

# Open and Distributed Design as a Capacity-Building Methodology: Digital Technologies for Sustainable Creative Practices

Valentino Stella, Matteo Mojoli, Luca Grosso, Andrea Somenzi  
Stefano Maffei, Massimo Bianchini

Department of Design, Politecnico di Milano, 20133 Milan, Italy

**Abstract.** Drawing on a theoretical framing of the relationship between Open and Distributed Design (ODD) and digital technologies (DTs), the contribution adopts a critical, practice-based approach to investigate two interrelated questions: where and how digital technologies intervene across the stages of ODD processes, and whether, and under what conditions, their application can support sustainable and capacity-building design practices within the creative industries. Framing ODD as a design methodology rather than a mere production model, the contribution conceptualises DTs not as inherently sustainable but as enabling devices situated within ODD practices and the communities that sustain them. Two experimental initiatives developed by an academic makerspace within the Creative Europe Distributed Design Platform ground an empirical analysis read through three analytical dimensions: Social, Technical, and Systemic. The findings reveal that while DTs foster capacity-building, through the translation of tacit knowledge and forking, and democratised access, significant barriers persist, from regulatory tensions to infrastructural dependence and the cognitive demands of long-term maintenance. This situated relevance is not incidental to ODD's sustainability infrastructure, but points to a structural conditionality: the same place-based grounding that constrains scalability is also what sustains ODD's capacity-building potential for the creative industries.

**Keywords:** Open and Distributed Design, Digital Technologies, Design Methodology, Capacity-building, Creative Industries

## 1. Introduction and Methodology

Creative industries (CIs) are collaborative and strongly territorialised activities whose contribution is increasingly assessed not by economic growth alone but by the social, cultural and environmental development they enable [1],[2]. This broadened understanding of value follows from the very nature of creativity within the sector, which arises not within individual minds but in the interaction between thought and socio-cultural context, amplified by exposure to a diversity of ideas, framing collaboration as the heart of creative work [3].

A parallel shift is documented within design itself, one of the disciplines through which the CIs operate, which has progressively moved its focus from individual products toward broader systems of production and consumption, adopting an

integrated understanding of social, environmental and economic value [4]. Alongside this, design practice has moved from closed toward increasingly collaborative and open forms [5],[6].

Openness is not external to the creative sector: open innovation is recognised as a driver of sectoral innovation, favoured by the territorial and relational organisation of these industries [7][8]. Within this frame, open, collaborative and distributed design practice finds its most consolidated methodological expression in Open and Distributed Design (ODD), understood as a methodology that designs the design process itself and enables users and communities to act as co-designers [9][6]. Accordingly, this contribution adopts ODD as its methodological frame, treating it as the approach that best systematises the open, collaborative logic of the creative industries. In doing so, it foregrounds ODD's double relevance: both as an infrastructure for sustainable transition and as a capacity-building methodology.

Sustainability, in this light, is understood less as a technical output than as the situated, bottom-up co-design of viable futures [10]. This, jointly with the distributed competences and capacities that such co-design fosters within communities, addresses directly the civic, collaborative and cultural value that the creative industries embody.

ODD's capacity to coordinate distributed collaboration and to build local competences rests on a specific subset of digital technologies (DTs) such as digital fabrication, physical computing, shared repositories and coordination platforms that form its enabling backbone. As sustainability is not framed only as a technical property but as a social achievement, the efficacy of DTs lies not only in the tools themselves but in their fusion with creative practice and social and relational capital [11][8]. Thus, in this article DTs are not framed as inherently beneficial devices but as situated enablers, whose effects depend on the practices, communities and systemic conditions in which they are deployed.

While open practices in OD have been extensively analysed, and the centrality of DTs to ODD acknowledged [12], the literature has not yet examined comprehensively where and how these technologies intervene across the stages of the ODD process. From this critical standpoint, the research addresses two interrelated questions:

- (i) where and how do DTs intervene across the stages of ODD processes;
- (ii) whether, and under what conditions, their use within an applied setting can facilitate sustainable and capacity-building design practices.

To address these questions, the study combines a critical review of the literature with a practice-based analysis of two applied initiatives. Rather than a systematic search, the review followed a critical and exploratory logic: relevant works were identified across Design, Science and Technology Studies, and environmental and social sciences, and progressively expanded by following cited and citing works of particular relevance. AI-assisted discovery tools (Ai2 Asta / Semantic Scholar) supported the initial scoping, with all sources subsequently screened and read by the authors. This cross-disciplinary scope reflects the composite nature of ODD, which sits at the intersection of design methodology, open-source principles, digital fabrication practices, and sustainability transitions. The empirical component draws on two initiatives developed within the European Project Distributed Design Platform (DDP) (2022–2024) and conducted at Polifactory, Politecnico di Milano's academic

makerspace and research laboratory. Both initiatives were directly observed by the authors and treated as a situated case study rather than a representative sample. This case study comprises five ODD projects developed across the two initiatives, analysed across three dimensions (Social, Technical, and Systemic) using the seven-step ODD process model of Boisseau et al. [13] as the analytical scaffold.

The contribution unfolds from theory to situated practice. Sections 2 and 3 build the theoretical foundations, framing ODD as a design methodology and mapping how DTs intervene across each of the seven steps of its process model. Sections 4 and 5 apply this framework empirically, introducing the two DDP initiatives and reading their outcomes through three analytical dimensions: Social, Technical and Systemic. The contribution closes by drawing out what small-scale, locally situated ODD experimentation implies for community-centred design practice.

## **2. Open and Distributed Design as a Design Methodology: Sustainability, Capacity-building, and the Role of Digital Technologies**

Open design (OD) is a movement that arises from the convergence of the democratisation of product design and open approaches to knowledge and production [14]. The present contribution focuses specifically on OD as applied to the design of tangible objects, a domain frequently associated with the concept of Open Source Hardware (OSH). In this context, OD is defined as the condition of a project in which both the development process and the sources of the final output are made freely accessible, modifiable, and reusable by anyone and for any purpose [15],[14],[16]. In contrast to black-boxed or exclusive design models, OD enables project configurability and extensibility. Fabrication can take place in a distributed and scalable manner through the use of multipurpose, standardised means of production that are widely available on the commercial market [15].

When the principles of OD extend and merge with peer-to-peer, diffuse and decentralised network architectures, OD develops into ODD [9]. In OD, distributed networks signify a structural movement away from centralised, hierarchical systems of control and production toward architectures in which knowledge is no longer concentrated in institutions or experts, but shared across evolving networks of collaboration enabled by digital infrastructures [17], [4]. Such peer-to-peer networks embody an organisational logic alternative to mainstream cultural production, thriving in environments that require collectivity and collaboration as conditions of their existence [18].

This section aims to frame ODD as a learning and capacity-building design methodology within the creative industries, able to intervene in the development of educational and sustainable design practices. At the same time, particular attention is paid to the role that DTs play within ODD. The literature has approached this terrain from several angles: some contributions explore the relationship between openness and the design process [19], [14], [20]; others attempt to define an ideal-typical model of the OD process [13]; and several works examine the role of DTs within design processes and open innovation more broadly [21], [22], [23]. As noted in Section 1,

despite Bonvoisin and Mies [12] acknowledging the centrality of DTs to ODD, no attempt has yet been made to construct a comprehensive conceptual framework that jointly explores how and where DTs intervene across ODD methodologies.

ODD provides a theoretical, infrastructural, and strategic framework capable of redefining the fundamentals of the design process. Its primary goal is to create socio-technical infrastructures, such as collaborative platforms, open tools and toolkits, and spaces for creation and collaboration, along with the relational conditions that enable users and communities to actively function as co-designers [6], [9]. This requires the development of hybrid organisations and models in which openness is not incidental but must itself be designed into the process, strategically establishing which phases are open to external collaboration and which are not [6].

ODD, as anticipated in Section 1, can thus be seen as a complex design methodology that functions simultaneously as an infrastructure for sustainable transition and as a pedagogical model for capacity-building within the creative industries. By moving the focus from the creation of closed, proprietary artefacts toward the design of processes, platforms and socio-technical systems, ODD has triggered a profound paradigm shift in contemporary creative industries [9]. This context demands the development of new competencies and transforms the professional designer from sole creator into facilitator or meta-designer, operating within teams governed by a meritocratic hierarchy based on voluntary contribution [14], [6]. The designer's role translates into orchestrating collaborative networks and facilitating the agency of users and communities as co-designers. This methodological evolution aligns with *Participatory Design* (PD) and *Research through Design* (RtD) approaches to addressing complex social and cultural problems [10]. Drawing on this bottom-up logic, ODD enables creative industries to actively engage local communities in the co-production of knowledge, allowing them to imagine and materialise sustainable, achievable futures that reflect the specific identities, capacities and needs of their territories [10].

Beyond its socio-cultural impact, ODD operates as an infrastructure for generating and scaling sustainable practices. Design education and practice recognise the need to move beyond linear production models toward circular economy and whole-systems thinking [24], [25]. In this respect, ODD shares foundational principles with the circular economy, including collaboration, the democratisation of tools and knowledge, and the optimisation of resource flows. By relying on publicly available project resources, ODD enables distributed production and modularity [15],[14],[12],[26],[27]. This extends product lifecycles through circular design strategies such as reparability, upgradability and disassemblability, which are guaranteed by open-source code and transparent technical documentation [28]. By separating the creation of knowledge and data from actual physical manufacturing, ODD allows projects to spread worldwide as a digital commons and be produced locally. This process lowers the environmental impact of global shipping, maximises the utilisation of regional resources, and enhances the durability of production networks [29],[6]. More broadly, it fosters a shared knowledge ecosystem that renders advanced sustainable technologies accessible and economically affordable [19],[16],[26],[27],[30].

In parallel, grassroots initiatives, fab labs and makerspaces act as pioneers of the sustainable transition. They hybridise formal eco-design methods with frugal practices and low-tech solutions to empower communities, while fostering the development of

context-sensitive, adaptable solutions capable of responding to the heterogeneous needs of local environments [6],[31],[21],[32][33]. This is the role that Jurgilevich et al. [34] assign to niches: sites of small-scale experimentation that generate practical innovations capable of informing policy development and driving systemic transformation. Accordingly, they recognise the necessity of creating space for the transition to unfold simultaneously from the bottom-up, through localised prototyping and application, and from the top-down, through the design and implementation of enabling policy frameworks.

With regard to its educational characteristics, ODD is closely tied to the concept of Critical Making developed by Ratto [35], which provides the pedagogical and conceptual grounding for turning networked material production from a merely technical execution into a tool for actively investigating techno-social dynamics. Critical Making emerged with the aim of bridging the gap between critical, exploratory thinking and the physical act of making. By integrating with the open, collaborative and distributed processes of ODD, this practice shifts attention from the final artefact to the shared process of construction, using material prototyping as common ground for engaging with complex, indeterminate problems.

Following Ratto's approach [35], ODD uses the making process to turn technologies from a matter of fact into a matter of concern to be actively engaged with. [32] show how the active reappropriation of technology by grassroots initiatives serves to emancipate society from the monopoly of traditional industry. Through open practices and the use of convivial technologies, local communities reclaim control over their own means of production, developing appropriate solutions that secure their autonomy and technological sovereignty.

Finally, as illustrated by Kohtala [29], this affective investment and this drive toward emancipation find their spatial and cultural expression in Fab Labs, which act as countercontexts to the logics of mass consumption. Within these environments, communities critically interrogate the social role of their artefacts, using open practice to substantiate their values and actively imagine new production paradigms. The dissemination of digital fabrication through Web 2.0 has further positioned Fab Labs, makerspaces and hackerspaces as hubs for citizen-based innovation and unconventional educational environments. They function as genuine communities of practice and sites of peer-to-peer learning, distributing design processes across shared, internet-mediated knowledge networks where the open sharing of knowledge democratises access to innovation and technical skills [36],[29],[9],[6],[10].

In such settings, online and physical communities alike foster collaborative and instructive environments in which design skills are practised and developed [37], enabling a form of learning that empowers participants to take initiative in deciding how they learn and to be involved in creating something from beginning to end [1]. This situated learning environment exposes novices, whether future designers or citizens, to liminal spaces of design uncertainty, which prove essential for developing the critical thinking, autonomy and systemic skills needed to navigate the complexity of today's ecological and technological transitions [36],[28].

Building upon these capacity-building, socio-technical, and sustainable foundations, the focus now shifts to the technological infrastructure that operationalizes ODD, identifying the role that DTs play within it. The scientific literature identifies a subset of DTs as being deeply intertwined with ODD practices. DTs may be defined as

systems, tools, and infrastructures based on digital information processing, encompassing heterogeneous domains. They span big data and artificial intelligence (AI) to cloud computing, Internet of Things (IoT), blockchain, and digital manufacturing, and are configured as integrated ecosystems of components, and platforms capable of enabling programmable, scalable, open, and interconnected functions across hardware and software layers [38]. Driven by the digitalisation of design tools and the broader permeation of Participatory Culture [20],[37], DTs have democratised both product manufacturing and design, fuelling the rise of ODD. Rather than constituting a uniform category, DTs exhibit varied characteristics that determine their degree of compatibility with the openness paradigms underlying ODD.

By computing key design steps, enabling domestic digital fabrication, and facilitating the circulation of digital files, these tools have lowered skill barriers and made low-cost customisation widely accessible. Progressively easier to use and embedded earlier in the workflow, DTs dramatically accelerate iteration and experimentation while reducing time and costs [37].

Collectively, these developments constitute the technological backbone of ODD, acting not only as operational tools for localised creation, but as global coordination platforms and physical-digital integration layers [14], [13], [12], [6], [39], [40]. Beyond these foundational enablers, the field is currently expanding through the integration of Industry 4.0 technologies, including Augmented Reality, AI, advanced automation, and the Internet of Services, whose implications for OD practices represent an emerging frontier of investigation [41].

Yet, the efficacy of these technologies rests less on the tools themselves than on their fusion with creative practice. While dominant STEM-centred views tend to place the creative sector outside the core innovation cycle, empirical evidence highlights that *fused* organisations, combining digital technology and creative design, achieve higher levels of innovation than their non-fused counterparts [11].

To systematically analyse how this technological architecture supports distributed practices, the following section explores how DTs intervene across the constituent elements and iterative stages of the ODD process.

### **3. Exploring the Role of Digital Technologies in Open and Distributed Design Processes**

Having examined how DTs underpin the sociotechnical infrastructure of ODD, this section turns to the constituent structure of the design process itself, in order to locate precisely where and how DTs intervene. Building on a two-axis conception of openness, in which the openness of the process and the openness of its output (or plan) are treated as independent dimensions, Boisseau et al. [14] decompose a design project into three elements along which ODD departs from traditional design: the gap, the process, and the final output. Boundaries are blurred, iterations are frequent and informal, and the output has the potential to trigger new cycles of external innovation [20], [13], [14].

The literature converges in identifying fundamental differences between ODD and traditional design both in the process and in the output, though notably not in the gap,

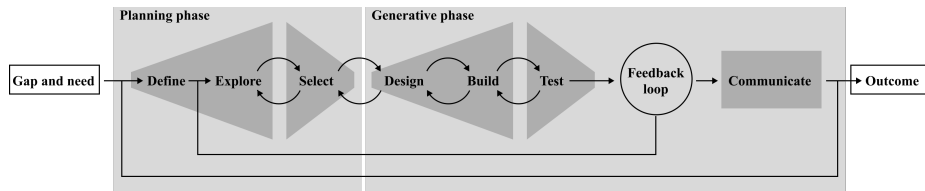
which remains an external and uncontrollable input. Unlike conventional product design projects whose final output is typically a static, closed specification of a finished artefact, the ODD output is conceived specifically to be manipulated and extended [20], [6], [14], [12].

Regarding the process, Boisseau et al. [14] decompose it into three core elements: boundary objects and their supporting infrastructures, contributing stakeholders and their competencies, and the constituent phases and activities.

Boundary objects, the intermediary artefacts used to share and align project understanding among diverse actors, assume critical importance in sustaining asynchronous and decentralised collaboration. These objects must be digitized and managed through collaborative web-based platforms, preferably leveraging open standards to establish a shared language across contributors [14].

As stated in Section 2, at the stakeholder level, ODD hybridizes the traditional roles of designer, producer, and user. End-users become active co-designers and testers from the outset, requiring new competencies and shifting the professional designer's role from creator to facilitator or meta-designer within networks [14],[6]. This blurs expert/non-expert boundaries, opening development to distributed crowdsourcing and co-creation [20].

Regarding the constituent phases and activities, following the framework established by Boisseau et al. [13], the ODD process can be structured into seven distinct yet interconnected steps: Define, Explore, and Select (forming the Planning Phase), followed by Design, Build, Test, and Communicate (constituting the Generative Phase).



**Fig. 1.** Open-Design process model and iterative phases. Reworked from Boisseau et al. [13].

These steps are interpreted as co-evolving activities rather than strictly sequential stages, drawing on design theory that conceptualizes the process as iterative and non-linear, characterized by continuous cycles of problem framing and reframing. As Smith and Eppinger [42] argue, understanding iteration is fundamental to improving quality and accelerating product development. DTs can drive iteration within a project, as well as cumulative learning across consecutive or concurrent projects [43]. By leveraging existing knowledge, insights, and artefacts, particularly those arising from ODD initiatives, it becomes possible to accelerate key steps of the design process, especially research and development activities, thereby enabling more frequent and effective iterative cycles.

As Aitamurto et al., [20] and Bonvoisin et al. [19] note, different forms of openness may be activated at different moments within the same project. Since each step concentrates on distinct boundary objects and diverse stakeholders, the digital tools

required to support them vary accordingly. As a result, current software environments offer only fragmented support, with no single platform yet capable of uniting community management, co-creation, and convergence support into a single, integrated solution [21].

As documented by Boisseau et al. [13] in their empirical analysis of OD projects, the Planning Phase, concerned with preparing and setting boundaries for generative activity, tends to be systematically underweighted relative to the generative one. Quality is thus pursued primarily through an increase in iterative design cycles rather than through the efficiency of the initial planning process, a pattern that aligns OD more closely with agile software development methodologies than with the structured, sequential and traditional design models such as Cross's one [44]. This structural imbalance makes the Planning Phase a particularly consequential site of DT intervention.

Building on this theoretical framework, this section examines how DTs intervene across the constituent elements of the ODD process, analysing the resulting shifts and reconfigurations within its underlying logics, practices, and organisational dynamics. Through this lens, each phase and step is examined to assess how DTs act upon its associated boundary objects and stakeholder dynamics.

### 3.1 Planning Phase: Define, Explore, and Select

During the Planning Phase, comprising the Define, Explore, and Select steps, DTs primarily function as cognitive and organisational infrastructures that structure the conditions under which ODD activity becomes possible. The role of DTs in this phase is threefold:

- They enable geographically dispersed stakeholders to negotiate product functions and directions in real time;
- They extend participation to actors typically excluded from traditional design processes, such as end users, makers, and community members;
- They turn boundary objects into a shared representational substrate, enabling collective decision-making across heterogeneous communities.

Furthermore, DTs enable a key structural dynamic: the emergence and evolution of decentralised *micro-groups* around one or several *pivot agents* [45]. In ODD contexts, digital platforms can act as these pivot agents, providing the permanent infrastructure needed to maintain coherence and coordinate these spontaneously formed sub-groups over time.

Specifically, DTs shift the process from a designer-led synthesis conducted within closed teams toward a distributed, participatory framing of the problem space. By leveraging collaborative platforms, shared repositories, and real-time documentation systems, DTs enable heterogeneous stakeholders to co-define requirements and evaluate design trade-offs.

This shift from internally driven synthesis to distributed knowledge integration resonates with the concept of cross-boundary knowledge flows found in Open Innovation theory [46]. In this context, Prisco et al. [47] demonstrate that such platforms manage knowledge flows and coordinate multi-stakeholder networks,

enabling heterogeneous actors to align conflicting priorities, co-create foundational practices, and overcome early systemic barriers before execution begins.

At the same time, the adoption of DTs in this phase introduces structural challenges. The multiplicity of actors and inputs involved requires significant coordination effort to prevent conflicts, redundancies, and misalignments. Furthermore, participation is conditioned by access to digital infrastructure and the competencies required to operate it effectively, introducing potential asymmetries within ostensibly open processes [48], [49], [50]. The platforms most relevant to the Planning Phase as a whole are those that operate transversally across its three constituent steps, such as Product Lifecycle Management (PLM) systems and Quality Function Deployment (QFD) platforms. More broadly, the ensemble of digital tools engaged across the Planning Phase can be understood as constituting what Fischer and Giaccardi [22] describe as a meta-design environment: a socio-technical infrastructure that enables distributed actors to participate in and shape the design process itself.

**Define.** As established by Boisseau et al. [13], the Define step acts as a bridge between the identification of user needs and their translation into technical specifications, ultimately supporting the development of a proof of concept. In ODD contexts, this stage represents a critical site for boundary object mediation, requiring heterogeneous actors to converge on shared requirement matrices and design briefs without a common uniform institutional vocabulary [13]. Consequently, the selection of digital tools at this step is a substantive act of design that determines the composition of the stakeholder network, the form of the boundary objects produced, and the process's overall degree of openness.

The primary digital infrastructure supporting the Define step consists of PLM systems, which allow teams to create, structure, trace, and validate product requirements from the earliest iterations onward. In ODD contexts, the most relevant PLM solutions are those built around open or low-barrier architectures, such as Aras Innovator, which adopts a hybrid open-source approach, or CAD-Git platforms such as Wikifactory and GrabCAD, which merge version control with PLM functionality [51]. Conversely, Quality Function Deployment (QFD) operates as a structuring mechanism to translate diverse stakeholder inputs into shared functional specifications [52]. In ODD practice, however, QFD remains largely constrained by spreadsheet-based or standalone applications with limited collaborative and distributed capabilities.

Where QFD structures participation within a defined stakeholder group, co-design and crowdsourcing platforms reconfigure who counts as a legitimate contributor altogether. Environments such as OpenIDEO enable distributed communities to propose and prioritise product functions before any technical commitment is made [20], though this openness simultaneously introduces coordination costs and risks of misalignment [21].

**Explore.** The Explore step involves a search for already existing systems capable of fulfilling one or more of the functions identified in the Define step. As Boisseau et al. [13] note, this inventory is intentionally non-exhaustive and may be bypassed when operating on prior knowledge, a shortcut that remains open to challenge in subsequent prototyping. In ODD contexts, DTs transform this step from passive retrieval into an active reconfiguration of the project's informational substrate. They expand the search

scope beyond the core team's tacit knowledge and redefine the nature of what is found: moving from solutions to be merely adopted to solutions to be forked.

The primary digital infrastructures supporting this step are open repositories and knowledge commons. Platforms such as GitHub, Thingiverse, and Wikifactory function as public inventories, hosting documented artefacts (CAD files, BOMs, and functional documentation) that render prior solutions reusable across heterogeneous communities [6]. However, the effectiveness of open repositories as exploratory infrastructures depends directly on the quality and consistency of the documentation they contain, a condition that remains unevenly met. Empirical evidence shows that many OSH products are backed by documentation covering only a subset of the required design elements [19], [12].

A structurally distinctive dynamic enabled by digital platforms in this step is forking: rather than simply adopting or rejecting a solution, teams can branch from an existing project, inheriting its documented artefacts, design rationale, iterative history and situated knowledge, while redirecting development toward new objectives. Forking also allows the coexistence of parallel development branches and the possibility of branching out when conflicts within a contributor community prove irresolvable [19], transforming the Explore step into a socio-technical reconfiguration of both the artefacts and the stakeholder community itself.

Forking can thus be read as a distinctively distributed form of collaboration, which can be understood as the pooling of different perspectives and the combination of complementary skills and knowledge in pursuit of the best possible outcome, a principle realised through specialisation across distinct functions within a network [3].

**Select.** The Select step marks a structural shift within the Planning Phase, transitioning from the divergent logic of Define and Explore toward the convergence of the solution space onto a single implementable choice. As Boisseau et al. [13] specify, core selection criteria include time, cost, and available know-how.

Unlike previous steps, the literature does not identify a systematic role for DTs in this stage. The Select step appears to remain primarily a negotiated, dialogic process, relying on collective judgment, contextual knowledge, and interpersonal trust within the design community rather than on digital mediation. In many ODD practices, this can be conducted through lightweight, peer-based evaluation without specialised digital tools. While CAD-integrated simulation, open PLM, or digital twin environments may occasionally support the process, their adoption depends heavily on the team's technical competencies. Although digital boundary objects, such as sketches, visual schemes, or 3D models, often inform these decisions, and digital platforms facilitate the underlying communication, these tools serve as support mechanisms rather than core drivers of the selection logic. Ultimately, this limited technological intervention reflects the deeply tacit and relational nature of the decision-making process itself.

### 3.2 Generative Phase: Design, Build, Test, and Communicate

Where the Planning Phase establishes the conditions for design activity, the Generative Phase is where that activity materialises. Comprising the Design, Build, Test and Communicate steps, this phase constitutes the operational core of the ODD process: it

is here that candidate solutions are architecturally defined, physically implemented, and empirically evaluated.

As Boisseau et al. [13] observe, the Generative Phase is systematically overweighted relative to the planning one in OD practices, with quality pursued primarily through the accumulation of iterative cycles rather than through the efficiency of upfront planning. In this phase, DTs primarily function as fabrication, coordination, and documentation infrastructures, enabling four key dynamics:

- They enable geographically dispersed contributors to negotiate architectural decisions and co-design product structures in real time;
- They reduce the material and operational costs of physical prototyping, lowering entry barriers to fabrication [12],[53],[54];
- They extend evaluation beyond individual observation into shareable, cumulative evidence across distributed testing contexts;
- They transform iteration outcomes into legible, reusable documentation that extends the design's reach beyond its originating team.

A structurally distinctive feature of this phase is the centrality of the feedback loop. When testing fails to yield satisfactory results, the process does not terminate but resets, forcing teams to re-evaluate prior steps from design adjustments to a fundamental reframing of the problem space [13]. By significantly lowering the economic and operational costs of this reset, DTs transform potentially catastrophic failures into productive, evolutionary iterations.

**Design.** The Design step translates the architectural implications of the selection made in the preceding step into a concrete technical plan: before any physical prototyping begins, the design team defines the global architecture of the product, determining where and how the chosen system is to be integrated into the existing state of the project [13].

In ODD contexts, this step introduces a distinct structural challenge: architectural choices must be negotiated across geographically dispersed contributors with divergent technical backgrounds. DTs intervene here primarily as coordination and co-design infrastructures. Cloud-based collaborative CAD platforms such as Onshape or Fusion 360 allow distributed team members to work concurrently on the same model, making architectural decisions visible and negotiable in real time across the contributor network. Version control systems for CAD files, already operative in the Explore step, assume a different function here: rather than managing repositories of existing solutions, they trace the evolution of architectural decisions across iterations, rendering design rationale legible and recoverable for future cycles.

Generative design systems contribute to this step by producing multiple design variations within predefined parameters, supporting architectural exploration while leaving evaluation, decision-making, and refinement to human designers [55]. Within fabrication contexts, these systems can optimise geometries according to performance criteria such as material efficiency, structural strength, or modularity, embedding optimisation routines into accessible tools and reducing the specialist expertise required to produce high-quality results.

Beyond parameter-based variation, generative AI also enables the automated translation of natural language and multimodal inputs into structured parametric CAD operations through the integration of large language models (LLMs) into modelling environments [56]. LLM-based systems can generate executable modelling sequences, propose geometric configurations, and iteratively refine design intent, lowering the threshold of participation for contributors without advanced CAD expertise. It should be noted, however, that precise dimensional accuracy remains a current limitation of such systems, particularly when specifications are imprecise or geometries are complex [56]. Before committing to physical prototyping, lightweight simulation environments such as FEM modules allow contributors to anticipate discrepancies between the digital model and its physical behaviour, validating structural or thermal performance directly on the model and reducing the risk of costly failures once the Build step begins.

Together, these tools transform the Design step from an exclusive activity reserved for a core team into a distributed process of architectural negotiation, where parametric models, versioned CAD files, and generative outputs function as shared boundary objects across heterogeneous communities of practice.

**Build.** The Build step materialises architectural decisions into physical prototypes, confronting abstract designs with the complexity and material friction of physical components, which must be sourced, assembled, and integrated into a functioning system [13]. In ODD contexts, this process occurs within distributed communities where fabrication capabilities, available tools, and local constraints can vary significantly across contributors.

DTs intervene primarily by lowering the threshold for experimentation and expanding the conditions under which distributed prototyping becomes possible. The decreasing cost and accessibility of tools such as 3D printers and CNC machines enable the production of geometrically complex artefacts without specialist craft expertise, allowing multiple design iterations to be conducted within compressed timeframes and opening up meaningful participation to contributors with limited manufacturing backgrounds [53], [54].

This dynamic is further sustained by digital fabrication infrastructures, such as Fab Labs, makerspaces, and manufacturing-as-a-service platforms, which reduce production costs and democratise both manufacturing and design processes [39], [14], [19], [40].

A key dynamic enabled by this infrastructure concerns the replicability and adaptability of prototypes across contexts. Digital files function as transferable knowledge units, allowing open-source designs to be reproduced, modified, and re-contextualized across geographically dispersed nodes while retaining the freedom to adapt to local materials, regulatory conditions, or production scales [12].

Achieving this degree of local autonomy and replicability, however, depends on two structural conditions. First, the modularity of the product architecture: decoupled subsystems allow independent parallel development; without it, the build process inevitably realigns around a coordinating core. Second, the quality of associated documentation, which functions as the primary boundary object rendering architectural decisions legible to external contributors. Unlike its role in Explore as a solution inventory, here documentation operates as a transferable build protocol, enabling replication without direct knowledge transfer.

Physical computing extends this dynamic by integrating material and informational dimensions within prototypes. Through the embedding of sensors, actuators, and microcontrollers into material artefacts, physical computing connects tangible systems to data flows and computational logic [57], transforming prototypes into digital-physical systems capable of real-time feedback, effectively turning hardware into an open, modifiable technology analogous to software. The physical computing and IoT paradigm enables makers to enhance artefacts with embedded intelligence without relying on expensive proprietary equipment, thereby lowering barriers to innovation.

Within OD, microprocessors act as foundational, modular building blocks that allow a broader population to build complex systems affordably [58], progressively expanding open-source innovation ecosystems [38]. This democratisation is further reinforced by Open-Source Hardware (OSH), free programming environments, and accessible modular components from platforms like SparkFun and Adafruit [39].

In ODD contexts, this capability acquires a collective dimension through distributed sensing: prototypes deployed across geographically dispersed settings can feed performance data back into shared repositories, enabling the distributed community to accumulate empirical evidence across diverse contexts and inform subsequent iterations collectively rather than individually [59],[60].

Generative AI contributes to the Build step primarily through its role in coding and system integration, particularly within physical computing environments. AI-assisted programming tools support the rapid prototyping of firmware, sensor logic, and data-processing scripts, enabling contributors with limited coding backgrounds to implement functional digital-physical systems [61],[62]. By accelerating debugging and code iteration, AI reduces development cycles and enhances the adaptability of prototypes.

From an OD perspective, however, the integration of proprietary software and generative AI into the Build step also introduces structural tensions. Song et al. [63] observe that AI tools alter collaboration dynamics in open-source development, enhancing productivity while simultaneously increasing coordination overhead.

More fundamentally, while OSH and distributed manufacturing aim to decentralise production, reliance on centralised software and AI platforms may reintroduce asymmetries in access and control, raising questions regarding transparency, reproducibility, and infrastructural dependency within ostensibly open communities.

This tension underscores the need for grassroots approaches grounded in technological sovereignty, allowing local communities to regain autonomy over their fabrication infrastructure rather than relying on centralised systems. By shifting toward the co-production of knowledge, these communities can materialise solutions tailored to their specific needs and capacities [64],[32]. Ultimately, this ensures that digital fabrication fosters local empowerment and autonomous maintenance rather than new forms of technological lock-in.

**Test.** The Test step constitutes the evaluative counterpart to the generative logic of the Build step, serving as the mechanism through which the physical prototype is assessed against the functional and operational expectations that motivated its construction. As Lim et al. [65] argue, the best prototype makes a design idea's possibilities and limitations visible and measurable in the simplest, most efficient way.

In ODD contexts, however, the Test step is characterised by a structural tension between three distinct evaluative registers that rarely operate independently.

The first is quantitative and parameter-based: where prototypes integrate sensing technologies, performance is evaluated by measuring operational variables against expected thresholds. DTs extend testing beyond qualitative observation into shareable, cumulative data sets, a dynamic enabled by OSH replication logic where instrumentation designs and outputs circulate freely [56].

The second register is empirical and contextual: performance cannot be fully reduced to quantifiable parameters; real-world environments introduce situational variability and emergent behaviours. As Camburn et al. [66] observe, iterative prototyping in complex spaces relies on exploratory validation where success criteria emerge through situated observation and reflective practice.

The third register that proves significant in ODD contexts concerns expert involvement. Domain-specific expert evaluation combines technical assessment with the interpretive flexibility of experiential judgement [66].

In this setting, moments of collective critique transform the Test step into a pedagogical and educational device in its own right [29],[24].

Together, these three registers constitute a composite evaluative logic that is neither purely quantitative nor purely empirical, but situationally calibrated to the nature of the prototype, the characteristics of the domain, and the competencies available within the distributed community conducting the test. The outcome of this step determines whether the design proceeds to the Communicate step or returns to an earlier stage for further iteration, functioning as the convergence mechanism through which the open and exploratory logic of distributed design is progressively focused toward a stable and releasable configuration [65], [14].

**Communicate.** The Communicate step moves the design process outward, translating internal prototype knowledge into accessible, reproducible documentation that allows others to replicate, modify, and build upon the solution. In this step, DTs intervene primarily as documentation, coordination, and dissemination infrastructures, converting tacit prototype knowledge into transferable digital artefacts. In ODD, this externalisation is critical: actual openness is achieved not by the mere act of design, but through the quality and accessibility of its documentation [14].

In this context, documentation evolves to encompass new typologies of deliverables: shareable digital files (including CAD models, ECAD schematics, Bills of Materials (BOMs), and source code released under open licences), assembly instructions, construction kits, and meta-design artefacts, understood as parametric models or design generators that afford users significant degrees of freedom, enabling them to input their own variables and produce customised outputs [14], [12]. A central challenge concerns documentation completeness and accessibility [67]. Because ODD projects engage contributors with diverse skills and backgrounds, effective documentation must translate domain-specific expertise into layered, procedural guidance that does not presuppose the originating team's prior knowledge.

Ultimately, the Communicate step functions as an instrument of epistemological translation: it codifies informal and embodied domain knowledge into explicit, transferable guidance, extending the reach of the design far beyond the community that created it [14].

Transparency in this documentation accelerates incremental improvement and problem-solving across peer production communities [68]. Within this ecosystem, digital sharing platforms serve as both repositories and essential coordination tools, enabling design files to circulate instantly across global networks while facilitating asynchronous collaboration, issue tracking, and the remixing of projects without requiring physical co-presence [14], [12], [40]. Repositories and version control platforms, such as GitHub, provide the foundational infrastructure for this externalisation [67]. Underpinned by open licensing frameworks [12], this architecture integrates a branching logic directly into day-to-day development: unlike traditional patent-based disclosure, ODD allows design branches to coexist, merge, or diverge as the contributor community requires [18]. Open documentation further fosters reciprocal learning: the sharing of documentation contributes to collective knowledge accumulation, enabling distributed communities to customise and combine existing solutions rather than developing them from scratch [12].

The systemic implications of this practice extend beyond the individual project. Branching and forking mechanisms amplify this systemic dimension: each public release does not mark the terminus of a design trajectory but opens it to derivative development by independent contributors [18]. Each documented project thus functions as a knowledge node within this ecosystem, a reference point that subsequent designers can fork, adapt, and build upon, contributing to the cumulative and recombinant character of open innovation [67]. In this sense, the Communicate step closes the iterative loop of the design process while simultaneously opening it toward futures exceeding the original team's intent, positioning open documentation as both the terminus of one cycle and the generative condition of the next.

#### **4. Situating Open and Distributed Design in Practice: The Distributed Design Platform and the Circular Transition of Food Systems**

Having established ODD as a design methodology and mapped how DTs intervene across its constituent phases, this chapter situates that framework within a concrete institutional and empirical setting. The Creative Europe programme, established by the European Union in 2014 and subsequently renewed for the 2021–2027 financial framework, provides this institutional structure, positioning the research within the broader discourse on the cultural and creative industries [2]. Among its objectives, Creative Europe places particular emphasis on capacity-building and skills development within these sectors, notably by supporting grassroots organisations in cultivating talent and stimulating innovation [69].

Within this vision operates the DDP, a multi-year project co-funded under the Creative Europe programme, coordinated by Fab Lab Barcelona and bringing together 17 partner organisations. DDP delivers Europe-wide programming to support emerging creatives, with a focus on education and training, capacity-building, skills development, peer-to-peer exchange and networking. Beyond its educational role, the platform carries out advocacy activities to promote excellence in distributed design and engages in collaborative action-research. Its core aim is to equip designers and makers with

frameworks for steering the design discipline toward more sustainable, inclusive and collaborative practices [70],[71].

This contribution adopts DDP as its empirical context to observe and critically analyse the role of DTs within ODD practices. Specifically, the study examines two DDP initiatives, Open Food Factory [72] and Distributed Food Factory [73], which together produced five solutions exploring the relationship between ODD and circular food systems.

Open Food Factory [72] (April 2022-February 2023) investigated micro-scale and self-production in relation to emerging food practices and socio-technical regimes, framed within a circular economy perspective. It centred on ODD and the prototyping of open-source devices for plant-based fermentation and distillation, fostering sustainable, decentralised and knowledge-sharing approaches to food production [72]. Distributed Food Factory (September 2023-February 2024) examined the intersection of ODD and local food ecosystems, integrating the principles of the European Farm to Fork strategy with those of ODD to explore product-service systems and systemic solutions enabling individuals and organisations to monitor and manage food ecosystems at both macro and micro levels [73].

Both initiatives were structured around an open call centred on hacking, making and circular economy, addressed to young designers and independent innovators working in collaboration with an academic makerspace. More than 30 participants submitted proposals, which were selected for their alignment with ODD principles and their innovative approach to the circular transition of food systems. The resulting designs and prototypes were released on the DDP together with all materials required for open-source production.

At a theoretical level, these initiatives can be read against four structural challenges facing the transformation toward more resilient and sustainable food systems, as identified in FAO's policy framework [74]:

- First, persistent inequities in knowledge and technology access marginalise small-scale producers, particularly in low- and middle-income contexts, accelerating market concentration within food supply chains [74], [75];
- Second, existing innovation infrastructures fail to coordinate heterogeneous actor networks spanning divergent economic scales and technological capacities, frequently neglecting the context-specific needs of family farmers [74], [75];
- Third, transitioning toward long-term resilience creates a critical trade-off with short-term operational efficiency, as diversifying supply sources and introducing systemic redundancies generate immediate costs that low-margin producers struggle to absorb [25], [74];
- Finally, reconfiguring supply chains to prioritise local sourcing necessitates a holistic alignment of public policy, private innovation, and behavioural shifts, moving beyond isolated measures [25], [74], [76], [77]. Implementing a design thinking approach is therefore vital to unite stakeholders, navigate efficiency-sustainability tensions, and guarantee food security while regenerating natural resources [25], [76], [77].

Importantly, these challenges are not peculiar to food systems alone. Analogous barriers recur across circular economy transitions in other sectors. These include the persistence of knowledge- and technology-related obstacles along the eco-innovation

pathway [78], a lack of value-chain stakeholder collaboration in industries such as construction, plastics and textiles [79], structural trade-offs between operational efficiency and resilience in closed-loop supply chains [80], and the broader reconfiguration of manufacturing toward localised, distributed models [81].

Within this broader landscape of circular transitions, and as discussed in Section 2, ODD's structural affinity with the circular economy, grounded in the democratisation of knowledge and production, positions initiatives such as Open Food Factory and Distributed Food Factory as niches [34]. This situated orientation resonates with a defining trait of the creative and cultural industries themselves, which are strongly territorialised activities whose value creation depends on localised assets, proximity and place-specific knowledge [7]. ODD's insistence on addressing design problems within their own local context, rather than importing solutions devised by external actors with little awareness of situated conditions, thus positions ODD as a methodology particularly attuned to the community-centred, place-based logic of CIs practice [10].

The projects developed within the two initiatives, in this light, constitute cases of situated design that illustrate how, in practice, DTs enable ODD methodologies for sustainability-oriented capacity-building. The fact that these experiences took place within a makerspace embeds them in an ecosystem that, as highlighted in the literature, fosters informal learning, peer-to-peer exchange and community-building [29]. Within these spaces, education does not occur passively but through a constructivist approach, in which the democratisation of tools and open collaboration make the makerspace an educational environment grounded in situated, hands-on learning [29],[35]. In this context, the design process is elevated to a practice of critical making, in which fabrication helps designers internalise ethical, environmental and social challenges, reconnecting lived experience to critical theory [35]. This mode of learning echoes long-standing calls within design education to move beyond the transmission of isolated technical skills toward a model in which learners actively shape their own learning environments and practise situated, collaborative decision-making [1]. Such a pedagogy is inherently team-oriented and integrative, demanding precisely the broad, systemic perspective that complex social, industrial and environmental problems require. Responding to a call centred on ODD, hacking, making and circular economy within a makerspace already deeply permeated by this culture therefore becomes a powerful experience of active education in sustainable practice. This aligns design practice with the current demands of design education, which, as discussed in Section 2, requires moving beyond isolated solutions to embrace systems thinking.

Moreover, this convergence between education, sustainability and open creative ecosystems has a profound impact on CIs. Trained through this pedagogy of action, designers acquire the competencies needed to address the wicked problems characteristic of social and environmental dynamics. In this sense, the makerspace functions as an incubator for future agents of change, capable of orchestrating social, cultural and ecological solutions tailored to local communities [10],[36],[29],[9],[6]. Crucially, the capacity to generate such situated responses is not an individual attribute but a collective and networked one: within the CIs, collaboration and the sharing of knowledge across distributed actors operate as primary drivers of innovation and of the spill-over effects through which local challenges are met [3]. Understood in this light, open innovation becomes a major factor of development for these territorialised

industries, opening new growth opportunities not only for the actors involved but for the very territories in which they cluster [7].

The three threads introduced in Section 2, DTs as enablers of capacity-building, ODD as an infrastructure for sustainable transition, and its implications for the CIs, now converge to organise the empirical findings of Open Food Factory and Distributed Food Factory. Rather than being uniformly distributed, these threads intersect distinctively across three interpretative dimensions:

- The Social Dimension foregrounds the capacity-building thread most directly, examining how DTs support the translation of tacit knowledge, knowledge forking as a driver for sustainable design innovation, the coordination of heterogeneous participants within the two initiatives, and the reshaping of the designer's role toward facilitation and co-design.
- The Technical Dimension centres on the sustainability thread, showing how DTs are mobilised to negotiate material and regulatory constraints through frugal, adaptable design responses, and the adequacy of these responses to specific functional and contextual requirements.
- The Systemic Dimension draws the three threads together at a larger scale, connecting circular design strategies for product longevity to the redistribution of production and knowledge ownership toward local communities, where sustainability and the CIs' capacity-building potential most visibly intersect.

Read together, the three dimensions offer a situated account of how DTs concretely enable ODD's methodological, sustainable and pedagogical facets within a CI context.

## 5. Digital Technologies as Enabling Devices Situated within Open and Distributed Design

Having established the analytical framework, this section empirically analyses five ODD projects developed within the DDP. It first provides a concise overview of the selected projects, followed by findings structured around the three analytical dimensions, Social, Technical and Systemic, introduced in Section 4.

### **Analysis of the solutions developed within Open Food Factory.**

*Hacko:* Kit for nukazuke. The project uses ODD on nukazuke, a Japanese technique preserving vegetables in salted rice bran (nukadoko). This process requires daily upkeep to maintain lactobacilli cultures and regulate moisture and aeration. The proposed solution consists of an open-source kit combining standard containers, 3D-printed components, and a digital monitoring system for real-time humidity and temperature control.

*Breath:* Parametric valves for lacto-fermentation. The project develops a system supporting traditional fermentation through accessible and easy-to-use tools. It consists of three components: a valved cap and two silicone membranes, designed for additive manufacturing, with food-safe materials. The parametric cap adapts to different jar sizes, and the 3D-printed moulds are reusable.

*Olea:* Distiller for essential oils and hydrolats. The open-source steam distillation project uses a maker and citizen science approach to make non-alcoholic distillation

accessible. This hacking method combines reversibly adapted household items (steel pot, lid, colander, steamer basket, glass jug with tap, induction cooker) with custom technical components (copper tube, brass valve, silicone tubes, 3D-printed parts).

### **Analysis of the Solutions Developed within Distributed Food Factory.**

*Open Farmer Kit:* Kit for social urban farming. The project is an open-source, modular system for monitoring environmental conditions and biodiversity in urban social farming ecosystems. It adapts precision agriculture to small-scale urban gardens and orchards managed by citizens, enabling distributed municipal monitoring of urban agricultural ecosystems. The system combines semi-automated operation with intuitive user interaction and a modular architecture capable of measuring air quality, key soil parameters, and pollinator activity through image-based monitoring.

*Circle Fermenter:* Modular circular fermenter. The project addresses domestic food ecosystems through a modular, open-source fermenter for experimenting with sustainable food transformation and self-production. It combines commercial components, digitally fabricated parts, and electronics for controlled growth monitoring, supporting safe and participatory fermentation.

## **5.1 Social Dimension**

The empirical analysis supports the hypothesis that DTs, especially in the Planning Phase of ODD, can function as enablers of sustainable and inclusive design practices within food systems. The contribution reveals how, in this phase, DTs operate not as mere functional tools, but as agents of social reconfiguration. Open Food Factory and Distributed Food Factory represent experimental spaces, or niches in the sense of the Multi-Level Perspective on socio-technical transitions [82], in which civil society appropriates technology to address needs unmet by the conventional market. This configuration aligns with the concept of Grassroots Innovation movements, wherein communities develop alternative socio-technical arrangements outside mainstream institutions [83].

As stated in Section 2, within this framework, ideation moves beyond producing finished goods toward codifying open knowledge systems that can be appropriated, modified, and evolved by their users. This repositions the designer from a technical translator into a meta-designer and facilitator within Participatory Culture. Consequently, the focus turns toward capacity-building, empowering local communities to shape their own futures by gaining agency over complex socio-technical processes. From the analysis of the five projects, this social dimension unfolds across two mechanisms: the pedagogical translation of tacit knowledge and knowledge forking as a lever for sustainable design practice. The coordination of heterogeneous participants and the reshaping of the designer's role toward facilitation, both anticipated in the previous section, are not treated here as autonomous mechanisms but as constitutive dynamics running through each of the two. Together, these mechanisms articulate a coherent model of grassroots technological democratisation, wherein the ODD process itself becomes the primary driver of social impact, directly addressing the challenges outlined in Section 4.

Ultimately, by enabling distributed actors to continuously adapt, contextualise, and redistribute open knowledge, both the forking of knowledge and the pedagogical

translation of tacit knowledge shift the core focus of ODD from the delivery of static technological artefacts to the cultivation of an evolving, community-driven meta-design ecosystem, thereby positioning ODD as a mechanism for community empowerment and localised sustainability.

**Translation of tacit knowledge (selected case: Hacks).** Hacks constitutes a paradigmatic case of how ODD and digital fabrication can transform a tacit traditional practice into an accessible and engaging process for non-expert users. The design challenge consisted in transposing *nukazuke*, a Japanese fermentative ecosystem grounded in complex, unwritten, and deeply embodied variables, into a Western domestic context. Traditional food practices are often intrinsically rooted in gestures, rituals, and local sensibilities that resist formalisation and distant transmission. DTs in ODD operate here as a translation mechanism through which knowledge is extracted and codified into open, shareable digital assets, enabling what Manzini and Rizzo [84] conceptualise as an open participated process: a model in which multiple small, distributed design initiatives interact to produce large-scale sociotechnical change. During the Planning Phase, a collaborative dynamic emerged among stakeholders with heterogeneous backgrounds, expertise, cultures, and origins. In this context, DTs rendered boundary objects legible and actionable across a diverse stakeholder network, enabling real-time negotiation of product functions and directions. This capacity for open, technology-facilitated collaboration proved foundational, as it structured the iterative logic that would guide subsequent design steps.

During the Build step, a critical tension emerged between conflicting hygienic paradigms. The initial attempt to align the Japanese practice with the Western Pasteurian model of sterility, through the use of spatulas and gloves, caused the failure of fermentative activation. As Niwa et al. [85] demonstrate, the bacterial community underlying *nukazuke* fermentation depends on direct hand contact with the rice bran bed, which promotes the transmission of lactic acid bacteria between the human skin microbiome and the fermentation environment. This friction revealed that accessibility to the practice required a layer of technological mediation capable of bridging distinct hygienic frameworks, making legible a set of invisible microbial dynamics that expert practitioners manage intuitively through accumulated experience.

Observations gathered during the Test step reinforced this dynamic. The collaboration across a diverse team intensified the project's iterative cycles, ultimately converging on a solution capable of making the *nukazuke* technique accessible by dismantling both geographical and knowledge barriers.

This iterative collaboration converged on a solution that addresses fermentation management through affective, gamified mediation. Raw data detected by pH, humidity, and temperature sensors is translated into an accessible interface featuring an empathetic digital avatar that guides the user through context-specific micro-interventions. By framing the microbial colony as a responsive entity requiring care, the system transforms opaque bacterial management into an emotionally legible ritual, incrementally building tacit competence and reducing dependence on explicit guidance. Therefore, designers do not merely translate practices; rather, they create a device and the enabling conditions to foster a learning experience.

**Acceleration through Open-Source Models (Case: Circle fermenter).** Parallel to tacit knowledge translation processes, the investigation conducted within Distributed Food Factory has highlighted a second fundamental mechanism of technological democratisation: the acceleration of innovation through design forking practices on OSH, defined in Section 3.1. Circle Fermenter's case study illustrates how access to shared knowledge repositories functions as a methodological lever that compresses the early validation phases of development and redirects creative effort toward the incremental optimisation of performance and accessibility. In this sense, the forking of open knowledge is not merely a technical mechanism of code reuse but a sustainable design practice in its own right: by allowing communities to build upon empirically validated foundations, it redistributes competencies and shortens the path from local need to viable solution. Specifically, the project develops from the Domingo Fermenter, an open-source device for domestic fermentation distributed through a web repository, whose publicly documented architecture provided the design team with a stable and empirically tested technological foundation [86].

It is fundamental to underline that the adoption of a previous design did not entail bypassing process validation but rather provided a stable technological base to conduct essential preliminary tests, reducing the technical risk associated with early development.

In the first Build step, designers replicated the functional components of the original system and assembled them in a provisional configuration to verify basic dynamics and microorganism response in a controlled environment. This phase was a deliberate methodological choice: by validating the inherited technological core before modifying it, the team could isolate with precision the specific performance gaps that required redesign, rather than operating in conditions of compounded uncertainty.

Only following this empirical validation did the project evolve toward a substantially redesigned version. The analysis of limits encountered in the starting model guided the implementation of new active monitoring parameters absent in the original version but critical for managing complex fermentations. The system was enhanced with the integration of sensors for relative humidity control beyond temperature alone, and actuators for environmental heating, aligning the device with sophisticated open-source environmental regulation frameworks exemplified by projects such as Mycodo. This architectural progression illustrates precisely the mechanism that makes forking methodologically significant: the effort shifts from the invention of basic mechanisms, which the inherited design already provides, to the optimisation of environmental performance necessary for microorganism survival in more demanding biological conditions.

The architectural decisions that emerged from the forking process reflect precisely the social logic that motivated it. The structural decoupling between control unit and fermentation chambers was not driven by technical optimisation alone, but by the need to make the system accessible across heterogeneous user profiles and productive contexts, from beginners requiring a low-barrier entry point to more experienced practitioners demanding granular environmental control. The OSH repository that enabled forking thus shaped not only the technical trajectory of the project but also its social architecture, embedding scalability and modularity as design responses to the unequal distribution of technical competencies within distributed maker communities. This dynamic instantiates what Kostakis et al. [87] propose as the *design global*,

*manufacture local* model: a commons-oriented productive configuration in which openly shared digital designs circulate freely across distributed networks, while their material realisation remains anchored to local constraints, resources, and needs. In this sense, the technical versatility of the resulting system carries social implications that extend beyond its immediate functional scope.

## 5.2 Technical Dimension

As analysed in Section 3, DTs potentially offer generative freedom across Design, Build and Test steps of ODD processes. However, the need of the final project output to interface with food and living materials, combined with the requirements of strict regulatory frameworks, exposes a structural tension between theoretical possibility and material practice.

The Technical Dimension therefore examines how DTs, principally CAD platforms and digital fabrication technologies, intervene in the Generative Phase when ODD processes are applied to devices that come into contact with food. In this phase, DTs directly influence the materialisation of the output, which must interface with the biological, active, and perishable nature of food matter. As highlighted by Karana et al. [88], this matter possesses its own agency and cannot be fully predicted.

Digital fabrication technologies are particularly critical in this context, as they are structurally incompatible with food-contact certification requirements. In the European regulatory context, the Food Contact Materials (FCM) legislative framework [89] establishes chemical inertness requirements that expose a systematic gap across the principal families of digital fabrication: FDM fabrication generates micro-porous surfaces that create bacterial niches and risk polymer migration into food matter [90], [91]; SLA resins leach toxic compounds into surrounding media regardless of biocompatibility certifications granted for dental or medical uses, which do not extend to food contact [92]; and laser cutting releases volatile organic compounds that deposit on cut surfaces independently of the material's nominal food-contact status [93]. Across all three technologies, this normative friction is not a marginal or correctable limitation but a structural condition rooted in the physical and chemical nature of the fabrication processes themselves, acting as a design constraint that propagates across the design process, with particular relevance in the Generative Phase. The entire process must indeed take into consideration this normative obstacle, requiring compliance to be designed in from the earliest steps. Generative DTs, however, offer the morphological and functional freedom necessary to respond to biological variability and context-specific needs, through targeted design strategies.

The iterative cycle across Design, Build, and Test steps thus becomes the primary mechanism through which normative compliance is evaluated and design solutions are progressively refined. Within this cycle, prototypes function as selective filters within design space exploration [65]: rather than representing complete solutions, they isolate and make testable specific dimensions of a problem, reducing complexity across successive cycles. These filters may target a single dimension per iteration or operate in parallel, collapsing multiple variables into a single material test. Camburn et al. [66] reinforce this interpretation, framing iterative prototyping as the mechanism through which divergence and convergence are navigated within complex design spaces, a

dynamic that becomes particularly acute when those spaces are simultaneously bounded by technical constraints and the unpredictable behaviours of living materials. In this context, the Generative Phase situated in a makerspace doubles as a situated learning environment in the sense introduced in Section 2: navigating the material uncertainty of living food matter through iterative prototyping is itself what builds designers' systems thinking, rather than a by-product of it.

Building on this iterative-filtering logic, the empirical cases examined in the following sections illustrate two instances of this filtering dynamic. Both adopt hybrid production strategies as a resolution to normative friction, in which digitally manufactured components act as connective infrastructure between heterogeneous certified commercial and industrial elements. The first section examines the dissociative strategies through which projects resolve normative friction by structurally precluding any direct contact between digitally fabricated elements and food matter. The second extends this analysis to the concept of parametric interoperability, examining how computational customisation generates adaptive interfaces between digital fabrication outputs and standardised industrial components.

**Dissociative strategies for solving normative friction (Case: Olea).** One strategy identified in the empirical cases is material dissociation. The development process of Olea exemplifies this shift: the effort moves toward selecting existing industrial kitchen components and designing their integration into a system. Digitally manufactured components thus serve only to support and connect off-the-shelf certified industrial elements.

Olea addresses compliance by separating the food-contact layer from the digitally fabricated structural layer, assigning each the appropriate materials and logic. This mirrors the Open Source Syringe Pump [94], where the printed frame is parasitic, and sterile industrial syringes handle fluid containment.

During the Design step, CAD tools were used not to design vessels or containers, but to model the connective and auxiliary components through which certified industrial elements can be integrated into a functional system. This reframing transformed the generative freedom typical of parametric design into a precision instrument for interface resolution. During the Build step, digital fabrication was operationalised in two distinct functional registers. First, printed components served as connective infrastructure, physically integrating certified standard elements: a stainless steel pot, glass carafe, and copper tubing, all capable of withstanding distillation-process temperatures, into a coherent and functional system.

Second, digital fabrication generated auxiliary crafting tools, most notably a bending jig designed to guide the precise shaping of copper tubes for the condensation coil. This dual role illustrates how DTs in the Build step can simultaneously support system assembly and expand the productive capabilities of a non-industrial workshop environment. The Test step then functioned as an empirical validator of the dissociative strategy elaborated during the Design step and enacted during the Build step. Iterative prototyping cycles were used to verify that the structural separation between digitally fabricated components and food-contact surfaces held under operative thermal and chemical conditions, progressively narrowing the solution space toward a configuration satisfying both functional and normative requirements.

**Parametrisation and parametric interoperability (Case: Breath).** While the Olea analysis focuses on physical dissociation, this section focuses on how parametric modelling can act as a mediator between standardised industrial production and localised resources and needs.

The design challenge arose from a specific functional requirement of anaerobic lactic fermentation: the need to guarantee an oxygen-free environment, to vent the CO<sub>2</sub> produced by bacterial activity, and to resist an acid environment. The adopted technical solution recovers and digitalises a water seal principle typical of traditional Chinese jars for Paocai (Sichuan fermentation practice).

Breath invites observations analogous to those developed for Olea, but with a distinctive focus on parametrisation. During the Design step, CAD platforms enabled the parametric modelling of the component geometry, a decision that propagated structurally into all subsequent steps.

Accordingly, during the Build step, DTs operationalised material partitioning through a two-step fabrication sequence: parametric moulds were first produced via FDM printing; food-grade silicone was then cast into these moulds to produce the final food-contact components. This process ensures that digital manufacturing technology never enters the biological circuit.

Moreover, the material partition assigns to each productive logic the domain in which it operates most efficiently, allowing the computational layer to focus on adaptability and interoperability without compromising food safety compliance.

Unlike projects such as the Bio-Scaffold for Mycelium Growth [95], where generative and digital fabrication logic orchestrates the co-creation between machine, organism, and shape across the entire object, Breath applies the parametric interoperability strictly to the interface level, adapting to standard industrial components such as the threads of standard commercial glass jars (e.g. the IKEA 365+ series).

The evaluation of the mechanical reliability of the silicone-to-jar interface and the functional adequacy of the water seal generated iterative cycles during the Test step.

When geometric mismatches emerged, corrections were implemented directly at the parametric level, regenerating the mould without redesigning the component from scratch, thereby accelerating the overall Generative Phase. In this context, the designer operates as a translator between parametric digital fabrication and standardised industrial production.

This scenario also redraws the profile of the project's implicit user. The parametric approach allows the file to be adapted to accommodate a wide range of standard container formats through accessible modifications, lowering the entry barrier to users with limited technical background, while 3D printing enables the materialisation of the parametric component not through direct manufacturing but through producing the moulds used to cast the silicone. The result is a form of distributed frugal innovation [96] that does not merely reduce costs, but redistributes competencies and points of control across the entire Generative Phase, leveraging normative constraints to find new and creative solutions. This redistribution of competencies and control echoes, at the scale of a single case, the broader dynamic that [32] describe in grassroots reappropriations of technology: by shifting who holds the parametric and material knowledge required to produce the device, Breath moves the process closer to the autonomy and technological sovereignty such practices aim to secure for local communities.

### 5.3 Systemic Dimension

The third and final investigative direction, defined as the Systemic dimension, maintains its focus on the Generative Phase of the ODD process while shifting the analytical axis from the role of DTs applied to individual objects to their application within distributed and interconnected networks. In this third dimension, the device is understood as an active node capable of connecting into broader architectures and generating measurable impacts at the scale of the city and its biological cycles.

The theme of distributed networks is particularly relevant in the context of food systems. Drawing on Manzini's [97] theory of social innovation, the projects developed within Open Food Factory and Distributed Food Factory are reinterpreted as interventions in what Kennedy et al. [98] describe as urban metabolism: the ensemble of technical and socio-economic processes governing the flows of energy, materials, nutrients, and food that sustain urban life. Distributed open-source devices and ODD prototypes that enable citizen-scale sensing and local production nodes, understood through this framework, become instruments for rendering those flows more legible, locally governed, and ecologically conscious, democratising metabolic systems that have historically been managed exclusively at industrial and administrative scales.

This systemic perspective, however, inevitably encounters the friction of implementation reality. The theoretically unlimited scalability of open-source solutions, enabled by digital replicability and global file distribution, is practically constrained by material, cognitive, and infrastructural barriers that limit their effective diffusion beyond maker communities and expert networks.

In this regard, the discussion that follows describes how DTs can proactively address this complexity within the ODD process itself, designing for scalability by anticipating and mitigating these barriers.

**Designing for Scalability (selected case: Open Farmer Kit).** Open Farmer Kit functions as a mediation device between active citizenship and the biological metabolism of the city, addressing a structural asymmetry in access to precision agriculture technologies. As Wolfert et al. [99] and FAO [75] document, big data-based smart agriculture tends to centralise control in the hands of a few technological actors, historically excluding small-scale urban and community agriculture from the benefits of environmental monitoring. Open Farmer Kit inverts this paradigm through a modular, open-source, and energy-autonomous monitoring station designed specifically for urban social agriculture contexts, transforming the urban farmer into an active producer of granular, situated knowledge that top-down infrastructure is unable to furnish [100]. When replicated across multiple urban nodes, this distributed knowledge production generates what Kitchin [101] defines as a data-driven approach to urban governance. At the same time, this dynamic empirically instantiates the proximity-driven knowledge spillovers through which distributed contribution turns the urban fabric itself into an open-innovation platform at the city scale [7]. By maintaining the open-source nature of both hardware and data, the project ensures the citizen community remains the primary owner and interpreter of the knowledge produced.

The systemic ambition of Open Farmer Kit, however, renders its scalability problem intrinsic to the design challenge itself. Two structural barriers constrain the

democratising potential of distributed OSH infrastructures. The first concerns access to fabrication: the global accessibility of digital files does not translate into universal productive capacity, as physical materialisation remains bound to machinery geographically concentrated in urban contexts, reconstituting the very centralisation that ODD claims to overcome [29]. The second barrier, more structurally insidious, concerns cognitive and maintenance complexity. Even if carefully engineered, projects like Open Farmer Kit require hybrid competencies spanning agronomy, electronics, and code management, and the greatest difficulty resides not in the initial assembly but in long-term maintenance: locally established knowledge may not endure if key contributors leave [102], a fragility compounded by the chronic underinvestment in maintenance relative to innovation [103].

These two structural barriers are not merely implementation challenges to be addressed post-hoc. The empirical investigation reveals that the ODD process itself, when aware of these systemic constraints, can embed proactive mitigation strategies across its own unfolding.

The first strategy observable in the project concerns what may be defined as design for documentation: the sharing and legibility of knowledge become a structural design objective co-developed alongside the device itself. The Communicate step, in this reading, is not the terminal output of the design process but its primary vector of social diffusion, carrying within its structure the conditions for its own replication and adaptation in contexts remote from the original development environment. This dimension is structurally supported by version control platforms such as GitHub.

A second and structurally related strategy concerns modular scalability, consisting of the fragmentation of the device architecture into discrete, independently operable subsystems that generate differentiated entry points for users with heterogeneous technical competencies. Open Farmer Kit's modular sensing architecture, capable of operating as a minimal air quality monitor or as a fully integrated monitoring station, exemplifies this logic. The combined effect of these two strategies helps realise, within CIs, the pedagogical dimension of ODD's capacity-building potential discussed in Section 2, facilitating the acquisition of new skills and promoting civic technological autonomy. The Communicate step emerges as the primary vehicle for learning, social dissemination, and replicability, while the fragmentation of the architecture into independent subsystems lowers the barriers to participation.

The third strategy consists of interpreting the Test step not solely as a functional validator of technical principles, but as a deliberate simulation of the future user's manufacturing and assembly experience. This methodological reframing transforms prototyping, itself a DT-mediated process, into a prospective scalability instrument. The Test step thus operates across two simultaneous registers: it validates the device's technical behaviour under operative conditions, and it stress-tests the project's replicability assumptions against the material and cognitive realities of distributed fabrication.

The fourth strategy, design for maintenance and improvement, responds directly to the second barrier by treating reparability, disassemblability and upgradability not as post-hoc concerns but as design constraints active from the earliest stages of the ODD process, integrating the principles of the circular economy to extend the product lifecycle. In doing so, the systemic dimension links eco-design strategies for product

longevity to the need to redistribute control over production and knowledge to local communities.

Taken together, these four strategies articulate a design posture in which scalability is not a property that emerges from the device after its completion, but a dimension actively constructed within the Generative Phase through targeted DT interventions. The digital file simultaneously becomes a technical artefact and a social instrument: its architecture encodes not only how the device functions, but for whom, under what conditions, and across what time horizon it can remain operational. A further dynamic cutting across all four strategies, specific to sensor-equipped devices, concerns distributed testing through distributed sensing. Replicating such devices across multiple urban nodes simultaneously produces situated environmental data and empirical evidence about behavioural variability across heterogeneous conditions. The distributed network thus functions not only as the product of the ODD process but as one of its primary testing instruments.

The availability of programmable microcontrollers and their open programming environments lowers the threshold of technical expertise required for codebase construction, enabling contributors with limited coding backgrounds to develop a complex software architecture and to produce more accessible and structured documentation. This represents a concrete instantiation of the grassroots innovation dynamic described by Smith et al. [104], in which the progressive accessibility of advanced tools widens the community of practitioners capable of contributing to open technological development, compressing the expert/non-expert gap that has historically constrained the social reach of ODD projects

## 6. Conclusions

This contribution has examined how DTs intervene across the steps of ODD, and whether their application within an applied setting can support sustainable, capacity-building design practices. On the first question, Section 3 mapped an uneven distribution of DTs across the seven-step ODD process, concentrated in the mediation of boundary objects, distributed collaboration and knowledge accumulation. This mapping confirms, at the level of individual steps, the imbalance already noted in the literature [13] between the two constituent phases: the Planning Phase, concerned with preparing and setting boundaries for generative activity, tends to be systematically underweighted relative to the generative one, where DTs assume primary importance. On the second, the analysis of Open Food Factory and Distributed Food Factory initiatives in Section 5 suggests that such support is neither automatic nor unconditional, but depends on how DTs are situated within the practices, communities and systemic conditions of a given project.

Read against the three threads introduced in Section 2, the three empirical dimensions foreground this conditionality differently. The Social dimension shows DTs enabling capacity-building directly, through translation of tacit knowledge and through forking as a means of redistributing competencies rather than merely reusing existing designs or technical solutions; in both mechanisms, the designer's role shifts from author to facilitator, as anticipated in Section 2. The Technical dimension shows

the sustainability thread meeting material limits: the incompatibility between digital fabrication and food-contact regulation, examined in Section 5.2, does not disqualify DTs but redirects their generative freedom into dissociative and parametric strategies, turning a normative obstacle into a structuring design constraint. The Systemic dimension draws the three threads together at a larger scale, connecting the strategies for designing scalability, documentation, modularity, test-as-simulation and maintenance, to the redistribution of production and knowledge ownership towards local communities, where CIs' capacity-building potential and ODD's sustainability infrastructure most visibly intersect.

Taken together, these findings qualify rather than confirm any straightforward claim about scale. The Systemic dimension shows that scaling ODD prototypes beyond the maker community that produced them meets two structural barriers: uneven access to fabrication infrastructure and the cognitive and maintenance demands of long-term operation, which the four mitigation strategies documented in Section 5.3 address only partially rather than resolve. What the two initiatives demonstrate most directly is not that small-scale experimentation is preferable to industrial-scale deployment, but that ODD's value, on this evidence, is inseparable from the situated, community-centred, place-based logic that Section 4 identified as constitutive of CIs practice: the same local grounding that constrains straightforward replication is also what allows ODD to function as a pedagogical model for capacity-building. Within this logic, the educational function of ODD, evident in the makerspace as a site of informal, situated learning, is not incidental to its sustainability infrastructure but structurally continuous with it: both rest on the same redistribution of competencies and control from centralised experts towards distributed communities.

These findings rest on a deliberately narrow empirical base: two initiatives and five projects developed within a single platform, and make no claim to statistical representativeness. Their transferability should be understood through Smith's [105] concepts of analytical, naturalistic, and inferential generalisation, whereby it is for the reader to judge whether the challenges engaged here: unequal access to knowledge and technology, the coordination of heterogeneous actors, and the friction between openness and situated constraint, resonate with their own context. Furthermore, this approach aligns with Flyvbjerg's [106] defence of context-dependent case knowledge, which travels through the specificity of the mechanisms identified rather than through sample size. Section 4 already indicated that such challenges are not unique to food systems; the present findings offer one situated account of how they may be addressed, not a template for unmediated replication.

This account should not be read as an uncritical endorsement of open and distributed methodologies. As the empirical cases show, openness carries hidden costs of coordination, documentation and long-term maintenance that are not evenly distributed among participants and that can reproduce rather than resolve pre-existing disparities in access to digital infrastructure and technical expertise. The Systemic dimension's account of scalability barriers and the Social dimension's account of the unequal distribution of technical competencies that forking-based design responses had to accommodate, both point to the same underlying asymmetry, one that design strategies can mitigate but not fully resolve. What this contribution offers, then, is not proof that ODD scales sustainability, but an account of the conditions under which digital technologies render operative the sustainability and capacity-building potential that

ODD already holds, by design, for the CIs: conditions that are situated, educationally embedded, and dependent on the communities that sustain it over time.

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