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A NEW BREED OF SUSTAINABLE AUGMENTED URBAN FURNITURE. DESIGNING FOR EXTRUSION-BASED ADDITIVE MANUFACTURING

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Abstract
Cyber-physical devices are the backbone of a postdigital society in which the virtual and real spaces are seamlessly integrated by ubiquitous computing, networking and IoT. The design, fabrication and deployment of such devices in public space are central subjects of a strategic Research Project multidisciplinary team from architecture, product design, polymer science and ICT R&D units, bridging the gap between urban intelligence, physical and digital elements. A shared commitment to develop replicable local and sustainable added value products to drive new uses of urban spaces. This objective is materialized in a full-scale outdoor-ready demonstrator of a modular augmented street furniture system comprising: (i) cyber-components, (ii) solar energy, (iii) recycled plastic, and (iv) robotic extrusion-based additive manufacturing (EBAM). At a first stage, the demonstrator was thought to support University Campus activities and facilitate common urban tasks that also takes advantage of renewable energy sources to further create awareness of global pressing issues. The research project literature review was materialized in a case study Atlas of urban interactive cyber-physical devices, identifying design, sustainability and deployment strategies. Alongside an organized design workshop, it fed the demonstrator's design guidelines, which focused on: (i) product design process, (ii) interaction design and digital twin, (iii) renewable energy and electronic components integration, (iv) material and fabrication process, and (v) deployment evaluation. Fabrication tests and prototypes are being conducted in a large-scale robotic arm EBAM setup, using rPET pellet and experiencing with functional additives from local natural waste origin (e.g., olive pit). The design team coordination task is being supported by a digital workflow, based on Grasshopper VPL, which encompasses: (i) 3d modelling and parametrization, (ii) stress analysis, (iii) infill pattern generation, (iv) slicing and path analysis, (v) fabrication simulation and robotic control code generation.

1. INTRODUCTION
The combination and coordination between physical public space, urban (big) data and ICTs is tied to the concept of Smart City. This is an approach to urbanization that uses innovative technologies to enhance community services and economic opportunities, improve city infrastructure, reduce costs and resources consumption, and increase civic engagement [8]. The addition of Urban Cyber Physical Devices (UCPDs) into public spaces transforms them through a seamless *phygital* experience by facilitating quotidian tasks and improving conveniences, such as fast access to information and services and improved safety. UCPDs are responsive urban devices comprised of deeply intertwined physical and software components [9], and can be seen as a class of what has been called Cyber-Physical-Social Systems (CPSSs): The extension of Cyber-Physical Systems to seamlessly integrate cyber space, physical space and social space [13], in the context of the (smart) city. This synchronic coexistence has been changing how we use public spaces, the spaces themselves, and the emergence of new breeds of augmented urban objects. Data collected by IoT enabled devices can be used to feed city *digital twins* with information from its state and environment. These tools permit governance agencies to make informed decisions on urban life and are the technologic backbone for Smart City sustainable urban transformation.

The design of UCPDs as sustainable opportunities to local economy and development is the central subject of Lab4U&Spaces Research Project. Defined as a living lab for interactive urban space solutions, it gathers a multidisciplinary team from architecture, product design, polymer science and ICT R&D units. This paper focuses on the central activity shared by all research lines and coordinated by the design team: the development of a use case integration demonstrator. It is materialized in a full-scale outdoor-ready augmented urban furniture system involving: cyber-components, solar energy, recycled plastic, and robotic extrusion-based additive manufacturing (EBAM). This demonstrator was thought to support University Campus activities creating awareness of global pressing issues thru its functioning and example.

2. BACKGROUND

The integration of smart functionality into urban devices allows their incorporation into larger smart city systems [12]. On the other hand, these devices are becoming increasingly designed with sustainability concerns, namely energetic self-sufficiency and recycled materials usage with new fabrication methods that minimize waste, costs and promote Circular Economy (CE).

2.1. DESIGN REFERENCE CASE STUDY PROJECTS

The scope of design case studies reviewed encompasses urban devices with (i) digital components integration (ICTs), (ii) solar-power energy, (iii) recycled plastics, and (iv) large scale EBAM. These four research vectors are related by sustainability concerns, but case studies present several degrees of integration. The first two vectors often appear together, as is the case of the last two, nonetheless designs exploring all these vectors are rarer. Only one recent example was found: *Desko* [5], although very one-dimensional in functioning and digital interaction. Other projects like *Birloki* [3], *Smart Pole* [19], *Bench Mark* [2] and *Soofa Sign* [20], are also design references due to their modular and customizable multifunctional approach, energetic and network solutions, alternative interfacing (e.g. body, tangible, light and soundscape interfaces), and open-source, low-tech, playable and emotional design strategies which allows for a greater resistance to trivialization and early obsolescence. The analysis of these devices and their contexts fed some shape and functioning guidelines for the demonstrator. On the other hand, *The New Raw* [22], *NAGAMI* [11] and *Studio RAP* [21] are some of the reference robotic EBAM studios. They feature many designs, including urban furniture, from which we could understand design, technical and material limitations that also informed fabrication and material expression guidelines.

2.2. UCPDS AND SUSTAINABILITY

Outdoor UCPDs are increasingly designed to ambient energy harvesting and self-sufficiency. Solar photovoltaic is the most implemented small-scale solution, boosted with developments in battery technology and low-energy electronic solutions. Premier [15] provides an overview on the design and potentials of solar-powered smart urban furniture. Sustainability global challenges have also pushed for alternative models to the linear economy production and consumption wasteful paradigm. CE proposes a set of strategies to extend the life cycle of products and materials by reuse, recycling and waste valorisation [4]. Waste plastic as a secondary raw product is becoming increasingly important in the product value chain as a way of tackling the environmental and public health problems of non-degradability of fossil-fuel plastics and waste contamination.

On the other hand, Additive Manufacturing (AM), also known as 3D print, is an increasingly adopted technology. Popularized by filament desktop 3D printers, within the open-source and Fablab/DIY culture and initially seemed like a prototype and tooling process, AM has now scaled to industrial applications and allows direct fabrication of a wide range of end-user products. Its benefits include material, time and cost reduction in fabrication and product development, freedom in shape modelling and customization. Based on distributed production and localized supply-consume-disposal chains, the opportunities to local economy (and design) from the join possibilities of recycled plastics and AM are a key factor promoting CE. Cruz Sanchez *et al.* [4] examine the advances on plastic recycling via AM, proposing a new Distributed Recycling via Additive Manufacturing (DRAM) concept as a centrepiece of CE, and Romani, Rognoli and Levi [16] presents a design viewpoint on the subject of recycled materials in EBAM. Conscientious design incorporating such concepts and technologies are becoming increasingly adopted. Sauerwein *et al.* [18] presents a general view on the potentials of AM to product design in a CE based on distributed manufacturing.

2.3. DESIGNING FOR RECYCLED PLASTIC LARGE SCALE EBAM

From the ISO standard main AM process categories, material extrusion (EBAM) is the most widespread technology [7], and polymer thermoplastics are the most used materials [10] in what is called Fused Deposition Modelling (FDM), or MatEx, 3D printing. Large scale EBAM (or Big Area AM), notably, robotic arms equipped with large debit extruders are increasingly adopted. Fed by pelletized materials, these systems dispense the filament fabrication step, with sustainability, economic and material versatility gains [4]. Large scale plastic EBAM raises new fabrication problems, not occurring in desktop FFF 3D printing, related with temperature and heat gradients control during fabrication [14]. Delamination, sagging, warping and surface imperfections, are defects resulting from undesired correlation between shape geometry, fabrication parameters and material features. Fibre-reinforced materials minimize these problems, and general design guidelines should follow: (i) carefully choose slicing plane step offset and direction (avoiding shear forces in line with layer bounds); (ii) proper bonding of first layer to printing bed; (iii) avoid support material; (iv) avoid holes, bridges and overhang angles over material capability (typically over a 45^o threshold); (v) optimize layer paths geometry for continuity, layer cooling times, maximum extruder throughput and minimum fabrication time and material; and (vi) optimize overall piece shape (e.g. topologic optimization) [17].

2.4. THE DESIGN-FABRICATION PROCESS: TOOLS, MATERIALS AND WORKFLOW

The fabrication line setup includes a six axes *KUKA KR 120 R3100-2* robotic arm, with *KUKA KR C4* controller, and a *PERIPLAST Extrubot* pellet extruder and controller. These are complemented by a material hopper with integrated dryer, a piston electro-compressor and a 2x2m printing bed. With no local plastic recycling line implemented, the chosen material was the *BIO4-PP820* composite: an industrial matrix of polypropylene (PP) copolymer reinforced with 20% (w/w) of olive pit. The presence of fillers in its polymeric matrix contributes to the low warping, good mechanical resistance, low density and natural colour of the produced parts, which has been compared to virgin PP and PETG.

The demonstrator's design and fabrication are integrated into a digital workflow that takes advantages of algorithmic design and the computer-controlled fabrication technique, streamlining customization of processes and products. The workflow is operationalized using algorithm-parametric design and simulation tools combined with physical modelling, small and real-scale 3D printing experiments and mock-ups. The design cycle involves a set of cross related tasks and stages interwoven by feedback loops.

3. THE DESIGN OF THE DEMONSTRATOR

The demonstrator responds to a series of design guidelines delineated from the Research Project preliminary goals and subsequent investigation. The demonstrator is being materialized as an augmented urban furniture system with interaction capabilities showcasing the potentials of integrating sustainable solutions into the design of local added value product that promotes CE and behaviour change. Developments on the demonstrator's shape, function and interaction concepts took place with the unfolding of the design process, but some intentions (such as outdoor placement) determined a set of specific requirements concerning ergonomics, structure, anti-vandalism, weatherproofing, safety and overall construction quality.

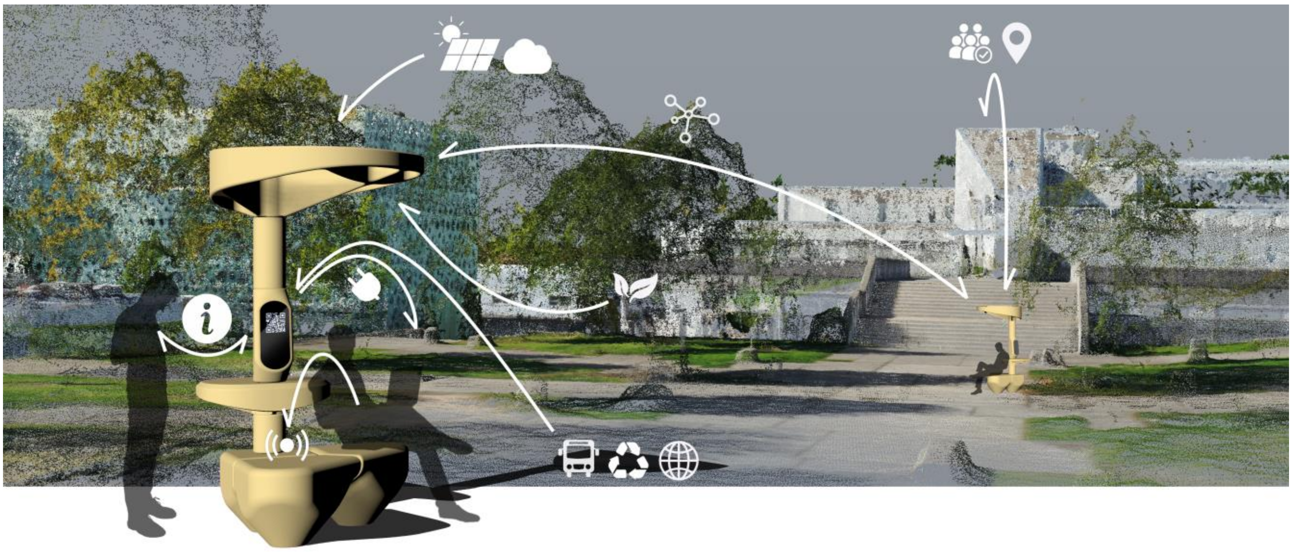

Figure 1. Demonstrator implementation in University Campus and Interaction Diagram.

The general design of the device consists of a wide base (the benches), a high pole (covering a structural profile) and a canopy (providing shadow and solar energy) (Figure 1). Modularity plays a key role in counteracting obsolescence allowing for custom-made add-ons as well as making its 3D printing process easier by reducing its parts size. The set of modules can grow in number, be assembled in a variety of ways (Figure 2, right), and the components themselves can be tailored to different contexts and requirements through parametric design and the digital fabrication process.

3.1. THE DEMONSTRATOR MODULES

Currently, the demonstrator's basic modules are: (1) Bench, (2) Table, (3) Screen, (4) Canopy and (5) Spacers (Figure 2, left). These were defined by the particular functions (digital and physical affordances) determined that the demonstrator should provide.

1. The Bench Module is the basic unit, with three slightly distinctive designs that allow for greater association variation. To ensure stability and enough area for at least two people to seat informally, a set of 3 (one of each design) should be used. Its aggregation arrangements are compatible with most standard orthogonal building constructions (Figure 2). These were thought as containers for batteries and ballast weight (being light enough for transportation) but the empty interior also potentiates its use as an urban planter. Thus, the module is separated into the container itself and an ergonomic removable cover, the seat, where proximity and magnetic field sensors are added. These activate the interface and track the demonstrator's usage.

2. The Table module can be used standing or seated for meals or device use, depending on the height it is fixated in. It is equipped with a watertight wireless charging station and a 220v plug for e-scooters, laptop chargers, etc.

3. The Screen module is a simple housing for a small waterproof LED dot-matrix screen, a bidirectional button with selection (to navigate the interface) and a set of speakers. The user interface is a simple menu designed to display place-relative relevant information such as classroom's affluence, indoor and outdoor navigation services, event calendar, transports schedule, local environmental and weather data etc. The location and the interface content are thought to be intuitive and useful for both people who have experienced the device (and the space) and new users. Using a QR code system as a bridge between the demonstrator and the users' personal device, the heavy computational tasks can be outsourced allowing for a simplification of the demonstrator hardware and software. This approach provides the wanted "analogue" feeling of the experience and independence of high-end technologies improving its longevity.

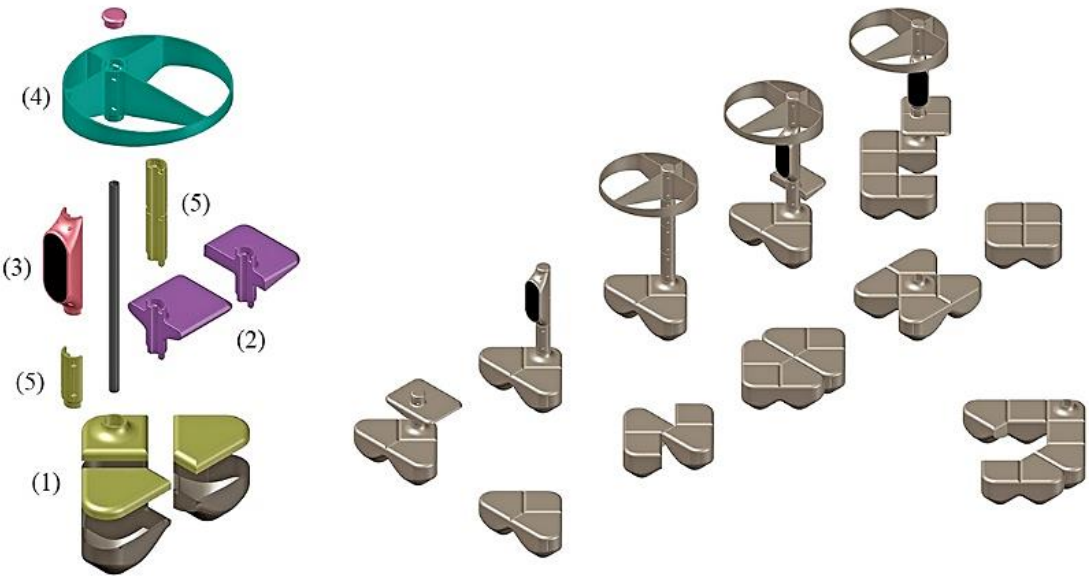

Figure 2. Exploded view and modular combinations of the demonstrator.

4. The Canopy is designed to support two main functions of the device: the solar energy system and the sensor box. Like the table, its shape is a parametrized superellipse that can be easily tweaked. Two openings hold the photovoltaic panels and reduce the total weight of the piece. Taking advantage from its elevated position, the environment status sensors (air quality, temperature, humidity, solar light and sound) are installed in a pocket, protected from rainwater, alongside a presence light and a video camera. The latter is used for outdoor tracking to assist navigation systems and building access control, using ICT team's edge computing technology. The lighting system works as night and presence illumination with light and soundscapes customization possibility to generate various atmospheres, creating a sense of *placemaking* and a more attainable and small-scale public space experience.

5. The Spacer modules are simple cover parts but can also house sensors or LEDs. These protect and ensure weatherproofing of the whole and the routing of cables.

3.2. THE DESIGN-FABRICATION PROCESS AND DIGITAL WORKFLOW

Initial design explorations comprising sketches, physical and CAD models where tentative approaches to the shape definition of the compliant parts comprising the demonstrator (Figure 2-3). As the solution became stabilised, the CAD models were parametrized resorting to Rhino3D Grasshopper VPL algorithm editor. This allows for a continuous digital workflow from plan to fabrication in an environment that optimizes the reuse of information and the integration of analysis and optimization throughout the design process. The current bench shapes are defined by a parametrized 3D "S" meander like infill pattern of a defining mass model, with both structural and decorative objectives (Figure 3, right). The resulting uninterrupted 3D extrusion path must allow fusion to previously deposited material both to layer below and to the same layer, at intervals where it touches itself. Informed by extrusion parameters (like layer offset and bead section) the objective is to create a unique smooth 3D path over the defining geometry, respecting bead horizontal and vertical admissible overlaps and layer times. Predictability of material behaviour during fabrication called for the development of new scripts for CAD geometry pre-processing and analysis.

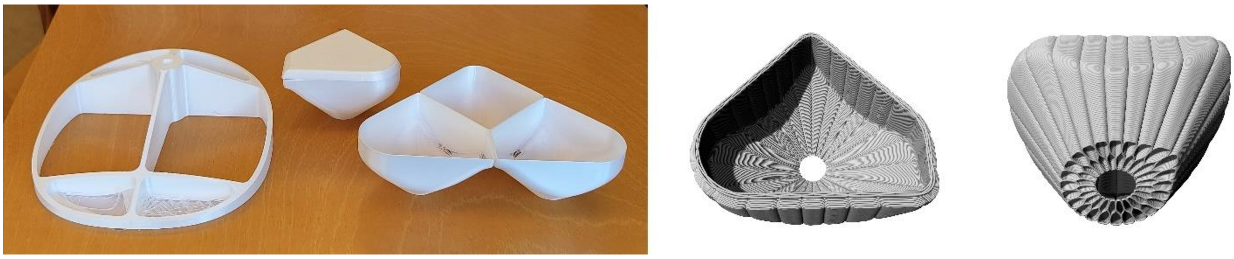

Figure 3. Small FFF 3D prints of demonstrator modules, and current bench parametrized pattern design.

Although Grasshopper plugins exist for the pre-processing steps of AM, in general these target desktop FFF 3D printers and G-code generation [6]. On the other hand, robotic arm EBAM has no automatic 3d model-to-robot code specific plugins or drivers, the robot must be programmed, and toolpaths defined from geometry explicitly. These new EBAM fabrication algorithms are mainly dedicated to the generation and analysis of toolpath curves geometry used to program the robot. These are used in the following tasks: (i) Model slicing and spiralling (slices, pseudo spirals, true spirals); (ii) 2D and 3D sparse and dense infill (regular grids and morph mapping of parametrized pattern units); and (iii) contour and final toolpath angle and distance analysis (3D/vertical angle and 1D/along path distances to previous or the same layer touching points). If the robot speed is known (and extrusion and environmental settings are profiled) this gives a hint on material fusion state and thermal bounding at deposition time along toolpath (Figure 4, right). Other related analysis computed from the parametric model are: point and linear extruded material vertical and lateral overlaps analysis (both analytical, visual and derived geometric representations of overlaid bead sections) and total job material and time.

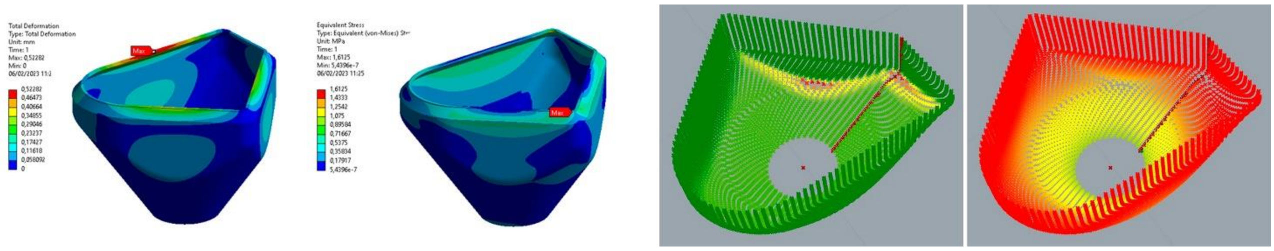

Figure 4. Stress simulation of bench (total deformation and von-Mises stress); and toolpath geometric analysis (vertical angle deviation and length along path to supporting point in previous layer).

FEM stress simulations were conducted using ANSYS simulation software on a simplified 3D CAD model of the bench modules, considering a solid 1 cm wall thickness (approximated to the extruded tests bead section). The mechanical properties from the selected materials were used as input to characterize the performance of the design solution under a static compression load of 1000 N applied on the top surface of each component. The resulting total deformation and von-Mises stress accomplished the specifications imposed for the system, with both virgin and composite material solutions (Figure 4, left). For the parametric robot control and fabrication simulation, we resort to the standard Grasshopper Kuka plugin: KUKA|prc by the *Association for Robots in Architecture* [1]. The initial setup of the virtual fabrication line in Grasshopper (virtual robot, tool, bases and end positions, etc.; Figure 5, centre) is a digital twin of the lab setup.

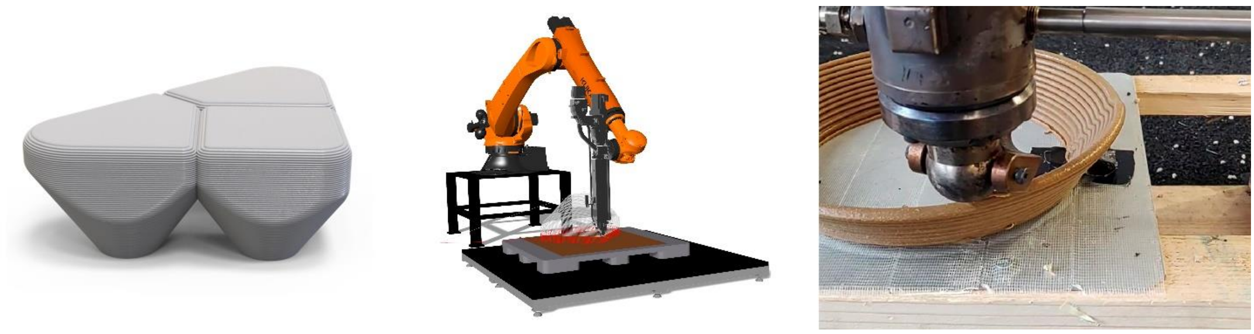

Figure 5. Benches 3d model, KUKA|prc simulation in Rhino3D/Grasshopper, and fabrication process.

Material and time resources, besides structural quality, are crucial factors when working with big scale 3D printing. One ideal design step would be optimization of shape and toolpath (e.g., overall job material and time, layer cooling times, material throughput, arm velocity and path smoothness, etc.). We have not delved deep into such processes, besides initial experiments on minimizing toolpath while maximizing layer overlap, using Grasshopper's Galapagos evolutionary solver to freely rotate the contouring base plane. Optimal solutions had no guarantee of fabrication feasibility, e.g., the object's base area (first layer) was too small at such slicing angle and, predictably, object would become unstable as fabrication unfolds.

First fabrication test pieces and full-scale experiments, conducted with the polymer team, were mainly devoted to profile admissible parameters given fabrication setups (robot-extruder-material-environmental settings) (Figure 5, right).

4. DISCUSSION AND CONCLUSION

In this paper we have outlined the current state of the ongoing design and fabrication process of a demonstrator for an UCPD materialized as an interactive urban furniture system. Following the Research Project aim of showcasing how sustainability and digitalization goals can be opportunities to local economy, the demonstrator is framed in the context of the contemporary trends in digital design, smart urban furniture design and large scale EBAM, highlighting their potentials for the smart city and the CE. The most disruptive consequences come from recycling and manufacture distributed models and the effects of open-source communities where digital manufacturing, low-cost electronics and free software form ecosystems for innovation [4].

The demonstrator, developed to a specific site, aims to be easily customizable for new local contexts and requirements, by taking advantages of the digital workflow that melds all the steps from design to fabrication into a continuous process, linking parametrization, analysis, optimization, simulation and fabrication control.

The analysis of a set of UCPDs case studies and related literature revealed main design strategies to counteract digitally hostile environments, trivialization and early obsolescence of smart urban devices. As most solar-powered devices in urban settings, the demonstrator energetic efficiency is very susceptible to its natural and built surroundings, so solar exposure studies are vital to its functioning. A set of fabrication guidelines were also outlined from first fabrication tests and the literature review on large scale EBAM. Main importance is given to the control of layer overlaying and cooling times during fabrication as a way of ensuring proper thermal bounding, final surface quality and compliance to designed shape. Analysis scripts were developed that may give an approximation on those (in simple fabrication setups) by analysing 3D distances (layer deviation and bead overlaps) and 1D distances (elapsed time) on sampling points along the toolpath curve.

The robotic arm fabrication setup is recent and currently presents several limitations related with the synchronization between robot and extruder (parameters like arm velocity, extrusion rate and temperature must be constant, extrusion angle vertical and material throughput uninterrupted). Continuous extrusion means continuous toolpath, which is a design challenge but, nonetheless, highly desirable in fabrication guidelines.

Future work encompasses: (i) develop the polymer team's ongoing fabrication profiling tests and expand on experimenting alternative recycled plastic - natural fibres composites from local origin; (ii) identify admissible fabrication parameter ranges (on those profiles) and deepen how to integrate them as constrains on the final shapes' geometry and derived toolpaths (as it unfolds over time during fabrication); (iii) develop the integration of components and tooled parts into the fabrication process or final products, and the design of joints compliant with large scale EBAM tolerances. As the development process of the demonstrator is desired to be sustainably exemplar, assessment of the environment footprint of the fabrication process itself and on-site performance are central tasks to be undertaken as the design workflow post-fabrication step.

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