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Drawing metro maps in concentric circles: A designer-in-the-loop approach with visual examples

Ho-Yin Chan[1] | Yingying Xu[2] | Anthony Chen[2,3] | Xintao Liu[4] | Kason Ka Ching Cheung[5]

[1]Transport Studies Unit, School of Geography and the Environment, University of Oxford, Oxford, UK

[2]Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

[3]Hong Kong Branch of National Rail Transit Electrification and Automation Engineering Technology, The Hong Kong Polytechnic University, Kowloon, Hong Kong

[4]Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Kowloon, Hong Kong

[5]Department of Education, University of Oxford, Oxford, UK

Correspondence

Ho-Yin Chan, Transport Studies Unit, School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK.

Email: ho.chan@ouce.ox.ac.uk

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Abstract

This article presents a proof-of-concept designer-in-the-loop schematic map drawing tool, based on the marriage of two approaches—manual and automated, which provides the technical interactivity of drawing tools between the user and the computer. We focus on concentric circle maps as opposed to the commonly used orthogonal mode representation, which is suggested by previous studies that it could promote better network learning. In comparison with existing methods, the proposed method is more compatible with the framework of effective map design from psychological and aesthetic perspectives, and a range of options can be provided in conjunction with users' preferences. We evaluated our approach on a set of iterations with case studies of Hong Kong metro with a group of three co-authors from the fields of geography, transport engineering, and education.

1 | INTRODUCTION

1.1 | Background

This article presents a proof-of-concept designer-in-the-loop schematic map drawing tool, with the focus on the concentric circle style in transportation studies (schematic map is also known as linear cartogram in cartography studies). Closely related to everyday life, transportation, as a field of studying everyday mobilities of people, information, and goods, has long been a field that arouses the interest of academics and professionals working in various forms of (geo)visualization and digitalization of the complex realities and problems (Brovelli et al., 2017; Mobasheri et al., 2017a, 2017b, 2020; Roth, 2021; Vrenko & Petrovič, 2015), apart from well-thought-out quantitative models and simulations. For many if not most of these academics and education professionals, visualization has always been an important tool for people to convey and verify the known, explore the unknown, and convey ideas that cannot be easily expressed in writing but can be readily translated into (geo)visuals or non-verbal representations (Carbonell-Carrera & Hess-Medler, 2019; Edsall & Wentz, 2007; MacEachren, 1991; Sun & Li, 2010).

Network visualization is a foundation of transportation (Cheng et al., 2013), which is not only crucial for operational purposes in navigation, but also impactful when trying to utilize various data in the education process (Bednarz & Ludwig, 1997). Schematic maps offer a simplification of elements of a real system and are commonly used worldwide to depict urban rail systems in official maps (Ovenden, 2015). Schematic maps are traditionally drawn manually, which can be a difficult and time-consuming process. Although increasing attention has recently been given to automated map-generation methods, these are typically based on an optimization approach (e.g., Jacobsen et al., 2021; Lan et al., 2019, 2020; Li, 2015; Mark Ware et al., 2006; Sester, 2005; Stott et al., 2011; Wang & Chi, 2011), which may not satisfy both the psychological and aesthetic needs of users simultaneously. To date, work in this area has advanced in parallel. On the one side, researchers in psychology have sought to embellish maps and emphasize their usability. Roberts et al. (2013) categorized five design elements, including usability in terms of simplicity, coherence, balance, topographicity, and aesthetic as harmony. The framework emphasizes the necessity and discreteness of design categories for the creation of usable and popular metro maps. Map designers are advised to fully address these design categories and have the flexibility to prioritize among them. On the other side, researchers in computer science have attempted to improve the optimization algorithm used to design maps. Lan et al. (2019) classified the constraints commonly adopted in the optimization approach into three levels, namely the feature level (individuals), the class level (groups of features), and the map level (the whole representation). They suggested that the automated approach largely only focuses on the local (or individual) level, rather than the global (or map) level, despite that the importance of the global-to-local perceptual process has long been recognized in cognitive psychology.

While such analyses have offered many useful insights into the quality criteria for metro maps, as identified by research in the psychology communities, most research has been conducted using optimization approaches. Thus, it may be difficult for designers to efficiently draw maps to pursue balanced solutions that incorporate both usability and aesthetic perspectives (Demaj & Field, 2012). Differing from previous research on automated schematic mapping, this article adopts the usability and aesthetic perspective to automate the drawing of concentric circle maps, which is the effective map-drawing framework proposed by Roberts et al. (2013) and one that many designers/scholars have followed (Chan, 2018; Chan et al., 2021; Huang, 2017; Konovalov, 2016). Roberts et al. (2016) have argued that these may have useful properties regarding coherence and network learning, but these potential benefits need to be tempered with actual findings. Crucially, a concentric circle map for Berlin was both objectively harder to use and less popular than a more conventional octolinear design. This should sound a strong note of caution to anyone advocating more widespread use of such designs. A follow-up article by Newton and Roberts (2018) suggested more practical uses for such designs, but mainly for cities in which the actual topography of the city is genuinely ring/radial at the physical level rather at an abstract/conceptual level. Cologne (Köln) is a notable example of this, and a concentric circle version has recently been adopted as the official design for the city (University of Essex, 2022). Xu et al. (2022) utilized Roberts et al. (2013)'s usability framework by adopting map design criteria as a mixed-integer programming problem. The numerical experiments conducted using small and large networks in Vienna, Montréal, and Beijing suggested the applicability of concentric circles style in various cities. Considering the strong emphasis on single center, which might not be applicable to polycentric cities like New York and London, the design method is still in their early stages of development and potentially controversial in the domain of schematized maps and should be studied to gain a deeper understanding of their potential benefits.

By combining the benefits of both automation and manual revision, this article aims to design an interactive metro map drawing algorithm as an alternative specific to concentric circle maps under the framework for effective schematic-map design. Our approach uses constraint equations to determine the optimal graphical features of maps; however, rather than optimizing objective functions, the procedures provide an interactive way to allow users to define parameters that generate multiple optimal solutions and subsequently determine the subjectively optimal one. The proposed approach is therefore tailored to the various user's preferences regarding the usability and aesthetic properties of map designs.

The interactive nature of design procedures provides not only the technical interactivity of drawing tools between the user and the computer, but also pedagogical interactivity as a teaching strategy to facilitate active learning (Heintzman, 2020; Liu & Zhu, 2008). The proposed map-drawing algorithm in this study could be a potential interactive learning software for developing users' knowledge of constructing schematic network maps (Weeden, 1996). The drawing algorithm provides users explicit and instant reports on the map-drawing design attributes of their constructed concentric circle maps. These criteria provide learners clear and focused guidance on the parameters to formulate a compromised concentric circle map. The interactivity facilitates users' reflection-in-action (Kolb, 1984), enabling users to recognize the limitations of their maps and adjust their concentric circle maps in order to realize their ideas (Kennewell et al., 2007). Through a series of attempts of map construction, users can develop their understandings on four usability values from Roberts et al. (2013)'s usability framework, namely simplicity, coherence, balance, and topographicity. The findings might also shed light on the possibility of introducing interactive map-drawing algorithms to public geography education. In this paper, we utilize the open geospatial data from the Hong Kong Government's Geospatial Lab, which aims to nurture a geospatial community to encourage the public to harness the use of open spatial data (HKSAR Development Bureau, 2021).

1.2 | Contribution of this study

An important question in the automation of schematic map design is how the decision on the final solution is made. For any given input embedding, several acceptable solutions may exist. Although computers have limited decision-making ability, an automatic schematization procedure may provide a useful starting point for a design, based on which a designer can produce a final representation. While Roberts (2014) devised a framework for designers to use to determine an efficient map, it is difficult to incorporate the criteria of this framework into the current multi-objective optimizations. Inspired by the personalized interactive experiences in the literature (Degbelo et al., 2019; Taylor and Plewe, 2006; van Dijk & Haunert, 2014; Wang & Peng, 2016; Wilson et al., 2010; Zhu et al., 2021), we implement a novel set of flexible and personalized map-drawing procedures as an alternative to the above efficient map framework. Essentially, our approach relieves the user of the burden of deciding on the criteria and weighting combinations and generate non-extreme and balanced solutions. We also establish a framework for analysis and decision-making on efficient solutions. We believe that while mathematical models can solve problems, humans remain the best equipped to decide which solutions are desirable. In particular, two specific advantages from manual and automatic approaches are integrated into the proposed procedure, as follows:

- **Advantages from the manual approach**: The effective map framework provides guidelines for schematic map design practices that facilitate the management of psychological and aesthetic issues to optimize the usability and attractiveness of schematic maps. This manual approach can identify key subjective characteristics, especially from an aesthetic point of view.

- **Advantages from the automatic approach**: The initial layout from the automated generation set enables the decision-maker to become more thoroughly acquainted with the prototype. Multiple trials can be conducted more quickly and with less effort to enable a final satisfactory solution to be discovered.

The article is organized as follows: Section 2 gives a literature review regarding effective schematic map design and automated generation of schematic maps; Section 3 provides the methodological framework for the designer-in-the-loop design of schematic metro maps and setting/formula of the qualitative and quantitative evaluation of maps; Section 4 presents a proof-of-concept with a case study of Hong Kong metro; Section 5 discusses the results and way forward and Section 6 concludes the findings of this article.

2 | LITERATURE REVIEW

2.1 | Effective schematic map design

Despite many established design guidelines, there is no universally accepted standard for metro map design (Roberts, 2014). To improve the design of metro maps and adapt them to the needs of travelers, designers and researchers are interested in understanding the theories of design layout preferred by the public and transport operators, to compile general principles for effective design. Based on a comparison of design theories, Roberts (2014) organized the various criteria and proposed a broad framework for effective metro map design. This design framework consists of five categories, namely *simplicity*, *coherence*, *balance*, *topographicity*, and *harmony*, which emphasize the basic requirements for effectiveness.

Once these criteria have been specified, quantitative measures can be established to evaluate the effectiveness of map design. The simplicity of line trajectories is quantified in terms of the numbers of bends. Balance is a measure of the overall equal density of map features. Coherence requires higher-level measures of relatedness between lines. In the case of concentric circle maps, coherence may be relevant to how well lines relate to each other by forming concentric circles with a common center. Topographicity (or topographical distortion) is related to the deviation of station locations on a map from the actual locations. Among the five categories, harmony influences attractiveness, which is a subjective aesthetic judgment that connotes acceptance rather than achievement of an objective measure of usability. The main principles of the five design categories are illustrated in Figure 1. For a comprehensive review of design issues, the reader is referred to Roberts (2014). Although satisfying all five criteria is essential to maximize map usability and engagement, the prime consideration is the configurational issue of design. In this context, fulfilling all five criteria requires a compromise, necessitating a subjective judgment to prioritize these disparate and possibly conflicting measures.

To date, the octolinear drawing style is the most commonly used, based on its first application by Henry Beck in his map of the London Underground, published in 1933 (Readers are referred to a survey by Wu et al., 2020). Although this was the pioneering style for metro maps, it lacks empirical evidence that users perceive octolinearity as the "gold standard" design style (Roberts et al., 2013). This has encouraged attempts to investigate whether alternatives might result in better designs (Roberts et al., 2013, 2016). Recently, a completely different style for drawing metro maps has attracted attention: the concentric circle style (Chan, 2018; Huang, 2017; Konovalov, 2016). Roberts (2013) shared his experience of reviewing and creating different concentric circles-based metro maps, including those for the metro systems of London (UK), Tokyo (Japan), Madrid (Spain), Paris (France), Chicago (USA), Berlin (Germany), Barcelona (Spain), and Moscow (Russia). He suggested that a layout that emphasizes a city center and the ring-radial network structure of a metro system is highly suitable. The concentric circle representation further improves coherence by having a common center from which radial lines emanate, and the resulting ortho-radial grid is conducive to effective

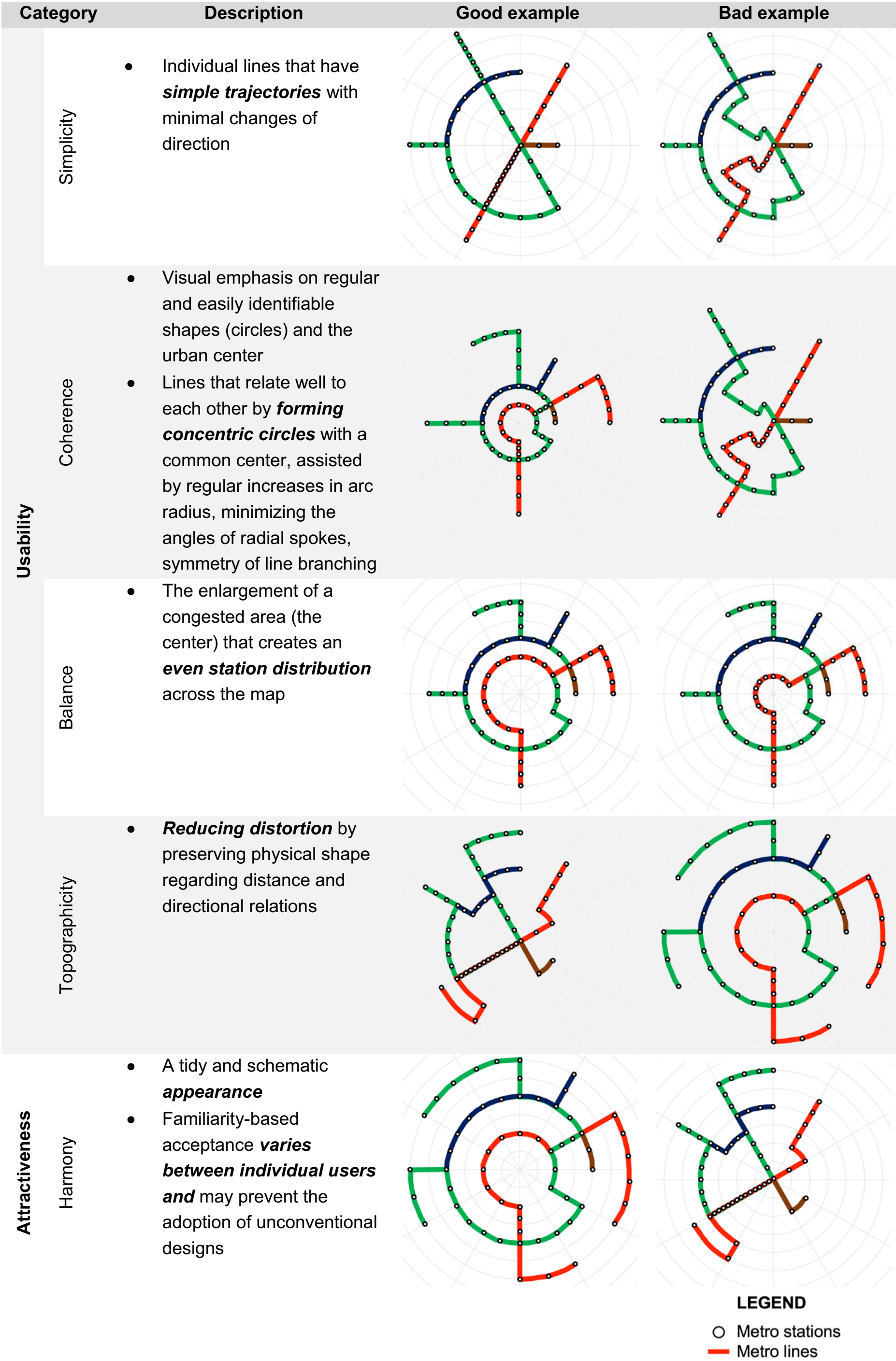


FIGURE 1 Framework for effective design of schematic maps.

map design. However, designers may neglect or face challenges in improving the remaining four categories after a certain level of coherence has been achieved. Inspired by two concentric circles maps, Roberts attempted to draw a concentric circles map of the London metro by harmonizing the circles and straight lines. The solution, however, did not have all of the straight lines intercepting every circle at the same angle, which reduced the harmony of the design. Roberts's experience of mapping other dense metro networks using a concentric circles approach indicated that finding an appropriate center may be a challenge that multiple trials are required. His attempt to map the New York subway using concentric circles also demonstrated the difficulty of placing a center point when there are no circle or loop lines in a network.

Table 1 summarizes the difficulties of addressing the five design categories in manual practice. We propose an automated approach for rapidly sketching concentric circle maps using the geographic information of metro stations, which increases productivity and consistency.

2.2 | Automated generation of schematic maps

In recent research, the automated generation of schematic maps has been treated as an optimization[1] problem according to the researchers' understanding of the usability criteria (Bekos et al., 2022; Nöllenburg & Wolff, 2011; Ti et al., 2015). They have worked with constraints that govern different properties. Optimization techniques use various sets of constraints governing different features of a map. Constraints are modeled as soft constraints embedded in the objective function or hard constraints in a constraint set. An objective function may consist of multiple terms to emphasize different design criteria. However, although weights can be assigned to different terms to normalize the effect of each constraint, weighting is often determined through trial and error. Moreover, only one optimal solution results from a single objective function, and this may not be considered as a good design from other perspectives.

Later, Nöllenburg and Wolff (2011) presented a multi-objective model that produced multiple optimal solutions with octolinearity as a hard constraint. Subsequent researchers, such as Oke and Siddiqui (2015), argued that

TABLE 1 Difficulties in the manual practice and automated generation method for schematic map drawings

Category	Manual practice	Automated generation method
Simplicity	Designers generally struggle with topographical distortion and line trajectory simplification. Attempts to conserve complex line trajectories may generate multiple bends (Roberts, 2014)	Minimizing the number of bends uses multiple design variables and constraints, which requires a carefully balanced weight vector to obtain reasonable drawing solutions (Nöllenburg & Wolff, 2011)
Coherence	Designers may experience difficulty in configuring radial features about an unsatisfactory center point (Roberts et al., 2016)	The center is chosen randomly and manually and is not a design variable in the optimization problems (Barth, 2016)
Balance	Attempts to enlarge congested areas in a map may cause suburban areas to become overly compact, leading to high topographical distortion (Roberts et al., 2013)	When focal regions are greatly enlarged, considerable computational time is required to minimize significant distortion (Ti & Li, 2014)
Topographicity	Distortion may decrease user confidence in and acceptance of a design (Roberts et al., 2013)	Specific efforts are needed to achieve a balance between area distortions (i.e., enlarging areas of interest to improve clarity, which is a subjective goal) and orientation distortions (minimizing over-distortion that may reduce map recognition, which is an objective goal) (Ti et al., 2016)
Harmony	Designers may create a map with a tidy and schematic appearance but neglect to depict the topology of a metro network. Such a design may be easy to use but be rejected by users for unfamiliarity such as the focal center and overall density of maps (Roberts et al., 2013)	The use of the octolinear drawing style is considered as the golden rule of aesthetics and is formulated in the objective function (Oke & Siddiqui, 2015)

Nöllenburg and Wolff's model might ignore some potentially desirable solutions, and emphasized that identifying the entire set of non-dominated solutions may be valuable for decision-makers. However, there is a lack of agreement on the number of objective functions that are required and how integer constraints should be relaxed to achieve better performance. Moreover, the algorithm does not allow users to determine an intermediate solution from an existing pool of efficient solutions. Efforts are needed to create a more dynamic and personalized procedure that will produce solutions that address all considerations and facilitate the decision-making process.

Recently, researchers of automated schematic-map design have implemented algorithms for creating concentric circles maps. Fink et al. (2014) adopted a mixed-integer programming approach, which is often used in the automated generation of schematic maps, to draw concentric circles versions of the Vienna and Montreal metro networks. They detailed the constraints and optimization techniques used to restrict the geometric properties of individual features (e.g., the minimum bends and distinct angles required). However, their simple extension of the traditional approach did not produce results suitable for use in metro mapping; their algorithm must be modified to use this mixed-integer programming approach to map more extensive metro networks. Barth (2016) developed an algorithm for drawing concentric circle maps and demonstrated its usability for mapping a larger metro network in London. However, the methodology used by Barth provides only one solution, and although this is an optimal solution, it may not be a good design from an aesthetic perspective, and thus may not be a balanced solution.

While the insights provided by the above studies mathematically formalized Roberts's framework for effective schematic concentric circles map design, a constraint may contribute to two or more categories, whereas in other cases, a single category is the product of two or more parameters. Consequently, it may be onerous to develop a general principle for formulating an optimization problem that incorporates the complex relationships between the constraints and the categories for effective map design. Table 1 summarizes the difficulty in addressing the five design categories in the automated generation method. To address these difficulties, we propose a flexible and interactive approach to sketching concentric circle maps, whose solutions may be adjusted with the aid of several user-defined parameters, thereby enabling users to test different strategies.

3 | METHODOLOGY

The conceptual framework consists of three parts, namely user-defined parameters, an automated map-drawing procedure, and quantitative evaluation indicator/framework. The user-defined parameters are adjustable variables that may make a significant contribution to the map layout. These parameters are the fundamental elements by which users may adjust the solution layout on a trial-and-error basis. The automated map-drawing procedure facilitates the exploration of alternative map-drawing options; not only those that incorporate optimization objectives and relevant constraints from the optimization approach, but also those that are compatible with the framework of effective map design. The qualitative evaluations are developed from the five categories of the framework to evaluate the quality of the solution maps. The integrated model provides an interactive platform upon which metro map alternatives may be generated from concentric circles. The general structure of the interactive design of schematic metro maps is shown in Figure 2.

3.1 | User input and parameters

Line trajectories and station coordinates are the primary input for the network topology. In addition, users are required to define three different parameters to customize and adjust their map layout design, including the center point, line importance, and polar grid line sets, as discussed as follows.

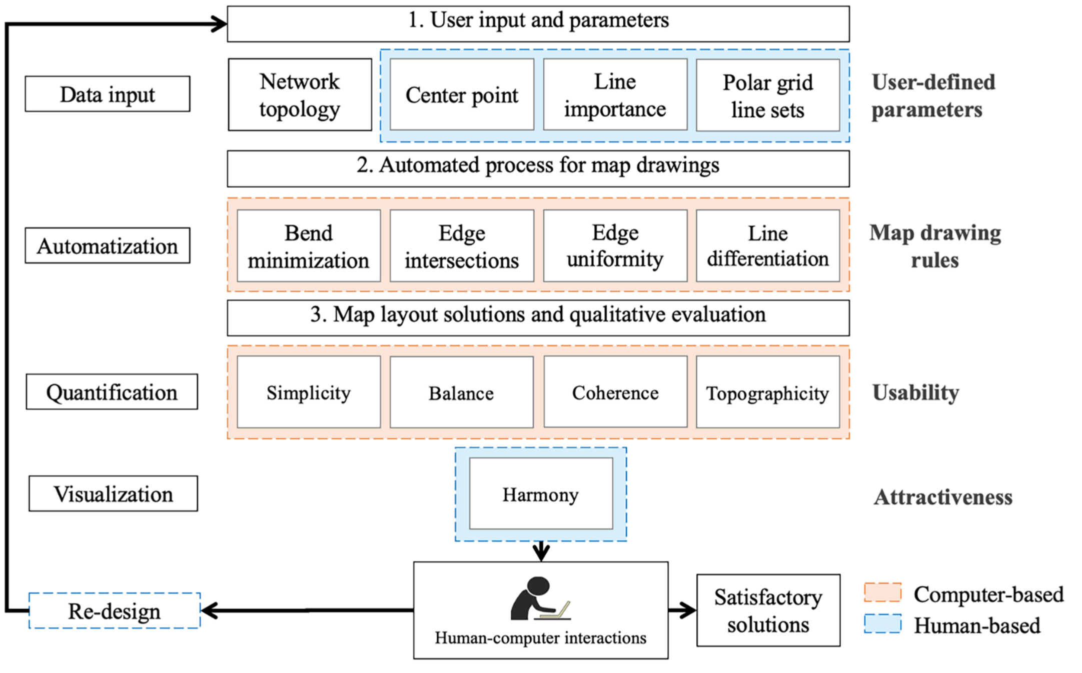


FIGURE 2 The methodological framework for the interactive design of schematic metro maps.

3.1.1 | Choice of the center point

The center point is not necessarily a station but is the geographical center of the metro network, or the point with the highest concentration of stations. A good selection of a center point will result in the stations being distributed evenly on the map and will create sufficient space for configuring all regions without over-compression. This will generate a map that is balanced overall. Lines that have stations at/near the center are better represented as radial lines to maximize the simplicity of the individual line trajectories. The selection of the location of the center point and circular lines will affect how the radial features may be configured in a coherent manner.

Roberts et al. (2016) attempted to manually draw the Berlin, Germany network in a concentric circles style. His endeavor to choose different stations as the center point demonstrated the importance of identifying the common center of radiation, which contributes to the coherence of a design. As particular attention is paid by map users to the center of the concentric circle, the center may affect the overall acceptability of a map to users, which is the primary concern from the harmony design aspect. Inspired by Roberts, many examples of attempts to draw concentric circles maps can be found on the Internet (Chan, 2018; Huang, 2017; Konovalov, 2016), with many opinions expressed on the chosen centers of maps. As observed in previous studies, the most acceptable choice for a center appears to be one that matches users' perceptions of identity in terms of urban toponyms (Bucher et al., 2013), such as the historical center of a city, an existing central business district, or a natural geographic focus.

3.1.2 | Polar gridline set

In concentric circle schematic maps, stations are mapped on predetermined circular or radial gridlines, which are some of the user-defined parameters. Once the center of the circle has been selected, the remainder of the map can be constructed outward from the center. However, where station nodes are located greatly affects the outcome of the final drawing of the metro map. For the circular grids, we specify the radius (c1, c2, c3, …, cn) and the circular grid spacing ($gk = ci - cj$) along which a node can be located. The density of stations within each radial or circular segment is highly determined by the radius. Circles with a larger radius can provide more space for stations lying on radial or circular sections. It is better to have fewer stations lying on the small circles and more stations on the large circles, as this affords a balanced distribution. However, the spacing of the adjacent circular grid g has to be small enough to incorporate enough grid intersections for the nodes in the dense center of the map, while the extremities are relatively sparse. Balance can be achieved via even (or at least gentle) spacing of the circular features. Enlargement of congested areas with large values of g may be necessary; however, this may alter the map such that it differs significantly from reality, and thus affect topographicity. Thus, the preservation of the overall balance of maps must be considered.

The angle set is the most fundamental determinant of the structure of the radial grids on a schematic map. Usually, a restricted number of angles is permitted for octolinear schematic maps (Nöllenburg & Wolff, 2011) to reduce visual complexity and improve harmony (Roberts et al., 2013). In a concentric circles map, however, the number of angles is correlated with the number of radial lines. Larger networks should have more radial lines to prevent too many transit lines lying on the same radial line. However, angles need not be evenly spaced, that is, need not necessarily be a sequence of angle sets. Nevertheless, the even spacing of radial lines can help to improve the overall consistency of drawings of more extensive networks, and therefore the coherence of the design. Meanwhile, a map with many angles may have simple line trajectories and improved simplicity. However, it is likely to suffer from poor coherence if the line spacing is uneven. An effort is needed to strike a balance between these two factors.

3.1.3 | Line importance

The drawing priority is determined by the line importance, to minimize the number of bends stated in the drawing rules (as elaborated in the following subsections). Lines with a higher priority generally have fewer bends. When designing the line importance ranking, it may be particularly important to take public perceptions into account, to increase public acceptance of the map. Lines that are commonly perceived to be important and that have greater simplicity may be more harmonious with the familiar and readable format of maps (Roberts et al., 2013). However, it has been increasingly emphasized in the literature that schematic maps affect users' route choices (Hochmair, 2009; Morgagni & Grison, 2019; Xu, 2017). Users generally prefer routes that are initially simple and straight, even if these routes are not the optimal routes. A possible application of this preference is in the priority drawing of newly constructed lines. Specifically, if new lines are drawn with higher simplicity (i.e., with fewer bends and appearing more straight/direct), this may attract travelers from the congested lines to the new lines. Overall, the incorporation of line importance into drawing priority may enable users to customize or make changes to their travel experience to meet their specific needs by focusing on specific lines.

3.2 | Automated process for map drawings

3.2.1 | Step 1: Determining the Cartesian coordinates for each station

The network topology and geographic information of stations are the input data. The network topology is not changed, to ensure that the concentric circles map is not extensively distorted. The geographic coordinates of stations determine their relative position in the schematic map. The geographic data need to be pre-processed so that we can denote the stations with Cartesian coordinates. This is performed by the following equation:

$$(x_i, \quad y_i) = [(Lon_i - Lon_c), \quad (Lat_i - Lat_c)], i \in N \tag{1}$$

where Lon_c (Lon_i) and Lat_c (Lat_i) are the longitude and the latitude of the center point c (station i). Center-point selection influences the coherence of the concentric circles map, and a poor center point will result in an unbalanced schematic map design. Usually, the geographic center of the metro system or the generally accepted central station is selected as the center point.

3.2.2 | Step 2: Converting Cartesian coordinates to polar coordinates

Polar coordinates are two-dimensional coordinates that comprise a distance ρ from the pole and an angle θ from the polar axis. This system is the most convenient to describe a location originating from a central point. The equations for converting Cartesian coordinates to polar coordinates are as follows:

$$\rho = \sqrt{x^2 + y^2} \tag{2}$$

$$\theta = \text{atan2}\left(\frac{y}{x}\right) \tag{3}$$

where atan2 is the arctangent function in which quadrants are considered.

3.2.3 | Step 3: Forming possible coordinates sets for each station

In concentric circle schematic maps, stations are mapped onto predetermined circular or radial grid lines, which are user-defined parameters. For example, as shown in Figure 3, three radial gridlines r1, r2, and r3 with even spacing and two circular lines c1 and c2 are set in advance. With respect to station A (ρ, θ), A1 (ρ1, θ), and A2 (ρ2, θ) are possible mapping points on the circular gridlines with the same angle θ, while A3 (ρ, θ1) and A4 (ρ, θ4) are possible mapping points on radial gridlines with equal radii ρ. Therefore, for each station, there are at most four possible mapping points in the set of coordinates. The optimal mapping point is then determined based on the map-drawing rules in Step 4.

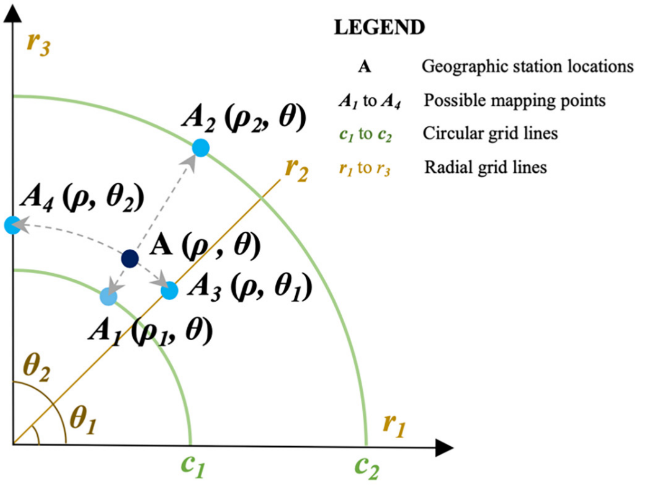


FIGURE 3 Illustrations of a possible set of coordinates for a station.

3.2.4 | Step 4: Mapping stations on concentric circles

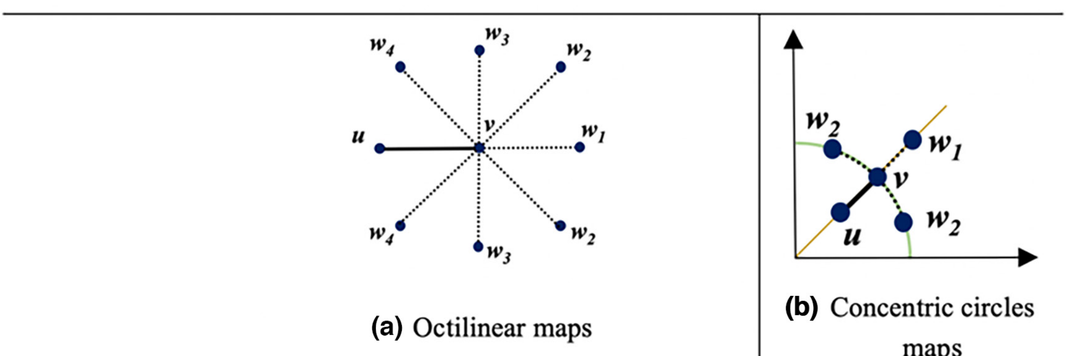
This subsection introduces four map-drawing rules, which are strictly enforced to restrict the mapping-point selection.

3.2.5 | Rule 1: There should be as few bends in each line as possible

Minimizing bends in the lines facilitates the usability of the map. In octolinear map drawing, four possible bend costs are quantified based on the angles between the links (Nöllenburg & Wolff, 2011), as shown in Figure 4a. The total bend cost is one of the optimization objectives that can be calculated by summing the cost of all the bend sections in the network. In concentric circle map drawings, there are three possible bends with two possible bend costs, as shown in Figure 4b. Minimizing the total bend cost BC of a line (Equation 4) by reducing the number of bends (uv, vw_i) can simplify line trajectories by reducing the number of circular and radial lines that have to be used.

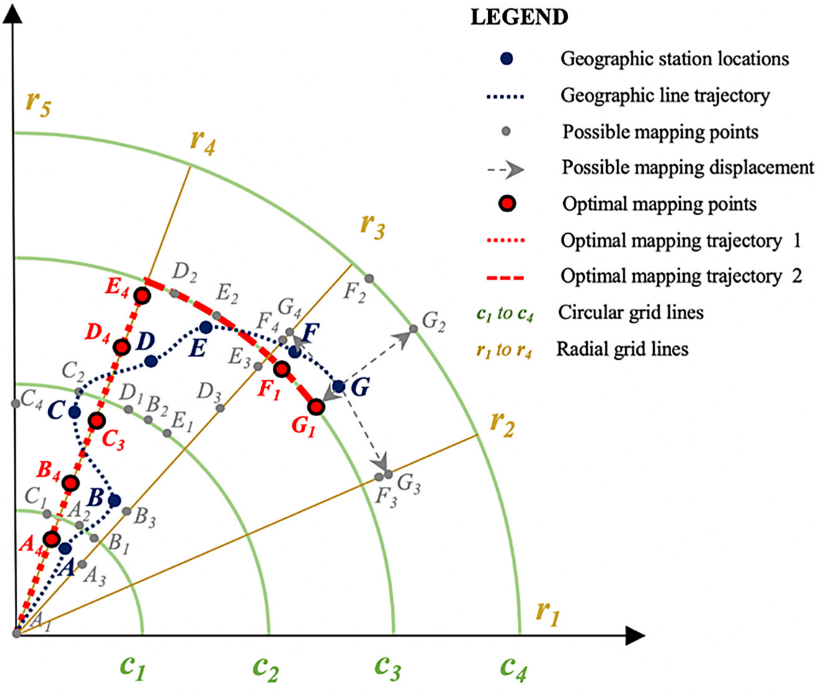
$$BC = \sum_{l \in L} \sum_{vu,uw \in l} bc(u, v, w) \tag{4}$$

Based on the possible sets of coordinates from Step 3, we determine the mapping point of each station by optimizing the trajectory of each line that uses the fewest circular and radial lines. An effective procedure for identifying an optimal line trajectory is to select the circular or radial line that involves the most consecutive stations. For example, a line with seven stations shown in Figure 5a has one optimal line trajectory, using c3 and r4, with one bend. This line trajectory is determined by selecting mapping points from X_i ($X \in \{A, B, C, D, E, F, G\}r| \ i \in \{1, 2, 3, 4\}$). The mapping table in Figure 5b lists all the possible mapping points of each station. For example, as shown in Figure 5a, there are four possible mapping points for station G, which are then converted into four mapping variables in the mapping table in Figure 5b for further processing. In the first iteration, there are five consecutive mapping points at R4, which is determined as radial trajectory 1. In the second iteration, focusing on the circular grids, c_3 and c_4 can provide solutions for the remaining consecutive stations. The possible mapping segment with a minimum distance from the trajectory 1 (i.e., c_3) is selected for trajectory 2.



Line bend	uv-vw1	uv-vw2	uv-vw3	uv-vw4	uv-vw1	uv-vw2
Bend cost (bc)	0	1	2	3	0	1

FIGURE 4 Illustrations of line bends and bend costs in octolinear and concentric circle maps.



(a) Example of individual line trajectory

Possible Mapping Points

Station	Circular Grid Lines c_1	c_2	c_3	c_4	Radial Grid Lines r_1	r_2	r_3	r_4	r_5
A	A_2						A_3	A_4	
B	B_1	B_2					B_3	B_4	
C	C_1	C_2						C_3	C_4
D		D_1	D_2				D_3	D_4	
E		E_1	E_2				E_3	E_4	
F	Trajectory 2		F_1	F_2		F_3	F_4	Trajectory 1	
G			G_1	G_2		G_3	G_4		

Possible mapping points for station G

(b) Corresponding mapping table

FIGURE 5 Illustrations of mapping-point selection.

3.2.6 | Rule 2: Transfer stations on different lines should be located at the same point or with minimal displacement, to differentiate the lines

An additional rule is adopted to address the possible inconsistency of transfer stations on different lines that may mislead map readers. To ensure that transfer stations on different lines are located at the same point, we introduce line importance IM_l. Lines that are considered more important are drawn at a higher priority, and naturally and ideally have fewer bends and spatial constraints than transfer stations of other lines. Based on the line importance, we determine the mapping points of the lines of higher importance, and then update the location of transfer stations in the other lines that have not been processed in the mapping-point selection procedure.

3.2.7 | Rule 3: The distance between adjacent stations should be as uniform as possible

Maintaining a uniform length between adjacent stations ensures there is a harmonious layout that balances dense and sparse space in the map. Such uniformity is commonly achieved in the optimization of automatic map drawing by restricting the length between adjacent stations within a range (Lan et al., 2019) or minimizing the absolute difference between the length of the edges connected to the same station (Stott et al., 2011). Inspired by this, we space the stations between the transfer stations on the line trajectory to make the inter-station distance as uniform as possible. By fixing the locations of transfer stations, the locations of the non-transfer stations are adjusted to be evenly distributed between the transfer stations. In the polar coordinate system, the lengths of the edges on the radial and circular gridlines are calculated by Equations 5–6, as follows:

$$E_{ij,radial} = |\rho_i - \rho_j| \tag{5}$$

$$E_{ij,circular} = \rho_i |\theta_i - \theta_j| \tag{6}$$

3.2.8 | Rule 4: The lines located on the same circular or radial lines should be distinguishable

An additional rule is applied to address the problem of different lines overlapping on the same circular or radial line segments. A small displacement of sections of such coincident lines is sufficient to enable their distinguishability, thereby ensuring that the map is easy to follow. Generally, there are two cases of overlapping lines. For lines on circular grid lines, such as Line 1 and Line 2 in Figure 6a, the radius of overlapping sections is modified by adding a small value, Δr, to distinguish between overlapping segments. For lines on radial lines, such as Line 3 and Line 4 in Figure 6b, the overlapped segments are moved horizontally by drawing them with respect to a shifted origin O′ (Δx, 0).

The procedure for automated concentric circles map drawing is summarized in Table 2.

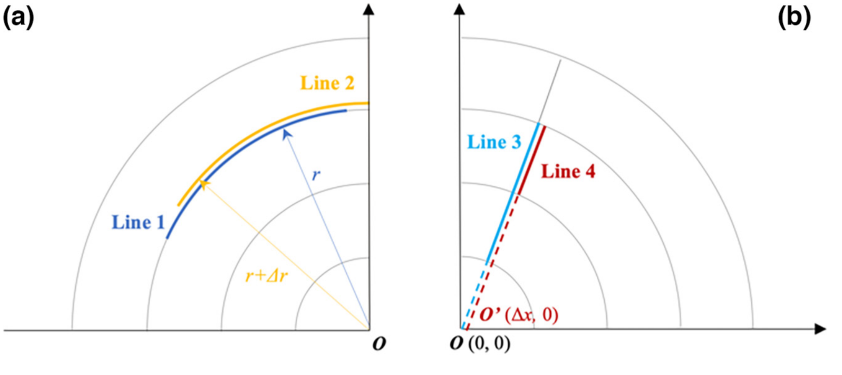


FIGURE 6 Illustrations of adjustment of overlapping lines: (a) on circular gridlines; and (b) on radial gridlines.

TABLE 2 Pseudo-code for concentric circles map drawing procedure

Item	Description
Initialization	Geographic coordinates of all stations $(Lon,Lat)_i \| i \in N$
	Network topology (all sorted links $\{a \in A \| i = 1,2,...,\|A\|\}$)
Users	Center point (Lonc, Latc)
Parameters	Circular line set $\{c_1, c_2, c_3, \ldots\}$
	Radial line set $\{r_1, r_2, r_3, \ldots\}$
	Line importance IM
Procedure	
Step 1:	Determine the Cartesian coordinates $(x,y)_i$ based on the geographic coordinates $(Lon,Lat)_i$ for all stations $i \in N$
Step 2:	Convert the Cartesian coordinates $(x,y)_i$ to the polar coordinates $(\rho,\theta)_i$ for all stations $i \in N$
Step 3:	Generate the possible coordinates sets $\{(\rho,\theta)_m \| m = 1,2,3,4\}$ for all stations $i \in N$
Step 4:	Determine the polar coordinates (ρ_i,θ_i) for all stations $i \in N$
	Sort all lines $\{l \in L \| l = 1,2,...,\|L\|\}$ in ascending order of line importance IM.
	for $1 \leq l \leq \|L\|$ do
	for $1 \leq i \leq \|N\|$ do
	Select the circular or radial line that involves the most consecutive stations
	end for
	Delete all other possible mapping points of transfer stations i for all lines according to the mapping results of lines l
	end for
Outputs	Schematic metro maps in concentric circles style

3.3 | Solutions and quantitative evaluations

We define several criteria for use as quantitative measures by designers in evaluating the quality of maps, to ensure that the maps represent a balance of all five design rules. We avoid expressing criterion-weights information and solve the problem in an optimization fashion. Thus, multiple decision-makers are involved in the decision-making process. The generation of maps may be considered as the first screening of options to provide fruitful information to users. Subsequently, the decision-makers use this information to proceed via an interactive approach to their final map selection. The aim of this is to provide users with as much information as possible before they express their preferences.

3.3.1 | Simplicity

A simple schematic map should have as few bends as possible. Here, we quantify the simplicity of a design in terms of the average number of bends B, which allows us to compare the schematic maps of different networks under different parameter settings. The corresponding equation is as follows:

$$B = \frac{\sum_{l \in L} B_l}{|L|} \tag{7}$$

where $|L|$ is the total number of metro lines.

3.3.2 | Coherence

Concentric circles maps follow circular features by having a natural focus: a common center. The coherence variance is primarily contributed by the radial features, which are affected by the number of radial angle sets. Therefore, the coherence is evaluated by the circular-grid occupied rate CR, which can be estimated as follows:

$$CR = \frac{\sum_{C_i \in C} S}{2\pi \, |c|} \tag{8}$$

where S is the radian of used segments for circular line ci; c is the set of predetermined circular lines; and $|c|$ is the number of predetermined circular lines.

3.3.3 | Balance

Balance can be achieved by enlarging the congested area (such as the center) to ensure an even station distribution across a map. To quantify the balance of a concentric circle scheme map, we introduce indices to measure link length between adjacent stations and thus characterize the station distribution on a map. Ideally, the link lengths between all adjacent stations are identical. To quantify the variance of the link lengths, we use the Gini coefficient as a measure of the dispersion about the mean, that is, a variance measure, that ranges between 0 and 1 for comparison between different interactive solutions, and is given by Equation 10, as follows:

$$G = \frac{\sum_{i}^{|A|} \sum_{j}^{|A|} \left| a_i - a_j \right|}{2|A|^2 \bar{a}}, a \in A \tag{9}$$

where $\left| a_i - a_j \right|$ is the absolute difference of all pairs of the population link lengths; and $|A|$ is the total number of links; and $\bar{a}$ is the mean length of all links. As $G = 0$ for perfect balance, then the score for balance is $1 - G$.

3.3.4 | Topographicity

In octilinear map design, the topographicity is realized by preserving the relative position of stations (Roberts et al., 2016). Lan et al. (2019) guarantee the relative position of stations by constraining the coordinate values in the generated schematic map to have the same degree of relativity in position between the mapped and original location. In concentric circles maps, a series of concentric circles create a polar plane with the center at the origin, and points $[r, \theta]$ are plotted by moving distance r from the origin at an angle θ from the horizontal. Therefore, following Lan et al. (2019), we converted the formulation of the constraint into the polar coordinates, mathematically described in Equation 10 as:

$$\theta_i \le \theta_j, \text{if} \theta_{i,o} \le \theta_{j,o}$$

$$\theta_i \ge \theta_j, \text{if} \theta_{i,o} \ge \theta_{j,o}$$

$$r_i \le r_j, \text{if} r_{i,o} \le r_{j,o}$$

$$r_i \ge r_j, \text{if} r_{i,o} \ge r_{j,o} \tag{10}$$

where $\theta_{i,o}$ and θ_i, $r_{i,o}$ and r_i are the original and the mapped angular and radius coordinates of station i, respectively.

After addressing the position relativity as a hard constraint, we qualify a map with good topographicity as the one in which the distortion is controlled such that an angular projection preserves directions from one central location to all the other points on the map (i.e., maintain an angular relationship). In this respect, we adopt a conventional approach to evaluate topographicity in terms of the station-average angular distortion ε, which can be estimated by Equation 11, as follows:

$$\varepsilon = \frac{1}{i} \sum_{i \in stations} \left| \theta_i - \theta_{i,o} \right| \tag{11}$$

3.3.5 | Harmony

Harmony is a subjective category for aspects that are likely to influence the aesthetics of a design. As there are substantial differences between individuals' aesthetic judgments, harmony is unlikely to be measurable by any index. However, the visualization of a metro map offers decision-makers a convenient and efficient way to inspect its layout.

3.4 | Manual visual assessment

After several iterations by adjusting the user's parameters, users can decide a satisfied solution based on the qualitative and quantitative evaluations of the five design categories. The generated prototype can then be further manually modified based on their needs. Fine-tuning is accomplished manually for the last editing action, such as positioning and labeling of stations, so as to create a final product of concentric circles map.

4 | CASE STUDY

4.1 | Study area

This section presents a numerical example from Hong Kong to demonstrate the feasibility of the proposed method and its application to a real-world metro network. Hong Kong's current metro system is operated by the Mass Transit Railway (MTR) Corporation Ltd. The metro map is designed based on Beck's octolinear style. By the end of April 2020, there were 11 lines and 115 stations in operation. The geographic map and the display map of the Hong Kong MTR are shown in Figures 7a,b, respectively. To many Hongkongers, the metro map is a part of daily life and is their cognitive map of Hong Kong. A similar phenomenon can be observed in many railway-reliant cities, such as London,

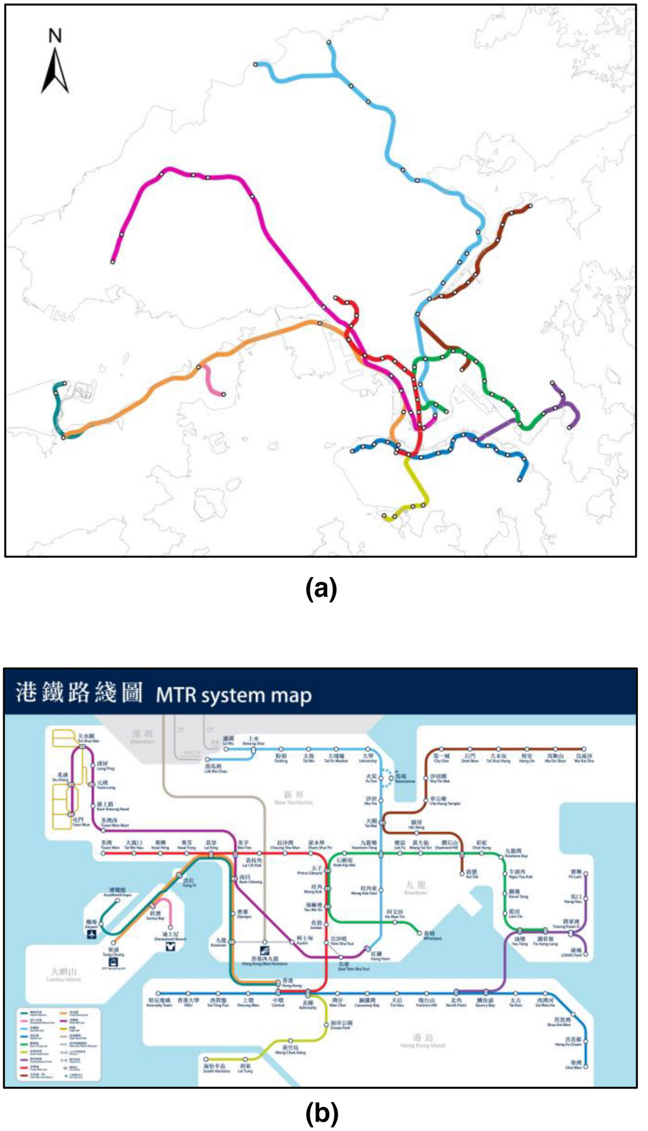


FIGURE 7 The metro map in Hong Kong.

UK. Given that few metro maps enjoy such public popularity as the Hong Kong MTR metro, we explored alternative ways to draw the metro map using concentric circles.

4.2 | Experimental setup

Our study involved a group of three co-authors with various backgrounds: one from a transport geography research institute who can take a lead to explain different parameter settings, evaluate the performance of iterations and suggest model evolution solutions; one from a local transport consultancy who can gives comments from a transport planner perspective with local living experiences; and one from the secondary education field who can help to evaluate the visual attractiveness of iterations from the user, especially for the educator perspective. A 'Reference iteration' (Table 3) is first generated with consensus and the performance in each of four criteria were calculated by the equations stated in Section 3.3. We manually co-evolve with iterations based on the performance indicators and select the final solutions with consensus.

4.3 | Parameter settings

There are four parameters to set for the automated process, namely the choice of center, the polar grid (radial r and circular c) line sets and the line importance IM. The initial setting is crucial for a real-world application of a metro network. By conducting several attempts from a harmonious perspective, we fix an initial value of the radial line set with 32 radial lines evenly distributed on the map to provide adequate space for mapping. We then calculate the corresponding performance of this layout and adjust the other parameters until a satisfactory layout is obtained. Only one parameter is changed each time.

The choice of the center is the key for exploring new solutions. We list three possible candidates for the center, namely Central, Kowloon Tong, and Whampoa stations in Table 3. Central station is in the historical center of the city; Kowloon Tong station is in the existing central business district of the city, and is the most central node in betweenness-centrality measures (Wu et al., 2018); and Whampoa station is the topological center in an online-available manual concentric circle map of the Hong Kong metro (Chan, 2018). For the circular line set, it is important to decide how large the map should be; thus, finding the approximately suitable values for this set is a focus in developing the demonstration loop of our design. Line importance is randomly assigned in this loop, as it is likely a minor attribute considering that there are relatively few lines in this Hong Kong case.

5 | RESULTS

5.1 | Iteration process

In turn, only one parameter is set as a variable, and then the values for the quantitative measures of each category in Equations 7–10 are obtained. We base our design with the judgment that even spacing of gridlines provide better solutions (i.e., $R = \{0, 0.0625, 0.125, \ldots, 2\} * \pi$ for $|R| = 32$; $C = \{1, 2, 3, \ldots, 9\}$ for $|C| = 9$) and integrate these as reference points to find the satisfactory solution, so the relative interactive process can be simulated. The results are shown in Table 3 and Figure 8. However, due to conflicts, the solution may not identify the best values of all categories simultaneously, and it has to be some compromise. Given this, users may choose to ignore some of the other categories, often topographicity, to guarantee that simplicity benefits are obtained at the first interaction. Thus, the spacing of the radial line set is increased, and the number of radial gridlines decreases to $|R| = 16$ to avoid bends due

TABLE 3 Parameter settings and usability values of the four iteration scenarios

Category	Choice of center	Radial line set	Circular line set	Simplicity	Coherence	Balance	Topographicity
Items	–	R	C	B	CR	G	ε
Reference itineration	Central	32	9	4.364	0.192	0.416	0.086
First iteration	Central	16	9	3.727 (+)	0.173 (−)	0.466 (−)	0.119 (−)
Second iteration	Whampoa	16	9	3.636 (+)	0.185 (−)	0.436 (−)	0.100 (−)
Third iteration	Whampoa	16	7	3.545 (+)	0.286 (+)	0.437 (−)	0.086 (+)
Fourth iteration	Kowloon Tong	16	7	4.000 (+)	0.280 (+)	0.385 (+)	0.087 (−)

Note: Signs (+/−) indicate improvement or deterioration with respect to the reference scenario.

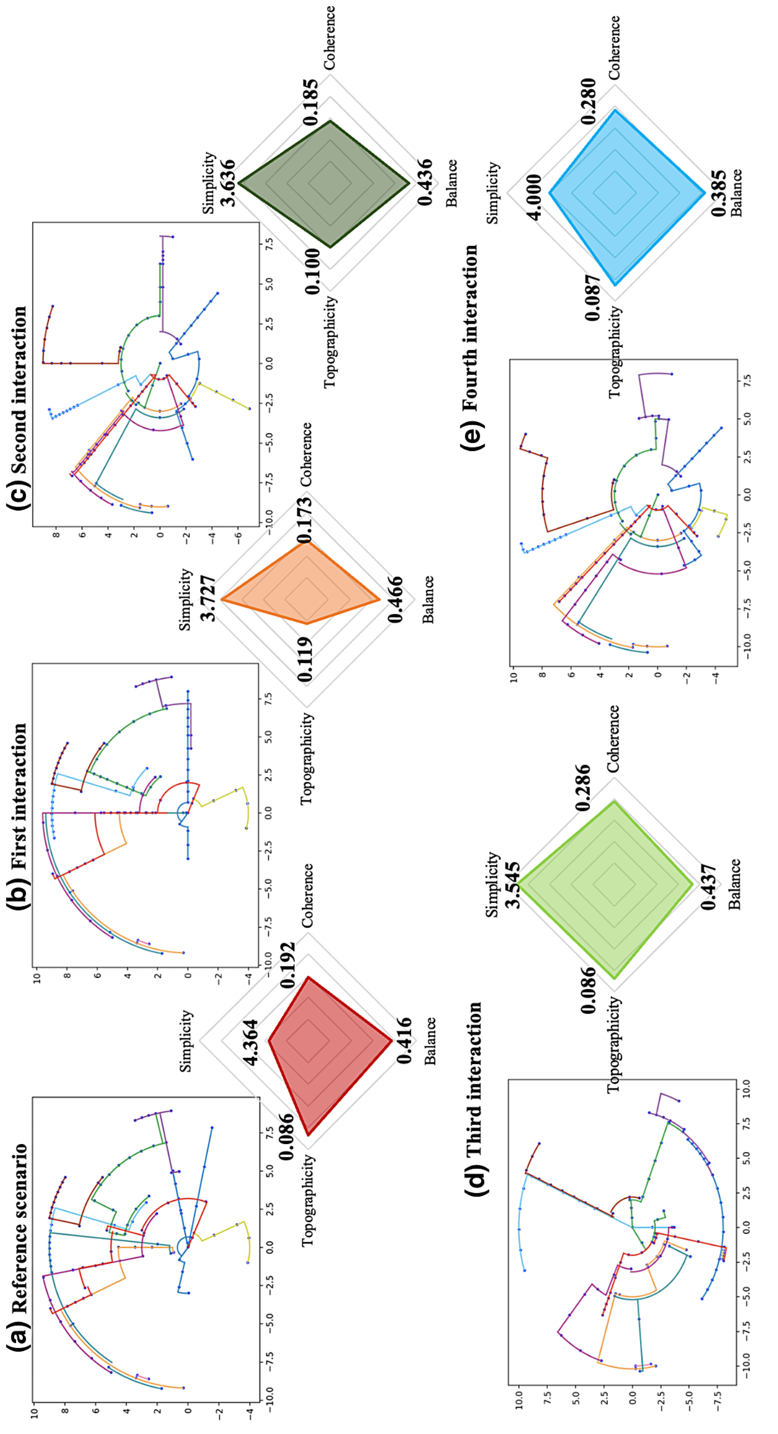


FIGURE 8 Trade-off process among multiple categories of the four interactive solutions.

to the topology. From the results of the first interaction, it can be seen that simplicity is enhanced from 4.364 to 3.767, while the other categories worsen in value compared to the reference scenario. Surprisingly, the balance is reduced substantially from 0.416 to 0.466. This may indicate that the current choice of center results in a layout that is concentrated on one side, showing that Central station is not a suitable topological center.

Given this result, users may wish to choose another logical center to achieve a better balance. Thus, at the second interaction, the topological center, Whampoa station, is selected as the new center; this has been used in another manual concentric circle map (Chan, 2018). The results for the second interaction indicate that the values of all four categories are improved compared with the first interaction. However, only simplicity is enhanced compared to the reference layout. The corresponding spatial arrangement also changes, with metro lines being distributed more to all directions, and circles are more conspicuous in the city center, giving a harmonious design.

Thus, at the third interaction, we keep the choice of center and modify the circular grid in the outer circles (i.e., $c = \{1,2,3,4,5,8,10\}$ for $|c| = 7$) where lines are densely packed in the radial grid to enhance coherence. The result of the third interaction demonstrates that we can customize the circular grid based on the network topology. While maintaining the level of balance, the other categories are much improved: simplicity increases from 3.636 to 3.545, while coherence increases from 0.185 to 0.286, and topographicity from 0.100 to 0.086.

To determine the final solution, users may wish to see the balanced scenario that has the minimum cost. Thus, at the fourth interaction, we shift the center slightly to Kowloon Tong station, as this is a reasonable way to sacrifice part of the topographicity in exchange for a potential gain in balance. In addition, simplicity is sacrificed (3.545 to 4.000), as is coherence, slightly (0.286 to 0.280), but an increased balance is achieved (0.437 to 0.385).

Based on the results of these four interactions, we can straightforwardly select two potential candidates that are significantly improved compared with the reference scenario. The third interaction with Whampoa station as the center gives a simpler layout while sacrificing balance. The fourth interaction with Kowloon Tong station as the center provides a more balanced design with a slight sacrifice of topographicity. As shown in Table 3, each of these solutions has its advantages in terms of simplicity and balance. Even with the center unchanged (i.e., keeping Central station as the center), the first interaction gives a much simpler layout. It is difficult to determine an ideal solution, as the final choice depends on the value orientation of the users, and users may require a certain interaction period to determine their preferred scheme. The solutions produced then serve as a prototype from which map designers can create maps with the concentric circle style.

Generally, the overall layout, usually shaped by circles, is a preliminary version of a map. Each full metro line can be drawn as a combination of different line segments (e.g., a line composed of a partial circumferential arc and a radial straight-line segment). Our method is able to fit the network into circular and radial lines based on their network topology and on different choices of center. Designers can thus save time and costs by visualizing their ideas with supporting statistical quality evaluations. The proposed method, however, still requires users to decide which solutions are desirable and subsequently develop the prototype into a product with additional modifications such as labeled stations and harmonized line trajectories.

For demonstrations, we modified the optimal map manually with minor adjustment of station locations and labelling as shown in Figure 9. All major changes made manually are as follows:

- Labelling of stations;
- Distinguishable icons for interchange stations; and
- Minor displacement for overlapping lines (e.g., brown and blue lines).

5.2 | Sensitivity analysis

Based on the final choice of center (i.e., Kowloon Tong) and gridline sets (i.e., $|R| = 16$ and $|C| = 7$), we conduct a sensitivity analysis to investigate how the result of estimated usability values (i.e., simplicity, coherence, balance, and

FIGURE 9 Illustrations of a final solution after both automated and manual processes.

topographicity) varies depending on the change in the number of radial and circular gridlines. The steepest line in the spider plot (Figure 10) represents the most influential and significant changes in number of gridlines, which have significant impact on the change of usability value.

A significant improvement in topographicity can be observed when $|R|$ changes from 8 to 16 and $|C|$ changes from 6 to 7. This is because $|R| = 8$ and $|C| = 6$ provide inadequate space for plotting all stations. When stations are plotted to the nearest gridlines, they are forced to be distorted with a longer distance of relocation. Similarly, for simplicity, the number of bends is lower when $|R|$ and $|C|$ is lower, since all the line segments are forced to plotted in the same gridlines with no bends. On the other hand, coherence slightly increases when number of radial gridlines increases and significantly decreases when the number of circular gridline decreases. This is simply because the occupancy rate of circular gridlines generally decreases when the number of gridlines increases. A change in the number of gridlines does not give any significant impact to the change of balance throughout all scenarios, implying that the choice of center has the critical impact on the change of balance, as demonstrated by the previous iteration process.

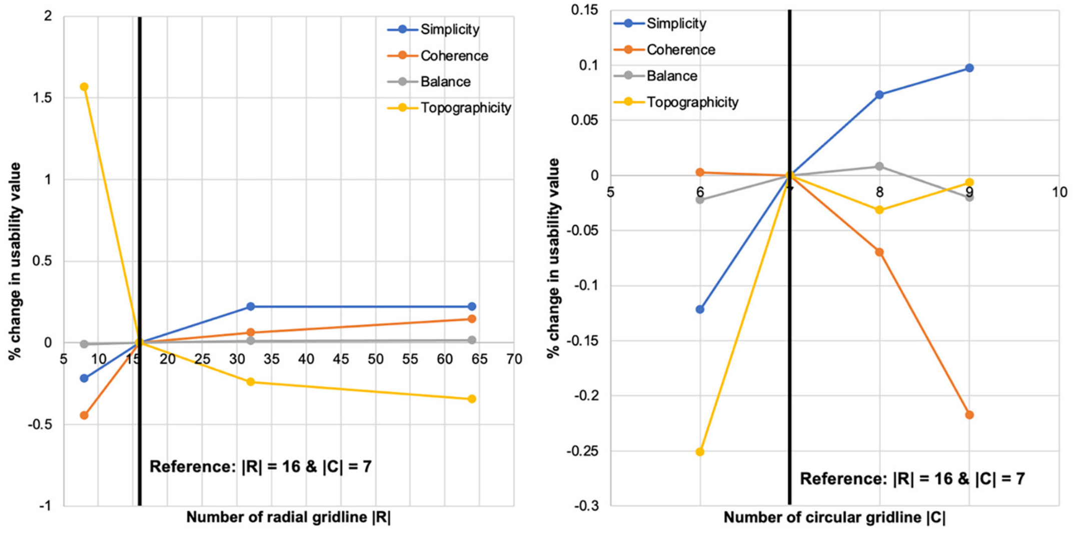


FIGURE 10 How the choices of number of gridlines affect the changes (%) in different usability values.

6 | DISCUSSION

6.1 | Implications to Roberts' usability framework

Regarding the usability framework proposed by Roberts, our proposed method still is not able to evaluate harmony, considering that it is in part subjective as a preference of readers. Considering the strong underlying relationship between visual balance and harmony, it might be, however, not entirely a question of preference. Potential ways to operationalize the holistic design considerations are from Dondis (1973) as cited in Muehlenhaus (2013), whose work suggested that persuasive maps could sometimes ignore and defy established cartographic conventions for effective visual communications in society (Cheung & Winterbottom, 2021a, 2021b). How schematic maps are artistically comprised and can be persuasive is worth future investigation for better capturing harmony as part of the design and evaluation process. Meanwhile, with individual differences in aesthetic appreciation and beliefs in factors that influence usability as a recurring feature in the literature (Roberts et al., 2017), it would have been interesting to see individual differences in the final outcome as a result of interactivity from a future user study. An interesting question, for instance, would be whether the software magnify individual differences, resulting in notable different designs, or does it smooth them away, causing people with different views to converge on similar solutions in the process of learning-by-doing. In this respect, these findings might tell us a lot about the utility of interactive software in creating designs for personal consumption versus designs suitable for mass distribution. Beside, given user-input in final design and that users differ both in their beliefs about usability as well as aesthetics (Roberts et al., 2017), creation of an optimal design for public consumption using any interactive method requires further investigation. Aside from the various constraints that need to be solved in order to produce a complete metro map, another issue that needs to be resolved is the issue of station labels. While there are various techniques that can be used to place station labels in the drawing, these might not be ideal for a circular style (e.g., Lan et al., 2020, 2022).

6.2 | Designer-in-the-loop prototype for maximizing benefits of concentric circle maps

To promote a widespread use of concentric circles maps, the map-drawing algorithm in this study creates a designer-in-the-loop prototype to maximize its usability and aesthetic values of concentric circles maps. This designer-in-the-loop prototype allows the human designer to examine the usability values of constructed concentric circle maps and adjust according to the user's preference (Kessentini et al., 2018). As shown in Figure 8, three usability values, namely simplicity, coherence, and balance (Roberts et al., 2016), were improved after the fourth revision of the map. Moreover, the sensitivity analysis shows that the choice of center, instead of the number of gridlines, affects the usability values of the map. The findings contribute to the cartography literature by highlighting the importance of considering both usability values and the effects of choice of center on the balance of four usability values in constructing concentric circle maps. More importantly, this designer-in-the-loop algorithm can attract more users from cities with radial topography, creating a practical and aesthetic concentric circle map for their own cities (University of Essex, 2022). It allows users from various cities to interactively create usable concentric circles maps that would be widely used by the public (Kimm, 2020).

6.3 | Open spatial data with map-drawing algorithm for promoting public interests

The automated map-drawing algorithm is an initiative that encourages the transformation of authoritative open spatial data to creation of different travel routes by members of the public. Open spatial data need to be coupled with software tools with standardized elaborations and visualization techniques so that public engagement can be enhanced (Gagliardi et al., 2017). The map-drawing algorithm, which will be available on the public website, manifests the notion of "openness" because the algorithm offers diagnostic, non-norm-referenced evaluation and puts emphasis on the role of individual users in drawing concentric circle maps (Giaconia & Hedges, 1982). In this algorithm, users can create their own version of maps (e.g., the choice of center as a representation of the city as seen through the eyes of the users' locations). The concentric circle maps demonstrated its attractiveness and popularity by being featured on numerous blogs, websites, and (academic) articles (e.g., Chan, 2018; Roberts, 2013). Members of the public can access the construction of various concentric circle maps. This publicly available algorithm triggers open communication, dialogue between members of the public and autonomous exchange (Garrison et al., 1999). This resonates with the notion of open spatial data and open education (Wright, 2013).

6.4 | Future research directions

It is reasonable to extend the usage of maps considering that alternative versions of the same network may encourage different travel patterns, either due to the visual appearance of the directness and distance of routes (Guo, 2011) or by making certain parts of the map look more or less formidable to navigate (Xu, 2017). This may be increased if the map is believed to be very accurate topographically, which is a possible by-product of concentric circle map design. These issues warrant further investigation. In addition, lines are ranked by importance in the proposed method. How importance is understood varies across individuals with different backgrounds and institutions with different purposes. The degree to which people understand their importance varies depending on their backgrounds and institutions. For instance, while transit operators may perceive importance of a particular line as the volume of riders, transit users with a different cultural practice might interpret importance differently (Perkins, 2008). The complex and meandering representations is worth investigated in the future.

7 | CONCLUSIONS

We develop an alternative automated map-drawing algorithm that attempts to combine the advantages of automatic and manual approaches. The procedures use constraint equations to identify the graphical features of an effective map. The drawings produced by our framework can serve as a prototype from which map designers can create maps with a concentric circles style. Instead of using an optimization technique, as in most automated methods, we propose an interactive approach incorporating user-defined parameters, which can reflect both usability and aesthetic evaluations of map designs. The interactive interface of the prototype can also be incorporated in open education, facilitating learners to shape their spatial thinking. This publicly available algorithm provides opportunities for the public to construct and discuss diverse concentric circle maps.

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CONFLICT OF INTEREST

All authors declare that no conflicts of interest exist.

DATA AVAILABILITY STATEMENT

Data and code download link with guidelines for researchers testing and utilizing the proposed model: https://github.com/transgeo/CCHK.

ORCID

Ho-Yin Chan https://orcid.org/0000-0002-5455-3386
Yingying Xu https://orcid.org/0000-0002-4377-4255
Anthony Chen https://orcid.org/0000-0003-4363-5041
Xintao Liu https://orcid.org/0000-0002-7323-9878
Kason Ka Ching Cheung https://orcid.org/0000-0002-6431-1129

ENDNOTE

[1] We acknowledge that all attempts at design by humans and machines are intended to be subjective optimization; in this article, 'optimization approach' refers to the automated generation of schematic maps treated as an optimization problem.

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