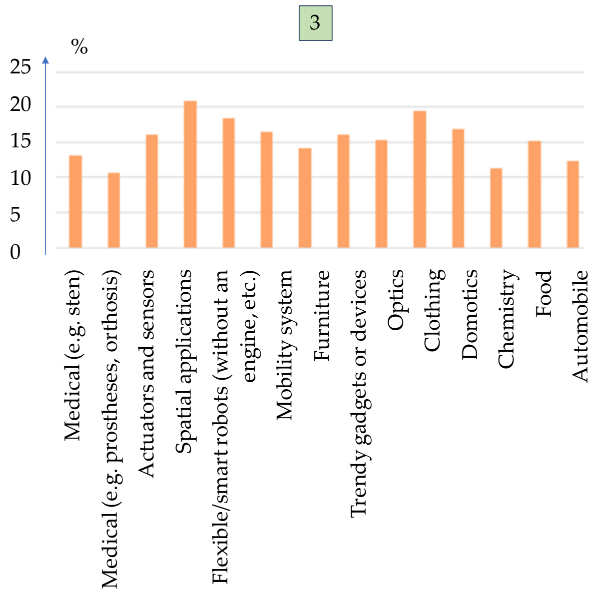
Figure 2.13. *Responses by category (2: not interested – A: now; B: future)*



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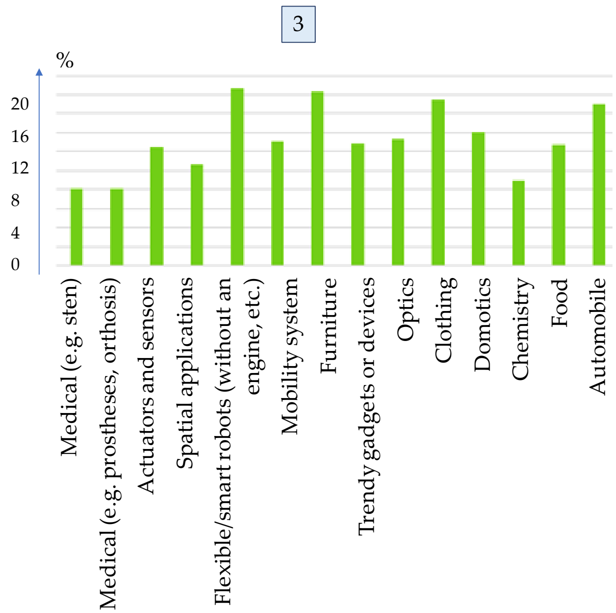

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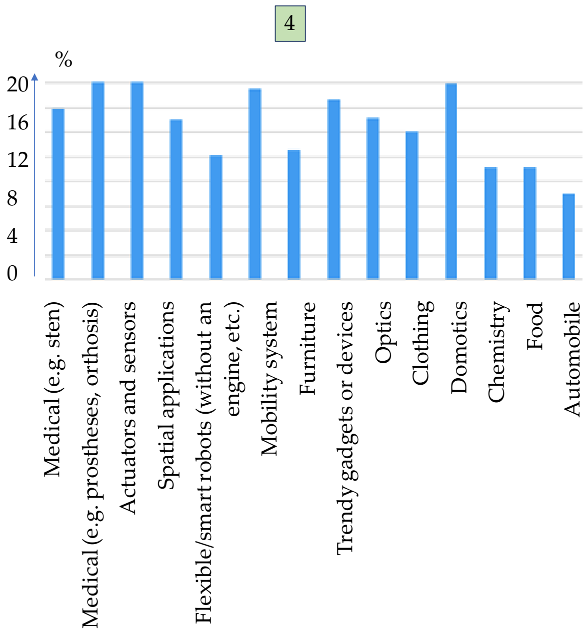
Figure 2.14. *Responses by category (3: moderately interested – A: now; B: future)*



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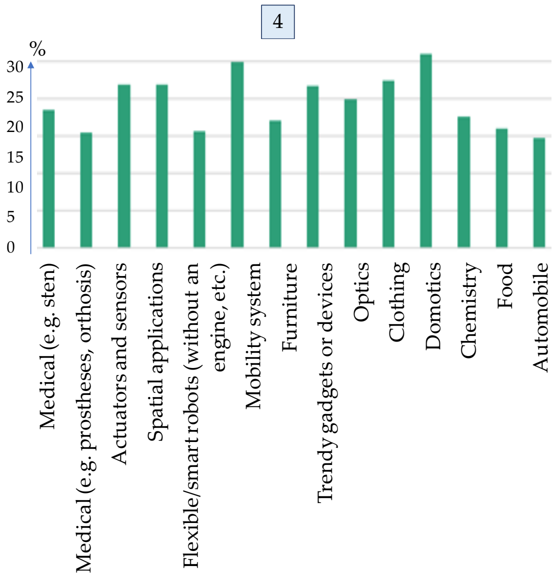

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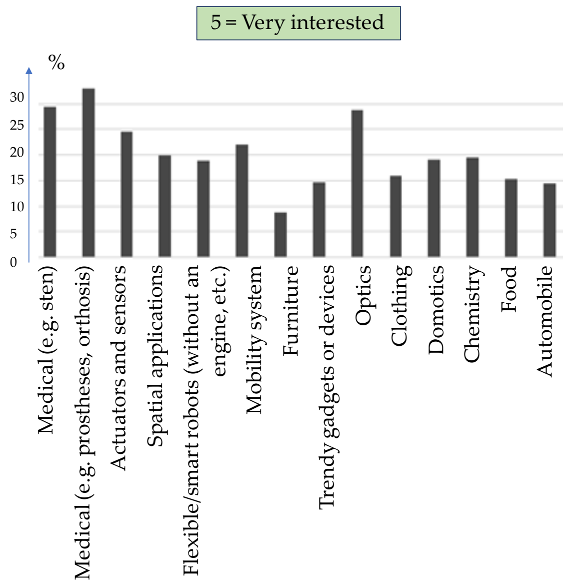
Figure 2.15. *Responses by category (4: interested – A: now; B: future)*



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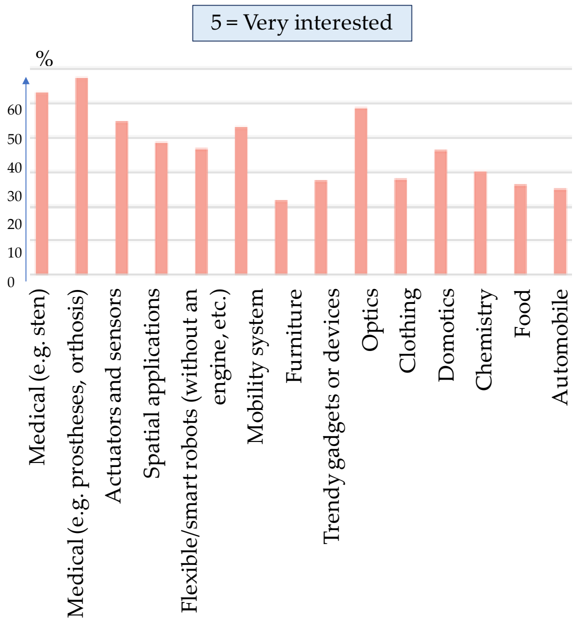


b)

Figure 2.16. *Responses by category (5: very interested – A: now; B: future)*

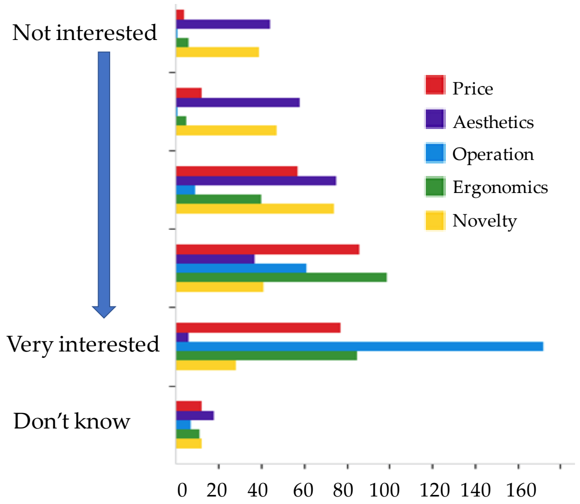
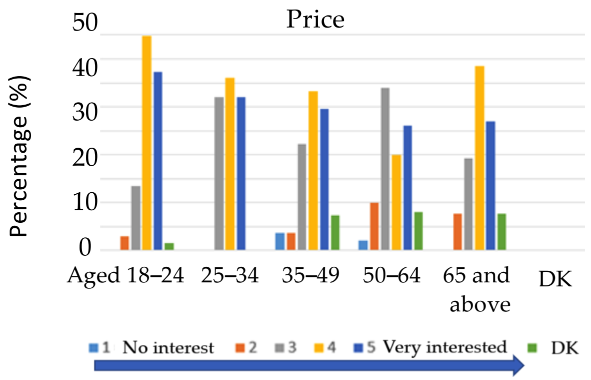


Figure 2.17. *Specificity of choice*



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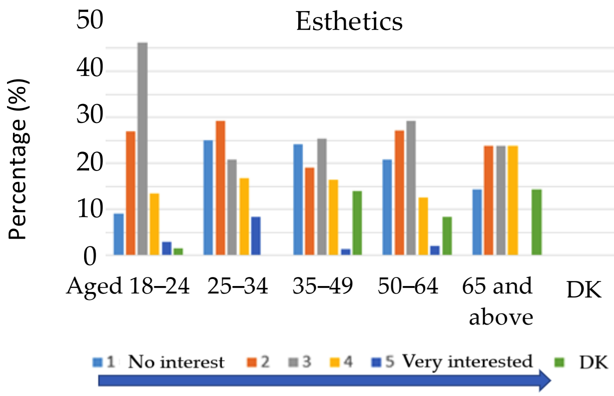

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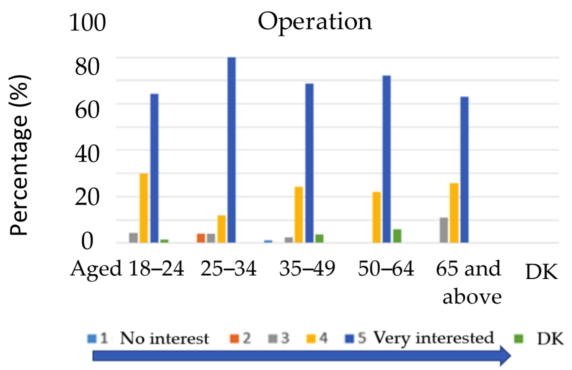

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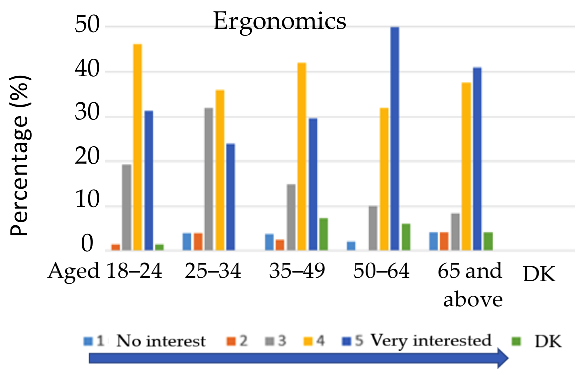

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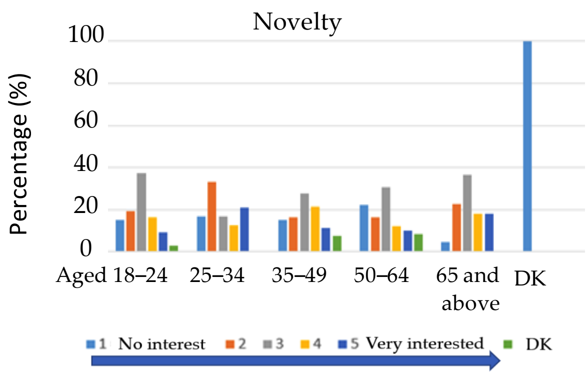


e)

Figure 2.18. *Effect of age on responses (A: Price; B: Esthetics; C: Function; D: Ergonomics; E: Novelty)*

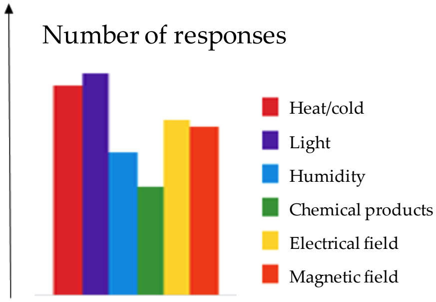


Figure 2.19. *Responses (very favorable) regarding preferred stimulation methods*

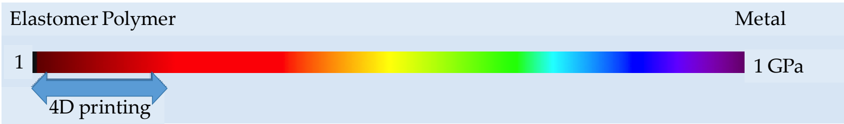


Figure 2.22. *Situation of 4D "polymer" printing in the spectrum of Young's moduli*

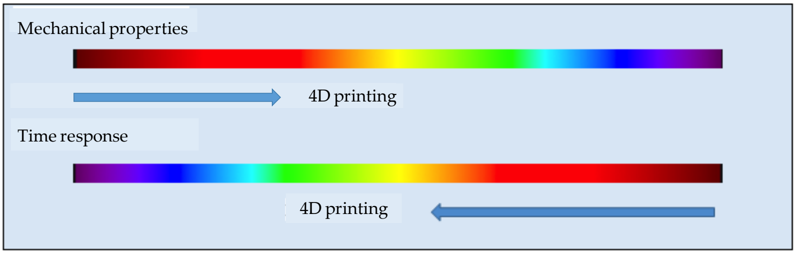


Figure 2.23. *Position of 4D printing in terms of mechanical properties and time response to stimulation*

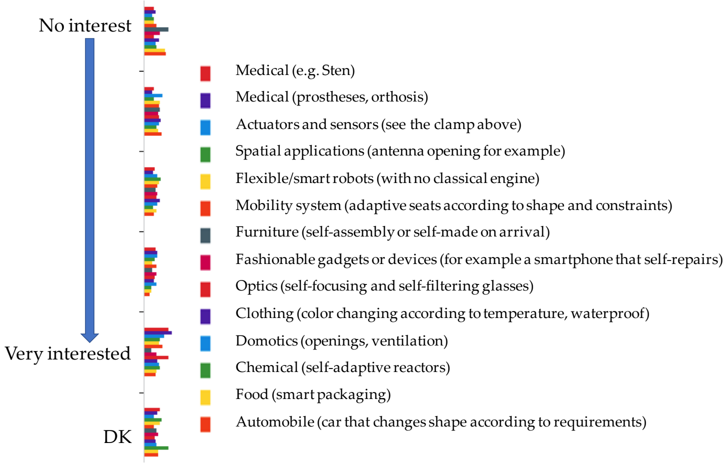
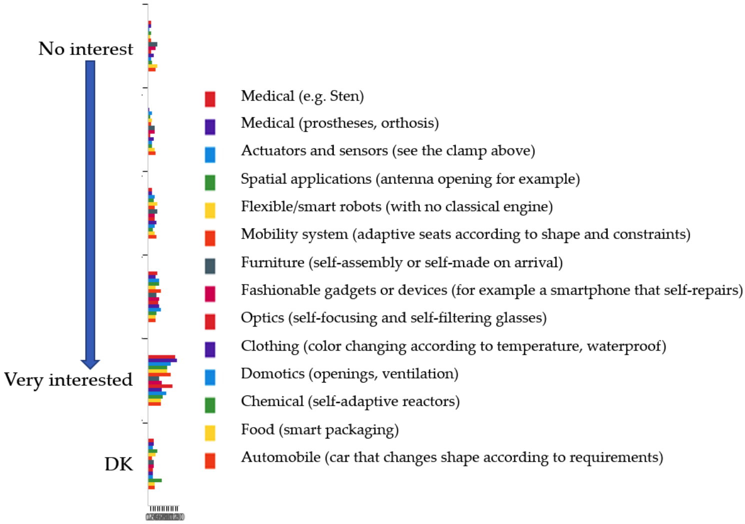


Figure 2.25.



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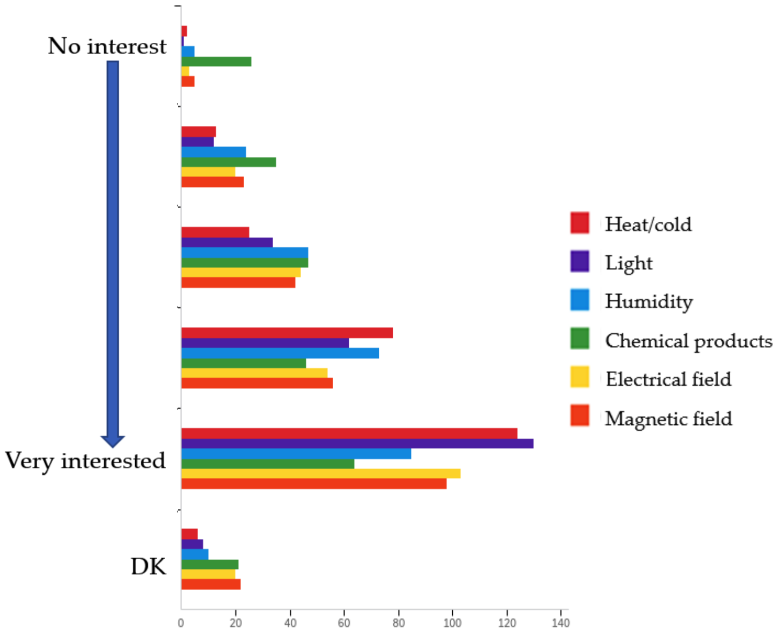
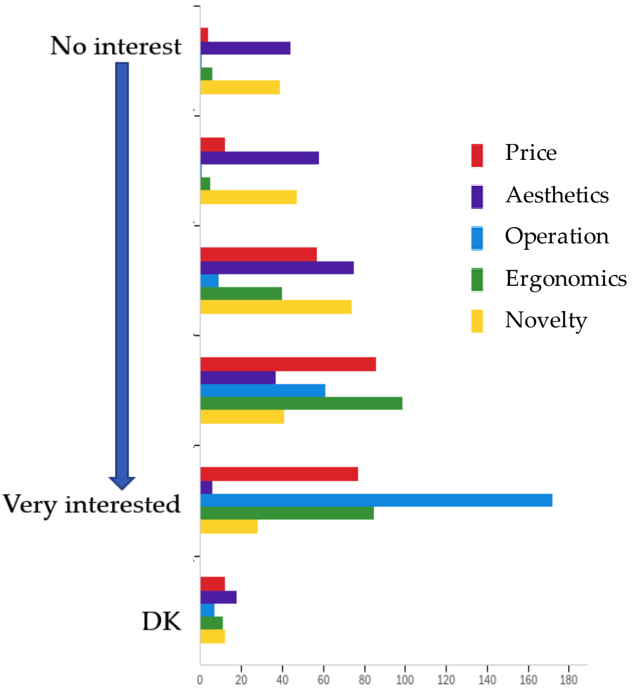


Figure 2.27.



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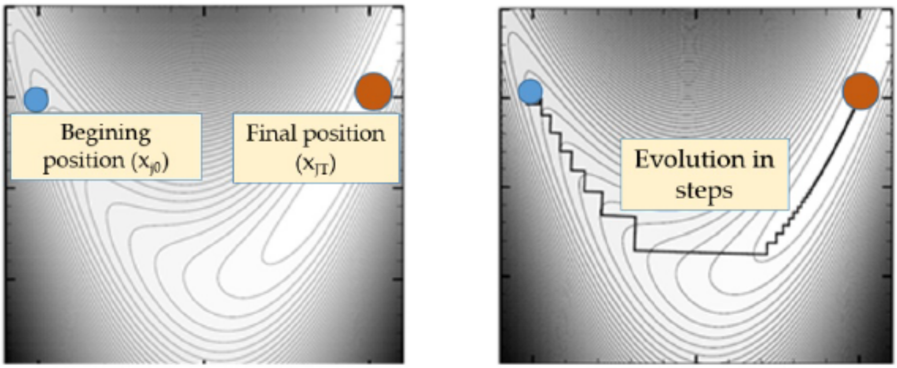

Figure 3.3. *Search for an optimum (supposedly unique) by successive changes of variables that are considered as independent (in the case of Figure 3.1, positioning of the active elements in the support matrix): Alternating path with unidirectional search for the local optimum*

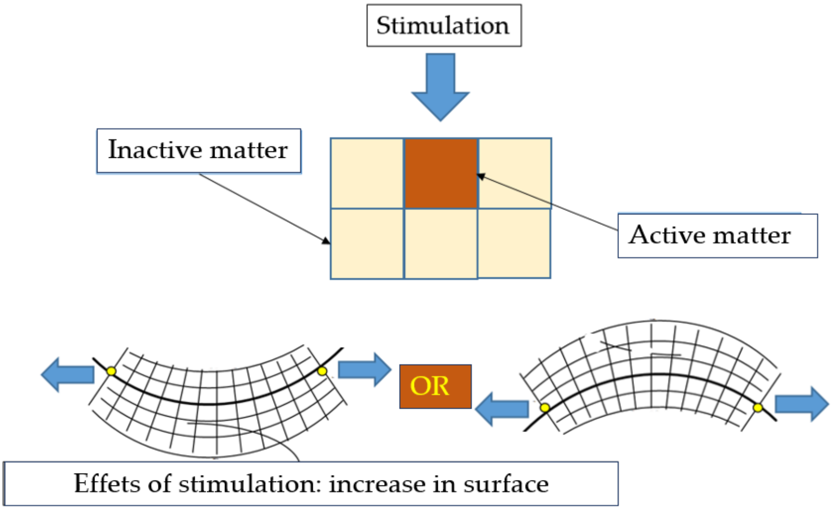

Figure 3.4. *Demonstration of stimulation-induced bifurcations*

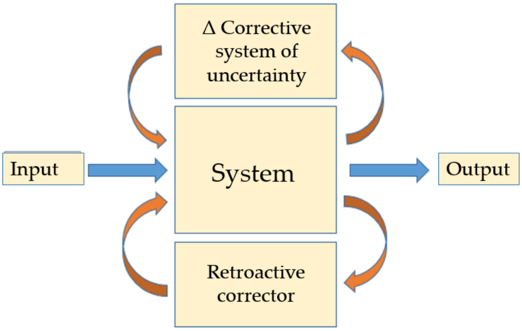

Figure 3.6. *Control model*

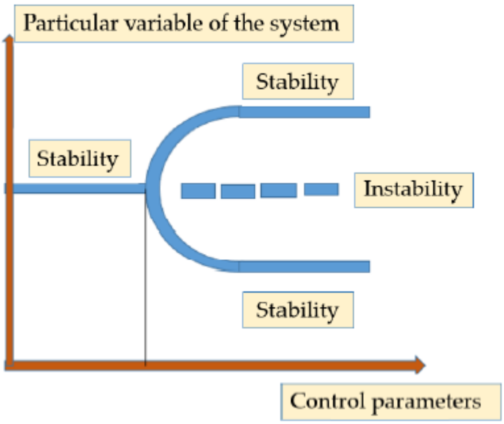

Figure 3.7. *Fork bifurcation*

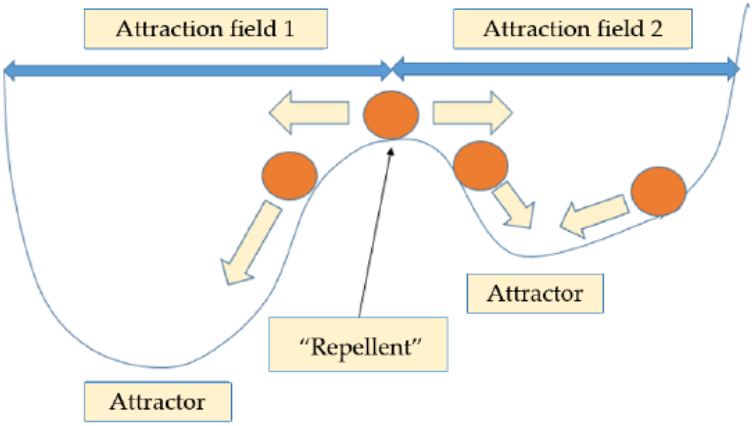

Figure 3.8. *Schematic representation of a landscape of attractors*

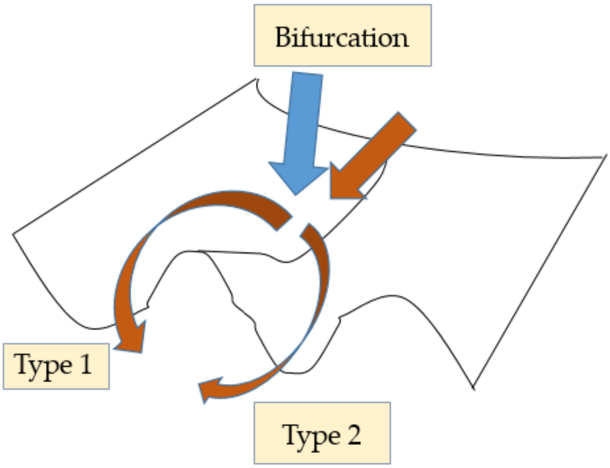

Figure 3.9. *Bifurcations in a 4D system: in the displacement (red arrow from the top) the system arriving at the bottom of the blue arrow can go either left or right*

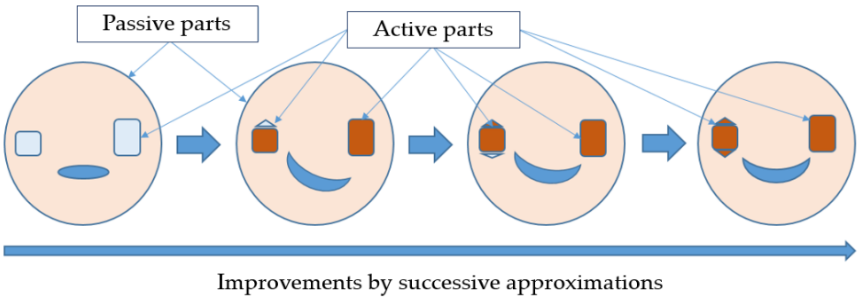

Figure 3.10. *Improvement by incremental approach to the objective (by acting successively on each active element)*

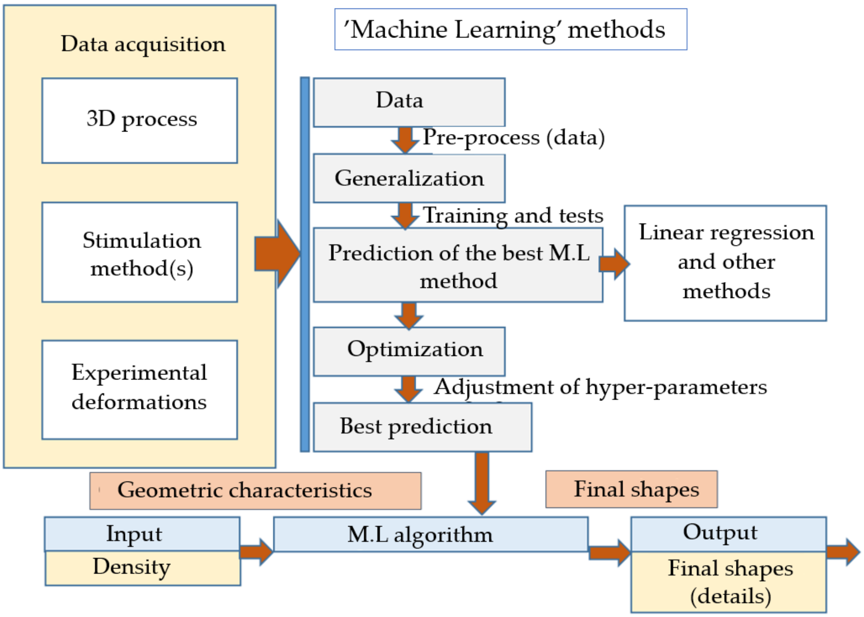

Figure 3.11. *Data-driven modeling flowchart for predicting morphing behaviors of active 3D printed structures (it includes data collection, preprocessing and hyperparameter setting for additive manufacturing model development)*

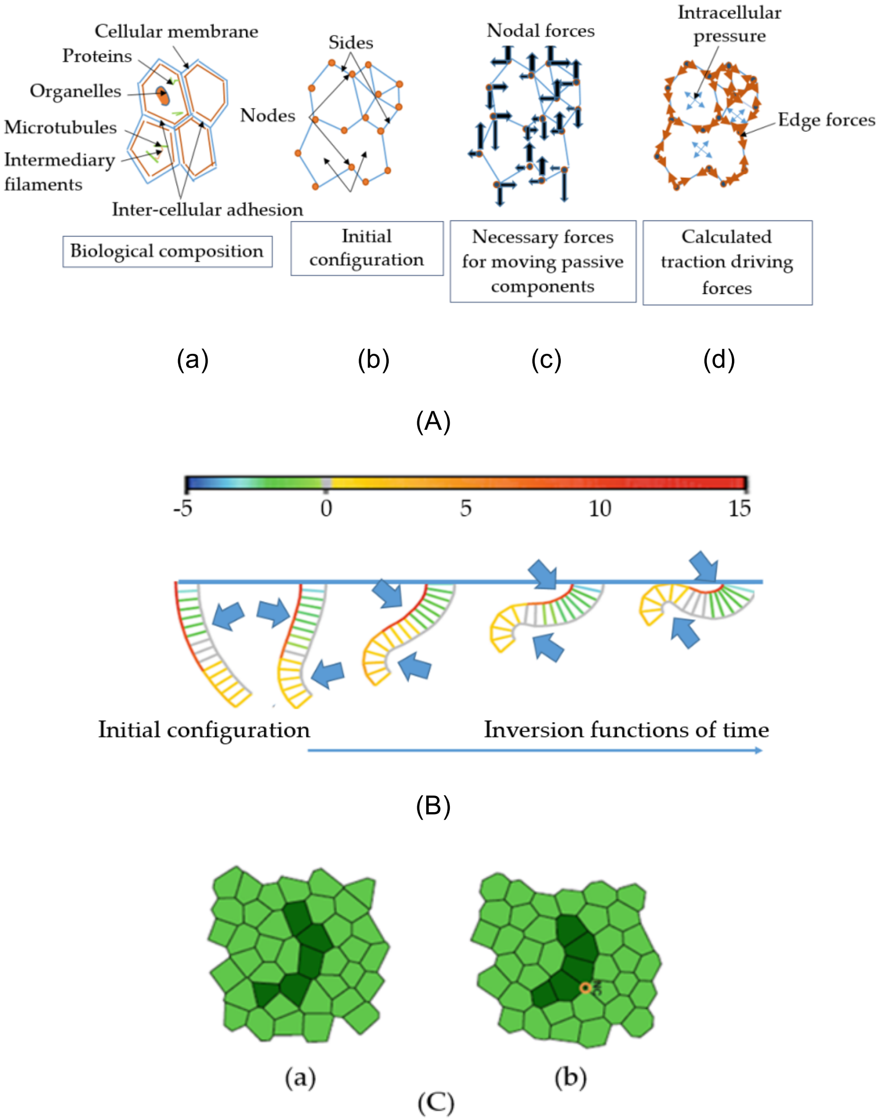

Figure 3.13. *A) Steps of the Cranston et al. (2010) method: (a) Components of direct or indirect structural importance in a typical epithelium; (b) Initial configuration subdivided into discrete regions; (c) Overall forces required to deform the passive components, calculated using the finite element method; (d) Processing of the inverse problem to reveal the forces and pressures to generate the overall forces shown in (c). B) Application to a cross-section of a generic intussusception – Initial configuration. The indicated stresses are those entering the finite element model before deformation – Noise corresponding to 5% of the step displacements was added to the nodal positions before they were passed to the algorithm. C) Aggregate of cells undergoing deformation: (a) Initial configuration of an isolated planar patch, composed of 40 cells of two types; (b) Evolution over time*

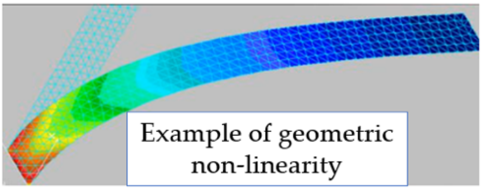

Figure 4.1. *Geometric nonlinearity*

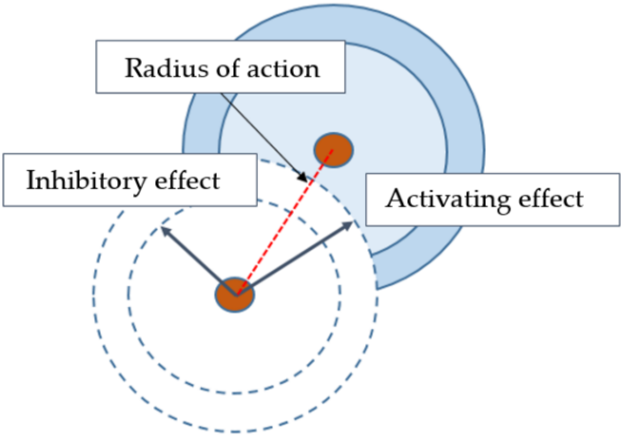

Figure 4.3. *Short- and long-range interactions*

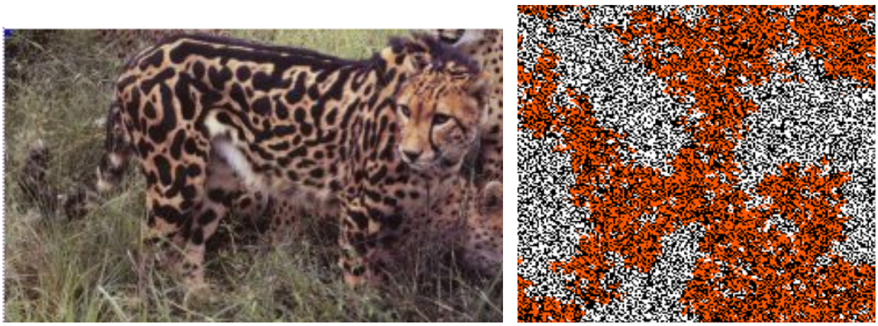

Figure 4.4. *Illustrated (left) and calculated (right) spots from the Turing morphogenetic model*

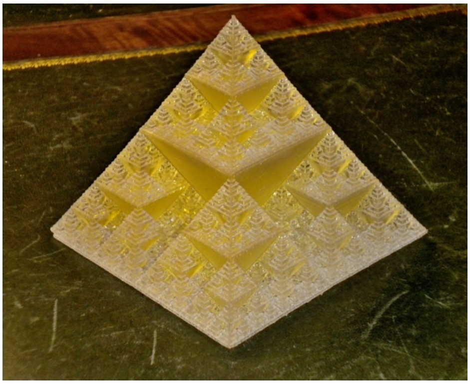

Figure 4.5. *Self-similarity as illustrated by the fractal pyramid realized in the 1990s (Dionnet et al. 1992/1993)*

Figure 4.6. *Examples of artifacts (man-made according to Mathis (2011))*

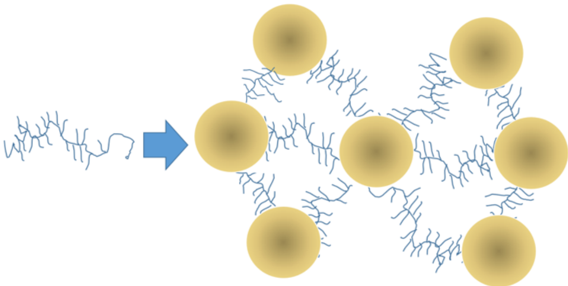

Figure 4.7. *Active "chameleon" structure*

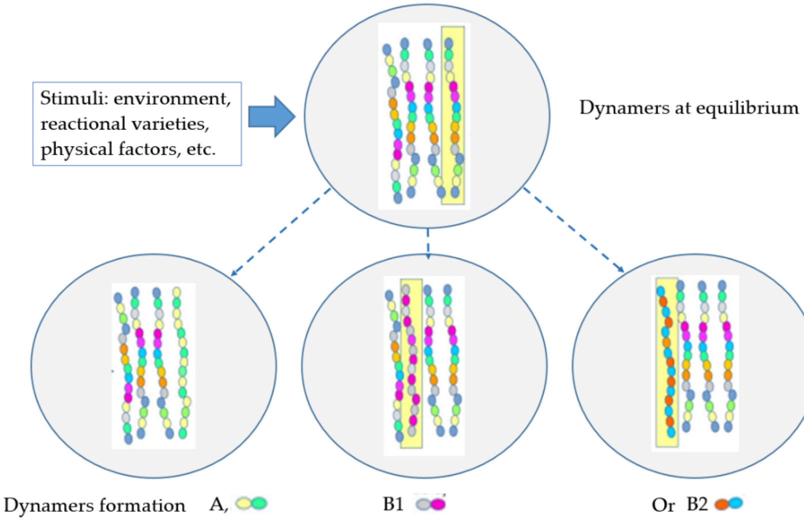

Figure 4.8. *Adaptation of a dynamers library (center) to the application of various stimuli (A, B, C) by generating a stimulus-specific dynamer*

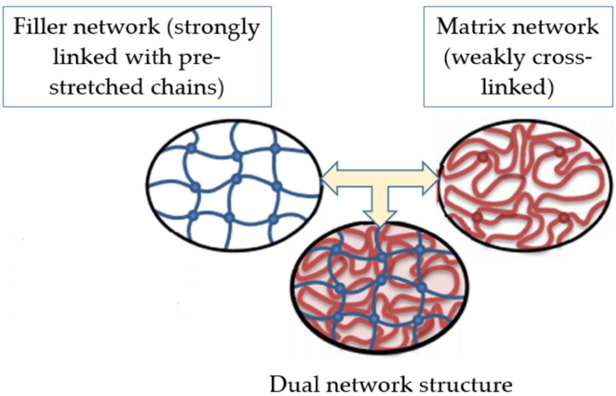

Figure 4.9. *Schematic representation of a "dual network structure" – the charge lattice is shown in blue, and the matrix lattice in red. The two networks are interpenetrated at the molecular level*

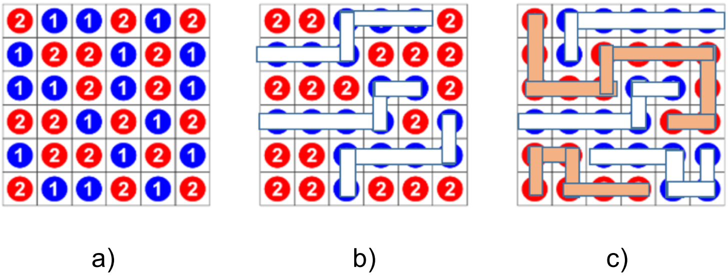

Figure 4.10. *Lattice model of a binary mixture of: a) two simple liquids (regular solution), b) polymer in solvent (polymer solution) and c) immiscible polymers*

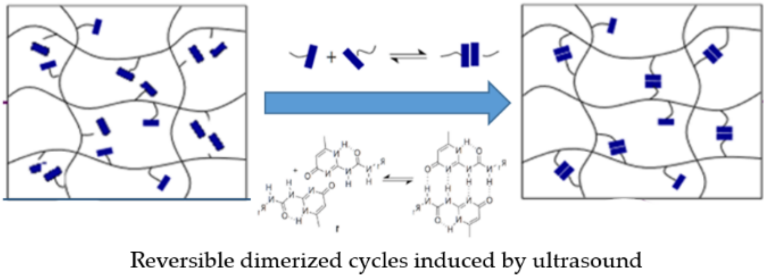

Figure 4.11. *Removal of loose links between polymers according to Li (2016)*

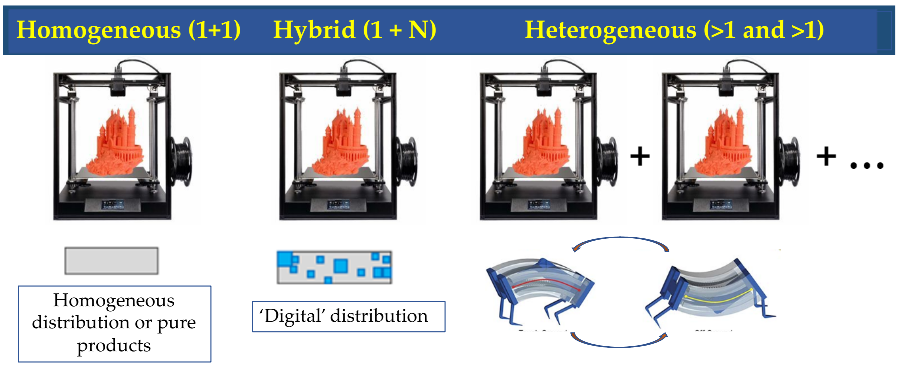

Figure 4.12. *Reminder on 4D printing methods (figure presented in other chapters)*