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Exploring the structures and design effects of EU-funded R&D&I project portfolios

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ABSTRACT

Joint R&D&I projects and programs increase performance but entail project-related risks; namely, concurrent projects may share resources, delays may be inherited by later projects, and costs may overrun. With a project portfolio, one can better plan budgets, timelines, and risks, manage the resource-sharing of parallel projects, and map content-related projects as one program. However, large (publicly funded) research programs are rarely designed and managed as portfolios. This paper discerns the structure of the European Union-funded 7th Framework Program from a project management perspective. The proposed method estimates the structure based on the content, collaboration, and duration, which enables very accurate mapping of a naturally evolved, unstructured portfolio using limited publicly available data. We tested the sensitivity of overruns/delays, relative costs, and outputs to changes in the distribution of single projects, multi-projects, and programs. The results indicate that supporting programs leads to an improvement in performance, while the duration increases only slightly. The relative costs and output can be improved by moderately increasing the proportion of multi-projects and programs without the risk of overrun or delay. Although we used data from an unstructured portfolio, we believe that the results are valid for R&D&I portfolios in general. To address research policy, we suggest that understanding framework programs as portfolios of projects and managing their structure support collaboration and increase output with only a marginal impact on the cost and duration.

1. Introduction

Projects provide an outstanding platform for collaboration. They may be implemented as standalone projects, as parallel running projects that use common resources managed by one or more organizations, or as dependent projects that can be considered programs of projects (Milošević and Patanakul, 2002; Patanakul and Miloševic, 2009; Platje and Seidel, 1993). To improve the effectiveness of a variety of projects, organizations often apply multi-project management practices (Archibald, 2003; Clegg et al., 2018; Patanakul and Miloševic, 2009), especially project portfolio management (Patanakul, 2020).

Portfolio management was originally invented by Markowitz (1952) for financial purposes and later extended to the field of project management (McFarlan, 1981). A coordinated project portfolio reflects the sponsor's investment strategy, adds value beyond the results of an individual project, optimizes the available resources (Pennypacker and Dye, 2002), and represents a balance among associated risks. The focus is on the alignment of projects and programs with the sponsor's strategy and the balance of the project portfolio while recognizing the risks of overruns/delay and costs on the one hand and benefits on the other hand. The scoring, screening and selection of projects are important phases to find an optimal project portfolio structure (Wei et al., 2020). In a project portfolio, one can better plan budgets, timelines, and risks, manage parallel projects that share resources and designate programs when projects are interdependent in content (Lock and Wagner, 2019; Too and Weaver, 2014). Nevertheless, many large (publicly funded) research programs are neither designed nor managed as project portfolios.

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In research, development and innovation (R&D&I) studies, portfolio management has received increasing attention (Chang et al., 2020; Lerch and Spieth, 2012; Meifort, 2016; Mikkola, 2001), and this trend can be observed in the European Framework Programmes (FPs) for Research and Technological Development (Bellandi et al., 2021; de Arroyabe et al., 2021; Di Cagno et al., 2016; Fresco et al., 2015; Hoekman et al., 2010; Kastrinos and Weber, 2020; Rodríguez et al., 2013). Kaiser et al. (2015) demonstrated that the analysis of the project portfolio structure is vital for project or organization success, and we believe that this is also true for European Union FPs. Using data from the 7th Framework Programme (FP7), this article offers new insights into the structure and tradeoffs of R&D&I portfolios that policy makers need to consider. We show that the structure of a naturally grown portfolio can be mapped very accurately by little, often publicly available data. Furthermore, under specific conditions, altering the overall structure of a naturally grown project portfolio leads to improvements in the relative cost and output, although this requires implementing project portfolio management practices at the (supranational) level of the funding organization. Although we use data from an unstructured EU-funded research framework program, we believe that these results are also valid for organizational, national and structured R&D&I portfolios.

In this paper, we provide a method for classifying projects within unstructured portfolios into the following three groups: (1) single projects, (2) multi-projects, and (3) programs. The proposed method is tested on the network of FP7 funded by the European Union, and an analysis is presented that investigates the sensitivity of the portfolio to the effect of delays and the sharing of resources. The database is provided by the Community Research and Development Information Service (CORDIS) as the European Commission's primary source of project results. We analyze the costs (i.e., the risk of overruns/delays and relative costs of the projects) and the benefits (i.e., the expected publication outputs) of the existing distribution of single projects, programs, and multi-projects in a project portfolio. We also demonstrate how costs and benefits would change if this distribution were altered.

The article is structured as follows. First, we discuss project portfolios from a design perspective. The structuring of the portfolio has a significant impact on success, although the effect of the execution of the management of the portfolio should not be underestimated. At the same time, the design perspective enables comparison of portfolios with FP7, while the management of the portfolio can hardly be comprehended using only publicly available data. Subsequent to the definitions, we present and test a method for classifying projects into three groups based on data from the FP7 network, including a sensitivity analysis of the change in the structure of the portfolio to the risk of overruns and delays, costs and sharing of resources. The conclusion addresses the managerial and research policy implications and limitations.

2. Project portfolios

2.1. Designing project portfolios

Pennypacker and Dye (2002) define a project portfolio as "a collection of single projects, multi-projects and programs that are administered under a single sponsorship and typically compete for scarce resources". The optimal project portfolio structure, i.e., the distribution of single projects, multi-projects and programs, has long been discussed in both academia and practice – with a particular focus on selecting projects into an existing portfolio (Too and Weaver, 2014). A traditional strand of literature focuses on the value creation of single projects as linearly adding to the total value of a project portfolio, whereas more sophisticated research endeavors include other aspects, such as quality and the baseline value (Liesiö and Punkka, 2014; Szczepaniak, 2019), balancing risk (Ahmadi-Javid et al., 2020; Colvin and Maravelias, 2011), flexibility and endogenous uncertainty (Belenky, 2012; Shakhsi-Niaei et al., 2011). Subsequent efforts have examined the interdependence and mutual influences among projects (Colvin and Maravelias, 2011; Golghamat Raad et al., 2020), i.e., the joint use of resources (Abbassi et al., 2014), time dependencies (Belenky, 2012) and acquisition of know-how (Ghapanchi et al., 2012). In addition to production portfolios, R&D (and even EU-funded research programs) are a particular focus of project selection research (Flechas Chaparro et al., 2019; Schauer, 2008; Schluga and Barber, 2008). Traditional selection models focus mainly on quantitative tools, some of which are quite traditional, such as discounted cash flow, net present value or return on investment. Other approaches include mathematical programming (Feng et al., 2011; Mild et al., 2015), stochastic models (Colvin and Maravelias, 2011; Solak et al., 2010), fuzzy logic (Bhattacharyya et al., 2011; Kuchta, 2019; Pérez et al., 2018) and simulation approaches (Iamratanakul et al., 2008). In contrast to the vast but older literature on project selection, the effects of the interconnections within existing projects (Hoffmann et al., 2020; Killen and Hunt, 2013) and how to manage structure vs. flexibility (Jerbrant and Karrbom Gustavsson, 2013; Kopmann et al., 2017) are rarely discussed.

Wei et al. (2020) showed that the interdependence among projects may influence the benefits of project portfolios. Related projects organized by a program can have more benefits (i.e., scientific output) because adopting centrally coordinated management of a group of goal-related projects can better achieve strategic objectives and benefits (Ferns, 1991). However, the concept of a program is larger in terms of the business scale, complexity, scope, management range, decision-making processes, and simultaneous progression of activities; additionally, the level of recognition for a program differs from that of a project (Lycett et al., 2004). Therefore, having related projects means that a program has more and larger risk factors, such as the ability to maintain deadlines and budgets, than do individual projects.

If parallel projects have no common goal but are managed by the same organization, then they have to share their resources among parallel running projects (so-called multi-projects). Because of the sharing of resources within multi-projects, the relative cost of a project can be lower than that of a single project; however, scarce resources can cause delays (Fricke and Shenbar, 2000).

Accordingly, there is no superior management concept when all the risks and benefits are considered for the three forms. If there is no dependency between the individual projects and if they are managed by different organizations, then they are ultimately less risky than programs or multi-projects; however, they may have lower (research) output and higher relative costs. Multi-projects may have lower relative costs, but it can be more difficult to maintain deadlines in such efforts. Programs can produce greater scientific impact, but they are more sensitive to time delays. Our research questions are thus as follows.

RQ1: How sensitive are costs (the risk of overruns/delays, and relative costs of projects) and outputs (benefits) to changes in the distribution of single projects, multi-projects and programs in a given portfolio structure?
RQ2: Is there an optimal ratio of single projects, multi-projects and programs with respect to costs (the risk of overruns/delays and relative costs of projects) and outputs (benefits)?

2.2. EU framework programs

In 1984, the European Union (EU) launched the First FP with the aim of coordinating individual research activities and enhancing cooperation among researchers (Georghiou, 2001). FP7 was adopted in 2006 to

complement the other EU actions in research policy that are necessary for the implementation of the Lisbon strategy. The aims and objectives of FP7 were set by European Parliament Decision No 1982/2006/EC[1], whose overriding aim is to "contribute to the European Union becoming the world's leading research area." Considering its legal basis, ex post evaluators derived the following objectives for FP7: 1. promoting excellence in research; 2. fostering competitiveness and economic growth; 3. contributing to solving social challenges; 4. strengthening human potential and researcher mobility; and 5. fostering transnational research cooperation. Ultimately, six categories of organizations participated in FP7 (universities, research and technology organizations, large private companies, small- and medium-sized enterprises, public authorities and others) (Fresco et al., 2015).

FP7 can result in various types of outputs, notably publications such as scientific articles, books, book chapters, conference papers and proceedings, symposia and seminar contributions, and dissertations. Other types of outputs related to EU-funded projects may be patents, improved tools, methods, and techniques, new networks, (inter)national recognition, and Ph.D. projects (Larédo, 1998; Muldur et al., 2006; Tuominen et al., 2011). Muscio (2006) found in an early study that the primary output of FPs in numerical terms was publications. Scientific publications and citation measurement have a long tradition of being indicators of research impact (Gonzalez-Brambila et al., 2013; Ovalle-Perandones et al., 2013). However, the quality of a scientific article is difficult to measure, and publications such as symposia, seminar, and colloquium contributions do not necessarily undergo peer review and proper publication processes that are essential to ensure quality and scientific rigor.. An indication of quality may be publication in peer-reviewed and high-ranking journals. It is generally assumed that the citation impact score of international co-publications is higher than that of purely national publications (Muldur et al., 2006); in fact, the output of the majority of FP projects also includes peer-reviewed publications (Muscio, 2006). In any case, it is important for both the applicant and the funder to publish the results of the earned R&D&I projects in a high-quality journal (Delanghe and Muldur, 2007).

Muscio (2006) found that new or improved tools, methods, and techniques were the second most important outcome of FPs. However, many outputs are poorly documented and have measurement issues. Alternatively, other approaches estimate the impact of research by counting patent applications (Bruno and Kadunc, 2019). Patent applications can take up to 4-5 years; therefore, they are not included in the project report, and the quality of a patent is even more difficult to measure. Lanjouw and Schankerman (2004). Even more so Muscio (2006) found patent applications to be quite uncommon in FPs. Patent applications can take up to 4-5 years; therefore, they are not included in the project report, and the quality of a patent is even more difficult to measure (Lanjouw and Schankerman, 2004). More recent considerations call for a broader perspective to be taken into account, in particular with regard to the economic and social impact of publicly funded projects (Tuominen et al., 2011). Even if this new orientation is reasonable and worthy of support, there are neither established indicators nor data or methodologies available to define and measure the societal impact in a broader sense (Bruno and Kadunc, 2019).

The European FPs have been investigated from various viewpoints. Substantial research interest has focused, inter alia, on the effects of cohesion policies and convergence (Ramajo et al., 2008), the effects on the European research area (Chessa et al., 2013), the performance of the program (Sebestyén and Varga, 2013), the impact of relational networks on regional development (Di Cagno et al., 2016; Maggioni et al., 2007) and companies (Caloghirou et al., 2001; Protogerou et al., 2013). Moreover, network analysis methodology has been successfully applied to research the effects of European research policies (Breschi and Cusmano, 2004; Fernandez de Arroyabe et al., 2021; Schluga and Barber, 2008). Although the European FPs – as with nearly all other European initiatives – are basically designed for project-type organizations, an analysis from this perspective is rare.

In an earlier paper, Söderlund (2004) developed a framework for classifying projects that spans two dimensions: single versus multi-firm and single versus multi-project. The term "project ecology" refers to contexts with multiple firms and multiple projects by focusing on the interactions between projects and their environment. At first glance, the FP7 structure looks like a project ecology because in FP7 we are dealing with multiple projects and multiple organizations. However, looking more closely at the notion of project ecology, Söderlund (2004) is not concerned with the internal structure of projects, programs, and multi-projects but with the "links between projects and actors (e.g., firms), the sociology of projects, in the economics of projects and in the links between project participation and company development. Research on project ecologies thus takes interest in the study of the interrelationships between projects and their environments." According to Grabher and Ibert (2011) the notion "provides a conceptual framework for analyzing projects from a contextual view. In short, project ecologies denote a relational space which affords the personal, organizational, and institutional resources for performing projects."

Rather than conceptualizing FP7 as a specific project ecology, we can refer to the European FPs as projects, multi-projects, and programs embedded into a specific project ecology of scientific research, shaped by international and research-oriented scholars and professionals in knowledge-based organizations. Even more, we could identify a variety of project ecologies, given the large differences between disciplines and regional networks. With the FP7 framework, we expect to see a diverse ensemble of organizations, communities, and personal networks, each with its own professional ethos, social logic, organizing principles, and culture (Grabher and Ibert, 2011), and linked to specific business systems (Whitley, 2007).

The focus on project ecologies underscores the importance of industrial and professional networks and of reputational and role structures within networks (Söderlund, 2004). Grabher and Ibert (2011) note that "collaboration on projects, for example, can create a personal network that later forms the basis for a core team that anchors a follow-on project. Personal networks are, in a sense, both context and project." Networks within ecologies help maintain contacts with potential future partners and keep open channels of information that can provide access to upcoming project opportunities. Latent networks, in particular, unfold a broader web of personal connections that endure and extend beyond the project itself.

In fact, research endeavors within FP7 grow from the bottom up, based on the social networks predominant in the research community (Maggioni et al., 2007; Maggioni and Uberti, 2009). Studies have found prevalent oligarchic network structures in EU FPs and path dependence in R&D&I collaborations based on experience (Amoroso et al., 2018; Breschi and Cusmano, 2004). The overlay between formal and informal networks has advantages (Oguguo et al., 2020; Rank, 2008); as this type of network reflects the mutual knowledge of partners before and during projects, enhances the trust between partners (Coleman, 1988) and third-party relations (Burt, 2008; Granovetter, 1973), facilitates information and communication flows (Hansen, 1999), enables agreement on common aims (Gulati et al., 2000; Provan and Kenis, 2007), and facilitates the negotiation of timelines and resources (Dietrich et al., 2010; Larson and Wikström, 2007). However, these advantages come with costs: bottom-up resource allocation might not be in the best interest of the sponsor or the most efficient way to achieve the goal for the entire portfolio, co-operations are not oriented to content-related necessities, timelines are suited to the partners' needs, not the overall needs, and risks are allocated by chance and not foresight or balance (Clegg et al., 2017; Macary and Ika, 2015; Pinto, 2014).

[1] European Parliament (2006) Decision No 1982/2006/EC of the European Parliament and of the Council of 18 December 2006 concerning the Seventh Framework Programme of the European Community for research, technological development and demonstration activities (2007–2013)

As European FPs are not "traditional" project portfolios, they also lack an official definition and structuring along the classification of single projects, multi-projects and programs. We coin them "unstructured project portfolios". The design of FP7 therefore has to be reconstructed by using available public data. A preliminary research question is thus as follows:

RQ3: How can projects in an unstructured project portfolio be meaningfully classified based on publicly available data?

2.3. EU FP7 as a project portfolio

Although many large (publicly funded) research programs, including FP7, are neither designed nor managed as project portfolios, we believe that interpreting FP7 as a portfolio of projects and programs enables us to better understand the opportunities and risks connected to the structure under the umbrella of the European FPs. This is all the more justifiable as FP7 gathers different projects under a common umbrella and is funded by a single sponsorship. Like a project portfolio, project proposals and ideas are developed in a decentralized manner, while approval is made centrally. Although there is a single (financial) sponsorship in FP7, there are also differences between the common definition of project portfolios and FP7. No instances combine different resources or timelines at one single point of decision, and no governance structure defines the aim and scope of sub-units from the top down. No steering committee or portfolio manager is responsible for the tasks of portfolio capacity and capability management, portfolio value management or portfolio risk management, as in a common sponsor organization (Project Management Institute, 2017). Projects and project proposal acceptance are constrained only by the general rules of FP7. Interventions are restricted to budgets, sometimes to timelines, based on self-reports and audits, which produces a considerable delay in reactions. Project portfolios are unlimited in duration, while the European Programmes are limited by the funding period. Moreover, projects and programs do not share resources at the portfolio level, but they might share scarce resources in multi-projects and programs at the participating organization level. Depending on the size and the involvement in FP7 projects, shared resources might be limited.

In most projects, for example, in construction projects, additional human or infrastructure resources will lead to acceleration of work; conversely, resource overlap will lead to delay. One might argue that delays in multi-projects and programs are not of great concern for the organizations that participate in FP7 because the sharing of resources is marginal. Furthermore, organizations will be able to hire additional personnel and purchase infrastructure with EU-funding, which might relieve other resources from the workload. The overlap for common, easily replaceable resources for projects might thus not be a problem. However, with R&D&I projects, simple manpower or machines do not ultimately make the difference, rather the very specialized, and thus rare, know-how of only a few people in the organization or very specialized facilities matters (Hendriks et al., 1999). These key resources are regularly subject to multiple loads in the case of multi-projects and programs but cannot be easily multiplied or purchased on the market (Jin et al., 2017; Radant et al., 2016). Therefore, an increase in the number of simultaneous projects will lead to a bottleneck in these key resources, entailing the risk of overruns/delays. This also applies to large organizations such as universities or major research institutes, because research projects are similarly not distributed equally across all parts but are concentrated on a few individuals or institutions that by far handle the largest share (Larivière et al., 2010; Madsen and Aagaard, 2020; Mongeon et al., 2016). Therefore, an effect of overlapping projects on delay has to be expected.

Nearly all FP7 funding operates on the basis of an initial call for proposals by the Commission or one of its agencies in one of the key FP7 program areas. The call for proposals contains details of the deadline, budget, relevant funding scheme and areas addressed by the call, plus any special conditions that apply to the call. All proposals are assessed by an independent peer review process. The Commission or an agency then negotiates with some or all of the organizations whose proposals have successfully passed the evaluation stage, depending on the budget availability. However, certain minimum conditions have to be met that relate to the participation from the EU and associated countries, which varies among funding schemes and from call to call. For some program areas, there must be at least three legal entities established in different EU member states or associated countries, with the entities being independent of one another, and for coordination and support actions, the minimum condition is the participation of one legal entity. In any case, for a given proposal, a coordinator acts as the single point of contact between the participants and the Commission or the agency. The coordinator is generally responsible for the overall planning of the proposal, for building the consortium that will do the work, for controlling the process during the execution phase and for reporting. The coordinator's scope of duties corresponds to that of a project or program manager.

Although coordinators assume the role of project or program manager in the set-up phase, formal authority is quite limited in the execution and closing phases. The coordinator is externally accountable, whereas their assertiveness is based on their informal power and network position, which further increase the coordinator's dependency on internal stakeholders. For bottom-up portfolios with weak governance, such as FP7, we thus expect a larger spread of complications over time, resources and results between the projects, multi-projects and programs than is common for traditional portfolios and more diverse results in delays and the resources needed.

3. Definitions

Patanakul and Miloševic (2009) uses the term *single project* for large and strategic projects that have a full-time project manager. In this case, the project manager leads only one project at a time, there is no significant temporal overlap, and the project targets are autonomous.

Multi-projects can be defined as smaller projects made more tactical; therefore, groups of projects can be simultaneously led by one project manager. These projects are not mutually dependent on one another; however, resources, especially key resources, are partly or totally shared between the overlapping projects, and they are managed together to improve efficiency (Miloševic and Patanakul, 2002).

In the case of *programs*, the grouped projects are mutually dependent, and they share a common goal (Miloševic and Patanakul, 2002; Patanakul and Miloševic, 2009). A program can be considered a bundle of related projects with defined goals that needs holistic management (Ribbers and Schoo, 2002).

A *project portfolio* is a collection of single projects, multi-projects and programs that are administered under a single sponsorship, and they typically compete for scarce resources (Pennypacker and Dye, 2002).

As argued above, the *benefits* of Framework Programs can be measured by publication outputs similarly to many other scholars (see, e.g., Breschi and Malerba, 2011; Bruno and Kadunc, 2019; Defazio et al., 2009). The measure of scientific output is usually based on quantity (the number of publications) and quality components of publications (Kaur et al., 2015). Given the longstanding tradition of publication measurements, these data are both readily available in relevant databases and reasonably reliable, while "there is also no systematic collection of information related to the research results, innovations attained, impacts achieved on the market (e.g. sales, market shares, further investment received, efficiency gains obtained, etc." (Bruno and Kadunc, 2019). Most of the projects have planned and published publications available in the final report, while quality data related to FP7 were not available in the CORDIS system. Accordingly, we considered the number of publications as the best proxy for measuring scientific impact, even if one has to be aware of the inherent limitations, e.g., difficulties in capturing medium- or long-term and wider effects, in particular for society or the

economy. Notably, we missed publications that were published some time after the project – particularly since some journals have a much longer lead time than others.

It is easy to define *costs* because they are typically published in reports, but evaluating *time* is not easy. Although time is also stated in official reports, the duration (3 to 7 years) is limited not only by regulations but also by the deadline of the portfolio, i.e., the end of the funding period (7 years). Reported delays are thus limited, especially at the end of the funding period.

4. Methods

In the first step, every project is assigned to one of three groups, namely, a single project, part of a multi-project or part of a program. Once the projects are classified, the structure of the project portfolio is identified. After identifying the structure of the project portfolio with Monte Carlo simulations, the risk factors for delays and overbudgeting are analyzed.

4.1. Classifying projects

To classify projects, the following distances are specified between the projects and the organizations.

1. ***Distance of the overlapping duration*** (d_t). Denote $t(p_i)$ as the time interval of project p_i.

$$d_t(p_i,p_j) = 1 - \frac{t(p_i) \cap t(p_j)}{t(p_i) \cup t(p_j)}, d_t(p_i,p_j) \in [0,1]. \tag{1}$$

$d_t = 0$ if given projects are fully overlapped, while in the case of $d_t = 1$, projects are separated in time. The main challenge of the multi-projects is resource sharing (Zhang and He, 2012); however, parallel resource use can occur only when projects are overlapped in time (Hans et al., 2007). Successor projects within a program are built upon the findings of predecessor projects (Hans et al., 2007); therefore, in this case, overlap is much less common. Single projects can also be overlapped in time; however, their ownership and their content may be different. Therefore, d_t mainly characterizes multi-projects.

2. ***Distance of precedence*** (d_p). Denote $s(p_i)$ as the (planned) start date and $f(p_i)$ as the (planned) finish date of project p_i.

$$d_p(p_i,p_j) = \begin{cases} 1 & d_t(p_i,p_j) < 0.5 \\ 1 - \dfrac{\min(|f(p_i)-s(p_j)|, |f(p_j)-s(p_i)|)}{\max(|f(p_i)-s(p_j)|, |f(p_j)-s(p_i)|)} & d_t(p_i,p_j) \geq 0.5 \end{cases} \tag{2}$$

$d_p = 0$ if projects follow each other immediately, $d_p = 1$ if projects are mainly overlapped, while $d_p \to 1$, if the given projects are distant from each other in time. Although projects in programs are less overlapped in time, in order for a successor project to take advantage of the findings of a predecessor project, they should preferably follow each other in time (Hans et al., 2007). Since multi-projects are overlapped in time and single projects are independent of each other, this distance mainly characterizes pairs of projects within a program.

3. ***Distance of ownership*** (d_o). Denote $o(p_i)$ as the set of organizations involved in project p_i

$$d_o(p_i,p_j) = 1 - \frac{o(p_i) \cap o(p_j)}{o(p_i) \cup o(p_j)}, d_o(p_i,p_j) \in [0,1]. \tag{3}$$

$d_o = 0$ if project owners are fully common for the given pair of projects, while $d_o = 1$ if there is no common organization regarding the given pair of projects. Multi-projects, in addition to the overlap in time, require a common organization; otherwise, resource sharing cannot be performed (Cooper et al., 2000). Programs rather require a common purpose (Patanakul and Miloševic, 2009) than a common organization. Common purpose can be analyzed by text mining of project purpose and description (see d_x). The ownership of single projects may be diverse (Patanakul, 2020); therefore, this distance characterizes multi-projects most.

4. ***Distance of volume*** (d_v) of the projects, such as the budget ($c(p_i)$).

$$d_v(p_i,p_j) = 1 - \min(c(p_i),c(p_j))/\max(c(p_i),c(p_j)) \tag{4}$$

$d_v = 0$ if the budgets of the given pair of projects are the same. More precisely, $d_v(p_i,p_j) \to 0$, if $|c(p_i) - c(p_j)| \to 0$, and $d_v(p_i,p_j) \to 1$, if $|c(p_i) - c(p_j)| \to \infty$, or $\min(c(p_i), c(p_j) = 0$. Since similar volumes of parallel projects are mainly assumed in multi-projects (Boyette and Fang, 2012), this distance characterizes multi-projects more.

5. ***Distance of the content***. Denote $desc(p_i)$ as the description and $y(p_i)$ as the type of the subprogram of project p_i. Denote $\cos(T,\tau)$ as the cosine similarity of text T and text τ.

$$d_y(p_i,p_j) = \begin{cases} 0, & \text{if } y(p_i) = y(p_j) \\ 1, & \text{if } y(p_i) \neq y(p_j) \end{cases} \tag{5}$$

$$d_x(p_i,p_j) = 1 - \cos(descr(p_i), descr(p_j)) \tag{6}$$

$$d_{xy}(p_i,p_j) = d_x(p_i,p_j) \cdot d_y(p_i,p_j) \tag{7}$$

Then, $\cos(T,\tau)$ can be calculated as follows:

$$\cos(T,\tau) = \frac{T^T\tau}{\| T \| \| \tau \|} = \frac{\sum_{i=1}^m T_i\tau_i}{\sqrt{\sum_{i=1}^m T_i^2}\sqrt{\sum_{i=1}^m \tau_i^2}} \tag{8}$$

where m is the number of terms extracted by a document-term matrix.

$d_x = 1$ if the descriptions of the given pair of projects are the same; $d_x = 0$ if the descriptions are not similar. This metric is measured by text mining of project purpose and description for different expressions and terms that indicate that the content is different, while common purpose in the description requires using similar terms and expressions. This distance mainly characterizes programs because they require a common purpose detailed in the project description (Patanakul and Miloševic, 2009). d_y is a binary value. $d_y = 0$ if the given pair of projects are in the same subprogram, while $d_y = 1$ indicates that the given pair of projects are in different subprograms. The strong content relation between projects is not necessary in the case of multi-projects (Elonen and Artto,

Table 1
Steps of the simulation.

Nr.	Step name	Simulation scenario	
		Multi-projects	Programs
1	Relationship characterization	The relationship between the multi-project membership value and the daily project cost was analyzed. The equation and its parameters were estimated through curve fitting.	A sample of 400 projects was taken based on Eq. (14), including 176 programs and 224 multi-projects. Note that the subgroup sizes cannot be completely equalized due to the missing values in the case of programs. Determination of the number of publications requires a manual search since there is no automatic database support for FP7 projects. The equation and its parameters were specified by linear curve fitting.
2	Distribution characterization	The distribution parameters (the expected value and standard deviation) of the multi-project membership values were estimated.	The distribution parameters (the expected value and standard deviation) of the program membership values were estimated.
3	Simulation of dependencies	The same numeric dependency structure matrix (NSDM) was generated as in the case of programs. Although in this case, the program membership values across the NSDM are constant (in every iteration), but the start dates of the projects were delayed in the ratio of their multi-project membership value to simulate the effect of resource sharing. For details, see Appendix B.	The NDSM was generated with the estimated distribution parameters, including the program membership values. Each value in the NSDM represents the probability of precedence (which is equal to the program membership values in our case). This was applied to calculate the total duration of the portfolio. For details, see Appendix A.
4	Portfolio performance estimation	The total daily cost of the portfolio is predicted project-wise with the substitution of each multi-project membership value with the equation derived from step 1. The total daily cost is calculated by the aggregation of the project-wise results.	The number of publications was estimated project-wise using the equation derived from step 1. Portfolio performance was estimated through the aggregation of project-wise publications.
5	Iteration	An iteration of steps 2-4 was conducted while increasing the expected value of the program multi-project membership values in each iteration.	

2003); therefore, $d_x y$ characterizes programs.

The EU-funded projects are separated into three groups. During the construction of the membership function, the multi-project definition given by Miloševic and Patanakul (2002) was considered. *A project is considered a part of a multi-project if there exists at least one overlap in the duration* ($d_t \to 0$) with another project and the set of partners also overlaps ($d_o \to 0$). In addition, the volume (i.e., budget) of the project should be as similar as possible ($d_v \to 0$). The content could be different; therefore, this distance is not considered in the case of multi-projects. We specified the membership for the multi-project ($\mathscr{M}_m$) function for every project as follows:

$$\mathscr{M}_m(p_i) = \max_j \{(1 - d_t(p_i, p_j)) \cdot (1 - d_o(p_i, p_j)) \cdot (1 - d_v(p_i, p_j))\} \quad (9)$$

If $\mathscr{M}_m(p_i) = 0$, then p_i is not a part of a multi-project because it has no overlapping duration with another project, the owners of project p_i have no other project.

(Sub)projects of programs have a strong content relation (they should be in the same subprogram of FP7 ($d_y = 0$), and their descriptions should be related to one another ($d_x \to 0$). They also have a precedence of completion ($d_p \to 0$). Following the definitions that have achieved consensus among scholars (Miloševic and Patanakul, 2002; Miloševic et al., 2009; Ribbers and Schoo, 2002), the membership of program ($\mathscr{M}_p$) for project p_i can be calculated as follows:

$$\mathscr{M}_p(p_i) = \max_j \{(1 - d_p(p_i, p_j)) \cdot (1 - d_{xy}(p_i, p_j))\} \quad (10)$$

A project can simultaneously be a member of both a multi-project and a program; nevertheless, if $d_p(p_i, p_j)$ is high, then $d_t(p_i, p_j)$ is low, and vice versa. Strictly following projects do not overlap, and overlapped projects usually have no precedence but can have common resources.

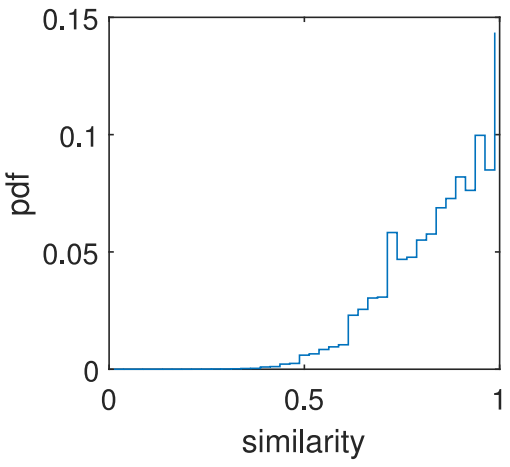
A project is a single project if it is neither a part of a multi-project nor a part of a program (Miloševic et al., 2009). Therefore, the membership of the group of a single project for project p_i, which is denoted as $\mathscr{M}_s(p_i)$, can be calculated as follows:

$$\mathscr{M}_s(p_i) = 1 - \max\{\mathscr{M}_m(p_i), \mathscr{M}_p(p_i)\} \quad (11)$$

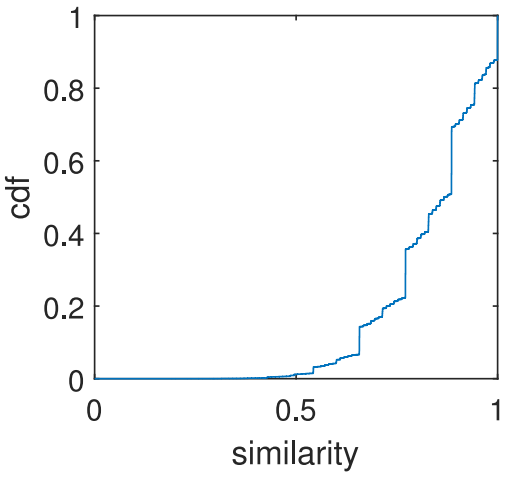
A project is categorized into a group where the membership value is the largest. Before the simulation, it is important to note that there is no superior project structure. Single projects are independent from one another; therefore, the risk to the group from single projects is the amount of risk derived from single projects. However, separated projects do not necessarily use previous project experiences, know-how, etc. Organizations that share their resources between projects can decrease the relative costs of the projects, while overlapping projects require more resources at the same time, and resource dependence can cause delays. The projects in programs are related to one another; therefore, the experience from previous projects and knowledge can be reused in later projects. However, if a predecessor project is delayed, then the successor project is usually also delayed. Therefore, the main risk of a program is delay.

4.2. Estimating the structure of the project portfolio and identifying the risk factors

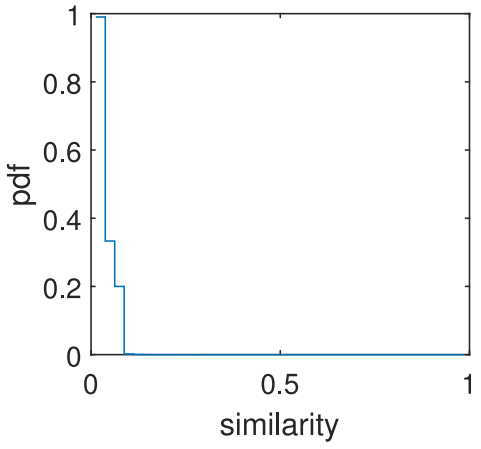
Since the real project structure within a project portfolio cannot be identified externally, first, the structure of the project portfolio is estimated using the classification of projects. As with the tasks in a project, the projects in a program are dependent on one another. If a predecessor project is delayed, then the start of the successor project might also be delayed, while in the case of overlapping projects, organizations have to manage common resources. If project p_j is a successor project of p_i, then the main risk factor is time delay. If projects p_k and p_l are in a multi-project organized by $o(p_k)$ and $o(p_l)$, then the main risk factor is the resources that common organization(s) ($o(p_k) \cap o(p_l)$) have to share. Since the duration of projects is known, in the first simulation, the risk effect of delay (i.e., an increase in delay) for the entire project portfolio will be explored. In an analysis of more than 1,100 software projects, McKinsey found an average time overrun of approximately 25 percent, and with 1,600 integrated-circuit design projects, the average overrun was approximately 30 percent. (Ben-Moshe et al., 2017). Multiple studies found that the average schedule overrun in R&D projects was between 25% and 37% (Kumar and Thakkar, 2017; Zwikael and Sadeh, 2007). Therefore, in our study, the risk effect, which is denoted as ρ_d, is assumed to be between 20% and 40%. This simulation highlights how an increase in the delay of a program is contingent on the ratio of dependent projects. The result helps decision makers at the project portfolio level balance the scope of the program and its risk of delay. In the second simulation, delay depends only on the rate of common resources in a



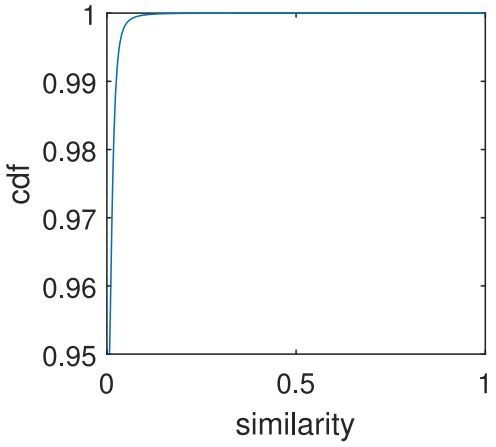
(a) Duration overlap (*pdf*)



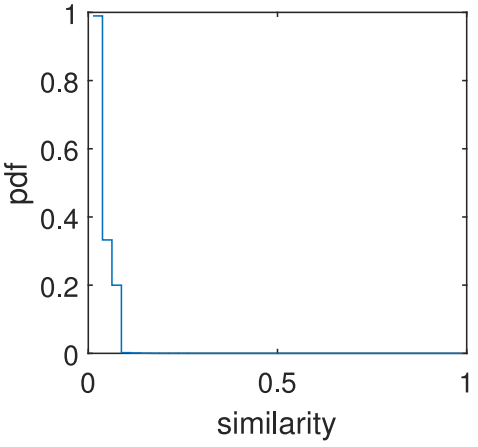
(b) Duration overlap (*cdf*)



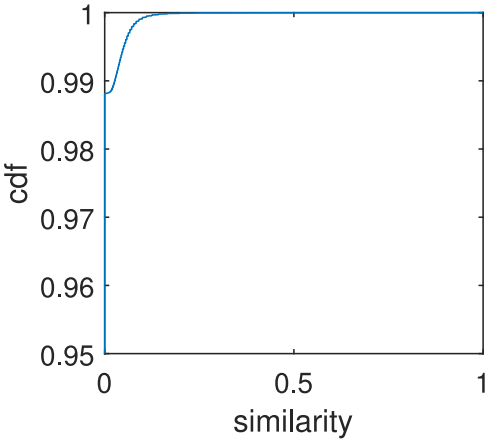
(c) Project description (*pdf*)



(d) Project description (*cdf*)

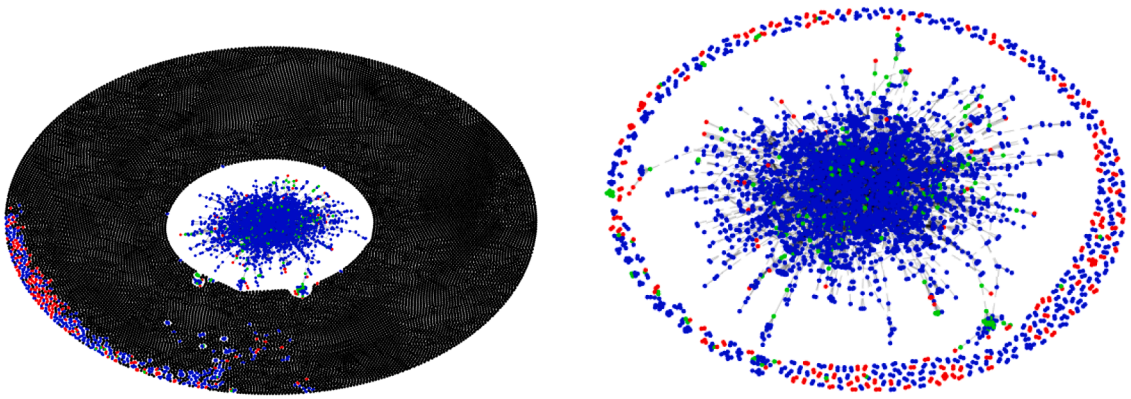


(e) Ownership (*pdf*)



(f) Ownership (*cdf*)

Fig. 1. Cumulative and probability distributions of the similarity metrics.



(a) Entire structure of the EU FP7 project portfolio including single projects, multi-projects and programs

(b) Structure of the multi-projects and programs in the EU FP7 project portfolio

Fig. 2. Structure of the EU FP7 project portfolio (links mean common resources in the case of multi-projects and dependencies in the case of programs).

multi-project. The rate of common resources ($r_c(p_i)$) for projects p_i is estimated as follows.

$$r_c(p_i) = \frac{1}{c(p_i)} \sum_j (1 - d_t(p_i, p_j)) \cdot (1 - d_o(p_i, p_j)) \cdot (1 - d_x(p_i, p_j)) \cdot (\min(c(p_i), c(p_j)) \tag{12}$$

where $r_c(p_i) \in [0,1]$. Since for the resource sharing, especially in the case of human resource sharing, which is the main resource used in R&D&I projects (Chen et al., 2019), overlaps in time (Elonen and Artto, 2003), in organizations (Camarinha-Matos et al., 2005), and in contents (Cooper et al., 2000) are required. In addition, in the multi-project environment, sub-projects often have similar resource needs (Yaghootkar and Gil, 2012) and nature (Zika-Viktorsson et al., 2006). Therefore, the rate of common resources (r_c) depends on the overlaps and the budget that can be allocated. $r_c(p_i) = 0$, considering all pairs of projects of project p_i in a multi-project, if either there is no overlap in time ($d_t = 1$), or there are no common owners ($d_o = 1$), or the project content is absolutely different ($d_x = 1$); otherwise, $r_c > 0$. $r_c \to 1$ if as many as possible related projects of p_i in the multi-project are overlapped, the organizations are common, the project description is as similar as possible, and finally the project budgets are also similar.

In the simulation, the duration ($t'(p_i)$) of a project (p_i) is related to the rate of common resources.

$$t'(p_i) \in (t(p_i), t(p_i) + t(p_i)\rho r_c(p_i)) \tag{13}$$

where $\rho \in [0,1]$ is the coefficient of the risk effect of delay, which according to Kumar and Thakkar (2017), was selected in [0.2,0.4].

This simulation indicates the risk effect of delay on common resources. This result is helpful for decision makers at the multi-project level who have to balance the number of projects and the sharing of resources.

4.3. Sampling

To estimate the relationship between program membership value and number of publications, a sample must be taken since in the case of FP7 projects, this information is not stored as a dataset. To determine the representative sample, multi-projects and programs are considered as proportions related to the population. The following equation can be used to determine an adequate sample size (Israel, 1992):

$$n^* = \frac{N}{1 + N(e)^2} \tag{14}$$

where N is the size of the population, e is the level of precision, and n^* denotes the adequate sample size. Using a 95% confidence interval and 5% precision, the sample size is 394, considering that the population size is 25,775.

4.4. Simulation steps

To simulate the risks across the portfolio, we conduct a simulation with two scenarios. On the one hand, we simulate how the change in the number of multi-projects affects the total cost and duration of the portfolio. On the other hand, the effect of a change in the program ratio on the total number of publications and portfolio duration is investigated. Table 1 introduces the structure of the two scenarios.

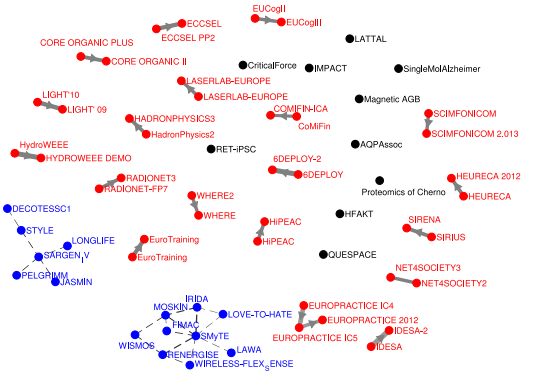
5. Results

5.1. Distribution of the similarities

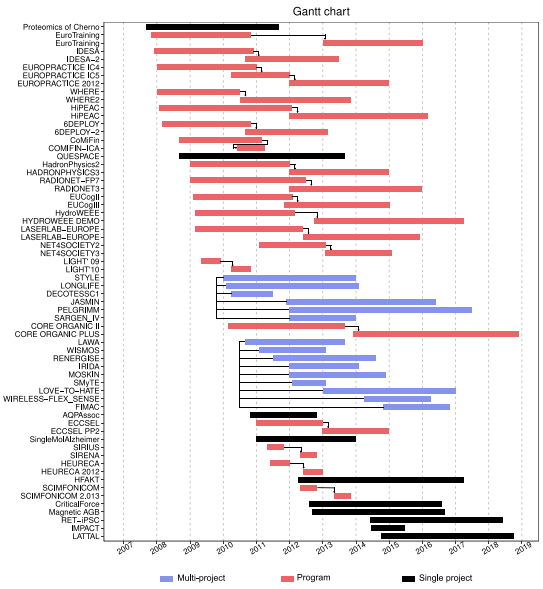
In this section, we introduce the distribution of the project similarity values across the entire portfolio (see Fig. 1). Note that although distances were used in Section 4.1, we apply similarity values ($s = 1 - d$) here for simplicity.

First, the pairwise similarity matrices were extracted in terms of duration overlap (Fig. 1(a-b)), project description (Fig. 1(c-d)) and ownership (Fig. 1(e-f)). Then, probability distribution functions (*pdfs*) and cumulative distribution functions (*cdfs*) were extracted and visualized for each similarity. A *pdf* shows the shape of the distribution, while a *cdf* is useful to observe important cutpoints (such as quantiles) of the population.

Fig. 1 (a-b) shows that projects highly overlap over time. This is due to the numerous (25,770) projects that had to be started within the seven-year period of FP7 and the long (1,203 days) average duration of projects. In addition, the low similarity value of the project descriptions (see Fig. 1(c-d)) indicates that the project scopes are very heterogeneous. The long average duration and the heterogeneity of the projects indicate that the number of programs where projects are related to one another is low. However, the overlap durations of projects provide an opportunity to organize them into multi-projects. In this case, the project owners should be (at least partly) common. Nevertheless, the low values of organization similarities (see Fig. 1(e-f)) indicate a small number of multi-projects.



(a) Structure of the sample; links between multi-projects and programs in the project portfolio



(b) Schedule and links of the project portfolio (links mean common resources in the case of multi-projects and dependencies in the case of programs

Fig. 3. A sample of the EU FP7 project portfolio.

5.2. Classification of projects

Fig. 2 depicts a graph of the project portfolio, where the points (nodes) represent the projects and the links represent the relationships (i.e., dependency and/or common owners) between them.

The red nodes are programs, and the blue nodes denote multi-projects. Projects with both multi-project and program characteristics are colored green; finally, the black nodes are single projects.

Fig. 2 (a) shows the classification of the FP7 project portfolio. Of the total 25,770 projects, single projects are the most common (13,555). The second-largest group is multi-projects (11,367) (see the blue points (nodes) in Fig. 2(b), while there are fewer programs (106) and only some (742) projects, which can be considered both programs and multi-projects.

To validate the proposed method, a classification based on the calculated membership values was investigated. We selected a set of projects including the ones with the top membership values in each category given by the proposed method. This sample yielded 64 projects for which we manually reviewed the project descriptions and owners to determine if the calculated membership values reflect the correct classification of the three project types.

Fig. 3 (a) shows the dependencies between the selected projects in a graph, and Fig. 3(b) presents their dependencies in a Gantt chart to show the schedule within the validation set.

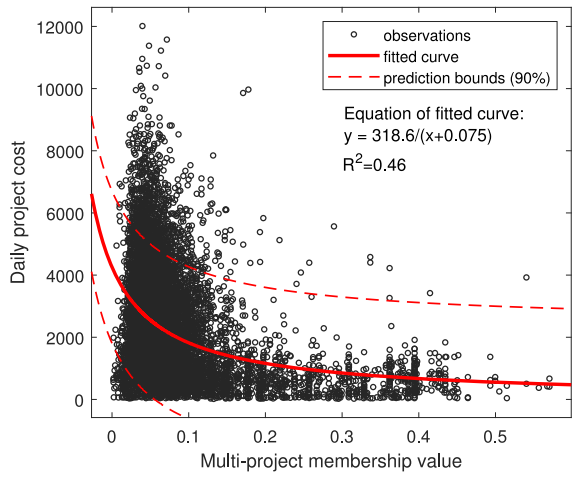
In the case of programs, not only the descriptions but also the acronyms of the projects are similar (see Fig. 3). The projects in a program either do not overlap or slightly overlap over time (see Fig. 3(b)), while multi-projects and single projects overlap more over time. Because of the limited timespan of FP7 and the long duration of projects, the number of projects in a program is very limited and includes only 2-5 projects. Similarly, the subnetwork of the programs (see the red points and their links in Fig. 3(a)) is more fragmented than the subnetwork of multi-projects (see the blue points and their links in Fig. 3(a)).

5.3. Effects of multi-project and program changes across the portfolio

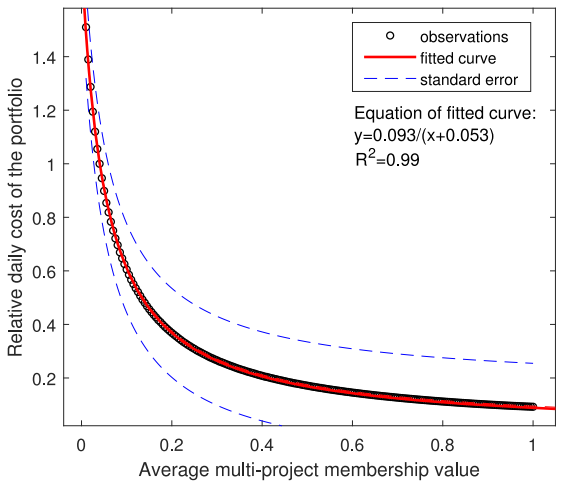
In this subsection, the daily cost and publication performance are investigated with respect to the multi-project and program membership values. Fig. 4(a) shows the daily project cost in terms of the calculated multi-project membership values. The daily cost values were extracted from the database for each project, and a robust curve fitting method, the least absolute residuals (LAR), was applied to characterize the relationship as a rational function (the result of step 1 in Table 1). The relationship between daily project cost and program membership value was also investigated, but no significant relationship was observed. Fig. 4(b) shows the aggregated results concerning the entire portfolio as described by step 2 in Table 1. Fig. 4(c,d) depicts the results related to the programs.

Fig. 4 (a) shows that the daily cost decreases if the rate of multi-projects (which is characterized by the multi-project membership value) increases. This result is in line with expectations (see Section 1). Multi-project managers can allocate resources and parallelize activities to reduce project costs. On the one hand, the result of the robust regression analysis yields a moderate coefficient of determination ($R^2 = 0.46$), but on the other hand, the variance is higher in the case of a low rate of multi-projects. This means that additional aspects play a role in daily costs; nevertheless, the rate of multi-projects (i.e., the multi-project membership value) is a significant structural variable for the project cost. Regarding the specified daily cost, the multi-project membership function can be extrapolated to the entire project portfolio. Fig. 4(b) shows how the relative daily cost changes if the rate of multi-projects (i.e., the average multi-project membership value) changes. Fig. 4(b) is aligned with 4(a). If the average multi-project membership value increases, then the daily costs can be reduced.

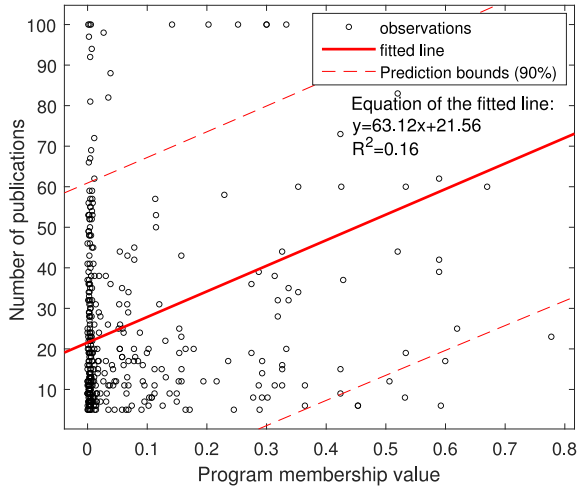
When the rate of programs (which is characterized by program membership) increases, the project output (i.e., the number of publications) can also increase (see Fig. 4(c)). We also tested the relationship between number of publications and multi-project membership value was also investigated, but no significant relationship was observed. This can be explained by the fact that the subsequent projects in a program can build on the results of prior projects. However, the rate of growth decreases 4(d)). One reason for this effect is that the number of completed projects decreases because the time of FP7 is limited and the overlaps between projects in a program are low. In addition, the number of projects in a program is limited (see Fig. 3(d)); therefore, later projects in a long program cannot be completed, and several manuscripts cannot be published in the funding period. Finally, dependent projects may have more time risks if a previous project in a program delays the



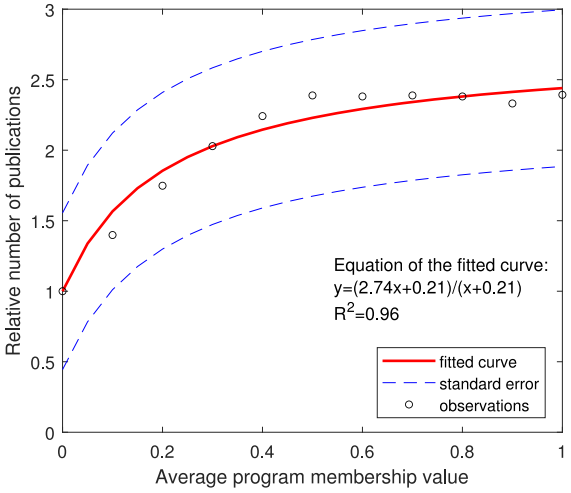
(a) Relationship between the multi-project membership value and daily project cost



(b) Effect of the change in the average multi-project membership value on the total daily cost



(c) Relationship between the average program membership value and the number of publications



(d) Effect of the change in the average program membership value on the total number of publications

Fig. 4. Publication and cost with respect to the multi-project and average program membership values.

start of a successor project. This problem can be addressed in different ways; therefore, the variance is higher in the case of a higher rate of programs (see Fig. 4(d)).

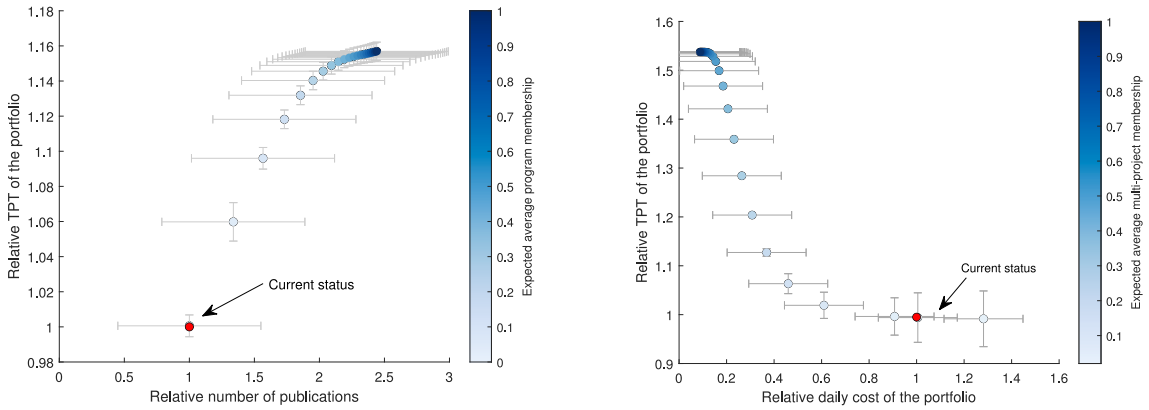
5.4. *Effect of restructuring the project portfolio*

In this section, the tradeoffs between time vs. cost and time vs. publication output are specified depending on the expected average membership value of multi-projects and programs across the portfolio.

As a further dimension, the previously presented analyses were extended with the duration of the portfolio (TPT) to estimate the tradeoff curves related to the number of programs and multi-projects within FP7. The TPT values were obtained during the steps described in Section 5.3. TPT and the number of publications were considered in the case of programs, while TPT and the daily cost were examined in the case of multi-projects (Fig. 5).

During the simulations, each point was generated multiple times. The circles represent the expected value, while the error bars reflect the standard deviation of the generated data points at a given iteration.

The coordinate (1,1) in Fig. 5 shows the current states of the rate of programs (Fig. 5(a)) and the rate of multi-projects (Fig. 5(b)) in the project portfolio. Increasing the rate of programs increases project output (i.e., publications) more significantly than the duration of the project portfolio (see Fig. 5(a)). Nevertheless, the growth of publications decreases, while the growth of the duration increases. A smaller change in the duration of the portfolio is only possible if the number of projects in a program does not increase (still 2-5 projects per program) and the rate of independent projects (in terms of content) decreases. The standard deviation of the data points continuously decreases as the expected program membership value increases, while the standard deviation of the simulated data points is nearly unrelated to the number of publications (as reflected by the error bars). Fig. 5(b) depicts a time-cost



(a) Relationship between the relative number of publications and the duration of the project portfolio (TPT)

(b) Relationship between the relative daily cost of the portfolio and the relative TPT of the portfolio

Fig. 5. Tradeoff curves.

Table 2
Results and policy implications.

Nr.	Research question	Result	Policy implications
1	How sensitive are costs (the risk of delays and relative costs of the projects) and outputs (benefits) to changes in the distribution of single projects, multi-projects and programs in a given portfolio structure?	Programs are more sensitive to outputs than to TPT. Multi-projects are more sensitive to the relative daily cost than to TPT up to approximately a 0.3 expected average multi-project membership value, but above a value of 0.3, multi-projects are more sensitive to TPT than to the relative daily cost.	*Implication 1a:* Supporting programs results in significant performance growth, while the duration only increases slightly *Implication. 1b:*. Funding for multi-projects makes sense from a cost perspective up to a certain point, and then, the longer duration takes effect.
2	Is there an optimal ratio of single projects, multi-projects, and programs with respect to costs (the risk of delays and relative costs of the projects) and outputs (benefits)?	Since the rate of single projects is high, increasing multi-projects and programs (with a share of approximately 10%) at the expense of single projects results in cost reductions and an increased number of publications, while TPT hardly increases.	*Implication 2:* The relative cost and output with a high proportion of single projects in the portfolio can be improved by moderately increasing the proportion of multi-projects and programs without a considerable risk of delay.
3	How can projects in an unstructured project portfolio be meaningfully classified based on publicly available data?	Projects can be meaningfully classified by pairwise distances in terms of overlap duration, precedence, ownership, volume, and content (description). The membership values for each project can be estimated using the distance matrices introduced in Section 4.	*Implication 3:* The structure of a naturally grown, unstructured portfolio can be mapped very accurately with little, often publicly available, data.

tradeoff curve. Increasing the expected average membership value of multi-projects decreases the daily cost and increases the duration of the project portfolio. The longer duration multiplied by the daily cost induces additional costs, but these additional costs are smaller than the cost reduction achieved by the reduction in the daily cost of the portfolio. The standard deviation during the simulation is constant in the case of the daily cost, while it rapidly decreases to zero when the change in TPT is simulated.

6. Discussion

Our study investigated the structure of FP7 from a project management perspective in several ways by utilizing the FP7 database provided by CORDIS. We estimated each project's membership value based on specific characteristics for the classification of portfolio elements. In addition to an analysis of the current structure, we also conducted several simulations to investigate the tradeoffs. Table 2 summarizes the results and policy implications related to our research questions.

First, our research reveals the sensitivity of the costs (the risk of delays and relative costs of the projects) and outputs (publications) to the changes in the distribution of single projects, multi-projects and programs in a given FP7 project portfolio. Our findings indicate that programs are more sensitive to outputs (i.e., the number of publications) than to the duration of project portfolios (TPT). This means, for example, that if the expected average program membership value is increased from nearly zero to 0.5, the number of publications is increased approximately by a factor of 2, while TPT is increased by only a factor of 1.15 (see Fig. 5(a)). Notably, because of the 7-year limitation of the FPs and the average 1.5-year duration of a project in an FP, only 3-5 projects can be started within an FP; therefore, the effect of delays is much lower than the increase in publications. This result suggests an important policy implication because supporting programs at the detriment of single projects results in a considerable increase in publications (performance), while TPT increases only slightly. Moreover, our findings demonstrate that multi-projects are more sensitive to the relative daily cost than to TPT up to an approximately 0.3 expected average multi-project membership value, but above a value of 0.3, multi-projects are more sensitive to TPT than to the relative daily cost. For example, if the expected average multi-project membership value is increased from nearly zero to 0.2, the relative daily cost is decreased by approximately 40%, while TPT increases by only 5% (see Fig. 5(b)). This implies that it is worth supporting multi-projects only up to a certain point where the advantages of multi-projects can be utilized without a significant TPT increase. Finally, increasing the rate of multi-projects does not necessarily mean that few organizations should earn more projects. The impacts of sharing resources between parallel projects can already hold with only a few projects; however, the adequate management of parallel projects can significantly reduce project costs.

Second, since the rate of single projects is high, increasing multi-projects and programs (which represent approximately 10% of the portfolio) at the expense of single projects results in cost reductions and an increased number of publications, while TPT hardly increases (see Fig. 5). As a result, the relative cost and output in a portfolio with a high proportion of single projects can be improved by moderately increasing the proportion of multi-projects and programs without a considerable

risk of delay. These results offer new insights into the tradeoffs within FP7 that must be considered by policy makers in the future.

Third, this paper provides, for the first time, empirical evidence of the classification of FP7 project portfolios such as single projects, multi-projects, and programs. Our findings indicate that more than half of the projects (13,555) are single projects in the FP7 project portfolio. It is also interesting to note the very low rate of programs in the FP7 project portfolio, including 106 programs and 742 further projects, which can be considered both programs and multi-projects (see Fig. 2). These findings shed light on the real structure of the EU FP7 project portfolio and the distribution of different projects within it. This result offers new insights regarding the policy implications. Although one of the main goals of the EU FP7 projects is to increase collaboration among organizations (Decision N° 1982/2006/EC;European Parliament, 2006), our results show that the FP7 project portfolio still predominantly consists of separate single projects. Although programs including related projects could produce more output, e.g., publications and other research output, this goal is not achieved given the relatively low number of programs in the FP7 project portfolio.

7. Conclusion and limitations

Our study contributes in several ways to the understanding of R&D&I funding structures, such as FP7, from a project management perspective. On a theoretical level, we showed that the structure of a naturally grown "unstructured" portfolio can be mapped very accurately with little, often publicly available, data, e.g., precedence, ownership, volume and content. Each project can be classified as either a single project embedded in a multi-project environment or part of a program. Moreover, single project, multi-project (independent but overlapping resources and time), and program (mutually dependent and shared goals) proved to be useful concepts to describe even an unstructured project portfolio. Although this study is based on the project data of FP7, the proposed method is not limited to the presented framework program if at least the following five properties of every project in the framework program are known: (1) budget; (2) duration, including the start and finish times of the project; (3) project output; (4) project ownership; and (5) a description of the project content. In this way, it is possible to characterize not only the collaboration network of the framework program but also the structure and relations of the projects.

We showed that considerations proposed in the literature regarding the effects of the distribution of single projects, multi-projects, and programs on time, costs, and output hold true even in an unstructured project portfolio. The ratio of multi-projects is – up to a certain threshold – more sensitive to the relative daily cost than to the duration, while the ratio of programs is more sensitive to the output than to the duration. Although this study uses data from an unstructured project portfolio, we believe that the results are even more valid for structured and managed R&D&I portfolios.

On a practical level, our results demonstrate that the relative cost and output can be improved in a high proportion of a single projects with an almost unchanged duration in a project portfolio by altering the overall structure, i.e., by moderately increasing the proportion of multi-projects and programs. This is especially true for undermanaged project portfolios such as FP7. In such bottom-up portfolios, structure is the result of social (oligarchic) networks and path dependence in collaborations, which proliferates in a specific project ecology characterized by internationally and research-oriented scholars and professionals in knowledge-driven organizations. Although these types of networks have some advantageous effects on trust and communication, the structure of the network often suffers from the formation of local islands and little integration. The structure is highly fragmented compared to common project portfolios and cannot therefore take full advantage of opportunities.

We acknowledge that the appropriate ratio of single projects, multi-projects, and programs in each FP with respect to costs and outputs depends on the goals of policy makers, but the results offer new insights into the tradeoffs within FP7 that need to be considered in the future. The aim of EU framework programmes centers on increasing collaboration among organizations; however, our results show that this aim is not fully met. Moreover, publications and other research outputs can be increased with only a slight effect on the cost and duration by restructuring the design of the portfolio. Decision makers in the EU are aware of the lack of interdependence since there are more efforts in this direction in the current H2020 framework programme. Nevertheless, the EU continues to fund projects and programs but does not manage them appropriately.

We therefore suggest that the EU should (also) understand its FPs as project portfolios embedded in a distinct project ecology and more clearly implement at least rudimentary instruments of portfolio management. FPs have to establish a governance structure that not only more accurately specifies the objectives and scope but also places significantly greater emphasis on the establishment of programs in the run-up to their launch. Beyond EU frameworks, publicly funded R&D&I programs often fail to be planned with foresight; rather, they are executed by bottom-up networks that tend to fragment with only a few well-established clusters. R&D&I programs should thus be initiated, encouraged, and cultivated by influential (external) policy makers, e.g., public funding agencies, government departments, and multilateral promotion services, in line with a clear strategic goal.

Finally, this study has some limitations. As described above, FP7 features specific characteristics, in particular the lack of an identity as a project portfolio and subsequent managing instruments. Fundamentally, we believe that most of the results, especially with respect to the distribution effects of the project types on the costs, duration, and output, apply to all R&D&I portfolios, including those with a stronger structure. However, the concrete effects would have to be tested on other research project portfolios, especially with contrasting designs and management philosophies, and in various project ecologies. Project portfolios in a national or corporate context, for example, may have significantly different conditions regarding organization and control. Furthermore, both the design and the subsequent management of project portfolios are critical for success, and we would not choose one over the other. In this paper, we focused on the impact of design. Given the limited data from the CORDIS system and setup of the study, we could not examine the trade-off between design and management effects. In addition, we accessed only publicly available data; therefore, we rely on the accuracy of third-party data collectors and completeness at the time of the project reports. We provide an external view of only a project portfolio; the internal views of project promoters, especially regarding basic considerations about the policy and the structuring of a portfolio, remain to be examined. The possible effects and resistances on the part of the supported institutions must also be examined.

Data statement

All Python code is available for decision makers to test different ratios of single projects, multi-projects and programs to optimize the structure of the desired project portfolio.

Declaration of Competing Interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

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Appendix A. Illustration of the iterative changes in the NDSM matrix

Dependency probabilities are reflected by the program membership values in the NDSM matrix. The program membership values were generated with MATLAB's "*persrnd*" random number generator function. During the generation, only $n \times n$ submatrices across the diagonal were applied to prevent the joining of unrealistic numbers of projects into a program. In our analysis, n was set randomly from 2 to 5 following a uniform distribution, which means that only 2-5 random submatrices were allowed across the diagonal, and all the remaining values in NDSM were set to zero. We chose 5 as the maximal value for n because we found that considering the average project time, 5 projects can follow one another within the time frame of FP7. The program membership values (dependency probabilities) were generated with specific distribution parameters (with continuously increasing expected value), and only the upper triangle of the submatrices was considered because symmetric matrices cannot be interpreted in the case of dependencies. In each iteration, the duration of the portfolio was calculated using the start and end dates, the duration of the projects and the generated NDSM matrix (Fig. A.1).

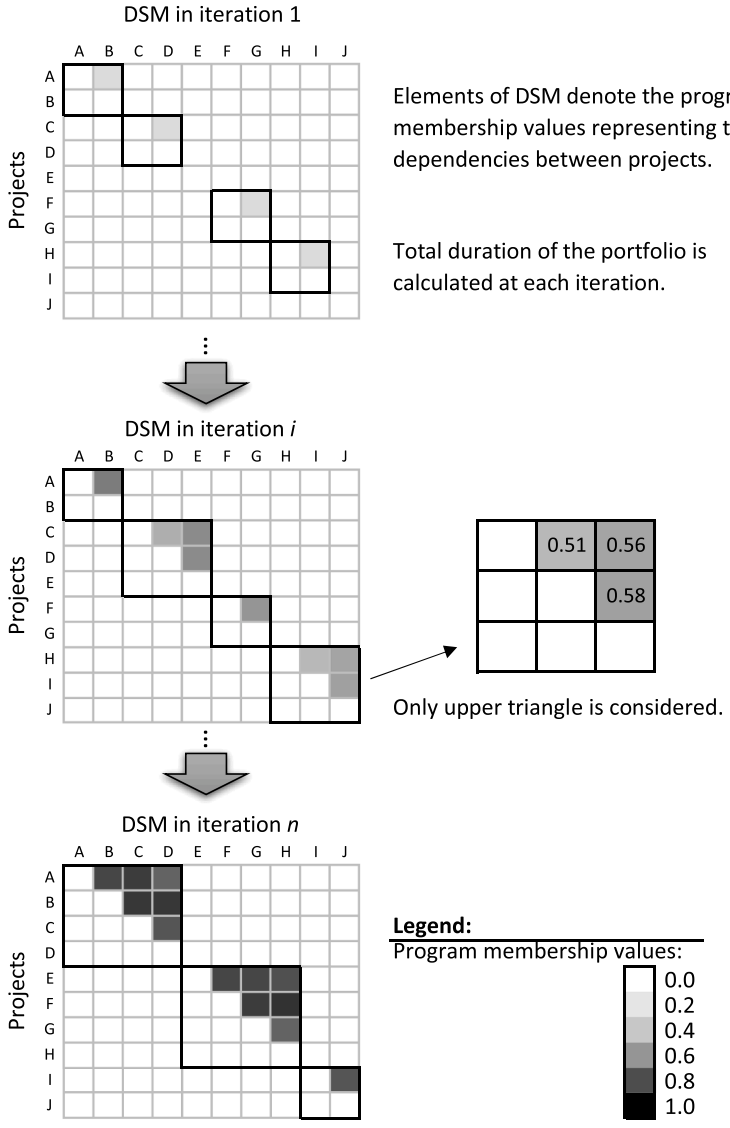


Fig. A.1. Illustration of the simulation.

Appendix B. Illustration of the delay in the case of multi-projects

To simulate the delay given the share of resources, we adjusted the start dates of the projects that were part of a multi-project considering their multi-project membership value, as reflected by Fig. B.1. First, the earliest project was selected, and the following projects' start dates were delayed based on the following formula:

$$s_i^* = s_i \cdot [1 + \mathscr{M}_m(p_i)] \tag{B.1}$$

where s_i is the initial start date, s_i^* is the delayed start date, and $\mathscr{M}_m(p_i)$ is the multi-project membership value of the ith project. That is, the projects that had stronger multi-project characteristics indicated by $\mathscr{M}_m(p_i)$ were delayed more since $\mathscr{M}_m(p_i)$ also represents the share of resources.

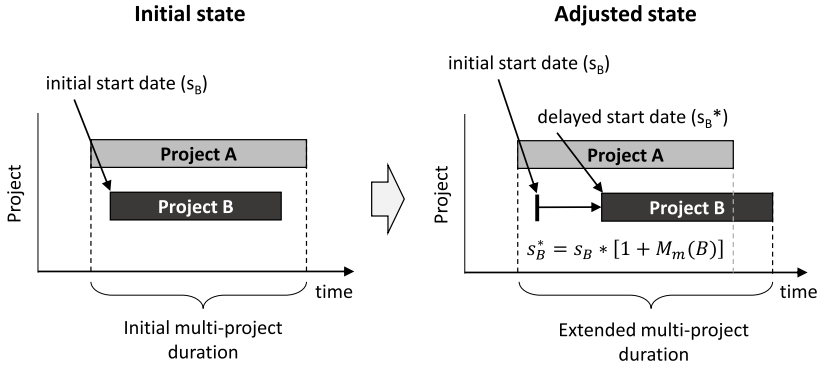


Fig. B.1. Illustration of the delay in the case of multi-projects.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.techfore.2022.121687.

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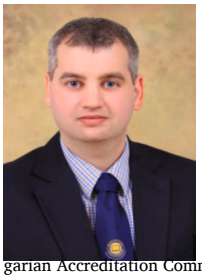
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