

Interactive Input and Visualization for Planning with Temporal Uncertainty

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Abstract: Data with temporal uncertainty is ubiquitous in everyone's life. Popular examples are holiday planning or train trips. There are several approaches to visualize temporal uncertainty, but common research usually does not take uncertainty into account, neither as input nor output. We propose a new approach that provides both an interactive drawing for data with temporal uncertainty and their respective visualizations. The user can draw both variable and fixed activities and also has the possibility to set probability distributions and enter indefinite activities. A quantitative user study shows the need and suitability of our new approach.

1 INTRODUCTION


Uncertainty is ubiquitous in everyone's life. In many of the domains that feature data and information with uncertainty (e.g. physics, meteorology or the method of data collection itself (Greis et al., 2017)), temporal information plays an important role (MacEachren et al., 2012) (e.g., the start of a rain period). A typical use case familiar to many people (soon again) is the planning of a holiday trip.


A planned trip can be delayed already at the start, i.e. a delayed outbound flight or traffic jams, and after further potential issues during the trip, the end becomes increasingly difficult to predict. In general, a temporal activity consists of three components that can be categorized as "Start" (\mathcal{S}), "Duration" (\mathcal{D}), and "End" (\mathcal{E}). For a *certain* activity, these three components are in the relation $\mathcal{S} + \mathcal{D} = \mathcal{E}$ to each other. Therefore, each component is determined by the other two parts. Usually, each of these three components can be uncertain, complicating the relation between \mathcal{S} , \mathcal{D} , and \mathcal{E} significantly.


Scheduling is the planning of times, at which par-


ticular activities will happen (Pinedo, 2012). It usually refers to future activities – in general as well as in personal use. For each of the three components (\mathcal{S} , \mathcal{D} and \mathcal{E}) of an activity we differentiate between variable (e.g. 'in between 12:30h and 13:30h') and fixed (e.g. 'either at 12:30h or at 13:30h') occurrences. A variable activity could be a sightseeing trip during the holiday, which lasts *between* four and five days, whereas a fixed activity could be the flight itself, which starts *either* at 12:30h *or* at 13:30h. Furthermore, a probability distribution can be set for the uncertain components. If a probability distribution is known, it can be either cumulative (e.g. 'the activity is expected to end at 13:15h, but may last until 13:30h') or discrete (e.g. 'the activity ends at 12:30h with 70% or at 13:30h with 30% probability').


To draw activities with temporal uncertainty and a probability distribution, users must be able to externalize their internal knowledge. Often, users are not able to quantify the temporal uncertainty (Lipkus et al., 2001; Wallsten et al., 1988; Shipman and Marshall, 1999). An interactive visual method can help to give this input in a faster and more reasonable way (Greis et al., 2017). There are several, already evaluated approaches to visualize uncertainty in general (MacEachren et al., 2012; Chittaro and Combi, 2001; Hullman et al., 2019; Boukhelifa et al., 2012) and visualizations for temporal uncertainty in specific (Aigner et al., 2005; Gschwandtner et al.,

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2016). Commercial solutions like Microsoft Project provide options to quantify activities as *optimistic* or *pessimistic* as well as PERT-like network diagrams to visualize uncertainty within a schedule (Microsoft, 2021). Nevertheless, none of these approaches offer a complete solution for drawing, editing and visualizing schedules containing activities with temporal uncertainty to externalize implicit knowledge.

With our new approach, we provide the following contributions:

- An extension of existing methods for visualizing temporal uncertainty that enables the user to display
 - certain and *uncertain* activities
 - fixed and variable components of activities
 - indefinite activities
 - probability distributions for uncertain components.
- A sketch-based interface to enter schedules that include both certain and uncertain activities with all the above characteristics.
- A quantitative user study to evaluate both the system usability and the user performance. Therefore, the study was split into two tasks: a drawing assignment and a reading assignment.

2 RELATED WORK

The visualization of time-dependent data and schedules is a well researched problem.

Charts and Diagrams. *Gantt charts* are one of the most common visualization techniques used for planning activities (Aigner et al., 2011). Each activity is represented by a bar. Its left-most position on a time axis represents the start, whereas the width represents the duration of an activity. The description of the activity can be displayed as textual labels in the left part of the diagram or within their respective activities. The main advantage of Gantt charts is their simplicity and the similarity to bar charts, which are intuitive and self-explanatory (Cleveland and McGill, 1986; Marty, 2009). Nevertheless, Gantt charts are not suitable to visualize activities containing temporal uncertainty, since every bar has a fixed position, i.e. a fixed start and a fixed duration (Aigner et al., 2005). To overcome this drawback, several approaches have been developed, that form a good foundation for our new research.

Program Evaluation and Review Technique (PERT) diagrams were developed in 1958 (Cook,

1966) and are used for scheduling tasks since then (Merten, 1966; Biffel et al., 2005). In a PERT diagram, an activity is visualized as a table with the following properties:

- earliest starting time (EST) and earliest finishing time (EFT)
- latest starting time (LST) and latest finishing time (LFT)
- a (minimal) duration and a buffer time

The buffer time describes the difference between the minimal and the maximal duration of the activity. With these properties, a PERT diagram is able to visualize *certain* activities ($EST = LST$ and $EFT = LFT \rightarrow$ buffer time = 0) as well as activities with temporal uncertainty ($EST < LST$ and $EFT < LFT \rightarrow$ buffer time > 0). A complete schedule consists of several single PERT diagrams, where constraints can be visualized as arrows, similar to Gantt charts. Although the PERT diagrams can be arranged in a temporal order, it is not trivial to determine the whole time span of a schedule (Kosara and Miksch, 2002). Besides this issue, the missing visualization is the obvious disadvantage, because all properties are represented as text labels (Aigner et al., 2005).

In 2005, Aigner et al. presented a new technique that combines the advantages of Gantt charts and PERT diagrams – the PlanningLines (Aigner et al., 2005). PlanningLines are designed as bars similar to Gantt charts. Accordingly, the scalability for large project plans has also been maintained. They also allow the visualization of uncertainty with the same properties as in PERT diagrams. The start interval between EST and LST is visualized as an open bracket and the end interval between EFT and LFT as a closing bracket. The (minimal) duration of the activity is visualized as a dark bar within these brackets. The optional buffer time is visualized as a lighter-shaded extension of the respective bar, divided equally between both ends.

Drawing. For an interactive input of uncertainty Greis et al. (Greis et al., 2017) developed a set of different sliders to quantify uncertainty. The sliders provide different configurations to specify uncertainties with several degrees of freedom. They also provide a good baseline for the latest research (Kleemann and Ziegler, 2020) as well as our development. Since most visualizations and periphery are based on a 2D interface (Wang et al., 2013) a sketch-based input is already used in scientific fields like mathematics (LaViola Jr and Zeleznik, 2004; Zeleznik et al., 2008) for more than 15 years. Furthermore, sketch-based

interfaces are especially suitable for application areas with predominantly beginners and inexperienced users (Wang et al., 2013; Zheng et al., 2021). Lee et al. presented a system to support users during sketching (Lee et al., 2011) with dynamic shadows, to give them an idea of a possible outcome. This technique is still used in modern research (Ghosh et al., 2019; Shen et al., 2021).

Uncertainty Visualization. To visualize (temporal) uncertainty several studies were conducted (Aigner et al., 2005; Correll and Gleicher, 2014; Greis et al., 2017; Lee et al., 2011; Wang et al., 2013). MacEachren et al. evaluated eleven techniques (e.g. *location*, *orientation* or *fuzziness*) and several icons to visualize temporal and spatial uncertainty. As a main result, they propose that icons are not suitable to visualize any kind of uncertainty, since pictorial representations require an understanding of the underlying uncertainty on the part of the viewer and the viewer must also be able to correctly interpret the metaphor of the icon (MacEachren et al., 2012). Instead, they recommend the use of uncertainty visualisation techniques that introduce a small error into the data but, on the other hand, provide a faster assessment of the uncertainty presented.

Gschwandtner et al. conducted a survey to evaluate visualizations for temporal uncertainty (Gschwandtner et al., 2016). The main aspect of this survey was to assess which visualization should be used for quantitative uncertainty (with knowledge about the probability distribution) and qualitative uncertainty (without such knowledge). The survey shows that for quantitative uncertainty, a gradient brush performs best but is not the favourite visualization among the participants. For qualitative uncertainty, ambiguity performs best and is also the favourite visualization among the participants. Since Aigner et al. uses ambiguity to visualize the buffer time in their PlanningLines and the results are also used in recent publications (Sondag et al., 2020; Procopio et al., 2021), we decided to use these techniques to visualize the uncertain parts of our visualization.

Finally, error bars are often used to visualize uncertainty in data, but are often misinterpreted by users (Correll and Gleicher, 2014; Hofman et al., 2020). Furthermore, error bars are frequently associated with high certainty in the data (Belia et al., 2005) and value labels inside the bars are usually assumed to be more certain than value labels outside (Newman and Scholl, 2012). To avoid this kind of incorrect interpretation of the visualization, we use brackets instead of error bars, similar to Aigner et al. (Aigner et al., 2005), to visualize the time span of an activity.

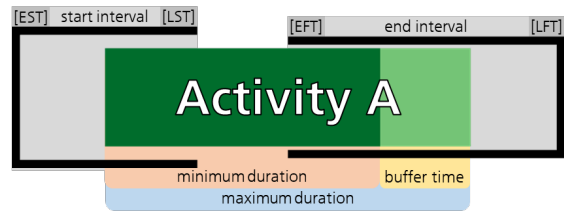


Figure 1: A *Tube* with its attributes. The time span of the activity is limited by the start and end interval. The maximum duration consists of the minimum duration and the buffer time.

3 VISUALIZATION METHOD

The visualization of activities with temporal uncertainty is not trivial. As mentioned above, uncertainty is ubiquitous in everyone’s life (MacEachren et al., 2012) and especially in the planning of future activities. For example, a simple holiday trip with five activities features a variety of temporal uncertainties.

1. A flight to the destination has a fixed S and D , and thus fixed \mathcal{E}
2. Packing a suitcase before the trip takes at least one day.
3. Sightseeing during the holidays for at least four days but maximum five days
4. A two-day trip during the holidays
5. The return flight is expected to take place on the scheduled day, but could be delayed by one day due to a pilot strike

Such schedules and taxonomies (Shneiderman, 2003; Gschwandtner et al., 2012) suggest the following visualization characteristics to be fulfilled by the design of our new approach:

- C1 *certain* activities
- C2 *uncertain* activities with a *certain* S and *uncertain* \mathcal{E} interval and vice versa
- C3 *uncertain* activities with an open S or open \mathcal{E} (indefinite activities)
- C4 both *certain* and *uncertain* activities within a time span
- C5 fixed characteristics for S , D and \mathcal{E}
- C6.1 a cumulative probability distribution for S , D and \mathcal{E}
- C6.2 a discrete probability distribution for S , D and \mathcal{E}
- C7 dependencies between two activities

PlanningLines (Aigner et al., 2005) already provides a good basis to visualize activities with temporal uncertainty, especially C1, C2 and C4 are al-

Table 1: Representative configurations of *Tubes* according to the characteristics (Char.) C1–C7. For C5[†], the buffer time *has* to be used, if the first possible start is taken. The rows marked with * each show two representatives with different probability distributions. C6.1* shows activities, which are probable finished after 25% or 75% of the buffer time. C6.2* shows activities for which the whole buffer time happens with a probability of 25% or 75%. In C7, the dependency between two activities is visualized by an orange arrow.

Char.	\mathcal{S}	\mathcal{D}	\mathcal{E}	Representative
C1		■		■
C2	 □	■ ■	□	■ ■
C3	— 	■ ■	— 	■ ■
C4	□ □	■ ■	□ □	■ ■
C5	↑ ↑ ↑ ↑	■ ■ ■	 ↑ ↑ ↑ ↑	■ ■ ■
†	↑ ↑	■	↑ ↑	■
C6.1	□ 	■ ■	□	■ ■
*		■	□	■
C6.2	↑ ↑ 	■ ■	 ↑ ↑	■ ■
*		■	↑ ↑	■
C7		■		■ → ■

ready supported. Although Aigner et al. provide simple projects plans with uncertainty in their publication, their approach does not support interactive input and differs in various visual aspects as detailed below. Thus, we slightly modify their components to present the opportunity for an interactive drawing as well as the editing of activities within a schedule. We named our new development *Tube*. A schematic representation of a tube with all its attributes is shown in Fig. 1. Examples for different configurations of *Tubes* fulfilling the Characteristics C1–C7 are shown in Table 1. As PlanningLines were already successfully evaluated (Aigner et al., 2005), the formal constraints and properties of them were adopted. The temporal attributes were also adopted to visualize the \mathcal{S} , \mathcal{D} and \mathcal{E} properties of an uncertain activity (see Fig. 1). The start interval is limited by the earliest starting time [EST] and the latest starting time [LST], the end interval is limited by the earliest finishing time [EFT] and the latest finishing time [LFT] and the maximum duration of an activity is defined by the minimum duration and the buffer time – the time difference between

the maximum and the minimum duration.

The major visual difference between PlanningLines (Aigner et al., 2005) and *Tubes* is the visualization of the buffer time. Usually, PlanningLines divides the buffer time equally between both ends. In contrast, we designed our *Tubes* with the buffer time always visualized on the right side of the minimum duration to foster easier understanding. The user therefore does not have to add two parts of the buffer time, but can perceive it at once.

As written above, PlanningLines already covers some requirements of the characteristics. To support the remaining demands, several combinations of the visual variables for visualizing uncertainty by MacEachren (MacEachren et al., 2012) are used. To find a good solution, we created several sketches in an iterative process on a whiteboard (Roberts et al., 2015) and discussed them during the development of our system.

Indefinite activities (C3) are visualized with an open bracket on the open side. Therefore, the horizontal lines are the remaining parts to foster a more intuitive understanding. To support C5, \mathcal{D} is visualized with a texture for a discrete setting. \mathcal{S} and \mathcal{E} are visualized as arrows with the direction of the arrowhead indicating whether it is about \mathcal{S} or \mathcal{E} . For a variable activity with a known probability distribution of \mathcal{S} , \mathcal{D} or \mathcal{E} , a cumulative distribution function is chosen to visualize the user input using a linear gradient brush (C6.1*) (Fig. 5). The calculation is adapted from Correl et al. (Correll and Gleicher, 2014). The probability for a fixed buffer time is represented by a chessboard texture. The granularity is varied based on the set probability, so less probable buffer time is sparser than more probable buffer time (C6.2*). For cases when \mathcal{S} has a known probability, ambiguity is used, so a less probable fixed start is visualized in lighter colors than a more probable one. Different configurations are shown in Fig. 6. This is also applied to a discrete \mathcal{E} .

4 APPLICATION

To support drawing, editing and visualizing activities with temporal uncertainty, a system architecture was developed. All user controls are grouped into three categories within a menu bar. The main category provides the options for input and editing of *Tubes* (see Section 4.1 & 4.2). The other categories contains I/O features and several possibilities to personalize the schedules. As an extension to Aigner et al. (Aigner et al., 2005), we provide the means to draw and visualize both continuous and discrete activities. Further-

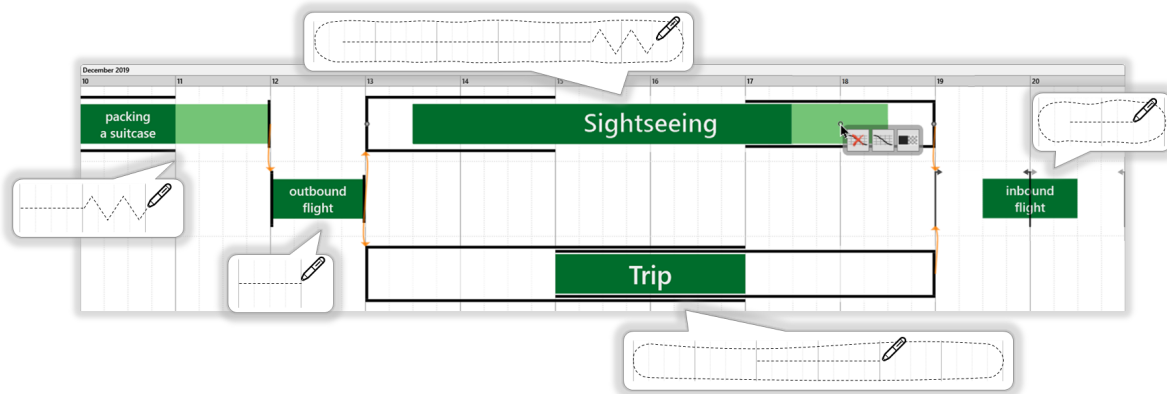


Figure 2: The figure shows a schedule of a holiday trip planned with temporal uncertainty. Our new *Tubes* visualize the activities with different properties. The user can draw each activity with simple inputs. The corresponding drawing actions are shown in the bubbles near each *Tube*. Furthermore, the mouse-sensitive context menu for editing is shown at the "Sightseeing" *Tube*.

Table 2: Drawing an uncertain activity with the different input methods and the resulting *Tube*.

mouse	
stylus	
result	

more, we also allow the input of probability distribution for all *uncertain* components of a *Tube* and offer the possibility to draw indefinite activities.

4.1 Input of *Tubes*

There are two possible methods to draw a single activity: *input with mouse and keyboard* and *input with stylus* on a tablet. For both methods, the user can enter either a start interval, an end interval, or a duration with an optional buffer time. If the time span of an activity is known, the user can also enter a time range instead of a start and end interval. The components are drawn as shadows and after finishing the input of all components the user receives suggestions for possible *Tubes* (Fig. 3). A schematic representation for the in-

put of an uncertain duration with both input methods is given in Table 2.

Drawing with Mouse and Keyboard. To draw an activity with mouse and keyboard, the user has to use the control (CTRL) and shift (↑) buttons as modifiers. The position of the mouse defines the position of an activity within a schedule. The user can draw the duration with the mouse while pressing the left mouse button and move the mouse on a straight line. The user can also draw *Start*, *End* and *Range* elements in the same way. To draw a buffer time, the user starts to enter a duration and presses the shift button additionally from the point where the buffer time should start and moves the mouse with pressed left button as far as the buffer time should go. During the sketching process, all elements are classified due to their relative position to each other, whereas the first drawn element is always classified as a *duration* element – regardless of a possible buffer time. The user can monitor its input due to the shadow drawing method (Lee et al., 2011).

Drawing with a Stylus. Beside the input with mouse and keyboard, a drawing method with a stylus is also implemented to provide a compatibility with modern touchscreen devices, e.g. tablets. In this mode, the user can draw lines with the stylus, which are automatically classified afterwards depending on their shape. To enter a *certain* activity, the user has to draw a straight line, similar to the movement of the mouse in the alternative mode. Due to the circumstances that no keyboard or other additional devices can be used to press certain keys as modifiers, the line classifier has to distinguish between *certain* and *un-*

certain activities in a different way. If there is a point with a slope $|m| \geq 1$, then the buffer time applies from this point onward (Table 2, red circle). Further input elements, *Start*, *End* and *Range*, can be drawn and are analysed by the classifier. The following code outlines the classification, where *PC* is an ordered collection of 2D points representing the internal structure of the input. The algorithm first extracts three important points of *PC*: the first point *f*, the last point *l*, and the point *d* with the greatest horizontal distance from *f*.

```

1:  $f \leftarrow PC.first, l \leftarrow PC.last$ 
2:  $d \leftarrow p \in PC$  with  $\max(|f.x - p.x|)$ 
3: if  $l = d$  then ▷  $\mathcal{D}$  entered
4:    $m_i \leftarrow \frac{p_i.y - p_{i+1}.y}{p_i.x - p_{i+1}.x}, i \in \{1, \dots, |PC| - 1\}$ 
5:   if  $\max(m_i) > 1$  then
6:     return uncertain  $\mathcal{D}$ 
7:   else
8:     return certain  $\mathcal{D}$ 
9:   end if
10: else ▷  $\mathcal{S}, \mathcal{E}$  or Range entered
11:   if  $\Delta(f, l) < \tau$  then
12:     return Range
13:   else if  $d.x < f.x$  then
14:     return Start
15:   else if  $d.x > f.x$  then
16:     return End
17:   end if
18: end if

```

After classifying the input, the components are displayed as shadows to support the user for further input (Lee et al., 2011).

Transforming input into Tubes. After the drawings are taken – either with mouse and keyboard or with a stylus – and the input is formally correct, the user gets suggestions for possible *Tubes* depending on the taken input. Since the input is only clearly defined through the triple of \mathcal{S}, \mathcal{D} and \mathcal{E} , the user can select the desired result *Tube* from a pop-up menu that shows all possible combinations for the drawn components. Fig. 3 shows an example of the user dialogue for the possible *Tubes* with a drawn user input of a duration (with buffer time) and a range.

4.2 Editing of Tubes

The editing of drawn *Tubes* is an important feature of the interactive input of activities. Beside the trivial actions like deleting or moving a *Tube*, more complex operations for editing *Tubes* and creating dependencies between two *Tubes* are implemented. In the corresponding editing mode of the software, the *Tubes* have mouse-sensitive editing points on certain ele-

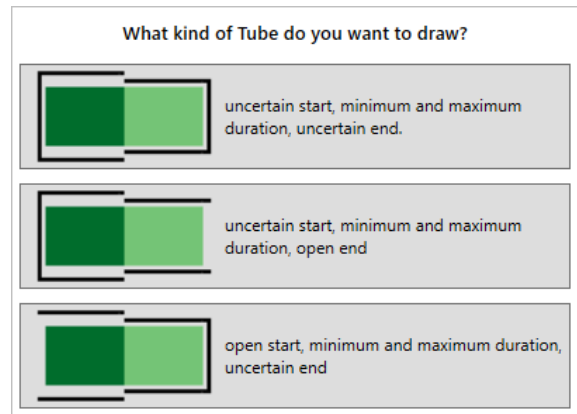


Figure 3: An example dialog for the supervised input. The user has to choose the *Tube* he wants to draw with the input of a duration and a range.



Figure 4: A context menu for editing of this *Tube* to change the buffer time from a continuous to a discrete one (right), add a new probability distribution (center), or remove a probability distribution (left).

ments to open a context menu for editing a component of a *Tube*. Fig. 4 shows this behaviour for the buffer time of an activity. You can either change this buffer time from variable to fixed or the other way round (right), add a probability distribution (center), or remove a probability distribution (left).

Probability Settings. In some cases the user wants to quantify the probability distribution of \mathcal{S}, \mathcal{E} or the buffer time. After selecting the corresponding menu item (see Fig. 4, center) a new user dialogue pops up

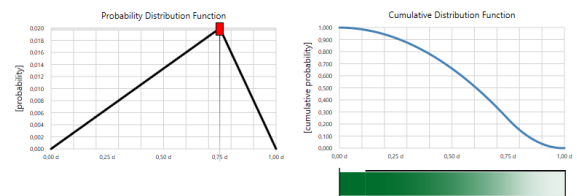


Figure 5: The user can set a known probability, whether an activity is more likely to last longer or shorter, with a slider in the probability distribution function (top left) and sees the resulting cumulative probability function directly (top right). Bottom shows the resulting *Tube* with the set probability distribution in the buffer time visualized with a gradient.

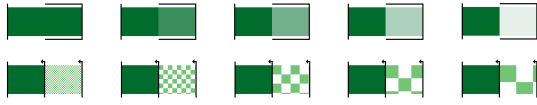


Figure 6: *Tubes* with a constant probability distribution from 1.0 to 0.0 (top row, left to right) and *Tubes* with a discrete buffer time and a respective probability from 1.0 to 0.0 (bottom row, left to right).

(Fig. 5) in which the user can set, whether the activity is more likely to last longer or shorter. The expected duration can be set with a slider in a probability distribution function (left, black). A cumulative distribution function (right, blue) shows the result of the input directly. The cumulative distribution is converted into a gradient (Correll and Gleicher, 2014) to show the probability distribution in the resulting *Tube* (bottom). The same technique can be used to quantify a probability distribution for the start and end components of a *Tube* (see Table 1).

Variable and Fixed Components. To quantify a constant probability for the buffer time (*every point in time has the same probability*) or a probability for fixed components in an activity (\mathcal{S} , \mathcal{D} , or \mathcal{E}), the dialogue only has to offer one slider to set the desired probability. The result for a constant probability with a fixed buffer time and different probabilities is shown in Fig. 6. To visualize a quantitative probability for a fixed buffer time, we chose the technique *grain* by MacEachren (MacEachren et al., 2012), where the rule is: the less likely the buffer time, the sparser the grid. For *Tubes* with a variable buffer time, the probability is mapped to the alpha value of the base color. The target function has a value range from 0.1 to 1.0 to avoid totally transparent components (zero probability). The same color is chosen for the base color and the color for the minimum time, so a buffer time with 100% probability is visualized like the minimum duration. Representatives for different probabilities are shown in Fig. 6. For fixed \mathcal{S} and \mathcal{E} components, the same technique as for variable buffer time with a constant probability is used. The components differ in their alpha value, depending on the chosen probability (see Fig. 7).

4.3 Additional features

To avoid conflicts within a schedule, the application has a built-in cross-check to highlight such risks. The system examines the drawn *Tubes* pairwise after each input to detect overlaps within the schedule. For this, only the part of an activity that will certainly happen is taken into consideration. If a conflict is detected,

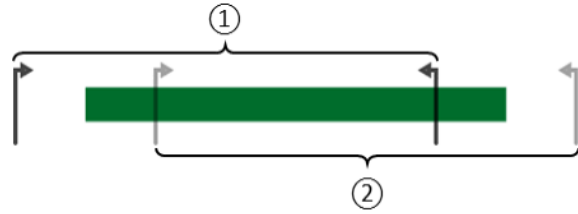


Figure 7: *Tube* with discrete start and end and constant probability. The activity happens with 70% in time span (1) and 30% in time span (2).

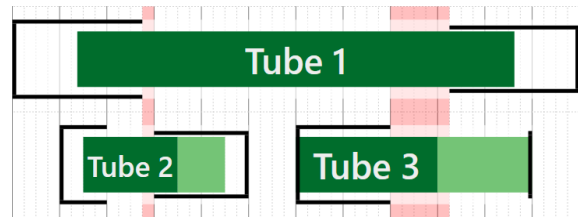


Figure 8: In the red-marked time spans, the *Tubes* conflict with each other, because *Tube* 1 and *Tube* 2, respectively *Tube* 1 and *Tube* 3 definitely happen there in this schedule.

the corresponding time span will be highlighted with a red marker (see Fig. 8). Furthermore, *Tubes* can be moved on the x -axis to re-define their time span within the schedule. They also can be moved on the y -axis into a different layer to avoid overplotting. As with PlanningLines (Aigner et al., 2005), the user also has the opportunity to draw dependencies between two activities (see Table 1, C7) to visualize that one activity has to be finished before the other one can start.

5 EVALUATION

We conducted a quantitative user study to evaluate both the drawing input with our new application and the corresponding visualization. Therefore, we divided the study into two parts – a drawing assignment to assess the potential of the input methods and the application, and a reading assignment to evaluate the visualization.

5.1 Experimental Setting

A total of 21 participants (10 male, 10 female, 1 preferred not to say) took part in the study. The age distribution was between 20 and 71, but the majority of the participants were between 20 and 30 years old (67%). The participants came from different professional fields, thus covering a broad spectrum of users. The study took place as a laboratory study and the conductor was present at all times to answer

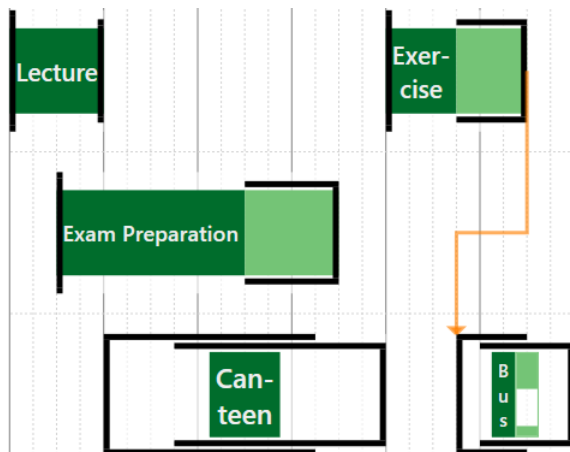


Figure 9: *Tubes* with different characteristics representing a hypothetical day at a university.

upcoming technical questions. All participants used the same technical equipment to ensure equal conditions. The study was designed within-subject to generate a significantly larger result set than in a between-subject design with the same number of participants (Charness et al., 2012). Thus, each participant worked on all assignments. After a brief introduction to the subject of the study and an explanation of the user interface by the conductor, the participants started with the study. There was no specific training phase, although all participants were asked to use the built-in help system to answer their questions concerning the application and the visualization by themselves. Each interview took between 60 and 150 minutes.

The initial setup of the study was to split the participants into two groups – one group working on the reading assignment first and finishing with the drawing assignment, and a second group working on the study in reverse order. The hypothesis was that participants would make fewer mistakes when drawing if they had seen and understood the visualization beforehand. However, the initial evaluation of the study showed that the groups had almost identical correctness, suggesting that there is no significant learning effect. This led us to consider all participants as one group for the result evaluation.

5.2 Assignments & Data

The drawing assignment addresses the newly developed software and its intuitiveness and robustness. Beside the known use case (Fig. 2), a second schedule had to be visualized (Fig. 9). For this schedule, a hypothetical day at a university was created with the following activities:

- Visit a lecture between 10:00am and 11:00am
- Exam preparation with fellow students at 10:30am with an uncertain end between 12:30pm and 01:30pm
- Visit an exercise starting at 02:00pm with a duration of at least 45min. After 45min, the assignments are probably not yet completed. However, the chances increase with each minute. In any case, the exercise will take a maximum of 90min.
- Go to the canteen for a maximum of 45min after the lecture, but before the exercise starts
- Take the bus after the exercise. It will take either 15min or 30min, depending on the route.

For this assignment the participants were asked to draw the two different schedules that were given to them in a textual representation. Each schedule consisted of five activities focusing on different specifics, e.g. *certain* start and *uncertain* end, or activities containing a probability distribution or discrete components.

The participants were also given a reading assignment as a prepared schedule with different activities, drawn in advance by the conductor with the new application. The shown schedule is a slightly modified version of the project plan evaluated by Aigner et al. in 2005 (Aigner et al., 2005) to ensure the comparability of the evaluation results. We have varied the activities so that all characteristics are represented by at least one *Tube*. The schedule is depicted in Fig. 10.

This assignment was conducted to evaluate the comprehensibility of the visualization. The participants were asked to answer questions on the details of the visualizations, e.g. “When is the earliest possible start?”, “When is the latest possible end?” or “What is the maximum duration of the activity?”.

Finally, the participants were asked to fill in a form for the system usability score by Sauro (Sauro, 2011).

5.3 Analysis

The drawing assignments were evaluated by the specific features of the *Tubes* to be drawn – an existing property was assigned a value of 1 and a missing property was assigned a value of 0. The reading assignment was evaluated with 1 for a correct answer and 0 for a wrong answer. Therefore, an average correctness value of 1.0 means, that *all* participants have fully met *all* requirements, while a value of 0.0 means, that no requirement was fulfilled by any participant. The results are shown in Fig. 11 and are further explained in the remainder of this section.

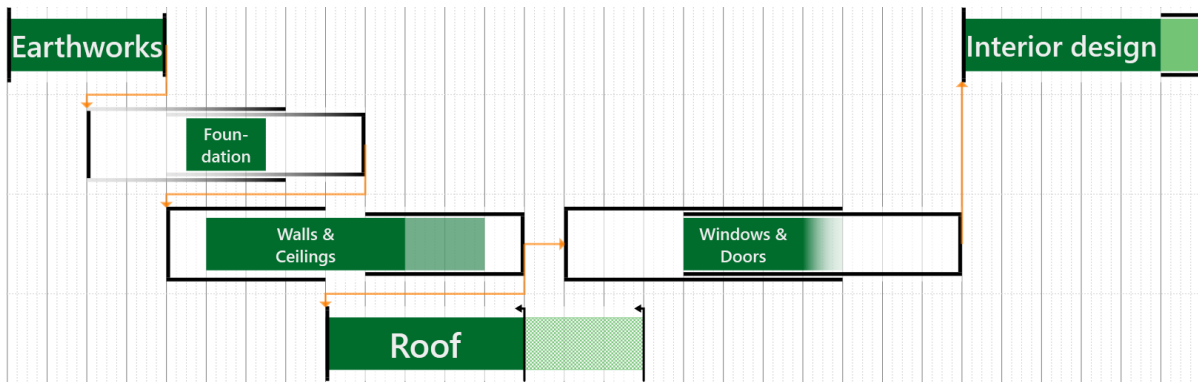


Figure 10: The example schedule of the reading assignment. The plan has been adopted from Aigner et al. (Aigner et al., 2005) and slightly modified so that all characteristics can be queried.

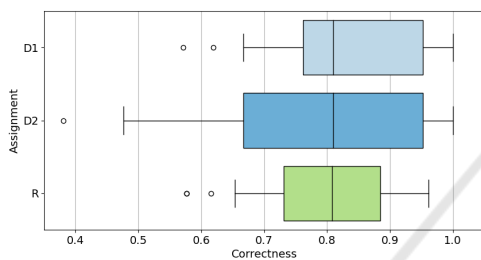


Figure 11: Results of the drawing assignments (D1, D2) and the reading assignment (R). The assignments had a similar average rating, but differ strongly in the variance of the results.

Drawing Assignment. The two schedules (D1 - a day at a university, D2 - the holiday use case) were evaluated individually, followed by a comparison between them.

D1 has an average correctness of 0.8413. The only activity with a comparably low correctness (0.7048) was the bus transfer. The main problem was to set the right start interval. The intended solution was an *uncertain* start within 45min and 90min of the duration of the exercise ahead. Instead, eleven participants drew a *certain* start right after the latest possible ending of the exercise. Furthermore, the probability distribution for this fixed and uncertain activity was not set correctly in 12 of 21 cases. Another difficulty in this schedule was to set the probability distribution for the duration of the exercise in the right way – 10 of 21 participants had problems with that aspect.

D2 has an average correctness of 0.7755. The main problems with this schedule came from the indefinite activity of packing the suitcase (0.7738) and the inbound flight (0.6667). In the suitcase activity, setting the right start was the main challenge, whereas the inbound flight causes multiple problems concerning the maximal duration, the fixed start and end interval, and the probability distribution.

Both drawing assignments have exactly the same median correctness value of 0.8095. This high number shows the good usability of the developed software, in particular for new users. Participants did not have much trouble entering *certain* activities, nor did they have much difficulty entering *uncertain* activities within a time span. Problems occurred only with activities with more specific properties, such as fixed components or probability distributions.

Reading Assignment. The reading assignments has an average correctness of 0.7875. The results show that users read the *certain* activity almost without errors, just like the *Tube* with fixed components. Problems occurred with the indefinite activity and its open end. The main problems appeared around the probability distributions and with the components \mathcal{S} and \mathcal{E} , causing significantly more problems for the participants than such a characteristic in \mathcal{D} .

Summary. The two different assignments show similar performances for the different characteristics of the *Tubes*. On the one hand, the participants had problems with the probability distributions, both during drawing and reading. This could be due to the fact that judgements under uncertainty are often mediated by intuitive heuristics (Tversky and Kahneman, 1983). Furthermore, 10 participants drew constraints between two activities. While this was not a task in the assignments, it is a good point to consider in future iterations of the research. On the other hand, *Tubes* with other characteristics than probability distributions seemed to be no problem for the participants, both during drawing and reading. This observation is also reflected in the similar statistics for the assignments (see Fig. 11). With an average correctness of 0.8117, the study shows good results in both drawing schedules with our software and visualization.

System Usability Score. The system usability score indicates the subjective evaluation of the usefulness and utility of the application by the participants (Sauro, 2011). The score of this evaluation for our system is between 30.0 and 92.5. The average score of 66.19 shows that our new application can be classified as ‘OK’.

6 CONCLUSION AND FUTURE WORK

We presented both a new visualization and a corresponding application for the interactive visual input for planning with temporal uncertainty. The visualization is based on the PlanningLines approach by Aigner et al. (Aigner et al., 2005). With our extension of this approach, it is also possible to visualize both variable and fixed activities. Furthermore, it is possible to visualize different probability distributions and indefinite activities. For the interactive drawing of schedules, the new application offers input methods using both mouse and keyboard as well as stylus input. After sketching a *Tube*, the user is supported with shadow-drawing (Lee et al., 2011) to get suggestions for the final visualized *Tubes*. We conducted a quantitative user study to show the added value of the new visualization and application. The drawing assignments emphasize the benefits of the new application in externalising the temporal uncertainties. With the reading assignment the suitability of the visualization was shown. Furthermore, the user study showed that the holiday use case example (see section 1) can be externalized by the majority of the participants without significant issues. The objective evaluation shows an average correctness of about 80% for both parts of the study. Since no participant used the application before the study took place, it can be assumed that the accuracy will increase with regular use. To evaluate the subjective perception, the participants were asked to fill in a system usability score (Sauro, 2011). The score shows, that the system can be classified as ‘OK’. Nevertheless, the broad range of scores shows that we have to work on an even more user-friendly way to enter complex configurations.

As upcoming steps, more functionality for editing tubes will be realized. This includes possibilities to vary the durations of *Tube* components as well as an advanced input dialogue to enter the probability distributions in an easier way. Furthermore, we plan extended quality-of-life improvements, like zooming and panning, or individual colors for single *Tubes* to provide more customizability for the schedule.

REFERENCES

- Aigner, W., Miksch, S., Schumann, H., and Tominski, C. (2011). *Visualization of time-oriented data*. Springer Science & Business Media.
- Aigner, W., Miksch, S., Thurnher, B., and Biffel, S. (2005). Planninglines: novel glyphs for representing temporal uncertainties and their evaluation. In *Ninth International Conference on Information Visualisation (IV'05)*, pages 457–463.
- Belia, S., Fidler, F., Williams, J., and Cumming, G. (2005). Researchers misunderstand confidence intervals and standard error bars. *Psychological methods*, 10(4):389.
- Biffel, S., Thurnher, B., Goluch, G., Winkler, D., Aigner, W., and Miksch, S. (2005). An empirical investigation on the visualization of temporal uncertainties in software engineering project planning. In *2005 International Symposium on Empirical Software Engineering, 2005.*, pages 10–pp. IEEE.
- Boukhelifa, N., Bezerianos, A., Isenberg, T., and Fekete, J.-D. (2012). Evaluating sketchiness as a visual variable for the depiction of qualitative uncertainty. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2769–2778.
- Charness, G., Gneezy, U., and Kuhn, M. A. (2012). Experimental methods: Between-subject and within-subject design. *Journal of Economic Behavior & Organization*, 81(1):1–8.
- Chittaro, L. and Combi, C. (2001). Representation of temporal intervals and relations: information visualization aspects and their evaluation. In *Proceedings Eighth International Symposium on Temporal Representation and Reasoning. TIME 2001*, pages 13–20.
- Cleveland, W. S. and McGill, R. (1986). An experiment in graphical perception. *International Journal of Man-Machine Studies*, 25(5):491–500.
- Cook, D. L. (1966). *Program evaluation and review technique: Applications in education*. Number 17. US Department of health, education, and welfare, Office of education.
- Correll, M. and Gleicher, M. (2014). Error bars considered harmful: Exploring alternate encodings for mean and error. *IEEE transactions on visualization and computer graphics*, 20(12):2142–2151.
- Ghosh, A., Zhang, R., Dokania, P. K., Wang, O., Efros, A. A., Torr, P. H., and Shechtman, E. (2019). Interactive sketch & fill: Multiclass sketch-to-image translation. In *Proceedings of the IEEE/CVF International Conference on Computer Vision*, pages 1171–1180.
- Greis, M., Schuff, H., Kleiner, M., Henze, N., and Schmidt, A. (2017). Input controls for entering uncertain data: Probability distribution sliders. *Proc. ACM Hum.-Comput. Interact.*, 1(EICS):3:1–3:17.
- Gschwandtner, T., Bögl, M., Federico, P., and Miksch, S. (2016). Visual encodings of temporal uncertainty: A comparative user study. *IEEE Transactions on Visualization and Computer Graphics*, 22(1):539–548.
- Gschwandtner, T., Gärtner, J., Aigner, W., and Miksch, S. (2012). A taxonomy of dirty time-oriented data. In

- Quirchmayr, G., Basl, J., You, I., Xu, L., and Weippl, E., editors, *Multidisciplinary Research and Practice for Information Systems*, pages 58–72, Berlin, Heidelberg, Springer Berlin Heidelberg.
- Hofman, J. M., Goldstein, D. G., and Hullman, J. (2020). How visualizing inferential uncertainty can mislead readers about treatment effects in scientific results. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pages 1–12.
- Hullman, J., Qiao, X., Correll, M., Kale, A., and Kay, M. (2019). In pursuit of error: A survey of uncertainty visualization evaluation. *IEEE transactions on visualization and computer graphics*, 25(1):903–913.
- Kleemann, T. and Ziegler, J. (2020). Distribution sliders: visualizing data distributions in range selection sliders. In *Proceedings of the Conference on Mensch und Computer*, pages 67–78.
- Kosara, R. and Miksch, S. (2002). Visualization methods for data analysis and planning in medical applications. *International Journal of Medical Informatics*, 68(1):141 – 153.
- LaViola Jr, J. J. and Zeleznik, R. C. (2004). Mathpad 2: a system for the creation and exploration of mathematical sketches. *ACM Transactions on Graphics (TOG)*, 23(3):432–440.
- Lee, Y. J., Zitnick, C. L., and Cohen, M. F. (2011). Shadow-draw: real-time user guidance for freehand drawing. In *ACM Transactions on Graphics (TOG)*, volume 30, page 27. ACM.
- Lipkus, I. M., Samsa, G., and Rimer, B. K. (2001). General performance on a numeracy scale among highly educated samples. *Medical Decision Making*, 21(1):37–44. PMID: 11206945.
- MacEachren, A. M., Roth, R. E., O’Brien, J., Li, B., Swingle, D., and Gahegan, M. (2012). Visual semiotics & uncertainty visualization: An empirical study. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2496–2505.
- Marty, R. (2009). *Applied security visualization*. Addison-Wesley Upper Saddle River.
- Merten, W. (1966). Pert and planning for health programs. *Public Health Reports*, 81(5):449.
- Microsoft (2021). Project help & learning. <https://support.microsoft.com/en-GB/project>. [Online; accessed 2021-09-09].
- Newman, G. E. and Scholl, B. J. (2012). Bar graphs depicting averages are perceptually misinterpreted: The within-the-bar bias. *Psychonomic bulletin & review*, 19(4):601–607.
- Pinedo, M. (2012). *Scheduling*, volume 29. Springer.
- Procopio, M., Mosca, A., Scheidegger, C. E., Wu, E., and Chang, R. (2021). Impact of cognitive biases on progressive visualization. *IEEE Transactions on Visualization and Computer Graphics*, pages 1–1.
- Roberts, J. C., Headleand, C., and Ritsos, P. D. (2015). Sketching designs using the five design-sheet methodology. *IEEE transactions on visualization and computer graphics*, 22(1):419–428.
- Sauro, J. (2011). *A practical guide to the system usability scale: Background, benchmarks & best practices*. Measuring Usability LLC.
- Shen, I.-C., Liu, K.-H., Su, L.-W., Wu, Y.-T., and Chen, B.-Y. (2021). Clipflip: Multi-view clipart design. In *Computer Graphics Forum*, volume 40, pages 327–340. Wiley Online Library.
- Shipman, F. M. and Marshall, C. C. (1999). Formality considered harmful: Experiences, emerging themes, and directions on the use of formal representations in interactive systems. *Computer Supported Cooperative Work (CSCW)*, 8(4):333–352.
- Shneiderman, B. (2003). The eyes have it: A task by data type taxonomy for information visualizations. In *The craft of information visualization*, pages 364–371. Elsevier.
- Sondag, M., Meulemans, W., Schulz, C., Verbeek, K., Weiskopf, D., and Speckmann, B. (2020). Uncertainty treemaps. In *2020 IEEE Pacific Visualization Symposium (PacificVis)*, pages 111–120.
- Tversky, A. and Kahneman, D. (1983). Extensional versus intuitive reasoning: The conjunction fallacy in probability judgment. *Psychological review*, 90(4):293.
- Wallsten, T. S., Zwick, R., Forsyth, B., Budescu, D. V., and Rappaport, A. (1988). Measuring the vague meanings of probability terms. Technical report, NORTH CAROLINA UNIV AT CHAPEL HILL.
- Wang, B., Ruchikachorn, P., and Mueller, K. (2013). Sketchpadn-d: Wydiwyg sculpting and editing in high-dimensional space. *IEEE Transactions on Visualization and Computer Graphics*, 19(12):2060–2069.
- Zeleznik, R., Miller, T., Li, C., and LaViola, J. J. (2008). Mathpaper: Mathematical sketching with fluid support for interactive computation. In *International Symposium on Smart Graphics*, pages 20–32. Springer.
- Zheng, R., Fernández Camporro, M., Romat, H., Henry Riche, N., Bach, B., Chevalier, F., Hinckley, K., and Marquardt, N. (2021). Sketchnote components, design space dimensions, and strategies for effective visual note taking. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–15.