Designing Interactive Technology Roadmaps: A Visual Analytics Approach

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Abstract. Technology Roadmaps (TRMs) are valuable tools for aligning research and development efforts with strategic objectives. Highly graphical in nature, TRMs often receive criticism for their static nature and designs. In this study, we propose the integration of visual analytics (VA) techniques to enhance the usability, insights, and interactivity of TRM applications. Following a user-centered design approach, we collected requirements from seven stakeholders and developed two interactive prototypes: a flat-style Dashboard design and a nested-style Drill-down design. Comparative user evaluations revealed differing strengths, favoring Dashboard design particularly for its simplicity and ease of access. Based on our findings, we present a set of generalized design guidelines and introduce a Three-Stage Design Model that guides developers from structuring data to enabling user sensemaking in TRMs.

Keywords: Technology Roadmaps · Visual Analytics · Design Study.

1 Introduction

In an era of rapid technological advancement and increasing uncertainty, technology forecasting tools have become indispensable for helping organizations and industries navigate future challenges.

One widely used instrument for technology forecasting is the technology roadmaps (TRMs), which visually represents the path of technology development and adoption over time. Technology roadmapping is defined as a process that combines structured systems thinking, visual methodologies, and participatory approaches to address organizational challenges, support strategic planning, and foster innovation management at different levels [26].

Highly visual in nature, roadmaps facilitate communication across diverse stakeholder groups to enhance decision-making and strategic alignment [13]. However, studies [4, 15, 16] have repeatedly criticized the graphical designs of

TRMs, highlighting their poor development and lack of intuitive design principles. Some of the design challenges addressed are information overload, off-putting color schemes, and distracting visual clutter [13]. Further due to its largely static nature, it includes the difficulty of conveying complex, multi-layered information [34] in an intuitive format. This has resulted in roadmaps often being ignored due to limited reliance [34] by practitioners and researchers alike. Kerr and Phal [15] emphasized that roadmapping should be approached as a visualization process for communication rather than a static product, requiring thoughtful integration of design principles, human perception, and visual metaphors. Addressing these shortcomings is especially crucial for the fast-evolving automotive industry, which is experiencing a shift due to current developments in electrification, connectivity, and automation. Companies are therefore faced with the question of which technologies and products will be relevant in the future.

For project *Technologiekalender Strukturwandel Automobil Baden-Württemberg (TKBW)*, a Technology Roadmap[4] is created as a website to visualize the expected technological developments of passenger cars until 2035 on the basis of more than 40 modules, with around 150 technologies in the areas of propulsion, connectivity, and automation. This roadmap outlines four parallel development paths: battery-electric drives, hydrogen-based drives, automated driving, and synthetically generated fuels. Although, this roadmap provides foundational guidance to their main stakeholders: small and medium-sized enterprises (SMEs) and research institutes, its static nature presents limitations in user engagement, data exploration, and decision-making support. Further, it fails to capture deviations from planned trajectories or visualize the interdependence of emerging technologies which is also shown in a Technology Roadmap in Appendix 1[5].

Incorporating Visual Analytics (VA) dashboards and storytelling visualizations can significantly improve the platform by intuitively presenting the complex information and making the platform interactive, insightful, and user-friendly. To attain this, we followed a participatory design approach [10], starting with the identification of user needs, followed by the development of functional prototypes, and then iterative evaluation sessions with domain experts. The insights gained from this process informed the derivation of a set of design guidelines and the formulation of a *Three-Stage Design Model* tailored to TRM development. While the guidelines emerged organically through our design, evaluation process and our literature analysis, the resulting framework addresses a critical gap between the fields of TRM and Visual Analytics.

Contribution – Our work represents one of the few VA-driven, user-centered design studies focused specifically on TRMs. The results are grounded in both empirical evidence from users in the vehicle technology sector and broader design knowledge from the VA and Human Computer Interaction (HCI) literature. The derived design guidelines are intended to be domain-agnostic, supporting the development of TRM systems across diverse fields. Additionally, we propose

[4] https://tkbw.transformationswissen-bw.de/

[5] 10.5281/zenodo.17053200

a Three-Stage Design Model that outlines a structured and practical pathway for developers seeking to build interactive, stakeholder-friendly TRMs.

Paper Structure – In this paper, we first present the insights from our literature study in section 2. Then we present the insights gathered from our requirement analysis study (section 3), to identify user needs and expectations for a TRM based VA application for vehicle technologies. Next, we incorporate these insights into the development of two design prototypes, presented in section 4. In section 5, we then present the results of evaluation conducted on the developed prototypes, focusing on their usability and effectiveness. In section 6 and section 7, we further contribute by proposing derived guidelines and a Three-Stage Design Model for VA-based technology roadmapping tool. Finally, we conclude and summarize the paper in section 8.

2 Related Work

Over the years, scholars have examined the design processes of TRMs and proposed different visual formats and metaphors to guide their construction [13, 27, 34]. For instance, Phaal et. al [27], identified eight types of TRMs depending on their role in business processes, such as product planning or service planning. Yet, these recommendations largely concern static infographic-style formats with little to no interactive functionality. Their static nature and diversity of formats mean that each new type of roadmap must be tailor made. Phaals survey [27] highlight this as a drawback, which limits their sustained use within companies and makes them difficult to keep alive and ongoing. Moreover, TRMs have traditionally been conceived as representational artifacts rather than exploratory tools [23], offering limited functional integration with underlying databases. By contrast, the visualization community has developed a broad repertoire of methods that actively support exploration and sensemaking in complex data environments [31, 32]. Dashboards, storytelling interfaces, and multiple linked views have been widely applied in different data domains (e.g., public health dashboards [3], transportation [22]). Despite that the application of VA techniques for TRMs are limited and is largely scenario and static infographic based, offering little support for interactive exploration or user-centered sensemaking. As Spaltini et al. [34] observed, visualization methods for TRMs are still underexplored and lack empirical validation. Thus addressing this gap is the central contribution of our work. To our knowledge, no prior study has systematically contrasted alternative VA interface strategies within a user-centered design study.

3 Requirement Analysis Study

The goal of our requirement analysis study was to gather requirements from different user groups about their current understanding, usage, needs, and expectations from the visualization tool representing TRMs. Participants were first shown an introductory presentation on TRMs. Then questions were asked about their familiarity with TRMs, their reasons for using them, and their specific information and visual preferences. The questionnaire is available in the Appendix 2[6]. It was developed by taking assistance from the professionals in vehicle technology management, HCI designer, and a visualization scientist. The requirement analysis study was conducted with three main stakeholder groups, who either provide the data or use the result of this roadmap. There were 3 academics, 3 industry experts, and 1 participant from state administration. The study was conducted online via a face to face interview and a questionnaire to gather their feedback. It lasts for an average of 20 to 30 minutes for each participant.

3.1 Result

In the following, we have summarized the result of our requirement analysis study:

– **Familiarity with TRMs:** On the 7-point Likert score, participants were asked about: their familiarity with TRMs, how often they use them, reasons for using them, and their specific information preferences. We found out a high level of awareness and familiarity about TRM tools among users with a mean average score of 5.14 out of 7. However, results also show that participants were not frequently using them (3.14 out of 7). This discrepancy among awareness and usage indicate a critical usability gap. Thus, it becomes more significant that TRM tools need to be both informative and accessible, with a limited learning curve.
– **TRM objectives:** We derived three key motivations for using the technology roadmap tools: 1) gaining insights into technological evolution and interdependencies; 2) facilitating communication and collaboration among stakeholders and 3) identifying trends to guide strategic decisions and product development.
– **Age-based user preferences:** We see differences in user preferences across different age groups. Users within age group 25-34 prefer complex, dynamic, and advanced visualizations (e.g., sunburst and network diagrams). They have particular interest in knowing the temporal trends and spans, relationships and different types of technology fields. Those within age group 35-44 value structured, focused visuals like gantt charts and narrations with filtering options. User within age group 55-64 prefer known and straightforward visualizations such as tree diagrams, reflecting their need for clarity and minimal complexity.
– **Sector based preferences:** Academics primarily utilize TRMs to gain insight into current developmental progress and to assess project milestones and technological readiness level (TRL). Industries leverage TRMs to stay updated on evolving technological trends, driving innovation and maintaining competitiveness. State Authorities utilize TRMs for comprehensive market research and analysis in technology-related decision-making processes.

[6] 10.5281/zenodo.17053200

– **Other prolific insights:** Timelines and timespan are the most important artifacts that are needed to be shown in these roadmaps. However, most participants were less interested in mega trends but were more interested to know the small trends in the evolution that can guide them to timely opt for corrective and transformative measures.As temporal trends were the important insight for them, thus gantt chart was selected as a prominent visualization type, followed by sunburst diagram and other network diagrams. Furthermore, one of the important information to show on the TRMs for vehicle technologies is, 'Market Share' followed by 'Patents' and 'Key Companies'. The most needed option for the tool is to have interactive features, automatic updates, and variant filtering options. Participants are further interested in detailed information with external links to data or information sources, translation, or narration options. These features thus needs to be highly customizable, so that it can be easily adopted to diverse demands and can be easily configurable.

Initial findings from this study, underscore the importance of tailoring the TRM application to meet the diverse needs of users. Table 1 shows the key derived requirements from this study. These requirements, strengthen our claims of using interactive narrative-based visual analytics techniques like storytelling visualizations to present the technology roadmap for its effective and broad usage. Lessons learned from these interviews were applied to the design and development phases, to ensure that the tool seamlessly aligns with user expectations and enhances their overall experience.

Table 1. Design Requirements for Technology Roadmapping Tool

Components	**Requirements**
Data and information artifacts	Timelines and timespans, relation between different technology modules and fields, market shares and patents.
Visualization artifacts	Gantt Chart, Sunburst and Network Diagrams.
Interactive Features	Filtering options, on-demand narrations, hovering, popups
Other features	Automatic updates and detailed information (documentation)

4 Technology Roadmap Designs

For the representation of complex information, VA techniques: narrative and storytelling, could play a critical role. Storytelling in visual analytics goes beyond aesthetics or layout. It provides structure, context, and a cognitive path through the data [32]. In the context of TRMs, by guiding users through sequential, contextual, or thematic progressions, storytelling along with narrative designs help bridge the gap between raw technical data and actionable insight [9, 17]. In our study, we operationalize two distinct narrative strategies from the findings of [32]: a *Dashboard-based design*, which offers a flattened overview with structured entry points, and a nested style *Drill-down design*, which allows users to progressively unfold information through guided transitions. Further, based on the Table 1, we decided which visualizations would be used for representing what relationship types and what information was mapped. These prototypes were developed with Oracle APEX environment[7] using our database [36] on the evolution of technologies over time. Oracle APEX enables rapid creation of scalable and secure data-driven applications through a powerful low-code development platform. The database use TRL and Manufacturing Readiness Level (MRL) for modules from 2019 to 2035 with data based on expert responses to the technology profiles. Both of our prototypes are based on the concept of Multiple Linked Views (MLV), a technique from information visualization that relies on interaction design principles. In this approach, user interaction with one view updates the data and results shown in other coordinated views on the canvas.

Dashboard Design: The Dashboard design prototype (Figure 1) first provides an overview of the essential components, connected and comprised on the same page. Then through interactions, user delve deeper into specific aspects of each components. There are three primary visualizations through which one can explore data and dive deeper into other options: 1) Sunburst Diagram (Figure 1a) shows hierarchical data structure based on vehicle types $\longrightarrow$ modules $\longrightarrow$ technologies. In Figure 1a, Sunburst Diagram shows different vehicle types. When user clicks on any vehicle type (Figure 1f), related modules open up. 2) The Network Diagram (Figure 1b) focuses on highlighting connected elements - competing technologies, keywords and competencies. Based on the selected information on the Sunburst Diagram, related data elements and nodes get highlighted as shown in Figure 1e. 3) The Gantt Chart (Figure 1d) emphasizes the chronological representation of project timelines and time spans. The Gantt Chart is combined with box plots to provide better view of the time span. Checklist and search option (Figure 1c) is provided for the user to further add or remove the needed technologies, modules, and competency types. As this tool was developed for German users thus the main language is German, however, on clicking on button "Sprache auswählen", user can change the language to English. The flowchart, full scale images of the design and video of this prototype is provided in Appendix 3[8].

Drill-down Design: The Drill-down design prototype (Figure 2) first presents general broad themes and then allows the user to select specific themes to reveal additional details and backstories. It provides a high level view of the data through one Network Diagram (Figure 2a) which is nested into four levels. This layout unfolds the option based on the semantic layering of different vehicle types $\longrightarrow$ Modules $\longrightarrow$ Technologies associated with it. Each version of this diagram

[7] https://apex.oracle.com/de/
[8] 10.5281/zenodo.17053200

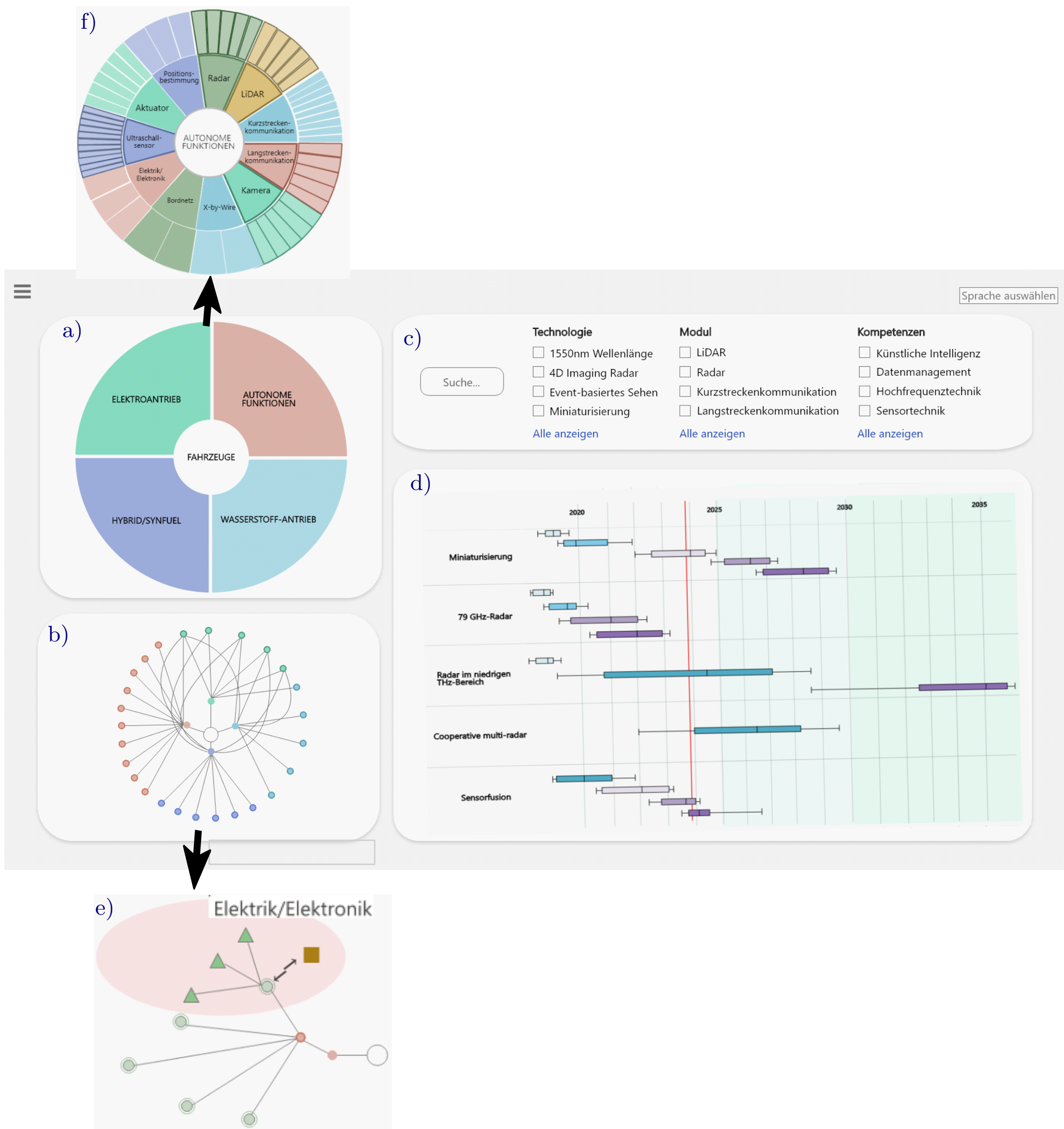

Fig. 1. This is our Dashboard design prototype. Screenshots of clicks are embedded for better understandability of the prototype.

comes with its own interactive components and insights. The upper most level shows the vehicle types which are further connected to modules on the nodes. Clicking on the nodes on this diagram opens up module network associated to the clicked vehicle types as shown in (Figure 2b). Further clicking on these nodes, opens up the technologies, timelines and timespan associated with that module in the form of Circular Gantt Chart as shown in (Figure 2c). Each circular bars are technologies and each diamonds are its MRL and TRLs. On the right of the Gantt Chart, user can read the relevant information about selected technology. By clicking on the button 'Gantt Chart', user can transform the Gantt Chart from Circular to Rectangular form in a full screen (Figure 2d). The flowchart, full scale images of the design and video of this prototype is provided in Appendix 4[9].

5 Evaluation

Further we conducted a usability evaluation of our two developed prototype designs. Participants were asked to perform real-world scenario-based tasks to assess the effectiveness of each design. The objective of this study was twofold: first, to introduce users to our TRM designs tailored to their requirements, and second, to systematically compare the two interface designs to determine which one better aligns with the needs of our stakeholders. The feedback was collected via a questionnaire which was developed by taking assistance of QUIS [5] and NASA TLX [8] survey templates. The study involved 10 participants. The questionnaire is available in the Appendix 5[10]. The results are summarized below:

1. **Task performance:** Participants were asked to perform tasks which were then evaluated to measure performance. Performance is measured in two ways - errors and response time. Errors refer to the incorrect answers of the participant's responses from the performed tasks [29]. Response time is the time it took a participant to complete one task. The performance with Dashboard design is better with an average error score of 7.3% and response time of 56.43 seconds. The average error score for the Drill-down is 12.9% with the response time of 78.36 seconds.
2. **Design choices:** Participants were asked questions about their design choices related to three different pair of alternatives. First comparison was related to the layout of the prototypes. Between Dashboard design and Drill-down design, majority votes (60%) were gone to the Dashboard design. The reason provided by participants were that they are simple and straightforward. Second comparison was between One Liner Gantt Chart (see Figure 2d) and Gantt Chart with Boxplot (see Figure 1d). Here, participants preferred One Liner Gantt Chart (70% votes) primarily because they were already familiar to them. Third comparison was between Sunburst Diagram connected with

[9] 10.5281/zenodo.17053200
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Fig. 2. This is our Drill-down design prototype. Screenshots of clicks are embedded for better understandability of the prototype.

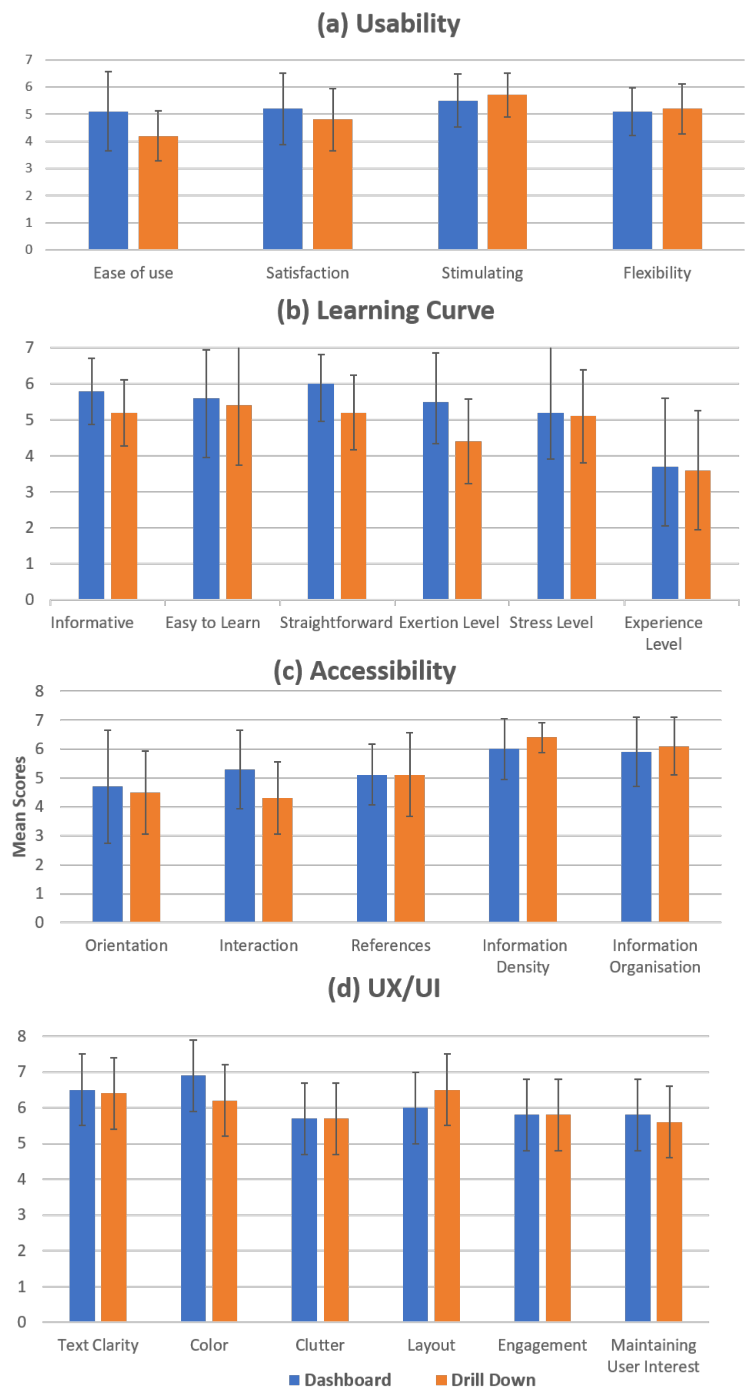

Fig. 3. This figure shows the user evaluation results comparing the Dashboard and Drill-down design prototypes. The bar chart presents mean scores with error bars showing deviation across four key categories: Usability, Learning Curve, Accessibility, and UX/UI.

Network Diagram (see Figure 1a,b) and Network Diagram (see Figure 2a) alone. Here, 80% of our participants opted for the connected Sunburst Diagram, owning to the clear overview of the data and insights thereof from this diagram.

3. **User experience:** We measured user experience across four main categories: Usability, Learning Curve, Accessibility and UX/UI elements. Each category included specific subcategories to capture detailed user feedback and assess different aspects of the experience. These were then rated using a 7-point Likert scale. The results are presented in Figure 3.
   (a) Usability: We analyzed overall usability of these designs based on four metrics: *Ease of use, Satisfaction level, Stimulating and Flexibility*. The results are shown in Figure 3a. Dashboard scored higher than Drill-down for *Ease of use* and *Satisfaction*. Whereas in *Stimulating* and *Flexibility*, scores of Drill-down are slightly better.
   (b) Learning curve: The parameters on which Learning Curve was scored were: *Informative, Easy to Learn, Straightforward, Exertion Level, Stress Level and Experience Level*. As shown in Figure 3b, Dashboard design scored higher in all categories. Dashboard design has a slight advantage in performing task straightforward due to its flat layout. Due to the nested layout of Drill-down, the amount of effort needed to perform the task is more and thus the Learning Curve for Drill-down is higher.
   (c) Accessibility: We evaluated different accessibility parameters of our designs: orientation on the screen (*Orientation*), *Interaction*, use of *References*, *Information Density* and *Information Organization*. Shown in Figure 3c, Dashboard design is rated higher across *Orientation*, *Interaction*, and *References*. Drill-down strongly outperformed dashboard in *Information Density* and is also better in *Information Organization*.
   (d) UX/UI: We evaluated User Experience and User Interface (UX/UI) via following parameters: *Text Clarity*, colorscheme used (*Color*), cluttered interface (*Clutter*), attractive layout (*Layout*), user engagement (*Engagement*) and *Maintaining User Interest*. As shown in Figure 3d, Dashboard design scored higher in *Text Clarity*, *Color* and *Maintaining User Interest*. Both prototypes have been equally or closely scored for *Clutter* and *Engagement*. Drill-down is scored better for its *Layout* design.

Across all evaluation dimensions (22), participants (n = 10) rated the Dashboard design higher in terms of overall usability, learnability, and accessibility. The Drill-down design was rated more stimulating, but better in information density and organization. Results shows a direct preference towards Dashboard type flat designs.

Further we tried to understand the dependencies and correlation among individual design factors from Figure 3. Here our goal is to explore which factors are consistent, and which are design-dependent. For that, we used Spearman Correlation Test [35] for our datasets. The results are presented in Figure 4 and labeled results are provided in Appendix 6[11].

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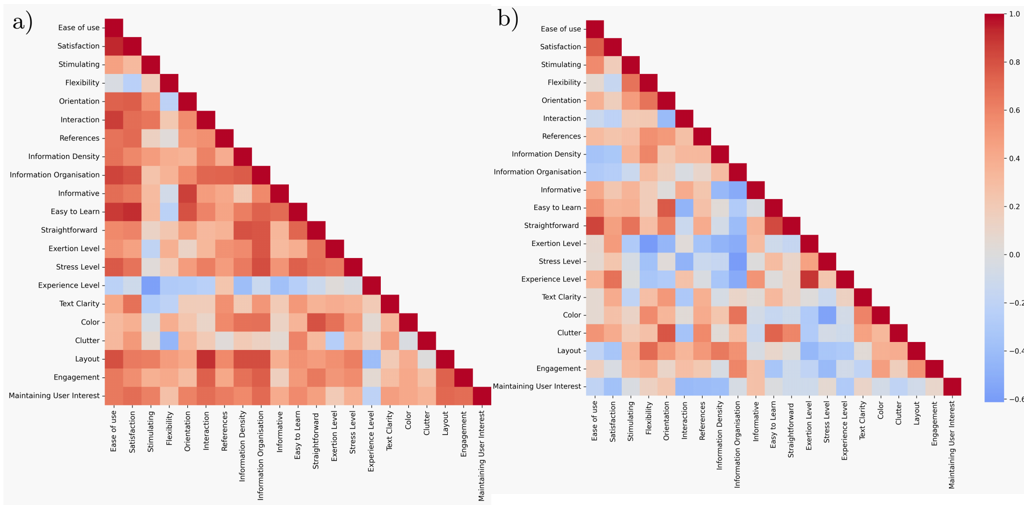

Fig. 4. This figure shows the lower triangle of spearmen's correlation matrix for correlation among different design factors for (a) Dashboard design and (b) Drill-down design. Red color shows the level of positive correlation and blue color shows the negative correlation.

As per the guidelines for interpreting the absolute value of correlation coefficients proposed by [6], above 80% is very strong, above 60% is strong and then below zero is negative. Figure 4a shows that Dashboard design has most positive correlation. Users who rated this design prototype as easy to use (*Ease of use*) has also rated it high in *Satisfaction*, *Interaction*, *Information Organization*, *Easy to Learn* and low *Stress level* and good *Layout*. There are very few none and negative correlations. However Figure 4b shows many negative correlation specially with *Experience Level*, *Information Organization*, *Stress*. It further suggest that for Drill-down design, the design factors didnt always support each other - improvements in one area often made another area worse. This caused users to experience the interface in different ways.

By analyzing the overall results, we identified both stable and volatile design factors. While core links like *Easy to Learn* ∼ *Satisfaction* remained strong across designs, other relationships such as *Layout* ∼ *Engagement* and *Information Organization* ∼ *Ease to Learn* proved sensitive to design context. Our results highlights the importance of validating interface patterns across multiple conditions rather than assuming universal user behavior.

6 Design Guidelines

Based on our experience from this study and literature analysis, we have derived design guidelines for constructing an effective visual analytics application for technology roadmaps.

1. **Follow Design Principles:** General design principles laid down by scholars [24,25] and researchers are critical and should be followed in the construction of either static infographics or interactive applications. These principles guide users in the creation of clear, uncomplicated, clutter free designs. For example, as per the principle of Alignment, grouping similar items together – visually makes scanning quicker and supports comprehension. Findings from our study as well as previous studies [1] have highlighted the role of creating clear, simple, and straightforward designs with user friendly layout which ultimately reduce unnecessary cognitive load.
2. **User-centric Design Process:** Studies have emphasized on rapidly involving stakeholders in the design and development process [14,33]. Construction of TRMs have been considered as a collective task [34] and thus it is essential that different kinds of stakeholder (data providers, decision makers, users getting influenced from those decisions etc.) should be in a loop during and after the development process.
3. **Scalability and Flexibility:** Scalable and flexible designs [12, 38] ensure that roadmaps can be tailored to future datasets and user requirements. They are adaptable to new updates both in data and requirements. Views should be easily customizable that can cater the need of diverse stakeholders' needs [1,7]. Further, scalable and modular design could be a solution to keep TRMs alive and ongoing, a challenge identified by [27]. Modular components and tailored workflows can meet specific user demands effectively. Some of the ways to achieve scalability and flexibility — choosing scalable databases like Graph or NoSQL types, use modular data pipelines, use more hybrid and hierarchical visualizations that are scalable and can show multiple dimensions, compatibility with different devices, allow user to hide and show views based on their requirements, provide role based access and provide more interactivity, filters and nested options.
4. **Collaboration and Knowledge Sharing:** Features allowing collaborative input and document sharing were noted as valuable additions to roadmapping tools as shown in our and also previous studies [1, 14]. Collaborative visual features to allow cross-departmental input and sharing views with external stakeholders is seen as successful implementations in large organizations [1].
5. **Guidance and Assistance:** To decrease the learning curve [34] and for better insight generation, it is important to include different guiding and assistive features in the TRM applications. Here, guidance means to allow all those features that provides knowledge about the proper functioning of the tool. Such as, providing proper onboarding, tutorials and contextual tooltips. Whereas assistive features are those which help to cater the need of different types of stakeholders irrespective of their age and other differences. As also showed in our study, that differences in age groups leads to different requirements for the TRMs.
6. **Data Security:** Addressing security concerns related to proprietary data ensures user confidence in the tool. Moreover, user login to a secure system and providing role based views and privileges on the system could further

assist in better management of data exposure to different types of interested parties.

Further options could be related to domain specific requirements, for example if data demands comparison among geographical regions then provide both local and global perspectives in technology trends, adoptions, and regulations. These guidelines help developers to decide on various features and the scale of work needed in the development of TRMs.

7 Design Model for Visual Analytics in Technology Roadmapping

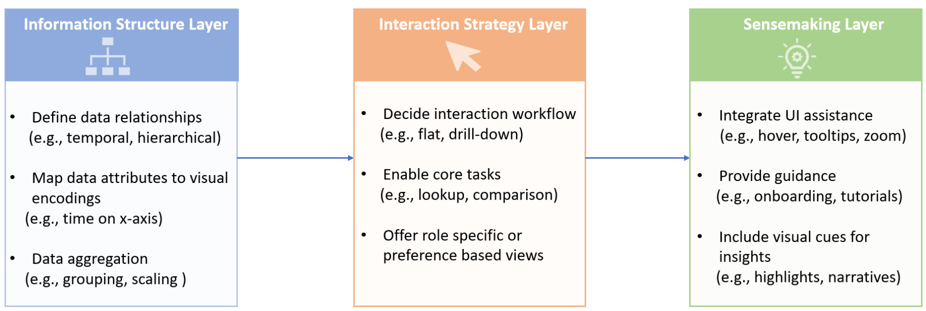

Fig. 5. Three-Stage Design Model for Visual Analytics in Technology Roadmapping. It guides TRM developers from data structuring to user interaction and then to insight generation.

Further, we propose our Three-Stage Design Model for Visual Analytics in TRM development. This framework is derived based on our own work, as well as, by taking inspiration from established cognitive and interaction frameworks in information visualization and human-centered design. This model builds up from data structure to user interaction and ultimately to communicative and interpretive visualizations. However before starting to implement this model, a developer has to understand the domain and data well by involving stakeholders and reviewing relevant literature.

1. **Information Structure -** *What has to be visualized?*
   In this foundational stage, developers model and understand the gathered data as a beginning of a design process. It corresponds to the data abstraction and encoding phase of the visualization pipeline, as conceptualized in classic models by [20]. The result of this stage would produce a table similar to the one presented in Table 1 but with more details. This stage can be divided into three layers:

(a) Define data relationships: Knowing the data well, first developer has to decide the relationship that are depicted from the data elements. These relationships further corresponds to the user goals that can further derived corresponding visualizations [11]. For example: if elements of the dataset shows series of date and time, then it shows temporal relationship and thus can be visualized by temporal visualization (gantt charts, timelines, or bar charts). Knowing such relationships within data elements at the earlier stage assists developer in searching for suitable visualizations and also other alternatives of similar visualizations. Some suitable questions at this stage could be:
** What kind of data is involved? (timeline, dependencies, modules, metrics, actors)?*
** Is there any apparent data relationship or structure exist? If so, then what are they? (Is it temporal, hierarchical, networked?).*
** How can this relationship be visualized (e.g., hierarchical ⟶ sunburst, treemap)*

(b) Map data attributes to visual attributes: Once a developer knows which visualizations to use, the next step is to map different data attributes to visual attributes. The developer then tries to answer the questions *What data elements will be mapped to which visual elements of the chart?* For example in Figure 1b, nodes in the circular network diagram represent vehicle types. For this process, it is important that developer has a good understanding of types of data attributes. *Is it categorical, nominal, temporal (Date/Time) etc.?* For example in temporal line chart, 'x' axis could be time line, and 'y' axis could be market shares.

(c) Data aggregation or categorization: Visualization relies on structured aggregation for clarity. As TRMs usually spans from long time horizons (e.g., 2025 2050), there are multiple scales of technologies (system subsystem module component) and has diverse stakeholders (policy, R&D, SME, industry). To structure this data, aggregation and categorization is an important step. Aggregation provides a semantic anchoring, without which user could get overwhelmed in multiple level of details. Here, the user has to decide *What levels of aggregation will be shown? (e.g., years months etc for temporal and, different nesting levels for sunburst diagrams.)*

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2. **Interaction Strategy Layer:** *How will it be explored?*
Once the visual content is defined, the next step is to design the exploratory workflow of the application. This layer addresses exploratory behavior, aligning with the interaction taxonomy defined by [37], cognitive models of exploratory search [21] and narrative flow by [32]. It encapsulates user-driven strategies for interaction flow on the interfaces such as overview-first ⟶ navigation ⟶ progressive filtering ⟶ detail-on-demand ⟶ comparison. These strategies reflect how users cognitively approach roadmap data. This stage is further divided into three sub layers:

(a) Deciding interaction workflow: Whether it is a VA based or any other UI based application, interactive workflow is highly dependent on the layout of the application. For example in our prototypes, we used two types of layouts i.e., flat type Dashboard and nested type Drill-down layout. Even in static infographics, a layout defines the organization of all the elements on the canvas which further intuitively guides the user focus.

(b) Enable core tasks: Next is to decide the core tasks performed by the user in the information seeking process. For example to look up on specific elements, selecting the date range from timeline, clicking and showing the nested hierarchies in sunburst diagram, dragging elements, entering the information, performing comparisons etc. Here the integral question that needs to be answered is *What tasks should the system support?*

(c) User specific views: It is common in data sensitive applications that not all information is relevant for all stakeholders. On the other hand, based on the specific age group or interests, some users prefer alternative views (see our findings from section 3) or have different requirements. Further, some features are only for decision makers, while others are intended for specific role types. To fulfill many of these goals, TRMs architecture should facilitate providing different views, access levels, alternative options, etc., to the users.

3. **Sensemaking Layer:** *How do insights emerge?*
This layer focuses on supporting users in interpreting complex data and generating insights – not just by showing results, but by actively guiding exploration. Rooted in sensemaking theory from visual analytics and exploratory data analysis [28, 30, 31], it aims to help users construct mental models, identify patterns, and reason about underlying phenomena. We observed that successful insight generation requires support at three levels:

(a) Interface-Level Assistance: The first level of support is to enhance the basic understanding of the application by providing different assitive features at the frontend. Foundational support includes tooltips, hover effects, axis labels, and captions that clarify the visual elements and reduce ambiguity.

(b) Guidance and Orientation: Onboarding flows, embedded documentation, and inbuilt tutorials facilitate understanding of both data and visual design. These elements lower the learning curve and support users – especially first-time users – in navigating the roadmaps effectively.

(c) Insight-focused visual cues: Cues such as highlights, annotations, hotspots, or time indicators serve as signifiers (based on principles from interaction design theory by [25]), helping users focus on relevant data regions or patterns. While optional, these cues enhance analytical reasoning by guiding user attention toward potential anomalies, correlations, or critical areas of interest. Their design should be informed by domain-specific knowledge to avoid misdirections.

8 Discussion and Conclusion

In this study, we propose the use of Visual Analytics based narrative and storytelling applications to overcome the limitations of static technology roadmapping tools. Following a user centric design approach, we first gathered requirements from seven different types of stakeholders. Results from the requirement analysis has emerged as a crucial factor, revealing diverse preferences across demographics and professional needs. Based on the gathered requirements, we developed two prototypes: a Drill-down design and a Dashboard design prototypes. A comparative user evaluation, indicated a general preference for Dashboard design, which was praised for its simplicity and accessibility, making them ideal for quick insights. Drill-down design was rated as detail oriented and better in information organization. To further understand the relationship between different design factors, we conducted a Spearman's correlation analysis. Results for the Dashboard design showed mostly positive and harmonious relationships among design factors, whereas, Drill-down design revealed a higher number of negative correlations. We further derived a set of design guidelines for the development of effective TRM applications. We emphasize the importance of user-centered design, flexibility, scalability, collaboration, guidance, and following established design principles for the creation of these applications. To address the gap of limited theoretical frameworks for designing VA-based TRMs, we presented a Three-Stage Design Model for Visual Analytics in TRMs development. This model guides a developer from the stage of data and information structuring to the facilitation of user sensemaking in the development of TRM applications. This model poses reflective questions at each stage and supports decision-making based on the data, user needs, and system context. Together, our design guidelines and framework provide a structured pathway for developing Visual Analytics-based TRM tools that are both functional and insightful.

By taking technology roadmaps (TRMs) in vehicle technologies as an application domain, we demonstrate that the choice of interface structureflat dashboards versus hierarchical drill-downsignificantly influences usability, accessibility, and sensemaking. While existing TRM literature primarily focuses on what to visualize [23], our study provides empirical evidence highlighting the importance of how to visualize. In particular, we contribute to understanding how interaction design impacts the overall user experience in roadmap exploration and decision-making. During the course of our study, we saw a limited research directly comparing flat Dashboard-style interfaces and hierarchical Drill-down interface designs directly in visualization studies. Although both styles are widely used in interface and web application development [19], their relative advantages for different types of data, users, and context remain largely underexplored. Our literature review revealed that most comparative studies focus on different visualization types (bar chart, scatterplot), or on evaluating usability of interactive visualizations [39]. Other studies concentrated on perfecting either of these designs in isolation [2]. Our findings extend prior roadmap visualization studies [4, 13] by empirically comparing interactive layouts. Despite a limited sample size (7 participants for first and 10 participants for second study) our results though not statistically significant but suggestive, indicate that interface layout choices has a measurable influence on user engagement, usability perception, and insight generation. This highlights the need of future research to systematically evaluate the usability, effectiveness, and decision making impact of different VA-based applications across different application domains. Future research can build on our comparative design model to evaluate interactive roadmap applications across additional domains and larger stakeholder groups.

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