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Ph. Avşar Gürpınar.

Colophon

diid
disegno industriale
industrial design
No. 76 — 2022

Year
XX

diid is an open access
peer-reviewed scientific
design journal

diid is published
three times a year

Registration at Tribunale
di Roma 86/2002
(March 6, 2002)

www.diid.it

Print subscription
(3 issues)
Euro 60,00
Subscription office
ordini@buponline.it

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Publisher

Bologna University Press
Via Saragozza 10
40123 Bologna
Tel. (+39) 051 232 882
Fax (+39) 051 221 019
www.buponline.com
info@buponline.com

ISSN
1594-8528

ISSN Online
2785-2245

DOI
10.30682/diid7622

ISBN
979-12-5477-097-9

ISBN Online
979-12-5477-098-6

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Cover image
44°04’20.3”N 9°56’46.8”E
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Contents

Editorial

6
Editorial
Flaviano Celaschi, Tonino Paris,
Elena Formia, Elena Vai

Open Debate

16
Endogenesis
Paolo Cardini

22
A School for Vernacular Algorithms: Knowledge Transfer as a System and Aesthetic Algorithmic Encounter
Tegan Bristow

32
Discussing Emerging Topics in the DIY Design of Healthcare Devices
Massimo Menichinelli, Jose Gomez-Marquez

44
Critical Jugaad Ontologies
Deepa Butoliya

58
Mixed Media on City: Endogenous Design in Istanbul
Avşar Gürpınar, Nur Horsanalı

70
Walls: Participatory Design Activism
Nikki Juen, Basma Hamdy

82
By Choice and by Necessity: Endogenous Design in the Time of Pandemic
Constantin Boym

Stories

90
Design in Conversation
José de la O, Renata Fenton

Designrama

102
Materials for SDGs: A Synergy Towards Sustainable Development
Romina Santi, Lia Sossini, Mattia Italia, Silvia D’Ambrosio, Francesco Zurlo, Barbara Del Curto

114
The Delphi Method as a Morphological Catalyst for Foresight-Oriented Design Research
Noha Essam Khamis

126
From Open-Source 3D Printing to Industrial Manufacturing
Matteo Zallio, Claudia Porfirione, Francesco Burlando

138
A Framework Towards Understanding the Performativity of Products
Gizem Çelebi, Çiğdem Kaya

146
Seniors and the Use of Digital Media in the Post-Pandemic
Giulia Panadisi

156
Design as a Driver for Multidisciplinary Teams: An Applied Research Case in El Quisco, Chile
Rodrigo Culagovski Rubio, Cala Del Río Alemparte

168
An Open Toolkit for Small-Scale Data Visualizations
Andrea Pronzati, Michele Mauri

178
Digital Architectural Design Inspired by and Created with Nature
Valentina Perricone, Silvano Arcamone, Francesco Monti

Forum and Reviews

Over the Mainstream

190
Research, Design, Action: The Story of a City’s Identity
Dolly Daou

Cultural and Creative Industries

200
Pixels Are Like Fruit Jelly Sweets
Giulietta Fara

From Open-Source 3D Printing to Industrial Manufacturing

A Life Cycle Assessment Study on Handy Multitool

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Abstract

The COVID-19 pandemic brought a tremendous change in people's behaviour, particularly with regard to direct contact with contaminated objects. Handy, a multipurpose tool to help prevent the spread of the virus, was designed as a response in 2020. Initially, it was shared as an open-source, 3D-printable device to allow contactless interaction with objects. Later, market demand increased, and the decision was made to manufacture Handy for mass distribution. This paper reports the methodological process for a Life Cycle Assessment aiming to understand the feasibility for mass manufacturing at an affordable cost that would allow people all over the world to use it sustainably.

The CES Granta software was used to benchmark materials for industrial manufacturing and to analyse the LCA, aiming to achieve an optimal trade-off when transitioning from a 3D printing manufacturing process to a mass manufacturing process.

Keywords
Life Cycle Assessment
3D printing
Open-source
Sustainability
Product design

Introduction

The COVID-19 pandemic brought a tremendous change in people's habits and behaviour (Tull et al., 2020). During the first few months of the pandemic, no clear information about the transmission of the virus was released, because the SARS-CoV-2 was a new strain of coronavirus that had never been seen before (Andersen et al., 2020).

In the early days, between March and April 2020, several opinions regarding the virus transmission were spreading around the globe (Jayaweera et al., 2020). Some experts were pointing to airborne virus transmission, others were mostly concerned about physical transmission through objects and surfaces, on which the virus could survive for several days, depending on the surface material. Studies have shown that the virus could survive for up to 72 hours on plastic and stainless steel, less than 4 hours on copper, and less than 24 hours on cardboard (Marquès et al., 2021).

It was interesting to note that with the spread of the virus, people became more concerned about contracting the infection through direct contact with the objects around them. Individuals became anxious about touching a surface or object that could potentially carry the virus, and consequently touch their mouth, nose, or eyes, causing contamination. Research showed that there was an impelling need to design solutions to reduce the contact with objects, and in particular to use devices to avoid direct contact with potentially contaminated items and reduce interaction between objects and hands (Sutherland et al., 2021).

As the need emerged to protect individuals from the spread of the virus, solutions had to be developed quickly and efficiently: from ventilators for hospitals to personal protection devices such as masks and gloves, to devices that would allow contactless interaction between people and objects.

When the virus started spreading in the United States of America around early-mid April 2020, there was a noticeable change in people's behaviour. It was possible to observe how people interacted differently with objects than before. Individuals started using disposable napkins and gloves to open doors, press buttons, carry bags, and in certain cases, it appeared evident that people were concerned about touching objects in the public space without a filter that would ensure a contactless experience.

Therefore, after documenting this change in behaviour through an ethnographic process, it became possible to identify an underlying challenge and consequently to prototype solutions that would support this changed behaviour.

Following the Design sprint method (Keijzer-Broers et al., 2016), in less than a week it was possible to identify a problem which concerned the difficulty of interacting with objects in the public space, to brainstorm ideas by sketching and creating 3D CAD models, to build prototypes with low-cost, recyclable materials, to create a product that could be mass-produced and finally to market it (Zallio, 2018). In just a few days Handy, a multipurpose tool to prevent the spread of COVID-19 (Zallio, 2020), was created and shared online as an open-source, 3D-printable device to support communities all over the world during the early stages of the pandemic Fig.1.
Its dimensions were quite compact, about the size of a wallet. Shortly

Fig. 1
Matteo Zallio, Handy multi-purpose tool to prevent the spread of COVID-19.
© Matteo Zallio.

thereafter, Handy became a worldwide award-winning design, used by millions of people, and featured in several design magazines. The success was buoyant, therefore from an open-source device, a second version of the multitool was developed with a slightly smaller more portable format, which could be used as a keychain Fig. 2.

Due to the shift in dimensions and rising market demand, there was a need to identify the best strategy to allow people from different markets to benefit from Handy, which was initially designed and optimised for a 3D printing manufacturing process that had to be sustainable, efficient and low-cost.

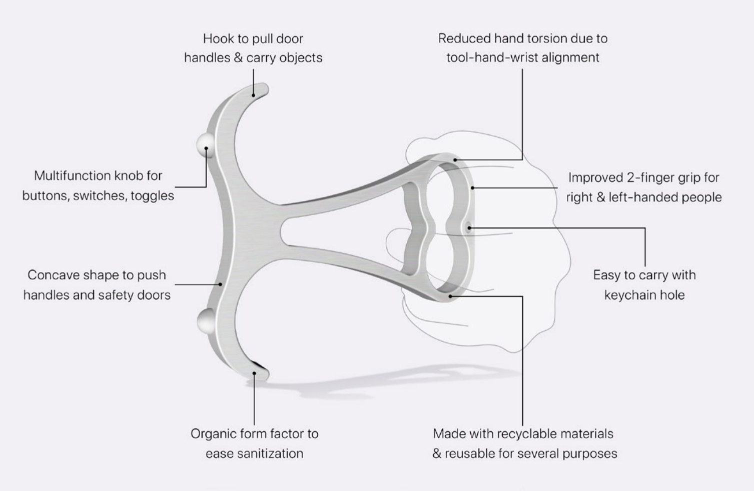

Fig. 2
Matteo Zallio, Handy keychain version. © Matteo Zallio.

This paper reports on the methodological process for a Life Cycle Assessment (LCA) that aims to understand the feasibility of manufacturing a larger number of devices to fulfil increased market demand, while achieving a high rate of sustainability at an affordable cost that could allow people from different countries to benefit from it.

This study compared possible choices of materials for mass production as well as the impact on the LCA to achieve the best compromise between the variables of the manufacturing process, technical specifications, sustainability, and cost by using the Cambridge Engineering Selector EduPack Granta software.

The reported case study aims to define a fast-track process that could support the future development of products that need to shift their main manufacturing process from a small number of items, produced through 3D printing, to a large-scale manufacturing process based on LCA principles.

Life Cycle Assessment

Handy was initially developed as a 3D-printed device shared with a Creative Commons licence, the goal of which was to reach the community with the assurance that, along with any derivative work, it would remain openly accessible in the future. This is a powerful licence as it offers the community of designers the freedom to modify and improve any product for the best (Laplume et al., 2016).

Later, having overcome the first emergency phase, it was decided to improve the initial design of Handy, and to answer growing market demand by shifting the manufacturing process from 3D-printing to an industrial process (Wittbrodt et al., 2013). When choosing the material suitable for manufacturing, strong attention was paid to considerations about the environmental impact and sustainability, as laid out in European policies (*European Green Deal*) and the *United Nations' Sustainable Development Goals* (*SDGs*) (United Nations, 2021).

Cambridge Engineering Selector Edupack Granta Software for Designers

Granta Design is a software house that develops software used for advanced materials selection in the industry. *Cambridge Engineering Selector EduPack* (*CES EduPack*) is the educational version specifically designed to guide and identify the steps in the decision-making process for selecting suitable materials during the design process in an educational setting. It helps students understand a rational and systemic approach which is invaluable to design.

Designers deal mainly with products, most of which are manufactured by combining several materials. The performance of these products depends to a large extent on the properties of the materials of which they are made. Working knowledge of material properties can assist designers in aligning anticipated behaviours with functional needs while, at the same time, ignorance of them can lead to missed opportunities and mistaken choices (Ashby et al., 2014). The idea behind the *CES EduPack* software is to educate and inspire designers with visually interactive, easy-to-use and engaging processes. (Ashby et al., 2010). The structure of the information is intended to facilitate and foster innovation and design using software tools that encourage positive outcomes. The *CES EduPack* database contains links between products, materials, manufacturing processes, and data on Eco-properties, such as the CO2 footprint. Due to the specificity of the software and the sustainability analysis needed for the Handy product, it was decided to use the *CES EduPack* as a tool to benchmark Handy's footprint and to analyse how the re-design and the choice of new materials could lead to improved sustainability (Walker et al., 2019), through an industrial manufacturing process.

Environmental Impact Evaluation with the Eco Audit Tool

A full life cycle analysis was carried out on Handy using the *Eco Audit* tool embedded in the *CES EduPack* software. The software allows calculation of the energy (MJ) and carbon emissions (Kg) over the lifetime of the product. The *Eco Audit* tool calculates them by taking into consideration the materials and manufacturing process, the use of the product, the power consumption, and any transportation involved.

Ore and feedstock, drawn from the earth's resources, are processed to create raw materials. These materials are transformed into products that are used by customers, and, at the end of their lives, discarded. A fraction of the material used for the product can enter a recycling process, a remaining part might go into incineration or a landfill. Energy and materials are consumed at each point in this cycle, with an associated penalty of CO2, SOx, NOx, and other emissions. These may be assessed using the technique of Life-Cycle Analysis (LCA).

For example, the materials and the phase of use (living) are typically the most energy-consuming over the product's life cycle. These can be estimated and explored using the *Eco Audit* tool.

Full LCA analysis is a demanding, time-consuming, and expensive process that requires a high level of detail and experience by the assessor, though a level of uncertainty remains. How can a designer use this data?

The *Eco Audit* tool can guide designers in the decision-making process with sufficient precision because it offers:

- Resources in terms of energy (oil equivalent);
- Emissions in terms of CO2 equivalent;
- Distinguishes life-phases;
- Potential benefits (Energy, CO2, or Cost).

An *Eco Audit* evaluation of the product reveals the energy requirements and carbon emissions, identifying the phases of life that create the greatest burden. The tool then allows rapid "what if…?" exploration of alternative materials, transport modes, use patterns, and end-of-life choices, revealing the consequences of a change in any one of these on the others.

The final step is a more systematic analysis of materials selection, targeting the most energy and carbon-intensive phases of life. The *Eco Audit* identifies the design objective that is a key input for the established materials selection methodology built into the *CES EduPack* software.

The *Eco Audit* graphically identifies the stage of life that has the greatest impact on *CES* to select new Materials and/or Processes, minimising five points:

- Material (material in part, embodied energy, CO2/kg);
- Manufacture (process energy, CO2/kg);
- Transport (mass, distance, transport type);
- Use (mass, thermal loss, electrical loss);
- End of Life (recyclable materials, non-toxic materials).

In the specific case of Handy, the first step in selecting the material was translating the design requirements into a specification for materials selection. This was done by breaking down the design requirements into function, constraints, and objectives. The analysis provided the input needed for the next two key steps in material selection: screening and ranking.

Function: Handy is a multipurpose personal device, created as an open-source response for the COVID-19 pandemic, to allow contactless interaction with everyday objects.
Objectives: Minimise CO2 footprint, cost, and mass.
Constraints: • Temperature resistance: -15°C to +90°C • Resistance to water and ethyl alcohol (ethanol) • Comfortable to touch • Recyclable or combustible

The second step was to set the limits for the calculation of the *Eco Audit* tool by using the following assumptions:

- Materials and Processing: Taking into consideration applications for Handy, such as door opener or bag holder, the following mechanical properties were required: a minimum value of 2 Gpa for Young's modulus and a minimum value of 2 Mpa*m^0.5 for Fracture Toughness. With regards to the price, the threshold was set at 6 €/Kg.
- Transportation: A production of 50,000 items was consid-

ered, with an estimated transport of 600 km on average divided into 500 km on a 32 tonne (4-axle) truck and 100 km on a 14 tonne (2-axle) truck, considering that the production would take place in Italy and the product would be meant for the European market.

- Use: It was also assumed that Handy would have a lifetime of ca. 1 year.
- Disposal: It was assumed that all materials that could be recycled would be recycled.

The CES EduPack Software to Perform a Sustainability Analysis

In this section, we provide a demonstration of the process that was carried out using the *CES EduPack* software to analyse and select the optimal material for the manufacturing process. In detail, the *CES EduPack* software (level 2 database) was used to compare possible choices of materials for manufacturing as well as the impact on the Life Cycle Assessment to achieve an optimal compromise between the variables of the manufacturing process, technical specifications, sustainability, and cost.

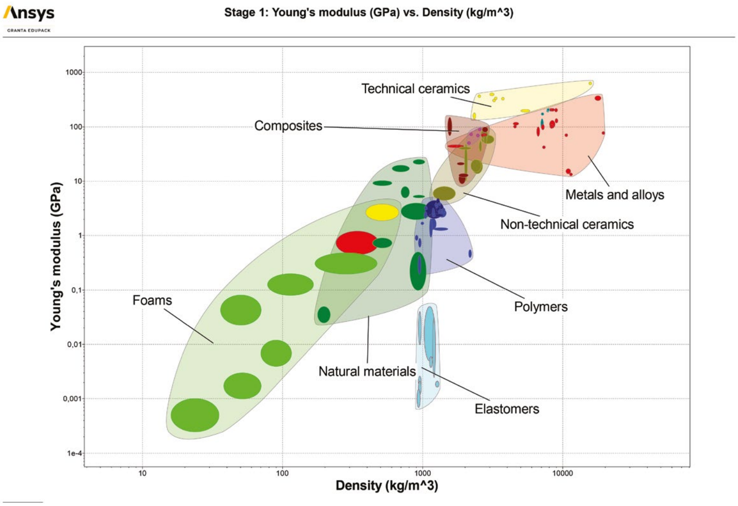

Fig. 3
Francesco Burlando. The chart displays the materials according to their Young's modulus (GPa) and Density (kg/m^3) properties. © Francesco Burlando.

Firstly, a chart was made showing all the materials displayed according to their Young's modulus (GPa) and Density (Kg/m^3) properties Fig. 3. The chart visualises the arrangement of material families in terms of these properties (Ashby et al., 2014). Every time a limit will be included, materials that do not fulfil the criteria will disappear from the chart.

With regards to the price, the threshold was set at 6 €/Kg. This was the first constraint to be included, as the retail price for marketing a product such as Handy should be quite low. This constraint would exclude those materials that would lead to an expensive product that wouldn't allow an optimal cost-benefit intended rate. As a result, certain metals, most technical ceramics, and some polymers were excluded due to such a limit. Taking into consideration the applications of Handy — such as door opener or bag holder — the following mechanical properties were required: a minimum value of 2 Gpa for Young's modulus and a minimum value of 2 Mpa*m$^{0.5}$ for Fracture Toughness (Ashby et al., 2016). The first limit excluded foams and cork, while the second led to the exclusion of vitreous materials. Subsequently, a minimum value of 2 (on a scale from 1 to 10) for castability was inserted. That led to the exclusion of brick and granite. Moreover, the following limits were included for durability: ethyl alcohol (ethanol) acceptable or excellent, industrial atmosphere acceptable or excellent, flammability: slow-burning, self-extinguishing, non-flammable. Due to these limits, PLA — which is the most commonly used material in 3D-printing production — was excluded.

Lastly, since one of the primary goals was to minimise the CO2 footprint in the Handy's LCA, a maximum value of 15 CO2kg/kg of CO2 emission during primary production was set as a limit.

Figure 4 displays a similar chart, as it appears after all limits were inserted. Very few materials remain available: only certain metals and polymers fulfil the above-mentioned criteria. Final consideration was made for Polycarbonate, Copper, Bronze, and Cast Al-alloys.

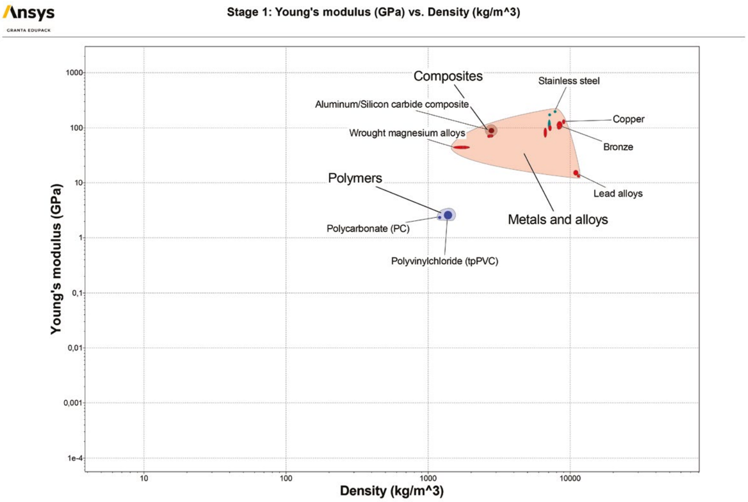

Fig. 4
Francesco Burlando.
The chart shows the materials that are still available when considering established limits. © Francesco Burlando.

Using the *Eco Audit* tool, these four materials were compared to discover which would affect the CO2 footprint of the product Fig. 5.

The production was estimated at 50,000 pieces, and the transportation was estimated at 600 km on average — divided into 500 km on a 32 tonne (4-axle) truck and 100 km on a 14 tonne (2-axle) truck — considering that production would take place in the north of Italy and the product would be initially available for the Southern and Central European market. The entire product life was estimated at one year and the weight was considered as follows: 0,015 kg for PC Handy, 0,1 kg for Copper Handy, 0,08 kg for Bronze Handy and 0,03 for Cast Al-alloys Handy. As a result, in terms of the CO2 footprint, Cast Al-alloys represent the best materials as they exceed PC in CO2 emission only during the transport phase. Bronze is the worst choice as it would mean a 33% increase in the CO2 footprint compared to Al-alloys. However, the

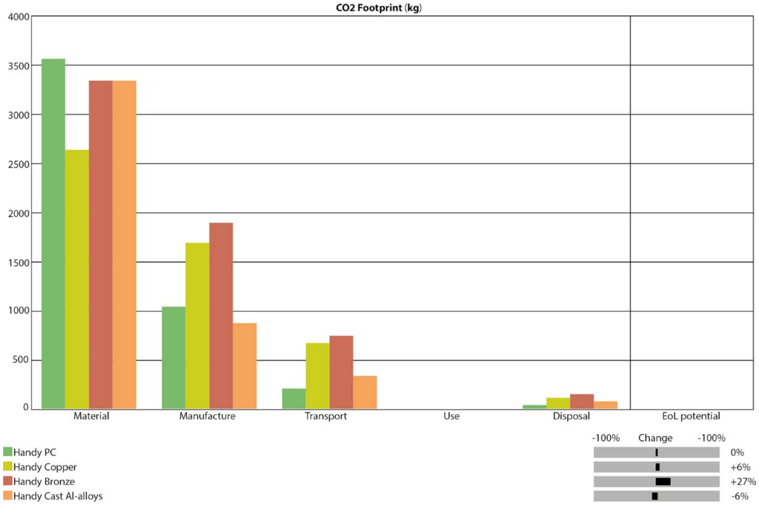

Fig. 5
Francesco Burlando. The chart shows the CO2 footprint (kg) of the four chosen materials during the different phases of their life cycle. © Francesco Burlando.

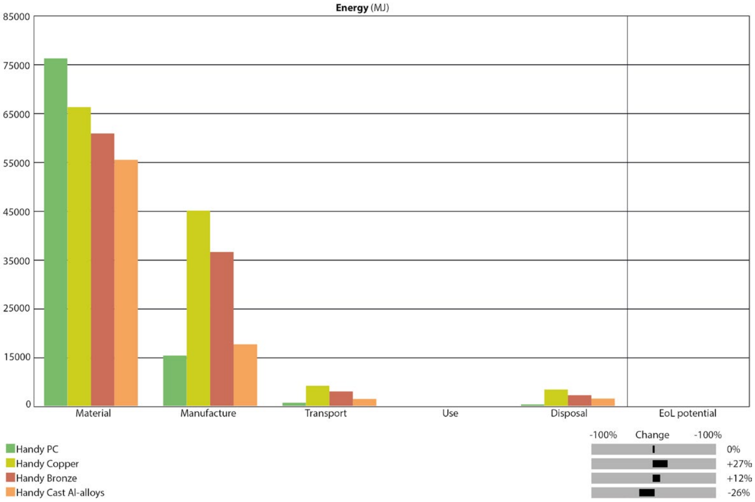

Fig. 6
Francesco Burlando. The chart shows the Energy (MJ) that would be used during the different phases of the life cycle of the four chosen materials. © Francesco Burlando.

percentage difference between aluminium and copper is quite negligible, so the choice could be made based on other parameters, such as aesthetics or logistics. Nevertheless, if we look at the similar chart that compares the Energy (MJ) used during the LCA of the product, the percentage difference increases. In this case, the manufacturing phase shows an increase in the percentage value of copper, which became worse than bronze. The result for Cast Al-alloys further improves, making it the best choice together with PC Fig. 6.

For completeness, it is necessary to consider the estimated data of the 3D-printing process initially used to produce Handy. We can consider the following specifications: Moulding technology: FDM (Fused Deposition Modelling), printer: Creality CR-10S Pro, nozzle size: 100µm – 1.0mm, filament diameter: 1.75mm, infill: 20%, material: eSun PLA+ (Grey), suggested material: ABS (Acrylonitrile Butadiene Styrene) or PLA (Polylactide), printing time: about 12 hours.

Considering the 3D printer Creality C10s pro, which was recommended for best efficiency and 3D printing quality, we can assume that it has an hourly consumption of ca. 500 watts. Considering an approximate printing time of 12 hours, we can assume that the total energy consumption might be 6000 watts. It is important to consider this data approximate, because the performance of the 3D-printer varies depending on the external environment, the electricity provider, and other contextual factors (Ashby et al., 2012).

Beyond the technical specifications, it is necessary to consider other factors for which a 3D-printing process-based production differs greatly from an industrial manufacturing process. During the pandemic period, an open-source approach and 3D-printing production made it possible to avoid logistical problems — and costs — related to distribution. Moreover, homemade 3D-printing productions mostly use PLA as a material, contributing to the sustainability of the process (Rajeshkumar et al., 2021). On the contrary, a large-scale production with 3D printers would change nothing in terms of distribution and transport. It would use ABS as a material for the reasons mentioned earlier, and each item would require excessive production times and costs. Given the pros and cons of the 3D-printing process and analysing possible materials to be used in traditional industrial production, the *CES EduPack* software allowed us to identify a method that offers enough evidence-based data to analyse and evaluate what manufacturing technology can lead to mass-production while keeping the whole process sustainable, in accordance with the future targets set by the *Sustainable Development Goals*.

Conclusions

While this paper focused on a specific product that was created as an open-source response to the COVID-19 crisis, its primary aim was to study and verify what best strategy could allow the transition from a 3D-printable manufacturing procedure to a large-scale industrial manufacturing process for a keychain-size product.

The use of the *CES EduPack* software allowed us to perform a thorough LCA on the choice of sustainable materials to be used for large-scale manufacturing, as well as to understand the optimal manufacturing process that would allow us to deliver the product sustainably and affordably across several countries.

This paper allowed us to define a fast-track methodological process to inform the decision-making process for manufacturing a 3D-printable device with an industrial manufacturing process.

The results confirmed that in terms of CO2 footprint, Cast Al-alloys represent an optimal industrial manufacturing solution to mass-produce Handy, as they exceed PC in CO2 emission only during the transport phase. It allowed us to guarantee technical specifications such as resistance to traction and compression, easy sanitization, high recyclability, and a low-cost manufacturing process. The difference in percentage between aluminium and copper is quite negligible, so that the choice could be made based on other parameters, such as aesthetics, or logistic modality.

This study confirms that the *CES EduPack* software can allow designers to methodologically perform a sustainability analysis with evidence-based data that would inform a sustainable manufacturing process. It represents a method that is useful to highlight pros and cons between 3D printing and industrial manufacturing processes, depending on the number of pieces to be manufactured, time, cost and LCA.

By understanding possible choices of materials for mass production, as well as the impact on the LCA to achieve the best compromise between the variables of the manufacturing process, technical specifications, sustainability, and cost, designers can base their decisions on a scientific and informed dataset that allows for fast-track development of sustainable products.

Acknowledgments

Matteo Zallio wrote the introduction and conclusions, Claudia Porfirione wrote paragraph 2, Francesco Burlando wrote paragraph 3.

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Printed in May 2022 by Bologna University Press

76

There is a different tradition in design that we have learned to know through the application of ethnography, anthropology, natural studies, climate studies and the study of complex social relations. This tradition flows like a river underground and occasionally rises to the surface carrying with it profound results that help us to understand design reality. What we are studying in issue number 76 of *diid* is a subterranean river that requires scrupulous and attentive researchers with uncommon delicacy and sensitivity to discover, understand and scientifically convey the phenomena that derive from it.

We are quite far from a quantitative and experimental performance analysis, from historical research in the archives, the phenomenology of the user's analysis and the use of the sophisticated technologies that enable the contemporary designer. Here the discussion is about how form, function, value and meaning retreat from market logic yet transform the behaviour and structure of society or individuals in a global and contemporary manner through the cultures of design and its practices.

Paolo Cardini has orchestrated this observation by highlighting a community of researchers who are studying and applying these themes at the intercontinental level, and with the awe-struck curiosity of children we remain drawn to and pensive before the array of images that illustrate this issue.

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No. 76 — 2022
Anno XX
ISSN 1594-8528
ISSN Online 2785-2245

Bologna
University Press

Euro 27,00
ISBN 979-12-5477-097-9
9 791254 770979