DEFINING A DESIGN SPACE OF THE AUTO-MOBILE OFFICE: A COMPUTATIONAL ABSTRACTION HIERARCHY ANALYSIS

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One advantage of highly automated vehicles is drivers can use commute time for non-driving tasks, such as work-related tasks. The potential for an *auto-mobile office*—a space where drivers work in automated vehicles—is a complex yet underexplored idea. This paper begins to define a design space of the auto-mobile office in SAE Level 3 automated vehicles by integrating the affinity diagram (AD) with a computational representation of the abstraction hierarchy (AH). The AD uses a bottom-up approach where researchers starting with individual findings aggregate and abstract those into higher-level concepts. The AH uses a top-down approach where researchers start with first principles to identify *means-ends* links between system goals and concrete forms of the system. Using the programming language R, the means-ends links of AH can be explored statistically. This computational approach to the AH provides a systematic means to define the design space of the auto-mobile office.

INTRODUCTION

Automated vehicles with SAE Level 3 automation (L3) and above will have the benefit of creating a space for drivers to engage in non-driving tasks on their work commute (Janssen et al., 2019). These might include work-related tasks or relaxation. We refer to the work environment in automated vehicles as the *auto-mobile office* (Kamaraj, Katrahmani, Li, & Lee, 2020).A systematic analysis can help define a holistic design space for the auto-mobile office.

When describing, analyzing, and designing the complex systems, the abstraction hierarchy (AH) is one of the most well-known representations and presents a top-down process based on reasoning from system goals and first principles (Bisantz & Vicente, 1994; Lind, 2003; Rasmussen, 1985). However, the processes of developing the AH requires domain knowledge. In contrast, the Affinity diagram (AD) provides a complementary perspective. The AD is a method for synthesizing qualitative data through a bottom-up process that integrates individual issues (Holtzblatt & Beyer, 1997). This research introduces a bidirectional and computational approach using the AD and the AH to analyze and define the future workspace made possible by L3 automated vehicles.

Abstraction Hierarchy for Deducing Design Considerations

The abstraction hierarchy is a multi-level representation of complex systems. Typically, the AH is described as a five-level *means-ends* relationship (see Figure 1). The first two levels describe the overall system goals and the constraints for the design, whereas the three lower levels show the physical implementation. The top-down process of the AH, starting with the system goals, can help deduce design considerations.

The system representation of the AH is based on links between a means to an end across levels. However, the validation of means-ends relations remains underdeveloped (Burns, Bisantz, & Roth, 2004; Lind, 2003; Reising, 2000). Additionally, the development of the AH follows a heuristic process where hand-drawn diagrams are examined with a series of probe questions. One exception used a computational approach to represent and reason about the AH content (Bisantz & Vicente, 1994). Here we use the statistical programming language, R, to explore computational opportunities to evaluate the means-ends links in the AH. Compared to using graphics-focused software (e.g., PowerPoint), R provides powerful statistical analyses along with various visualization techniques to represent and analyze the AH. Specifically, by documenting each node and its links between layers, R allows users to systematically highlight important links, apply seriation to reveal structural information, and evaluate the central concepts using the network analysis.

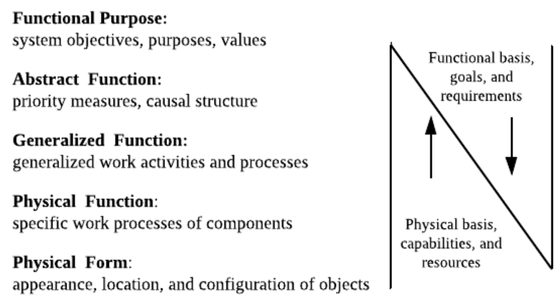

Figure 1. Abstraction hierarchy with five levels (Lind, 2003; Rasmussen, 1985).

The AH can be an effective theoretical tool for evaluating designs by checking the means-ends links (Rasmussen, 1985). Yet in practice, assessing the means-ends links in a complex diagram may not be effective to achieve the promise of the AH. Using R, the means-ends information of the AH and relevant statistical methods becomes transparent, repeatable, reproducible, and can be shared with other researchers with little effort.

Affinity Diagram for Inducing Design Considerations

Despite the benefits of the AH, it has some limits (Bisantz & Vicente, 1994; Lind, 2003; Patriarca, Bergström, & Gravio, 2017). A central challenge lies in acquiring background knowledge about the system (Lind, 2003). This is especially the case for novel systems, such as the auto-mobile office, where domain knowledge is underdeveloped. An affinity diagram (AD) can address this limitation by providing a bottom-up process to induce a hierarchical representation of a large amount of qualitative data (Holtzblatt & Beyer, 1997). The AD is an inductive process of integrating data elements, whereas the AH is a deductive process based on first principles and design intent.

The AD is a process of accumulation, interpretation, and integration of unstructured qualitative data into meaningful clusters (Babbar, Behara, & White, 2002). The AD can identify requirements based on detailed observations (Holtzblatt & Beyer, 1997), which is beneficial for early-stage idea generation, planning, and consensus-based decision making (Hahsler, Hornik, & Buchta, 2008).

The bottom-up process of the AD complements the top-down process of the AH to form a bidirectional approach. This approach can develop a design space for the auto-mobile office and associated evaluation criteria.

METHOD

The bidirectional approach starts with the AD analysis to gather qualitative information about the auto-mobile office. Then, the AH builds on the AD with an analysis of a multi-level mean-ends network.

Affinity Diagram Analysis

AD analysis aims to gather information for inducing design considerations for future work in automated vehicles. Because users or use cases of this novel system do not exist for observations or interviews, we used a systematic literature review to accumulate relevant articles. The first step involved defining the focus, which is the future workplace in Level 3 automated vehicles. Second, keywords, such as "mobile office, vehicle workspace, automated vehicle, interface design, commute time", were used to filter literature. Finally, the pertinent literature was selected, synthesized, and interpreted as qualitative data for the AD analysis.

Based on findings from the literature review, a four-step procedure of the AD analysis was conducted: creating notes, clustering notes, walking the wall, and documentation (Lucero, 2015). First, each finding from the literature review was documented in separate notecards. Second, the research team read each other's cards in silence and simultaneously formed clusters based on relations to the focus: designs of future work in automated vehicles. After several clusters were grouped, questions about conflicting arrangements were discussed. Once most notes were grouped, the names of the clusters were identified based on consensus. Finally, the group discussed merging, arranging, and removing notes.

Abstraction Hierarchy Analysis

Using the results in the AD and the knowledge of the authors, the nodes and links in the AH were constructed (Lucero, 2015; Salmon et al., 2019; Salmon, Regan, Lenné, Stanton, & Young, 2007). The nature of each level of the AH was adjusted to match the focus of this study: future work in automated vehicles. Based on applications in various domains (Burns et al., 2004; Salmon et al., 2019), five prompt questions were formulated for each level in the context of auto-mobile office:

1. Functional purpose: What are the ultimate goals of designing the auto-mobile office?
2. Abstract function: What evaluation criteria should be used to determine whether the design of the auto-mobile office achieved functional purposes?
3. Generalized function: How are the criteria in the level of abstract functions satisfied?
4. Physical function: What can the physical objects or components in the auto-mobile office do?
5. Physical form: What components make up each of the physical functions in the auto-mobile office?

To formulate the nodes in the AH, the clustered groups from the AD were matched to the appropriate level by the prompts. For example, "trust and acceptance" was arranged as a group in the AD, which is one of the evaluation criteria for the auto-mobile office. Thus, it fits in the abstract function level based on the prompts above. To formulate the links in the AH, the primary connections between concepts were identified. Multiple rounds of revisions between authors were conducted to refine the AH.

Computational Analysis of the Abstraction Hierarchy

R 3.5.2 was used to investigate the structural composition of the AH. First, the packages *ggraph* and *igraph* were used to plot the means-ends connections of the AH by defining the nodes (means, ends) and edges (links). The links of *means-ends* were denoted in a $m \times n$ matrix, which represents the m ends to the n means. Each matrix entry represents the links, which can be either 1 (connected) or 0 (not connected). This matrix was used to define a network that was plotted as the AH. Second, the package, *seriation*, provides the infrastructure for ordering objects and arranges the links to reveal the structural composition of the AH. The $m \times n$ matrixes of each adjacent level of the AH were computed across five layers. The method 'BEA_TSP' was applied to minimize the distance between linked elements (Hahsler et al., 2008). This method produced an optimal order of nodes by minimizing the crossings of means-ends links making the AH easier to read. It also identified the structural composition of the AH elements that share similar means-ends relationships.

RESULTS

Affinity Diagram

The AD consists of three main components: modality, tasks, and users (see Table 1). *Modality* describes the considerations of different types of interfaces for the workspace in automated vehicles. *Tasks* describe how people spend their commute time and how an auto-mobile office would affect the user's safety. *User* shows how people might trust the system and how the auto-mobile office might affect their wellbeing and privacy.

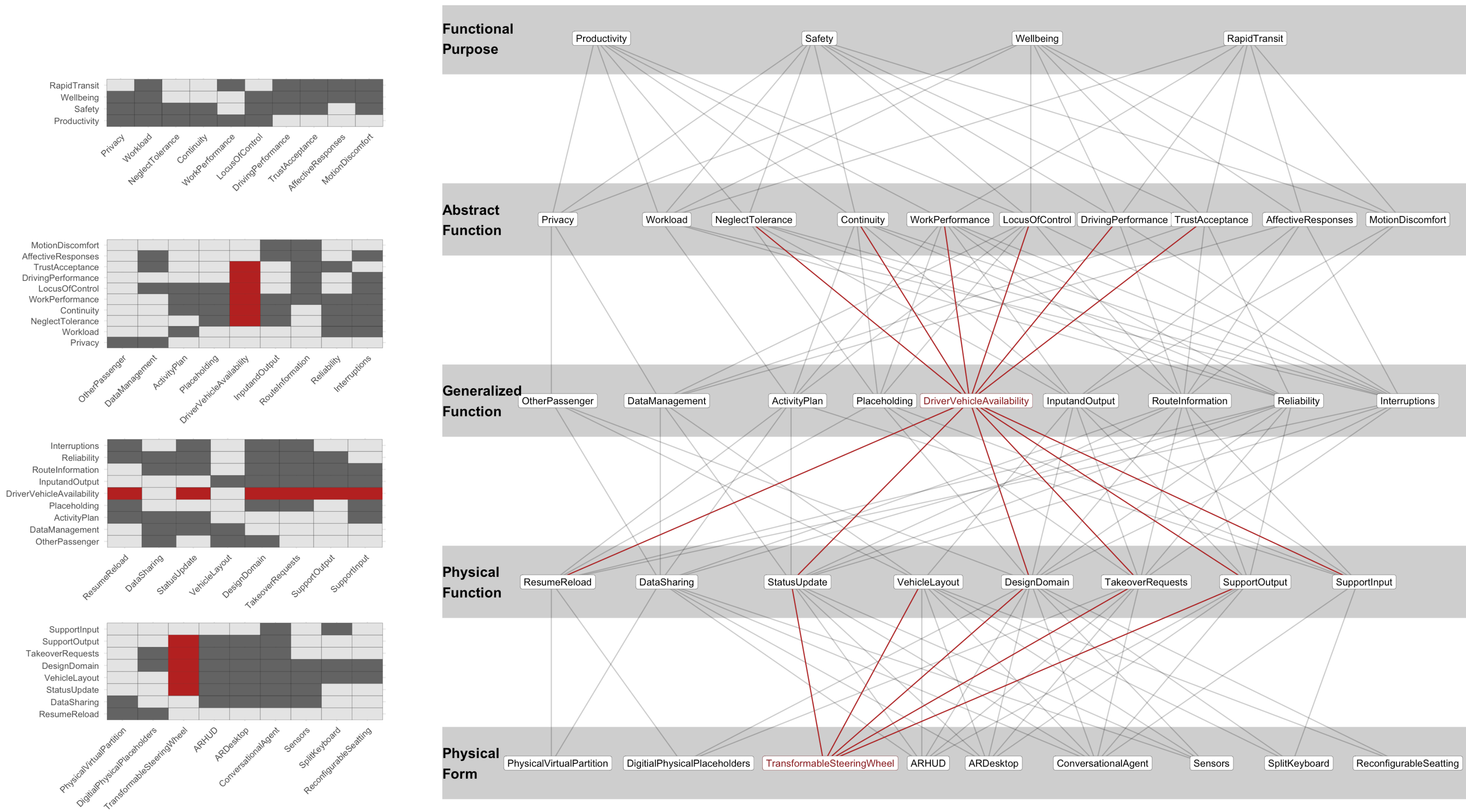

Figure 2. Abstraction hierarchy of auto-mobile office (right) with a global seriation (left) with an example of highlighted nodes of "TransformableSteeringWheel" and "DriverVehicleAvailability" and associated links. The lower two levels conclude a summary of physical implementations.

Table 1. Affinity diagram for auto-mobile office

Modality	Auditory	Voice dictation errors are hard to correct.
		The responses are slower compared to other modalities (Salminen, Farooq, Rantala, Surakka, & Raisamo, 2019).
	Visual	Response time is 6.9 seconds (Politis, Brewster, & Pollick, 2015).
		Insufficient because the user's visual attention may be occupied (Ferati, Murano, & Giannoumis, 2018).
	Tactile	For touch screens, users need to use at least one hand for input.
		Touchscreen demands more attention than other interfaces (Kun, Boll, & Schmidt, 2016).
	Augmented Reality (AR)	More suited for primary tasks and provides greater situation awareness.
	Heads-up Display (HUD)	Promotes sequential multitasking, reduces workload, and improves productivity (Ayoub, Zhou, Bao, & Yang, 2019).
		The number of use cases that can be implemented with HUDs is limited as they provide only a limited field of view (FOV).
Tasks	NDRTs	NDRTs are often secondary given the focus on minimizing the distraction. But in the context of auto-mobile office, NDRTs should be redesigned and accommodated with safety and productivity (Ayoub et al., 2019).
	Safety	One challenge is how to design the vehicle interior to accommodate the interplay among safety, productivity, and enjoyment.
		Multimodal cues often involve a tradeoff between safety and annoyance.
	Time Use	Current time usage (e.g. window gazing, conversation) limits users' perception on the future vision of the auto-mobile office (Singleton, 2019).
		Willingness to work while commuting remains low in automated vehicles.
User	Wellbeing	User's well-being (i.e. travel experience) weighs more heavily than productivity, ranging from the micro (e.g. stressors from work and travel) to the macro level (e.g. general life satisfaction).
	Trust	Trust is essential because users worry about liability, cost, and maintaining control of the vehicle (Howard & Dai, 2014).
	Locus of control	We should assure a strong feeling of control for the driver (Kun et al., 2016; Lefcourt, 1991).
	Privacy	Linking user profile from mobile devices can enhance the user experience (Ferati et al., 2018).
		Privacy and security have yet to be explored (Ferati et al., 2018).

Abstraction hierarchy

Based on the concepts identified by the AD, we developed an AH (see Figure 2). The first level, functional purpose, describes goals and purposes at the system level. The interplay between productivity, wellbeing, and safety was highlighted in the category of *Tasks* in the AD. Four goals were identified for the auto-mobile office in the Level 3 vehicles: (1) facilitate productive work; (2) support drivers' wellbeing; (3) ensure driving safety; (4) support rapid transit between work and driving.

The second level, abstract function, describes the priorities, values, and criteria used to achieve the functional purpose. These include privacy, trust and acceptance, driving performance, locus of control, work performance, continuity of the task flow, neglect tolerance, workload, affective responses, and motion discomfort.

The third level, generalized function, describes how each level of abstract function is achieved. Nine functions were identified: placeholding function to ensure the continuity of the work; operational design domain (ODD) that defines where the automation can operate; route information; automation availability to show the estimated duration of automated mode; the information input and output systems for working and driving updates; reliability of the automation; interruption functions like takeover requests; data management; and considerations of other passengers on board.

For the two lower levels, we only provided a few of the possible physical objects. The physical function shows the functions of physical objects in the auto-mobile office, which include updating vehicle status, prompting takeover requests, resuming and reloading the work, and supporting input and output. The final level, physical form, describes the instantiation of the physical functions. A few design concepts include digital or physical placeholders, transformable steering wheel, reconfigurable seats, augmented reality (AR) desktop and heads-up display (HUD), conversational agent, split keyboard, and physical-virtual partition.

Using the bidirectional analysis, we highlighted aspects of the design space of the auto-mobile office. Elements include a display integrated into a modified steering wheel (see Figure 3), which includes a split keyboard for typing. During manual driving, the steering wheel position and size remain the same as a conventional steering wheel. When initiating the automated mode, the steering wheel expands to support work functions with larger screen size. The display, as one of the possible physical forms of the auto-mobile office, provides updates regarding takeover requests and can be used to view work-related materials, as highlighted in the physical function level in Figure 2. These physical functions fulfill upper functional levels in the AH, such as the generalized function of vehicle automation availability, the abstract function of support work continuity, and the functional purpose of productivity. This computational AH can highlight the corresponding means-ends links, so the relationships between lower and higher levels become clearer.

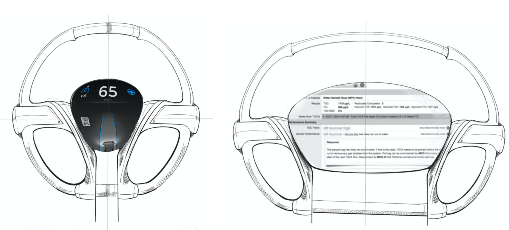

Figure 3. Design of the transformable steering wheel. Left: during the manual driving, the display shows the vehicle status. Right: during automated driving, the display expands and affords the working-relate tasks.

DISCUSSION

This study has begun to define the design space for the future of work in Level 3 automated vehicles with a computational abstraction hierarchy that incorporates an affinity diagram.

A Bidirectional Approach to Define Design Space. A bidirectional approach was developed for the auto-mobile office system. The approach combined the top-down goal-orientated AH and the bottom-up data-accumulated AD. The bidirectional approach provided a systematic method that echoes the design space analysis: Questions, Options, and Criteria (QOC) (MacLean, Young, Bellotti, & Moran, 1991). This approach can help researchers and practitioners identify the key design issues and system goals, outline potential solutions through the means-ends links, and provide a systematic assessment to evaluate potential solutions.

Identify Evaluation Criteria for an Auto-mobile Office. The evaluation metrics of the auto-mobile office can be extracted by evaluating each means-ends link in the AH. When designers have specific features and considerations that are located in the physical form or function level, the AH can provide guidelines following the seriated linkages to the system goals. Designs of the auto-mobile office should be congruent with the system goals: productivity, wellness, safety, and rapid transit. The abstraction function level specifies more concrete metrics for evaluating whether a given implementation will achieve the intended goals.

Computational Analysis of Structural Composition. This study used R to display and highlight certain means-ends connections in the AH. We augment the typical mean-ends link diagram with a seriated diagram that directly reveals the structural compositions of the system. This computational method also opens the opportunity for network analysis. One important analysis often used is the centrality measure, which identify the most important nodes within a graph. Future studies applying this analysis could pinpoint the important concepts defining the auto-mobile office across the five levels of the AH. This paper provided an initial application of R to analyze the AH systematically.

CONCLUSION

This paper presented a preliminary design space for SAE Level 3 automated vehicles based on a bidirectional and computational analysis. The bidirectional analysis uses a bottom-up affinity diagram to gather data of system specifications, which are then integrated in a top-down manner with the abstraction hierarchy. Using R to computationally represent the abstraction hierarchy shows benefits in both visualization and statistical analyses.

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