Visualisation as a Collaborative Decision Support Approach for Architectural Design for Excellence

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Abstract. An ongoing exploration of emerging visualisation technologies for design assistance has been observed; however, there remains a lack of systematic research on visualisation techniques and collaborative approaches to conceptual design. This study uses a systematic literature review to investigate the classification and application areas of visualisation techniques as well as visualisation collaboration approaches. A framework was proposed, covering three phases of the design process: pre-design preparation, design creation, and design evaluation. The study identified seven key areas of Design for Excellence (DfX) using visualisation techniques to facilitate effective communication and cooperation among stakeholders. By fostering a shared understanding of design solutions and enabling real-time, remote collaboration, visualisation tools have empowered stakeholders to make well-informed decisions throughout the design process.

Keywords: Visualisation Technologies, Decision Support, Architectural and Urban Design, Literature Review

1. Introduction

In the early stages of the design process, ambiguity is prevalent, with rough structures and elements, as well as iterative experiments (Rahimian and Ibrahim, 2011). According to Cross (1999), a designer's thought process relies on the interplay between internal mental processes and their external expression and representation through sketches. Consequently, an appropriate medium must enable the designer to express, reflect upon, and manipulate half-formed ideas, allowing them to consider, modify, develop, reject, and revisit these concepts. Thus, the early design phase of buildings and cities necessitates visualisation technology as a medium through which the output of conceptualised design can be continually refined and shaped.

Numerous studies have demonstrated the practical application of visualisation techniques in the early design phase. For instance, 3D renderings can be created from visual sketches early in the design process. By utilising virtual environments for communication, design teams can compare and evaluate design outcomes with clients and users (Bouchlaghem et al., 2005). Virtual Reality (VR) has found applications in the construction industry for design, collaborative visualisation, and as a tool to enhance the construction process (Whyte et al., 2000). However, the existing literature scarcely analyses visualisation techniques for collaborative decision support and the Design for Excellence (DfX); instead, most studies only examine the application of a specific visualisation technique in design.

This study aims to provide a comprehensive and systematic literature review of the collaborative support applications of visualisation technologies in the early design of buildings and cities. To address this gap, the authors conducted a systematic review, collating thematic directions related to visualisation technologies and categorising them for a more in-depth investigation. This review identifies sources of evidence, application areas of DFX, and the framework of collaborative approaches in the design process to uncover trends in visualisation technologies. The findings will pave the way for future applications in design and provide insights into potential areas of development.

2. Methodology

The study systematically reviewed the literature to systematise and structure better the analysis of visualisation techniques in early design (Kitchenham, 2004). The study primarily searched two literature databases, WOS and Scopus, comparing their coverage of design disciplines, and the classification and application of visualisation techniques. The initial search consisted of queries for keywords related to visualisation techniques with spatial design combinations (see Figure 1). This research considers papers from academic core journals, excluding short reviews, errata, editorials, books, conference proceedings, and online publications. Considering state-of-the-art reviews, the search limits to literature published after 2000, and only view English-language literature. The total number of abstracts retrieved is 3287 (587 from WOS; 2700 from Scopus). After reviewing all the literature, the authors screen it in two steps: active screening (Endnote) and manual screening. Endnote removed a total of 277 duplicates. We exclude literature that wasn’t relevant to the study: (a) The article only focuses on using visualisation techniques for education, communication efficiency, user participation, and construction phases without emphasising their integration with spatial design. (b) The article focuses solely on visualising certain types of space (e.g., architectural heritage) but not on the process of designing these spaces. (c) The visualisation should be used as the main digital technology tool in the text, not just as a comparison or filler. The result is 51 articles imported into NVivo to conduct data analysis. A summary of the selected articles provides a systematic overview of the use of visualisation techniques in early design spaces, the classification of visualisation techniques and the embodiment of tools, and the application of visualisation techniques to support collaborative design.

("**visualization techniques**" OR "**visualization technologies**" OR "**data visualization**" OR "**computer visualization**" OR "**rendering**" OR "**virtual reality**" OR "**augmented reality**") (Topic) AND ("**Architectural Design**" OR "**Building Design**" OR "**Urban Design**" OR "**Landscape Design**" OR "**Environmental Design**") (Topic)AND **2022-2023** (Year Published) AND **English** (Language)

Figure 1: Keyword search in the WOS and Scopus database

In the analysis protocol, the authors divide the data analysis into a total of six parts: (1) reading the abstracts of the article papers, keywords, and conclusions; (2) generating codes using NVivo; (3) reading all articles in total; (4) developing initial themes and sub-themes for the coding according to the application areas of the visualisation; (5) summarising and combining the literature using a digital whiteboard (Miro); (6) developing a conceptual framework for visual collaboration in early design, analysing it from five different angles: Visual Collaboration Tools, Collaborative Media/Environment, Collaborative Methods, Collaborative Users, and Collaborative Aims.

3. Results and Discussions

3.1 Application areas of using visualisation technology

Table 1 presents the classification of 51 articles on DFX application in early architectural design into seven categories: Design for Assembly (DfA), Design for Cost (DfC), Design for Quality (DfQ), Design for Reliability (DfR), Design for Safety (DfS), Design for Sustainability (DfSU), and Design for Testability (DfT). It is noteworthy there is some overlap in the visualisation research between “DfQ” and concepts like “DfR” and “DfC.” This overlap is evident in the definitions provided by certain researchers studying “Design for Quality” (Nepal et al., 2006, Agard and Bassetto, 2012). Other researchers working on DfX pair “quality” with other concepts (Brad, 2021, Holt and Barnes, 2010), but they typically only provide a cursory examination of quality in their studies.

“DfC” represents the most populated application area, accounting for 24.1% of the total, with the primary categories being “computation consumption” and “labour effort”. The emphasis of “DfC” lies in utilising visualisation methods to reduce the time and effort expended by labour and computers in the building design process, rather than capital costs such as material and equipment expenses. Its primary objective is to decrease design stage costs while overlooking construction and operation phases. Although “DfSU” is a popular topic in the construction domain, it only accounts for a 5.4% share in this review.

Both “DfQ” and “DfT” hold the second-highest number of categories at 18.8%. These two categories exhibit logical continuity in the early building design visualisation process, implying that researchers tend to assess the results of “DfQ” using test methods mentioned in “DfT.” Researchers often invite users to experience the developed system or framework and provide feedback on the visualisation effect or spatial layout generated by the system or framework. More researchers prefer to have users evaluate their system or framework once it has been initially developed rather than involving them in the design process. This approach somewhat conflicts with (Schuler and Namioka) ’s views in “Participatory Design: Principles and Practices.” “DfA” and “DfS” are relatively smaller application areas, representing 8.9% and 11.6% of the total. “DfA” focuses exclusively on assembly simulation in virtual environments, encompassing simulation environment design and interaction design. Despite the common combination of manufacturing and assembly as DfMA, this review found no manufacturing visualisation instances.

Table 1. Classification of application area

Area	**Code**	**Description**
Design for Assembly (10)	Building Block Design (4)	Designing the most fundamental building blocks and their connection logic f or assembly. The main content involves the block size design and its compatibility with the physical building structure.
	Assembly Environment Design (6)	Designing the environment that allows users to perform virtual assembly, focusing on providing guidance on assembly and designing how users interact with the computer.
Design for Cost (27)	Computation Consumption (12)	Reducing the resources and time required by computers for computations such as rendering and simulation. The main methods employed include algorithm optimisation, database construction, etc.
	Labour Effort (10)	Reducing the effort and time construction practitioners spend during the design, construction, and operation stages. The primary methods to achieve this include reducing duplicated work, parameterisation, etc.
	Information Delivery Loss (5)	Minimising building-related information delivery loss due to inadequate system division or poor delivery methods.
Design for Reliability (14)	Data Source Reliability (4)	Optimising data sources in construction projects through upgrading data collection equipment and integrating multiple databases. Particular emphasis is placed on data related to distance measurement and equipment latency.
	System Design Reliability (10)	Optimising developed systems by applying new technologies, adding new functions, etc. The primary objective is to reduce errors and improve accuracy.

Design for Quality (21)	Positioning and Navigation Quality (4)	Developing the positioning and navigation of physical objects in virtual environments by building virtual coordinate systems.
	Lighting Environment Quality (2)	Analysing the lighting capacity of buildings. The main contents include visible sky ratio analysis and sunlight analysis.
	Spatial Layout Quality (7)	Optimising the spatial layout in the architectural and urban design process by integrating new visualisation techniques and collecting feedback from occupants
	Visual Effect Quality (8)	Optimising the visual effect of visualisation results. The focus includes image clarity, material authenticity and virtual environment stability.
Design for Safety (9)	Data Safety (4)	Protecting architectural data security and user privacy by building a database firewall and following the shareability.
	Life Safety (7)	Protecting stakeholders' life safety. The main contents are errors checking in design and construction, fire escape simulation and natural disaster monitoring.
	Infrastructure Safety (2)	Protecting infrastructure like pipelines by avoiding construction damage and optimising maintenance.
Design for Sustainability (6)	Ecological Conservation (1)	Protecting the surrounding ecology during construction activities by avoiding ecologically sensitive areas.
	Energy Consumption (5)	Optimising the energy consumption in construction activities. The content includes the energy consumption of the building life cycle, material transportation and visualisation computation.
Design for Testability (21)	Comparative Experiment (7)	Designing comparative experiments to validate the performance of developed systems. The main content includes comparing such as planning quality and image clarity.
	Usability test (14)	Designing experience tests to validate the performance of developed systems. The main content includes inviting experts and ordinary users to experience and evaluate the system and monitor volunteers' behaviour.

3.2 Conceptual framework of collaborative visualisation

3.2.1 Overview

This research categorises conceptual design into six steps: 1) data collection/database; 2) data analysis; 3) brainstorming; 4) 2D sketching; 5) 3D design generation; 6) interactive assessment (see Figure 2). The pre-design preparation phase involves the collection and preparation of data prior to the start of the design process. The design creation phase consists of brainstorming, 2D sketching, and 3D design generation, presenting the design from initial sketching to initial form generation. During the interactive assessment phase, various testing methods evaluate the design's validity to refine and enhance the concept design. There are three types of environments used in collaboration: a) software platform; b) physical environment; and c) virtual environment. The software platform allows different stakeholders to share information remotely and in real-time. The physical environment facilitates face-to-face communication and discussion. The virtual environment enables direct design simulation and testing. Moreover, user collaboration does not only consider the collaboration of the designers most directly involved in the design but also involves cross-collaborations between stakeholders, such as occupants, housing developers, and engineering builders.

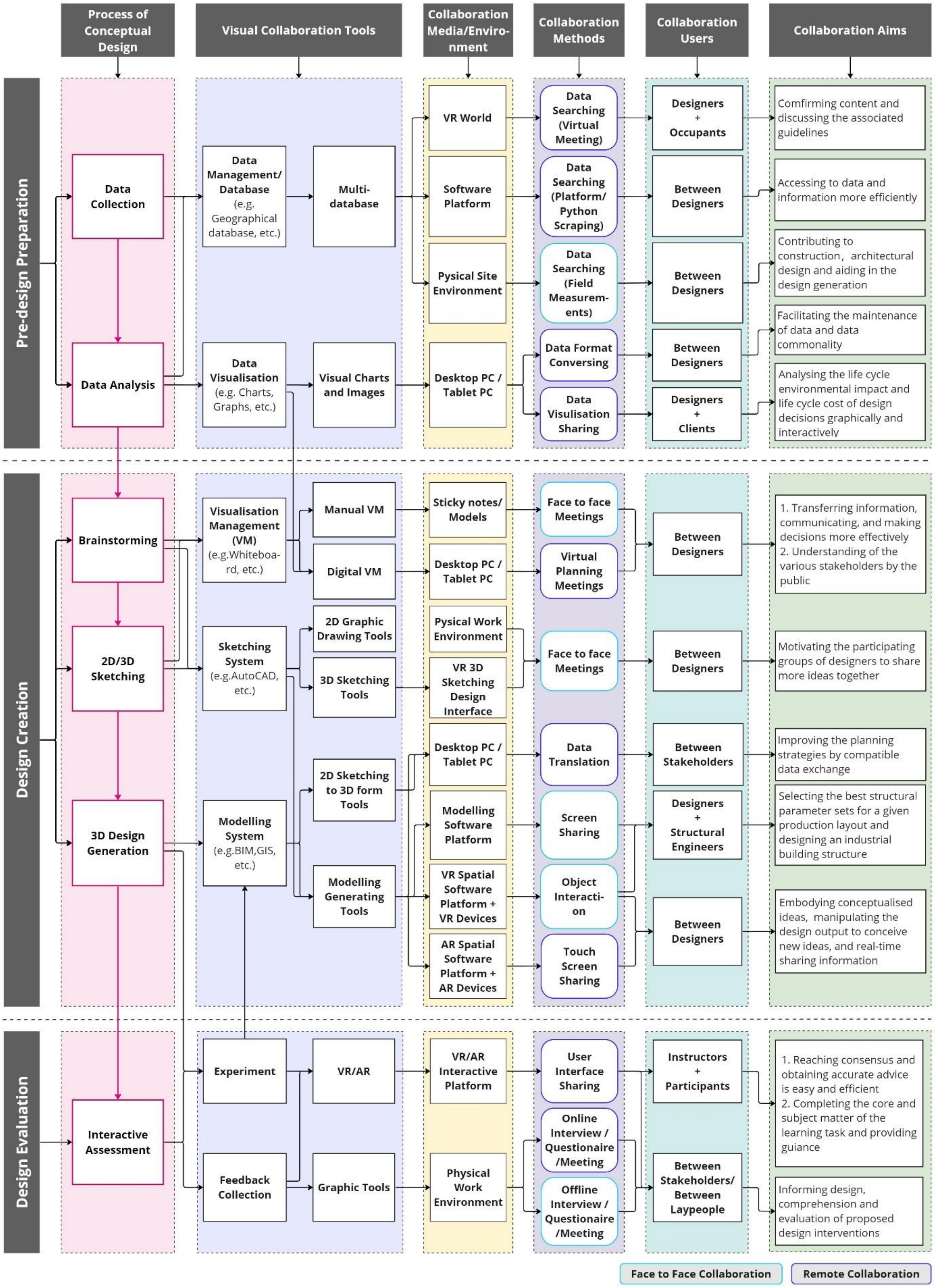

Figure 2: The conceptual framework of collaborative visualisation

3.2.2 Pre-design preparation

Pre-design preparation involves collaborating on data through visualisation before the design phase begins. In data collection, the main visualisation tools include databases and data management software, as well as the collation of multiple databases according to the previous research direction. The database collaboration method relies on data searching, which is divided into three approaches: 1) virtual meetings; 2) platform retrievals; and 3) field measurements.

Firstly, virtual meetings are collaborations between designers and occupants. It facilitates online discussions for designers to get occupant input on expected changes to the design site through virtual meetings. Occupants can even be key decision-makers in the pre-design process. Occupants update and edit the VR dataset in real-time but also share public images during the discussion to determine design guidelines from different perspectives (Shen and Kawakami Mitsuhiko, 2010), ultimately agreeing on design guidelines with the designers. Secondly, a software platform allows architects to not only browse and comment on data, but also modify and update data information to collect and share it. To retrieve information about the site location and urban architecture models, designers often collaborate by using software platforms such as the Google 3D Warehouse Platform (Shen and Kawakami Mitsuhiko, 2010), the Amap web service API (Li et al., 2019), and others. Thirdly, field surveys are also a crucial means of designer collaboration. To develop a design concept, the designer must conduct a site survey of the construction site, including the boundaries, dimensions, and location of infrastructure on the site (Rohil and Ashok, 2022). Designers can record site survey data manually or digitally and then collate it into a database, such as MongoDB (Xu, 2021).

Organising and analysing the data collected in the database is the next step once the data has been collected. Data analysis requires two considerations: converting the data format and sharing the data visualisation. Data collection is a multi-user collaborative process, so the data needs to be formatted to maintain data commonality. Designers can adapt formatting to individual file standards, including converting retrieved geolocation information from strings to floats (Li et al., 2019) and AutoCAD files to PNG files (Ye et al., 2022), to improve sharing efficiency in data collaboration. The designer can demonstrate the data results in a computerised view to the client, allowing consensus before presenting the concept. It has been shown that SuCoBRU charts and Sankey diagrams can be used graphically and interactively to analyse the environmental impact and cost of design decisions over the life cycle of a building (Miyamoto et al., 2022). By combining graphical methods such as pictures, tables, or color differentiation, visualisation can be used as a collaborative communication tool to facilitate communication between designers and clients.

3.2.3 Design creation phase

The design creation phase is the process of collecting and analysing certain data and then moving from design concept development to sketching and creating a three-dimensional space. Developing concepts is a brainstorming process. In order to organise the concept, the designer gathers data from a variety of sources, presents several design ideas, discusses and modifies them, and ultimately reaches a consensus on the initial design concept. There are two types of collaborative tools for brainstorming: manual visualisation management (VM) and digital VM (see Figure 3).


Visualisation Management - Miro **Data Visualisation - Charts + Images** **Sketching Tool - AutoCAD**


Modelling Generating Tools - Rhino + Grasshopper **VR Spatial Software - Gesture Control**

Figure 3: Examples of visualisation techniques

Manual VM is a face-to-face workshop with sticky notes or models (Moural et al., 2018) to record initial design ideas from stakeholders and share them. Digital VM uses virtual collaborative planning sessions as the primary method of collaboration and Miro as the digital whiteboard tool for remote collaboration. Digital VM not only facilitates the sharing of design ideas during the brainstorming phase, but also facilitates a shared understanding of the initial design solution by all stakeholders (Pedó et al., 2022).

Generally, designers use sketching for offline collaboration and to collaborate with one another. Two types of tools are available: 2D graphic drawing tools and 3D sketching tools. Through the designer’s hand drawing and software operation, 2D graphic drawing tools include pen and paper and 2D drawing software (e.g., AutoCAD), which are used to record a design prototype, including its layout and architectural form. 3D sketching tools, like a 3D sketching interface (Rahimian and Ibrahim, 2011), facilitate cognitive, conversational, and motor collaboration between designers. With 3D sketching tools, designers only need to enter accurate values on the computer and can consider spatial balance from a 3D perspective. As a result, 3D sketches are more accurate than 2D drawings, and creative design ideas are easier to generate. Additionally, the 3D sketching interface supports collaboration by allowing designers to share design suggestions.

After determining the initial sketch plan, 3D spatial generation begins. Through direct data translation, the designer is the main user of collaboration for the sketch to 3D modelling conversion. Several tools support direct translation between designers to facilitate the transition from 2D sketches to 3D models. These include digital clay (Schweikardt and Gross, 2000) and CAD to VRML translation (Whyte et al., 2000), removing the need for manual collaboration. Collaboration on model generation mainly takes place by screen sharing and object interactions. It relies primarily on a modelling software platform to share screens, and its main tools include BIM, GIS, and others.

Moreover, VR and AR integration can greatly improve modelling collaboration efficiency. It has been shown that traditional design approaches often require iterative revisions and iterations from data collection to modelling. VR technology can support the collaboration of simultaneous revisions by considering the needs of all stakeholders early in the design process (Podkosova et al., 2022). VR incorporation is mostly technical collaboration with modelling software platforms, including BIMFlexi-VR (Podkosova et al., 2022), 3DSMAX VR (Shan and Sun, 2021) and others. Using VR physical devices, VR modelling collaboration focuses on building models in physical space by roaming through virtual object interactions. VR physical devices mainly refer to media that assist motion collaboration, including head-mounted displays (de Klerk et al., 2019), hand-held controllers (Zhang et al., 2021), VR mobile headsets (Moural et al., 2018), etc. Through different gesture interactions, these devices allow designers to experience more immersive virtual environments and enhance their perception of space. Designers can also share the same virtual environment with each other, creating different 'layers' to compare and modify models. This creates a distributed 3D shared space.

The AR process involves projections of digital environments onto real desktops and scenes using environment tracking tools, such as AR Glass-HoloLens (Rohil and Ashok, 2022). Based on the projection of the virtual environment, the designer can change the terrain height, space size, and placement in real-time using the touch screen. Additionally, the touch screen can send changes to other collaborating designers in real time and show highlights of changes made between designers (Tomkins and Lange, 2019), thus encouraging modelling collaboration between designers.

3.2.4 Design evaluation phase

It is time to evaluate the design following the concrete modelling of the design. In this phase, stakeholders can participate as collaborative users. This phase involves a two-step process: 1) experimenting with the design results, and 2) collecting feedback from the tests. Drawings or models can present the design. Collaborative experiments can use VR or AR interactive platforms. The 3D virtual presentation can present the design from several viewpoints (Liu, 2020), allow multiple stakeholders to provide and receive feedback, and increase collaboration efficiency.

Furthermore, instructors and participants can collaborate through a user interface. Participants can upload their work to the VR exhibition space. Other participants or instructors can evaluate and provide feedback on their design (Lei et al., 2017). VR exhibition spaces allow users to keep comments and share them with other users, allowing collaboration in the design evaluation process. Many studies also use online or offline interviews, questionnaires, and meetings as part of feedback collection. Within these collaborative approaches, some visual charts can aid user assessment. In conclusion, collaborative design evaluation involving stakeholders is crucial in the design process. The use of VR, AR, and other online platforms enables collaboration to occur efficiently, allowing for valuable feedback collection and enhancing the design's quality.

4. Conclusion

In conclusion, this research has elucidated the importance of visualisation as a collaborative decision support approach in the DfX framework. By examining various stages of the design process, including pre-design preparation, design creation, and design evaluation, this research has identified key visualisation tools and techniques that facilitate effective communication and cooperation among diverse stakeholders, such as designers, occupants, housing developers, and engineering builders. The integration of technology, including software platforms, virtual and augmented reality, and various visualisation tools, has significantly improved the efficiency and efficacy of collaborative decision-making processes.

By fostering a shared understanding of design solutions and enabling real-time, remote collaboration, visualisation tools have empowered stakeholders to make well-informed decisions throughout the design process. Moreover, this research highlights the value of considering the needs and perspectives of all stakeholders early in the design process, which can lead to more sustainable, efficient, and user-centric designs. As architecture and urban planning continue to evolve, the adoption and advancement of visualisation as a collaborative decision support approach will undoubtedly play a crucial role in achieving DfX.

This research has limitations that present opportunities for future research in the area of visualisation as a collaborative decision support approach in DfX. For example, longitudinal studies: future research could conduct longitudinal studies to assess the long-term implications of using visualisation tools in the design process, including the potential impact on design quality, efficiency, and stakeholder satisfaction. In addition, future studies could investigate the role of visualisation tools in fostering interdisciplinary collaboration, where stakeholders from different domains contribute their expertise to the design process. These future research directions can contribute to a more comprehensive understanding of visualisation as a collaborative decision support approach in the DfX framework.

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