Immersive Visual Analytics for Modular Factory Layout Planning

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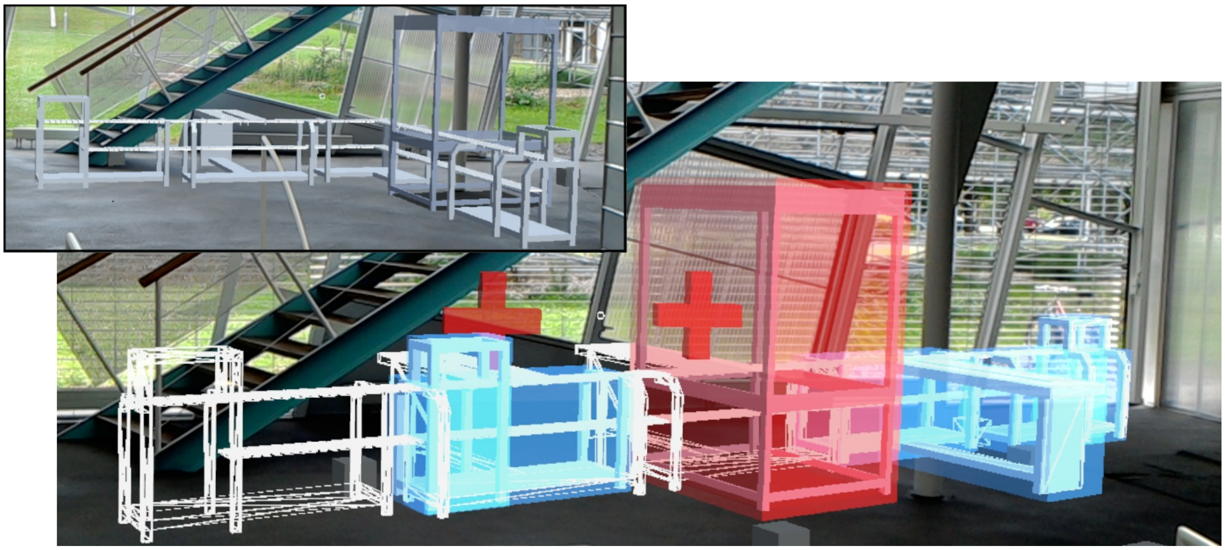

Figure 1: ARSAM enables users to inspect and edit modular factory layouts (top left). In addition, an automated algorithm proposes new layouts and provides information about the needed changes to transform a given layout (solid layout) to the proposed layout (as wireframe preview).

Abstract

To cope with the increasing demand for customized products, manufacturing processes become more adaptive and flexible, for example by using layouts that can be easily rearranged to adapt an assembly process with respect to the produced items. Specialized layout planning software is used to manage the multitude of possible arrangements and their effects in the production pipeline. However, not all conditions and dependencies can be tracked, modeled, and correctly interpreted in the virtual setup, making it challenging for domain experts to foresee real-world effects. To address this challenge, we contribute an immersive analytics approach that extends an existing factory layout planning tool. It employs augmented reality technology to superimpose existing setups and facilities for a more lifelike impression on production line layouts. The interactive planning is enhanced by automated layout suggestions using a genetic algorithm as well as automated layout comparison. A case study demonstrates the applicability in a realistic scenario.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Graphical User Interfaces (GUI)

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1 Introduction

Nowadays, factories have to be flexible and adaptable to address consumers' rapidly changing demands of highly customizable products. A multitude of product variants needs to be manufactured with a trend that every product is produced individually. One way to achieve this is to deploy quickly rearrangeable production line components, e.g., as presented in the *intelligent Transformable Assembly and Manufacturing Equipment* (iTRAME) system [8].

Different software tools have been developed [9] to ease the planning of such adjustable factories by automated approaches and to allow a tight integration of the domain experts to assess practical and financial effects. Wörner [10, pp. 34 ff.] presents a layout simulator for advanced manufacturing (SAM) that enables experts to create and optimize iTRAME layouts. His visual analytics approach combines the manual planning process with an evolutionary algorithm that automatically proposes potentially better layouts.

A major drawback of such tools lies in the high cognitive effort to conceive the final physical setup in the real-world environment from an abstract model (see Figure 2). It is challenging to imagine how the layout will be perceived and used by workers when it is built. An emerging research field to reduce the cognitive gap between a virtual scene and its mapping in the physical environment is augmented reality (AR) [2]. Head-mounted displays such as Microsoft HoloLens[1] and Sony SmartEyeglass[2] superimpose a real world scene with virtual items. The provided immersion, stereoscopy, and intuitive

[1]www.microsoft.com/de-de/hololens
[2]developer.sony.com/develop/wearables/smarteyeglass-sdk

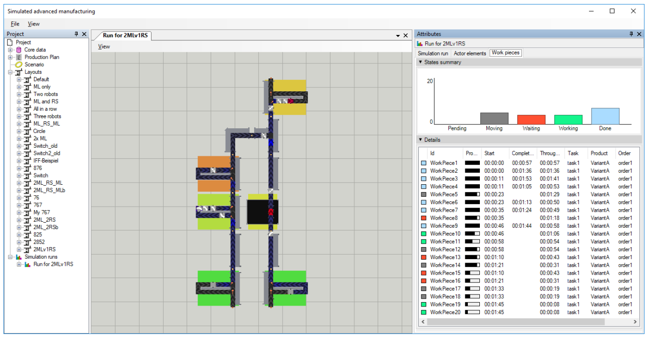

Figure 2: A production line simulation run with SAM. It shows the layout's components, the work pieces, the actor load (background color), and the work piece density (conveyor belt color). The right side shows the work pieces current status and processing progress.

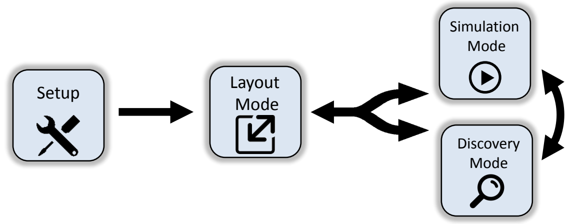

Figure 3: The layout planning workflow starts by setting the plane for the global coordinate system. Thereafter, the analysts load and may alter a layout. The layout can then be used as a basis for simulations (simulation mode). To explore other layout suggestions and optimizations the analyst can switch to the discovery mode.

interaction enable planners to gain a more lifelike experience. While there exist a few approaches that apply AR to assist factory layout planning [3–7], they mainly focus on overlaying the scene, and barely provide immersive analytical means [1] for decision-making.

To address this gap, we extend the approach by Wörner [10] to provide the intermediate and final simulation results in an augmented reality environment that can be overlayed on top of a deployed layout. The simulation is enriched with previews of automatically generated layouts that are potentially better performing. In addition, we give visual feedback about the costs to rearrange the current to the suggested layout.

2 Approach

In the following, we will first introduce the simulator for advanced manufacturing proposed by Wörner [10, pp. 34 ff.]. Then, we will present our approach, which extends this simulator by (1) providing the intermediate and final simulation data in an augmented reality environment and (2) enriches the simulation with additional information.

2.1 SAM – Simulator for Advanced Manufacturing

SAM [10, pp. 34 ff.] runs on desktop computers and is based on the iTRAME system. iTRAME uses standardized connection modules so that its components can easily be rearranged in an arbitrary order to produce different products. The simulator is able to simulate iTRAME production line layouts, which may be composed of linear and corner conveyor belts, as well as lift, robot station, manual labor station, automatic storage, vision station, and switch components. Users can manually design new production line layouts, manipulate existing layouts, or inspect layouts proposed by an evolutionary algorithm that uses previously created layouts to find better performing ones. Each layout's performance can be inspected by running a simulation that provides information about the load of each station, the average work piece density on the conveyor belt, and the work pieces' status history. Figure 2 shows a typical simulation run with SAM in which the left line creates the product with manual labor stations, whereas the right line uses a robot station to perform this task. The stations' color coding indicates that the right lane has a better average load and lower work piece backup.

SAM also automatically proposes new, better performing layouts using an evolutionary algorithm that creates new layouts based on the current and previously created ones. The process of the layout generation is presented in a separate view. It shows the current simulation progress for the generated layouts, the layouts' overall score, and their key performance indicators (KPIs), which comprise the number of used components, the layout's required area, the machines' running costs, the current order's completion time, and the average of the actors' loads. Furthermore, regardless of its overall score, information about the best-suited layout with respect to the KPIs are given. SAM visually indicates whenever it finds a new, better layout, which the users can then inspect in detail and improve manually, for example, by rearranging some of the parts. Each of the layouts is shown in a separate tab, so it is possible to open and quickly compare multiple layouts by hand. The manipulated results are then used by the evolutionary algorithm to find layouts that are more suitable.

Overall, SAM enables users to plan, simulate, and assess manually or automatically processed layouts. However, it is difficult to assess aspects related to real world distances, paths that can be walked through, or work safety aspects based on a result presented on a 2D or 3D scene on a desktop workstation.

2.2 Augmented Reality Extension

We propose ARSAM, which extends SAM with augmented reality technology, allowing for an immersive analytical layout planning process. We implemented ARSAM's approach as a HoloLens application. It complements SAM by enabling users to assess and evaluate physically existing layouts by overlaying them with a virtual model. In addition, ARSAM can be used with entirely virtual layout models that are presented in a real environment so that layout planning experts can quickly find possible layout issues in context of the environment it will be deployed in. The workflow consists of a setup step and three planning modes that enable the users to interact with the layout, assess its current performance, and find and compare it to better layouts (see Figure 3). To minimize the amount of menus, the modes can be accessed through voice commands.

Initial Setup

Before the users can use ARSAM, they need to set the plane for the global coordinate system. This configuration step is required at every start and can be done semi-automatically, wherein the plane is aligned to the automatically detected floor, or the plane can be set entirely manually. The position of the plane affects, where the layouts are positioned when they are loaded. Then, the users can load the layouts that were either created using SAM or saved in previous analysis sessions.

Layout Mode

The *layout mode* enables users to get a first overview of the loaded layout and rearrange the parts if they see potential to improve its performance or solve unmodeled restraints. Too narrow paths to walk through, the obstruction of safety relevant inventory, or unmodeled objects such as supports are easily noticeable by an expert in an in-situ situation. Users can view the current layout either in an adjustable model size that could be placed on a table or in its real world size. Much like SAM, the model-sized layout provides a good overview of the entire layout. If the users want to compare an already

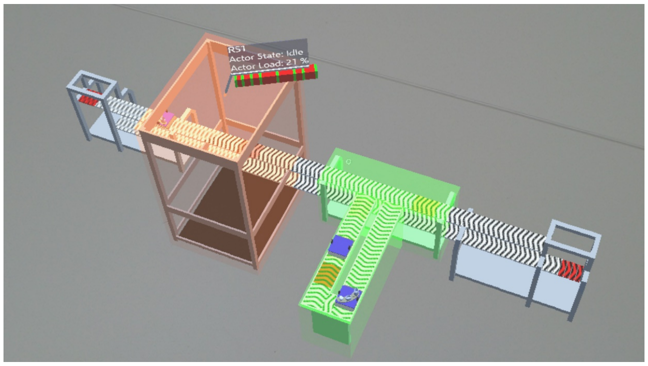

Figure 4: Screenshot of a simulation run taken from the users' view. It shows the layout components, their load (bounding volume color), the work pieces, and information about a specific robot station.

deployed physical one with other alternatives, the physical layout needs to be modeled with SAM and then transferred to ARSAM. Afterwards, the digital layout can be shown in the augmented environment. Currently, the users need to align the loaded layout manually to the physical layout, either by selecting and moving all layout elements as a group or by moving the global plane. The parts can be selected either individually or as an entire group of connected components. They can then be moved around and rotated until the users are satisfied with the result. During the manipulation, ARSAM shows the manipulation's effect by presenting a wireframe "ghost" model preview of the manipulated layout element(s). Ideally, users perform minor layout changes in ARSAM to get a direct impression of their effects in a real environment. However, current ways to interact with augmented and virtual environments are still not as efficient as classic interactions with mouse and keyboard. Therefore, in case the users want to perform major layout adjustments, it is more effective to perform the changes in the desktop application and transfer the new layout to ARSAM.

Simulation Mode

To analyze the current layout's performance, users can switch to the *simulation mode* to run a simulation that shows how the layout performs during a production run. Analogous to SAM, the simulation provides real-time information about the location of all work pieces and the status of the work stations (working / idle) and the work pieces (e.g., moving between stations, being processed, finished). It also provides information about the load of individual work stations by color coding their bounding volume between red (for no load) to green (used permanently). Similarly, the conveyor belt segments' work piece density is encoded in their color intensity. The higher the intensity (which indicates a work piece backup at a station), the higher is the opacity of the red coloring. The color scheme ranges from transparent for a low density to red to indicate a high density.

The users can inspect the station's status history for the simulation run through a tooltip, which is shown when the users directly look at them. It provides information about its current state, average load, and a continuously updating status bar that quickly indicates the stations load distribution over time. Figure 4 shows, how ARSAM provides an overview of the layout's overall performance. Further, it shows, how the robot station's performance can be assessed through an inspection of its detailed information tooltip showing the stations' current and the past load.

In addition, the current status and the status history of the individual work pieces can be inspected during the simulation run in the same manner as ARSAM presents the stations' performances. An example is shown in Figure 5. At this point, users are able to get an overview and detailed information about the current layout's performance, find possible performance bottlenecks and use their expertise to assess possibly unmodeled layout issues such as the spacing between the work stations.

Discovery Mode

In the *discovery mode*, an evolutionary algorithm automatically searches for new layouts that are better than the currently viewed layout regarding the KPIs explained in Section 2.1. The users can then choose to inspect any discovered layout in detail and compare it to the originally existing layout. The users are first presented a tabular view that contains the currently discovered layouts sorted by their overall score. Any of the layouts can be selected for further analysis and comparison with the currently loaded layout. In contrast to SAM, where the layouts were inspected in separate tabs and compared in a summary view, ARSAM makes use of the augmented space to show both layouts at the same time for an in-situ analysis. This enables users to directly compare the layouts' differences, see the needed changes to transform the loaded into the proposed layout, and inspect and edit the proposed layout in the *layout mode*. The comparison is especially useful if the originally loaded layout is also physically available, but it can also be used to compare two possible layout solutions immersively.

During the layout comparison, the original layout's geometry can optionally be hidden, for example, if a physical layout is already available. Either the proposed layout can be shown as a solid object model, or it can be simplified to its wireframe structure. The latter is useful to distinguish between the proposed and the original layout (if it is still visible), and to see more easily, what other real world objects are nearby the proposed layout.

While the discovery mode is active, ARSAM visualizes the differences between the original and the proposed layout to further assist the users in comprehending the necessary effort to transform the original into the new layout. To do so, we encode the needed changes visually into the bounding volume of the original and new the layout's components. In case elements need to be moved, their bounding volume is filled with a light blue. Components that are not used anymore are filled with red and components that need to be bought have a red '+' on top of their geometry (see Figure 6). All colors are semi-transparent to make sure that the users are still able to perceive the underlying components, regardless if they are physically present or virtually added. This additional visualization enables the users to assess, if the possible performance increase outweighs the costs to buy new layout components or remove them from the layout.

To provide this information, ARSAM converts both layouts into a string representation where each character represents one component. It then compares the strings using a modified Levenshtein distance. Originally, the Levenshtein distance transforms a string into another using three operations: *insert* or *delete* a character, and *replace*

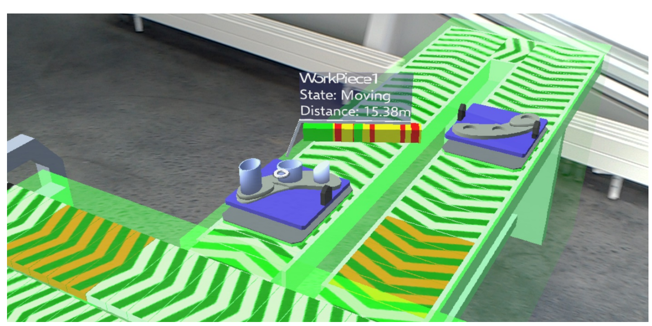

Figure 5: Screenshot of the detailed information of a specific work piece. It contains the work piece's ID, its current state, its moved distance from the start of the production line, and its status history.

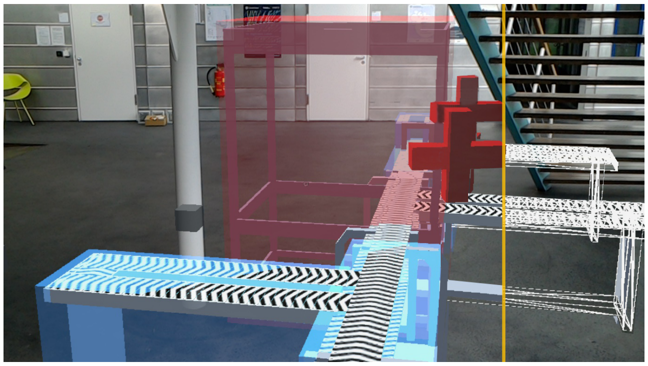

Figure 6: ARSAM presents the compared layouts' difference through a color coding. Further, it can provide the proposed models as either solid (left side) or wireframe objects (right side).

Figure 7: After inspecting the layout components' loads, the user notices that that the manual labor station's load is optimal (indicated by its green bounding volume) whereas the robot station's load is low (orange). Therefore, the load needs to be rebalanced.

a character with another. However, in our context, *replacing* a component is only reasonable if the original layout already contains the new component. Therefore, the replace operation is only possible if the needed component is still available in the original layout. We named the resulting cost *transformation cost*, which can be used by the evolutionary algorithm that searches for new layouts. A layout with faster completion time and fewer operations cost may still be bad, if most components of the new layout first need to be bought. We encode the differences between the layouts by reconstructing the performed operations from the cost table.

3 Case Study

In the following, we assume the role of a layout planning expert that got the task to transfer a production line from an old facility to a new one. The new facility has some spatial restrictions, as the new layout should be placed nearby the stairway, while it must not obstruct the door on the right wall. After setting the coordinate plane, we load the layout that was used in the old facility. It comprised of lifts at both ends and a manual labor station, a corner element and a robot station in between (see Figure 1, top left).

As we inspect the real world sized layout in-situ, we notice that a major issue of the former layout in the new facility is its cornered structure, as the second half obstructing the door on the right. We solve this issue by first removing the angled conveyor belt and then add the rotated robot station and lift back to the layout. After an analysis of our new layout, we notice that the robot station's load is not ideal (see Figure 7).

Rebalancing the load of the layout's components is not a trivial task, so we start the layout discovery mode to find a more suitable layout. After inspecting some generated layouts, we end up with a layout that replaces the robot station with two additional manual labor stations (see Figure 1, bottom right). By inspecting the layout preview, we notice a remaining issue of this layout: its manual labor stations are facing towards the glass front of the hall, so they may be difficult to reach. Therefore, we edit the proposed layout one more time and turn the manual labor stations by 180 degrees, which results in a well performing layout that meets the spatial restrictions of our current location. We further notice that the ceiling of the robot station barely fits under the stairway without colliding with it. In this case, there is no need to further change the layout. However, without an in-situ inspection this problem may have stayed unnoticed, as the height and geometry of the staircase are not modeled by the simulator.

4 Discussion and Future Work

Although ARSAM enables users to analyze a given factory layout's performance and compare them to other layouts using an augmented reality environment, one might argue that all of the presented features could also be provided with a fully immersive virtual reality application. However, several aspects lead us to the conclusion that an augmented reality approach is better suited for this task.

On the one hand, it is easier to navigate and interact with an environment that users are familiar with. A virtual reality application introduces a certain degree of abstraction from reality, as it is very difficult and computationally expensive to provide a visual experience that is comparable to the real world. This is necessary in this case, as it is important to consider the surroundings when planning a factory or production line layout.

On the other hand, virtual reality applications share the same issue with desktop applications that all constraints need to be modeled to be considerable by users. In an augmented reality application, unmodeled constraints cannot be processed or considered for automatic optimization, but human experts are still able to perceive them because they are able to cognitively connect the virtual augmentations with the real world. Such restrictions can range from physically existing layouts to just having a shop floor that only contains doors.

However, augmented reality brings along other issues that may impair the immersive analytics experience. One example that we encountered is that the matching of a physical model to a digital representation is problematic when there are no further annotations given in the real world, such as markers on the machines. The depth sensors of current augmented reality hardware, like Microsoft HoloLens, do not provide precise enough spatial information to be used on their own to match the models. Also, a registration through the camera and depth information is computationally too expensive to be computed directly on the HoloLens. Although the latter will likely be solved through better hardware in the future, it poses an issue at present.

In addition to general advantages and current limitation of utilizing augmented reality technology for immersive analytics solutions, we identify three open tasks for our ARSAM prototype. First, the modified Levenshtein distance is used as an indicator in the evolutionary algorithm and is used to show, *which* layout components will be changed. The general difference between the available components and the needed ones could also be calculated through a multiset difference, but the Levenshtein distance also provides information about which elements should be moved and which ones should be removed or inserted. However, there is currently no optimization regarding the actual effort that is needed to move the existing components from one place to another. We plan to look into this optimization in more detail in the future, as its visual indication may help layout planning experts to get a better overview of possible logistical issues, such as the order in which the components should be moved. Second, we plan to study, if detailed information can also be shown on tangible objects in near space and if such a solution is preferred by domain experts to floating views. One example for such an application could be a sheet of paper that shows an overview of a layout on the front page and when the users select any specific component and turns the paper, it provides more detailed information about that component. Last, we plan to test ARSAM in a real iTRAME setup and carry out a study with domain experts to evaluate if an immersive analytics approach can help them to optimize existing production layouts.

5 Acknowledgements

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