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# Challenges of Open Design in Low-income Communities: A Case Study of Residential Rainwater Harvesting Systems

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## Abstract

Open design (OD) is a promising approach to address global sustainability challenges. At the same time, however, the increased use of OD brings new challenges. To understand the potential of OD in a specific context, we adopted the concept of a residential rainwater harvesting system (RWHS) as a case study. We first identified the critical design features of the RWHS. After that, we analysed the potential for local reproduction of these features at the grassroots level of low-income communities in developing countries. This analysis revealed that varying limitations related to materials, skills, and manufacturing tools may hamper the adoption of OD by local communities when trying to improve their water management. In the light of our findings, we argue that OD processes are likely to face challenges if replicability, substitutability and adaptability are not successfully integrated into the design. We suggest *a design-for-frugality mindset* and *adoption of parametric design processes and design parameters* as key strategies to boost OD processes in low-income communities. We also stress the importance of safety and liability aspects in the studied context.

**Keywords:** do-it-yourself; open design; replicability; residential rainwater harvesting systems; sustainability

## 1. Introduction

The concept of open design (OD) has increasingly attracted the attention of designers, scholars, grassroots communities, and companies over the last ten years. Aitamurto et al. (2015, 22) define OD as *'provid[ing] public access to participation in the design process and to the product resulting from that process, as well as the data created in the design process'*. In this article, we argue that OD faces significant challenges, especially in low-income communities, if do-it-yourself (DIY) aspects, such as replicability, substitutability and adaptability are not thoroughly considered throughout the design process. We illustrate this point with a case study on the adoption of a residential rainwater harvesting system (RWHS).

To explore these challenges that the dissemination of OD projects may face, we selected a global sustainability challenge with significant local implications, namely water safety. Water management is an area where innovative solutions are urgently needed to solve diverse local problems, especially in the developing regions (Hyvärinen et al. 2020). We therefore adopted RWHS as our research object of interest in order to understand important aspects that are related to water safety at a local level. An RWHS can be individually installed, representing a decentralized approach for widening water access through self-organization. This should improve the quality of life for those people living in vulnerable conditions, especially in rural communities and urban settlements that are not connected to a traditional water supply infrastructure. The increased use of RWHS is therefore directly applicable to the United Nations' Sustainable Development Goals (SDGs).

OD increases access to technologies that may be important in order for local communities to adapt to changes in environmental conditions (Phillips et al. 2014). It can also promote the distributed, participatory, and decentralized co-design and production processes that are necessary to respond to wide-scale sustainability concerns like water safety (Kadish and Dulic 2015; Melles et al. 2011).

Based on previous research, we know that replicability, substitutability and replicability can turn out significant obstacles to scaling up OD projects in low-income contexts (Hyysalo, Jhonson, and Juntunen 2017; Kohtala, Hyysalo, and Whalen 2020; Kostakis et al. 2015; Ostuzzi et al. 2016). Replicability refers to the possibility for the self-assembly of a product, having — as an output of the process — similar if not the same practical functions as the original design. Substitutability refers to a possibility to replace specific design aspects with something locally reachable whereas adaptability refers to capacity to modify solution by removing, adding or combining components to make the design fit into local circumstances. In practice, challenges related to replicability, adaptability and substitutability are often linked to difficulties in accessing the range of technologies (e.g. personal computers and digital manufacturing tools), a lack of design processes focused on local needs, and the absence of multi-lingual documentation of the design process (Kostakis et al. 2015; Ostuzzi et al. 2016).

We argue that putting emphasis on DIY aspects throughout design processes may help to overcome some challenges that OD faces when applied among low-income communities. In practice, a focus on DIY in OD can entail, for example, minimising the need for specific tools, technologies, and expertise (Bonvoisin et al. 2017; Kostakis et al. 2015; Song et al. 2009). Aspects that are important from a DIY perspective can also be facilitated through the clever use of online platforms and small-scale workshops, such as Fablabs and Makerspaces (Haldrup et al. 2017). Finally, design appropriation through modifications and adaptations, has been observed by researchers in DIY studies as a successful practice to meet the local needs (Laet and Mol 2000; Usenyuk, Hyysalo, and Whalen 2016; Hyysalo and Usenyuk 2015).

This article is structured as follows: In the following section, we present a systematic literature review and discuss the data and the analytical framework for the analysis. In the third section, we present the results of the analysis, thus illustrating the potential of OD in the local construction of RWHS components. Next, in the fourth section, we discuss challenges of OD in the studied context and indicate potential strategies for overcoming them. Finally, in the fifth section, we draw some brief conclusions about our work.

## 2. Materials and Methods

### *2.1. Systematic literature review*

We conducted a systematic literature review of the RWHS phenomenon to identify associated design features. First, we used the search expression ‘Rainwater Harvesting (AND) Case’ on Scopus and Google Scholar, with the search being limited to the 1998–2019 period. This expression was applied to the fields ‘title’, ‘abstract’, and ‘keywords’, resulting in a list of 351 results (288 journal articles and 63 conference articles). Books, book chapters, and reviews were excluded from these initial results. In the second round, the title, abstract and keywords were further considered to identify whether the case studies related to the sort of small-scale projects that we were interested in. The remaining 103 articles were read in their entirety to identify cases that mentioned design features or components that were associated with specific issues or proposed design solutions. Following this, 20 studies were selected. Backwards citation tracing, however, identified an additional 13 references that met the requirements of our study, thus increasing the final number of analysed articles to 33.

### *2.2. Article analysis*

The selected articles were analysed to identify critical design features associated with RWHSs. However, we limited the analysis to the hardware aspects of a system, by which we refer to the physical design choices and functionalities that affect a system’s performance. For instance, material deposition on rooftops, which can lead to water contamination, is included in our analysis once hardware adjustments minimise its negative impacts. Hence, our analysis does not consider the system standards domain, which refers to a briefing phase that defines a set of technical requirements for the correct functioning of the system, such as rooftop size. Our focus on the hardware domain therefore enabled us to discuss OD from a manufacturing perspective that considers critical aspects related to materials, tools, and standardisation.

Our analysis focused on RWHS components, and each of the studied components related to a specific subsystem of an RWHS, namely the collector system, the storage system, and the supply system. Table 1 presents a summary of the main aspects discussed in the literature, together with some excerpts from the articles.

Table 1 - Aspects of RWHs for water quality

| **Aspects** | **Subsystem** | **References** | **Excerpt example** |
|---|---|---|---|
| Taste / Odour | Collector, Storage, Supply | (1), (4), (6), (8), (14), (15), (22), (24), (25), (26), (28), (30), (31), (32) | *'Materials used for construction such as cement and lime may impair the taste of water and scare away consumer.'* (22) |
| Component Materials | Collector, Storage, Supply | (2), (3), (5), (6), (7), (8), (9), (12), (14), (18), (19), (20), (22), (23), (24), (25), (26), (27), (28), (29), (31), (32) | *'All the materials used were locally available, including storage containers which in many cases were locally made clay pots.'* (5) |
| Material Deposition | Collector, Supply | (2), (4), (5), (6), (7), (8), (11), (12), (14), (16), (17), (20), (21), (22), (23), (24), (25), (26), (27), (28), (29), (31), (32) | *'(...)This suggests that after the contact with the roof, the rainwater was significantly contaminated by biopolymers and humic substances.'* (16) |
| Maintenance | Collector, Storage | (4), (6), (8), (10), (18), (20), (22), (21), (28), (29), (31), (32) | *'(...) proper preventive and maintenance procedures may guard the microbiological quality and safe use of stored rainwater'* (28) |
| Positioning | Storage, Supply | (6), (11), (21), (22), (24), (26) | *'(...)water outlets located at the bottom of the tank let sediments flow out with supplied water'* (11) |

**List of References**

(1) Amin and Han, 2011
(2) Arku et al., 2015
(3) Baguma and Loiskandl, 2010;
(4) Baguma et al., 2010
(5) Burt and Keiru, 2009
(6) Campisano et al., 2017
(7) Chang et al., 2004
(8) Daoud et al., 2011
(9)Ghimire and Johnston, 2015
(10) Gomes and Heller, 2016
(11) Han and Ki, 2010
(12) Helmreich and Horn, 2009
(13) Song et al., 2009
(14) Kim et al., 2005
(15) Kim et al., 2016
(16) Kus et al., 2010
(17) Lee et al., 2016
(18) Lo and Gould, 2015
(19) Lye, 2003
(20) Lye, 2009
(21) Magyar et al., 2007
(22) Mayo and Mashauri, 1991
(23) Morales-Pinzón et al., 2015
(24) Mwenge Kahinda et al., 2007
(25) Nalwanga et al., 2016
(26) Nguyen et al., 2013
(27) Opare, 2012
(28) Schets et al., 2010
(29) Simmons et al., 2001
(30) Song et al., 2009
(31) Thomas, 1998
(32) Tobin et al., 2013

We also collected 10 manuals that had been published by NGOs, NPOs, public agencies, and international organisations. The manuals outline how to produce RWHS components

(Hartung and Heijen 2016), assemble them, and install the complete systems, and they also present design recommendations and good practices (Kalimuthu 2016; Rainwater Harvesting Research Group — RHRG 2001) and detail the risks associated with low maintenance and how to avoid them (Thomas and Martinson 2007). The manuals identify the design features of the various RWHSs and the maturity of each design feature. For example, for water storage tanks, there may be a wide range of options with varying complexity, materials and configuration. Some may present design plans and construction methods for different tanks, indicating a certain degree of openness.

### *2.3. Analytical framework*

When talking about OD, commentators have emphasised that the nature of openness should be seen as a combination of *process openness* and *product openness* (Aitamurto et al. 2015; Boisseau et al. 2018). When a design process is truly open, it is possible for any interested party to participate in it (West and O'Mahony 2008). Similarly, when a product is open, it is possible for anyone who is interested in it to build and assemble it (Balka 2011)."

In addition to the new opportunities presented by OD, recent developments in the field of DIY emphasise the increasing potential of digital design tools, digitally driven production technologies and the Internet (Fox 2014), all of which are seen as the drivers of a renaissance in craftsmanship (Rognoli et al. 2015) and the emergence of a maker movement (Hyysalo et al. 2014). We argue that the current OD discussion, especially in the context of improving living conditions and addressing the sustainability challenges of low-income communities, has thus far emphasised process openness at the expense of product openness, which may in turn have hindered OD from achieving its true potential. In developing regions in particular, the possibility to self-build different products is often the most important aspect of OD. We therefore argue that an analysis of OD measures should actively aim to recognise factors that affect both process and product openness.

We created an analytical framework that simultaneously brings together openness evaluation in the process and product dimensions (Figure 1). We then adopted a product profile chart named the ‘Harris Profile’ to evaluate how each component of an RWHS relates to the issues of process and product openness. This model was initially proposed by John S. Harris (1982), and it presents a visual representation of the strengths and weaknesses of various designs. As illustrated in Figure 1, we used eight questions to evaluate the process and product openness potential for each component of a RWHS. Each question maps to four parameters in a chart, each of which is weighted from -2 to +2. When a -2 or +2 grade is given, the -1 or +1 cells, respectively, are also marked.

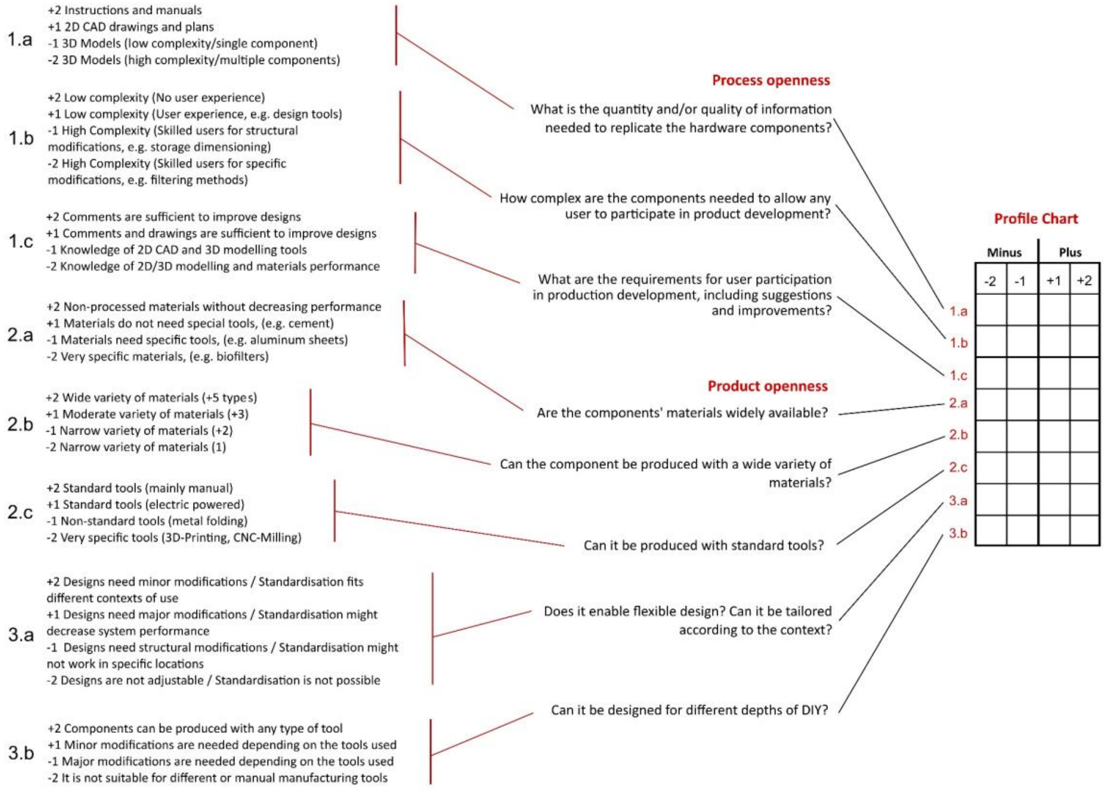


Figure 1. The analytical framework

In addition to considering accessibility and transparency, we argue that focusing on the DIY aspect as part of product openness provides a good starting point for estimating the extent to which an OD can succeed in low-income contexts. DIY aspects typically relate to material availability, material variety, necessary tools, and the flexibility of the design, while accessibility and transparency in the same context typically relate to the accessibility of design processes, transparent documentation, and the availability of capital resources (Bonvoisin et al. 2017).

## 3. Results

Figure 2 presents a summary of our findings by connecting each studied component to the developed profile chart. Each profile is then discussed individually based on the subsystem of the RWHS that it belongs to.

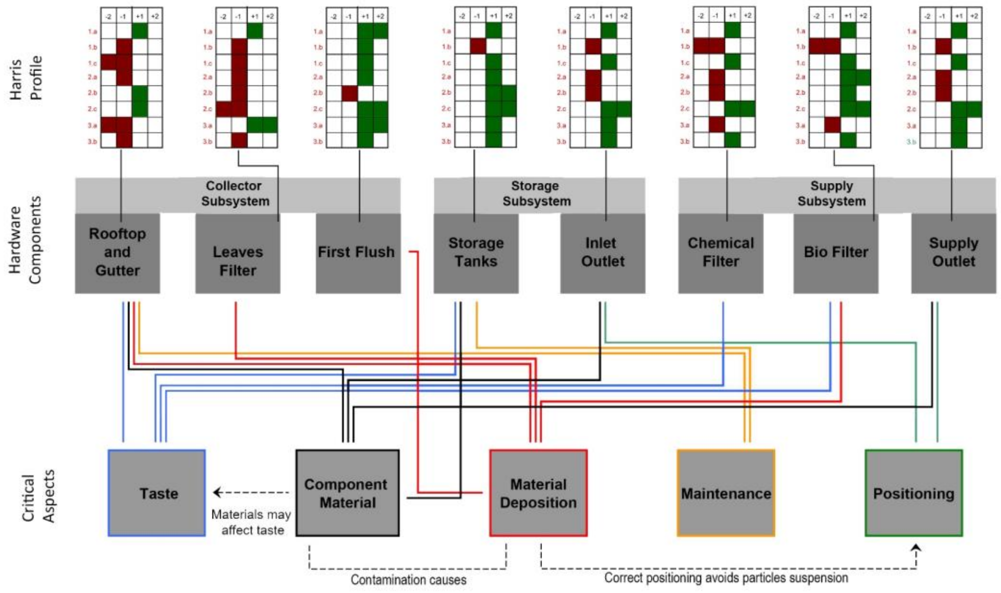
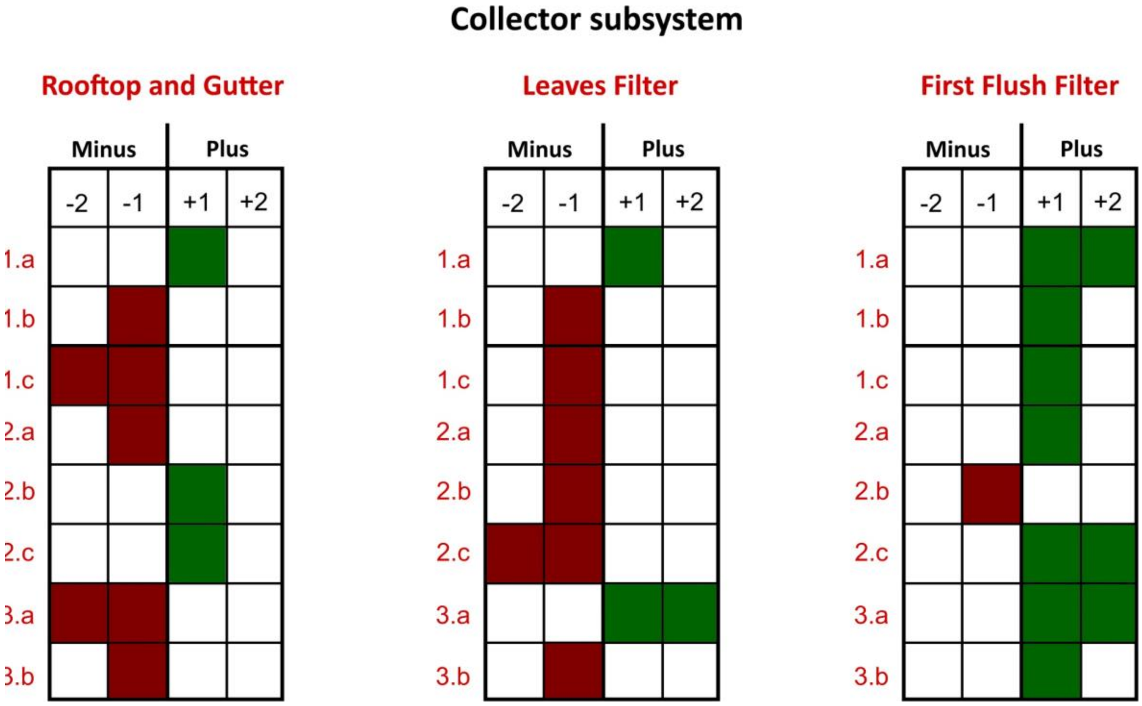


Figure 2. The profile charts for each RWHS component and their relations to sub-system specific issues.

### *3.1. Collection*



**Collector subsystem**

**Rooftop and Gutter**

| | Minus | | Plus | |
|---|---|---|---|---|
| | -2 | -1 | +1 | +2 |
| 1.a | | | 🟩 | |
| 1.b | | 🟥 | | |
| 1.c | 🟥 | 🟥 | | |
| 2.a | | 🟥 | | |
| 2.b | | | 🟩 | |
| 2.c | | | 🟩 | |
| 3.a | 🟥 | 🟥 | | |
| 3.b | | 🟥 | | |

**Leaves Filter**

| | Minus | | Plus | |
|---|---|---|---|---|
| | -2 | -1 | +1 | +2 |
| 1.a | | | 🟩 | |
| 1.b | | 🟥 | | |
| 1.c | | 🟥 | | |
| 2.a | | 🟥 | | |
| 2.b | | 🟥 | | |
| 2.c | 🟥 | 🟥 | | |
| 3.a | | | 🟩 | 🟩 |
| 3.b | | 🟥 | | |

**First Flush Filter**

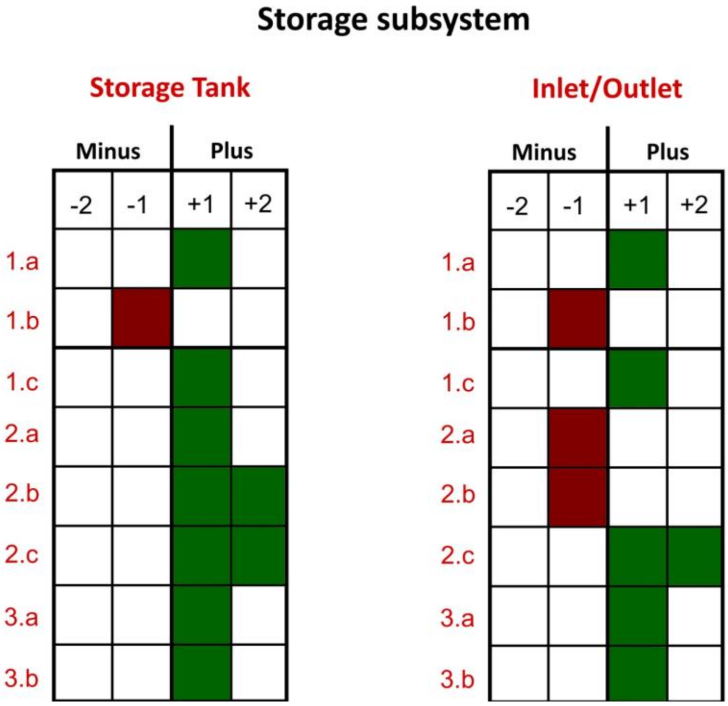
| | Minus | | Plus | |
|---|---|---|---|---|
| | -2 | -1 | +1 | +2 |
| 1.a | | | 🟩 | 🟩 |
| 1.b | | | 🟩 | |
| 1.c | | | 🟩 | |
| 2.a | | | 🟩 | |
| 2.b | | 🟥 | | |
| 2.c | | | 🟩 | 🟩 |
| 3.a | | | 🟩 | 🟩 |
| 3.b | | | 🟩 | |

Figure 3. Profile charts for the collection system: (a) rooftop and gutter, (b) leaves filter, (c) first flush filter.

For our analysis, the components of the collector subsystem were divided into the (a) roof and gutter, (b) leaves filter, (c) first flush filter and (d) outlet. Figure 3 presents the profile charts for each of these components. This subsystem is considered to be the main source of rainwater contamination (Han and Ki 2010), with two main contaminants being mostly responsible for degrading water quality in terms of potability, pH, taste, colour and odour. These are deposited particles — such as leaves, bird faeces, and chemical particles — and contaminants from the components' materials. To minimise the effects of material deposition on rooftops, it is advisable to use first flush devices, filters and screens and regularly maintain the roof (Lye 2009). The design and position of the outlet, which connects the collecting pipes to the storage tanks, is also mentioned as another solution for avoiding sediment resuspension (Magyar et al. 2007; Nguyen et al. 2013). Some authors also indicate that the materials used in components can contribute to the physical (taste and pH) and chemical nature of the harvested water (Chang et al. 2004; Mayo and Mashauri 1991; Morales-Pinzón et al. 2015). Other components may also be responsible for introducing chemical contaminants, such as PVC pipes (Morrow et al. 2010) and copper outlets  (Simmons et al. 2001).

Regarding its potential for openness, the rooftop and gutter components are unlikely to be designed for replication because of their complexity (1.b) in terms of design, with them requiring knowledge of 2D CAD software and a familiarity with materials and rooftop structural design (1.c). More specifically, dimensions and shape adaptation are needed to suit each context (3.a). On the other hand, it can be produced using a wide variety of materials (2.b) and standard tools (2.c), although some precautions are warranted to avoid the use of materials with a greater potential for contamination. In contrast, the filters show a higher potential for openness due to its easier adaptation to different contexts (3.a and 3.b). The leaves filter, however, is a challenge to replicate because its functioning requirements mandate certain specific production methods, such as PVC moulding or 3D printing (2.a and 2.c). The first flush filters, conversely, are more likely to be replicated because their design is simpler than the other filters. It can also be produced using common materials to substitute industrialized components (2.a), although the type of materials is restricted (2.b). Finally, adjustments are possible without degrading its performance (3.a and 3.b), and it only needs low-tech tools to produce it (2.c).

### *3.2. Storage*



Storage subsystem

Storage Tank

| | Minus | | Plus | |
|---|---|---|---|---|
| | -2 | -1 | +1 | +2 |
| 1.a | | | 🟩 | |
| 1.b | | 🟥 | | |
| 1.c | | | 🟩 | |
| 2.a | | | 🟩 | |
| 2.b | | | 🟩 | 🟩 |
| 2.c | | | 🟩 | 🟩 |
| 3.a | | | 🟩 | |
| 3.b | | | 🟩 | |

Inlet/Outlet

| | Minus | | Plus | |
|---|---|---|---|---|
| | -2 | -1 | +1 | +2 |
| 1.a | | | 🟩 | |
| 1.b | | 🟥 | | |
| 1.c | | | 🟩 | |
| 2.a | | 🟥 | | |
| 2.b | | 🟥 | | |
| 2.c | | | 🟩 | 🟩 |
| 3.a | | | 🟩 | |
| 3.b | | | 🟩 | |

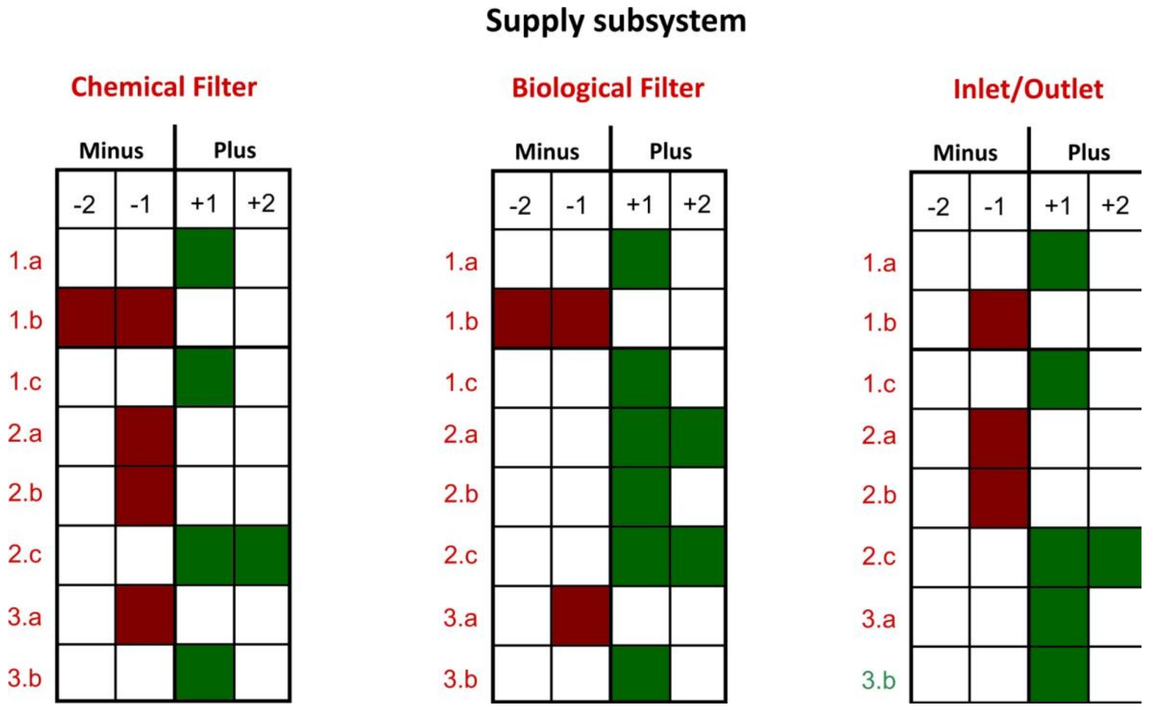
Figure 4. Profile charts for the storage system: (a) storage tanks, (b) inlet and outlet.

As parts of the storage subsystem, contamination and storage tanks have been well covered in the literature. Contamination can occur due to the materials or coating processes adopted but also because of the storage methods used and the length of storage. The materials used to build or coat the water tanks may affect the water's characteristics in terms of its odour, taste, colour, pH, and/or potability. Even if this does not affect the actual potability of the water, people may feel less confident about consuming the harvested water if it tastes, looks, or smells odd. Long periods of storage are also linked to microbial contamination (Kim et al. 2005). Constant maintenance and suitable cleaning is therefore recommended to minimise contamination  (Burt and Keiru 2009), but this needs training, an awareness of the risks, and the motivation to actually do it (Baguma et al. 2010; Gomes and Heller 2016). As for the storage tanks, we highlight the examples of design alternatives for cisterns and their construction methods. Some studies indicate different types of cisterns for different locations, while others focus on providing instructions for building specific types of tanks using local materials, such as the Calabash Tank (Hartung and Heijen 2016), which is an optimised ferrocement tank. In addition, different types of tanks are described in terms of their construction costs, their difficulty to build, and their replicability and materials (RHRG 2001).

For potential openness, the storage tank is rated as high in the Harris Profile (Figure 4), thus facilitating both low- and high-tech approaches. Existing examples have demonstrated that storage tanks can be built using a wide range of construction methods, design methods, and materials (e.g. bricks, clay, concrete, etc.) (2.a). We also point out that 2D CAD drawings and instructions are enough for design replication (1.a), but technical experience is required for modifications (e.g. for the structural design of the storage tanks) (1.b).

The inlet/outlet components of the storage subsystem are positioned in the literature as a minor issue mostly related to the correct positioning for preventing particle suspension in the tanks (Han and Ki 2010; Magyar et al. 2007). Adopting the design require *vitamins* (a jargon term for imported parts that cannot be self-made), however, due to the production processes and materials for the outlet/inlet pipes (2.a and 2.b). However, the assembly process only requires standard tools, mostly manual ones (2.c). Considering the use of manufactured components, improved alternatives for replication are feasible based on 2D drawings and/or instructions (1.a), but design modifications will require technical knowledge and water quality tests (e.g. to measure particle suspension during water inflow) (1.b and 1.c).

### *3.3. Supply*



**Chemical Filter**

| | Minus | | Plus | |
|---|---|---|---|---|
| | -2 | -1 | +1 | +2 |
| 1.a | | | 🟩 | |
| 1.b | 🟥 | 🟥 | | |
| 1.c | | | 🟩 | |
| 2.a | | 🟥 | | |
| 2.b | | 🟥 | | |
| 2.c | | | 🟩 | 🟩 |
| 3.a | | 🟥 | | |
| 3.b | | | 🟩 | |

**Biological Filter**

| | Minus | | Plus | |
|---|---|---|---|---|
| | -2 | -1 | +1 | +2 |
| 1.a | | | 🟩 | |
| 1.b | 🟥 | 🟥 | | |
| 1.c | | | 🟩 | |
| 2.a | | | 🟩 | 🟩 |
| 2.b | | | 🟩 | |
| 2.c | | | 🟩 | 🟩 |
| 3.a | | 🟥 | | |
| 3.b | | | 🟩 | |

**Inlet/Outlet**

| | Minus | | Plus | |
|---|---|---|---|---|
| | -2 | -1 | +1 | +2 |
| 1.a | | | 🟩 | |
| 1.b | | 🟥 | | |
| 1.c | | | 🟩 | |
| 2.a | | 🟥 | | |
| 2.b | | 🟥 | | |
| 2.c | | | 🟩 | 🟩 |
| 3.a | | | 🟩 | |
| 3.b | | | 🟩 | |

Figure 5. Profile charts for the supply system: (a) chemical filter, (b) biological filter, (c) inlet and outlet.

The supply subsystem corresponds to the filtering methods and processes and the inlet/outlet components. The filters have been well explored, which is warranted given their importance for water quality. The existence of two types of contaminants, chemical and microbiological, plus the possibility of suspended particles, has led to discussions about the effectiveness of design alternatives and treatment methods, especially for low-tech options such as solar disinfection (SODIS), boiling, and chlorination. However, the effectiveness of some methods is questionable because they do not meet international guidelines for water potability (Islam et al. 2015; Nalwanga et al. 2016). Consequently, it is often recommended to adopt two or more complementary treatment methods. For example, fast and slow sand filters are suggested to filter out particles and microbiological organisms (Thomas 1998), and there are low-complexity options for this (Opare 2012). For chemical decontamination,  more complex methods are suggested, such as membrane filtration, but the costs often make them prohibitively expensive for poorer communities (Helmreich and Horn 2009).

Microbiological filters (MFs) and chemical filters (CFs) are ranked differently in the Harris Profile (Figure 5), but both types of filters are similar in terms of their accessibility and transparency. Both can be reproduced using a set of drawings, instructions and manuals (1.a), but the complexity of the filtering processes and their associated safety requirements means that experts are needed for design modification and optimisation (1.b). However, suggestions can be made through comments, instructions and basic diagrams (1.c). While modifications and contributions to the system can be made through simple diagrams or comments, if they aim to improve its filtering performance, the effect on water quality needs to be evaluated.

MFs are more likely to be produced through a DIY approach than CFs, because a wide range of alternatives (2.b) exist for biological decontamination, ranging from simple processes like boiling and SODIS to more complex ones like sand filters (3.b), which are easily adaptable to match the availability of local components. What is more, the materials and tools needed for the simpler processes are widely available (2.a and 2.c). For example, SODIS can be performed using enclosed containers, while secondary treatment processes can involve lemon or vinegar (Amin and Han 2011) or use boiling. In contrast, chemical treatment involves a more complex process, although it can be adjusted to DIY approaches (3.b). The difference lies in the lower number of existing alternatives (2.b) and alternative treatment processes (2.a). When the components are available, however, a CF can be assembled using standard tools (2.c). Finally, both BF and CF are limited in terms of their flexibility (3.a), because changes may have a negative impact on overall system performance, i.e. the filtering quality.

The inlet/outlet components of the supply system were ranked the same as the inlet/outlet components of the storage system, which is unsurprising given that some components are identical and there is the same concern about the correct positioning of the outlet to prevent particles flowing with the supplied water.

## 4. Discussion

As pointed out in the previous section, OD is a potential alternative for promoting technologies like RWHSs in new contexts. However, as discussed in Introduction, we also know that especially in developing regions OD projects face diverse challenges related to replicability, substitutability and adaptability  solutions. In this section, we suggest that incorporation of *a design-for-frugality mindset* and *adoption of parametric design processes and design parameters* are strategies that designers and users can mobilize to cope with these challenges. Through these strategies it might be possible to improve the implementation of OD in low income-communities. We will also discuss importance of self-evaluation of safety and liability when designs are adapted to a different context and especially when related to health.

### *4.1. Incorporation of a design-for-frugality mindset*

The Portuguese word "gambiarra" is used in Brazil to refer to the creative use of components and arrangements to fix, modify and adapt existing objects for a specific purpose or to solve temporary issues. The Russian "karakats", transportation vehicles constructed of recycled automotive components with a DIY approach, exemplify what the word "gambiarra" can mean, illustrating flexibility in overcoming limitations related to materials, skills, and manufacturing tools. This kind of creativity is closely linked to frugality, which means doing more things with fewer resources (Radjou and Prabhu, 2014). Frugal innovations are especially relevant when the aim is to develop local solutions to global sustainability challenges (Albert, 2019; Levänen et al. 2016). Based on our research, we consider it very important to incorporate a 'design-for-frugality' mindset into OD practices. In the context of OD, design-for-frugality means collaborative development of products and processes that are adaptable, flexible and responsive to the context of use.

The ease of remote collaboration enhances the possibility for enthusiasts and users to participate in design processes according to their field of expertise. In this sense, the greater diversity of knowledge and experience aids the innovation process (Frey et al. 2011; Shah 2005) and makes OD a viable pathway for developing complex objects, such as prosthetics equipment (e.g. the Open Prosthetics Project). Good practices in OD also require producing complete documentation to enable design replication. However, in the context of low-income communities, we have noted that simpler designs, such as first flush filters, tend to facilitate inclusion more than co-design of more complex components, such as chemical filters.

In the context of our research, the increased openness of simpler designs seems to relate to three issues. First, self-production of simpler designs typically requires a relatively low level of skills, which allows users with a lower level of technical knowledge, but perhaps a greater awareness of the local context, to participate in the design process and provide input about locally important factors, such as manufacturing restrictions and material availability. Second, self-production of simpler designs are typically possible with manual tools that are largely available also in low in-come communities. And third, simpler designs may become widely usable because they typically require only minor adjustments to fit into different local settings, which is important because certain special characteristics of developing regions, such as limited public infrastructure, might not be supportive for more complex solutions.

A design-for-frugality mindset may also enable wider audiences for specific designs. Based on our research, it can be said that in the search for design replicability, pursuing strict reproduction of components might be tempting in many situations. These types of pursuits, however, easily turn to excessive rationalization of design, which may reduce the effectiveness gained through increased openness. This finding is in line with other recent studies suggesting that well conducted design appropriation is a common denominator of successful implementations of diverse solutions (Beck 2009). Appropriation describes how well particular solutions can be adapted to fit local conditions (Laet and Mol 2000), and it can be facilitated for example through substitution of different components (Usenyuk, Hyysalo, and Whalen 2016; Hyysalo and Usenyuk 2015). Authors also relate appropriation to “proximal design” (Usenyuk et al., 2016) “design fluidity” (Laet and Mol 2000) and “active design” (Kohtala, Hyysalo, and Whalen 2020).

### *4.2. Adoption of parametric design processes and design parameters*

Designing for uncertain scenarios is a true challenge for OD communities. A frugality approach is an initial step to build awareness of current bottlenecks for material and technology accessibility in different locations and search for low-cost solutions. At the same time, it also needs to be recognized that a frugal design is less dependent on the strict set of formal definitions than on structural ones. In other words, frugalization of design, in this context, means abstracting a solution into its fundamental parameters - from complexity to simplicity. Based on that, we continue with our second suggestion.

The above-mentioned abstraction process is a part of parametric design process, which consists of the adoption of editable variables and parameters that manipulate the resulting entity. Based on our research, we argue that increased utilization of key principles of parametric design may enable to increase adaptability of OD solutions. That is because the possibility to parametrise a high number of variables enables turning complex relations into simpler representations, which in turn may ease people with diverse interests and background to take part of the design process. On the other hand, by applying principles of parametric design, the designer can prevent such modifications to the solution that could negatively affect its functionality. For example, while it might be relevant for a single user of RWHS to adjust the storage tank dimensions based on the personal needs, this particular user may not be aware about the larger potential consequences of such a modification at the system-level. This is how parametric design can increase safety in OD processes.

Parametric design also helps in many practical arrangements related to OD. In the context of RWHSs, for example, a suitable sizing of the system depends upon a number of variables, such as the number of residents, rooftop dimensions and rainfall volume (Ghisi 2010), as well as optimum cost alternatives (Bocanegra-Martínez et al. 2014). Since the importance of specific variables differ between the locations, the components need to be adjustable accordingly. In this case, the potential of OD is directly associated with the degree of flexibility for the component. In other words, the easier it is to adapt a design to local conditions, the easier it will be to gain system-level benefits locally.

As observed in previous studies, it is not possible to fully predict how users will appropriate a design particularly in low resource settings (Kohtala, Hyysalo, and Whalen 2020; Laet and Mol 2000; Sandman, Meguid, and Levänen 2020), making it difficult to assure the quality of a design when adjusted to meet local conditions. The adoption of parametric strategies, on the other hand, holds potential for increasing the pathways an object has to be locally produced, for example by adjusting components for different lengths or switching from soldering to bolts. If critical variables are identified at the design level, it is possible to support the manual parametrization of objects at the context of its use, minimizing the safety and liability risks associated to it. In time, parametric design is not strictly linked to digital modelling tools, but also related to the definition of a “if this - then that” logic, which may guide the user to adopt the correct strategies when facing the need to adapt a design or substitute part of it.

### *4.3. Self-evaluation of safety and liability*

Most safety and liability issues reported in the literature relate to the quality of the harvested water. These concerns are therefore particularly important in the design and manufacturing as well as operation phases of the OD process. Some argue that a benefit of collaborative development processes, such as open source and open innovation, is the possibility of testing pilot versions in the early stages, thus optimising error finding and feedback (Lakhani and Wolf 2003; Lakhani and Panetta 2007). However, testing physical artefacts requires the production of prototypes (or simulations), which typically is a more complex endeavour than testing computer software. Nonetheless, a positive aspect of OD is how users with access to manufacturing tools and testing equipment can evaluate the design alternatives proposed by users who lack access to these necessary tools.

Regarding the manufacturing and operating phase, uncertainty about the quality of the harvested water might prevent users from adopting an RWHS or consuming the harvested water (Mankad and Tapsuwan 2011). In addition, it is impossible to guarantee the quality of harvested water due to possible manufacturing and operational issues, as well as other external factors. Water quality tests are therefore recommended for certainty, but the cost of the required instruments may well be unviable for certain communities (Wijnen et al. 2014). The development of open-source (OS) scientific tools may be a possible approach for addressing safety concerns. For example, OS water quality tests have already been proposed that cost between 7.5 and 15 times less than commercial equivalents (Wijnen et al. 2014). This important aspect should be considered in OD projects: Although projects are tested and evaluated by project collaborators, design could substantially benefit from methods for self-evaluating the quality of the manufactured product.

### *4.4. Limitations and areas for future research*

The subjectivity of the evaluation process presents a possible limitation for this study, and the principles adopted might not represent the full range of possible evaluation criteria. Areas of particular interest for future research may therefore include an exploration of each of the challenges we highlighted but with a less generic approach to fill any possible gaps, such as studying a broader range of cases. On the other hand, by addressing cases individually, new perspectives and solutions may well emerge. For example, we find it necessary to understand how safety and liability can be addressed in OD processes, especially when authorship is so diffuse in such an open and collaborative process.

## 5. Conclusions

The aim of this study was to explore the challenges of OD in low-income communities. For that purpose, we took the concept of RWHS as the object of our analysis and identified the critical components that determine its effectiveness and quality. These components were then evaluated according to their potential for re-production through collaborative development and adoption by end users. The results of our analysis indicate that some design limitations, which affect the correct functioning of a system, can be overcome through OD processes. At the same time, it is important to note that some RWHS components are harder to replicate than others due to specific requirements that may be difficult to meet in specific contexts.

Our findings highlight that the utilization of OD in low-income communities can be very challenging if do-it-yourself (DIY) aspects are not considered throughout the design processes. We identified incorporation of a design-for-frugality mindset and adoption of parametric design processes and design parameters as key strategies to facilitate DIY aspects in OD processes. Our results indicate that need for specific tools, materials and skills limits the potential of OD. In this sense, distributed manufacturing of elsewhere designed products locally could be one option to democratise design. This may indeed enhance the potential for replicating also more complex designs, but there is a bottleneck in terms of the limited access to resources, both economic and human, in poorer communities. The economic viability diverse OD processes will depend on the number of potential users of thus created products and services.

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## Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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