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Regular Article

Using Social Network Analysis to gain insight into social creativity while designing digital mathematics books

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ABSTRACT

Analysing the processes and products of creativity to better understand and support individuals and teams, is a difficult and elusive challenge despite years of research in creativity. In this article, we are particularly interested in social creativity in communities of interest. Building on Guilford's classic model of Divergent Thinking of fluency, flexibility, originality and elaboration, we employ Social Network Analysis to model the creative design process. The creative process in the current study takes place in a technological environment called the 'MC-squared platform', in which members of a community of interest collaborate in a social, co-creative process for designing digital, mathematical textbooks. Both the technological environment and the methodology are exemplified through two case examples, one on the design process of a digital book about a bioclimatic amusement park and one on the design process of a digital book about fractions. We conclude that, for these examples, both the technological tool and the data analysis approach provide insight into the social creativity process of the community of interest.

1. Introduction

Creativity is often deemed an invaluable feature of education. In their position paper *The Future We Want*, the Organisation for Economic Co-operation and Development (OECD, 2018) describes what they see as the knowledge, skills, attitudes and values today's students need to thrive and shape their world. Creativity is mentioned as one of the key underpinning constructs. At the same time, humans have collaborated to reach goals for thousands of years. It is therefore perhaps not surprising that creativity is seen to be vital in our current society, with a reliance on collaborative efforts to try and address society's challenges (Fiore et al., 2018). However, it has also been challenging to analyse creativity in these collaborative processes and products. When can a collaborative process or product be called a 'creative' or 'innovative'? Following several of Wise and Schwarz' (2017) provocations for Computer-Supported Collaborative Learning (CSCL), can we make use of the educational data within collaborative, technological environments to make advances in our understanding of such interaction dynamics? In a recent European project under the FP7 framework (Bokhove et al., 2014; Kynigos, 2015) the MC-Squared project aimed to "design and develop the c-book, a digital system as enabler for creative design processes and creative mathematical thinking". Creativity is both relevant for the students using the books, as the members of the Community of Interest (CoI) who design the books. One important requirement for this was to think about and conceptualise how to analyse both the creative process and the resulting creative end-products, creative digital books for mathematics. The project provided an authorable dynamic e-book infrastructure for professionals to collaboratively design such creative books for students. Communities of Interest from different countries, each consisting of diverse actors involved in design and production of the digital books, collectively produced a set of example books. As the members of the communities recorded their contributions to the design process, it was possible to get further insight in the role of creativity during the group's social creativity. As a result, we can use this project to take a new look at the way in which groups organise their creative processes within a technological environment. The aim of this paper is two-fold. Firstly, to describe the use of a digital support tool to record and map the creative design process in an authoring tool. Secondly, to show how the data can be critically analysed with common metrics and algorithms available from the discipline of Social Network Analysis (SNA), thus operationalising the creative design process. The use of such common metrics and algorithms steers clear from the

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limitation that arbitrary analysis methods apply to one context, but not another, for example as in work using the same platform (Kynigos et al., 2020). In doing so, this paper describes how adopting new approaches in creativity research might bridge methodological gaps that often arise when paradigms clash. As Plucker et al. (2019, p. 58) note, creativity research very strongly relies on traditional assessment approaches, and we think we can contribute to a call in exploring alternative methodological approaches, especially those that might scale up. We first describe some of the relevant literature that underpins our thinking.

2. Study background

The field of creativity has been studied for numerous decades, and it is, therefore, difficult to discuss its rich history extensively within the context of this article. Rather than do this we describe four important assumptions in this study. The first assumption is that groups of actors together can engage in a creative process to create (creative or non-creative) end-products, so-called 'social creativity'. Secondly, we draw from Wenger and Fischer's work on Communities of Practice and Communities of Interest to argue that groups or communities can contribute to social creativity through the use of socio-technical environments. To conceptualise this so-called 'social creativity', we provide a description of one way of measuring creativity, our third assumption. Finally, as a fourth assumption, we propose that Social Network Analysis (SNA) can be used for describing group creativity. We now describe these four assumptions more fully.

2.1. Social creativity in communities

'Social Creativity' has been proposed as a theoretical frame and as a construct for understanding and fostering creativity in collectives operating within particular environments. Clinton and Hokanson (2011), for example, highlighted the role groups have played in creative work. As a case in point they cite Feldman (1998): "It is common to find that the unique form of a creator's work is forged within a small group of peers … The group is catalytic to the transformation of style and content" (p. 176). Creativity can therefore be seen as part of a *social system*, and does not just pertain to the individual. In line with this, Csikszentmihalyi also highlighted that "creativity does not happen inside people's heads, but in the interaction between a person's thoughts and a socio-cultural context. It is a systemic rather than an individual phenomenon" (1996, p. 23). This aspect also can be described as *situated creativity*, in which the whole collective performance can be greater than the sum of its parts (Dennis & Williams, 2003; Hooker et al., 2003; Nemeth & Nemeth-Brown, 2003). Without neglecting or minimising the contribution of 'individual' creativities, Social Creativity treats them as sources and manifestations of a 'socio-cultural' capital (in terms of educational and disciplinary background, life experience and professional expertise, as well as the cultural and epistemological antecedents of all these) each individual brings with her, which is voiced in the individual's distinctive perspective towards addressing a particular problem or situation. In short, 'Social creativity' as a construct builds on the wealth of these diverse individual perspectives brought in by different stakeholders. For example, Montuori and Purser (1999) said that "many creative activities today involve social and collaborative processes" (p. 4). The 'social dimension' of creativity is thus recognised in the exchange and negotiation processes taking place between individuals leading to the co-construction of a new, shared and more enriched perspective (John-Steiner, 2000), and capitalised in achieving progress with regard to creative performance. As a recent example, Mavri et al. (2020) highlighted the creative outcomes of communities in a higher education context. In the context of healthcare, Coursey et al. (2018) highlight that "if a topic engages people with different perspectives to actively respond to others' ideas, this can increase the creative potential of idea sharing in groups" (p. 253). This study aims to look at social creativity in the design process of some digital mathematics books.

2.2. Communities of interest can foster social creativity through socio-technical environments

The construct of 'socio-technical environments' sometimes refers to appropriate and purposefully designed settings for supporting social creativity to attain specific goals. From a social creativity perspective, socio-technical environments are creativity-enhancing contexts, in the sense that they create opportunities for communities of diverse practitioners to learn from, work with and collaborate across the 'barriers' that divide them and by this to explore and expand their creative potential (Fischer, 2004). Their role is to technically support and successfully encourage the practitioners' participation in collectives (Fischer, 2011) and to empower them to become more effective and reflective through overcoming problems, learning from each other and extending their individual abilities (Fischer, 2005). Fischer (2001) put forth the idea of Community of Interest (CoI), a collective of practitioners from diverse disciplinary and professional domains. CoIs are "defined" by their shared interest in the framing and resolution of the problem they want to focus on and address (Fischer, 2004). They are also characterised by heterogeneity and specialization, two conditions that bring forth breakdown and conceptual collisions which in their turn are important elements in fostering creativity (Fischer & Giaccardi, 2007). A CoI's creative potential is the "symmetry of ignorance" or "asymmetry of knowledge" (Rittel, 1984) across their members (Fischer, 2001). Among the challenges a CoI has to face is to develop a shared understanding (Resnick et al., 1991) of the task-at-hand, not an obvious and easy thing to do, especially at the beginning of their joint work. Learning to collaborate, to communicate and learn from each other's perspectives (Engeström, 2001) are at the same time challenges and opportunities for CoI members in the pursuit of social creativity (Arias & Fischer, 2000). West (2008) dubbed communities with shared innovation 'Communities of Innovation' (unhelpfully CoI as well) and identified key principles for the formation of a community of innovation: diversity, interdependence and full participation among group members; idea generation and selection; and a supportive climate for innovation. Note, however, that innovation should be seen as distinct from a creative performance, aimed at "taking a creative outcome (i.e., idea, process, or product) resulting from creative processes and implementing it within a given context." (Porter et al., 2020, p. 54). One particular way of approaching such communities, according to West (2008), is to focus on the creation of physical or conceptual artefacts. Actors, actions, artefacts, audience and affordances come together in Glăveanu's (2013) Five A's Framework, which fits a dynamic group process. Glăveanu's (2020) socio-cultural theory of creativity considers creativity "as a process of recognizing differences, exchanging positions, developing perspectives and discovering affordances" (p. 335), bringing together the social, the material and the psychological. Rudnicki (2021) further explores the socio-materiality of the creative process, in which ideas are dynamic, socio-material and relational entities that come into being with the help of materials and technologies. Such instrumented activity also has roots in the anthropological views of Verillon and Rabardel (1995) where the artifact shapes the thinking of the user, and the artifact is also shaped by the user. Artefacts in the social creativity context can be seen as *externalisations*, in the sense how Dove et al. (2018) describe the role of Post-It notes: they have an informational function in communicating one person's idea so someone else can share a similar understanding; a formational function in helping an idea into being; a transformational function to support continuing cognitive activity; and a transcendental function supporting structuring and manipulation of new ideas, which lead to new concepts and insights. Other researchers have sometimes referred to artefacts on the boundary of communities as *boundary objects* and the process of crossing from one community into another a process of *boundary crossing* (Akkerman & Bakker, 2011). The activity in this study, creating digital mathematics books, could be perceived as such a boundary object. We see the task to work on this boundary object very much as a 'standard instruction', which according to Runco (2010) can be designed to encourage divergent thinking.

Numerous projects have tried to combine social creativity with technology. For example, Pifarre (2019) described how interactive technologies can be used to promote dialogic spaces for co-creative processes. In the context of science education, Aguilar and Turmo (2019), showed how technology can play different roles in promoting social creativity, including serving as a medium that builds the supportive environment to perform collective creativity processes. Gabriel et al. (2016) performed a systematic mapping study of the literature on existing digital tools dedicated to creativity as 'Creative Support Systems'. One of the points they flag is about *assistance* in the creative process. Coursey et al. (2019) used an electronic discussion board for ideational exchanges, with explicit divergent and convergent phases. The issue of the technological environment allowing both divergent and convergent ideation is something we return to in the discussion section of the paper. The idea behind the current study is that the assistance of a socio-technical environment would allow us to also capture the creative design process whilst designing digital mathematics books. But how could we measure that?

2.3. How could creativity be measured in online discussion environments?

Measurement issues in creativity can be broadly divided into two categories (Villalba, 2010). On the one hand, there are creative measurements derived from psychological-related literature. A second category of creativity measurement relates to aggregate levels of creativity. As reiterated again in the most recent Cambridge Handbook of Creativity, there is a tension between individual measurement and the challenge of 'scaling up' to larger groups (Plucker et al., 2019). In this study we aim to 'translate' classic, individual instantiations of creativity in a 'community' context. Many well-known batteries of psychometric tests of divergent-thinking have been developed and applied within this field of research, with an aim to provide a quantifiable measure for assessing creativity as a process of thinking (Getzels & Jackson, 1962; Guilford, 1967; Torrance, 1962, 1974; Wallach & Kogan, 1965). We can argue that creative outcomes appear in two forms: either in the form of ideas (the outcomes of the generation phase of the creative process) or in the form of final products, either tangible or intangible (the end-outcomes of the creative process). Nevertheless, final products are also closely associated with idea formation, and creative products in any field are said to embody 'good ideas'. How such ideas come about is not always clear. Sometimes creativity comes about through blind chance, serendipity, pseudo-serendipity or self-induced luck (Cropley & Cropley, 2010). In other cases, a creative outcome can be traced back to a good or bad idea that started it off. A creativity-enhancing environment, then, is one that seeks and manages to promote and maximise people's potential to generate lots of different ideas, advance the exploration and expansion of existing ideas, and/or the combination, merging and synthesis of more ideas into new conceptual entities. The four elements of fluency, flexibility, originality and elaboration form part of the classic Guilford's model of Divergent Thinking which stems from the 1950s (Guilford, 1967). Although several scholars have attempted to operationalise the four components of a creative cognitive performance, we base our study on four of Guilford's (1973) characteristics of creative adults.

- Fluency: the ability to think of many ideas; many possible solutions to a problem
- Flexibility: the ability to go beyond tradition, habits, and the obvious. To turn ideas and materials to new, different, and unusual uses.
- Originality: divergent rather than convergent thinking, going beyond commonly accepted ideas to unusual forms, ideas, approaches, solutions.
- Elaboration: the ability to work out the details of an idea or solution.

As per Runco (2010) we contend that these indices can be reported independently, but together can be taken to be a profile. In this study we explore whether we can use this terminology in a community context. We can model them as social networks.

2.4. Modelling communities as social networks

Now we have articulated that communities can display social creativity, and that we want to capture this creativity by looking at the fluency, flexibility, originality and elaboration in a group's creative process, we make the step that such group processes might be captured by Social Networks Analysis (SNA). Our line of reasoning is that the standardised terminology and metrics in SNA could provide a uniform method for analysing such processes. SNA looks at social relationships in terms of network theory, consisting of nodes, representing actors or ideas within the network, and ties (or edges) which represent relationships between the nodes. Originally the concept of 'social networks' has been studied since the early 20th century to explore relationships between members of social systems. In more recent years, SNA has found applications in various academic disciplines, as well as practical applications such as countering money laundering and terrorism. It is outside the scope of this article to give an overview of the whole field; for this there are basic introductory texts on SNA (e.g. amongst others, Prell, 2011; Scott, 2012; McCulloh et al., 2013). Freeman (2004) reviewed the development of SNA from its earliest beginnings until the late 1990s. He characterises SNA as involving four elements (i) the intuition that links among social actors are important, (ii) it is based on the collection and analysis of data that record social relations that link actors, (iii) it draws heavily on graphic imagery to reveal and display the patterning of those links, and (iv) it develops mathematical and computational models to describe and explain those patterns. SNA maps and measures relationships and flows between people, groups, organizations, computers, and other connected entities, and allows for both a visual and mathematical analysis of human relationships. SNA has been used before to capture learning as 'collaboration analytics' (e.g. see some examples in Becheru et al., 2018; Saqr & Alamro, 2019). However, to our knowledge, SNA has not yet been used to analyse the *creative* process of collaboration. The study by Porter et al. (2020) reviewed literature on network position and creative performance, but they focus on the relationships between *actors*, not *ideas from actors*. As an example of how studies using 'social networks' often focus on actors and not 'ideas from actors', Baten et al. (2020) used *alters* and *egos* in the networks, rather than networks of ideas. Given that the unit of measurement in divergent thinking is the idea (Runco, 2010), here a node represents an idea by a person, rather than just a person. By modelling the creative process with SNA, we will also have to our disposal quantitative methods to analyse the development of the social network i.e. it is our expectation that we will be able to describe the creative process through such SNA measures.

In sum, our four assumptions together give rise to the assertion that we can use SNA to represent social communities and the way they deal with new ideas during the creative design process, in our socio-technical MC-squared context the creation of digital mathematics books. If such an evolving, dynamic network is a faithful representation of the creative design process, then it seems reasonable to posit that measuring the (development of that) network tells us something about the creative quality of the design process. A next step would then be to see how we can operationalise fluency, flexibility, originality and elaboration in a network approach.

The main aim of the paper, then, can then be reworded as:

Can we utilise methods for Social Network Analysis in describing the creative process, operationalised as fluency, flexibility, originality and elaboration, within the socio-technical platform of the MC-squared project? And if we can, how?

Before we can further operationalise social creativity in terms of 'Social Network Analysis' (SNA) we first need to describe the technological environment, and especially the part used for recording the creative process, more extensively.

3. The technological environment

The socio-technical environment of the MC-Squared platform consists of authoring environment, in which teachers and designers can collaboratively design so-called ‘c-books’. Fig. 1 provides an overview of the interface and some features, as described by Bokhove et al. (2014).

The platform includes several features that constitute a socio-technical environment for students and teachers, and includes, among others.

- Embedded technologies to easier handle formulas (WYSIWYG and flexible editing, dynamic algebra) in all contexts (pages, emails, forums, questionnaires, collaborative documents);
- Interoperability; the feature that c-book resources can include components from other environments;
- Learning analytics; the platform with c-books allows for student registration and learning analytics, to inform designers on student behaviour and learning outcomes; and finally and most relevant for the focus of this article,
- A collaborative design space; the platform provides a space to facilitate designers/teachers collaborative design.

The tool for the collaborative design space of the platform is called ‘Coicode’, a tool based on a previous EU project called Dicode. Coicode is implemented in the platform to enable authors to collaborate on the design of c-books, creative mathematical digital books. In Coicode, authors can add ideas or comments on designed c-book units, to share these ideas with their team members and to comment on the ideas of others. Contributors are creating a ‘map’ or ‘graph’ of the process, for example like one presented later in the article in Fig. 7. The Coicode tool is implemented as a *linear* tool, and so usage results in a ‘directed graph’ or ‘tree’; it could perhaps be described as an alternative visualisation of a *forum* view in which users can post ideas and then they themselves or other users respond with ideas and so forth. In the remainder of the article we will use ‘map’ where ‘forum’ could be used as well. Objects or ideas can be categorised as being a ‘contribution’, ‘alternative’ idea, an idea that ‘objects’ to another idea, off-task comments and management comments. The result therefore is a *map* of the creative process. In order to provide usable and exploitable data that indicates the creativity rate of an idea, a creativity voting system is available. Each user can vote/rate any post they believe has had a strong contribution to the book design or raises a particularly important new idea. Three criteria are available for voting: novelty, appropriateness and usability. Coicode can export information and statistical data, for example regarding usage and ratings, in the form of an XML file. The data can be presented in the form of graphs, see Fig. 2 , and in the form of raw data.

It is the raw data that we intend to use with SNA, but before we can do that, we must operationalise creativity.

4. Operationalising social creativity with SNA

Taking the fundamentals of Social Network Analysis we now operationalise social creativity in a social network. We utilise mock (toy) networks to demonstrate this. Nodes represent ideas that are entered by the participants in the network, arrows the chronological progression from one node idea to another idea. To correspond with our definition creativity we have to think about the four features fluency, flexibility, originality and elaboration.

Fluency: we define this as the number of ideas generated, so the number of nodes in the network.

Every node represents and idea added by the designer. In Fig. 3 the left-hand process has only a few ideas, the right-hand process has a lot of ideas, or in other words the process to the right has higher fluency. Note this does not say anything about the quality or novelty of the idea. We attempt to capture the novelty through gauging the originality.

Flexibility: we define this as the average out-degree or modularity. The average out-degree is the average of the out-degrees of all nodes. The out-degree of a node consists of all the arrows *leaving* the node i.e. the number of new ideas that originate from an idea: the more different ideas ‘spin off’ from a node, the more flexibility has been demonstrated. A challenge here is that if we have a directed tree-like graph this will tend towards 1. Nevertheless the inclusion of nodes with a lot of *different* follow-up nodes would increase the value. One alternative solution for this would be to remove nodes with an out-degree of 0, the ‘end’ nodes, which we denote as ‘*average out corrected*’. A third metric might be the modularity: how well a network decomposes into modular *communities*, or in this case separate ‘groups’ or ‘strands’ of the creative process. Each strand of the process can be said to be an original sub-set of the complete process, denoting the flexibility we want to capture.

The three operationalisations are depicted in Fig. 4. For all three the creative process on the left shows less flexibility and the one on the right more flexibility.

Originality: we operationalise this by making use of the novel or non-novel votes for a particular idea (1 = non-novel, 2 = novel). This feature, as mentioned before, has been implemented in the Coicode environment. They can be aggregated into an average originality score per node. It could be argued that the process as a whole could then be perceived as the average of all the originality scores, but we would caution for this and we argue later on that some SNA metrics could more usefully be employed to discover ‘key events’ in the creative process.

Elaboration: we define this as either the network diameter or average path length. Rather than having ideas ‘fan out’ and spread, there also could be a lot of elaboration on the idea, or ‘depth’ of a network. This, for example, could be the average path length in the network, the average graph-distance between all pairs of nodes, or the network diameter, the length of the longest of all the computed shortest paths between all pair of nodes in the network.

In Fig. 5 on the left we can see a relatively short creative process with limited depth, limited elaboration, while on the right we can see a ‘deeper’ process where participants in the creative process respond and ‘bounce off’ their ideas. Finally, apart from metrics that say something about the creative process as a whole, it also is possible to focus more on particular key events during the process. For instance, we can look at the idea node with the highest out-degree,[1] the most arrows going out of the node, to denote key ideas that created a lot of ‘spin off’. Another metric might be so-called ‘betweenness centrality’[2] of a node, the number of shortest paths that pass through the vertex. It can be seen as an *essential* idea for the creation of other ideas in the book.

In Fig. 6 *essential ideas* are demonstrated with on the left a creative node with highest out-degree (of 7), a node that –because of the relatively ‘flat’ structure of the network– also has the highest betweenness centrality (also 7). To the right, however, we see that essential nodes with highest betweenness centrality (two nodes with value 20) do not necessarily have to have the highest out-degree, as there are multiple nodes with a similar out-degree of 2. Thinking about ideas in this way, can be aided by the typology of design ideas that Inie and Dalsgaard (2017) proposed. Essential ideas seem to correspond with what Inie and Dalsgaard (2017) called ‘General Type 1: Design Moves’ as they “generate a large number of links (they motivate many other design moves)” (p. 400). The taxonomy does not have an idea type that readily applies to ideas with high betweenness, so this is something that perhaps expands the taxonomy. We now turn to using this operationalisation in our methodology for analysing the social creativity in the design process of two creative mathematical books.

[1] Note that because of the tree-like nature of our graphs the in-degree always is 0 or 1, and thus not useful to determine key events.

[2] In the software we used, Gephi, an algorithm by Brandes (2001) is used to calculate betweenness centrality.

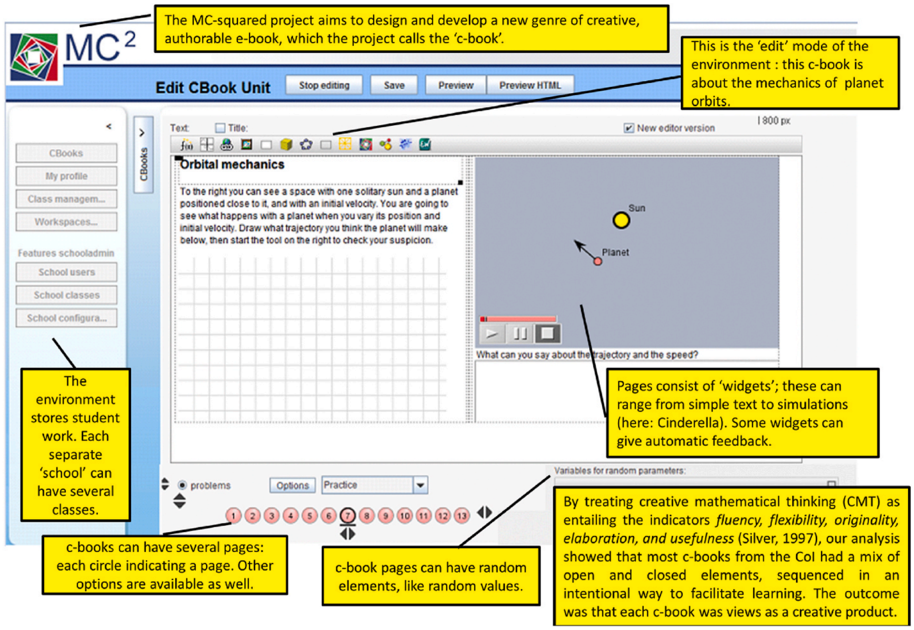


Fig. 1. Overview of interface and features of MC-squared platform, adapted from Bokhove et al. (2014).

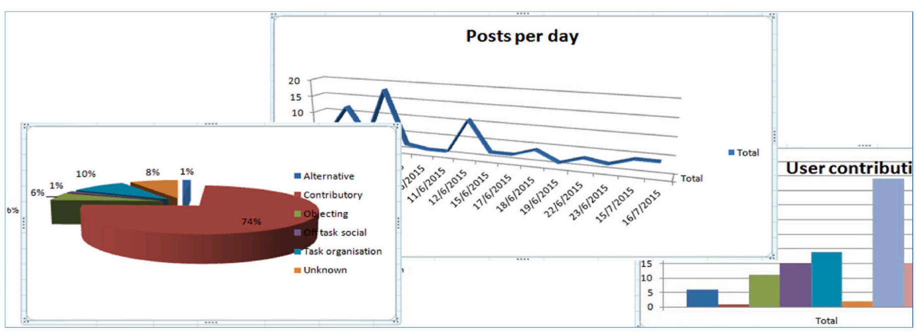


Fig. 2. Information that can be extracted from the Coicode environment.

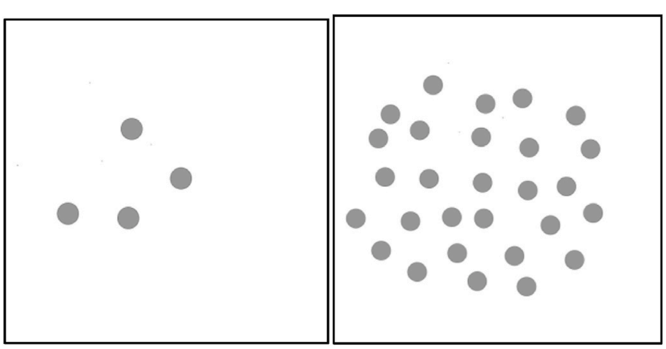


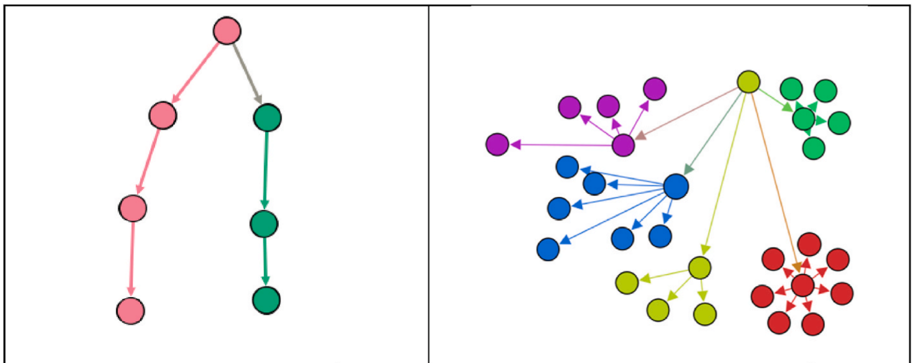
Fig. 3. A creative process with few ideas and thus fluency (left, N = 4) and many ideas (right, N = 28).

5. Methodology

We first started by choosing two books that looked quite dissimilar in their Coicode maps, as we wanted to see whether this dissimilarity would come to the fore in the way the SNA operationalisation would describe the respective creative processes. We exported the data for two digital books (described in the next sections) from Coicode in XML format. The exported data included node and edge data (so the ideas and their relationship to other ideas), as well as voting data, for example aforementioned 'novelty' data with 1 = 'non-novel' and 2 = 'novel'. The XML file was converted to a CSV file. Data processing consisted of separating node and edge data. The nodes file included a unique Id, a timestamp when the node was created, a creator name, an item title, an item type, and the content of the node. An edges file was created with a 'from' node ID and a 'to' node ID. As the structure was tree-like, the nodes had only one parent but *could* have several 'child nodes', and therefore the columns with '0's and '1's indicating these were not necessary.[3] The data was then imported into Gephi[4] beta version 0.8.2 as CSV files in UTF-8 format, as to preserve the Greek symbols. As the logfiles store all the created nodes and edges, also those that have subsequently been modified or deleted by designers, we took the nodes, with information on their types, as baseline. This meant that nodes sometimes had an in-degree of 2, namely one that still existed and one that might have been deleted. As it only concerned a very small amount of nodes we accepted this. However, to deal with this, when the 'edges' file contained an 'edge' with a non-existing node, it would not be

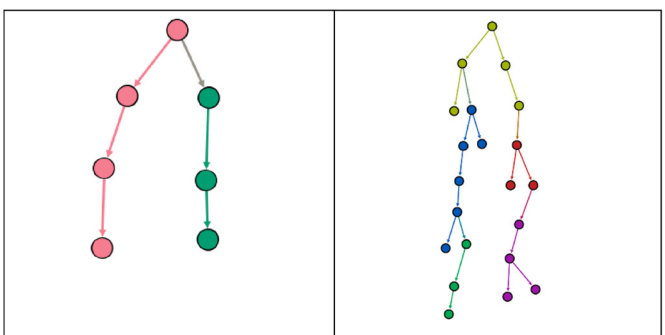
[3] If a node A was linked to a node B, necessarily A was the parent and B the child. Both links [A,B] and [B,A] would be in the file but the former with a 1, indicating A was the parent node of B, and the latter with a 0, indicating B was the child node of A.

[4] https://gephi.org/.



Average out:	**0.857**	Average out:	**0.967**
Average out corrected:	**1.20**	Average out corrected:	**4.83**
Modularity:	**2**	Modularity:	5

Fig. 4. A creative process with little flexibility (left) and a lot of flexibility (right).



Average path length:	**1.667**	Average path length:	**3.163**
Network diameter:	**3**	Network diameter:	**8**

Fig. 5. A creative process with little elaboration (left) and a lot of elaboration (right).

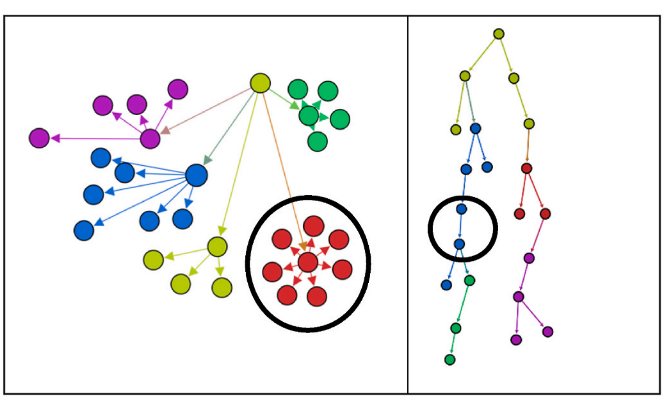


Fig. 6. Looking at individual nodes. To the left the circled node has highest out-degree (of 7) and betweenness centrality (of also 7), to the right the two circled nodes have the highest betweenness centrality (of 20) but there are multiple other nodes with out-degree 2.

included. We now describe two case examples where we applied our SNA approach to analyse the creative, collaborative process.

6. Results: two case examples

This section reports on two examples where the socio-technical environment described previously was used to record the (social) creative process in designing two creative digital mathematics book, books we called ‘c-book units’ in the MC-squared project. We have chosen these two examples as they are very different in nature. The first is an example from the Greek ‘community of interest’ (CoI) in the MC-squared project. Their design process of a c-book of bioclimatic amusement park created a very large network with numerous participants. The English CoI created a book about fractions, but its process was a smaller affair, resulting in a small network with relatively few contributors.

6.1. Case one: the Greek CoI - Bioclimatic amusement park

This rich narrative, touching many environmental issues, explores a lot of facets of early mathematics at stake in examples from the amusement park story: linearity, perimeter of a circle, programming with constraints, 3D exploration, combinatorial optimization, and curve adjustment. The c-book unit is an example of low threshold/high ceiling activities where lots of fun can be had easily while very interesting issues can be addressed and lots of questions can be investigated thanks to the rich half-baked micro-worlds made available by technology i.e. digital applications that are designed specifically to challenge teachers and students as they become engaged in changing them (Kynigos, 2007). There were seven Greek CoI members who were involved in the design of the “Bioclimatic amusement park” c-book unit. The target audience of the c-book was secondary students aged 15–16 year old. The c-book addressed a range of algebraic and geometry concepts. Fig. 7 give the complete map for the creative process. It can be observed that there were multiple strands, with different types of ideas. In total 195 contributions were posted between March and July 2015. 103 of these also received votes for novelty, with 49 at least three votes. Most strands involved at least 2 CoI members.

Fig. 8 shows the map transformed, as per our methodology, into a social network. As there are many nodes, we use the layout algorithm ForceAtlas. The size of the nodes indicates the out-degree. The colours indicate the modularity group. The novel/non-novel vote is 1.34 (recall

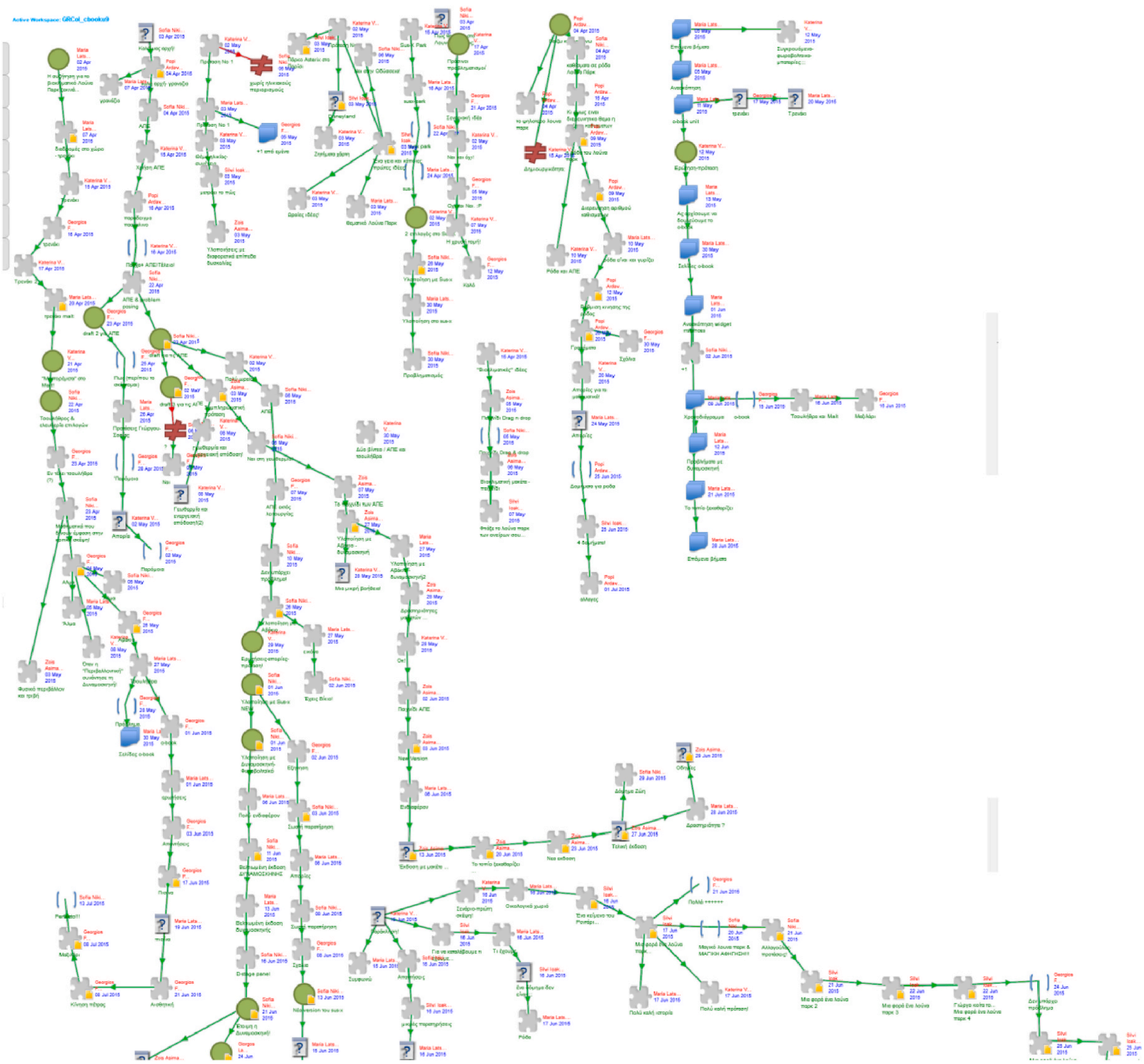


Fig. 7. Map of the creative process from Coicode for the Greek 'bioclimate' book.

that 1 = non-novel, 2 was novel). Average degree per node was included in the node dataset. The number of nodes with an in-degree of 2 (nine) indicated that some nodes had been deleted during the process. The nodes with in-degree 0 denoted new pathways of discussion, or solitary nodes; there were 12 in the Greek space for the book. The maximum out-degree was 4. The network diameter was 26, suggesting there was quite some elaboration. Visually, this seems to be plausible as the original map seemed to have quite a lot of nested ideas and 'depth' of discussion. The average path length of 7.56 also is an indication of this.

6.2. Case two: UK – Fractions book

This c-book did not end up in a final polished production and yielded a much smaller network map. Exploration of fractions is done in several ways, with digital scrap paper to express what a certain fraction of a set of cakes means geometrically, with an aim to understand why the usual operation on integer numbers turn out to be more delicate for fractions, and through a Tetris-like game to train students.

This was a Coicode space with relatively few nodes. Only three participants contributed to the creative process of this book. The size of the nodes again indicates the out-degree. The colours indicate the modularity groups. There were hardly any novel/non-novel votes. The nodes with in-degree 0 denoted new pathways of discussion, or solitary nodes, as nodes 27 and 30 depict in Fig. 9. The maximum out-degree was 5 (node 29). The network diameter was 6, suggesting there was little elaboration. Visually, this seems to be plausible as the original map seemed to have only a few ideas and limited 'depth' of discussion. The average path length of 2.47 also is an indication of this. Table 1 compares the processes for both c-books.

We can see that despite the striking differences, it is hard to –in general-call one or the other book 'more creative' than the other. Although the fractions book has fewer contributors, and therefore always was likely to have less fluency, one conceptualisation of flexibility, namely the average corrected out-degree seems to indicate that, despite the limited number of ideas and contributors, flexibility can still be apparent in the creative process. A further comparison can also focus on the 'critical' nodes in the creative process. For example, when it comes to the highest out-degree, we could argue these are the ideas that have the largest 'spin-off'. This *might* correspond with a high centrality, but it doesn't have to be the case. We could also look in more detail at the nodes with an in-degree of 0: these could be deemed to be at source of the creative process, as the creative process further developed from there. However, this can hardly be said about solitary nodes. A final metric that can be looked at is 'betweenness centrality'. For example, in the fractions book, the node labelled 'Fraction Lab tasks sequence' (node 29 in Fig. 8) has the highest betweenness with 20. This might be an indication of the centrality of the node: the idea was essential for the process. Upon closer scrutiny, the node was quite an extensive document

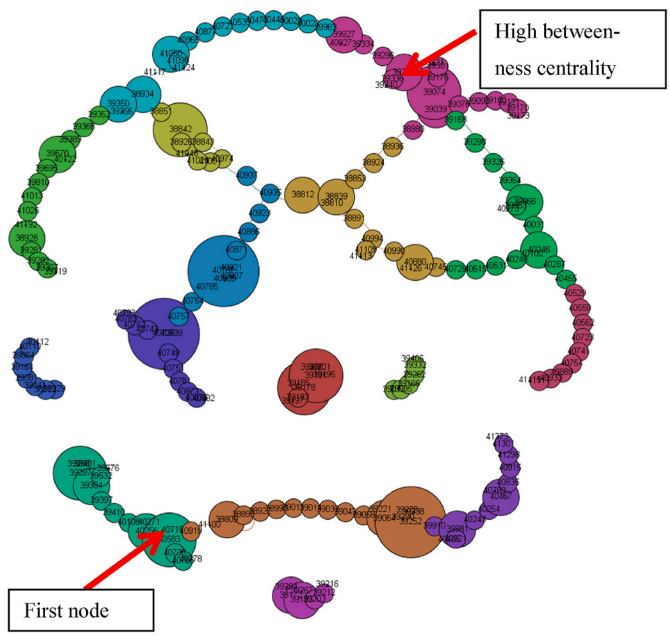


Fig. 8. The map is transformed into a social network (layout algorithm ForceAtlas).

with fraction lessons: a rich resource that 'sparked' new ideas in the creative process. In this particular case it also had the highest out-degree, so it could be seen as a Design Move in the sense of Inie and Dalsgaard (2017). In the Greek book the node with an 'alternative suggestion' labelled 'draft για τις ΑΠΕ' had a betweenness centrality of 431, but in that case, it did not have the highest out-degree. Although there seemingly is no direct mapping to Inie and Dalsgaard's (2017) taxonomy, we contend the ideas still can be deemed essential for the creative process, as although they do not have direct spin-off ideas, they are instrumental for the network of ideas as a whole.

The two examples show how a SNA, through a network representation and associated metrics, can give insight in the four indicators of creativity: fluency, flexibility, originality and elaboration. In addition, we can determine candidates for the sources of the creative process, *root ideas*, as well as *catalyst ideas*, ideas that might not be particularly novel or followed-up but are essential for the social creative process. By analysing educational data within the platform, we have gained insight into the creative, collaborative process of the teacher designers. Of course, these two examples are of modest scale, but the SNA metrics used to operationalise creativity can be applied at scale, so we think it serves as a convincing proof-of-concept.

7. Conclusion and discussion

In this article we set out to show how we used a digital support tool to record and map the creative design process in an authoring tool, and how the data it recorded could critically be analysed with Social Network Analysis. As a result, we managed to sketch a rich picture of social creativity. We explained how four criteria could be operationalised and how they could be applied to maps of the creative process, as created by designers of digital mathematics books (c-books) in the MC-squared project. capture parts of the creative process, allowing us to distinguish between different creative processes. The original research question 'Can we utilise methods for Social Network Analysis in describing the creative process, operationalised as fluency, flexibility, originality and elaboration, within the socio-technical platform of the MC-squared project?' can therefore be answered conclusively. The SNA approach highlights one possible answer to the follow-up question 'And if we can, how?'. The data from these maps served as a basis for social networks, after which fluency, flexibility, originality and elaboration were expressed in terms of several SNA metrics. As the data from the Coicode tool resemble a forum-like structure, we have shown that a socio-technical environment can contribute to the collection of such data. In that respect we are not bound to one particular tool. We think that both the tool and the SNA methodology have contributed to useful indicators for social creativity, broadening the methodological perspectives of creativity research, as mentioned by Plucker et al. (2019). Advantages lie in the fact that SNA metrics are standardised, with many tools available. The suggested metrics still distinguish indices of fluency, flexibility, originality and elaboration, which provides a profile of the creative process. We envisage that in further work these metrics can provide an appropriate explainable visualisation in the form of learning analytics for self-reflection, motivation and perseverance, as it presents a summary of the creative process up to that point. In those cases, measures of creativity do not only serve as creative collaboration analytics but also are part of a group awareness tool (Bodemer & Dehler, 2011). There are challenges, however, as well.

7.1. Challenges – divergence or convergence

In our case, for example, the characteristics of the tool matter. Typically, in forum environments the tree-like answer-and-response structure, means that ideas can not have more than one parent idea.

Our assumption of the creative process is one of having a tree-like structure; perhaps a network approach, where any idea can feed into any idea is more realistic (Fig. 10). To approach this more in terms of

Table 1
Comparing the SNA metrics for the two books.

Concept	Indicator	Climate c-book	Fractions c-book
Fluency	Number of nodes	197	26
Flexibility	Average out	0.985	0.923
	Average out corrected	1.28	1.71
	Modularity	16	6
Originality	Average novelty score[a]	1.34	2
Elaboration	Network diameter	26	6
	Average path length	7.56	2.47

[a] Note that this is the average of all raters, which means that it could be possible that only one rater contributed to a high mean.

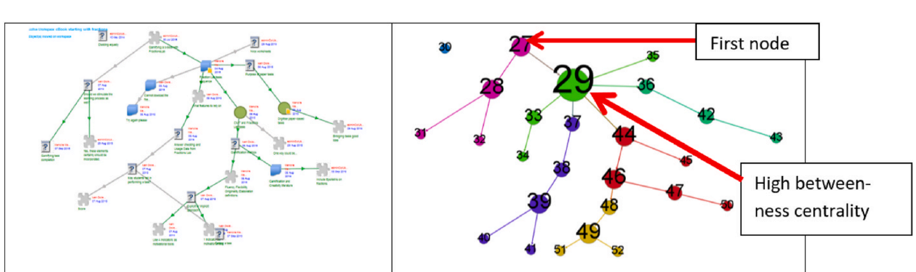


Fig. 9. The map (left) is transformed into a social network (right) for the UK fractions book.

creativity: a tree-like structure allows for *divergence* and therefore, in our view, can capture *divergent thinking,* but a tree-like structure can't capture *convergent thinking* because of the restriction of not being able to have more than one parent idea. However, convergent processes also are an important part of the creative process (Cropley, 2006), with such processes, for example, including evaluation after a divergent creativity stage, or the selection of ideas (Coursey et al., 2019). According to Cropley (2006), divergent thinking without convergent thinking can cause a variety of problems including reckless change. As counterpoint, too little and too much convergent thinking can also be bad for creativity. In looking at measurement development, Cortes et al. (2019) emphasised how divergence and convergence are separable subcomponents of creativity. In contrast, while reporting on creative activities in the design industry, Frich et al. (2021) suggest that digital ideation tools yield more convergent thinking compared to analogue tools, with no discernible impact on general productivity or divergent thinking. Their platform 'Cards and Boards' was designed to function as an alternative to the use of physical sticky notes, whiteboards, and flip charts in design, and not a forum which typically uses response-and-answer. Also arguing that current idea evaluation research and practice primarily facilitate "convergent production (narrowing down ideas to a few tangible solutions) but discounting divergent production (the development of wildly creative and novel thoughts patterns)" (p. 101), Ulrich (2018) created a support system that supports both divergent and convergent production. According to Acar and Runco (2019), a critical skill to include in any creativity training program is that of 'discretion': individuals should learn "when to be divergent and when to allow constraints to lead them to conventional thoughts and conformity" (p. 157). The importance of constraints in creativity has been highlighted in previous work (e.g. Sternberg & Kaufman, 2010; Stokes, 2006), also in the context of mathematics creativity (Bokhove & Jones, 2018).

7.2. Capturing ideas from the community

The methods described in this article rely on 'buy-in' by the 'Community of Interest'. Although some data are collected automatically through usage, there also are some additional activities for the designers of the c-book, which might detract from the core aim, the design. Perhaps the collection of these data can also be automated but then we are left with another challenge, namely for the system to automatically determine what *ideas* have been created. Although we are optimistic about the role 'intelligent' socio-technical environments can play in the creative process, we would posit this might be a 'bridge too far' for now. But even when these data are adequately captured, there also are numerous assumptions in the analysis process. Essentially, these analyses can only match the quality of that data that go into it. With an operationalisation of 'creativity' rooted in well-known theoretical constructs we think this study does both. Nevertheless, even with sufficient quality there are numerous assumptions in the data that cannot just simply said to be 'good' or 'bad'. Consider, for example, the granularity of the idea nodes. If one idea node incorporated a lot of different ideas, for example a multi-page draft resource, then the probability of being followed up with further ideas seemed greater. In our analyses this then resulted in a high out-degree and thus a sign of 'flexibility', but of course this does not have to be the case. Such challenges are associated with the nature of our metrics. These are based on Guilford (1967) and its relatively old publication year perhaps are symptomatic for the challenges associated with 'capturing' creativity. A key strength is that they measure output in a clear, quantifiable way; a weakness, however is that they might say little about the relevance or value of the creative output. For now, quantitative network approaches like these will therefore always have to be supplemented by qualitative analyses and evaluations. One obvious extension of our approach could be to include the *temporal* nature of the process. We looked at complete tree-like maps/forums, and not at the way they developed over *time*. Especially the chronology of who responds to who, could provide further valuable insight in the social creative process. Without this, networks can look the same but the number of people involved or the turn taking might differ considerably. The participants in the CoI can also have different attributes that could then be included; it could be interesting to see whether characteristics influence the way the social creative process develops over time. For example, Runco and Acar (2010) found that divergent thinking tests may depend heavily on experience, with the type of experiences mattering as well. Barron and Harrington (1981) already identified a vast list of characteristics supportive of creativity, including broad interests, independence of judgment, autonomy, intuition, self-confidence, comfort with ambiguity, propensity for risk-taking, and curiosity. Our position is that, whatever the view on how to best develop creativity through and in social processes, we first need to understand what is going on. We suggest that the combination of a tool that enables us to capture the creative process, here a digital mapping tool, as well as our SNA network approach can provide such insights.

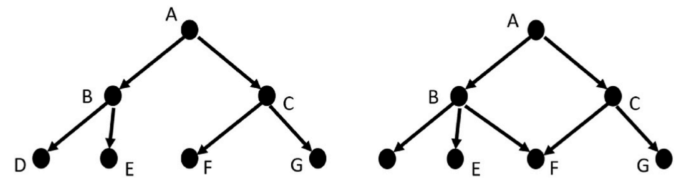


Fig. 10. In graph theory, a tree-like structure does not allow convergence of ideas (left) compared to compared to a net (right), where ideas B and C converge into F.

Statements

This research adheres to ethical standards.
There are no conflicts of interest.

CRediT authorship contribution statement

Christian Bokhove: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Marios Xenos:** Methodology, Writing – review & editing. **Manolis Mavrikis:** Methodology, Writing – review & editing.

Declaration of competing interest

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

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