How open innovation enhances productivity? An exploration in the construction ecosystem

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How open innovation enhances productivity? An exploration in the construction ecosystem

Abstract

The innovation literature on operations-based organisations describes the positive effect of open innovation (OI) on productivity. However, a systemic overview of how OI directly and indirectly impacts productivity is missing, particularly for project-based organisations. Hence, the article aims to fill this gap by providing a systemic representation of how OI enhances project-based organisations' productivity. The article focuses on the construction ecosystem since construction is an exemplary project-based industry and is known for its widespread and longstanding poor productivity. In particular, we investigated how OI is adopted and how OI can enhance productivity in the construction ecosystem. We conducted twenty semi-structured interviews with experts involved in OI construction projects in the UK. This paper makes three academic contributions. First, it provides an account of the most relevant causes for poor productivity in construction. Second, it consolidates primary and secondary data in a novel cognitive map providing a systemic representation of how OI enhances productivity in construction. The validity of the map goes beyond the boundaries of the construction ecosystem, being supported by several cross-sectorial references. Third, the paper offers six strategies that leverage OI to address the specific causes of low productivity in construction.

Keywords: open innovation, inter-organisational collaboration, construction, project-based firms, productivity, innovation ecosystem.

1 Introduction

Open Innovation (OI) is "*a distributed innovation process based on purposively managed knowledge flows across organisational boundaries*" (Chesbrough and Bogers, 2014, p. 17). OI describes purposeful interactions between different organisations, which share ideas, knowledge, and technologies to innovate, overcoming the limits of the firm's capabilities while nurturing them. While OI has been vastly studied in operations-based organisations, whose business model focuses on the delivery of the same output in volumes (such as manufacturing, automotive, pharmaceutical, biotech, and services), it has been under-investigated in project-based organisations, whose business model is based on planning and delivering unique outputs (such as infrastructure or consultancy). Hopkins et al. (2011) suggested that project-based organisations are inherently more open than other organisations, and their efficiency comes from economies of system, rather than from economies of scale (Nightingale, 2003). Hence, the paucity of studies on project-based industries and OI is surprising.

Several authors have observed that OI enhances productivity in operation industries (Aliasghar et al., 2019; Cincera et al., 2003; Lööf and Heshmati, 2002), whereas a gap in the literature remains on how the productivity of project-based industries could be improved through OI. Among the project-based industries, construction is prominent for the economy of many countries and is known to suffer from scarce productivity (Abdel-Wahab and Vogl, 2011; Fulford, 2018; Kapelko et al., 2015; Zhan et al., 2018), both in terms of labour productivity (Ghodrati et al., 2018; Teicholz et al., 2001; Thomas et al., 2003) and total factor productivity (Schriver and Bowlby, 1985; Zhan et al., 2018). Projects in the construction ecosystem bring together several organisations, professionals and stakeholders (Zhang et al., 2018), who are critical to identify and implement innovative solutions (Davies et al., 2014; Dodgson et al., 2015; Ozorhon et al., 2010), eventually giving birth to whole OI ecosystems such as the smart building one (Bogers et al., 2017). However, the characteristics of construction ecosystem can pose several obstacles to OI, including (1) the temporary nature of the relationships in the construction projects, which obstacles knowledge exchange and trust building (Lau and Rowlinsn, 2009; Wang et al., 2020); (2) the fragmentation of the construction projects (Miozzo and Dewick, 2004), which also impedes the development of stable partnerships; and (3) the small margins, which prevent significant investments in R&D (Love et al., 2017) that would facilitate the absorption of external knowledge (Cohen and Levinthal, 1989).

Examples of collaboration between different organisations to develop and implement innovations in construction exist (e.g. Brady and Davies, 2014; Davies et al., 2014; Dodgson et al., 2015; Krystallis et al., 2020) and could be considered as forms of OI. However, the role of OI in construction is exceptionally under-researched, with a paucity of articles discussing specific case studies (Dodgson et al., 2015; Ozorhon et al., 2010) or exploring niche topics (Rostoka et al., 2019).

Therefore, it is still unclear how OI can enhance productivity in project-based firms in general and construction firms in particular. Thus, this paper aims to provide a systemic representation of how OI enhances productivity, using the construction ecosystem (Zhang et al., 2018) as the research setting. Specifically, we seek a response to two research questions, RQ 1 "*How is OI adopted in the construction sector?*" and RQ 2 "*How can OI enhance productivity in the construction sector?*". We addressed these research questions by performing semi-structured interviews with 20 experts involved in OI projects in the UK construction ecosystem. The analysis of the transcripts allowed verifying the extent to which the inter-organisational dynamics in such OI projects were different from expectations drawn from the OI literature.

2 Literature review

Our paper sits on the intersection of two epistemological communities: project studies (where construction projects are a particular case) and innovation management (where OI is a particular case). We ground our literature on both disciplines, contributing to the area where they overlap. We follow Davies et al.'s (2018) recent call for cross-fertilisation between the project and innovation management, which they call 'neighbouring' disciplines, to study how projects can be managed effectively by using the insights from innovation management studies.

2.1 Project-based firms and construction

A project is "*a temporary organisation to which resources are assigned to do work to deliver beneficial change*" (Turner, 2009, p. 2). We are assisting to a '*projectification'* of society, with an increasing share of gross national product and time spent financing and enacting projects in all kinds of industries (Gemünden, 2013). Entire industrial sectors, such as construction - building and retrofitting - and Information and Communication Technologies (ICT such as the coding of new software or video-games) consist of "project-based organisations" (Sydow et al., 2004). According to Wikström et al. (2010), project-based firms engage in traditional project activities (selecting, planning and delivering projects). Still, they can broaden their business beyond conventional project boundaries by including maintenance and post-commissioning services, management of contracts, ownerships (totally or partially) and operations. The "project business" (Artto and Wikström, 2005) requires the interaction with several stakeholders that keep changing across the project lifecycle, such as suppliers, regulators, customers. Therefore, a project business needs well-designed processes to deal with the intrinsic uncertainties and risks of projects along with the careful cooperation and coordination, involving several technologies and stakeholders in the planning and delivery of systems that can be extremely complex (Liinamaa and Wikstrom, 2009).

The construction ecosystem is a typical example of project business. Accounting for 13% of the world Gross Domestic Products (GDP) (McKinsey&Company, 2017), it is a complex system composed of manufacture (e.g. supplies, materials, components, and equipment) and services (e.g. engineering, design, surveying, consulting). It includes both simple construction projects (e.g., a family home) and complex infrastructure such as railways, nuclear power plants, and long bridges. Project complexity is a crucial driver for project management and performance. Locatelli et al. (2014) studied the topic of complexity in infrastructure, showing that projects late and overbudget are delivered in context with one or more of the following features: rapidly evolving technologies with short life cycle and risk of obsolesce (Hanratty et al., 1999); interdependent and interoperable systems (Jaafari, 2003); focus on budget and schedule reduction, maintaining the same scope (Laufer et al., 1996); physical and organisational integration issues (Calvano and John, 2004); multidisciplinary, in terms of both hard and social science (Ryan and Faulconbridge, 2005); and competition from technologies delivering the same service (e.g. electricity produced by other power plants) (Kossiakoff et al., 2011).

A relevant problem in construction, particularly in the case of complex infrastructure, is productivity, or better, the lack of improvement in its productivity over the time, as recognised by both practitioners and academics (Abdel-Wahab and Vogl, 2011; Cox and Ireland, 2002; Fulford, 2018; Fulford and Standing, 2014; Kapelko et al., 2015; McKinsey&Company, 2017; The Economist, 2017a; Vrijhoef and Koskela, 2000; Zhan et al., 2018) since decades (Allen, 1985; Stokes, 1981).

2.2 Poor productivity in construction: Causes and remedies

A plethora of studies regarding many countries acknowledge that the improvement in productivity in construction falls behind other industrial sectors (e.g. Abdel-Wahab and Vogl, 2011; Cox and Ireland, 2002; Vrijhoef and Koskela, 2000). Other studies even reported a decline in productivity (e.g. Kapelko et al., 2015; Teicholz et al., 2001; Zhan et al., 2018). One of the most recent and comprehensive analyses reported that '*Globally, labour-productivity growth in construction has averaged only 1% a year over the past two decades, compared with growth of 2.8% for the total world economy and 3.6% in the case of manufacturing*' (McKinsey&Company, 2017). Thus, increasing productivity in construction is needed all over the world and has been acknowledged for decades. The following two subsections review the literature concerning causes and remedies.

2.2.1 Causes of the productivity issue in the construction sector

The literature provides an abundance of studies investigating the reasons for the disappointing productivity growth in construction, as summarised in Table 1. Notably, at the project level, design changes, errors, and omissions are critical determinants of low productivity levels (Love et al., 2014). These elements are so institutionalised that rework is expected and considered the norm (Love et al., 2011b).

Cause of the productivity issue	Description	Academic references	Non-academic references
Inadequate management of human resources	The labour quality relates to the skills and the experience of site workers, supervisors and managers. The presence of unskilled/not adequately trained workers, supervisors and managers is one of the most critical problems. Particularly problematic is the low investment in staff training, a relatively old problem that is vastly unaddressed even nowadays. Low salaries lead to difficulties in having a stable and motivated working force, leading to a high turnover of workers even from abroad, unfamiliar with the context of the project	(Abdel-Wahab and Vogl, 2011; Allen, 1985; Rahman et al., 2019; Teicholz et al., 2001; Zhi et al., 2003)	(Blanco et al., 2016; Bryer et al., 2016; CIDB, 1992; Hays, 2018; McNally, 2018)
Few ICT investments and ICT integration	Historically, ICT investments are often neglected. The increasing adoption of BIM (Building Information Modelling) should contribute to tackling this issue	(Abdel-Wahab and Vogl, 2011; Fulford and Standing, 2014)	(McNally, 2018; Woetzel et al., 2017)
Few investments in equipment and technology	Firms have relatively small margins of cyclical nature (booms and then depressions have been observed for years). Several contractors are small-medium firms often family-owned relying on the experience and know-how of the owner. Large investment in innovation often seems an unnecessary risk and thus often avoided in favours of tested practices providing predictable outcomes	(Abdel-Wahab and Vogl, 2011; Allen, 1985; Stokes, 1981; Zhi et al., 2003)	(Blanco et al., 2016; Egan, 1998; McNally, 2018; The Economist, 2017b; Woetzel et al., 2017)
Poor collaboration and adversarial relationships	The construction ecosystem is often characterised by adversarial relationships and conflicts rather than factual collaboration, even between firms working in the same project. Particularly concerning is the practice of outbidding competitors with unreasonable low bids leading to thin margins, litigations, even unethical practices like "modern slavery" that ultimately lead to quality loss	(Fulford and Standing, 2014)	(Blanco et al., 2016; CIOB, 2018; Egan, 1998; Latham, 1994)
Limited learning from other projects	The lack of ability to transfer lessons learnt, knowledge and best practices from project-to-project results in the repetition of the same mistakes	(Locatelli and Mancini, 2012)	(Blanco et al., 2016)
Fragmentation	The construction ecosystem comprises a few large firms and several small or micro firms struggling to innovate	(Fulford and Standing, 2014; Miozzo and Dewick, 2004)	(Blanco et al., 2016; Egan, 1998; Latham, 1994; McNally, 2018; The Economist, 2017a; Woetzel et al., 2017)
Project complexity	In the past decades, project complexity escalated, particularly in the case of mega projects	(Locatelli et al., 2014; Teicholz et al., 2001)	(Blanco et al., 2016; CIDB, 1992)
Overpromising and client dissatisfaction	Firms often fail to deliver the promised benefits and meet clients' needs, not always providing the "best value". Scope change and often reworks are a consequence, therefore reducing productivity	(Love et al., 2011a)	(Egan, 1998; Latham, 1994)
Regulations	Specific local regulations (including Health and Safety) evolve and can be a barrier to standardise operations or implement technologies or solutions from other sectors	(Abdel-Wahab and Vogl, 2011; Huang et al., 2009)	(Blanco et al., 2016; Bryer et al., 2016; The Economist, 2017b; Woetzel et al., 2017)

Table 1 The main reasons for poor productivity in construction.

2.2.2 *Remedies for the productivity issue discussed in the literature*

The literature suggests remedies to tackle the productivity issue. McKinsey & Company (2017) proposed seven strategies: to reshape regulation and raise transparency; to rewire the contractual framework; to rethink design and engineering processes; to improve procurement and supply-chain management; to improve on-site execution; to infuse digital technology, new materials, and advanced automation; and to reskill the workforce. For a long time, modularisation and prefabrication have been advocated as approaches to reduce cost and time (Mignacca et al., 2018). The implementation of such approaches has been proved worthwhile, enhancing the productivity in the case of simple projects (e.g. housing construction), while the performance improvement in the case of complex projects, such as nuclear reactors, has been more controversial (Budnitz et al., 2018).

Lean construction has also been advocated to reduce waste and reworks in construction improving the productivity and the value delivered to the customer (Andersen et al., 2012; Locatelli et al., 2013; Salem et al., 2015; Thomas et al., 2003). Defects and reworks conservatively account for about 5% of a project's total cost (Hwang et al. 2009; Love 2002). However, in the construction industry, let alone a few specific examples, the 'lean philosophy' has never gained popularity as in the automotive and manufacturing industries. Taggart et al. (2014) advanced that, when a collaborative and proactive environment is provided to the supply chain partners, it is more likely to identify the root causes of defects and propose cost-effective solutions.

Several other studies addressed solutions to the productivity issue. Ballesteros-Pérez *et al.* (2017) analysed the impact of adverse weather conditions and provided a tool to optimise the construction schedule according to the weather. Ghodrati et al. (2018) showed how management strategies such as communication and incentive programs have a strong positive relationship with labour productivity. Loosemore (2014) focused on subcontractors, showing the following determinants to improve the performance of construction: the quality of relationships with principal contractors; the opportunity for early involvement in design; transparent tender practices; growing administration and document control; design management; and improved project management skills. Rojas and Aramvareekul (2003) identified five opportunities to improve productivity in construction: improving methods and training programs, enhancing workers' motivations and strengthening strategic and procurement management.

In summary, the studies dealing with the productivity issue in construction often suggested the positive role of innovation (Bröchner and Olofsson, 2012; Dubois and Gadde, 2002).

2.3 Improving productivity through innovation and open innovation

2.3.1 Innovation in construction

We may consider innovation in the construction ecosystem according to two key categories. On the one hand, product innovation represents an enhancement of the construction outputs (e.g. a wind farm more efficient than before, but built with traditional construction methods). On the other hand, process innovation refers to the development of innovations enhancing the construction process, e.g. new construction approaches, such as lean construction; new construction tools, such us new cranes; new design methods, such as constructability studies; or new skills, as a result of better training for workers. Process innovation includes technological process innovation, triggered by technology, as in the case of new cranes; and pure organisational process innovation, which is not associated with technology, as the case of lean construction (Edquist et al., 2001).

Process innovations are the most likely sources of productivity improvement. However, the construction industry has long been considered resistant to it (Blayse and

Manley, 2004). Aware of this issue, early studies recommended greater collaboration among industry players to innovate their processes and achieve higher productivity (Bresnen and Marshall, 2000; Egan, 1998; Latham, 1994). Even though these calls often remained unheard in the construction industry, a few case studies of construction megaprojects corroborated them, such as London's Crossrail (Davies et al., 2014; Dodgson et al., 2015) or London Heathrow Terminal 5 (Caldwell et al., 2009; Davies et al., 2016).

2.3.2 Open Innovation and productivity

The OI paradigm, introduced in the early years of the twenty-first century (Chesbrough et al., 2006), describes how firms are opening their innovation process to other organisations, allowing ideas, knowledge and technologies to flow through their organisational boundaries. The literature has shown that OI can have both a direct and indirect positive effect on productivity.

Regarding the direct positive effect, Arvanitis (2012) observed that engaging in at least one R&D collaboration positively affects the value-added per employee. Other studies found that horizontal collaboration (i.e. with competitors) enhances labour productivity (Belderbos et al., 2006, 2004), while vertical collaboration (i.e. with the firm's customers and suppliers) fosters total factor productivity growth (Cincera et al., 2003). Collaboration with universities can enhance innovative sales productivity (Belderbos et al., 2004), while Aliasghar et al. (2019) observed that collaboration over the value chain enhances process innovations aimed to improve productivity. Some authors discussed a curvilinear relationship between OI and productivity. Bönte (2003) observed that the share of external R&D out of the total R&D shows an inverted U-shaped relationship with total factor productivity. This encourages using external R&D to enhance productivity but also warns against relying excessively on it, since scarce internal

R&D expenditures can harm the firm's absorptive capability, diminishing the positive effect of the know-how drawn from other organisations. Lokshin et al. (2008) found that the share of external R&D is curvilinearly related to labour productivity since the diseconomies of scale gradually decrease the positive marginal effect. Similarly, Hwang & Lee (2010) and de Leeuw et al. (2014) observed an inverted U-shape relationship between labour productivity and the variety of the collaboration portfolio (i.e., the extent to which different categories of partners, such as universities, competitors, and suppliers, are involved in innovation activities). These curvilinear relationships may be associated to the over-search problem (Laursen and Salter, 2006a), taking place when too many innovation inputs come from different sources, and the firm is unable to absorb them effectively (absorptive capacity problem). The firm may not be able to identify those that are more likely to be impactful (timing problem) and may find it difficult to pay adequate attention to the partners' ideas (attention allocation problem) (Dahlander et al., 2016).

Regarding the indirect effect, several factors positively (e.g., absorptive capability, innovation performance) or negatively (e.g., transaction costs, opportunistic behaviour) moderate the link between OI and productivity.

Concerning the positive moderators, the 'absorptive capacity', i.e. the '*ability of a firm to recognise the value of new, external information, assimilate it, and apply it to commercial ends*' (Cohen and Levinthal, 1990, p. 128) can improve the positive effect of OI on productivity (Berchicci, 2013; Lokshin et al., 2008). Firms may nurture their absorptive capacity through their R&D activities, which in turn can enhance innovation performance (e.g. Griffith, Redding and Reenen, 2004) and total factor productivity (Czarnitzki and Thorwarth, 2012; Griffith et al., 2004, 2003; Hall et al., 2010; Hall and Mairesse, 1995). OI is likely to enhance both product and process innovation performance (e.g. Belderbos et al., 2004; de Leeuw et al., 2014; Huang & Rice 2012; Parida et al., 2012; Reichstein & Salter, 2006; Rosenzweig et al., 2003), although a few studies also found negative relationships. Among them, Terjesen & Patel (2017) observed that resorting to many different sources of knowledge may hamper process innovation, due to the over-search problem. The same problem has brought many authors to hypothesize and find that the relationship between the variety of the external sources and innovation performance is likely to take an inverted U-shape (Bayona-Saez et al., 2017; Greco et al., 2016; Laursen and Salter, 2006a). Intuitively, an increase in innovation performance, *ceteris paribus*, is also likely to improve productivity. This was also discussed by Fernández Gual and Segarra-Blasco (2013) who found that both product and process innovation induce growth in labour productivity, and by Mention & Asikainen (2012) who found that innovation output positively influences labour productivity.

Some negative moderators, i.e., factors that can reduce the positive effect of OI on productivity, need to be acknowledged. Even though OI allows to share R&D risks and costs with partners (Arvanitis, 2012; Miotti and Sachwald, 2003), it also increases the chances of opportunistic behaviours (Dahlander and Gann, 2010; Zhao et al., 2016), especially when the collaboration is between competitors (Park and Russo, 1996) or when many different partners are involved (de Leeuw et al., 2014). A partner could subtract technologies, knowledge or information that another firm does not want to disclose. Firms might implement tight control and monitoring mechanisms to prevent this behaviour (Harmancioglu, 2009). Furthermore, collaboration built on trust can reduce opportunistic behaviours (Bunduchi, 2013; Kale and Singh, 2009; Ojala and Hallikas, 2006; Slowinski et al., 2006). In a collaboration, knowledge leakage can be either caused by opportunistic behaviour (Harmancioglu, 2009) or unintentional behaviour (Coras and Tantau, 2014). This risk can inhibit the innovation process and hinder the value of the collaboration (Coras and Tantau, 2014). To minimise the occurrence of leakages, firms may become too closed and overprotective, stuck in a mindset of control and secrecy, reluctant to share their knowledge with other players in the innovation system and, thus, unable to engage in knowledge trading activities (Laursen and Salter, 2006b). Given the risks of knowledge leakage, the inherent monitoring costs, and the need to face costs to coordinate the partners, OI might generate relevant transaction costs (Christensen et al., 2005; Faems et al., 2010; Greco et al., 2019), having an indirect negative impact on innovation (Coras and Tantau, 2014; Mueller et al., 2013).

In summary, scholars and practitioners agree that OI practices enhance productivity by creating and maintaining collaborative relationships between different organisations, nurturing knowledge spreading, fostering continuous learning and enhancing innovation development. To the best of our knowledge, no previous study has attempted to offer a systemic view of how OI enhances productivity. The remainder of this paper will investigate this gap by showing and discussing the direct and indirect impact of OI on productivity in a quintessential project-based business: the construction ecosystem.

3 Method

3.1 Research setting

Our research is set in the UK construction ecosystem. Similarly to other countries, such an ecosystem is historically led by a few large firms (that often takes the role of main contractors in the construction of complex infrastructure) surrounded by a plethora of small and very small firms acting as sub-contractors; over 99.9% of firms are small and medium-sized enterprises (Department for Business Energy and Industrial Strategy, 2020). The construction industry turnover in the UK, at £110bn, is bigger than aerospace and automotive combined but has been trapped in a cycle of low innovation and low productivity (Stacey, 2018). The UK government acknowledged these points with a key document called “Construction Sector Deal” (HM Government, 2018). Foreseeing that an infrastructure pipeline worth more than £600bn of spending over the next decade, it calls for an industry that is more productive, more highly-skilled, and ready to grasp the global infrastructure market's opportunities. The deal includes £725m in the new Industrial Strategy Challenge Fund programmes to capture the value of innovation.

The construction ecosystem in the UK includes very different stakeholders. According to Rutten et al. (2009), the fragmentation of the value chain in construction implies that organisations need to collaborate to innovate and underline the importance of systems integrators to orchestrate such collaborations. The systems integrators in construction usually act as prime contractors (Rutten et al., 2009). Such firms, often large-sized (employing more than 1000 people), lead most innovation activities. An array of smaller consultancy firms might support them, having specific know-how on particular technical aspects (e.g., special welding) or organisational aspects (e.g., value management). Smaller firms directly involved in construction usually do not have the personnel and resources to invest in innovation processes and seldom are involved in OI research. The government promotes innovation by subsidising research projects, like those analysed in this paper, bringing together firms and universities. While universities seek these collaborations to retrieve economic resources, scholars look forward to expanding their network, increasing their knowledge on specific topics accessing unique resources (Locatelli et al., 2020). Lastly, industrial organisations promote innovation in general and OI in particular, by offering grants to academics to work with the industry.

3.2 Research design

The research design to answer the two research questions that motivated this study is presented in Figure 1.

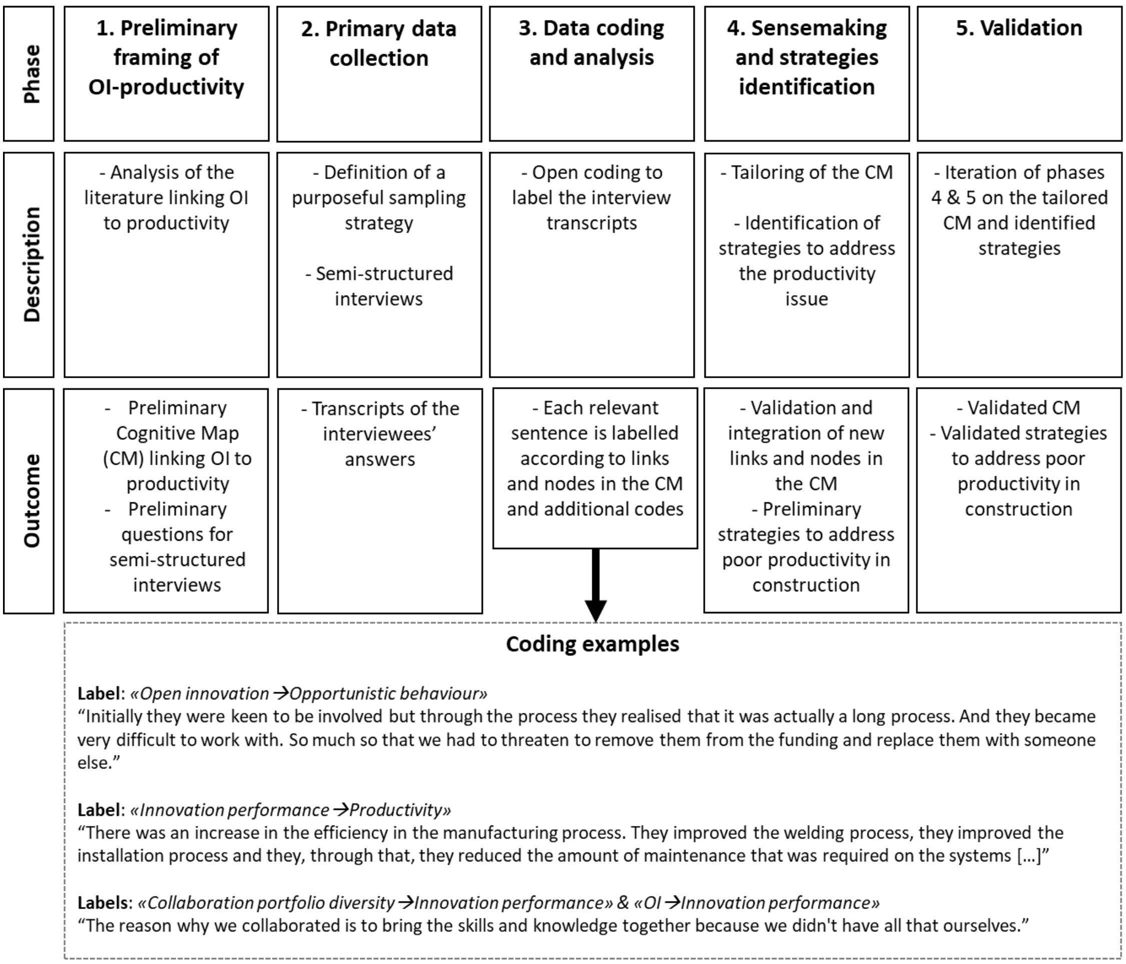

Figure 1. The research design of the study

3.2.1 *Phase 1 – Preliminary framing of open innovation and productivity*

In Phase 1, we leveraged a literature review[1] on OI and productivity to identify the direct and indirect effect of OI on productivity. We used a cognitive map (CM) (Axelrod, 1976) to organise the literature and systemically describe the relationships between OI and productivity. The CM is proved to be effective to describe cause-effect relationships between concepts (e.g. see Carayannis et al., 2018; Chang Lee et al., 2015; Mital et al., 2018).

Three principles guided the iterative process in drawing the CM:

- Clarity: the CM should be characterised by a parsimonious number of key factors and connections, possibly displayed intuitively.
- OI centrality: several factors can affect productivity, but the CM focuses on those stemming from OI, or capable to leverage/hinder its effect on productivity.
- Synthesis: several constructs have multifaceted nature (e.g., absorptive capacity); nonetheless, they should be displayed as single factors to avoid redundancies affecting clarity without adding much value to the CM.

After preparing a draft CM, we interviewed experts to improve and validate the map.

3.2.2 *Phase 2 – Primary data collection*

Leveraging a purposeful sampling strategy (Palinkas et al., 2015), we used the 'Innovate UK' publicly-available database[2] to identify experts in the construction ecosystem who had previous experience in projects aimed to develop innovations, which we deem as OI projects collaboratively. Innovate UK is a public-funded innovation agency that manages funding programs (Knowledge Transfer Partnerships (KTP), the

[1] The query TITLE-ABS-KEY ('productivity' AND 'open innovation') was submitted to the database Scopus. We also included relevant papers from backward and forward references. We identified 45 references.

[2] https://www.gov.uk/government/publications/innovate-uk-funded-projects

Small Business Research Initiative, Grant for Research and Development, Catapult centres, Collaborative R&D, Feasibility studies) with the mission of supporting business, de-risking, enabling and helping the development of innovation and the achievement of economic growth (Innovate UK, 2018). The list of projects supported by Innovate UK includes the name of the organisations and reference persons involved. Each project has a leading organisation (often a medium-sized firm) and a variable number of partners that might include other organisations (e.g., Universities, firms, and other stakeholders).

The sample selection protocol comprises five sampling criteria and is schematically described in Figure 2 and discussed hereafter. Two sources were used: the previously mentioned database of the Innovate UK projects (left-side branch of Figure 2), and the KTP projects database (right-side branch of Figure 2). The left-side branch includes the population of Innovate UK projects (17,314), among which we selected (sampling criterion 1) those related to the construction ecosystem, economically relevant (grant amount higher than £50.000), and reasonably recent to increase the chances that the interviewees properly recall the project. Since the overall Innovate UK database does not index the KTP projects properly, a parallel analysis was also conducted on the KTP database[3] (comprising 7,722 projects), as shown in the right-side branch. The sampling criteria 2 and 3 aimed to identify the completed sample of 85 KTP projects in the construction ecosystem, which were economically relevant and reasonably recent. The consolidation of these two samples comprised 1,753 projects whose description was analysed by the researchers to identify projects in the construction ecosystem and remove the others, such as bio-pharmaceutical, service, and network infrastructure projects (sampling criterion 4). Finally, the sampling criterion 5 aimed to exclude uncompleted

[3] https://info.ktponline.org.uk/action/search/complete.aspx

projects and the projects comprising only one partner (which could not be considered OI). The remaining 48 projects are the final sample targeted in this study.

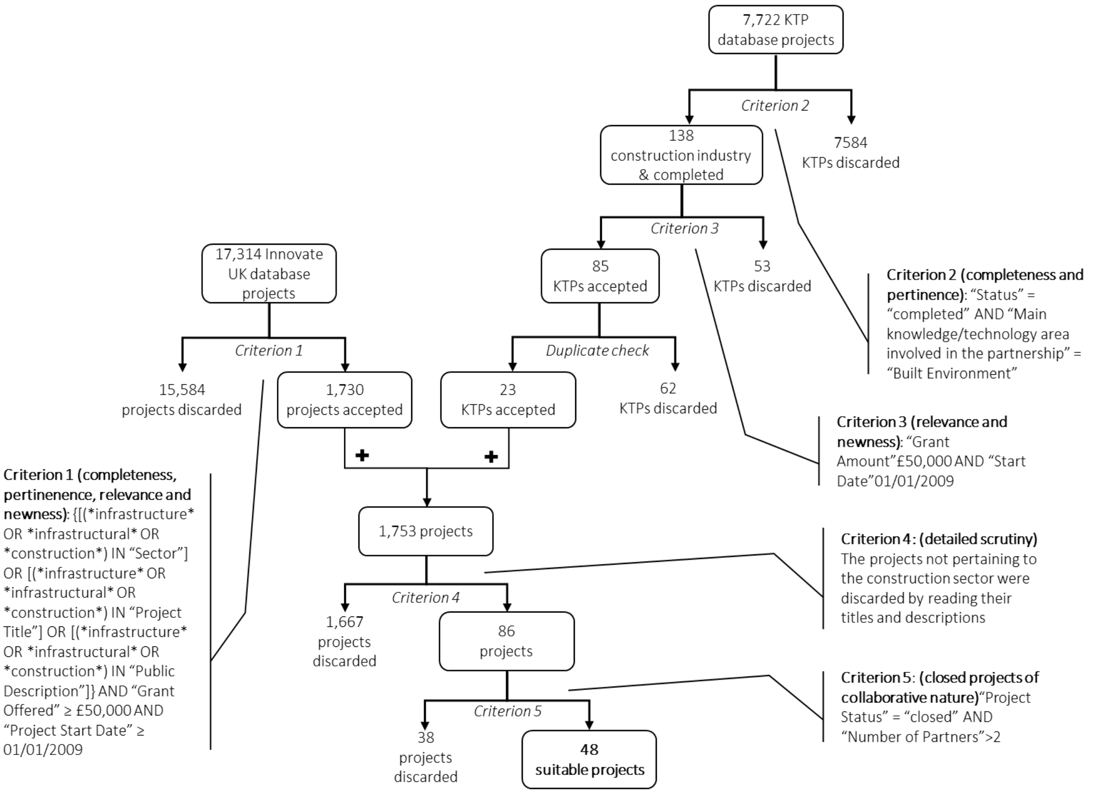

Figure 2. Sample selection protocol.

These 48 projects were funded by three Innovate UK programs: Collaborative R&D (27 projects), KTP (12 projects), and Feasibility Studies (9 projects). A detailed description of the targeted population of projects and the final sample is made available in Appendix C, a spreadsheet shared on figshare (Author et al. 2019), sheet "Sample". The key contact persons of the 48 projects were identified, and at least two contact attempts were made to arrange the interviews. This resulted in 20 interviews regarding projects that are examples of coupled OI since they involve two or more partners and specifically aim to innovate through collaboration. Seven out of 20 were KTP projects involving two partners, nine were Collaborative R&D projects, and four were Feasibility

Studies. On average, they obtained £155,242 in public grants (min £51,572, max £676,537). The interviewees had heterogeneous professional backgrounds (30% scholars, 70% practitioners) and worked in several sectors in the construction ecosystem (detailed information is reported in the online Appendix C, sheet “Interviewees’ profiles”). Two groups of interviews took place. The first group of 15 interviews aimed to tailor the CM. After those 15 interviews, we incorporated the feedback in the CM and performed a second group of 5 interviews to check that theoretical saturation had been achieved and no significant change to the map was necessary (see Phase 5).

The interviews were carried by phone or VoIP calls, with an average duration of 37 minutes. We defined a semi-structured questionnaire aimed to:

- understand the critical features of the project discussed in the interview and (possibly) of other OI projects where the expert had been involved;
- test the appropriateness of the nodes and links identified in the CM;
- elicit the perspectives of the experts about OI and productivity in construction;
- search for additional and unexpected factors affecting the relationship between OI and productivity in construction.

The unit of analysis of the interviews comprised the inter-organisational collaborations aimed to innovate in the construction ecosystem, starting from those associated with the Innovate UK project that allowed identifying the experts and spanning to other relevant previous or subsequent inter-organisational collaborations in which the experts had been involved.

The semi-structured questionnaire consisted of 27 questions divided into four groups:

(1) General information about the project, the organisations involved, and the collaboration dynamics;

(2) Advantages and disadvantages of the collaboration dynamics in the project;

(3) The role played by internal R&D and absorptive capacity;

(4) Closing questions not pertaining only to the specific project, but related to the experts' overall experience regarding collaboration benefits, costs, and possible impact on productivity in construction.

The questions, which are reported in Appendix A with their logical structure (Figure A1), aimed to verify whether the nodes and links identified in the CM suited the construction ecosystem and whether additional nodes and links could have been included (or existing nodes excluded). Assuming that many of the interviewed experts could not have been confident with the academic OI glossary and theory, the semi-structured questions mentioned inter-organisational collaboration rather than making explicit reference to OI. Such an approach is consistent with the OI literature, where the inter-organisational innovation-oriented collaboration is often used as a proxy for OI (e.g., Ahn et al., 2018; Kobarg et al., 2019; Llanes, 2019).

3.2.3 Phase 3 – Data coding and analysis

In transcribing the interviews, coding names guaranteed anonymisation: O-### for organisations, P-### for people and A-### for products and brands. In analysing the transcript, each answer was connected to its relative questionnaire item and the related CM elements. The data collected from interviews were coded through RQDA, an R package for qualitative data analysis.

We deductively defined an initial set of codes stemming from a conceptual framework (Azungah, 2018; Gilgun, 2013) - in our case grounded in the OI literature - and identify the core concepts to be confirmed/disconfirmed in the construction ecosystem. The sentences were labelled according to the links defined in the CM (e.g., «Innovation performance->Productivity», as exemplified in Figure 1). Then, we maintained flexibility in the coding process to include additional codes and keep track of other emerging themes (e.g., «cost-benefit ratio of collaboration», «regulation», «trust»). The codes are reported in Appendix B. To ensure consistency, a single co-author performed the coding of all the transcripts under the others' supervision. When iterative adaptations of the coding were implemented (mostly in the first five interviews), earlier transcripts were re-coded to consider the changes.

3.2.4 Phase 4 – Sensemaking and strategies identification

We analysed the transcripts of the interviews to confirm/disconfirm each node and link of the CM. We included emerging themes as new links and nodes in the CM after an additional purposeful search in the OI literature, to complement the experts' perceptions and enable general sensemaking of innovation in the construction ecosystem. Subsequently, the coded transcripts and the collected body of literature on OI and productivity were analysed given the known causes of the productivity issue in construction (Table 1) to identify suitable response strategies leveraging OI.

3.2.5 Phase 5 – Validation

In the last phase of the research, all the experts that had not offered their availability for the first round of interviews were contacted again. Therefore, the second group of five interviews was conducted to confirm the achievement of theoretical saturation (Eisenhardt, 1989). Having a final version of the CM and of the response strategies to the productivity issue, we purposely analysed the additional transcripts to integrate and extend the findings. As a result, more relevant quotations were identified, but no further amendments to the CM or the list of response strategies were deemed necessary. This also allowed us to control for the possible non-response bias that could have caused differences between the respondents and the non-respondents in Phase 2. The CM was, therefore, validated.

4 Results

This section presents insights into the relationships between OI and productivity in the construction ecosystem derived from our interviews. Subsection 4.1 describes the characteristics of the CM and presents it. Resorting to the transcripts from our interviews, subsection 4.2 shows how OI can directly impact productivity, whereas subsection 4.3 discusses the other factors related to OI that influence productivity. We quoted the transcripts and cited them between square brackets, specifying the anonymized code corresponding to the interviewee: [KTP Int. #], [Collab. R&D Int. #], [Feas. Study Int. #], for interviewees involved in KTP (#=1…7), Collaborative R&D (#=1…9), and Feasibility Study projects (#=1…4), respectively.

4.1 Linking open innovation to productivity: a systemic perspective

The CM (Figure 3) provides a systemic view of how OI (depicted as a circle) directly and indirectly enhances productivity (depicted as a square). The dashed sub-nodes inside the circle and the square describe four forms of OI and three productivity forms. The rectangular nodes describe the phenomena related to OI that affect productivity. Innovation performance, the typical OI output (Lopes and de Carvalho, 2018), is depicted as a trapezoid. For the sake of better readability of the CM, the trapezoid comprises both product and process innovation performance, also considering that product and process innovations are considered interdependent (Reichstein and Salter, 2006). The links reflect the articles drawn from Phase 1, while the Greek letters refer to new links added during Phase 4, and for which additional support in the literature was searched. Table 2 briefly describes the factors displayed in the CM. Figure 3 shows that OI has a direct and indirect effect on productivity. The direct effect, which is elaborated in subsection 4.2, includes the findings of previous studies that discussed how different forms of OI impacted different measures of productivity. The indirect effect, which is elaborated in subsection 4.3, includes the OI-related phenomena that can positively or negatively affect productivity as a consequence of embracing the OI paradigm.

Factor	Description
Absorptive capacity	A measure describing the ability to draw knowledge from other organisations; it is often defined based on the employees' knowledge and competences
Collaboration portfolio variety	An OI measure describing the number of partner categories (such as suppliers, universities, and customers) the firm collaborates with
Horizontal collaboration	An OI measure describing the collaboration with competitors
Innovation performance	A measure of innovation output (such as sales from innovative products, the introduction of at least one novel product or process in a certain period, and the number of new products or processes)
Innovation productivity	A productivity measure describing an innovation-related outcome (such as sales from novel products) on an innovation-related input, such as the number of employees or multiple inputs
Internal R&D	A measure describing the existence and/or size of an internal R&D function (such as the number of R&D employees and the investments in internal R&D activities)
Knowledge leakage	A measure describing the undesired spill over of knowledge from the firm to its partner
Opportunistic behaviour	A measure describing the presence of opportunistic behaviours, such as free-riding, and of collaboration issues
Labour productivity	A productivity measure defined as output (e.g., sales or value-added) per unit of labour (e.g., productive hours or number of employees)
Public support	A measure describing the receipt of public subsidies or public support to innovation
R&D collaboration	An OI measure describing the collaboration with universities and R&D institutions
R&D risks and costs	A measure describing the perceived technological risks and costs
Transaction costs	A measure describing the transaction costs of innovation co-development, such as those deriving from the negotiation
Total Factor Productivity	A productivity measure involving all the factors of production (e.g., total output, capital input and labour input)
Vertical collaboration	An OI measure describing the collaboration with customers and suppliers

Table 2. Description of the factors displayed in the CM

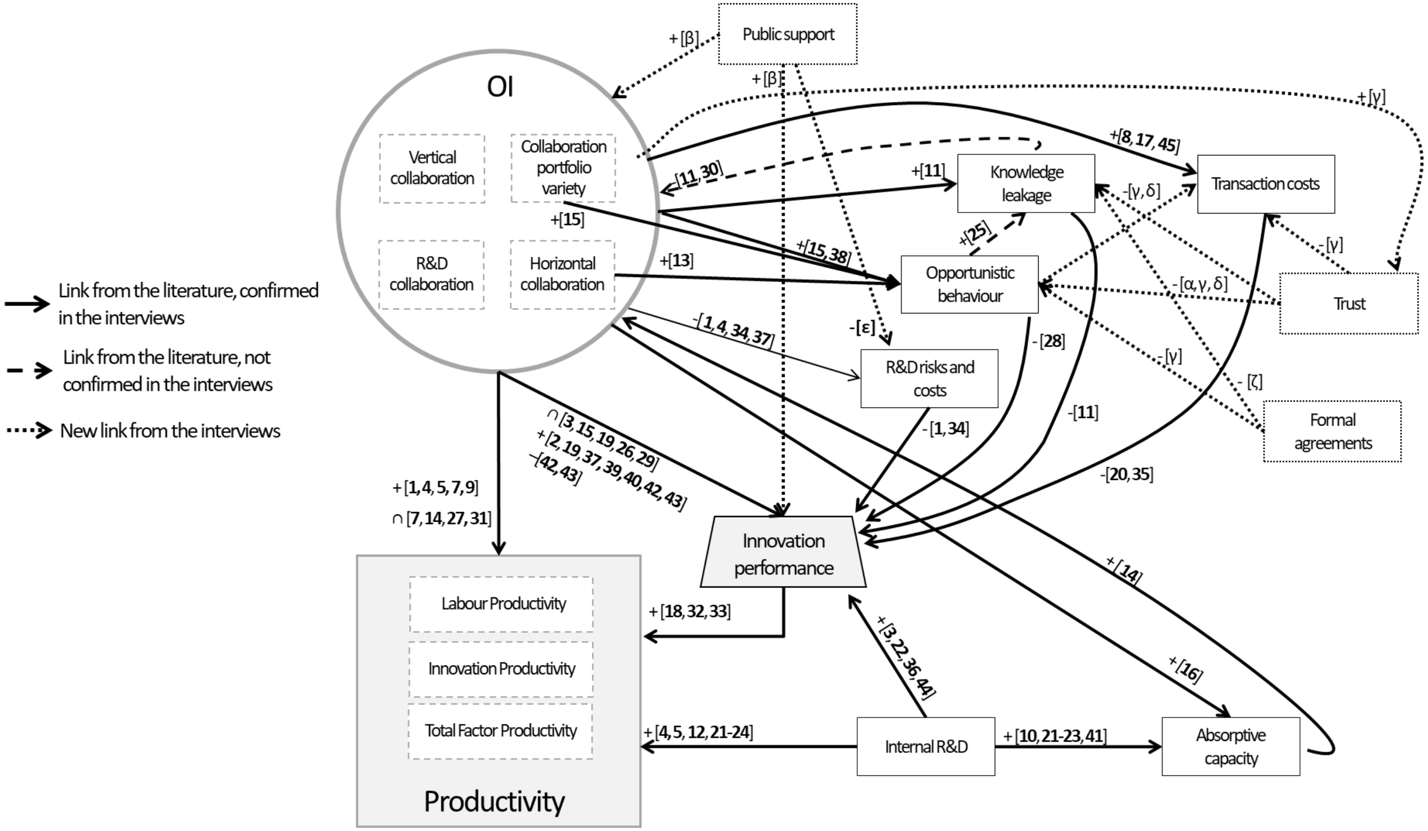

Figure 3. Construction-tailored cognitive map. Notes: ∩, inverted U-shaped relationship or diminishing returns; References[4]

[4] References from Phase 1: List of references: 1. (Arvanitis, 2012); 2. (Aliasghar et al., 2019); 3. (Bayona-Saez et al., 2017); 4. (Belderbos et al., 2004); 5. (Belderbos et al., 2006); 6. (Berchicci, 2013); 7. (Bönte, 2003); 8. (Christensen et al., 2005); 9. (Cincera et al., 2003); 10. (Cohen and Levinthal, 1990); 11. (Coras and Tantau, 2014); 12. (Czarnitzki and Thorwarth, 2012); 13. (Dahlander and Gann, 2010); 14. (de Faria et al., 2010); 15. (de Leeuw et al., 2014); 16. (Fabrizio, 2009); 17. (Faems et al., 2010); 18. (Fernández Gual and Segarra-Blasco, 2013) 19. (Greco et al., 2016); 20. (Greco et al., 2019); 21. (Griffith et al., 2003); 22. (Griffith et al., 2004); 23. (Hall and Mairesse, 1995); 24. (Hall et al., 2010); 25. (Harmancioglu, 2009); 26. (Huang and Rice, 2012); 27. (Hwang and Lee, 2010); 28. (Kang and Kang, 2009); 29. (Laursen and Salter, 2006a); 30. (Laursen and Salter, 2006b); 31. (Lokshin et al., 2008); 32 (Lööf and Heshmati, 2002); 33. (Mention and Asikainen, 2012); 34. (Miotti and Sachwald, 2003); 35. (Mueller et al., 2013); 36. (Nieto and Santamaría, 2007); 37. (Parida et al., 2012); 38. (Park and Russo, 1996); 39. (Reichstein and Salter, 2006) ; 40. (Rosenzweig et al., 2003); 41. (Spithoven et al., 2010); 42. (Terjesen and Patel, 2017) 43. (Un and Asakawa, 2015) 44. (West and Bogers, 2014); 45. (Zhao et al., 2016); Additional references: α (Bunduchi, 2013); β (Greco et al., 2017); γ (Kale and Singh, 2009); δ (Ojala and Hallikas, 2006); ε (Simachev et al., 2015); ζ (Slowinski et al., 2006).

4.2 The direct effect of open innovation on productivity

The projects under investigation unveiled the multitude of stakeholders involved in innovation projects in the construction ecosystem. Set aside the variety of firms that usually led the projects, 17 projects involved at least one research institution (usually, a university). At the same time, public stakeholders (e.g., a trust for the conservation of wildlife) were also involved either as key partners, facilitators (e.g., a city council that granted access to the seabed), or observers (e.g., the progress of the projects was followed closely by the funding agency).

The interviewees regard OI as essential to address specific innovation problems, such as the development of a new service (e.g., a benchmark for green infrastructure), a new process (e.g., the optimisation of timber sawing), or a new product (e.g., the introduction of an innovative material into the sector). Interestingly, when asked about the inter-organisational collaboration in their general professional experience (i.e., not pertaining only to the specific project that allowed identifying the interviewee), 80% of the experts were convinced that inter-organisational collaboration could contribute to improving productivity in the construction ecosystem. For instance, one expert said that collaboration is '*the only way I think we can improve efficiency in the infrastructure industry [...] [When] everyone is involved in the project, you can then come up with much better ideas about construction, prefabrication, detailing and everything else that will make that project much more efficient in the long run. I think the more people or companies that we involve in the initial design, within reason, it turns out to be a more efficient project in the long run*.' [Feas. Study Int. 2].

The construction firms involved in OI processes can achieve greater awareness about innovations from other industries that could be successfully implemented in construction. Furthermore, a firm can obtain a more accurate understanding of its market, juxtaposing its intra-organisational know-how with those of other organisations such as competitors and research institutions. One of the investigated projects accomplished exactly this task: the partners (including customers and suppliers) investigated their market to explore the demand for their product and the specifications required to maximise sales and customer satisfaction.

OI can improve the organisation of workers, enhancing labour productivity, as suggested by an expert: *'When organisations allow or empower their people to collaborate [...] they trigger better ways of working [...] making information sharing easier, then there can be huge steps forward in productivity.'* [Collab. R&D Int. 8]. OI fosters process innovations by improving the manufacturing and installation activities, saving costs and/or time, thus enhancing total factor productivity in construction. The decrease in costs can stem from introducing new-to-the-industry technologies or materials (i.e., technological process innovations). Often these technologies and material are well established outside construction. For instance, two experts reported: *'The intention was to use sensors and protocols and communication systems from the volume auto sector to keep the cost down. I'm aware of a lot of very elegant instrumentation and systems that have been developed for motor cars.'* [Feas. Study Int. 1]; *'We really need an interdisciplinary approach, we need to bring in other things that are not very common in construction, like robotics, like other industries that use it, like artificial intelligence. And interdisciplinary R&D is what we need to be able to resolve the problems.'* [Collab. R&D Int. 5].

Time savings are found throughout the construction process, from the design phase to on-site activities. A project's outcome allowed the leading firm to reduce the time required to deliver a building by 15%-20% in 4 years. The players' collaboration alongside all the supply chain (such as designers, architects, contractors, builders) produces new ideas to enhance the construction process.

Research institutions favourably contributed with their methodological rigour, laboratories, and know-how about the most advanced solutions both inside and outside the sector. Their contribution was often substantial to the development of the innovations, as reported in [Collab. R&D Int. 5]: '*And then is the technical collaboration with the university of course, which is very important. They do have facilities that our company doesn't have, like testing facilities, and also the expertise on fibre reinforced concrete*.'; or in [KTP Int. 5]: *'[...] we wanted the results [...], and that's what the university is good at, they're good at saying: 'Right, if you want that, then we need to look here, here and here, and do a study here, and we need this data, and we need that data"*. Nonetheless, scholars were criticised by one expert: '*I think, in particular, the challenge was with the university partner'* [Collab. R&D Int. 1].

The difficulty of managing the projects increases with the number of partners. In one case, the expert reported having issues in managing the project because there were too many partners (six). Two other experts asserted they had too many ideas in their respective projects' kick-off phase, thus experiencing the aforementioned 'attention allocation' problem (Dahlander et al., 2016). In one case, this abundance of ideas caused wasting time [KTP Int. 3]. Experts having prior experience about dealing with too many partners in a project came to limit the number of partners to involve. Therefore, the interviews reveal that too many partners in the project can hinder the performance, in line with the stream of literature suggesting an inverted U-shaped relationship, as discussed in subsection 2.3.2.

4.3 The indirect effect of open innovation on productivity

In line with the expectations, the majority of experts affirmed that collaborating with other organisations allows projects that otherwise would have been too risky and/or too expensive to be carried out alone. Some experts explained that firms in construction try to avoid pursuing truly innovative projects: *'[...] the situation is that research projects which are risky or too advanced will not be realised if they are offered to the industry.'* [KTP Int. 4]; '*[...] there can be a blockage to getting new things into the market, because [...] nobody wants to be the first person buy it. [...]'* [Collab. R&D Int. 7]. Indeed, reducing risks is one of the key reasons to engage in collaborative projects: *'One of our key phrases to external people is: "We are here to reduce your risk. Collaborate with us because that is our purpose. Every time you collaborate with other people [...], you're trying to reduce the risk by tapping into each other's knowledge.'* [KTP Int. 7].

When public subsidies are made available, the willingness to take risks increases, as confirmed by another expert: *'To be honest with you, nothing that I've ever done with industry has been that risky. I would say all the work I do with industry is fairly pedestrian. You sort of know that it would work, the risk in it is quite low. I mean, if I take an example of a highly risky thing like storing energy in a building, the building is a power station, I would never get the industry to get behind that. That would be impossible without the Research Council; you couldn't do it.'* [KTP Int. 6]. Therefore, public subsidies seem crucial to breaking the vicious circle that induces construction firms to avoid risks, because of their lack of resources, which lead to poor performance that further aggravate the lack of resource. Such a benefit is also apparent in the following excerpt: *'I probably would say if the funding wasn't available, we wouldn't have done such a rigorous job, we would have done it in a different way. [...] So, the alternative was we could have taken our product, and we could have taken it to a test house, and we could have said: 'Right, test, test, test and give us the results'. And we probably would have had one or two test results but* *wouldn't have had an understanding of: 'Well if we change it, how does it then mean or what effect does it have?'* [KTP Int. 5]. Furthermore, public funding builds trust among the partners and paves the ground for future, more challenging innovation projects, as observed by one interviewee: '*I don't think without public funding the project would have happened. Because one project sort of led. The first project introduced people to each other, who then went on to put the bidding to do the second project. And so, if the public funding mechanism wasn't in place to start it, none of this would have happened. [...] The first project was, we were brought together, we didn't know any other partner. And then, within that project, an idea came out for a form of construction, that was then developed into a patented product that was then the focus of product development in the second project. So really, without that initial project, the second project and the other business wouldn't have been formed, and the other product simply wouldn't have been invented*' [Collab. R&D Int. 7]. The relevance of public support, which was claimed in many ways by the interviewees, brought us to add a node to the CM to describe its positive effect on innovation performance and the propensity to collaborate with others (Greco et al., 2017) and to tackle the innovation risks (Simachev et al., 2015).

In several projects, the experts reported their partners' opportunistic behaviours or the collaboration issues with them. They mentioned free-riding behaviour, communication difficulties, efforts to get the necessary information, and time delays. No clear distinction between industrial and academic partners can be made in this respect. Sometimes, the negative behaviour arises from a lack of interest in innovation from the very people working in it: *'It is assumed that everyone that works in innovation and R&D is interested in innovation and R&D [...] But in the industry, there are other realities, you know, people are tired, bored or looking elsewhere and if they want to do the absolute minimum they can [...] At a personal level, that's what we're talking about, it massively* *affects the quality of the output'* [Feas. Study Int. 4]. None of the experts observed deliberate knowledge leakages, but control and monitoring mechanisms were active to protect the parties' intellectual property (e.g., in the form of non-disclosure agreements or embedded in the Innovate UK bureaucracy).

Transaction costs, including those associated with legal aspects (e.g., non-disclosure agreement and other intellectual property protection mechanisms) and red tape, are remarkable drawbacks of OI. The transaction costs embedded in collaboration can worsen when opportunistic behaviour occurs, for instance, due to the need to find new partners or sub-contractors to fill the gap left from a partner that was not fulfilling its duties.

As shown in Figure 3, two of the links identified in the literature were not explicitly confirmed by the experts. Such links, which are depicted as dashed lines, refer to the opportunistic behaviour and the knowledge leakage that can occur in collaborations. The few opportunistic behaviours experienced (or perceived) by the experts were not associated to knowledge leakage, but rather to the lack of commitment from some of the partners, which forced the others to cover for their missing contributions, hindering the project innovativeness, generating free riding, and increasing transaction costs. Regarding such behaviours, large firms can be tricky partners: *'I think if you get very large corporations involved in a project, it's very hard for very small organisations to work with because they [the big ones] don't actually contribute. They just turn up, let other people do the work. [...] I think, in particular, multinationals corporations exhibit unhelpful and negative behaviours. Unhelpful in the sense that they demand a lot of attention to legal agreements, generally obstacle the project and then, when the project is on the way, they don't maintain focus and don't maintain active contribution.'* [Collab.

R&D Int. 8]. At the extreme, in one case, a legal battle on R&D results commercialization has impeded the innovation from entering the market.

Overall, as mentioned before, none of the experts found evidence of knowledge leakage. However, one admitted that *'there is always the risk of leaking IP and especially for things that are not easy to have intellectual property control'* [Collab. R&D Int. 5]. As well, the risk of knowledge leakage was not seen as a relevant barrier for OI. Notably, those experts who experienced opportunistic behaviour agreed that the collaboration portfolio variety could be a factor that favours it. Only in one case, the opportunistic behaviour came from a competitor (i.e., horizontal collaboration), while it more often came from industrial partners or academics (at an individual level, rather than at an organisational one).

The recurrence of the concept of trust in the interviews brought us to extend the CM. Knowing and trusting partners is pivotal to avoid the criticalities of OI (Davis, 2016; Kale and Singh, 2009; Ojala and Hallikas, 2006; Slowinski et al., 2006). As reported by an expert: '*[...] we'd already been established as a team for nearly four years. So, we all knew how to work together; we all knew the team dynamics; we knew what was expected; we knew what the culture was*' [Collab. R&D Int. 3]; and also: *'The first project introduced people to each other, who then went on to put the bidding to do the second project. And so, if the public funding mechanism weren't in place to start it, none of this would have happened. [...] So really, without the initial project, the second project and the other business wouldn't have been formed, and the other product simply wouldn't have been invented [...] We knew each other before we went into the second project very well, which helps.'* [Collab. R&D Int. 7]. Also, reciprocal trust can reduce the transaction costs typically associated with setting up an OI project.

Notably, the collaborations funded by Innovate UK require signing several legal documents that protect the parties against opportunistic behaviour and unwilling leakage of sensitive information. Therefore, rather than a mere lack of validation of the two relationships, these results encourage to include in the tailored CM two additional nodes: ‘trust’ and ‘formal agreements’.

5 Strategies to enhance productivity

Bringing together the lessons learned from the literature and the interviews with the experts, this section proposes OI strategies to address the causes of poor productivity identified in section 2.2.1. We address, at different levels, all the causes except for sector fragmentation and regulations, for which no specific OI strategy stemmed from our empirical analysis. For each strategy, we elaborate on the general principle, and we offer a vignette of corresponding success stories from our interviews.

5.1 Productivity issue: Inadequate human resources' knowledge and competencies

Recommended OI strategy ***S1****: Increase the knowledge and competencies of less-skilled workers through formal and informal knowledge sharing with external partners.*

General principle: Construction often faces inadequate training of human resources. Scarce investment in training and the low salaries pose a challenge in establishing a stable and motivated workforce. OI can increase productivity through the sharing of knowledge among different organizations. Increasing expertise can be an explicit goal of the collaboration. Ideal partners to put this strategy into practice include research institutions, suppliers, and firms operating in other industries, which do not risk compromising their competitive advantage in the knowledge sharing process with the firm. Experts recognised knowledge acquisition from inter-organisational collaborations as a great benefit: *'It opened up a whole new area of information that [...] I wasn't aware of until I started doing this project.'* [Collab. R&D Int. 2] and *'We've got a whole spectrum of knowledge and skills'* [Collab. R&D Int. 3]. This subject has been taken to an extreme by one expert: *'The benefit of it was the diversity of views and experience as well. Without collaboration, there are some things that just will not be able to be achieved because of the lack of experience of the others. [...] They've [the organisation] also learnt a lot about offshore wind and floating offshore wind which they didn't know anything* *about before'* [Feas. Study Int. 1]. Another expert stressed the knowledge aspect of collaborating projects: *'Learning, being exposed to different experiences from different people, being exposed to different methods of work, different organisations, different backgrounds, they can do nothing but enhance your own capability. They are absolutely critical. Collaboration is, I think, critical for everybody to go forward.'* [KTP Int. 7].

A vignette from our interviews: One project had this specific objective: '*it's drawn in-house expertise, which was initially one of the main things they [the firm] were interested in doing [...] they've increased their in-house expertise in terms of green infrastructure*' [KTP Int. 1]. In another, much knowledge was gained: '*[...] we've gained a lot of knowledge internally from involving our people in developing intellectual property and interacting with other organisations that are probably, maybe cleverer than us or see things differently to us. [...] And that then has indirect spin-offs certain times, that we may look at the next project slightly differently, may gain a competitive advantage and maybe win a job differently.*' [Collab. R&D Int. 7].

5.2 Productivity issue: Few ICT investments and ICT integration

*Recommended OI strategy **S2**: Collaboration with ICT firms and ICT-savvy organisations to foster effective implementation of ICT.*

General principle: ICT can drive productivity growth (Brynjolfsson and Hitt, 2000; Gust and Marquez, 2004) bringing together customers, suppliers, and partners (Badir et al., 2003) but construction has not been able to leverage it at its full potential. ICT skills are necessary to leverage processes supported by various tools, technologies and contracts (such as building information modelling), which in turn can benefit both the building and the maintenance phases. However, as observed by Matthews et al. (2018), ICT requires specific skills and experiences, whose absence may hinder its positive impact. Therefore, partnerships with ICT firms would allow construction firms to implement ICT technologies at lower costs than usual and to be informed of technologies currently used in other industries. This was the case of one successful project aimed to transfer some ICT solutions from the automotive industry to construction.

A vignette from our interviews: The use of solutions originally developed in and for the manufacturing sector, particularly ICT tools, can improve the performance in the construction ecosystem. One of the experts observed: *'Colleagues came in from our construction department and we sat around the table and what they were saying at the time was: "Why can't we bring some of the manufacturing practices into construction?" It's taken us about 15 years to get to a stage where we are beginning to have some of the methodology, some of the techniques used in manufacturing to be sort of impacting construction. [...] So that is beginning to happen more and more, and you're seeing more and more robots coming along and participating in manufacturing parts of the buildings. So, this is happening, and yes, I think collaboration is going to be a very, very key part of all of this.'* [KTP Int. 7].

5.3 Productivity issue: Few investments in equipment and technology

*Recommended OI strategy **S3**: Promoting inter-organisational collaborations to share the risks and costs of investments in innovative equipment and technologies.*

General principle: Investments in new technology and equipment are a sore point in the construction ecosystem. Firms can leverage OI by resorting to their partners' assets, such as technology and equipment that may be too expensive to buy, particularly for small firms, as discussed in the OI literature (Andries and Thorwarth, 2014; Radziwon and Bogers, 2019; Spithoven et al., 2013). In this view, universities can be valuable partners to access the expensive equipment needed to test new materials and building techniques.

A vignette from our interviews: In a project, a large firm used a partner's robot to keep the cost of the project down and save time '*Instead of having to buy a robot and set it all up ourselves, they [the partner] had one already, and we configured it to meet the requirements of the demonstration we wanted.*' [Collab. R&D Int. 1]. Smaller firms gathered access to testing facilities too high-priced to be bought: '*The university has testing facilities that we don't have and we will not be able to ever get, because these are substantial investments that especially small firms cannot make. So only getting access to these facilities was a key benefit.*' [Collab. R&D Int. 5]

5.4 Productivity issue: Poor collaboration and adversarial relationships

Recommended OI strategy ***S4****: Build trust through repeated collaborations, starting from publicly funded projects.*

General principle: The construction ecosystem is characterised by poor collaborations and adversarial relationships, with a widespread practice of outbidding competitors with unreasonable low bids (called in this sector jargon "*crushed costs*" and "*dog-eat-dog*" competing attitude), both of which lead to quality loss. Developing partnerships with firms within the same industry and increasing the integration with supply chain firms can reduce conflicts, ultimately helping the parties to achieve common goals. The links created during a good collaboration often become durable. Even relatively low-budget publicly funded projects have the power to create durable connections among organisations in the construction ecosystem, enabling them to start long-term projects, improve their performance and build harmonious collaborations. This could be a starting point to a much-needed trust-building process among the players in construction.

A vignette from our interviews: on the importance of repeated collaborations, one interviewee reported '*we have sort of supplier agreement so with just one supplier for* *each component and they generally run for two or three years. And then it means that we can work closely with the manufacturers of our components, and therefore we can take lessons learnt from each of them and plough it back into the models and reinforce that*". [Collab. R&D Int. 3], while another stated '*So we [the project partners] know each other and two of the supply chain partners already worked with us, so some established relationships. But definitely the level of detail we needed to deliver, the scale of, the magnitude of the A-06 project involved some existing relationships early in place. And then you can start a conversation as a consequence of that.'* [Collab. R&D Int. 6]

5.5 Productivity issue: Limited learning from other and past projects

*Recommended OI strategy **S5**: Collaborating with other organisations to favour industrial learning*

General principle: If at the individual level, the construction ecosystem often suffers from the lack of knowledge and skills that we discussed for the strategy S1, a similar issue hampers productivity at the firm level. Indeed, it is still a challenge to learn across projects.

Industrial learning is a key factor in construction (Ingersoll et al., 2020) since an '*increase in efficiency and effectiveness can be achieved by building experience and learning how to perform a process and use tools to deliver a product*' (Ernst & Young Global Limited, 2016).

Carelli et al. (2010) highlight the difference between 'worldwide learning' and 'on-site learning'. The first is independent of where the units are built, while the second is determined by the construction of successive units at the same site. Particularly in the former case, collaboration can bring a firm to gather knowledge on new practices from their partners (and adopt them in the collaborative project and future projects). Such practices can become part of the firm's structural capital, i.e., explicit knowledge embedded in an organisation (Barrena-Martínez et al., 2020).

A vignette from our interviews: The strategy was exemplified well in several interviews, including '*But the benefits that we had, well, it introduced us to new and unusual techniques of design, manufacture, installation. So, it opened up a whole new area of information [...] It opened up a lot of avenues for us to explore both through this project and after the project as well.'* [Collab. R&D Int. 2] and '*[...] what we do is capture all the learning for the ones that we've handed over, delivered on sites, and also patient and being maintained and then we can take those lessons learnt and take those and put those back into the next version, the next generation of each model. So that hopefully we'll continually the improving on the product we deliver. There were benefits from the learning that we got from this project that we plough to be making it back into the base models for future benefit our sales and customers*.' [Collab. R&D Int. 3].

5.6 Productivity issue: Project complexity and client dissatisfaction

*Recommended OI strategy **S6**: Collaboration with customers can help tackle project complexity and improve their satisfaction*

General principle: Collaboration with clients allows understanding their needs and can help tackle the complexity deriving from their requests. Experts have emphasised that, without all their partners' joint competencies, their projects would not have been feasible at all. For instance, one project in the sample had several technical challenges that would not have been solved if it was not for the partners, including some future end-users of the product under development: '*(It is) technically and commercially extremely challenging to deliver something that would necessarily be an investment that neither entity without collaboration would do. And so that allowed us to innovate in ways you probably wouldn't have done.' [Collab. R&D Int. 6]*

A vignette from our interviews: Two quotations very well capture the essence of the proposed strategy: '*I think it's important [to collaborate with external organisations] because we, in our supply chain and value chain, deal with people from waste producers to end-users of construction materials and everything in between. And what we look to do is to reduce cost, environmental impact, and that includes carbon footprint. [...] By working with waste suppliers, we came up with a solution for their problem. And by working with construction material manufacturers, what happens then is that we can optimise products for their users, for their purpose*'. [Collab. R&D Int. 4]

'*I think the collaboration is key because you've got different people with different experiences [...] in this particular project we had O-076 who was a sawmill, they were talking very much to the contractor who wanted to buy the timber and the merchant to find out what exactly they wanted, because that may have never been asked before*' [Feas. Study Int. 2].

6 Discussions

Responding to the call for more integration between the innovation and the project management domains (Davies et al., 2018), this article leveraged a typical project-based industry to study how OI can enhance productivity, given the known causes for low-productivity in the construction sector that we collected and presented in subsection 2.2.

This research contributes to the OI literature through a CM that shows the direct and indirect effect of OI on productivity, enabling sensemaking on the topic. This is a compelling contribution since previous studies mainly focused on the single impact of specific OI forms on various measures for productivity (e.g., Arvanitis, 2012; Belderbos et al., 2006; de Leeuw et al., 2014; Mention and Asikainen, 2012), whereas the complexity of the OI-related factors impacting on productivity had not been elaborated before. In addition to the direct effect, the CM considers the positive effect of product and process innovation performance on productivity, since both new technologies and new work organisation can be pivotal to enhance productivity (Fernández Gual and Segarra-Blasco, 2013; Lööf and Heshmati, 2002; Mention and Asikainen, 2012). In turn, innovation performance is a typical outcome stemming from OI activities (e.g., Lopes and de Carvalho, 2018), hence describing a first important indirect link from OI to productivity. OI also has a second-level indirect positive effect on productivity through innovation performance, since it reduces the R&D risks and costs that may hinder innovation (Arvanitis, 2012). Possible second-level negative effects of OI on productivity also involve innovation performance, since OI may favour opportunistic behaviour (de Leeuw et al., 2014) knowledge leakage (Coras and Tantau, 2014), and increase transaction costs (Zhao et al., 2016), which can hamper the development of innovations (Arvanitis, 2012; Kang and Kang, 2009). A key role to soften these negative side-effects is played by trust and formal agreements (Kale and Singh, 2009; Slowinski et al., 2006).

Similarly, public subsidies can further enhance innovation performance and OI (Greco et al., 2017), and reduce the risks (Simachev et al., 2015). Since knowledge leakage was hardly a problem in the projects under investigation, we argue that their publicly funded nature may have mitigated this issue. However, additional counterfactual research should be conducted to verify this conjecture. Another important role is played by firms' effort in R&D activities, which can positively influence productivity both directly and indirectly. Regarding the indirect effect, they positively influence innovation performance and absorptive capacity (e.g. Spithoven et al., 2010), which in turn facilitates accessing external technological resources (Zobel et al., 2017) and cooperation (de Faria et al., 2010).

The second novel contribution of this article comprises a set of OI-based strategies to address the productivity issue in the project-based industry under investigation. If productivity growth in an industry underpins the convergence towards process improvements (Terjesen and Patel, 2017), the data on construction suggest that such a convergence still is far from sight. The interviewees remarked how the purposeful mix of knowledge, ideas, and technology brought in by different players was critical to the success of their innovation process. Furthermore, most of them declared that their innovation project would not have been possible without public funding. Therefore, public policy enacted by financial contributions confirms its importance as an enabler of OI and of its outcomes (Ahn et al., 2020; Greco et al., 2017; Jugend et al., 2020). Inter-organisational collaboration has the potential to play a major role to achieve the innovations that construction firms need, allowing them to overcome adversarial relationships (S4) and share best practices (S5). Consistently, Kim and Nguyen (2018) recently observed that collaboration along the construction supply chain, the support and commitment, and the sharing of the benefits and risks positively influence project performance. The importance of trained human resources to enhance innovation has been thoroughly discussed in the past (e.g., Huang and Rice, 2012), while the development and enhancement of knowledge through inter-organisational flows are at the heart of the OI paradigm (Chesbrough et al., 2006). The interviews showed that OI projects in the construction ecosystem are no exception. Thus, we advance that OI could nurture the growth of the construction ecosystem's human capital (S1) and structural capital (S5), consequently addressing the productivity issue. In the same vein, a stronger ICT adoption through the collaboration with ICT organisations (S2) will enhance the productivity, as it happened in other sectors such as services (Mention and Asikainen, 2012). OI can be very important for an ecosystem where risky investments in equipment and technologies are typically avoided or procrastinated. Kim and Nguyen's study (2018) supports our suggested strategy S3, encompassing the sharing of technologies and equipment during inter-organisational collaborations. We recommended a closer collaboration with customers (S6) to understand their needs and desires better, increasing customer satisfaction, as other industries do (Rohrbeck et al., 2009; van de Vrande et al., 2009). While collaboration among competitors may drive changes in the regulations and set standards it may have a detrimental effect on process innovation, as observed by Un and Asakawa (2015).

Lastly, our study adds to the literature on OI ecosystems showing that public subsidies can bring together multiple organisations and stakeholders of an ecosystem. Indeed, to build an OI ecosystem, the relationships between organisations and stakeholders need to be nurtured (Chesbrough et al., 2014). While a recent study showed that such relationships were strongly felt in firms in a mechatronic ecosystem (Radziwon and Bogers, 2019), the construction ecosystem has shown quite the opposite situation. According to the interviewees, the construction ecosystem still needs public interventions to embrace a cultural change and allow construction firms to experiment the advantages of OI, both in terms of innovation performance and in terms of productivity. In this vein, we found that public funding triggered the “unfreezing” of many organisations’ propensity towards OI, as observed by de Melo et al. (2020), preparing them for further OI efforts.

7 Conclusions

Productivity is a widespread, long-term issue in the construction sector, and an important venue in addressing this challenge is through inter-organisational collaboration, as described by the OI literature for other sectors. This study explored the relationship between OI and productivity and contributed to both practice and theory, which we describe below.

7.1 Contribution to practice

The analysis of the scientific literature, industrial and policy documents, the interviews with experts, and the cognitive map allowed deriving six OI-oriented strategies to enhance productivity in the construction ecosystem. Each of them is explicitly linked to one or more causes of the productivity issue in construction and is presented both in general terms and through vignettes drawn from the interviews.

We found that, by collaborating with research institutions, suppliers, and organisations from other industries, firms in construction could nurture their employees' knowledge and competencies, which is a cure for low productivity (Rahman et al., 2019), but also cultivate the firm's own structural capital through industrial learning, for instance through the identification of replicable best practices and construction processes. Furthermore, collaboration with organisations with ICT expertise can be pivotal for introducing new technologies in construction, which can smoothen the construction process. OI may also be leveraged by sharing equipment among partners, as in the case of costly testing facilities provided by research institutions, or in the case of horizontal collaborations, which would also benefit firms by mitigating the adversarial relationships that often characterise construction. Finally, we encouraged construction firms to collaborate more with their customers to tackle the complexity of their projects and increase customer satisfaction, consequently reducing scope changes and reworks that affect productivity in construction.

These strategies are particularly valuable, given the grand importance of construction in most economies and of the challenge that the productivity issue poses. We found that the general scepticism against collaborative innovation initiatives that permeates the construction ecosystem has been challenged by publicly-funded innovative projects. Indeed, most of our interviewees shared success stories of accrued knowledge, new technologies and new processes that would not have been possible without the encounter of different organisations. Furthermore, public support often leads to inter-organisational collaborations that were retained even after the end of the projects, thus having a prolonged impact on organisations' attitude towards OI.

7.2 Contribution to theory

This is the first study to extensively and systemically address the productivity issue in project-based business in view of the OI paradigm. Our deductive approach allowed testing a general OI theoretical framework, depicted as a cognitive map, into a specific context, the construction ecosystem. Given the peculiarities of such a context, and the fact that most OI literature studies operations-based industries, we were surprised by how closely the cognitive map matched it. We found confirmation that OI enhances productivity both directly and indirectly, through its positive impact on innovation performance and its beneficial mitigation of risks and costs. The possible negative indirect effects of OI, which include knowledge leakage, opportunistic behaviour, and transaction costs, could be mitigated through trust, public support, and formal agreements. This research also adds to the stream of literature linking absorptive capacity and R&D efforts to OI and performance.

The external validity of the map goes beyond the boundaries of the construction ecosystem since literature from different sectors solidly support it. As such, it could serve as a map of the important factors to acknowledge in future investigations on productivity in other industries and sectors. Only one result – the undesired leakage of knowledge during the collaborative projects – has not been encountered, since none of the interviewees reported it (yet, we should not mistake the absence of evidence as evidence of absence!). The result is similar to that recently presented by Radziwon and Bogers (2019), who also reported how just one of their interviewees was concerned about the risk of knowledge leakage. The result raises several questions: are individuals becoming less sensitive towards the risk of knowledge leakage? Is OI gradually changing the concept of knowledge leakage itself? Are firms becoming more able to safeguard the knowledge they do not want to share? Are publicly funded projects significantly different from others in this?

As a final contribution to theory, the set of strategies we proposed to tackle the productivity could be interpreted following the intellectual capital theory, which was recently juxtaposed to the OI paradigm (Barrena-Martínez et al., 2020). Indeed, nurturing individuals' knowledge pertains to human capital, improving industrial learning refers to structural capital, while the interactions with other organisations can describe a firm's relational capital. Since intellectual capital has been scarcely studied in construction (e.g., Rezgui et al., 2010), we encourage future research to study productivity and firms' intellectual capital.

7.3 Limitations and future developments

This research has three main limitations. Firstly, the sample size of interviewed experts, although similar sample cardinalities are common in articles resorting to semi-structured interviews. Secondly, this research is limited to a sample of experts involved in publicly funded research projects in the UK. Even though the experts were asked to provide information about their previous professional experience, a different sample of projects that did not benefit from public subsidies may return additional counterfactual evidence, especially concerning the factors negatively moderating the relationship between OI and productivity. Extending the study to other countries, other project-based ecosystems, or focusing on specific construction sub-sectors could identify further insights. Indeed, productivity may be affected by country-specific or sector-specific challenges that could be punctually studied in future research. The strategies we proposed would need to be operationalized according to the different construction sub-sectors' specific characteristics. Thirdly, in a micro-foundational perspective (Felin et al., 2015; Locatelli et al., 2020), additional interviews with construction workers and other employees involved in the projects could have returned different insights. Thus, we encourage future studies to address this gap.

The exploratory nature of this study leaves much space for future research on the relationship between productivity, OI and the other moderators described in the cognitive map. Future studies may address how different project variables can moderate the impact of OI on productivity, for instance controlling for the number of partners involved, the existence of previous collaborations, and the receipt of public subsidies. Future researches should also investigate how construction firms' characteristics and intellectual capital affect their productivity (such as change aversion, qualification of the human resources and the proximity to major universities) and which specific solutions can be proposed to address them.

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Appendix A

Semi-structured questionnaire

General information

Q1. Can you describe the project and the external subjects involved in it?
Q2. Which kind of benefits have you/your organisation obtained from participating in this project?
Q3. [in case of multiple partners] → Were such benefits deriving from one partner in particular?
Q4. Do you think that without receiving public support the project would have been undertaken anyway?
Q5. Would you have carried out such projects without this collaboration?
Q6. Do you believe the total number of organisations you worked with was optimal for this project's purposes?
Q7. Do you believe that the number of ideas developed in the kick-off phase of the project has been too high, too low or adequate?
Q8. [in case of too many ideas or partners] Why did you end up with so many partners and/or ideas? What is the effect you believe they had on the project and on your firm?

Advantages and disadvantages of the collaboration dynamics in the project

Q9. Regarding the project partners, did you observe any negative behaviour on their part? Which ones?
Q10. [if negative behaviour occurred] With which kind of partner did unfair behaviours occur more frequently?
Q11. Did you have to set up control and monitoring mechanisms to prevent these behaviours?
Q12. [if negative behaviour occurred] What effects the negative behaviours you stated had on the project and on your organisations?
Q13. [if negative behaviour occurred] Having these behaviours occurred, how likely is it that your firm will commit to external collaborations again to produce innovations again in the future? Why?
Q14. Did you observe other negative aspects (not related to partners or their behaviour) in the collaboration with external subjects to realise this project? Which ones?
Q15. [if involuntary leakages of sensitive information happened] Concerning involuntary leakages of sensitive information, what effects do you think they had on your firm's performance?
Q16. Do you think that starting and maintaining these collaborations involve costs?
Q17. [if yes] How do you evaluate these costs?

The role played by internal R&D and absorptive capacity

Q18. [if the information was not available before the interview] Does your organisation have an internal Research and Development unit?
Q19. [in case of internal R&D] Do you believe the existence of an internal R&D function has facilitated the collaboration with external subjects?

Q20. [in case of internal R&D] Do you believe that collaborating with external subjects for this project has had a positive impact on your internal R&D function? How?
Q21. [in case of no internal R&D] Do you believe this absence has somehow made it difficult to collaborate with external subjects? How?

Closing general questions

Q22. According to your experience, do you believe that the number of partners with which one collaborates affects the likelihood of opportunistic behaviour?
Q23. According to your experience in collaborations with external subjects (not limited to this particular project), what benefits did you obtain?
Q24. According to your experience in collaborations with external subjects (not limited to this particular project), what costs did you incur in, and what negative aspects did you find?
Q25. Do you think that these collaborations' cost-benefit ratio justifies their undertaking?
Q26. Do you think that collaborating with other firms has allowed the realisation of research projects otherwise too risky and/or too expensive?
Q27. Do you think that collaboration can actually improve the productivity in the construction industry?

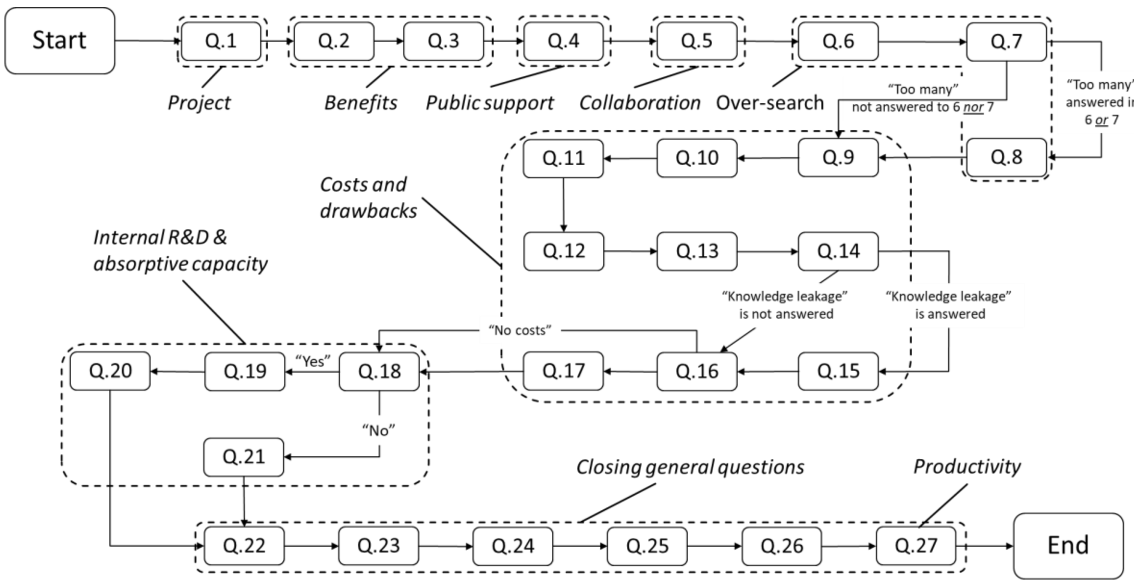

Figure A1. Questionnaire structure

Appendix B

Transcript codes

Absorptive Capacity->OI

Collaboration Portfolio Variety->Opportunistic Behaviour

Collaboration Portfolio Variety->Productivity

Horizontal Technological Collaboration->Opportunistic Behaviour

Horizontal Technological Collaboration->Productivity

Innovation Performance->Productivity

Internal R&D->Absorptive Capacity

Internal R&D->Innovation Performance

Internal R&D->Productivity

Knowledge Leakage->Innovation Performance

Knowledge Leakage->OI

OI->Absorptive Capacity

OI->Innovation Performance

OI->Knowledge Leakage

OI->Opportunistic Behaviour

OI->Productivity

OI->R&D Risks and Costs

OI->Transaction Costs

Opportunistic Behaviour->Innovation Performance

Opportunistic Behaviour->Knowledge Leakage

R&D Risks & Costs ->Innovation Performance

Transaction Costs->Innovation Performance

Vertical Technological Collaboration->Productivity

Cost-Benefit Ratio

Formal Agreements

Lack of skills (labour quality)

Regulation

Resistance to Innovation

Traditional Industry

Trust