Testing Open-source Visualization Tools with Small and Medium-Sized Enterprises Ecosystem Data: Towards the Understanding of Innovation Ecosystem Design

Abstract

This paper explores open-source visualization tools to enhance the understanding of SME ecosystem structures. Ecosystem approaches are becoming important in business strategy and innovation where organizations are heavily relying on inter-firm resources to innovate. Consequently, the traditional firm-focused business models face challenges, making it difficult for interconnected and diverse actors to co-create across firm boundaries. This challenge is even worse for manufacturing SMEs, who often lack the tools to make sense of their innovation ecosystem structures. We carried out a rich ethnographic investigation in three cases in the UK, i.e. the ceramic artist ecosystem, the 3D printing bureau ecosystem and the FabLab ecosystem. From the initial thematic analysis results, all actors highlighted the difficulty in understanding ecosystem networks. The following ecosystem attributes were identified as essential in understanding SME ecosystem structures: Clusters and bridges, tie size, structural holes, role structure, interactivity. In this paper, fourteen open-source visualization tools are tested to compare how well different tools reveal the six ecosystem attributes. Our findings demonstrate that open-source visualization tools have different affordances, most of which are useful in revealing ecosystem attributes. Results show that most visualization tools help aid the understanding of SME ecosystem structures. This study contributes new knowledge on the scarce subject of designing and managing ecosystems, presenting a unique approach to explore and understand ecosystem configurations. The study identifies limitations in open-source visualization tools and offers the design management community a set of recommendations for further development of visualization tools to support decision-making.

Keywords: visualization tools, innovation ecosystems, visual analysis, sense-making, ecosystem attributes, decision-making

1. Introduction

In this paper, we think about SMEs as ecosystem users who might be motivated to develop ecosystemic solutions to address their ecosystemic needs, deriving from Von Hippel's classic definition of lead users (Von Hippel, 1986). SMEs might benefit from understanding and leveraging ecosystem network effects (Lüthje and Herstatt, 2004) because they are part of a bigger complex, something Manzini (2015) referred to as 'cosmopolitan localism,' i.e. the society in which places and communities are connected nodes in a variety of networks. The primary research question is how SME decision-makers might be supported to see, understand and manage productive ecosystems under this 'cosmopolitan localism'.

Organizations continue to experience challenges in facilitating and managing innovations across ecosystem actors (Jacobides et al., 2018; Adner, 2017), and this is becoming a bigger challenge for SMEs with limited management capabilities and resources (Zulu-Chisanga et al., 2020; Songling et al., 2018). Other studies highlighted that external collaborations are key to survive market dynamics (Noh and Lee, 2015). Like in a natural ecosystem, part of the innovation ecosystem is organic (meaning that the ecosystem configures itself based on market forces and uncoordinated decisions by actors), and decision-makers consciously control part of the ecosystem. These uncoordinated and misaligned conscious actions make ecosystems difficult to influence and manage (Adner, 2017). However, there are different types of ecosystems, such as platform ecosystems, e.g. Apple, Amazon and innovation ecosystems, e.g. Silicon Valley (Basole et al., 2018), which are more developed and can be configured to a large extent. Our study focuses on SME ecosystems smaller in size than large ecosystems like Silicon Valley, Uber or Amazon. These ecosystems are neither platform based nor hub-centred. We look at how loosely connected SMEs, and their stakeholders interconnect to create shared benefits.

In a digital world, the diffusion of new technologies in innovation processes is changing the nature of ecosystem management in general (Nambisan et al., 2017) and how SME decision-makers make choices in particular. Over the years, there has been a gradual shift in innovation management from firm-centric approaches to ecosystem thinking (Iansiti and Levien, 2004; Moore, 1993). The ecosystem metaphor became increasingly crucial to strategy, innovation and entrepreneurship because firms were now heavily reliant on external resources to innovate (Adner and Feiler, 2019; Jan et al., 2020). Although business managers acknowledge the significance of ecosystems in growing their competitiveness (Lyman et al., 2018), they lack the tools to develop, understand and manage ecosystems in their environments (Jacobides et al., 2018; Adner, 2017). Consequently, there is a need for a better understanding of ecosystem structures and how to create new opportunities for interconnected actors (Su et al., 2018; Rong et al., 2018). Opportunities in networks include identifying and exploiting new connections.

Today, it is difficult for SMEs to innovate in isolation without involving other players such as knowledge centres, Government, financial institutions, other entrepreneurs, consumers, suppliers and inter-firm resources like data and digital tools. Developing innovations is shaped by the ability to create an ecosystem where actors such as firms, people, sectors can foster value creation and collaboration (Granstrand and Holgersson, 2020), which we believe is anchored on leveraging network effects or interconnectedness. Mark S. Granovetter posited that interactions amongst small groups sometimes aggregate to form macro-level patterns, which often becomes more complex to understand (Granovetter, 1973).

We pay attention to learnings from two theories in this paper, i.e. the actor-network theory (ANT) and the theory of weak ties. ANT suggests that everything in the social and natural worlds exists in changing networks of relationships, and nothing exists outside. According to Callon and Latour (1981, p.286), "actors are individuals who influence elements occupying space around them". Lamine and colleagues (2019) also highlight that opportunities and new network links emerge as diverse actors cooperate in networks. This theory is useful to open innovation processes across firms and understand the structure of connections.

The theory of weak ties implies that distant partners carry valuable information for innovation than close ones (Granovetter, 1973). This theory suggests that more actors can be reached through weak ties, leveraging new resources different from close ties. We argue that a combination of both weak and strong ties can lead to more innovation across firms. These two theories define SME ecosystems' complexity and guide this study to understand ecosystem structures better.

Many open-source visualization tools are available online, which might be useable to SMEs' decision-makers to understand ecosystem complexity by revealing ecosystem attributes such as ties. Therefore, we take a novel approach to test and evaluate how these tools might be helpful to SME decision-makers. We take an interest in exploring ecosystems using the power of exploratory visualizations rather than just focusing on the widely used explanatory quantitative techniques, e.g. quantitative surveys. This method has advantages because it may enable decision-makers to identify insights for innovation. We demonstrate how visualization techniques reveal the ecosystem structural attributes identified from three ecosystem cases. This work underlines that identifying insights from ecosystem visual attributes may lead to better understanding and decision-making, enhancing entrepreneurship and innovation.

The rest of this paper is arranged as follows. Firstly, we provide a brief rationale for why design is appropriate to study ecosystem structures and then highlight the significance of using design visualization tools to study interconnections across a wide array of subjects. Second, we highlight the ecosystem attributes tested in this study. Next, we explain the methodology and visualization tools used to test innovation ecosystem data. We also present visualization results and discuss emerging insights. Finally, we highlight key contributions, limitations and future research.

2. Design for ecosystems

Design approaches have been studied for years to support collaborative creations across organizations (Kello, 1996; Simonsen and Robertson, 2013). However, design has not been adequately exploited to address the complexity of innovation ecosystems. Scant research suggests that design needs to integrate sustainable ecosystems and the world around us to build local communities' responsibilities (Phillips et al., 2020). Researchers from the innovation management literature studied the dynamics and interdependences of ecosystem actors mostly by looking at what constitutes ecosystem actors, roles and management of dependencies (Iansiti and Levien, 2004; Dedehayir et al., 2018; Adner, 2017). Scant research attempted to use design visualization techniques as decision support and innovation tools (Basole et al., 2013; Park et al., 2016).

Looking at the old school definition of design by Papanek (1972), "Design is the conscious and intuitive effort to impose meaningful order". Papanek further emphasized that understanding our existence requires us to seek order in it continuously (Papanek, 1972). This definition seems relevant to what this study attempts in deciphering innovation ecosystem structures. Although seeking order in ecosystem design seems improbable because of constant actor relationship shifts, we argue for SME ecosystems to identify a more nuanced approach in understanding ecosystem configurations. Since human actions and choices partly affect the reconfiguration of ecosystems (Reed and Lister, 2014), SME decision-makers are in a good position to shape their innovation ecosystem structures.

Therefore, in this present paper, designing innovation ecosystems is a process of continuous sense-making to impose meaningful order in ecosystem configurations. Using visualizations to generate visual images or mental models of ecosystem structures, we impose form and order in ecosystems and use these images to make crucial decisions concerning the reconfiguration of the ecosystem networks. Emphasizing collaborative decision-making is key in ecosystems because they are influenced by all actors, not just a single 'designer'.

Previous literature suggests that there have been some attempts towards this direction to explore how visualization tools may be used by a group of networked people to explore their settings collaboratively. For example, Mortati and colleagues (2012) developed a remarkable design tool called NETS for SMEs to exploit social networks through visualizations. The Ecosystem Pie Model was developed to help businesses in modelling their existing ecosystems (Talmar et al., 2018). The dotlink360 was developed to assess business ecosystems' interconnectedness and decision making (Basole et al., 2013). Basole and colleagues (2018) later designed the ecoxight tool to discover, explore and analyze business ecosystems. Jan and colleagues (2020) recently proposed a 'Circularity Deck' tool to help firms analyze, ideate, and develop circular innovation ecosystems.

Therefore, we extend the above attempts to explore intuitive and easy-to-use open-source tools and offer a new perspective on SMEs' innovation ecosystem structures, taking advantage of the growing open-source environment. Our idea is to use visualization outputs generated using qualitative data to take advantage of free digital tools.

2.1. Ecosystem attributes

Ecosystem attributes are a vital part of understanding the design of SME ecosystem structures. Our selection of ecosystem attributes is based on the results from in-depth field interviews with three innovation ecosystem cases, i.e. the ceramic artist, the 3D printing bureau and the FabLab directors. All participants indicated the difficulty in understanding complexities associated with the dynamic ecosystem structures. The following attributes were highlighted as essential in understanding ecosystem network configurations.

- Clusters and bridges

  Clusters are a group of actors in a specific sector, and bridges are key actors or clusters that connect actors to allow resource flow across distinct communities. Understanding these attributes might help plan innovation activities between SME communities (Li et al., 2019).

- Node hierarchy

Node hierarchies represent how many stakeholders are connected to an actor compared to others regarding the degree of connection. This method may reveal influential actors to help decision-makers devise strategies to leverage resources outside their core networks (Bounegru et al., 2017).

- Structural holes

These are gaps between clusters in ecosystem structures, thus dividing communities in resource flow and innovation activities. Therefore, seeing these holes may lead to formulating interventions targeted at bridging gaps to allow resource flow across distinct communities (Ahuja, 2000).

- Tie size

Tie size is defined by the strength of a relationship between actors. We use the reciprocity of services between actors to determine ties' strength (Manzini, 2015). Identifying strong and weak ties is crucial because there is high value in understanding and combining external inputs with internal resources for innovation. This idea is associated with the theory of weak ties (Granovetter, 1973).

- Role structure

Role structures are defined by how the ecosystem is arranged in terms of actor's roles, i.e. whether actors are located at the centre of the network (keystones, hubs), or located all over the network (dominators) or in specific areas of the network (niche actors). This method is important because identifying these roles may guide actors in developing governance mechanisms (Iansiti and Levien, 2004).

- Interactivity

  Interacting with ecosystem data helps actors to see connections and identify structural insights. This process is achieved by using dragging, colour editing, rotating, mouse hovering, zooming in and out, 3D layouts, multiple views and filtering features (Mei et al., 2018).

In the next section, we briefly discuss some of the widely available visualization methods, benefits and trade-offs to demonstrate the potential of visualizations in supporting decision making (Lurie and Mason, 2007). This idea is important to explore what visualization methods are available and how we might leverage those affordances to support ecosystem structures' design and understanding.

2.2. Visualization methods

There are three fundamental intentions for data visualization given in Kirk (2012), which portray data as either explanatory, exploratory, or an exhibition. This paper is more inclined towards the visual exploratory function of data to promote discovery and new insights (Krzywinski et al., 2012). In contrast to explanatory approaches, visual exploratory techniques are about visual analysis rather than the visual presentation of data. There is a vast array of data visualization techniques offering different affordances (Kirk, 2016). For example, Sankey graphs are mostly used in genetic data analysis (Platzer et al., 2018) and in analyzing flow (Lupton and Allwood, 2017). However, Sankey methods face visual cluttering (Cuba, 2015; Maurits, 2019).

Recently, most researchers from biology and chemistry prefer 3D visualizations in exploring molecular, gene to gene and other protein interactions (Zhou and Xia, 2018; 2019), as demonstrated in Figure 1(B). The 3D tools have affordances in rotating and zooming to explore finer details. On the other hand, parallel coordinates are widely used for showing multidimensional data (Zhou et al., 2018), as demonstrated in Figure 1(A), although the methods also experience visual cluttering with an increase in data volumes. Force-directed layouts are arguably the most widely used in various network analysis projects (Mei et al., 2018; Jacomy et al., 2014). Chord layouts summarise the hierarchies of nodes and ties (Börner et al., 2016), although this method also experiences visual cluttering, as shown in Figure 1(C).

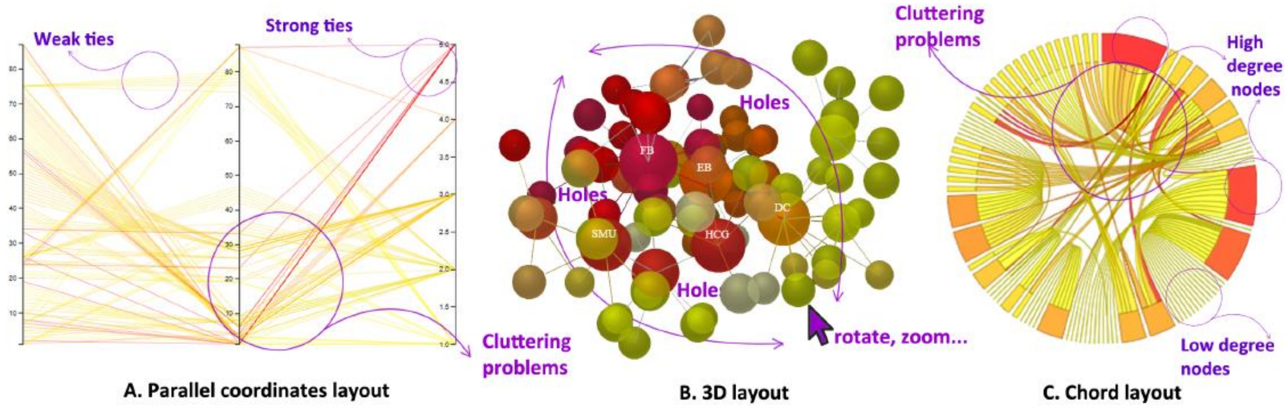

***Figure 1**: Examples of some visualization methods*.

There are different affordances in these methods which can help decipher complex ecosystem attributes. Within these visualization methods (and many others), we want to understand what type of methods and tools can help SME decision-makers in making sense of innovation ecosystem attributes.

3. Methods

We use the interview data from three case studies, i.e. Ceramic artist, 3D printing bureau and the FabLab ecosystem in Lancashire area, UK. The ceramic artist was selected because of its transition from pottery to using ceramic 3D printing technologies. The director had more than 20 years working with pottery, and this was important to study how 3D printing technology actors shape the ceramic ecosystem. The FabLab is one of the oldest makerspaces in the Northwest of England, and the owner/director was involved with setting up makerspaces across the UK in the last ten years. This FabLab was selected because we wanted to understand how FabLab owners and their stakeholders shape the local ecosystem. The 3D printing bureau was selected because of niche clients, e.g. motorsport, aerospace, and medical industry associated with this 3D printing bureau service. This ecosystem case appeared different and unique with many competing actors, e.g. equipment manufacturers, resellers, and 3D printing bureau firms. All directors had at least eight years working with 3D printing technologies. Although directors were interested in data visualization tools to improve their innovation systems with other stakeholders, they had limited knowledge and awareness of the open-source tools and how they can leverage these to improve their understanding of ecosystem structures.

The cases were investigated through semi-structured interviews and mapping techniques adapted from the position generator (Lin et al., 2001). We selected a case study approach because of the scarcity of empirical work on how interactions and interdependences of firms, people and sectors in these cases influence the design of productive ecosystems. This approach was also adopted to provide an in-depth and rich account of what is happening in SME ecosystems or micro-ecosystems (Yin, 2012). We then conducted a detailed thematic analysis to make sense of innovation ecosystem data. Highlights of the thematic findings include the following; we found that the ceramic artist relied entirely on the gallery to access markets and focused more on the design and manufacturing side, thus investing time in expanding his ecosystem through research and development with other actors.

In the FabLab case, more actors have access to experimental and co-innovation activities, and SMEs were using the FabLab ecosystem because they felt it was accessible, resourced, free and fun. However, in the 3D printing bureau case, equipment manufacturers were dominating the ecosystem in terms of value creation and capture. This was not a surprising finding given the nature of 3D printing bureau services. In all cases, decision-makers found it challenging to make sense of their ecosystem attributes such as key roles, ties, clusters, structural holes, bridges and patterns formed as a result of these interactions. Without a clear understanding of these attributes, it was challenging to make sense of innovation ecosystem configurations. Hence the need to further explore qualitative data using design visualization techniques.

3.1. Data analysis techniques

Qualitative data was mined through a coding process to identify actors and ties from the interview transcripts and mapping outputs from the fieldwork. The actors' websites were used to search for more information about the actors' interconnections, coupled with follow-up email inquiries. Actors' ties were judged based on reciprocity of services, e.g. sharing data, equipment and working spaces. Then the data was translated into weighted edge lists and different formats for visualization (Figure 2). Table 1 shows a sample of datasets used to produce network visualizations. Various formats such as comma-separated values (CSV), edge list, JavaScript Object Notation (JSON) were adopted depending on which software packages were used.

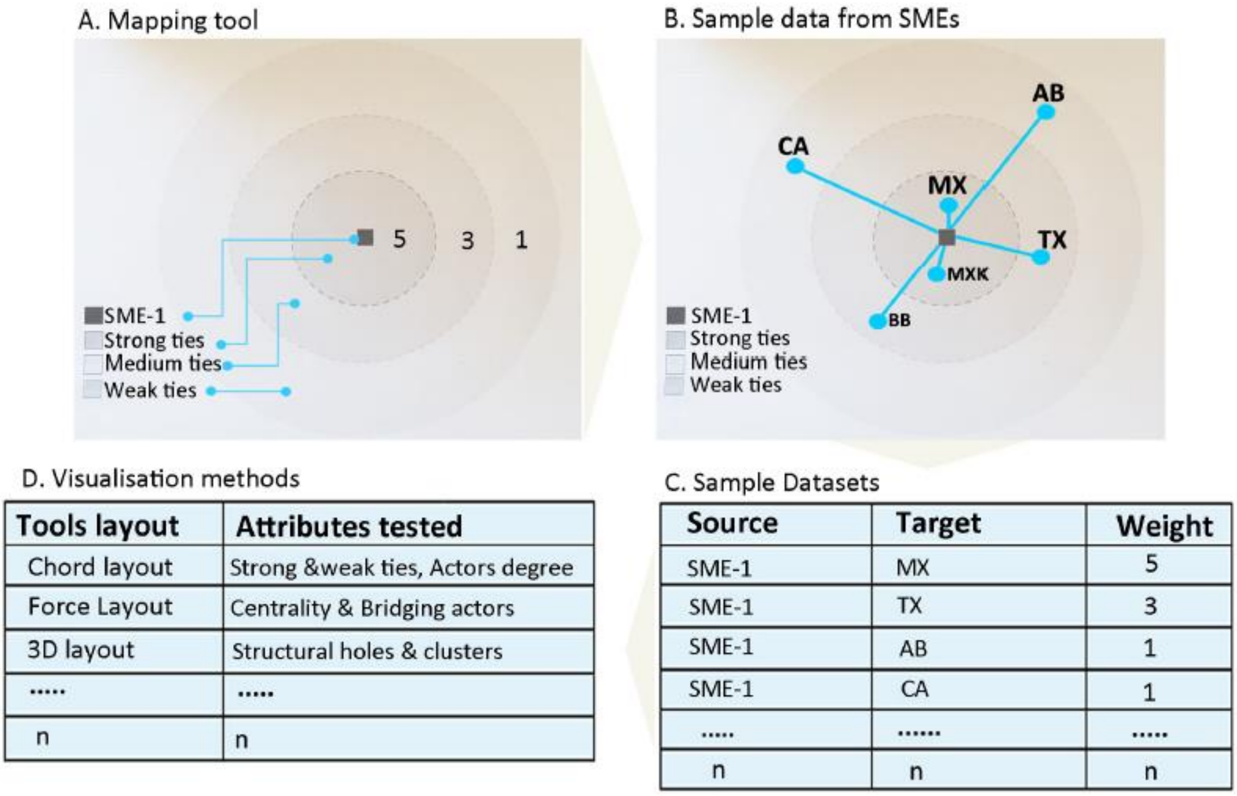

Figure 2: Showing examples of how the mapping tool (A) was used to transform transcripts data into a visualization map (B) and then into edge list data (C) for visualization with software tools (D).

Table 1: Example of ceramic artist ecosystem datasets extracted from qualitative data (interview transcripts, actors maps and websites).

Type	**Name**	**Description**	**From Type**	**From Name**	**Edge**	**To Type**	**To Name**	**Weight**
Person	FA	Ceramic artist	Person	FA	Design	Person	OA	5
Person	OA	Other ceramic artist	Person	FA	Design	Organization	G	5
Organization	MC	Chemical Manufacturing through 3d printing	Person	FA	Design	Person	DC	3
Places	UKM	UK domestic markets	Organization	G	Sales	Service	CR	3
Events	PA	Public auctions	Organization	G	Sales	Organization	UNS	3

We randomly tested many open-source tools before settling for the 14 most useable tools. First, useability was defined based on the tools' ability to reveal ecosystem attributes discussed in this paper. Second, we selected free tools which required less coding and simple data formats, e.g. edge lists and CSV. Third, we selected tools with many layout algorithms to explore various layout possibilities. The following tools were selected; *Gephi*, *NetworkX*, *Chord Snip*, *Sankeymatic*, *D3*, *Tableau public*, *SocNetV*, *RNA Arc*, *OmicsNet*, *GraphCommons*, *RAWGraphs*, *Cytoscape*, *HighCharts* and *Zingsoft*. During the preliminary tests, these tools exhibited the potential to help decision-makers discover insights about their ecosystem through an exploratory process rather than just offering a visual explanation of data (Kirk, 2016). The anonymized datasets used in this paper are found online (Nthubu, 2020).

4. Results and discussions

This section will first review the different results from case studies against the key ecosystem attributes and then compare different visualization tools. Table 2 shows the results from three ecosystem case studies. These insights highlight valuable aspects of exploring visualizations.

Table 2: Summary of results from three ecosystem case studies tested against 14 open-source visualization tools.

	Artist ecosystem	**FabLab ecosystem**	**3D printing Bureau ecosystem**
Main clusters	**Seven tools reveal the artist and gallery as the main clusters** *[Gephi, Cytoscape, Sankeymatic, GraphCommons, Zingsoft, OmicsNet,*	**Three main clusters are revealed: FabLab Staff** *[Gephi, Cytoscape, Sankeymatic, GraphCommons, Zingsoft, OmicsNet, NetworkX]* **Design and prototyping** *[Cytoscape, Sankeymatic, GraphCommons, Zingsoft,*	**Two tools reveal clusters as 3D bureau service and UK manufacturer** *[Gephi and NetworkX]*

	NetworkX]	*OmicsNet, NetworkX]* **Equipment booking** *[Gephi, Cytoscape, GraphCommons, Zingsoft, OmicsNet, NetworkX]*	
Main bridges	**Seven tools reveal the gallery and artist as the main bridges.** *[Gephi, Cytoscape, Sankeymatic, GraphCommons, Zingsoft, OmicsNet, NetworkX]*	**One main bridge: FabLab staff** *[Gephi, Cytoscape, Sankeymatic, GraphCommons, Zingsoft, OmicsNet, NetworkX]*	**Three main bridges: 3D bureau service, resellers and niche clients** *[Gephi, Cytoscape]*
Node size	**Six tools show the gallery having higher degree followed by the artist node** *[Gephi, RAWGraphs, SocNetV, HighCharts, Zingsoft, Tableau]* **Three tools show the artist having a high degree than the gallery.** *[Chord Snip, Cytoscape, Sankeymatic]*	**Eight tools show FabLab staff with high degree followed by equipment booking** *[Gephi, Chord Snip, Cytoscape, Sankeymatic, SocNetV, HighCharts, Zingsoft, Tableau]*	**Nine tools show a high degree of connections in Equipment manufacturers, 3D printing Bureaus services and equipment resellers** *[Gephi, Chord Snip, Cytoscape, RAWGraphs, Sankeymatic, SocNetV, HighCharts, Zingsoft, Tableau]*
Structural holes	**Holes between:** **Gallery and 3d firms** *[Gephi, Cytoscape]* **Int markets and Gallery collectors** *[Gephi, NetworkX, Zingsoft]* **Chemical Co and 3d firms** *[Gephi]* **Gallery and creative Industry** *[Cytoscape, Zingsoft]* **Artist and Int markets**	**Holes between:** **Equipment booking and Universities, Co-working and Universities, Community users and FabLab staff, Community users and Design** *[Gephi]* **Equipment booking and Co-working, Bespoke service and equipment booking** *[Cytoscape, Zingsoft]* **Design and Universities** *[Cytoscape]* **FabLab staff and Hack//burn** *[Sankeymatic]* **Design and Hack//burn** *[Zingsoft]*	**Holes between:** **UK manufacturers and Aerospace clients** *[Gephi, Cytoscape, Sankeymatic, OmicsNet]* **Manufacturers and resellers** *[Gephi, Zingsoft, NetworkX]* **3D printing bureau and resellers, Foreign Manufacturers and UK markets** *[Gephi]* **Motorsport clients and foreign manufacturers** *[Cytoscape, Zingsoft, OmicsNet, NetworkX]*

	[Cytoscape, OmicsNet] **Artist and other galleries** *[Sankeymatic]* **Int markets and Chemical Co** *[Zingsoft]* **3d firms and Int markets** *[OmicsNet]* **Chemical Co and Int markets** *[Zingsoft]*	**Co-working and Markets** *[Zingsoft]* **Design and Markets,** **Design and Equipment booking** *[OmicsNet]* **Equipment booking and community users** *[NetworkX]*	**Manufacturers and resellers** *[Cytoscape]* **Resellers and UK markets** *[Sankeymatic]* **Motorsport clients and 3D printing bureaus** *[Zingsoft]* **Manufacturers and bureaus** *[OmicsNet]*
Weak ties	**Weak ties between: Gallery and Chemical Co** *[Gephi]* **Gallery collectors and 3d firms** *[Gephi, D3]* **Artist and Int markets** *[Gephi, Chord Snip, RAWGraphs, D3]* **Gallery and 3d firms** *[Gephi, RAWGraphs]* **Galley collectors and Other galleries** *[Chord Snip, D3]* **Int shows and Creative industry** *[R-chie]*	**Weak ties between: FabLab staff and universities, Hack//burn and Bespoke service** *[Gephi]* **FabLab staff and Hack//burn** *[Chord Snip]* **Community users and Equipment booking** *[Chord Snip]* **Markets and design** *[RAWGraphs, D3]* **FabLab staff and Community users** *[RAWGraphs, D3]*, **Markets and FabLab staff** *[R-Chie]*	**Weak ties between: Aerospace and motorsport clients, 3D printing bureau and resellers, 3D printing bureau and equipment manufacturers** *[Gephi, D3]* **UK equipment manufacturers and 3D printing bureaus** *[Chord Snip, D3]* **UK manufacturers and resellers** *[Chord Snip]* **Aerospace clients and manufacturers** *[RAWGraphs]* **Foreign manufacturers and UK markets** *[R-Chie]*
Roles structures	**Five tools show the gallery as the keystone actor and artist as a niche actor.** *[Gephi, RAWGraphs, SocNetV, Zingsoft, Tableau]* **Two tools show the artist as the keystone actor and gallery as the niche actor** *[Chord Snip,*	**Six tools show FabLab staff as keystone actor and equipment booking, hack//burn and design prototyping services as niche actors.** *[Gephi, Chord Snip, SocNetV, Zingsoft, Tableau, Cytoscape]*	**Six tools show equipment manufacturers, 3D printing bureaus and equipment resellers as dominators** *[Gephi, SocNetV, Chord Snip, Cytoscape, Zingsoft, Tableau]*

	Cytoscape] **No dominators are shown in all tools**		
Interactive features	**Colour editing tools** *[Gephi, Chord Snip, Cytoscape, RAWGraphs, OmicsNet, Tableau, NetworkX, R-chie, D3]* **House hover [only one tool did not have mouse hover features]** **3D views and rotations** *[OmicsNet]* **Filtering** *[Gephi, Chord Snip, OmicsNet, D3]* **Zoom** *[Gephi, Cytoscape, GraphCommons, HighCharts, Zingsoft, OmicsNet]*		

4.1. Clusters and bridges

Clusters and bridges have two main observable properties, i.e. size (number of nodes) and density (a measure of cohesion). Although several tools reveal clusters and bridges across cases (Table 2), *Gephi*, *NetworkX*, and *Cytoscape* layouts reveal these attributes more clearly than in other layouts (Figure 3). Under the artist ecosystem, the artist and gallery clusters divide the ecosystem into a two-sided ecosystem network, i.e. manufacturing and business sides. By observing the ties' thickness in *Gephi* and *Cytoscape*, we notice the main bridge connecting the two sides. This arrangement could be so because the gallery creates markets for the artist, allowing the artist to focus on the ecosystem manufacturing side. This observation is consistent with findings from the thematic results. This bridge seems to be the most critical in determining ecosystem health, and its absence may completely cut off the artist from accessing markets. The gallery's role is more than just a link; it augments the artist's knowledge and market intelligence. This finding corroborates those highlighted in (De Silva et al., 2018) about the significant role of innovation intermediaries.

The FabLab layout also exhibits a two-sided network (Figure 3). In this network, the FabLab workforce acts as a bridging cluster between equipment booking and prototyping clusters. This phenomenon may indicate that the absence of self-motivated FabLab workers could create gaps in information between the FabLab users and equipment services, affecting its health. FabLab workers play a keystone role in mentoring and supporting the ecosystem structure, making it livelier and more enjoyable. By appreciating these bridges may help decision-makers initiate interventions to motivate the workers, e.g. through appropriate incentives. A low density of clusters is observed in the artist ecosystem compared to the FabLab, and this may be so because the artist ecosystem actors are sparsely distributed and do not know their neighbours. In comparison, the FabLab ecosystem has a high density of clusters because actors are local and having physical proximity.

Regarding the 3D printing bureau case, many clusters and bridges are observed across the network, forming a group of small star-shaped communities appearing everywhere in the network (Figure 3). These communities suggest that actors are connected to their hubs, possibly as customers or clients. Therefore, this network appears to have many hubs with competing interests. This finding corroborates the thematic results where it was reported that the ecosystem is crowded with bureaus, resellers, equipment manufacturers, all competing for a small market.

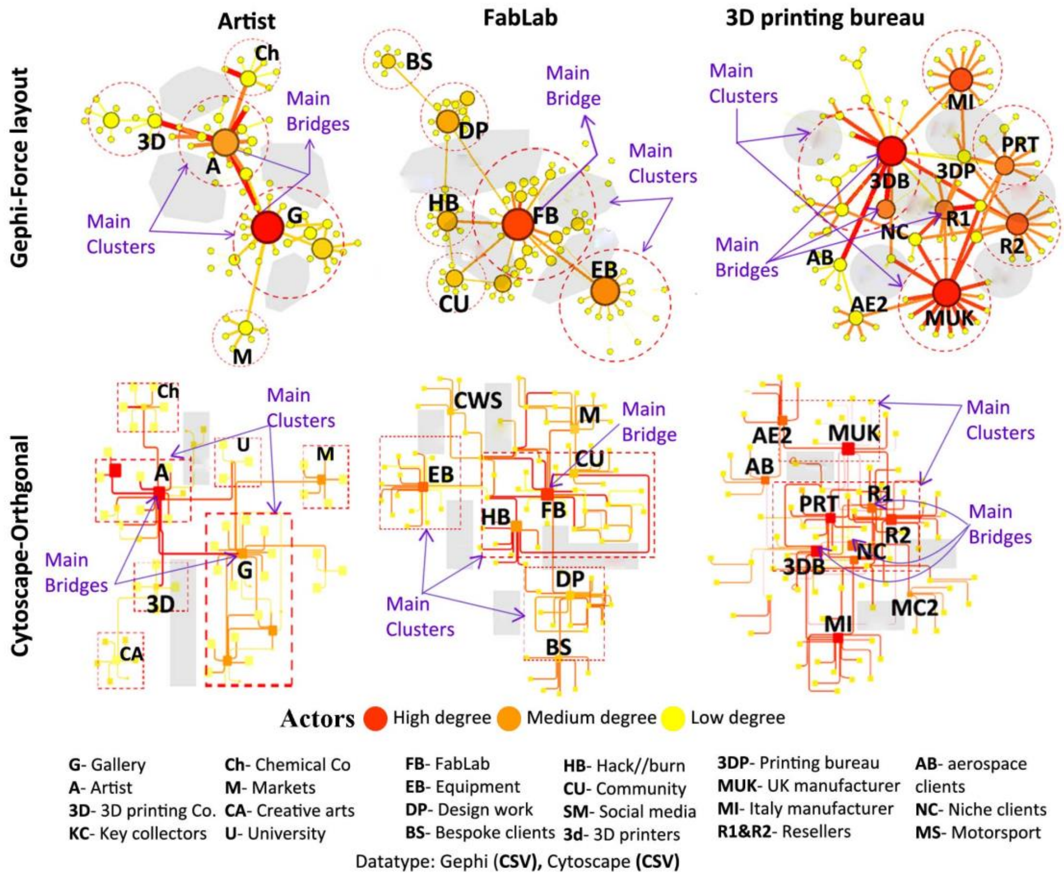

Figure 3: Showing examples of visualizations of clusters and bridges using Gephi and Cytoscape tools across three ecosystem case studies data.

These findings may guide the SME leaders to identify potential hubs and bridges by observing visual weights or densities of clusters, where high-density clusters may function as keystones or hubs to enhance the ecosystem network effect. These findings confirm previous work on using visual weights of graphs to improve decision-making (Bradley, 2013).

4.2. Node hierarchy

Node hierarchies have two main observable properties, i.e. size and colour. We use these key visual attributes to identify the most influential nodes in the ecosystem. Node hierarchy results are quite revealing in several ways (Figure 4). Nine tools allowed for colour scheme customizations. *Chord Snip* and *Tableau treemaps* show node hierarchies more clearly than in most tools. For example, by analyzing the artist ecosystem using *chord snip,* we can quickly observe that the artist node is bigger than the gallery node, possibly because the artist engages more frequently in innovation activities than the gallery. This observation suggests that the artist has more influence on the ecosystem. Meanwhile, the FabLab ecosystem reveals a consistent and similar pattern to the artist case (Figure 4). The FabLab workforce node has a high degree of connection, suggesting a more considerable influence on the ecosystem innovation process.

However, in a 3D printing bureau ecosystem, several players appear to have high node hierarchies; this could be because they are both involved in isolated innovation activities and only connected to a few mutual customers. Implications for this are that the ecosystem is highly dominated by competing manufacturers and bureau services for a small niche market, leading to uncertainties in the ecosystems. A 3D printing bureau service leader may explore alliances with equipment manufacturers to survive in these kinds of ecosystem structures.

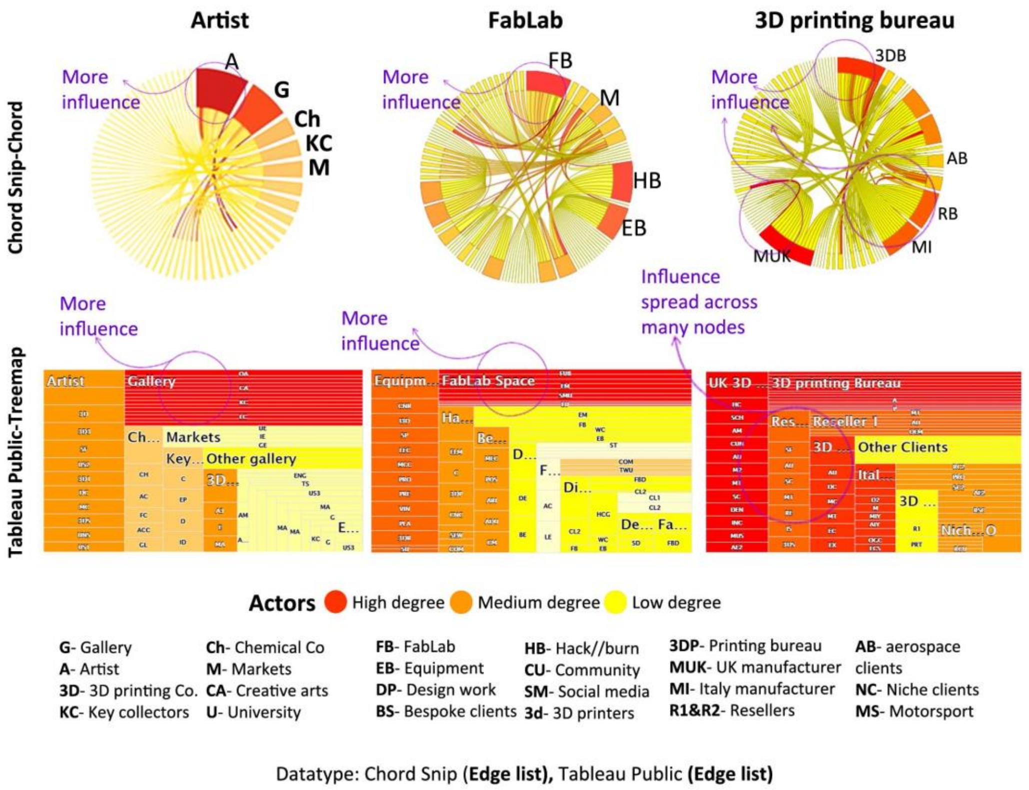

Figure 4: Showing examples of visualizations of node hierarchy using Chord snip and Tableau public tools across three ecosystem case studies data.

4.3. Structural holes

Visualizing structural holes allow us to see information and resource gaps possible than in exploring text data. This can allow actors to see relationships and explore insights. Further visual analysis revealed that most tools generated similar structural holes (Table 2). Few examples are shown where the *OmicsNet* tool has affordances in revealing holes more clearly through 3D interfaces than in other tools (Figure 5). We also observed that the Kamada Kawai layout generated through *D3.js* also reveal holes more clearly. Although other layouts also show holes, it was challenging to establish consistency and significance, e.g. in *Sankeymatic* layouts. Hole 1 separates the gallery and 3D printing firms, and this could be because the gallery is not involved in the design and development process.

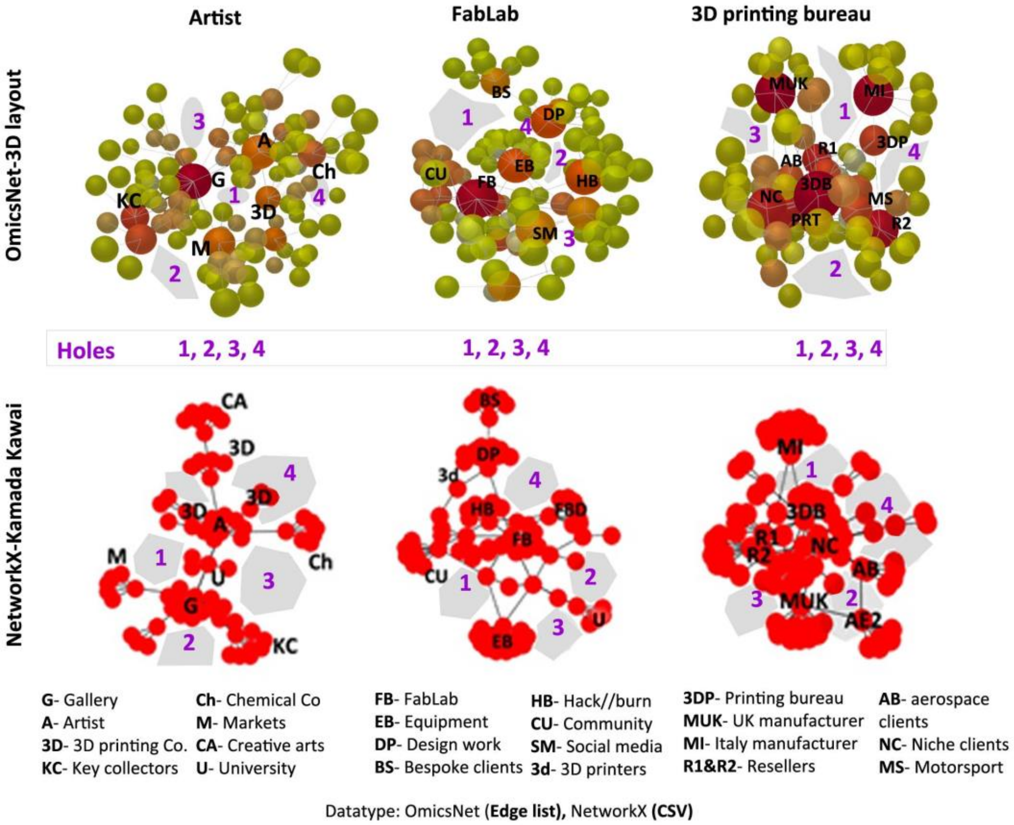

Figure 5: Showing examples of visualizations of structural holes using OmicsNet and NetworkX across three ecosystem case studies data.

In contrast, hole 2 separates international markets and key collectors, and this could be because collectors seem to be interested in the gallery private events as opposed to international trade fairs. Hole 3 separates the artist and international markets; this could be because the artist depends entirely on the gallery for markets, and in most cases, they do not see the need to participate in international events. Finally, hole 4 separates 3D printing equipment manufacturers from the chemical industry, and this could be because they are both focusing on different industries and not connected. Looking at the FabLab case, most of the holes identified are within a geographic space compared to the artist and 3D printing bureau cases. These holes may be bridged through improving processes within the FabLab. For example, hole 1 separates equipment booking and community users, and this could mean that most people using the space do not frequently book the machines. Hole 2 separates universities and FabLab directors, which is not surprising because Universities also have digital fabrication equipment found at the FabLab; this may mean less exchange of knowledge between the two groups.

In a 3D printing bureau ecosystem, hole 1 divides UK manufacturers with foreign manufacturers, probably because they compete for the same market. Hole 2 separates aerospace and motorsport clients, possibly because they are not aware of each other or not interested in working together. Hole 3 mostly separates manufacturers and equipment resellers, possibly due to competition for the same niche market. These structural holes and many others (Table 2) may inform decision-makers in designing relevant strategies to link separate clusters. Increasing network density by expanding links may lead to increased network effects, leading to productive innovation ecosystems (Giustiniano and D'Alise, 2013). Although some holes are irrelevant to strategy, careful choice of consistent visualization methods and structural holes analysis may provide helpful insights.

4.4. Weak ties

Most tools reveal strong, medium and weak ties across the case studies (Table 2). We can see that *RAWGraphs*, *R-Chie,* and *D3.js* tools reveal ties more vividly (Figure 6). However, it was challenging to make sense of individual ties, particularly in *R-Chie,* because of visual cluttering and the absence of mouse hovering features to isolate connections and labels. We also refer to *Gephi* and *Chord Snip* (Figures 3 and 4) to make sense of weak ties. There are weak ties between the artist and international markets across three tools in the artist ecosystem, i.e. *Chord Snip*, *RAWGraphs* and *D3.js*. This may be because the artist is connected to collectors and international exhibitions through the gallery actor. Other weak ties can be observed between the gallery and 3D printing firms, key collectors and other galleries. A possible explanation for these weak ties could be because of minimal interactions between communities. The practical implications are that the artist might explore weak connections with key collectors to leverage valuable information to co-design artefacts to their liking. Key collectors seem to be niche actors, holding valuable knowledge about historical artefacts in the artist innovation process.

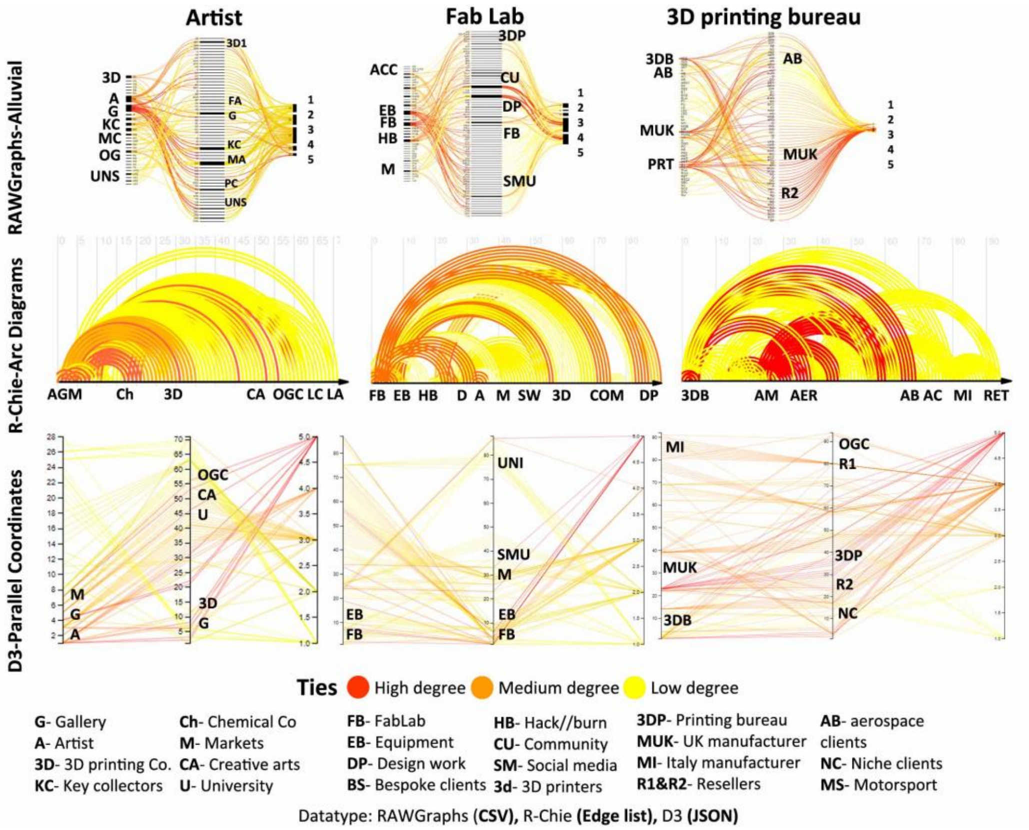

Figure 6: Showing examples of visualizations of weak ties using RAWGraphs, R-Chie and D3 across three ecosystem case studies data, i.e. the Artist, FabLab and 3D printing bureau service.

The FabLab visualization shows weak ties between international markets and design work, FabLab staff and community users, markets and FabLab staff (Figure 6). Tools like *Gephi* and *Chord Snip* also show weak ties between FabLab staff and Universities. Weak ties between markets and design work could be because design services at the FabLab are not widely advertised outside the space. Weak ties existing between FabLab staff and some community users could be caused by the fact that the space is understaffed, and users are not getting the maximum support they need. Weak ties between the space and Universities could be caused by minimal interactions with students and FabLab staff, and although the two actors are aware of each other, there is no bridging role between them.

Interestingly, the 3D printing bureau appears different (Figure 6), and we see many strong ties shown in red and few weak ties in yellow, particularly in *RAWGraphs* and *D3.js,* and in *Gephi* (Figure 3). This structure might be partly because most actors are connected to their regular customers and less engaged in collaborations. Decision-makers may use weak ties in their ecosystem to explore how they might gain access to new information and resources.

4.5. Role structures

We identified *SocNetV* and *Zingsoft* as two distinct tools revealing role structures in terms of nodes' positions in the structure, demonstrating a degree of influence depending on where nodes are relative to others (Figure 7). For example, *Zingsoft* and *SocNetV* show the gallery having a central and high degree position than the artist, which might mean that it has more influence over the artist in the ecosystem network, where most information passes through it. Therefore, the gallery act as a keystone player in the ecosystem, providing stability and health to the artist ecosystem. Under the FabLab case, the FabLab staff have a high degree of connection and central position, as shown by the large diamond node in the *Zingsoft* layout (Figure 7). The FabLab and its staff also act as keystone players to the community users, incubates and external customers. Consequently, the gallery and FabLab roles resemble keystones.

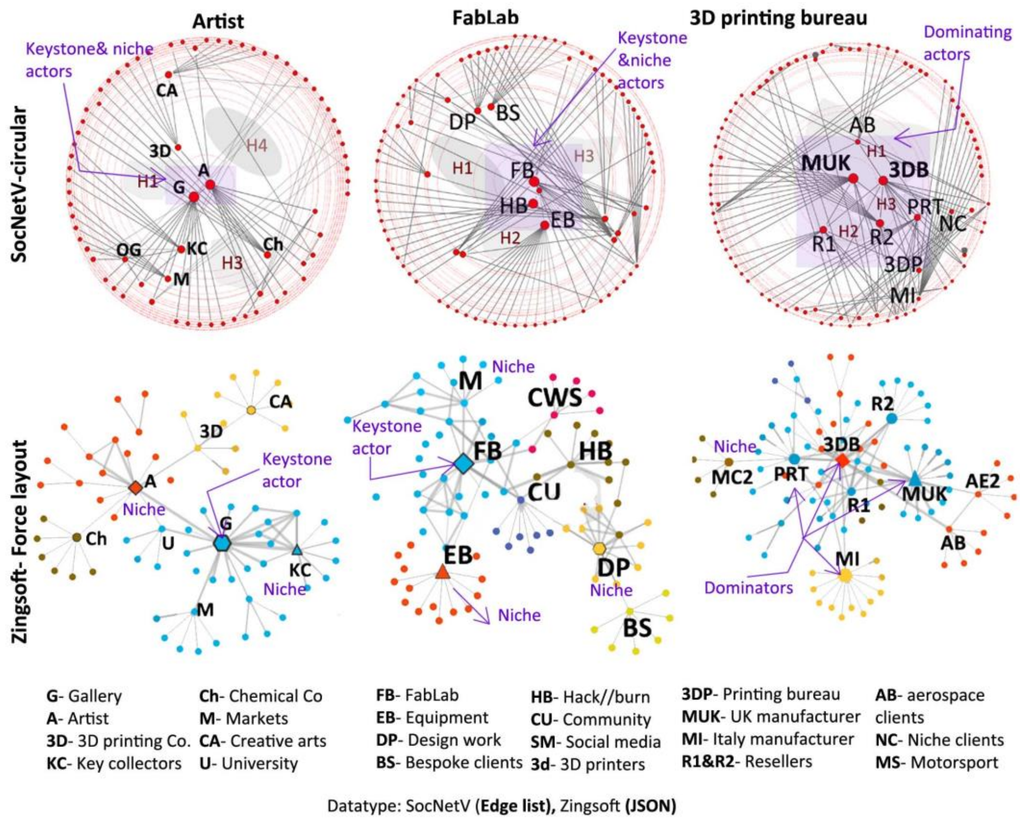

Figure 7: Showing examples of visualizations of key roles using SocNetV and Zingsoft across three ecosystem case studies data, i.e. the Artist, FabLab and 3D printing bureau service.

Contrarily, the 3D printing bureau case has many dominating players spread across the ecosystem, represented by manufacturers, resellers and bureau services, all competing for the same customers. Although the 3D printing equipment manufacturers control most value chains, bureaus and resellers also control the clients, thus creating a highly unhealthy milieu. Ecosystem actors may benefit from actively cooperating with well-resourced players (keystones and dominators). Knowing what role each actor occupies in the network may help SMEs and decision-makers to allocate resources better.

4.6. Interactivity

Most tools have limited interactive features. For example, it was challenging to use *RAWGraphs* to identify ties through filters and mouse functions. During analysis, it was also difficult to manipulate the visuals using mouse functions to make sense of structural holes and clusters. Some tools like *Chord snip* and *Cytoscape* did not have label adjust features, so node labels overlapped, making it difficult to read. Interestingly, the *OmicsNet-3D* layout allowed us to visualize different 3D layouts and analyze hidden features like holes and clusters quickly and easily. Making use of dragging, hovering and rotating features without distorting visualization layouts was key in making sense of the ecosystem configuration structure. Colour customization was challenging to perform in many tools to define ecosystem attributes. Interactive capabilities are reported as key in providing insights on the outbreak of Norovirus (Smith et al., 2019) and now widely used to communicate Covid-19 pandemic updates.

5. Conclusions

The study aimed to test 14 open-source visualization tools with three SME ecosystem cases and compared them across ecosystem design attributes (Clusters and bridges, Node-link size, Structural holes, Role structure, Interactivity). These attributes may help SME leaders to make sense of ecosystems. We found that all tools studied have different benefits and trade-offs.

Various tools revealed clusters and bridges in the artist, FabLab and 3D printing bureau ecosystem (Table 2). The ability to see clusters and bridges might guide SME decision-makers about where to invest resources for innovation. Most tools also revealed node and edge hierarchies. Node hierarchies identify significant actors having a high influence in the ecosystem. This information may be vital in alerting decision-makers on where and how to allocate roles in the ecosystem. Some tools also revealed strong and weak ties. We were able to identify weak ties, which may be essential in accessing new resources aside from close contacts. Most tools also revealed structural holes, which are key in showing decision-makers where gaps are in the ecosystem structure and how they may bridge some to promote interactions and interconnections.

We were able to use interactive features in *OmicsNet* to engage with the ecosystem structure by rotating, filtering and zooming in and out to search for details about actors and relations. Finally, one of the key attributes was to see if the tools can reveal ecosystem role structures. We found that the arrangement and positions of actors in the structure may determine which actor is more influential than the other. Knowing how and where each actor is located is key to identifying keystones or hubs, niches, and dominators in the ecosystem.

5.1. Contributions

We evaluated and reflected on an array of existing open-source visualization tools that may be used to make sense of innovation ecosystems by testing SME ecosystem attributes. This study demonstrated that open-source visualization tools could be used to gain insights into SMEs ecosystem attributes where other quantitative and qualitative methods have limitations. Secondly, we identified gaps that require further research and development towards providing a solution for SME decision-makers in making sense of innovation ecosystem configurations.

5.2. Limitations of the open-source tools

There are many properties in open-source visualization tools that are useful for making sense of ecosystems. However, there is still some limitation in using visualization tools to make sense of ecosystem attributes. Further work is now needed in the following areas.

- Colour customization

  We found a few tools such as *Gephi* with flexible colour customization to make sense of the innovation ecosystem. However, further work is needed in creating standard colour schemes with high customization, specifically for exploring innovation ecosystem attributes.

- 3D and dynamic graph layouts

  OmicsNet tool allowed a three-dimensional and dynamic graph layout to rotate and inspect the network structure. However, the 3D layouts only showed clusters and nodes, and it could not accept edge weights. Future work is required to incorporate edge attributes in 3D layouts.

- Mouse-hovering and filtering features

  Further work is needed to incorporate more features on the mouse function to explore structural holes between ecosystem clusters and identify significant holes from insignificant ones. It would be more useful if we could use the mouse functions to select holes and clusters just like we did to nodes and ties in most tools.

- Algorithms and data formats

  Most tools accept a range of data formats. Having a tool that provides various layout algorithms and data formats may help load the datasets once and run different algorithms. So, instead of switching from one tool to another, we could run the data on one platform. Further work is needed to develop a tool with many layout algorithms and take different data formats to avoid wasting time changing formats.

- Web-based and zero coding

  Since innovation ecosystem data affects various actors, more work is needed in incorporating online interactive and collaborative features to allow ecosystem actors to engage in real-time sense-making of networks. A zero-coding platform is also essential to facilitate prompt adoption and use by SMEs decision-makers.

5.3. Limitations of the data

The datasets used in this paper are from a qualitative study conducted with three SMEs innovation ecosystem leaders. The data was from a single actor in each ecosystem case made up of many actors. Hence, it may be limited in scope and interpretation, and this is also coupled with the fact that ecosystems are forever changing. Images presented here may not be an accurate representation of current ecosystem structures. Notwithstanding, the datasets helped test the useability of the visualization tools, which was the main focus of this paper. In the future, using datasets from multiple actors may increase the validity of the study.

5.4. Future research

This research has demonstrated the capacity of various open-source visualization tools in making sense of ecosystem structures using qualitative data. Further work remains to test these or similar tools with a wide range of SME ecosystems to explore how they can explicitly support the sense-making and understanding of ecosystem network attributes.

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