An Interactive Graph Layout Constraint Framework

Jette Petzold[1][a], Sören Domrös[1][b], Connor Schönberner[1][c], Reinhard von Hanxleden[1][d]
[1]*Department of Computer Science, Kiel University, Kiel, Germany*
{jep, sdo, cos, rvh}@informatik.uni-kiel.de

Keywords: Automatic Graph Layout, User Intentions, Layout Constraints, Layered Layout.

Abstract: Several solutions exist to constrain nodes or edges for creating desired graph layouts or arrangements via automatic layout. However, these constraints, which are often handled in separate views, tend to produce conflicts if not handled carefully. We present an interactive layout framework that visualizes existing constraints and available new constraints interactively in the diagram. Adding constraints via diagram interaction allows reevaluation of existing constraints based on the intended movement of the constrained node and prevents conflicts between constraints. The framework can easily be utilized by new layout algorithms and is independent of the actual layout implementation.

1 INTRODUCTION

Automatic graph drawing is concerned with generating graph drawings or layouts optimizing a subset of layout properties. As suggested by (Böhringer and Paulisch, 1990), layout constraints are a powerful tool to tweak graph layouts and to create stable layouts for automatic layout algorithms, such as the Sugiyama algorithm (Sugiyama et al., 1981), also called the layered algorithm. They allow users to adjust diagrams to special use cases that are not supported by general layout algorithms and can improve layout stability, node grouping, and, in certain cases, even edge crossings. Layout stability and node grouping are especially important since they preserve the mental map (Purchase et al., 2006), while edge crossings is one of the most important criteria (Purchase, 1997).

Since constraints might be complex or contradict each other, the user needs to have an intuitive interface when working with them. The question how automatic layout can be augmented by a constraint framework is separated into four sub-questions:

RQ1 How to visualize possible constraints?

RQ2 How to add constraints?

RQ3 How to address conflicting constraints?

RQ4 How to visualize existing constraints?

[a] https://orcid.org/0000-0002-5559-7073
[b] https://orcid.org/0000-0002-8011-8484
[c] https://orcid.org/0000-0002-9298-6641
[d] https://orcid.org/0000-0001-5691-1215

An interactive layout framework, solving these questions, utilizes an interactive layout overlay or integrates it into the used layout algorithm and resolves conflicts between constraints, while keeping the layout stable. An integration in a layout algorithm requires changing its implementation, which prevents the overlay from being applied to other algorithms. An interactive overlay instead visualizes existing constraints and offers manipulation of constraints, while being independent of the concrete algorithm implementation. The overlay should only depend on the output format of the layout algorithm and not its configuration. The overlay informs users about possible constraints, solving RQ1.

Solution options for RQ2 are adding layout constraints textually, provided a textual source exists, or interactively in the diagram. We focus on diagrams that are generated automatically based on a textual source and propose to interact with the diagram. We use drag-and-drop interaction to add constraints since it directly corresponds to the semantics of the constraint, i. e. moving a node to the desired position. The interactive addition of constraints allows reevaluation of existing constraints if they would otherwise contradict each other.

Constraints need to be serialized into the textual source model to persist them. That is why constraints can also be added textually which can lead to conflicting constraints. The framework should anticipate this and be robust even if contradicting constraints are introduced in such a manner. This robustness and the reevaluation solve RQ3.

In the following, we introduce our framework as a showcase how an interactive layout overlay for the layered algorithm can look like. The focus lies on how constraints need to be reevaluated preventing conflicts.

Figure 1 shows the integration into VS Code. On the left, we see the editor with the textual *source model*. On the right we see the interactive diagram *view model* with a diagram option side panel, which can be used to configure the layout or the diagram itself. In both models the existing constraints can be seen (RQ4). In the source model they are determined with *positionChoiceConstraint* and *layerChoiceConstraint* and in the view model they are visualized with icons attached to the nodes.

1.1 Contribution & Outline

Section 2 presents related work. The main contributions covered in Section 3 are as follows: We present an interactive layout overlay, show how absolute and relative constraints for layered layouts can be set, and present their interaction. Section 4 introduces the implementation of our framework and evaluates the proposed constraint reevaluation steps for the layered algorithm. Finally, Section 5 concludes this paper.

2 RELATED WORK

(Böhringer and Paulisch, 1990) introduce constraints for the layered algorithm. The created layouts are stable and respect semantic constraints that cannot be expressed as part of the layout algorithm itself. A constraint manager allows adding, deleting, and querying the constraint network of absolute positioning, relative positioning, and clustering constraints. In contrast to our approach, which allows to drag-and-drop nodes in the diagram itself, the user works with popup menus. The drag-and-drop allows providing an overlay that illustrates the available constraints and hence clarifies the consequences of an action.

(Borning et al., 1987) introduce *constraint hierarchies* to solve conflicting constraints. The user can set priorities on constraints and an algorithm is introduced solving conflicting constraints by preferring the constraint with the highest priority. We, in contrast, want to prevent the creation of conflicting constraints instead of solving them afterwards via priorities.

(Waddle, 2001) focuses on constraints for laying out data structures with a layered algorithm. The decisions the algorithm takes during the layout are adjusted such that the introduced constraints are considered. The contrast to our work is, that we do not modify the algorithm itself, which allows our framework to be utilized for several layout algorithms.

(McGuffin and Jurisica, 2009) provide selection of multiple nodes and radial menus containing actions to modify the selected elements. This way a range of actions can be supported. However, we want to follow a more intuitive approach, where only drag-and-drop of nodes is used.

Wybrow showcases how constraints are specified and evaluated using the Dunnart tool (Wybrow, 2008; Dwyer et al., 2009). The introduced constraints work on real positions and specify the alignment of nodes and the direction of edges. We instead focus on semantic constraints dependent on the used layout algorithm. Wybrow visualizes constraints by marking constrained edges and showing alignment help lines. This is similar to our approach as shown later.

3 INTERACTIVE LAYOUT FOR LAYERED LAYOUT

As an example how such an interactive constraint overlay looks like, we showcase on the example of the layered algorithm, how absolute and relative constraints, as proposed by (Böhringer and Paulisch, 1990), can be implemented.

The layered layout places nodes in consecutive layers. E. g., the graph in Figure 1 has three layers with the nodes AAA, AA, and A in the first one. Naturally, this supports absolute position constraints constraining the layer and the position in the layer, presented in Section 3.1. Relative constraints constrain the position of a node relative to another node and are explained in Section 3.2. Section 3.3 presents the interaction between the two constraint types. Adding constraints (RQ2) is done by moving a node and releasing it on the desired position in the diagram, which adds the constraint to the source model. We provide the user with a diagram overlay for each constraint type indicating available constraints (RQ1).

The interactive addition of constraints allow constraint reevaluation. If reevaluation is not possible, the overlay forbids to set the constraints (RQ3).

In the following we assume, without loss of generality, a left to right layout. Additionally, we have written the values for the constraints manually into the shown diagrams if they are important.

3.1 Absolute Constraints

We introduce two absolute constraints: *layer constraint* and *position constraint*. The layer constraint determines the layer of a node, where 0 is the first

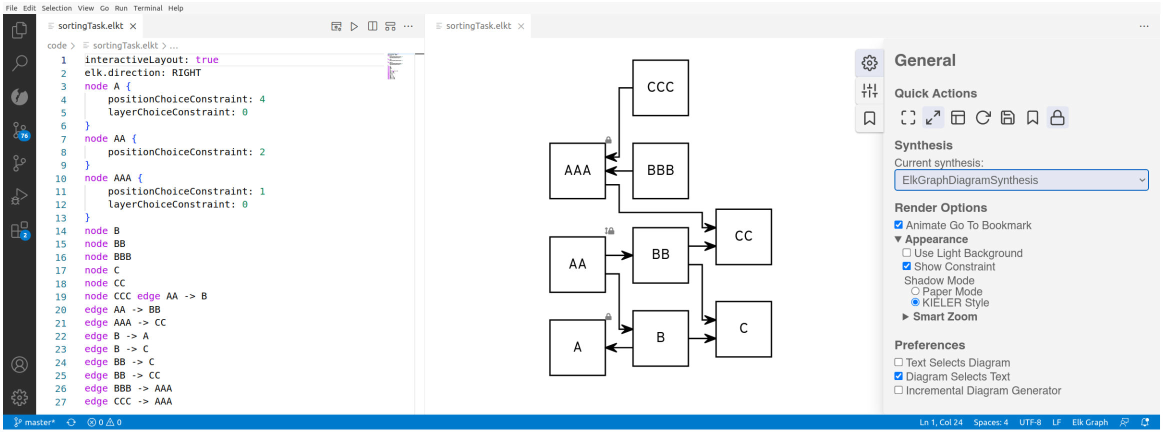


Figure 1: The Visual Studio Code (VS Code) Extension for our interactive layout framework.

layer. The position constraint determines the position in the layer, where 0 indicates the first position, which is the top position. When moving a node, the release position determines the constraint that should be set. In the following, layer constraints are abbreviated in figure annotations with LC and position constraints with PC.

Calculation Since our framework is independent of the algorithm and the layer structure as later explained in Section 4.1, the layer bounds have to be derived from the node positions. The leftmost and rightmost node of a layer determine the horizontal bounds, while the topmost and bottom-most node determine the vertical bounds.

A new last layer can be created by releasing the node to the right of the last layer. A node can also be released to the left of the first layer. This sets the desired constraints, but this constraint alone does not always create a new layer with only the moved node in it. Nodes that are in the originally first layer, are not connected to the moved node, and do not have a layer constraint, will be in the new first layer as well. This can be prevented if all other nodes, even the previously unconstrained ones, are constrained to a layer. Since this is most likely undesired and creates many potentially unnecessary constraints, we refrain from doing so.

The new position of the moved node is calculated by comparing its vertical coordinate with the coordinates of the other nodes in the layer. If the value of the moved node is lower than all the other, the new position is 0. Otherwise, it is the position of the node with the highest coordinate that is lower than the target coordinate increased by 1.

Each constraint can be set separately. Releasing the node within its original layer only sets a position constraint. Releasing the node above or below a layer that is not its original layer only sets a layer constraint. Both constraints are set when releasing the node inside the layer bounds of a layer that is not its original layer. Releasing the node at its original position sets no constraint.

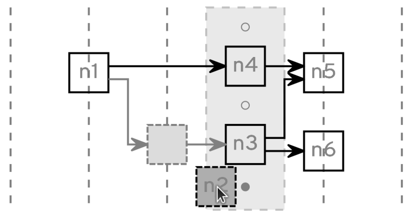


Figure 2: Moving n2 activates the interactive layout overlay. Layers are shown as lines. A bounding box shows the current layer and circles the available positions in it.

Giving a node the same layer constraint as a node connected by an edge is forbidden, since in-layer edges are forbidden by the used layered approach. Alternatively, we could allow the movement and delete the existing layer constraint. However, this could require deletion of layer constraints of all nodes connected to the first connected node, which compromises layout stability.

User Interface When moving a node, the incident edges are not moved, which leads to edges that point to empty space. That is why we place a *shadow* of the moved node at its original position, as seen in Figure 2. The shadow has the same shape as the original node but is grayed out. The incident edges are grayed out as well indicating that they belong to the moved node.

When moving a node, we visualize the available layers and the positions in the layer (see Figure 2), which informs the user about available constraints. The layer a node is assigned to when releasing is visualized by a dashed rectangle that surrounds all nodes in the layer. Dashed vertical lines in the middle of a layer indicate the other layers a node can be moved to. The current layer is highlighted in light gray to prevent confusion if the layer bounds are not visible. The color changes to gray when the node is moved above or below the layer and hence only a layer constraint is set when releasing the node.

Forbidden layer constraints are visualized by highlighting the forbidden layer red. Forbidden position constraints do not exist.

The available positions are visualized by circles, in the following referred as *node slots*. The node slots are placed above the first node, in the middle of two consecutive nodes, and below the last node, as seen in Figure 2, excluding the original position of the moved node. A filled circle indicates that the node would be assigned to the position the node slot represents. If only a layer constraint would be set, the node slots are not shown at all.

Feedback on existing constraints (RQ4) is given by icons attached to the nodes visualizing the set constraints. Nodes with a layer constraint as well as a position constraint have a lock icon. In the cases where only one of the constraints is set, the icon is a lock with an arrow. The arrow is horizontal if the layer constraint is set, indicating that the horizontal position of the node is determined by the constraint. Analogously, a vertical arrow indicates a locked vertical position and hence a position constraint. The user can reduce visual clutter by deactivating the icons.

Constraints of a node can be deleted interactively, by pressing the Alt key and clicking on the node.

Reevaluation When setting a constraint, updating already existing constraints might be necessary, e. g., when a node is released at position 0, but another node in the same layer already has a position constraint with value 0. We call this process *reevaluation*, which solves RQ3 and adheres to four principles:

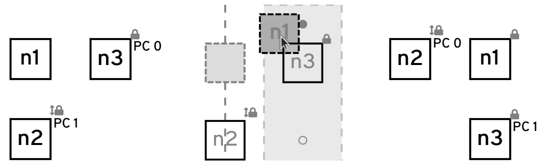
(1) There should be no conflicts between constraints.

(2) No unintended changes in node ordering and edge routing should occur.

(3) Nodes without constraints do not get constraints, except the moved node.

(4) Constraints of not moved nodes should only be changed, if it violates principles (1) or (2).

Principle (1) is the most basic one. If two constraints are conflicting, we have to drop one of them to resolve the conflict. In this process the most recent action taken by the user has priority.



(a) Initial Graph (b) In Movement (c) Result

Figure 3: Releasing n1 in layer 1 on position 0 updates the position constraints of n2 and n3.

Principle (2) ensures that the layout remains stable. If too many nodes or edges move simultaneously in unpredictable directions, the mental map cannot be maintained.

Principle (3) ensures that an interaction with the graph does not introduce unexpected constrains to the graph. Multiple unnecessary constraints that are not intended by the user may compromise aesthetic criteria, which compromises the readability of the node-link diagrams (Purchase, 1997), since they constrain the graph unnecessarily.

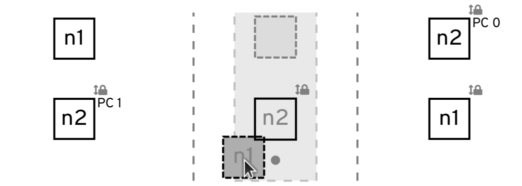
Principle (4) ensures that an interaction does not delete previous work if this is not necessary, since this might confuse the user.

The first case where reevaluation is needed is assigning a node a new layer and position simultaneously (see Figure 3). In the original layer of the moved node, as well as in the layer the node is moved to, the position constraints of the other nodes must be updated. For nodes in the original layer that were below the moved node, the values of the constraints must be decremented by 1, as done for node n2 in Figure 3. Otherwise, the node ordering would have to change to fulfill the constraints, which would violate our second principle. Nodes without constraints need no reevaluation. Analogously, nodes in the target layer that are below the new position of the moved node are updated. The values of the constraints are incremented by 1 to keep the node order, as done for node n3 in Figure 3. This also prevents identical position constraints for nodes in the same layer.

Another case can be seen in Figure 4, where only a position constraint is set. There are two cases that need to be considered: moving a node up and moving a node down. When moving a node up, the position constraints of all nodes the moved node passes, are incremented by 1. For the down case, the constraints are decremented by 1, as seen in Figure 4c.

When assigning only a layer constraint, only the original layer of the moved node needs to be reevaluated. The position constraints of all nodes below the original position of the moved node are decremented by 1.

If two nodes get the same position or layer constraint via textual editing, only the constraint for the



(a) Initial Graph (b) In Movement (c) Result

Figure 4: Releasing n1 at position 1 updates the position constraints of n2.

node that is last in the view model is fulfilled. The same happens in other cases where constraints that were added textually contradict each other.

3.2 Relative Constraints

Besides the absolute position constraints, we introduce two relative position constraints as well: *successor-of* and *predecessor-of*. Both constraints determine the position of a node in relation to another node. When a node has the successor-of constraint, it is placed below the target node and when a node has the predecessor-of constraint, it is placed above the target node in the same layer. Since absolute and relative constraints overlays partly use the same positions to highlight available constraints, a second overlay is required. Holding the Shift key enables the relative constraint overlay.

Calculation The node closest to the middle of the moved node is the target node. Moving the node above the target node sets a predecessor-of constraint while moving it below sets a successor-of constraint. In contrast to the calculation of the absolute constraints, the original position of the moved node does not influence the calculation.

Since connected nodes are not allowed in the same layer, relative constraints between them are forbidden. Releasing a node on a position where a forbidden constraint would be set sets no constraint. The same applies when the target of the moved node has a relative constraint to a connected node of the moved node or is in another way in relation to a connected node, which would lead to positioning the moved node in the same layer.

User Interface The overlay for interactively setting relative constraints uses blue as the main color to differentiate it from the overlay for absolute constraints.

Moving a node to a position where it would get a relative constraint highlights the moved node as well as the target node, as seen in Figure 5. When the calculated constraint is forbidden, no highlighting is

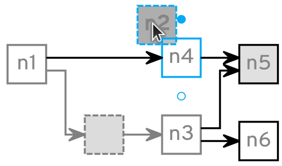
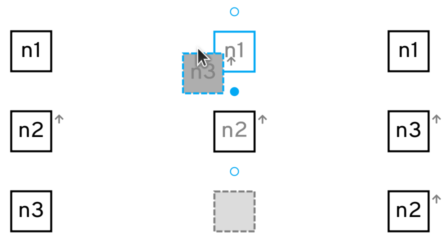


Figure 5: Releasing n2 above n4 fills the circle over n4 and highlights n4 and the moved node n2. The interaction results in a predecessor-of constraint.



(a) Initial Graph (b) In Movement (c) Result

Figure 6: Releasing n3 inside an existing chain makes n3 part of the relative constraint chain now consisting of n1, n3, and n2.

done. Additionally, forbidden target nodes are grayed out when moving a node.

The type of the constraint that will be set is visualized by circles, as seen in Figure 5. If the circle below the target node is filled, a successor-of constraint will be set, and when the circle above the target node is filled, a predecessor-of constraint will be set.

An arrow icon pointing to the target node visualizes existing constraints (RQ4), as seen in Figure 6. If both constraints are set for a node, the arrow points in both directions.

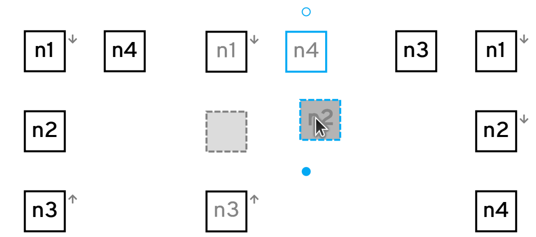
Deleting a relative constraint is done by pressing the Alt and the Shift key while clicking on the node.

Reevaluation The reevaluation adheres to the same principles introduced for the absolute constraints.

If a node is released between two nodes that are connected with a relative constraint, as seen in Figure 6, the original constraints that connected the two nodes are updated to point to the moved node.

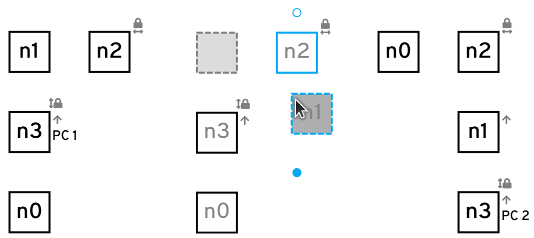
Another case is moving a node that is originally the target of two other nodes. One of them is the successor and the other the predecessor. When the moved node gets a predecessor-of constraint, the constraint of the original successor is deleted (see Figure 7). Analogously, if the successor-of constraint is set, the constraint of the original predecessor is deleted.

Setting a predecessor-of constraint while the target has a predecessor-of constraint to the moved node deletes the constraint of the target because the constraint that is set the latest has the highest priority.



(a) Initial Graph (b) In Movement (c) Result

Figure 7: Releasing node n2 to succeed n4 deletes the constraint of n3 since it is no longer viable.



(a) Initial Graph (b) In Movement (c) Result

Figure 8: Releasing n1 to succeed n2 requires moving chained nodes with it and updates the position constraints of the chain.

3.3 Interactions of Absolute and Relative Constraints

In the following, we present interactions between absolute and relative constraints that need reevaluation. We will use the term *chain* for nodes that are connected with each other through relative constraints, e. g. n1, n2, n3 in Figure 7.

When adding a relative constraint, the moved node is assigned to the same layer as the target node. This requires updating the layer constraint of the moved node. The same applies if the moved node belongs to a chain containing a node with a layer constraint.

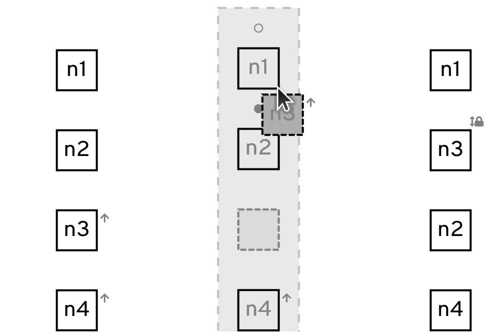
Assigning a node a relative constraint needs reevaluation of two layers. The position constraints of nodes in the original layer of the moved node and in the layer of the target node must be updated similar to the first reevaluation case of the absolute constraints. E. g., when the moved and the target node are originally in different layers, the constraints of all nodes below the moved node must be decremented by 1 and the constraints of all nodes below the target node must be incremented by 1. This way the node orderings of both layers are preserved.

When a chain containing a node with a position constraint moves or a node is added, the position constraint is reevaluated. If the top node of the chain is assigned a successor-of constraint, the position constraint is adjusted such that the chain moves together with the moved node, as seen in Figure 8.

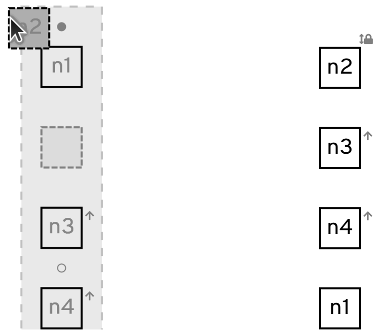
If a node is released on the position between two nodes connected by a relative constraint, the moved node becomes the new target of the relative constraint to be consistent to the first case in Section 3.2.

When a node in a chain gets a layer constraint, the nodes of that chain have to be reevaluated. Since the user expects to move the whole chain, nodes with layer constraints in the chain are updated to the new layer.

When assigning a node that belongs to a chain only a position constraint, two reevaluation cases must be considered. If the moved node is in the middle of the chain, its relative constraints and the relative constraints that have the moved node as a target are deleted, as seen in Figure 9c. In contrast, if the top node of a chain is moved, the whole chain moves together with it, as seen in Figure 9e.



(a) Initial Graph (b) In Movement (c) Result



(d) In Movement (Case 2) (e) Result (Case 2)

Figure 9: Setting position constraints inside a layer with a relative constraint chain requires constraint reevaluation.

3.4 Consider Constraints in Layout

The introduced constraints must be considered by the layout algorithm. For that the following procedure is used:

1. Generate an initial stable layout with the layered layout algorithm.

2. Adjust the coordinates of the nodes based on their constraints assigning all of them pseudo positions, which are a representation of the relative positions between the nodes and not real coordinates that are assigned by the layout algorithm.
3. Generate the final layout of the graph with the layout algorithm using the pseudo coordinates.

When calculating the pseudo coordinates, all nodes that should be in the same layer get the same horizontal coordinate. The coordinate for the first layer can be set to any value while the value for the following layers is set such that the coordinate does not overlap with a node shape of the previous layer. The vertical pseudo coordinates are based on the ordering inside the layer. The top node can be assigned any value and all other nodes get a value that is greater than the node that is directly above them.

During the assignment to layers it must be considered that connected nodes are not allowed to be in the same layer. One option is to forbid setting a layer constraint that lead to connected nodes in the same layer. However, this would heavily limit the constraints, since neighboring layers often contain connected nodes and would be forbidden. That is why we solve the problem by moving connected nodes to the next layer.

4 VALIDATION

In Section 4.1, we present the implementation of our interactive layout framework. Section 4.2 presents informal user studies and expert feedback.

4.1 An Interactive Layout Framework

Our interactive framework utilizes Sprotty's[1] VS Code diagram view, which we extended to fit our need, and a language server, which calculates the layout automatically using the Eclipse Layout Kernel (ELK)[2].

Since this separates layout and visualization into client and server, the interactive layout overlay must work independently of the layout. The overlay must be able to work with the view model and is not able to access the source model.

If interactive layout is enabled, the user can pick up nodes and drag them around in the diagram. Depending on the used algorithm, an interactive layout overlay visualizes the available constraints. Releasing a node on a specific position creates a constraint notification, which is handled by the language server. The framework supports all languages supported by the language server, which utilize the same view model.

As also mentioned by (Wybrow, 2008), the constraints have to be saved. Since the source model is the textual model in the editor, serializing the constraints is language dependent. This does not only persist the constraint, but also supports constraint creation by textual editing and the IDEs reverse action in the editor to undo the last changes.

[1]https://github.com/eclipse/sprotty

[2]https://www.eclipse.org/elk/

4.2 Preliminary User Studies

Discussions with users of the framework revealed that the interactive layout overlay should show available constraints and clearly highlight the one that will be set. Moreover, users want the possibility to only constrain the layer or only the position of a node and not always set both constraints, which can be generalized to all possible constraint types. Disabling the constraint icons allows to get a normal diagram view, which is important if the diagram is used for documentation or papers.

A user study for the layered absolute position constraints was conducted with ten computer science students with prior knowledge in graph drawing. Before the experiment started, participants were reminded about the characteristics of layered graphs.

The first experiment should evaluate and gather feedback on the basic user interaction. Participants were given the graph shown in Figure 1 and the task to move all nodes with the same letter in the same layer, as it is nearly already done by introducing constraints for A, AA, and AAA. As a second task participants were asked to sort the nodes in each layer by the number of letters. All participants reported the interaction with the diagram — our solution for RQ2 — as intuitive and the circles for the different positions (RQ1) as helpful. Two participants wanted to have bigger and flashier node slot indicators.

Two participants reported highlighting the forbidden layer in red (RQ3) as helpful, two other participants wanted to have more information why this movement was not allowed. As part of future work it should be evaluated if hiding forbidden options is the better alternative, as it is done for relative constraints.

Participants requested new features to create new layers between existing ones, to the left, or to the right of the graph, which was partly implemented (RQ2). Moving nodes to the first or between layers would require to constrain all nodes after them, which was not implemented, as already discussed in Section 3.

The limited number of participants and the differing feedback does not allow inferring definitive solutions and requires further evaluation. However, the generally positive feedback indicates the overall effectiveness of our approach.

The interaction between absolute and relative constraints (RQ3) was presented to graph drawing experts and users of graphical languages supported by the language server and reported as intuitive.

5 CONCLUSION AND OUTLOOK

We presented a solution to inform the user about possible constraints using an interactive constraint overlay (RQ1). Adding constraints (RQ2) via simple drag and drop is intuitive as reported in a preliminary user study. Possible conflicting constraints (RQ3) are either resolved by reevaluating or forbidding the constraint, given they are introduced interactively, or by being robust such that the latest constraint overrides existing ones. As reported in the preliminary user study, the constraint icons are sufficient to perceive existing constraints (RQ4). The framework was tested by adding interactive layout for tree drawing algorithms, which was able to utilize the already existing features for the layered approach to change the order of nodes inside a tree level.

Developer feedback revealed that although the specification of constraints is intuitive, constraints of the layout algorithm itself, such as forbidden in-layer edges of the layered algorithm, might change the layout in an undesired way.

Future work on interactive layout goes in several directions: (Domrös and von Hanxleden, 2022) constrain the layout via the source model. As part of future work it should be evaluated whether users prefer constraints or textual order to create desired layouts. Textual order for a stable layout and interactive layout for tweaking the layout of the diagram might be the ideal solution.

Introducing a new first layer, when using the layered algorithm, would require to constrain all other nodes to make this possible. Since this seemed undesired at first glance, this was not added to the framework for the layered approach. Whether it is actually desired or whether the absence of this option seems unintuitive should be evaluated as part of future work. Additionally, other ways to express such a constraint should be explored.

The movement of a node that belongs to a chain can be further improved. All nodes that will be moved together with the moved node, when releasing it should already move with it to indicate the consequences of the reevaluation.

REFERENCES

Böhringer, K.-F. and Paulisch, F. N. (1990). Using constraints to achieve stability in automatic graph layout algorithms. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 43–51, New York. ACM.

Borning, A., Duisberg, R., Freeman-Benson, B., Kramer, A., and Woolf, M. (1987). Constraint Hierarchies. In *Conference proceedings on Object-oriented programming systems, languages and applications*, pages 48–60.

Domrös, S. and von Hanxleden, R. (2022). Preserving order during crossing minimization in sugiyama layouts. In *Proceedings of the 14th International Conference on Information Visualization Theory and Applications (IVAPP'22), part of the 17th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP'22)*, pages 156–163. INSTICC, SciTePress.

Dwyer, T., Marriott, K., and Wybrow, M. (2009). Dunnart: A Constraint-Based Network Diagram Authoring Tool. In *Revised Papers of the 16th International Symposium on Graph Drawing (GD '08)*, volume 5417 of *LNCS*, pages 420–431. Springer.

McGuffin, M. J. and Jurisica, I. (2009). Interaction Techniques for Selecting and Manipulating Subgraphs in Network Visualizations. *IEEE transactions on visualization and computer graphics*, 15(6):937–944.

Purchase, H. C. (1997). Which aesthetic has the greatest effect on human understanding? In *Proceedings of the 5th International Symposium on Graph Drawing (GD '97)*, volume 1353 of *LNCS*, pages 248–261. Springer.

Purchase, H. C., Hoggan, E. E., and Görg, C. (2006). How Important Is the "Mental Map"? – An Empirical Investigation of a Dynamic Graph Layout Algorithm. In *Proceedings of the 14th International Symposium on Graph Drawing (GD '06)*, volume 4372 of *LNCS*, pages 184–195. Springer.

Sugiyama, K., Tagawa, S., and Toda, M. (1981). Methods for visual understanding of hierarchical system structures. *IEEE Transactions on Systems, Man and Cybernetics*, 11(2):109–125.

Waddle, V. (2001). Graph Layout for Displaying Data Structures. In *Proceedings of the 8th International Symposium on Graph Drawing (GD '00)*, volume 1984 of *LNCS*, pages 98–103. Springer.

Wybrow, M. (2008). *Using semi-automatic layout to improve the usability of diagramming software*. Dissertation, Clayton School of Information Technology, Monash University.