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INCREASING OR DECREASING FRUGALITY: THE CONNECTION BETWEEN DIGITALISATION AND FRUGAL INNOVATION

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Within wider debates on sustainability and digitalisation, frugal innovation (FI) scholars largely assume that digital technologies are important for FI in realising more sustainable outcomes. However, very few studies interrogate this causality. To tackle this challenge, we connect FI with digitalisation. Thereto, we conceptualise digital technologies *as* and *within* FIs and discuss three frugality dimensions to analyse three empirical case studies of digitally-enabled FIs. We use these cases to introduce new nuances on how digitalisation affects frugality and scaling.

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Our results unveil that digitalisation can increase frugality by enabling more *accessible and affordable* solutions through new flexible funding schemes and pay-as-you-go models. However, our evidence also implies decreasing frugality by an increase in end-user costs and digital exclusion. Likewise, increasing frugality through *complexity reduction* seems mainly to benefit intermediaries and frugal innovators themselves, whereas benefits of digitalisation in terms of complexity reduction for end-users seem to be limited. Digitalisation can even increase complexity for end-users, thus suggesting decreasing frugality. Finally, just like with non-digital innovations, *scaling* of digitally enabled innovations is dependent on the quality of logistical infrastructure and local adaptation practices. Moreover, scaling of digitally-enabled innovations is limited to users in regions with a proper ICT infrastructure.

Keywords: Digitalisation; frugal innovation; digital platforms; Africa; sustainability; qualitative case studies.

Introduction

One of the key themes in societal and academic debates is the convergence of digitalisation and sustainability (Castro *et al.*, 2021). On the one hand, digital technologies enable poor communities in remote areas to access basic products such as energy (Rastogi, 2018) or banking (Knorringa *et al.*, 2016), to increase social networking (Koskinen *et al.*, 2019), and to facilitate collective action (Bonina *et al.*, 2021). The COVID-19 pandemic has further accelerated the role of digital technologies in sustainability discourses (Clark *et al.*, 2022:1). On the other hand, digitalisation brings new challenges, such as the dominance of large platform operators (e.g., Alphabet) (Srnicek, 2017), and digital technologies that are used to monitor citizens (Zuboff, 2019) or challenge existing labor rights or jobs (Wood *et al.*, 2019). Despite large debates, there is still limited empirical evidence on how digitalisation contributes to sustainability (Castro *et al.*, 2021:1).

One key concept to analyse sustainability is Frugal Innovation (FI) that in its simplest form can be defined as 'an approach to creatively solving local problems through complexity reduction' (Busch, 2021:14) in a resource-constrained context (Agarwal *et al.*, 2017). Initial FI literature focused on developing affordable and accessible (Bhatti *et al.*, 2018) resource-scare solutions (i.e., products, services, processes, or business models) to overcome resource constraints (e.g., financial, technological, material, skills) to meet basic needs of unserved customers in the Global South (Hossain *et al.*, 2016:133). These solutions are either developed by grassroots entrepreneurs and (social) enterprises in the Global South (Radjou *et al.*, 2012) or by multinationals in the Global North who strip down Western products (Zeschky *et al.*, 2014; Agarwal *et al.*, 2020a). Later FI literature (Hyvärinen *et al.*, 2016; Albert, 2019, 2022; Stöber *et al.*, 2022; De Marchi *et al.*, 2022) explicitly links FI with sustainability. Sarkar and Mateus (2022:1) stress that 'FI shows potential to

effectively provide valuable products for underserved communities while sparing resources globally and contributing for social and environmental change.' Such 'truly frugal products' combine low-cost and environmental sustainability (Von Janda *et al.*, 2020:1), whereas frugal design to create such products is important to realise a sustainable economy by resource saving during the entire life cycle (Liefner *et al.*, 2020:1). Accordingly, FI is linked to various concepts within the sustainability discourse, such as the circular economy, resource saving consumers (Prabhu, 2017), sustainable business models (Rosca *et al.*, 2017; Howell *et al.*, 2018; Hossain, 2021; Levänen *et al.*, 2022) and social transitions (Tunio and Memon, 2023).

Digital technologies are often regarded as relatively frugal as they are perceived as being low-cost, can scale rapidly, and can be accessed and used by a larger number of users (Prabhu, 2017). Furthermore, empirical studies have shown that digital technologies within FI processes (i.e., 'digitally-enabled FIs') can help to quickly overcome medical constraints during the COVID-19 pandemic (Vesci *et al.*, 2021; Corsini *et al.*, 2021; Harris *et al.*, 2020) and offer products to unserved customers in various domains including education (De Waal *et al.*, 2019), agriculture (Agarwal *et al.*, 2020b; Musona, 2021), and banking (Knorringa *et al.*, 2016:148–149). Likewise, social media platforms can support grassroots frugal innovators to reach overseas buyers (Van Tuijl and Knorringa, 2023). Finally, it is suggested that FI and digitalisation enables 'affordable green excellence' (Tiwari, 2021:273), thus implying the importance of digitally-enabled FIs for environmental development. Taken together, FI literature assumes that digital technologies are important for FI in realising more sustainable outcomes.

However, it is not clear how digital technologies contribute to sustainability (Tiwari, 2021). As a first modest step to tackle this challenge, we connect digitalisation with FI to introduce new nuances on how digital technologies affect frugality. To this end, we first combine literature on FI with that on digitalisation, to conceptualise digital technologies *as* and *within* FIs (Maric *et al.*, 2016). Second, based on empirical data from qualitative case studies and inductive reasoning, we introduce new nuances on how digital technologies can increase or decrease frugality *within* innovation processes. We thus define FI as a process (and not as a philosophy or product; Soni and Krishnan, 2014), and analyse three empirical case studies of digitally-enabled FIs along three frugality dimensions that we use to introduce our nuances. We elucidate how digital technologies contribute to *affordability* of, and *access* to (Bhatti *et al.*, 2018:3; Weyrauch and Herstatt, 2017; Rao, 2013) digitally enabled FIs targeted to unserved customers. Second, we investigate the role of digital technologies in processes of *complexity reduction* (or 'simplification') (Rosca *et al.*, 2017) to develop products that are 'easy to use' (Rao, 2013). Finally, we explore *scaling* challenges of digitally-enabled FIs, complementing earlier literature on the scaling of FIs (Hossain *et al.*, 2016; Busch, 2021).

We investigate three qualitative case studies of FIs enabled by platforms and other digital technologies: Apollo Agriculture (agricultural platform); Futurepump (smart solar-powered water pump and platform); and Kijenzi (3D printers and platform). The case studies aim to use digital technologies to create new affordable solutions to unserved customers in Africa.

Our main contribution to FI literature is that we introduce new nuances on how digitalisation affects frugality. Digitalisation can increase frugality by enabling more *accessible and affordable* solutions through new flexible funding schemes and pay-as-you-go models. However, we also provide evidence implying decreasing frugality by an increase in user costs and digital exclusion. Likewise, increasing frugality through *complexity reduction* seems mainly to benefit intermediaries and frugal innovators themselves, whereas benefits of digitalisation in terms of complexity reduction for end-users seems to be limited. Digitalisation can even increase complexity for end-users, thus suggesting decreasing frugality. This also provides nuances to platform literature that suggests that platforms reduce the role of intermediaries or form a new type of intermediary.

The rest of this paper is structured as follows. The Theory section connects frugality with digitalisation literature to make a distinction between frugality as and within FIs, and to discuss the frugality dimensions that we use to structure our empirical analysis. The Research Method section provides the method, whereas the Results and Discussion and Conclusion sections detail the results, discussion and conclusion.

Theory

Frugal innovation

FI is an overarching approach to innovation (Pisoni *et al.*, 2018) that encompasses a philosophy, a process, or an outcome of innovation (Soni and Krishnan, 2014) and is a topic across different scientific disciplines, including social studies (e.g., management and economics), engineering (Liefner *et al.*, 2020), and medical studies (Lai *et al.*, 2020). The approach is complex since it is interchangeably used to describe various components of innovation processes (e.g., drivers, outputs) (Ploeg *et al.*, 2020:4) as also becomes clear from studies on defining criteria (Bhatti *et al.*, 2018; Weyrauch and Herstatt, 2017; Von Janda *et al.*, 2020) and the differentiation of FI vs. other innovation types, including resource-constrained innovation (Agarwal *et al.*, 2017) and reverse innovation (Rosca *et al.*, 2017).

Despite this diversity, the common principle of FI is to develop affordable, adaptable, appropriate and accessible solutions in resource-constrained contexts (Bhatti *et al.*, 2018). This context and the rationale for resource-saving differ

across streams within the FI literature. Initial streams focused on resource-constrained contexts of societies in developing and emerging economies (Leliveld and Knorringa, 2018). Later, FI has become a core topic in developed countries as well, as becomes clear in a recent stream on FIs as a response to overcome shortages of medical equipment and skills during the COVID-19 pandemic in developed as well as developing countries (Harris *et al.*, 2020; Vesci *et al.*, 2021). Also, the sustainability stream on FI deals with different constraints by actors in developed as well as developing countries. For instance, grassroots entrepreneurs in developing countries innovate to overcome their urgent constraints (e.g., water shortage), but are also regarded as sustainable from an environmental perspective by reusing discarded materials (Hossain, 2021:2). In contrast, western consumers with a 'frugal lifestyle' want to save on material-usage and consumption for societal concerns like climate change (Herstatt and Tiwari, 2020) and western entrepreneurs save on input resources to make their production processes more efficient (Ploeg *et al.*, 2020). To conclude, and although there are different ways of framing, a commonality in the FI literature is the core principle of using fewer resources and to do more with more easily available resources (Bhatti *et al.*, 2018).

Accordingly, due to the focus on resource saving and making affordable products that can be accessed by many people, it is argued that FI is important to enhance sustainability (Pisoni *et al.*, 2018). Some empirical studies have indeed shown positive evidence of FIs contributing to sustainability (Albert, 2019; Rosca *et al.*, 2017; Hossain, 2020; Ebolor *et al.*, 2022). However, other empirical studies unveil the challenges of FI in realising sustainability outcomes (Hyvärinen *et al.*, 2016), such as trade-offs between economical and societal development (Howell *et al.*, 2018). Hence, empirical results are mixed for each sustainability dimension (Stöber *et al.*, 2022), and there is still limited knowledge about how FI contributes to sustainability (Hossain, 2020:2) and what the negative effects of FI on sustainability are (Hossain, 2018:934). We contribute to this sustainability discourse by connecting FI with digitalisation.

Digital technologies as and within frugal innovation

We distinguish two perspectives on how digitalisation is linked to FI based on the dual nature of digital technologies (Maric *et al.*, 2016). From the *digital technologies as FIs* perspective, it is argued that platforms, such as WhatsApp and M-Pesa, are frugal as they can be accessed by a large number of people at low costs (Prabhu, 2017). This perspective also refers to the development of frugal (e.g., simple, affordable, accessible) versions of digital technologies, such as self-made drones or low-cost 3D printers (Maric *et al.*, 2016; Lai *et al.*, 2020:323).

In the *digital technologies within FIs* perspective, frugal innovators use digital technologies to develop new affordable products that can scale quickly and reach customers that could not be reached before (Agarwal *et al.*, 2020b), as is shown in empirical studies. For instance, in healthcare, platforms and 3D printers are used to globally share and locally print 3D designs of medical equipment to overcome urgent medical shortages (Vesci *et al.*, 2021) or to print limbs in remote areas with poor healthcare facilities (Lange *et al.*, 2021). Furthermore, platforms support smallholders in remote areas with services, such as access to funding and markets (Altamirano and van Beers, 2018), advice on soil conditions (Musona, 2021), landmapping, and water monitoring systems (Agarwal *et al.*, 2020b). Similarly, platforms enable affordable off-grid energy supply to low-income populations in remote areas through pay-as-you-go models (Rastogi, 2018), and Artificial Intelligence (AI) supports frugal innovators to develop affordable educational tools (De Waal *et al.*, 2019).

Digital technologies could also be used in earlier innovation stages. For instance, communities of grassroots innovators share ideas through social media and open-source platforms (Corsini *et al.*, 2021; Sheikh *et al.*, 2023). Frugal innovators can also use funding platforms (e.g., VC4A) to obtain financial capital, whereas social media platforms can be used to promote frugal innovations in overseas markets (Van Tuijl and Knorringa, 2023). Finally, initial evidence shows that digital technologies in various stages of the wind energy value chain can contribute to realisation of 'affordable green excellence' (Tiwari, 2021), and AI and Internet-of-Things technologies can support Small and Medium Sized Enterprises in developing countries to develop FIs (Qin, 2024).

Platforms within FI processes

We focus on platforms as a platform is a central concept in the digital economy (Sturgeon, 2021) that has narrow linkages with other digital technologies (Van Tuijl and Knorringa, 2023), such as cloud infrastructures (Narayan, 2022) and AI (Kenney and Zysman, 2020). Therefore, platforms are appropriate to provide insights into the broader digitalisation discourse which encompasses the development and use of digital technologies within society, which increasingly rely on these technologies (Tilson *et al.*, 2010). Moreover, the platform concept has had limited attention in sustainability debates in the Global South (Bonina *et al.*, 2021), despite a large number of studies on specific platform types such as ride-hailing (Heeks *et al.*, 2021; Paundra *et al.*, 2020) or 'gig workers' (Wood *et al.*, 2019).

We contribute to these debates by exploring platforms *within* the process of FI along three dimensions. The first dimension encompasses *affordability and access*.

FIs need to be low-cost to provide solutions that can be used by a large group of unserved customers who cannot afford existing products (Bhatti *et al.*, 2018). Platforms can support frugal innovators in developing such solutions. Due to the usage of low-cost or even 'free' platforms in combination with the declining costs of smartphones and other IT products (e.g., sensors) (Sturgeon, 2021), frugal innovators can lower (user-)costs. For instance, platforms reduce monitoring costs and information asymmetry leading to lower transaction costs (Altamirano and Van Beers, 2018:87). Platforms also enable pay-as-you-go models, such as M-Kopa that provide solar energy in rural areas (Rastogi, 2018). Such models increase access to (basic) services through flexible funding based on the usage of products instead of high purchasing costs.

The second dimension is *complexity reduction* (or 'simplification') of products, services, technologies and business models (Rosca *et al.*, 2017; Leliveld and Knorringa, 2018) to develop solutions that are 'good enough' to fulfil users' needs (Hossain *et al.*, 2016). This means that FIs encompass no-frill design (Rao, 2013) and concentrate on core functionalities (Weyrauch and Herstatt, 2017). We study complexity reduction seen from the perspective of (end-)users in terms of getting a simplified product that is easy to use, and from the innovator's perspective regarding simplification of tasks within innovation processes (e.g., distribution). Platforms can reduce complexity within FIs. For example, frugal innovators can use YouTube videos as instruction manuals on how to use these products (Van Tuijl and Knorringa, 2023). Likewise, platforms simplify maintenance and repair work due to options for predictive maintenance (Tiwari, 2021).

Whereas platforms seem to increase frugality by enabling increasing affordability and access, and complexity reduction, platforms can also be used as a tool in *scaling* processes of FIs. We operationalise scaling as a multi-scalar process (Busch, 2021) where frugal innovators diffuse FIs to other regions (Hossain *et al.*, 2016). Platforms are important for scaling of FIs. For instance, open-source platforms can quickly scale 3D designs in a global community (Corsini *et al.*, 2021), agricultural trading platforms support smallholders to get fairer prices on global markets (Bonina *et al.*, 2021), whereas 'free' social media platforms can be used by frugal innovators to promote their products overseas (Van Tuijl and Knorringa, 2023).

To conclude, existing FI literature assumes that platforms can increase frugality by enabling increasing affordability and accessibility, although digital exclusion (Leliveld and Knorringa, 2018:10–11) can be regarded as an indication of declining frugality. Thereto, digital exclusion can be caused by various factors that decline access to and deployment of platforms, including infrastructural constraints (e.g., lack of ICT infrastructure), digital illiteracy and lack of skills (not knowing how to use platforms), and high costs for using platforms (for digital infrastructure or devices). In fact, digital exclusion is a social issue that can be

rooted in socio-economic causes beyond access to the internet, equipment, and ICT infrastructure (Fernandes Da Silva Ranchordas, 2022). Furthermore, platforms seem to increase frugality by enabling complexity reduction. This paper complements this literature by adding new nuances on how digitalisation affects frugality and scaling.

Research Method

Research design

We opted for a multiple-case study design (Yin, 2003) as it provides in-depth valuable insights into a particular phenomenon (digitalisation) within its real-life setting, where researchers have little or no control over the dynamics of societal events. In addition, it also enables the understanding of cause-and-effect relationships (e.g., effect of digitalisation on affordability) in interventions that are too complex for survey or experimental studies (Jensen and Rodgers, 2001). Thus, this research design is appropriate for our aim to elucidate how digitalisation affects frugality within innovation processes. The multiple-case study method is particularly suited when in-depth analysis of the specificities of a certain phenomenon (like digitalisation) is more important than the generalisation of the results based on large samples (Flyvbjerg, 2006). Analysing multiple case studies makes it possible to include many different dimensions (e.g., different countries or actors), and are more valid and generalizable than single-case studies because findings are based on a larger variety of empirical evidence (Yin, 2003; Eisenhardt and Graebner, 2007).

We conducted three qualitative case studies of digitally enabled FIs (see Table 1). *Apollo Agriculture* ('Apollo' in brief) is a Kenyan-Dutch agro-tech

Table 1. Characteristics case studies.

Case	Apollo	Futurepump	Kijenzi
Technologies	Platform; agronomic machine learning	Smart water pumps; Remote monitoring platform	3D printing; platform
Sectoral domain(s)	Agriculture	Agriculture	Health, agriculture, education
Countries	Kenya, The Netherlands, USA	Kenya, India, UK, The Netherlands, other Asian and African countries	Kenya, Sudan, Czech Republic, China, UK, USA
Year of foundation	2016	2012	2019

platform with the mission to 'bring commercial farming to everyone'. It realises this mission by providing an affordable bundle of commercial agricultural inputs (including seeds, pesticides, training) through a loan to smallholders in Africa who are normally unattractive as customers due to their small size and high-risk profiles. Apollo can reduce this risk through various technologies (like machine learning and mobile phones), satellite data and a network of local field agents to obtain field- and behavioural data to develop credit profiles. Based on these profiles, Apollo provides bundled input loans, and connects smallholders to insurers and local agro-dealers to obtain insurance and 'customised' inputs respectively.

Futurepump's vision is to offer 'clean and affordable pressurised agricultural irrigation to improve the quality of life of smallholders worldwide'. This UK-based firm with production and field-testing facilities in the Global South sustains smallholder irrigation through smart solar-powered water pumps coupled with GSM-based remote monitoring platforms. These platforms enable affordable pay-as-you-go models and predictive maintenance and water management as new services.

Kijenzi is a USA-Kenyan firm that focusses on local manufacturing of parts and products to serve non-profit organisations with the aim of creating well-being in the fields of health, education and agriculture. It realises local manufacturing through 3D technologies in local 3D hubs and through a repository of 3D designs, hosted on the platform Airtable.

We have selected these cases for the following reasons. First, all have a frugal rationale with the mission to deliver affordable products to a large group of unserved users. Second, all are beyond the concept stage and diffuse their innovations to other regions, allowing us to study scaling processes. Third, all use platforms — although different types and for different purposes — helping us to provide more insights into platforms in the Global South (Bonina *et al.*, 2021). Finally, we have selected diversity in other dimensions, such as the countries where the firms operate and sectoral orientation beyond agriculture (Kijenzi). The latter helps us to shed more light on the scaling potential of frugal innovations to other sectors.

Data collection and analysis

The empirical data for this paper have been gathered through interviews conducted during a comparative study on the effects of digital innovation on sustainability outcomes in the Global South. All interviews were done online due to COVID-19 restrictions.

This article draws mainly on twenty-two in-depth interviews with innovators, research partners, funders, local distributors, and governments. We interviewed

CEOs, managers, engineers, and data specialists. We had interviews with actors in the Global South as well as in the Global North. The interviews were semi-structured and lasted between 45 and 70 min. Interviewees were asked about their daily work activities, usage of digital technologies in these activities, interactions with other actors, rationales, barriers and drivers of the innovations, and usage and effects of the innovations on sustainability outcomes (see Appendix A). This diversity in interviewed actors and their disciplines helped us to get insights into the role of digital technologies across the entire innovation process, ranging from concept development to usage by end-users.

As we could not interview end-users due to COVID-19 travel restrictions, we tried to limit this bias by asking other interview partners how they interact with end users and the effects of the innovations on end-users. The interviews with local distributors and researchers (e.g., who are testing the innovations in the local context with end-users), as proxy participants in direct relation to end-users, were particularly insightful about end-users' deployment and experiences with the innovations. Moreover, we conducted an intensive desktop research strategy to gain insights into the perspective of end-users and to triangulate the interview data. These secondary data included existing studies (e.g., Kelly, 2021; Van Tuijl *et al.*, 2022), news items, podcasts (e.g., BNR, 2019), press releases, reports to investors (EfD, 2017), and other information on the case studies. Thus, despite not obtaining direct primary data from the end-users, information from proxy respondents and secondary sources still offers reliable insights about end-users. This approach is also followed in many other frugal innovation studies that have a more supply-side perspective (for illustrative examples, see Winterhalter *et al.* (2017) and Park *et al.* (2022)).

We captured information through audio recordings of the interviews. The recordings were transcribed, coded and analysed. The codes are based on the core dimensions of the study, including accessibility, affordability, complexity reduction and scaling. We anonymised interviewees by using IDs consisting of a combination of the following letters and numbers:C#G#AT#P#I#. These letters and numbers (#) refer to C# = case number (with C2 = Futurepump; C3 = Kijenzi; C5 = Apollo); G# = Geographical location where the interviewee is based (G1 = Global South; G2 = Global North; G3 = Brazil; Russia; India; China; South Africa); A# = Actor type number (AT1 = Profit-oriented firm; AT2 = Social enterprise and Non-Governmental Organisations; AT3 = Research, knowledge and educational institutes; AT4 = Local, regional or national governments; AT5 = Citizens and communities; AT6 = Other) P# = position number of the interviewee (I = Inventor; E = Expert; F = Founder; D = Director; M = Manager).

Results

Table 2 summarises the nuances of how digitalisation can increase and decrease frugality, structured along the dimensions of access and affordability and complexity reduction. We have combined the dimensions of access and affordability, also following the core intention of frugal design (and FI) to develop products that are affordable and accessible at the same time (Singh and Das, 2020). Moreover, both dimensions are closely interrelated as shown in empirical studies, such as Krell *et al.* (2021) who show how affordability acts as a component of smallholders' accessibility to digital services.

Affordability and access

All cases aim to create affordable and accessible solutions for unserved users. This has been done through various strategies linked to the usage of digital

Table 2. Results.

	Increasing frugality	Decreasing frugality
Access and affordability	• Use of low-cost 3D printers (Kijenzi) • Platform to share 3D designs (Kijenzi) • Use of M-Pesa platform (Apollo) • Apollo platform to deliver bundled input loan (Apollo) • Flexible payment schemes (Apollo, Futurepump) • Pay-as-you-go model (Futurepump)	• Direct exclusion by underperformance (Futurepump) • Costs sim card registration (Futurepump) • Lack of GSM connections (Apollo, Futurepump) • Distance to 3D printing facilities (Kijenzi)
Complexity reduction	• Platforms to simplify maintenance (Kijenzi, Futurepump) • Data to support agro-dealers with inventory management (Apollo) • Voicemail-based training (Apollo) • Social media as training material and for troubleshooting (Futurepump)	• Additional features beyond end-users' needs (Futurepump) • No understanding how digitally-enabled products create end-user value (Apollo, Futurepump, Kijenzi) • Less options for self-repair (Futurepump)

technologies. *Kijenzi* uses a European 3D printer supplier (Prusa 3D) that focuses on the production of low-cost and reliable 3D printers (Kelly, 2021) (i.e., digital technologies as FIs), suitable for resource-constrained contexts (C3_G1_AT2_F5), instead of using 3D manufacturers (e.g., MakerBot) that focus on advanced and relatively expensive 3D printers for large-scale industrial customers. Kijenzi wants to cut costs even further by using local 3D suppliers from Kenya, although this is still in an experimental stage. Furthermore, Kijenzi works with a cloud-based repository of 3D-designed products, hosted in the platform Airtable (C3_G1_AT2_E3), so designs are shareable and readily available whenever required.

Apollo delivers its affordable input bundle through a network of field agents who visit smallholders, and local agro-dealers who deliver the inputs. Field agents visit smallholders to explain the input bundle and insurance, and to gather field- and smallholder's behaviour data through the Apollo for agents' platform. Through this platform, smallholders fill out a survey on personal questions (e.g., civil status), data on assets (plot size), and performance data (acres farmed). The platform is also used to add pictures and to mark the borders of the plot via a field walk and GPS technology, so Apollo can get further insights into the customer's farm (e.g., distance to roads) via satellite data and remote sensing technology. This combination of field-, behaviour- and satellite data is crucial to develop credit profiles of smallholders without a credit history:

'*Most customers have not had a formal loan before and so the data available about them is very small. We believe that there's enough information about them available and that we can use these sorts of modern technologies to drive insight about that customer and they are likely to repay*' (C5_G1_AT1_M1).

Hence, in this way, Apollo can reach relatively poor smallholders. Furthermore, Apollo reduces transaction costs by using its platform to enable a 'one-stop-shop' for smallholders: '*On Monday the bank visits the famer; on Tuesday the input dealer; on Wednesday the agronomist; and maybe on Thursday a seed supplier and on Friday a supplier of technical equipment. . . You can also go to the farmer once. When you do that in a data-driven way and use standardised data for multiple aims: for a bank, for farm inputs, for forecasting of production; for buyers, maybe for an insurer, for newly financial products. . . . That is what Apollo does*' (C5_G2_AT1_M2).

Moreover, Apollo reaches smallholders without a bank account as payment takes place through the M-Pesa payment platform. Finally, based on satellite data, Apollo can see when the rainy season is delayed and can automatically adjust the repayment period of the bundled input loan to the delayed harvest time. The harvest time is the period when smallholders get their income and are able to repay their debt.

Also, *Futurepump* makes its pumps more accessible by using a payment period based on the harvest and reduces smallholders' user costs by connecting the pumps to a monitoring platform to enable a new pay-as-you-go model. Hereby, smallholders pay much smaller and out-of-pocket payable amounts for a service of solar irrigation instead of paying upfront as was the case of conventional pumps (C2_G2_AT2_F7).

Despite these strategies to create more affordable and accessible solutions, we also identified processes of exclusion and increasing costs. This was especially the case for Futurepump for two reasons. First, collected data through the platform may not benefit smallholders: '*The end-user <of the platform> is the company itself, Futurepump. That is because the farmer is not using the system... Futurepump is gathering the data, trying to analyse that, and trying to identify the potential failures. And as far as the pay-as-you-go systems are concerned, that is yes, the distributors use them for switching pumps on and off*' (C2_G3_AT1_D4). Thus, this quote illustrates a possible downside of the new payment model that smallholders can directly be excluded from the product (s)he needs, while they may have limited benefits from additional services.

Second, the smart pump is based on GSM technology. This implies extra costs for smallholders to obtain SIM cards. This is particularly a challenge for smallholders in countries whose legislations do not facilitate mass acquisition of SIM cards. For example, in Uganda, SIM cards are only delivered after a thorough user registration (C2_G1_AT1_F8). Thus, it excludes smallholders who are unable or unwilling to get registered. Furthermore, as the technology is dependent on GSM networks, smallholders in remote areas with weak or no GSM network coverage are also excluded from the new pumps.

Also, in other cases, remote customers can still not be reached due to the limitations of digital technologies. Smallholders require GSM connections to obtain bundled input loans and training from Apollo, whereas Kijenzi cannot reach patients of healthcare facilities outside main Kenyan cities and farmers located in remote areas who are too far away from the 3D printing facilities (C3_G2_AT2_M4).

To conclude, in all cases, the frugal innovators use digital technologies to deliver more affordable and accessible solutions by enabling new flexible funding schemes, pay-as-you-go models and cost-reduction strategies. This suggests increasing frugality. However, digital exclusion, and in some cases an increase in user costs, suggest decreasing frugality due to reduced access to frugal innovations.

Complexity reduction

The frugal innovators also use digital technologies for complexity reduction. For instance, *Kijenzi* uses 3D printers based on open-source platforms, providing

advantages for repairing: '*It's quite easy for us to be able to repair them wherever we are... We can access a kind of global knowledge network on this through the Internet, and then determine how to repair and maintain them ourselves, because they are open-source*' (C3_G1_AT2_F5). Similarly, *Futurepump* uses social media platforms for troubleshooting for installation, operation and maintenance of the smart pumps. Furthermore, Futurepump's predictive maintenance platform reduces complexity of repair work for distributors by providing specific data on when repair work and staff mobilisation takes place, and what spare parts are needed. Likewise, *Apollo* uses smallholders' data from the purchased credit bundles (collected through its platform) to support agro-dealers with inventory management (C5_G2_AT1_M2).

At the same time, we have observed an increase in complexity in two ways. First, there is a risk that the products become more complex in terms of too many functions. For instance, the additional features of Futurepump's smart pumps (e.g., water management or predictive maintenance) may have limited extra value for smallholders. Moreover, the features make the pumps less robust (more parts could be prone to fail) and limit options for low-cost self-repair by smallholders (C2_G2_AT2_E1; C2_G1_AT1_F8). Second, it is hard to explain to smallholders how complex service models such as bundled input loans and smart pumps create value. Likewise, 3D printing opens a 'universe' of options on what can be produced, making it more complex to find a focus and prioritisation on what to print first to make an 'impactful product'. Accordingly, there is a need for physical demonstrations and in-person meetings to convince users how and why to use the new technologies (Van Tuijl *et al.*, 2022). For instance, Futurepump undertakes a process of education and familiarisation with smart pumps and the new services. This educational process takes place in different forms, like workshops and demonstrations during agricultural fairs or at distributors' facilities; and through digital material on social media platforms. However, training material through these platforms are regarded as a main hurdle:

'*I guess it's always just getting the market education so managing to reach the rural customers, the people who need to get the pump.... Maybe they're not on Facebook, and because we're working from the UK, being able to reach those customers, and actually explain that. And now, our pumps are more expensive than cheaper options, but you can save money over time, but it's hard to explain that sometimes*' (C2_G2_AT1_M2).

Also, Apollo explicitly indicated not using social media platforms to reach smallholders who often still use 'dumb phones' and lack internet access. Therefore, in-person meetings and physical demonstrations turn to be crucial to convince smallholders to buy complex bundles with products that they may not have used before. 'Seeing is believing' is important to sell new digitally-enabled

agricultural products (BNR, 2019). Likewise, in-person meetings are crucial to build trust and credibility among smallholders (Tridios, 2022). Therefore, road shows, referral farmers and sales via field agents turn to be the most efficient acquisition channels of Apollo. Furthermore, usage of simple technologies and local adaptation of technologies is important to support smallholders who do not all have the same level of literacy and experience with commercial agricultural inputs. For instance, Apollo provides voicemail-based training as customers may have 'crappy old phones with cracked screens' and may not be able to read everything (C5_G1_AT1_M1).

To conclude, digital technologies seem to reduce complexity (i.e., increase frugality) for intermediaries (agro-dealers and distributors) and innovators themselves by using platforms in tasks like inventory management and maintenance. However, digitally-enabled innovations may also increase complexity (i.e., decrease frugality) for end-users due to an increase in the number of features beyond the end-user's (direct) needs, and end-users' unawareness of how to generate value out of these innovations. Accordingly, frugal innovators train users through physical demonstrations and workshops in temporary proximity of end-users (e.g., during road-shows) to explain how complex digitally-enabled products work and create user value. Moreover, frugal versions of digital technologies (e.g., digital technologies as FIs) are used to include end-users with limited digital skills or assets.

Scaling

Limited usage of social media platforms to communicate with potential end-users already suggests limitations to the fast scaling of digitally-enabled FIs. We unveil factors that hinder fast scaling. First, similar as non-digitally-enabled products, scaling is dependent on the quality of logistical infrastructure. Accordingly, users in remote areas with poor roads can still not be reached, as put forward on last mile distribution of fertiliser (an agricultural input in the bundle of Apollo): '*It is difficult to move bulk tons of fertiliser around. . . trucks can only go on certain roads only in certain seasons and certain times. Those logistical barriers are daunting*' (C5_G2_AT1_E5). Even though, smallholders do not need tons of fertilisers, supplying this input in smaller quantities to distributors leads to an increase in price, making it less accessible for smallholders. Likewise, smallholders in remote areas underserved by road infrastructure and supply chains cannot receive smart pumps from Futurepump C2_G1_AT1_D3; C2_G2_AT2_F7; C2_G1_AT1_F8).

Second, digitally enabled products are hard to scale to regions with poor ICT infrastructures (see section 4.2) as evidence that Apollo focuses its extension to regions with proper GSM networks (e.g., within Kenya) and not to regions with a

poor GSM infrastructure (e.g., South Sudan) (C5_G2_AT1_M2). Likewise, Futurepump's smart pumps do not work in regions without a GSM connection.

Third, digitally enabled products require knowledge of and adaptation to, the regional context. For example, Apollo builds on specific agricultural expertise that differs per region: '*We will both draw on official regionalised agricultural expertise (Kenya maize farming differs from Zambia) and work in subsequent phases to build our own, sophisticated crop input models to optimise input regime design for the regions where our farmers live*' (EfD, 2017:9). This quote, thus, illustrates the need for regional expertise to build specific yield models for each region. It also suggests the time needed for the adaptation of models and for machine learning (e.g., to collect data on different crops and to provide credit profiles in different regions). Similarly, Kijenzi still sources its 3D printers from the Global North, where environmental conditions are more favorable for the functioning of 3D printers. However, when the machines are imported to low-income settings, they may face harsher environments while operating, such as atmospheric dust. Thus, these conditions may impact negatively the performance of the machines, which can turn into shorter lifetimes or reduction of accuracy of the 3D printed parts (Rogge *et al.*, 2017). Also, Futurepump is challenged to adapt the smart pumps, that are developed in The Netherlands, for local markets: '*(It) is completely different with trying to develop something from for another market to the other end of the world. They only have vague ideas about the requirements, but not very precise and if there is a problem, it's all far away. You depend on other people to fix it*' (C2_G2_AT2_E1).

Hence, for digitally enabled innovations, local testing is needed to adapt products to environmental and market conditions. Accordingly, innovators build on expertise and networks of local actors, who also play an essential role in sales and distribution. For instance, Kijenzi uses local healthcare facilities, NGOs and trade organisations that provide 3D-printed products to end-users in different regions (C3_G1_AT2_F5). Likewise, Apollo uses local field agents and distributors to explain the concept of the bundled input loan, and to deliver the agricultural inputs. Furthermore, local radio producers are used by Apollo to record training sessions (provided by voicemail) as they speak the 'language of the smallholders' and make complex training understandable for smallholders (C5_G1_AT1_M1). Also, Futurepump uses local distributors to provide smart pumps, as well as after-sales services. This also implies a quality risk: '*Futurepump is very dependent on the performance of the distributors. Every country has a distributor, but not all of them are as serious or as good as they should be.... You buy the pump cheap, and you sell it for as much as possible and you give it little service as you can*' (C2_G2_AT2_E1).

To conclude, just like with non-digital innovations, scaling of digitally-enabled innovations is dependent on the quality of logistical infrastructure and local

adaptation practices. Moreover, scaling of digitally enabled innovations is limited to end-users in regions with a proper ICT infrastructure.

Discussion and Conclusion

This paper has connected digitalisation with FI as a first necessary step before exploring how digital technologies contribute to sustainability. Thereto, we have conceptualised digital technologies *as* and *within* FIs and discussed three frugality dimensions to structure our empirical analysis of qualitative case studies of digitally-enabled FIs. We use these three cases to inductively introduce nuances on how digitalisation affects frugality and scaling.

This last section discusses the empirical results (see Table 2) with existing literature and provides the main conclusion and suggestions for further research. Regarding *access and affordability*, we show that digitalisation can increase frugality through new pay-as-you-go models (Rastogi, 2018), flexible funding schemes and specific cost-reduction strategies. Frugal innovators can use digital technologies (e.g., low-cost 3D printers) as FIs (Maric *et al.*, 2016) within such cost-reduction strategies (Kijenzi). Furthermore, digital technologies are indeed beneficial to reduce transactions costs (Altamirano and Van Beers, 2018), as evidenced in the case of Apollo. Moreover, the digitally-enabled FIs can, to a certain extent, reach unserved customers (e.g., smallholders) (Agarwal *et al.*, 2020b). However, we also show evidence for digital exclusion (Leliveld and Knorringa, 2018:10–11) by a lack of digital infrastructure and options for direct exclusion by switching-off service delivery through monitoring platforms. The case of Futurepump unveils that platforms can also lead to an increase in (end-user) costs, which is in line with Hossain (2021:5) who shows additional costs for frugal innovators to use social media platforms. Thus, digital exclusion and increasing cost suggest that digitalisation can decrease frugality as well.

Concerning, *complexity reduction*, we confirm that frugal innovators use open-source and social media (Vesci *et al.*, 2021) as well as predictive maintenance platforms (Tiwari, 2021) to simplify repair work. Platforms can also reduce the complexity of other processes, such as inventory management. This suggests that digital technologies reduce process complexity for intermediaries and frugal innovators. However, digitally-enabled innovations may also increase complexity for end-users due to an increase in the number of features beyond the end-user's needs, and end-users' unawareness of how to generate value out of these innovations. Accordingly, we show the importance of temporary proximity through exhibitions, demonstrations, and customer visits to gain trust and to explain how digitally-enabled innovations may generate user value. Moreover, digital

technologies such as FIs (e.g., voicemail-based training) are used to reduce digital exclusion. Taken together, digitalisation can reduce complexity (i.e., increase frugality) for intermediaries and innovators, but can also increase complexity (i.e., decrease frugality) for end-users. This 'tension' between the demand and supply side of FIs is not only a topic to explore further but also provides nuances to platform literature that refers to a declining role of intermediaries vs. end-users or platforms as a new type of intermediary (Kenney and Zysman, 2020:18), whereas we show that platforms can support existing intermediaries as well.

Finally, we provide limitations to *scaling* of digitally-enabled FIs. In line with literature on business-to-business platforms (Friederici *et al.*, 2020; Grabher and Van Tuijl, 2020; Sturgeon, 2021:15) and rural logistic complexities in the last-mile delivery of goods and services to smallholders (Intriago Zambrano *et al.*, 2023), we show that just like with non-digital innovations, scaling of digitally-enabled innovations is dependent on the quality of logistical infrastructure and local adaptation practices. Rapid deployment of digitally-enabled FIs (Harris *et al.*, 2020) is thus not possible, also because of the time needed to convince users of the value of innovations, similar to non-digital innovations in the past. Finally, we show limitations to usage of social media platforms as marketing channels for FIs (Van Tuijl and Knorringa, 2023) as end-users in rural Africa do not always have access to such platforms. As such, we confirm processes of digital exclusion (Bonina *et al.*, 2021) as scaling of digitally-enabled innovations is limited to users in regions with a proper ICT infrastructure.

Our main contribution to the literature is that we introduce new nuances on how digitalisation can increase as well as decrease frugality. Moreover, we make a distinction between digital technologies as and within FIs and show how digital technologies as FIs can be used within the innovation processes of digitally-enabled FIs. As this is only a first step on the connection between FI and digitalisation based on a small number of case studies, we recommend more case studies (also including surveys among smallholders) to further 'test' our findings on the introduced nuances. We also suggest the next research step to elucidate how digitally-enabled FIs contribute to sustainability and to explore the negative effects of such innovations. Furthermore, we do have initial evidence on how frugal innovators use platforms to source ideas, but we could not explore the role of platforms in mobilisation of different resources. This is another suggestion for further research, thereby focusing on resource mobilisation in and between resource-abundant and resource-scare contexts (Sarkar and Mateus, 2022) and interactions within innovation systems (Barnikol and Liefner, 2022) or frugal digital ecosystems (Ahuja, 2021). Finally, we suggest a study focusing on the end-user's perspective, taking into account total users' costs along the life cycle of digitally-enabled FIs.

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Appendix A. Interview Guide

Intro

- Thanks for time
- Purpose of the study + Relevance for stakeholders; Workshop & Share (draft) results and final reports & co-create new agenda
- Recording allowed?
- Our data protection strategy → anonymisation & comment on draft version before publish + follow standards our universities.

1 Personal questions

- *Personal background*: Could you briefly introduce yourselves?
- *Involvement in project*: How, why and since when are you involved in the project? (e.g., first contact point; how know project, etc.)
- What is your *role in the project*? (Examples and description of your daily activities)
- What are the persons you work with in this project; internally and from other organisations? (why, how, and frequency of cooperation)
- What are the *major places of your work*; and what do you do on these different locations (GS versus GN; + lab, office, home, physical test-site)?
- When, how often and for what purposes did you *travel abroad* before Covid-19? (e.g., project meetings; visits conferences; visit labs; test in physical locations; get permissions; negotiate with partners; etc.) Which parts delayed?
- How did *Covid-19* change your work place and travel behaviour? To what extend did it delay the project?
- Where most proud on? Why and how realized?
- Personal largest frustrations in the project and how do you cope with these?

2 Questions on the project

- Do you know the *first idea (or vision)* of the project? How was this idea formed; the project born?

  - *Founding mothers/fathers*; the person(s) with the brilliant idea? How and met each other?
  - What was the *inspiration* for the project? (e.g., linkages previous projects; follow-up previous projects; local urgencies; inspiration existing (competing) products; social media; etc.)?
  - Largest *enablers and hurdles*of the project at the *start*? Examples?
- What is *currently the core aim* of the project? Still the original vision?
- Are there any adaptations in the core idea in time, and why?
- Which *actors are currently involved*in the project and what are their *roles*?
  - Geography of actors: Global North versus Global South?
  - Since when each participates?
  - Who is leading the project? How are important decisions taken?
  - Major changes in time (drops outs vs new actors; changing role; leadership)? Why?
- Who are the *end-users/target groups* of the new concept?
  - Where are they based, and how to reach them?
  - Frequency (how often), purposes (why) and way of *interaction* (visits; online; . . .)?
  - Hurdles to reach them?
- What *activities can only be done locally* in the Global South? Why? (e.g., local resources; local knowledge; test product; interaction end-users; legalization; gain trust; etc.) and when (e.g., start or later in project)?
- Specific moments that speeded up the project in later stages? Examples?
- Largest hurdles to overcome in later stages? What delayed the project? Examples? How to overcome?
- How do you safeguard data management in the project?
  - Is new data collected?
  - What types of data are relevant in the project?
  - Who has access to it? Is it available online? How to avoid that data has been mis-used?
  - Is it re-usable?
- What *largest successes of the project* so far? Where most proud of?
- What are the *societal contributions* of the project?
- Any *other effects* that happened, but that were not planned?

3 Use of new (digital) concepts and for what purposes

- To what extent do you make use of the following new technologies: platforms; AI blockchain; drones/automatic vehicles; CAD manufacturing (3D printers & laser-cutting); other?
- Why: for what *purpose*; <expected benefits; rationales>
- How obtain access to concept (e.g., physical/technical; legal/institutional; logistical; financial; skills/usage; etc.);
- Largest challenges to overcome for using the concept.

< + ask for why and concrete examples of when used>
Specific for platforms

(1) Social media platforms (Facebook, YouTube, TikTok, Twitter, ... African ones????)
   (a) *Purposes*: Why on these social media platforms?
   (b) *Access*: Payment; training; enrollment/membership; purchase of supporting software; etc.
   (c) *Largest challenges*: . . . why and ask for examples)

(2) Other digital platforms → mention examples of platforms
   (a) Purposes (+ examples platforms + ask for other platforms, including own build or unknown ones in global south)
      (i) Get funding (Kickstarter, KIVA, VC4A)
      (ii) Crowdsourcing; innovation and knowledge sharing: Find or provide research ideas, partners (Ushadidi, Innocentive, IdeaConnection, HeroX, . . .)
      (iii) Software or data development (Eclipse, GitHub, Kaggle)
      (iv) Source materials (Amazon; eBay; Alibaba/Taobao; Jumia)
      (v) Test products (?)
      (vi) Sell products (Amazon; eBay; Alibaba/Taobao; Jumia)
      (vii) Communicate with project partners (how often and with whom)
         (1) Video conference platforms (Zoom, MS Teams, Skype, ... 'own')
         (2) Chat platforms (WhatsApp, Telegram)
      (viii) Other. . .
      (ix) What not done on theses platforms and why (discussion of secrets; fear lose of data; too complex to discuss; lack of internet access/ infrastructure)
   (b) *Access*: Payments; data size; . . .
   (c) Largest challenges (internet connection; physical infrastructure; . . . ?>

4 Next steps and closure

- Coming steps in their project? Expectations?
- Our follow-up and invitation online workshop
- Reports and other complementary data to ask
    - Overview of users/partners? + their location?
    - Access to further interview contacts
    - Other

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