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LITERATURE REVIEW

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# The sustainability of open source commons

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**ABSTRACT**

The sustainability of commons has benefited from Elinor Ostrom´s analysis of shared resources. In her work, sustainability was described in a univocal manner–successful or not–depending on the common's long-term capacity to survive within an uncertain environment. In recent years, this view of sustainability has been applied to the study of digital commons, including open source. Building on more recent work on sustainability, this paper challenges this univocal conception of sustainability in open source. Through a critical review of the literature, it unveils the coexistence of multiple notions of sustainability in open source and proposes a typology of sustainabilities (resource-based, infrastructural, and interactional). We propose that the degree and quality of the interrelationship between these different types of sustainability need to be explored, leading to the theorisation of three possible scenarios (trade-offs, synergy, and independence). We discuss and put forward a research agenda.

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Open source; online communities; sustainability; digital commons; Ostrom; review

## 1. Introduction

Open source is an approach to software development based on the openness of the source code, its modification, and the freedom to distribute it (Stallman, 2015). It is an exemplar of digital commons (Allen & Potts, 2016), featuring prominently in theorising open innovation communities (Kyriakou et al., 2017) and repeatedly proposed as an alternative way of managing software development life-cycles and organising social practices around shared resources (Dong et al., 2019; Jarke & Lyytinen, 2015). Despite extensive research in open source, why it is sustainable remains a key question in information systems (Maruping et al., 2019).

Answers have often relied on Elinor Ostrom's understanding of sustainability, derived from her institutional analysis of Common Pool Resources (CPRs). For her, "sustainable systems are those that meet current needs of many individuals involved in producing deciding and using a commons (...) without compromising the ability of future generations also to meet their needs" (Ostrom & Hess, 2007, p. 63). In this sense, sustainability is achieved "as long as the average rate of withdrawal does not exceed the average rate of replenishment" (Ostrom, 1990, p. 30).

Ostrom's view has been imported into models of open source and digital commons, often without acknowledgement or problematisation, with notable exceptions (e.g., Von Krogh 2002). This has resulted in a stable notion of sustainability based on "institutional equilibrium", whereby robust and resilient institutional arrangements that hinged on ecological notions of "replenishment" of the underlying resource (e.g., "revitalisation" of the commons in Mindel et al. 2018) served as the essential criterion of "success" and "failure" (Ostrom, 1990, pp. 58, 30, 59). This univocal view of sustainability as success or failure is inadequate to accurately cater to the complexity behind open source commons. It was developed primarily in the context of natural resources which are finite, making the commons vulnerable to overuse and in need of limiting withdrawal to the replenishment rate (Ostrom, 1990, p. 32). This may apply to bounded commons but not to open commons which are often unconstrained by a limited number of users (Benkler, 2014). An overreliance on sustainability theories centred on the tragedy of the commons debate, emphasising stabilised success or failure, may impede our current and future ability to study the complex ways in which sustainability in open source and other digital commons are organised. In contrast, the literature in information systems suggests the existence of multiple complementary takes on sustainability (Dao et al., 2011; Elkington, 1997), which hold varying epistemological assumptions influencing how sustainability is studied.

By means of a critical review of the literature on open source sustainability in information systems, this article questions the success-oriented approach to sustainability in open source and proposes an alternative understanding, involving

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a typology of multiple sustainabilities. Such approach invites theoretical reflections regarding the interaction between different types of sustainability in open source, their varying antecedents and consequences, or their unfolding over time.

The paper is organised as follows. Firstly, we review the literature's take on the concept of sustainability in information systems. We then introduce the problem of sustainability as framed in Ostrom's classic approach to CPRs as well as its extension to open source commons. Next, we review the information systems literature on open source to suggest that sustainability has been called upon and redeployed through five different themes: participation, focal actors, time, dimensions, and the underlying logics behind open source actors. We then construct relations between these themes to argue that there are three types of sustainability in open source commons: resource-based, interactional, and infrastructural. We propose three scenarios (trade-offs, synergy, and independence) based on the extent to which these different types of sustainability are interrelated and the quality of their relation (negative or positive). Finally, we discuss the consequences that the coexistence of three types of sustainabilities in open source has for research and in particular, how it affects the way we think about the coordination and the management of open source actors, which is a key concern when studying open source (Maruping et al., 2019).

## 2. Sustainability in information systems

Sustainability has been argued to be an elusive concept (Sumner, 2018), purposefully open to multiple interpretations, accommodating a wide range of views (O'Riordan, 1993). Indeed, Latouche (1995) notes 60 definitions of the concept (Brightman & Lewis, 2017).

Building on Zeng et al. (2020), sustainability in information systems has been looked at in three principal ways: sustained competitive advantage, creating (online) communities and inclusive collaborative efforts, and "green IS". The first view has focused on sustaining competitive advantage through the deployment of IS (Kettinger et al., 1994). Issues studied in this category refer to the deliberate elaboration and alignment of IS and business strategies and the development of organisations' capability to take advantage of strategic opportunities (Clemons, 1986; Peppard & Ward, 2004).

The second view explores how communities, collaborative efforts, and IS artefacts endure in time. Papers in this stream have studied enduring social dynamics of groups, online (Butler, 2001; Naidoo et al., 2019). Some scholars have proposed methodologies based on humanist and interpretivist traditions (e.g., Mumford's (1995) ETHICS () as useful avenues to develop sustainable IS (Standing & Jackson, 2007). Others have put forward that the development of IS artefacts needs to consider social inclusion and social justice to create a sustainable society, meeting the UN's SDG goals (Trauth, 2017).

The third stream, "green IS", urges us to consider environmental and social concerns alongside economic ones and the role that IS have in increasing, mitigating, or even reducing environmental harm (Gholami et al., 2016; Hertel & Wiesent, 2013; Melville, 2010).

All three streams have contributed to definitions of sustainability which mirror Elkington's (1997) triple bottom-line approach. The sustainable competitive advantage stream tends towards an economic and organisational performance view (Kettinger et al., 1994). The community-building and collaboration effort stream defines sustainability as the "challenge to make an information systems work, in practice, over time, in a local setting" (Braa et al., 2004, p. 338)., favouring a social understanding. Green IS papers focus more on preservation and environmental policies. For Malhotra et al. (2013, 1265) define sustainability as the "conservation, deployment, and reuse of resources in responsible ways".

This definitional variability shows how flexible different interpretations of sustainability can be, even within the same discipline. Some have argued that such multivocality of the sustainability concept is purposive (O'Riordan, 1993) because it provides interpretative flexibility to respond to different challenges in different contexts (Kates et al., 2005). Yet, definitions of sustainability may co-opt our understanding and favour certain outcomes over others (Sumner, 2018). Definitions hold epistemological assumptions that influence the way we study and think about sustainability. For example, the prevalent view of sustainability put forward by dominant institutions argues for working towards the resilience of the system in place to cope with ecological shocks, thus avoiding rethinking the causes behind the symptoms (Brightman & Lewis, 2017).

In the context of open source, understandings of sustainability have not been unpacked. As a result, the assumptions about sustainability that pervade open source studies remain latent and unacknowledged, which may result in a partial understanding of the complex realities of the open source phenomenon. Still, sustainability is a key problem in open source (Maruping et al., 2019). In fact, much of the early theorisation on open source (e.g., Benkler, 2002) derives from Ostrom's (1990) seminal work on the commons (Allen & Potts, 2016) in which sustainability is a core concept. Although not all papers on open source have used or been based on Ostrom's understanding of sustainability and that other theories of collective action have been used (e.g., Olson 1967), her work still inspires important contributions on the sustainability of commons, open source, and collective action more generally (e.g.,

Mindel et al. (2018); Riemer et al., 2020). To start unpacking sustainability in open source, the following section discusses the problem as framed in Ostrom's classic approach to CPRs as well as its application to open source.

## 3. Sustainability and the commons

In her seminal study on common pool resources (CPRs), Ostrom (1990) analysed the institutional failings and successes of multiple collective action initiatives in different countries and policy settings. While dominant economic and political thinking had described such initiatives as ultimately doomed, Ostrom argued that CPRs could in fact form complex institutional arrangements where individual behaviour would become meaningful collective action through appropriate incentives. As a result of such arrangements, individuals behaved in the long-term interests of the CPR, no longer seeking their immediate – but ultimately sub-optimal – personal benefit, thereby resolving the inherent dilemma between individual and collective action in the commons.

Through her comparative analysis of CPR situations, Ostrom arrived at seven "design principles" (eight in the case of large-scale CPRs) that seemed to characterise the workings of enduring and robust CPRs. Although she did "not claim that the institutions devised in these settings are in any sense 'optimal'", preferring to speak instead about them being "successful" (Ostrom, 1990, p. 59), she did go a long way to describe and justify why their presence warranted their "sustainability and robustness" (Ostrom, 1990, p. 89).

Sustainability plays a major part in Ostrom's analysis, although it remains largely untheorised. To some extent this is explained by the fact that she was originally concerned with explaining the collective provisioning and management of renewable (but potentially finite) resources, where sustainability was narrowly tied up to replenishment. Indeed, for as long "as the average rate of withdrawal does not exceed the average rate of replenishment, a renewable resource is sustained over time" (Ostrom, 1990, p. 30, emphasis added). The threats of "crowding effects" and "overuse" are always looming large over CPR situations (Ostrom, 1990, p. 32), which is why, for Ostrom, the sustainability of the commons is self-evidently indicated by the sustainability of the underlying resource.

When in the late 1990s and early 2000s the framework for institutional analysis of CPRs was applied to knowledge and digital commons, the resource-centred concept of sustainability was retained. In Ostrom and Hess's (2007, p. 63) framework for analysing knowledge commons, "sustainable systems" are thus defined as "those that meet the current needs of many individuals involved in producing, deciding, and using a commons . . . without compromising the ability of future generations to also meet their needs". There is only one type of sustainability at stake here, that which indicates "whether these systems can *survive* over time" (Ostrom & Hess, 2007, p. 63, emphasis added). Schweik and English's (2012) authoritative account of open source software commons follows Ostrom's to similarly draw on a conception of sustainability in terms of the "success" of Internet-based collaborative design and production. Indeed, an open source commons project is successful "if it produces useful software or else useful software that continues to be developed over time" (Schweik & English, 2012, p. 7).

In recent years, there has been increasing recognition on the part of scholars that Ostrom's evaluative criteria for the successful governance of CPRs may not necessarily apply to all knowledge commons equally. As Cole (2014, p. 49) observed: "in a socio-ecological systems context, Ostrom *assumed* that more robust and resilient resource-management regimes tended to be more successful (perhaps by definition) and, therefore, better. From that point, we might legitimately argue that the 'design principles' from *Governing the Commons* were informed by an implicit normative commitment to long-run sustainability of socio-ecological systems" (original emphasis). This should alert us to the fact that there might be limited profitability in applying Ostrom's institutional framework for CPRs to all commons systems alike. In fact, Benkler (2014, p. 71) calls for distinguishing the existence of two broad paradigms of commons' regimes: the bounded commons, best exemplified by CPRs, and the "open commons", characterised by "freedom to operate under symmetric constraints, available to an open, or undefined, class of users", including for example, roads, urban sidewalks, public utilities or, indeed, open source software.

## 4. Sustainability in open source studies

Surprisingly, throughout the literature, the notion of open source sustainability is problematic but never unpacked. "Why should thousands of top-notch programmers contribute freely to the provision of a public good?", asked Lerner and Tirole in one of the leading contributions to the fundamental economics of open source. "Any explanation based on altruism", they answered, "only goes so far" (Lerner & Tirole, 2002, p. 198). Their paper concludes that people come to participate in open source projects because, while it provides hackers with enjoyment, it also benefits them in the long-term. The economic undertone is evident, as well as an epistemological stance of the research that centres on individual rationality and utilitarianism. Similarly, Mindel

et al. (2018) define commons-based sustainability as the continuous provision of value that stakeholders consume. Ultimately, open source is but a tool for career advancement and the betterment of individual sovereign subjects. Despite or because of such clear undertones, this question was reprised in the pioneering legal and economic literature that set the mark for future research (Benkler, 2002), giving a sense that an economic rationale sealed shut the epistemological problematisation of open source sustainability once and for all (e.g., Fang & Neufeld, 2009; Roberts et al., 2006; Von Krogh et al., 2012, 2003). Indeed, the provision of a rational explanation for why contributors do in fact contribute, and that this explanation is in line with traditional conceptions of economic theory (Ducheneaut, 2005), provided the logical conclusion that open source was reliably sustained by a global, ad-hoc workforce.

At the same time, several scholars have argued that open source sustainability is a latent key issue (Krishnamurthy et al., 2014), that requires detailed study (Von Krogh et al., 2012). How to sustain open source in the long run remains an active question and failure is all too often a common outcome (Cai & Zhu, 2016; Fang & Neufeld, 2009). Whilst some authors have drawn attention to problems of maintenance and "survivability" of open source systems (Aksulu & Wade, 2010), or the relations between sustained participation, coordination and leadership (Crowston et al., 2012), there has been no larger effort at reckoning with the theoretical dimensions of sustainability in open source.

There remains, in sum, no substantial analysis of the meaning of sustainability in open source because open source has relied heavily on Ostrom's univocal reading of sustainability. This reading, meant primarily for finite resources (Ostrom & Hess, 2007), frames sustainability exclusively in terms of success or failure and assumes a stable notion of sustainability. However, the broader literature on sustainability in information systems and beyond, points towards the existence of multiple understandings of the concept, which hold varying epistemological assumptions that influence the way sustainability is studied. The remainder of this paper focuses in critically reviewing the literature to explore how sustainability in open source has been deployed and the implicit meanings ascribed to it.

## 5. Methodology

We first searched for key texts drawing on a list of top-tier, academic journals relevant to information systems provided by Willcocks et al. (2008). The list contains journals in information systems, general management, and organisation studies. Additional journals not included in the list were added (e.g., *Research Policy or Journal of Software and Systems*). In total, 50 journals were included in the search. These journals were searched in the *ISI Web of Knowledge* database for the appearance of open source related terms (e.g., OS OR open source, FOSS) and "sustain*". This resulted in a limited number of papers (29), out of which 22 were pertinent.

This literature review follows an interpretative research approach that seeks to problematise current literature and study how certain phenomena are explained within key texts (Schultze, 2015). Our review is "narrative" and "critical", grounded on the qualitative discussions of papers (Post et al., 2020), and the problematisation of existing literature and its underlying assumptions (Paré et al., 2015; Schultze, 2015). The foregrounding of interpretation in this kind of review places the burden of justification on its exposition and the researcher's knowledge of the literature, rather than on the procedural systematicity of the search and the breadth of papers analysed (MacLure, 2005). As such, the research process is attuned to the goals of the paper: to show that open source sustainability is a complex and nuanced concept that must be made explicit and requires theorisation. This approach enables us to identify that, within the existing literature, there lay unacknowledged multiple types of sustainability whose interactions matter to understanding how, in what ways, and why is open source sustainable.

To organise the literature, we developed a template as we analysed the papers. The purpose of template analysis is to derive from the data a list of codes and relations, commonly obtaining a hierarchical structure. Some of the codes are developed a priori, based on the research question and the researcher's knowledge. Others emerge from the data as the coding unfolds. This technique involves a thorough revision and refining process that enables codes and their hierarchical structure to evolve (King, 2004). Our initial template included only one basic code, "participation", because of its central place in explaining sustainability in the open source literature. All other codes emerged from the analysis of the papers and were added to the template as the analysis progressed. The initial 'participation" code was refined and revised by the addition of sub-codes. For example, sometimes notions of participation were more akin to accumulating resources (e.g., Sun et al., 2012) and were coded under the term "quantity of participation". Other times participation was related to open source sustainability in terms of its quality and was coded under the term "type of participation" (e.g., Von Krogh et al., 2012).

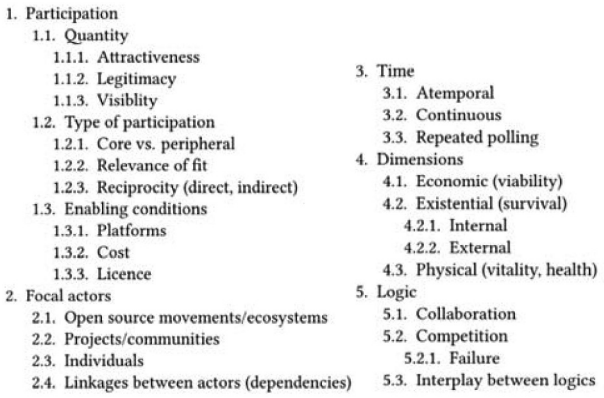


Figure 1. Resulting template from the analysis.

We developed a structure for the emerging codes to integrate them into wider codes or themes (King, 2004). For example, codes such as "developers", "users", and "leaders" were initially coded separately. When the list of these codes became very large but conceptually similar, they were integrated into the single code "individuals". In turn, this code was categorised as part of the wider code "focal actors", which encompassed other codes such as "project and communities" or "open source movements". In total, five main themes are included in the final template (see, Figure 1).

The hierarchical nature of template analysis "depicts the relationship between themes as a linear one" (King, 2004, 267). Therefore, to further explore and contrast the relationships between codes, we built different conceptual maps and matrices that helped visualise possible connections between codes and sub-codes (Crabtree & Miller, 1999). Doing so helped us observe how sub-codes for the different themes tended to be reflected in the same papers. For instance, when the sub-code "quantity" was present in relation to "participation" the codes "projects and communities", "repeated polling", "economic (viability)" and "interplay between logics" were also present. The way the different sub-codes combine into three categories is reflected in Table 1. In this way, a typology of three different understandings of sustainability latent in the papers emerged, helping to clarify the construct (Rivard, 2014). We then propose relations from the typology as an avenue to generate theory (Post et al., 2020).

## 6. The building blocks of sustainability in open source: five themes

We identified five themes that contribute in different ways to sustainability in open source: *participation*, which is a condition for, a cause, or a property of sustainability; the *focus on certain actors*, which characterises sustainability; the way *time* is considered in thinking about sustainability; the *dimensions* or registers through which problems of sustainability are made explicitly; and the *logic* used to reason about sustainability. Here, we analyse each theme in turn.

### 6.1. Participation

Participation is a theme that repeatedly appears in relation to open source sustainability. Participation is used to understand open source sustainability in three main ways: by the quantity of participation and participants present in the project or community; by the type of participation that can be enticed from participants; and finally, by the conditions that enable such participation to take place.

One way the literature understands sustainability is by the quantity of participation and participants (L Chen et al., 2012). The more participation and activity takes place in a project or a community, the more likely it is to be sustainable (Park et al., 2013). Sun et al. (2012, p. 14) argue that "A sound virtual community should preserve its membership base and sustain participation (Fang & Neufeld, 2009; Roberts et al., 2006)". The literature points to two main ways to preserve and recruit participation: attractiveness and legitimacy. A project is attractive to individuals because they perceive visible qualities and values that induce their participation (Santos et al., 2013). Such qualities can be, for example, perceptions of task completion, the project's chosen programming language which can affect the number of potential developers, or the frequency of releases (Gamalielsson & Lundell, 2014). Similarly, Chengalur-Smith et al. (2010) highlight the role that project legitimacy and demographics (e.g., niche size) have in attracting and retaining participant resources, thus positively impacting project sustainability. Because larger and older projects are seen as more established, it may lead to "larger projects to grow faster and smaller projects to decline at a higher rate" depending on the development base and niche size (e.g., programming language; Chengalur-Smith et al., 2010, p. 679). The quantity of participation in a project relies on the visibility of certain attributes which make it attractive or legitimate, and which pulls and motivates people into sustaining their participation (Sun et al., 2012).

Other papers argue that a certain type of participation is necessary for projects and communities to be sustained. Not all participation is equal (Hann et al., 2013), and projects and communities need to encourage positive social relations. This involves participants becoming core members through situated learning and identity construction, two mechanisms that explain how participants create ties and engage in meaningful practices within the community (Fang & Neufeld, 2009). It is unclear whether a project could be sustained only through peripheral contributions, even

**Table 1.** The configuration of themes elicited from the literature produces three different sustainability definitions.

| Themes | Category 1 | Category 2 | Category 3 |
|---|---|---|---|
| **Participation** | Quantity/Accumulation | Of a particular kind | Enabling conditions |
| **Focal actors** | Projects/communities composed of individuals | Projects/communities, intra-community interactions by individuals | Large focal actors: open source movement, ecosystems, or regimes of innovation |
| **Time** | Repeated polling | Continuous | Atemporal |
| **Dimensions** | Physical, economical | Existential | Economical, existential |
| **Logic** | Competition (over resources), collaboration (be converging towards similar tools or projects | Competition (different roles in open source can lead to different economic rewards), collaboration (to form positive social relations) | Competition (against dominant models), collaboration (to form an ecosystem) |
| **Understanding of sustainability** | **Resource-based**<br>The sustainability of projects and communities depends on their capacity to attract and retain resources or value | **Interactional**<br>The sustainability of projects and communities depends on their capacity to entice a certain kind of participation that conforms to their values and expectations | **Infrastructural**<br>The sustainability of open source as a whole depends on the sustainability of key parts of open source |
| **Exemplary papers** | Chengalur-Smith et al. (2010)<br>Santos et al. (2013)<br>Sun et al. (2012)<br>L Chen et al. (2012) | Fang and Neufeld (2009)<br>Hann et al. (2013)<br>L Chen et al. (2012)<br>Faraj and Johnson (2011)<br>Oh et al. (2016)<br>Von Krogh et al. (2012) | Krishnamurthy and Tripathi (2009)<br>Osterloh and Rota (2007)<br>Benner and Tushman (2015)<br>Krishnamurthy et al. (2014) |

though it is considered essential (Kilamo et al., 2012). In addition, the type of participation that is sustaining is one which fits with a project's or a community's social practice. Through educational activities, established members can ensure that contributions adhere to the community's standards and fit with the project's long-term purpose (Curto-Millet & Shaikh, 2017; Von Krogh et al., 2012). Leaders can have this role and interact with the community to affect participation. Thus leaders should "wisely and flexibly adjust their leadership style depending on many factors, including community size, maturity state, network structure, and environmental uncertainty" (Oh et al., 2016, p. 16). Another quality that is important to project or community participation is that which entices reciprocity, which is also conducive to positive social relations and to welcoming newcomers (Faraj & Johnson, 2011).

Another stream connects sustainability in open source to the existence of enabling conditions without which participation in open source is unlikely to happen. For Krishnamurthy and Tripathi (2009, pp. 409, 404), "[t]he presence of the platform is crucial to any [open source] project's success" as platforms "play a vital role in creating an ecosystem that enables their creation and growth". In question here is the platform's role in the sustainability of the wider open source ecosystem, and therefore the criticality behind its own sustainability. If platforms were to cease existing, the conditions allowing open source movements to be sustainable may not be met, because low-costs situations "maintain the collective invention model" (Osterloh & Rota, 2007, p. 169). Low-cost situations are crucial for open source: it is precisely when coordination and communication costs are low, that open innovation models hold a competitive advantage over traditional ones (Benner & Tushman, 2015). Linked to the creation of low-cost situations are open source licences. These play a vital function in creating a fair playing field and hindering the "exploitation of voluntary donors" (Osterloh & Rota, 2007, p. 167) and resource investments (Karhu et al., 2018), echoing Ostrom (1990) when arguing that commons tend to thrive when the monitoring and enforcement of appropriate conduct is not costly.

### 6.2. Focal actors

Actors are a key theme in the characterisation of sustainability in open source. These actors range from the large, such as the open source movement (e.g., Benner & Tushman, 2015; Osterloh & Rota, 2007), platforms and ecosystems (e.g., Krishnamurthy & Tripathi, 2009), down to the individual (e.g., Santos et al., 2013), passing by what could be considered intermediary actors such as projects (e.g., Kazman et al., 2016), communities (e.g., Faraj & Johnson, 2011), or specific types of communities (e.g., Sun et al., 2012).

The largest actor referred to in the literature is the open source movement itself and the ecosystem it creates. When considered, the open source movement is described as an alternative mode of innovation production, which may also be complementary to traditional ones (Benner & Tushman, 2015; Osterloh & Rota, 2007). It tends to rely on self-organised and spontaneously emergent communities of volunteers which have the capacity of creating new markets (Benner & Tushman, 2015). The open source ecosystem is another large actor which emphasises the range of necessary actors for the movement to work (Linåker et al., 2018). Platforms, for example, facilitate the creation and coordination of other open source projects (Krishnamurthy & Tripathi, 2009). Because of their central role in encouraging project development, they are often thought to foster an ecosystem under the sponsorship of a platform leader which develops and provides specific functionality to smaller projects (Gawer, 2014).

Projects and communities form the bulk of the actors whose sustainability is latent in studies. Projects usually form around an online code repository and a roadmap of future functionality (Howison & Crowston, 2014). The project's code and documentation are created via contributions made by a decentralised community mostly composed of volunteers (Choi et al., 2015; Fang & Neufeld, 2009). Projects are an important component of open source development efforts (Howison & Crowston, 2014) by hosting forums and mailing lists around which a community forms. These provide public ways for the community to coordinate and members to meet and exchange views (Shaikh & Vaast, 2016). The community, thus, is often considered a part of a project and establishes collective norms (De Laat, 2012). The collective abilities of the community as a whole determine the project's viability (Butler et al., 2020). Communities can be of various types such as "working" communities which have a clear and tangible output (Oh et al., 2016), or transactional communities out of which participants expect tangible returns (Sun et al., 2012).

The community is composed of heterogeneous individuals: users and developers (Santos et al., 2013), some of which are considered "core" or "virtuous" depending on their standing with the community or the movement (Puranam et al., 2014). Individuals have different levels of resources such as knowledge and time, which affects their motivation to continue participating (Butler et al., 2020; Sun et al., 2012). Because open source is often composed of volunteers, intangible rewards such as social capital are sought by contributors (Barron, 2013; L Chen et al., 2012).

Individuals can also be seen as critical open source actors that, when taken together, help explain the sustainability of larger actors such as the open source movement (Krishnamurthy et al., 2014).

What results from this diversity of actors is that papers often focus on the sustainability of a focal actor to which other actors contribute. Krishnamurthy and Tripathi (2009) capture this relation of sustainability between actors well. They note how, "[b]y providing the infrastructure at no cost and acting as a volunteer firm, online OSS development platforms lay the foundation for OSS development" (Krishnamurthy & Tripathi, 2009, p. 406). Such a critical role is valued by individuals involved in "active and prestigious projects" for the hand they played in the success of their own project. In turn, studies that focus on the sustainability of projects do not always look at the sustainability of individual participants (Chengalur-Smith et al., 2010). Thus, when certain papers focus on study the sustainability of certain actors, they often assume the sustainability of others. For example, the sustainability of a project may depend on individual perceptions of attractiveness and legitimacy (Chengalur-Smith et al., 2010; Santos et al., 2013), but the sustainability of individual participation may rest on an exploitative practice because it is largely based on the fragile promise of accrued social capital gained through networks of influence (Barron, 2013; Terranova, 2000).

In addition to the range of diverse actors whose sustainability can be considered, the literature sometimes treats the same actors differently. Participants can be seen as individuals who care about their work and the social good they create, wishing "to sustain practices that cultivate internal goods that match their individual sense of the common good and the life they wish to live" (Von Krogh et al., 2012, p. 668). Alternatively, other papers see individuals as "resources [that are] influenced by attractiveness, are recruited and act to maintain and improve software, and their recruiting and actions influence project attractiveness" (Santos et al., 2013, p. 29). The same actor may be treated differently depending on when they are studied. Oh et al. (2016) suggest that projects change and require different supervisory management styles depending on their lifecycle stage.

### 6.3. Temporality

Another theme which characterises sustainability in open source is that of time. Considerations of time permeate the literature and can be classified into three different categories: continuous temporality, repeated polling, and atemporality.

In regimes of continuous temporality, time flows unproblematically without being put into question. In these papers, open source sustainability happens when interactions between actors become positive, thus encouraging reciprocity. Such positive interactions end up creating patterns of relations (e.g., Faraj & Johnson, 2011). In these cases, time is relatively stable because these patterns tend to self-reinforce and favour similar participation. It is only when the interactions become negative that sustainability is undermined. There is a sense of build-up that time accompanies in this stream of papers, with Von Krogh et al. (2012, p. 669) asking further research to consider "[u]nder what conditions does an initial interest grow or wane over time, given exposure to the social practice, learning, social interaction, moral premises, help received, or a sense of reciprocity in contributions to OSS?" Phrased in this way, developer interests in nurturing the "correct" social practice within a community, evokes naturalistic images, instead of abrupt changes in project or community sustainability. When significant changes take place from outside the project's environment, such change is limited to increasing uncertainty (Oh et al., 2016), and not, say, changes in the deep structure of the project (Barrett et al., 2013), and the way it may frame sustainability. The institutional norms in communities that affect and sustain interactions cushion drastic changes.

For Chengalur-Smith et al. (2010, p. 660), time is what differentiates success from sustainability in open source, where the "key distinction is that sustainability requires certain levels of activity to be maintained over a long period of time, whereas success can be measured at one particular point in time or over the entire life of the project". In making this distinction, they put forward an interesting idea: the way researchers measure time influences sustainability. Indeed, sustainability in open source is neither found at a particular instant, nor on a global timescale, but through repeated polling of a project's activity; if the polling indicates that the activity is maintained or has grown, then it is more likely to be sustainable. The way this type of study considers time is similar to the way individual participants consider it: contributors repeatedly poll themselves to decide whether to continue participating or not. The motivation to keep participating may change over time depending on perceptions of task complexity and self-efficacy (Sun et al., 2012) or because they deem that the project remains attractive (Santos et al., 2013). This type of consideration of time is called "repeated polling" because the sustainability of a project is measured by the repeated polling of individuals who asses the projects they participate in and the future interest it holds for them according to the same variables.

Finally, certain papers do not provide any information regarding their take on time. Time, in these papers, is not an issue for sustainability and is not considered. As long as a number of conditions are met such as the low cost of participation or the presence of protective licences, open source is likely to be sustainable (Osterloh & Rota, 2007). These conditions are unlikely to change in the future because they depend on their installed base, which gives them stability. Therefore, time is mostly unproblematic and unlikely to affect sustainability.

### 6.4. Dimensions

The notion of sustainability in open source is often accompanied with other terms that are close to its meaning and which focus on a particular perspective. For example, when Chengalur-Smith et al. (2010, p. 659) say: "we draw on organizational ecology, a theoretical framework specifically concerned with organizational survival and sustainability", it is not specified how "sustainability" differs from "survival". When talking about how their results could help managers plan strategies, Krishnamurthy and Tripathi (2009) mix "viability" and "sustainability". It may well be argued that the use of such words is for rhetorical purposes, and yet, the repeated occurrence of some of them within and across papers may also indicate attempts by scholars to specify different and specific aspects of sustainability in open source. Three recurring terms are viability, survival, and vitality or health which are used interchangeably. Each responds to a specific dimension of open source sustainability, respectively, economic, existential, and physical.

The term "viability" is often used to indicate the capacity of the open source movement or of a project to sustain itself by its own means, suggesting an economic dimension to sustainability (Butler et al., 2020). The sustainability of open source as a whole or of a project or community is evaluated by other actors when they decide to participate in a project or to maintain their participation. For Oh et al. (2016), the stability of a project signals to participants that it is worth the cost and effort to learn how to contribute. Krishnamurthy and Tripathi (2009) encourages managers to consider strategies to make platforms viable by suggesting ways to monetise their business model. Hann et al. (2013, p. 17) refer to meritocracy as "the explicit governance approach for many prominent and commercially viable OSS projects … " Alternatively, Faraj and Johnson (2011, p. 1475) suggest that "different viable alternative configurations of network exchange patterns may exist in sustainable online communities", denoting the possibility of different patterns that can sustain interactions.

Another recurring dimension is existential, exemplified by the term "survival". When Osterloh & Rota (2007, p. 157), talking about open source, say "most collective invention regimes did not survive after the development of a dominant design", there appears a side of sustainability that denotes an existential threat to open source by other, more established regimes of innovation. Other open source projects can be a threat as well, competing over finite resources often identified as developers (e.g., Oh et al., 2016; Santos et al., 2013). Others yet see the survival of open source challenged by internal threats instead of external ones (Gamalielsson & Lundell, 2014). Von Krogh et al. (2012) explore how social practice can survive in open source communities by the involvement of virtuous developers. In other words, without the continuous implication of these developers, the project's intended production of social good may be endangered by substandard contributions. The idea of a threat, whether external or internal, is telling of the struggle that open source actors have to be sustained or to sustain themselves, of having to fight against the odds, shifting the meaning of sustainability in open source. In this dimension, sustainability focuses on a certain way of doing things, the continuance of a certain social practice. Others associate vitality with sustainability, denoting a physical dimension to it. Indeed, vitality is the perception of a project's or community's "physical" health (e.g., Chengalur-Smith et al., 2010). For example, a project that has completed bug reports or that is responsive with the implementation of feature requests will be seen to be more active (Santos et al., 2013). The idea is that contributors will more likely join a project or community that shows positive, visible signs that it will endure before going through the costs of joining. Under this light, open source sustainability is no longer a general idea, but a *perception* of a rational choice to invest in joining and continue participating to a project which is already functioning well.

### 6.5. Underlying logics

The literature projects two main logics onto open source actors: competitive and collaborative. Logics frame both the research attitudes that seek to explain sustainability in open source and the way actors themselves reason about achieving sustainability.

A logic of collaboration is said to underpin many elements in open source. Individuals collaborate together to build complex projects openly (Howison & Crowston, 2014; Shaikh & Vaast, 2016). The code is licenced openly and shared so that others may inspect, comment, or use in their own projects and collective creation permeates the idea of participation in open source (Von Hippel & von Krogh, 2003). When associated to sustainability, the logic of

collaboration describes the context in which individual actions take place. Von Krogh et al. (2012) argue that individuals are interested in maintaining the social good, which explains their drive towards creating high quality code that meets shared, community standards of excellence. Beyond the code itself is the participation that takes place, which is influenced by the construction of individual participant identities within communities of practice. Open source sustainability therefore sediments as the outcome of collaborative work.

However, there is also a logic of competition in the studied literature which can take various forms. First, developers are seen as essential resources to compete for. For example, Fang and Neufeld (2009, p. 10) argue that "[d]espite the notable success stories, many more OSS projects have failed, frequently due to insufficient volunteer participation". The volunteer aspect of participation is often seen as a burden instead of as a boon (Chengalur-Smith et al., 2010; Krishnamurthy et al., 2014; Krishnamurthy & Tripathi, 2009), where volunteers may be unstable (Von Krogh et al., 2012). Projects compete against each other since individuals have limited time to spare, particularly core developers (Butler et al., 2020). Developers are understood as finite resources (Oh et al., 2016), that should influence strategic project decisions such as the choice of programming language (Santos et al., 2013). The goal of projects is thus to achieve competitive advantage over others (Chengalur-Smith et al., 2010; Karhu et al., 2018).

Additionally, individuals are also competing against each other and themselves for certain leadership roles such as package maintainers who have the authority to pull code into the main branch (Fang & Neufeld, 2009). The idea is best summed up by Raymond (2001) who saw open source as a meritocratic movement in which, because the code is open to inspection, only the best are chosen. Some have argued that this captures the new spirit of capitalism, pushing individuals to contribute for the promise of social capital (Barron, 2013).

The logic of competition is embedded in studies mentioning the failure of open source. A project that does not manage sustainability is considered a failure, not simply unsustainable. Osterloh and Rota (2007) argue that collective invention regimes are usually subsumed by dominant innovation paradigms and the success of open source is evaluated on its capacity to compete against proprietary alternatives (Dalle & Jullien, 2003)

These two logics can interplay interestingly. Although other projects may be potential competitors over finite resources, strategies to avoid competition might hold particular sway in open source and in fact, lead to strategies to augment potential collaboration. As Chengalur-Smith et al. (2010, p. 677) suggest: "FLOSS project leaders seeking to attract developers should make their projects more similar to others, as opposed to trying to differentiate on the basis of audience, operating system or programming language". In this sense, leaders of different projects may want to scale their demographics by establishing common grounds.

## 7. A typology of multiple sustainabilities in open source

The five themes emerging from the analysis of the literature can be made sense through different semantic relationships (Spradley, 1979). First, the literature appears to treat participation as the core element in distinguishing between sustainable and non-sustainable open source. As such, participation holds multiple semantic relations with sustainability in open source. Some literature puts great stock on participation and is sometimes considered "a condition" for sustainability. For others, it is the degree of participation that matters, making participation "a cause" of sustainability. The greater the level of participation, the more likely sustainability is. Finally, participation can be "a property" of sustainability, with different kinds of participation contributing differently. As such, participation and its influence on sustainability ranges from the absolute (necessary condition), to a causation (the more the better), to being a more contextual influence (what kind of participation is needed in different contexts).

As for the work of focal actors (i.e., open source movements/ecosystems, projects/communities, individuals), these are stakeholders and recipients of open source sustainability. The focus on one actor or another is *a characteristic* of sustainability. Many different kinds of actors with different degrees of importance take part in open source sustainability. The decision to focus on one over another influences the assessment of sustainability and the factors related to it. Temporality *is a way of analysing* sustainability in open source. The way time is measured (i.e., through repeated polling or continuously) or whether it is overlooked (i.e., atemporal) affects the meaning of sustainability, both for the researchers and the actors involved. Certain keywords (i.e., viability, survival, vitality) are repeatedly used as a way to specify and bound open source sustainability to particular dimensions (i.e., economic, existential, physical). These dimensions are *ways to look at specific aspects* of sustainability in open source. They give it a precise meaning relevant to the context of the research. Finally, actors have an underlying logic

(i.e., collaboration, competition) that *gives them a rationale* for striving for sustainability. Because the literature counts many different focal actors, it may be that different actors hold different rationales. A community may be collaborative on the whole, but a contributor in that community could exhibit competitive logics. The same actor may show, at different times, different logics. An incipient project may veer more towards collaborative behaviour and, once mature, become more competitive towards other projects.

By making sense of the five themes through semantic relationships, we observe that they can be combined to create categories or types of sustainability in open source. For example, when the literature considers participation as a cause of sustainability it tends to present projects and communities as the locus of such participation. In addition, in these studies, time tends of be accounted for multiple times, through repeated polling. Since the focus here is on the quantity of contributing resources, the specific aspects of sustainability to be looked at are primarily physical and economical. The assumed rationale behind these studies is that projects need to compete over finite resources or to increase the pool of collective resources by collaborating. This emerging type of sustainability can be labelled as "resource-based" and refers to the capacity of open source actors to attract resources such as developers or value such as knowledge, content, or social capital.

The literature's understanding of participation as a property of sustainability is concerned with the quality of participation and tends to see open source sustainability as a result of individual interactions within projects and communities. These studies usually have a continuous approach to time, which unfolds unproblematically. Social ties and the idea of social good form slowly and coalesce around specific ways of interacting. The most prevalent dimension in these studies is the existential one, which highlights the importance of encouraging social positive interactions for the project or the community to survive. Since the concern here is on eliciting a particular kind of participation, the rationale of the involved actors tends to be one of collaboration. We label this type of open source sustainability "interactional" because it focuses on the kinds of relations that are created in the project or community and how these add a particular needed value to the project.

Studies seeing participation as a condition for open source sustainability are generally concerned with larger focal actors such as ecosystems, regimes of innovation or open source itself. In these studies, time is largely undefined as a global element because the onus is placed on the enabling conditions that, if existing, are assumed to be stable. This literature tends to look at economic or existential aspects of open source sustainability: "economic" inasmuch as focal actors show a capacity to maintain themselves involved in the project through their own means; "existential" because of the ability of the actors to survive against threats, such as dominant models of innovation. In these studies, both competition and collaboration underwrite the logic of the actors. There is a sense of competitive struggle that pits the open source movement against a dominant alternative which, in many ways, could complement it. This type of open source sustainability is labelled "infrastructural" because it emphasises how the sustainability of key parts of open source adds to the sustainability of open source as a whole.

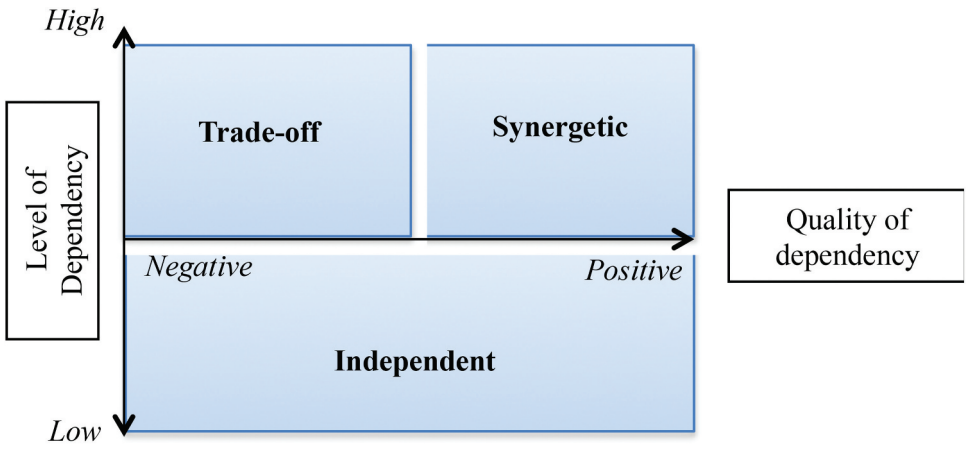


Figure 2. Summary of sustainability changes depending on relationship.

Table 1, summarises these findings and provides some exemplary articles for each of the types of open source sustainability identified in the literature.

## 8. Theorising the relationship between types of sustainability in open source

The existence of different types of sustainability challenges the univocal "success/failure" conception of open source sustainability inherited from Ostrom and opens the door to important theoretical reflections, such as their potentially different antecedents and consequences at different levels of analysis (e.g., project, community), their varying unfolding over time, or their interrelation.

The wider literature on sustainability has explored the existence of trade-offs and complementarities between different aspects of sustainability (Elkington, 2018). Examples of organisations experiencing trade-offs between economic and social or environmental outcomes (e.g., Kolk, 2012) coexist with evidence of complementarities or synergies (Margolis & Walsh, 2003), and ways to mitigate potential trade-offs (Longoni & Cagliano, 2018). Recent studies on sustainable development goals (SDGs) have also explored interactions between different indicators of sustainability (Biggeri et al., 2019). For instance, emphasis on one SDG can have negative implications for attaining others (Barbier & Burgess, 2019). Kroll et al. (2019) find both synergies and persistent trade-offs between different SDGs and propose that in time the latter can evolve into synergies. As Savaget et al. (2019, p. 885) note: "conceptual responses to sustainability challenges represent great sources of tension" between "confrontational" approaches (e.g., privileging environment outcomes over economic ones) and "pacifying" approaches (e.g., privileging win-win situations).

Drawing on this literature, we argue that two aspects of interrelationship between different types of sustainability in open source need to be observed: degree and quality. *Degree of interrelation* refers to the extent to which the unfolding of one type of sustainability depends on any of the other two. If it is high, changes in one type of open source sustainability necessarily affect the other, whereas if it is low, one sustainability may remain constant while the others change. When the degree of interrelation is high, it becomes essential to look at the *quality* of that relationship. If the relationship is positive, increase in one type of sustainability will lead to subsequent increases in other types and vice versa. If, on the other hand, the relationship is negative, increase in one type of sustainability will lead to the decrease of another type. As a result of these two aspects of interrelationship, three alternative scenarios emerge (see, Figure 2).

*Trade-off*. A high degree of negative interrelation would imply the existence of trade-offs between different types of sustainability in open source. This means that desirable and detrimental effects may coexist and that resource-based, interactional, and infrastructural sustainabilities may pose conflicting demands. In this scenario, it would be important to study the extent to which practices or events enhance one aspect of open source sustainability, while decreasing another aspect. It would also be interesting to analyse the prevalence of these trade-offs and examine how they can be mitigated. Acknowledging the existence of sustainability trade-offs in open source may contribute to explain mixed effects and unveil unintended consequences of practices assumed to be favourable. This scenario implies that open source sustainability may not be maximised in all aspects: an open source project may show more capacity to sustain in some aspects than in others, leading to specific strategies being adopted by the involved actors.

*Synergy*. A high degree of positive interrelation would imply the existence of synergies between different types of open source sustainabilities. In this scenario, sustainabilities are amplified by their interaction: improving one type of sustainability would boost at least one of the others, while impairing one of them would weaken at least one of the others. This means that an event or a practice could trigger virtuous circles where, for example, an increase in infrastructural sustainability is followed by subsequent enhancement of resource-based and interactional sustainability. On the contrary, events or practices could also trigger vicious circles where, for instance, the decline of infrastructural sustainability would drag resource-based and interactional sustainability down. Thus, in this type of scenario, research should look at which practices or events have either beneficial or adverse effects on multiple types of open source sustainability, particularly triggering ones. It could also explore causal effects and path dependencies between different types of sustainability, unveiling the ways in which multiple effects follow one another and unfold. Research questions on synergistic relations would thus look into the combined effects to the three types of sustainability.

*Independence*. When the degree of interrelation is low, different types of sustainability in open source are independent from one another. Changes in one type of open source sustainability should not affect the other two. Thus, we can assume that their antecedents are different and should be identified and explored. This scenario also implies that focal actors (e.g., projects, communities . . .) may decide to focus on one particular type of sustainability while disregarding the others. How such a choice is made, why, and its resulting consequences, are also important research avenues.

Table 2. Research question.

| Area | Examples of research questions |
|---|---|
| **Multiple levels and competing understandings of sustainability** | How do different types of sustainability affect different levels of focal actors? Do different kinds of open source projects instantiate different and local meanings of sustainability? If this is the case, then comparative analyses could provide finer conceptualisations of open source sustainability. |
| **Consequences to basic open source constructs** | How do different notions and understandings of sustainability influence basic open source organisational constructs? Is this influence mutual? |
| **Evolution of sustainability and scenarios of evolution** | Can there be an evolution between these distinct scenarios? How does the life-cycle of projects and communities relate to each sustainability scenario? |
| Trade-offs | Can sustainability be maximised across all units of analysis? What causes trade-offs to happen or to exist? Do different focal actors depend on certain types of sustainability than others? If so, are there strategic priorities to improve certain types of sustainability over others? |
| Independence | Is an open source actor more resilient if the different types of sustainability are independent from each other? Or on the contrary, are independent types of sustainability suggestive of problematic organisational processes? |
| Synergy | What initiatives can launch a virtuous cycle and stop a vicious one? |
| **Epistemological and methodological considerations** | How can different epistemological traditions be put to use to reveal complex sustainable issues in open source information systems? Do they involve conflicting notions of sustainability? |

Moreover, in comparison with the synergy scenario, the independence scenario would mean that developing each type of sustainability would require separate sets of effort because effort exerted towards increasing one type of open source sustainability would not influence the others. In this scenario, the research questions would focus on the consequences of independent types of sustainability.

The identification of these different types of sustainability and our theorisation based on the nature and degree of their relation challenges assumptions of univocality and stability. In the rest of this paper, we will focus on discussing and proposing research questions that result from this coexistence.

## 9. Discussion and research agenda

In contrast to Ostrom's conceptualising, our proposal suggests sustainability in open source may not be "achieved" or stabilised and that sustaining a project or a community is a continuous effort. Our proposal is also aligned with advances in the information systems literature which see sustainability as a multifaceted and interrelated concept (Dao et al., 2011). In what follows, we discuss four areas propitious for future research and propose a number of research questions for each area (see, Table 2).

### *9.1. Levels and competing understandings of sustainability*

The coexistence of multiple types of sustainability added to the presence of multiple focal actors and other stakeholders suggests that sustainability in open source is layered through multiple levels. The open source movement(s) may well have different sustainability requirements than projects or communities, and projects themselves may interpret sustainability and sustainability practices differently from the embedded communities within the project. As it stands, the literature has tended to consider open source sustainability as a "flat" phenomenon where the sustainability of smaller units of analysis (e.g., developers) conform or compose the sustainability of larger actors (e.g., projects or communities). The sustainability literature has shown how different conceptions of sustainability can favour certain actors over others (Sumner, 2018). As such, the assumed harmonious alignment of sustainability may be erroneous, with conflicts between analysis levels and types of sustainability arising. The recent fierce debate in open source regarding the institutionalisation of codes of conduct to regulate interactions and resolve long-entrenched misogynistic behaviour (i.e., interactional sustainability) pitted communities against highly visible open source projects who did adopt such codes, fearing the loss of certain key and historical figures of the open source movement (e.g., resource-based sustainability). Open source sustainability is thus likely to be a multi-level construct that will require researchers to understand the complex entangled relations between actors and types of sustainability across multiple levels.

On the other hand, comparable units of analysis (e.g., focal actors) may have localised and competing notions of open source sustainability. Certain open source projects emphasise collaboration between autonomous small projects rather than directed by a larger umbrella project. One of the philosophies behind the development of open source and to which part of that community tends to associate is the Unix development philosophy. It argues that programmes should be as small and as specialised as possible, thus reducing coordination efforts even further, allowing less coding dependencies, and overall more reusability through combining together small programmes that do one thing and do it well (Kernighan & Mashey, 1981). Resource-based and interactional sustainabilities may differ in this particular context with their

open source variants (e.g., Free Software, BSD software, etc.). Methodologies that consider and compare between local and contextual takes on sustainability could help explore this aspect further.

### 9.2. Consequences to basic open source constructs

Another important consequence is that the coexistence of multiple sustainabilities also challenges the role and meaning of reciprocity in open source contexts, a key element in previous studies of commons sustainability (e.g., Osterloh and Rota (2007), Faraj and Johnson (2011), Von Hippel and von Krogh (2003), and Von Krogh et al. 2012). Reciprocity in Ostrom's CPRs arguably followed more simple norms centred around the shared monitoring of commonly understood resources within relatively small groups. However, the open source context might be more complex, with new contributors to a project needing to understand and establish common values with the community (Maruping et al., 2019). Since membership is fluid in open source, contributors need to be able to navigate value differences between multiple projects and communities. The way these values affect localised notions of sustainability in open source may be important for participants to effectively contribute. What kind of reciprocity should a contributor prioritising infrastructural vs. resource-based or interactional sustainability expect? What should be considered as fair? Do the expectations and values change as open source sustainability needs evolve in time? This is a complex issue in online communities because cultural norms have a large influence over engaged participation (Daniel et al., 2013), and basic sustainability constructs, like reciprocity, may take various forms. Tying these concerns together is the question of the mutual influence of different types and understandings of sustainability with basic coordination and organising constructs in open source.

### 9.3. Evolution of sustainability in open source and scenarios of evolution

In alignment with the sustainable development goals literature (e.g., Barbier & Burgess, 2019; Biggeri et al., 2019; Kroll et al., 2019), one of the core contributions of this paper is theorising on the possible relationships between the three different types of sustainability in open source and proposing the existence of three possible scenarios. Depending on the degree and quality of their interrelation different assumptions can be made regarding the evolution of open source sustainability. Taking Ostrom's approach, a digital common would go from a sustainable to an unsustainable state or vice versa. Drawing on the typology presented in this paper, a scenario where the three types of sustainability in open source are independent from one another suggests that changes in one type would not affect the other types. A trade-off scenario would involve types of sustainability in open source being incompatible with one another, meaning the increase in one type of sustainability would lead to the decay of another. A synergistic scenario would posit that a change in one of the sustainability types would affect the others in a similar direction (e.g., if resource-based sustainability grows, interactional and infrastructural sustainability would grow too).

Each of these scenarios on their own can further question the meaning of sustainability in open source. For example, empirical evidence of trade-offs in projects, especially if they are recurrent, could be indicative of an impossibility to maximise all kinds of sustainability. This would imply that sustainability in open source is much more of a strategic concern than the result of a process of resource accumulation within projects. If, on the other hand, types of sustainability are independent, would that indicate greater resilience on the part of an open source actor, or a greater organisational problem in which opportunity costs must be thought of? Presumably, it would be advantageous that all types of open source sustainability would share from positive amplifying effects in one sustainability as we theorised in the previous section. On the other hand, negative cycles could be triggered that would make synergistic scenarios less resilient to certain events compared to scenarios where the different types of sustainability are more independent.

Understanding when and why these different scenarios occur and how they may relate are important avenues for future research. For instance, the relationship between different types of sustainability may evolve as projects mature (Kroll et al., 2019). Indeed, in the context of open source, as O'Mahony and Ferraro (2007) suggest, governance structures emerge later in a project's lifecycle, meaning that issues of interactional sustainability may grow in importance in time and become connected with the other types of sustainability as the project matures. On the contrary, it could be argued that in a new-born project all types of open source sustainability are intertwined, and that, as it grows, they drift apart. In this sense, further work could look at what sorts of events or practices change the degree and quality of interrelationship between types of sustainability. Furthermore, a project or community may move from one scenario to another, perhaps caused by events or naturally as part of the lifecycle of the project.

### 9.4. Epistemological and methodological considerations

Finally, each of the previous areas for further research have epistemological and methodological consequences. As far as we are aware, research in open source sustainability has not made explicit its epistemological assumptions. Our interpretation is that those works that have imported Ostrom's conceptualisation have largely been based on a rationalist lens. For example, for Ostrom (1990), threats like free-riding can only happen if appropriate norms encouraging collective-behaviours do not exist or cannot be enforced. As such, individuals become collectives only through the evaluation and alignment between their own interests and that of others, disregarding emotions which have been posited to articulate collective behaviours such as passions or despair (Barberá-Tomás et al., 2019). Such emphasis on interests may preclude us from important insights that do not rely so heavily on rational behaviour of interest-seeking individuals.

How notions of sustainability in open source become developed within these contexts could benefit from constructivist stances. Indeed, future work could interrogate the sociomaterial participation of technology in the development of shared meaning on open source sustainability across different actors. For example, constructivist research could study the role of codes of conduct in relation to the stabilisation of interactive sustainability. Finally, a more critical take on sustainability could further challenge assumptions and research of who ultimately pays for the sustainability of open source. As Terranova (2000) and Barron (2013) have argued in the past, the ideas of open source may be subverted by certain organisations to capture free labour in exchange for the promise of positive market signals of worth (Hann et al., 2013), which research has shown is an incentive to commit (W Chen et al., 2018). The rewards of participation, however, may not be shared equally between actors, with some bearing the brunt of the effort and shouldering more risk than others.

### 9.5. Practical Implications

Our typology can be used by project maintainers to evaluate what type of sustainability is lacking and prioritise actions towards a specific type. For example, a few years ago, an important bug was introduced into OpenSSL, a popular security communications protocol. As a response to the costly bug, solutions emphasising different sustainabilities were proposed. Some argued that a better test suite would have caught the error (Wheeler, 2014), thus recommending infrastructural sustainability investments; others argued that there were limited maintainers and money (Kamp, 2014), thus recommending resource-based sustainability investments; others yet argued that maintainers valued performance more than security (De Raadt, 2014), suggesting interactional sustainability changes. Sustaining open source projects and communities implies taking strategic decisions that may prioritise certain sustainabilities over others.

In addition, the typology provides a way for organisations to guide their involvement into socio-technical systems' sustainability. Companies sponsoring open source projects can use their resources to better support sustainability needs and to evaluate their own impact. When Oracle bought Sun Microsystems, a major contributor to OpenOffice, the community's preoccupation with Oracle's values pushed many to create a rival open source project. Certain companies may negatively impact an open source project's interactional sustainability despite providing resources and infrastructures. Issues from interrelated open source sustainabilities may help us understand better the complexity of open source development and the relations with the increasing involvement of companies (Daniel et al., 2018).

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