The Digitally Enhanced Planning Table: A Tangible System for Rough Layout Planning With Automatic Digitalization

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ABSTRACT
In this paper, we present a tangible system for rough layout planning using quickly producible physical models. The physical 3D representation is backed by an automatically synchronized digital model of the current planning status with extended functionality, such as a version control system that easily allows users to re-create previously planned states. In contrast to existing approaches, we do not restrict our system to a set of pre-defined components, but rather support rapid extensions by creating new components using Styrofoam, wood or similar materials and digitalizing them automatically. The development of this system was guided by expert interviews done at two large German manufacturing companies. A prototype was evaluated with planning experts from one of these companies, showing that the features introduced are much appreciated by the participants.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

Author Keywords
Rough layout planning; rapid prototyping; simulation; tangible user interfaces; factory layout planning.

INTRODUCTION

In the past, many analog methods, e.g. drawing plans or traditional 2D/3D models, were used to design and analyze layout drafts. Besides being time-consuming, accurate time and cost analysis was not feasible [12]. Computer-aided design (CAD) systems simplify these processes as they allow users to work with precise data and automated simulations based on a digital representation [12]. However, the pure digital approach also has disadvantages: CAD systems are often complex and require expert knowledge in modeling and simulation. Furthermore, collaboration is often cumbersome in these desktop-based systems. The lack of tangibility (in comparison to analog 3D models) increases the complexity regarding aspects such as distance estimates.

DFKI Tech Report 2015

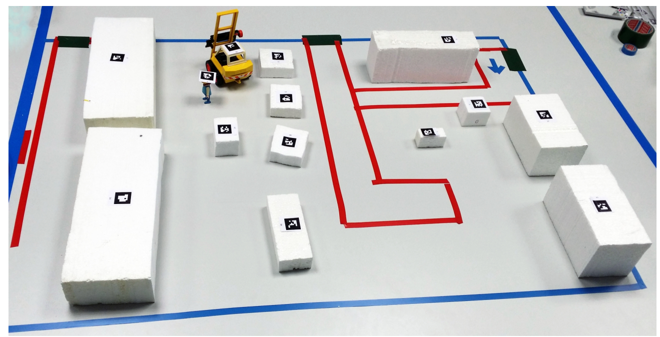


Figure 1: Final planning result created during the evaluation.

In this paper, we discuss combinations of analog and digital planning with experts. Based on these interviews, we present a system that allows physical 3D planning (see Figure 1) while automatically providing a digital representation. The implemented features are not domain-specific, hence it can be used in any rough layout planning setting, e.g. for event planning, urban planning or floor planning. However, we selected planning experts from the manufacturing domain for our initial interviews, since most factory components can be arranged freely in this domain (in contrast to urban planning), thus offering flexibility while planning. Furthermore, the factory layout is crucial for cost- and time-effective production [6] with clearly defined objectives. Therefore, we also evaluate our prototype in a real-world planning task at a German manufacturing company.

We focus on the initial planning stage, in this domain called *rough factory layout planning*. Here, mainly the general arrangement of plants, channels of supply, etc. is considered as it has a large influence on the production efficiency [6]. The manner in which materials, intermediate goods and the final products are transported throughout the plant is determined in this early planning phase. General optimization goals, such as noise protection, must already be considered here as the correction of suboptimal decisions in later planning steps is more time and cost intensive [25]. Hence, the rough factory layout planning builds the basis for further planning stages [2].

REQUIREMENTS ANALYSIS

To understand how rough layout planning is done nowadays, we performed an unstructured group interview with five planning experts involved in planning factory work floors in a company producing domestic cooking appliances (~800 employees). Each of the five planners had several years of experience with digital as well as analog planning tools. In their current rough factory layout planning approach a group of planning experts create and rearrange physical models made out of Styrofoam or wood on a large table. Depending on the planning task, the analog planning sessions can stretch from a few days to weeks or even months. The final result is then manually modeled in CAD software to run simulations and refine it in further planning stages. Intermediate planning states are only rarely digitalized due to the huge effort, hence there is no possibility to easily review and compare different versions. This was also identified as the main drawback of the state-of-the-art approach.

During the interview, we analyzed strengths and weaknesses of current planning approaches and discussed possible improvements. To refine these first findings, we conducted a semi-structured interview with one of the planning experts afterwards. To avoid focusing on only a single company's needs, we also talked to another planning expert from a different company (~37,500 employees) involved in planning manufacturing sites for agricultural machines. Based on the conducted interviews, we conclude that the following aspects are essential to rough factory layout planning systems:

- As is the case with the current analog approach, even non-experts should be able to participate in the planning, i.e. there should not be a high learning effort.
- Since planning is usually done in groups, the planning process should support collaborative group work.
- The planning should be done using true-to-scale physical objects to increase spatial awareness among the users. This, according to all interviewees, would also help in discussions with decision-makers who are not directly involved in the planning process. However, as rough factory layout planning only targets the overall layout, no detailed shapes for the objects are required.
- Since planning is an agile process, no long preparation phases should be necessary, i.e. the objects must be easily and quickly producible.
- To avoid the time-consuming manual modeling of planning states, the physical model should be backed up by a digital model which provides further information and can be used as a basis for simulations such as material flow.
- This digital model should automatically adapt to changes in the physical world so that no additional manual effort for synchronization is needed, resulting in a continuous workflow as disruptions are minimized.
- It should be possible to see and restore previous states, allowing an easy overview of former drafts and differences between them.
- The annotation of physical objects and planning states should work via speech input, as it can be done in situ.

RELATED WORK

In the domain of factory planning, the use of physical models dates back a long time [13]. The idea to simplify CAD-planning by using these physical models as input was already proposed by Aish in 1979 [1] and a first prototype was presented in 1980 by Frazer [9]. In contrast to pure digital models, physical representations increase spatial awareness and simplify handling relationships between models.

A Tangible User Interface [8, 16] for construction and design tasks called BUILD-IT was presented by Rauterberg et al. [22]. It allows users to manipulate virtual objects with a tangible brick as interaction handler, while at the same time being able to run external simulations on the virtual data.

Another early tangible system for urban planning called Urp [28] allows placing pre-defined models of buildings on a luminous workbench supporting simulations like shadows, traffic or wind flow. An extension of the system also integrates sketches and paper maps and puts a special focus on dynamic digital simulation [14].

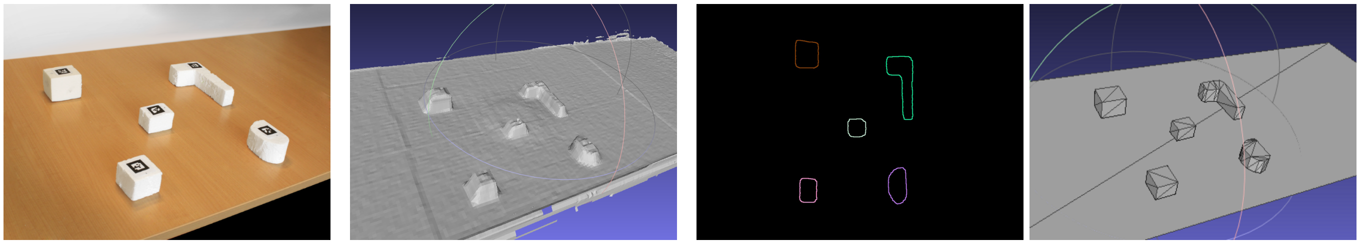
Bruns et al. [4, 7, 24] proposed a graspable user interface for factory layout planning to avoid the error-prone manual digitalization and to quickly evaluate layouts by running simulations on pre-configured behavior of the elements. First, digital representatives of physical objects used during factory layout planning are modelled and linked to their physical counterparts. Afterwards, data gloves are used to recognize grasps in the vicinity of objects and to map their movements and rotations to the digital representatives.

A true-to-scale approach for indoor layouts was presented by Hosokawa et al. [11]. Pre-built tiles and plates can be arranged on a floor plan to create walls and flooring. A corresponding 3D model is instantaneously shown on a monitor. Unlike the aforementioned approaches, RFID technology is used to detect the tangible objects, which requires the objects to be placed on a fixed grid.

Zuffrey et al. [30] provide another to-scale tool for apprentices in school to increase their understanding of planning processes in logistics. The system allows positioning of pre-built wooden shelves on a storage warehouse map and offers simulations to test aisle widths and layout efficiency. This work shows that the tangible approach is well-suited for groups working together, providing an easily understandable way to bring across complicated concepts. In our use case, this is also important, as not only will groups of planning experts be working with the models, but decision makers also have to get an understanding of the current planning state.

Siemens presented IntuPlan [23], a system using 3D-printed tangibles for arranging production components on a table. The result can later be digitalized by a semi-automatic process based on manually created photos.

In contrast to all of the above systems, we do not restrict our planning tool to the rearrangement of pre-defined objects but instead want to use arbitrary, quickly producible, tangible models. No time-intensive modeling phases to register new objects prior to the actual planning task are required, instead



(a) Physical model **(b) Initial Kinect Fusion output** **(c) Extracted contours after cleanup** **(d) Generated meshes**

Figure 2: Steps of our object digitalization process.[1]

they can be created and used on-the-fly. As in several of the presented works, an always-congruent digital representation will be computed in the background without time-intensive manual digitalization. This digital model can then be used in any external simulation environment by offering export functionality in standardized format.

PROTOTYPE

Based on the results of our expert interviews, we want to provide a seamless integration [15] of digital concepts into the analog planning process. To retain the benefits of planning in the physical world, users of our system plan with physical models on a large table as it provides a good basis for collaborative group work. New physical models can be easily and quickly created when needed using common materials and tools. Such analog planning sessions also allow non-experts to participate in the planning session. To integrate the advantages of a digital planning process, all physical objects are directly mapped to a digital counterpart in the background via a 3D scanning process. Every manipulation (i.e. rotation or displacement) of one of the tangibles is then directly applied to the digital representation as well, which can be saved and loaded at any time. We enable versioning including visual assistance for reconstruction via projections on the table. Furthermore, the digital model is exportable to other applications such as CAD software via a standardized format. A graphical user interface (GUI) can be used to equip the digital representatives of the physical models with additional information such as a label or properties of the represented object. Speech input can also be used to avoid interrupting the planning process.

Hardware and Components

Our rough layout planning tool uses a standard table as planning space. Similar to the work of Zufferey et al. [30], one or several projectors (depending on the size of the table) are mounted above the planning space to provide information directly on the table and the placed objects. A Microsoft Kinect (version 2) is placed next to the projector. Its RGB-D (color and depth) camera is used to automatically create the digital model and the integrated microphone array records voice commands and audio annotations. We decided to use Styrofoam for the tangible objects as it is cheap, can be handled with standard tools and allows for rapid prototyping of rough components. Apart from the objects, paths also play an important role, e.g. for transport. We selected colored adhesive tape to visualize paths as it is cheap, can easily be added or removed, and is easily recognizable. Furthermore, different tape colors allow users to define different types of paths, e.g. based on the vehicles or people that can use them.

Software

The software of our prototype can be divided into two parts: the framework to digitize the physical objects and a front-end which can be used to annotate the digitalized objects and enables import and export functionality.

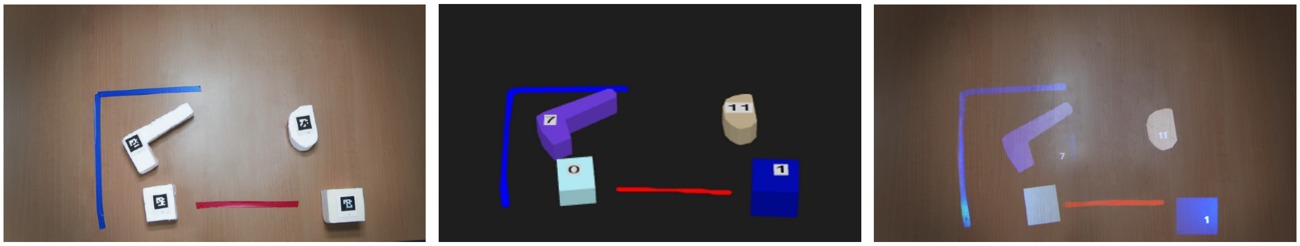
Object digitalization

Although originally designed to fuse frames from different perspectives, the Kinect Fusion algorithm [17, 20] also yields a mesh of the entire scene from the stationary position of the Kinect which we use as a basis for the digitization (cf. Figure 2a and 2b). To create individual models, the objects are separated from the table's surface by thresholding and we require new objects to be initially placed separately to distinguish them visually. Since rough layout planning only requires relatively coarse structures which can be quickly created, we decided to create clean and simple 2.5D models from the noisy 3D meshes returned by the Kinect Fusion. For this, we extract the 2D shape of each object using a combination of standard image processing algorithms [5, 10, 26] (cf. Figure 2c) and extract the height from the object's height histogram. Since edges might be cut imprecisely and the objects considered in our application domains mostly have a straight outline, we rectify objects by using their convex hull [18] or oriented minimal bounding box (OMBB) [27] if their area is not much larger than the unchanged contour area. Finally, meshes of the detected objects are created [19] (cf. Figure 2d) and their translations and rotations are tracked via pre-printed adhesive optical markers (Chilitags 2 [3]) of about 2×2 cm that can be attached to them.

Tape recognition

To recognize the colored adhesive tape defining the paths, we threshold the color frames in the Hue-Saturation-Value (HSV) color space and then use image processing algorithms to extract the contours [5, 26]. Since these routes are reorganized several times throughout the planning process, we recalculate them regularly. To reduce noise-induced flickering, we built a mechanism to find matching contours between the current and last run and only update the model on significant changes.

[1] b,d visualized with MeshLab



(a) Physical layout of the planning state **(b) Digital representation of the planning state** **(c) Projected layout for reconstruction**

Figure 3: Example of the different representations of a planning state for a rough layout.

Figure 3a and 3b show the physical representation of an example planning state together with the automatically created digital counterparts.

Front-end

Our front-end serves two purposes: Firstly, users are able to assign properties to the digitalized models. Here, common characteristics can also be created independent of actual representations and can then be attached to the digital models with a single markup step. This allows to quickly assign the same features to several models or to exchange the physical shape without reassigning all characteristics. This approach in combination with the automatic capturing of the physical representations enables fast exploration of design alternatives with very little effort during the actual planning process.

The second feature the front-end provides is a version control. On an automatic basis as well as on a user's request, the current planning state is saved in CAD-readable format. Whenever a state is loaded again, our system assists the users during the recreation process of the physical model by projecting the shapes together with the marker ids of the rigid objects and the positions of the colored tape (see Figure 3c). As soon as a user places the correct object at the correct position, the projection for this object is switched off to indicate a matching. For all of the GUI's functionalities, we offer speech recognition based on the Microsoft Speech SDK to enable people to interact seamlessly with the GUI without the need to disrupt the actual planning process noticeably.

EVALUATION

We conducted an evaluation to find out whether our approach facilitates an actual planning process of experts. Furthermore, we wanted to know about potential feature enhancements and further improvements for rough layout planning systems.

Participants

We used a purposive sampling approach, selecting planning experts on factory work floors for domestic cooking appliances whom we had already interviewed in our expert interviews. As described in the introduction, their current approach is very similar to our concept (despite of the digital extensions), so the experts can judge our system in comparison to this baseline. To receive a realistic impression and meaningful usability feedback [21], we decided to conduct the evaluation with five experts (all male, $M_{age} = 33.6$) planning collaboratively. Two of them were not involved in the initial interview, but all reported having experience with the way the rough factory layout planning is currently done at the company. On average, they have planning experience of 5.9 years (SD=5.4).

Apparatus

We set up our system in the room at the company where their analog planning is usually conducted; here the planning experts could work with those tools they usually use in their analog sessions, e.g. Styrofoam or a hot-wire cutter. The available planning space covered an area of $1.56 \times 1.40\ m$.

Method

To prepare the evaluation, we talked to the manager of the planning experts and decided on a current planning task that has not yet been planned in an analog session, but with which all experts are familiar and which will become important in the near future. We thus minimize the risk of receiving non-reliable results, as could have happened with an arbitrary planning task. After handing out a pre-session questionnaire to collect demographic data, the planning background, and an assessment of problems the experts have with their current analog planning approach, the planning task was illustrated by the superior on a flip chart. He not only provided the general task and made clear which operating resources were available, but also provided optimization goals that should be met by the new factory layout (e.g. noise protection or value flow). After that, the superior left the room. A printed 2D factory layout was available as a reference for estimating correct dimensions. Before the actual planning started, we demonstrated the system and its different functions and afterwards, the planning session lasted for approximately one hour. After this, the planning experts received a post-session questionnaire and a semi-structured group interview was conducted. Two experimenters observed the whole session and took notes while a third was available for any questions that might arise.

Results

Overall, two layouts for the given task were planned (see Figure 1 for the final result). All participants were able to use our digitally enhanced planning table without any noticeable problems regarding the main planning task. We received interesting feedback during and after the planning session:

Directly after the initial explanation of the system, the participants collaboratively started the actual planning process in a similar fashion as they were used to from the completely analog version. The subjects stated that the additional effort of attaching the adhesive markers to the objects was unproblematic and could be easily done in the course of the planning process. They also recognized the option to build up a set of standard objects (with already assigned prototypes) that could be re-used across planning sessions.

When introducing new objects at the very edges of the table, the created digital models were not completely accurate which was probably caused by the diminishing 3D quality towards the camera viewport's edges. A possible solution would be the use of a scanning station with a turntable as proposed by Weichel et al. [29], however, this would interrupt the actual planning process. Nevertheless, all five experts reported to be satisfied with the quality of the digital model created by our tracking system. Therefore, we believe our approach with a camera at the ceiling which works in the background was a good choice for this scenario.

The tape as a feature was perceived positively, but for fast restructuring (e.g. switching between saved versions) it was cumbersome to remove adhesive tape from the table. An option suggested by the participants was to use a whiteboard as table surface and markers to illustrate the areas that would otherwise be marked with tape.

The possibility to interact with our system without disrupting the actual planning process by using speech input was appreciated by the participants. However, as the speech recognition was not trained to the participants and the microphone was on the ceiling, the recognition was not optimal. We discussed potential solutions with the participants and they stated that they would be willing to use headsets to improve the quality.

All participants really appreciated the concept that the system mainly works in the background and that users are not required to interact with it regularly (if they do not want to). The GUI was perceived as clearly structured and the participants stated that the amount of functionality offered is sufficient: More options would only complicate the interaction, which then would hinder the planning process. However, we noticed that one participant was mainly engaged with the GUI during the first planning approach. Nevertheless, he stated in the post-session interview that this will not be a problem anymore as he becomes familiar with the GUI quickly.

Regarding shortcomings of their current analog planning approach, four participants reported in the pre-questionnaire that the digitalization of the analog planning state is time-consuming and sometimes difficult, which makes it hard to archive or document the planning process. According to one participant, the process of digitalization would take approximately two hours to reach the same level of detail as our automatically generated export. A transfer of the current analog planning state (to another location) was also mentioned as problematic by one participant which is also an issue where our visual assistance while rebuilding might help.

One participant described the major advantages of our system as follows: In analog planning, intermediate states are rarely digitalized (due to the effort required; see above), but this restricts the creative process. With our system it would now be possible to start over on a clean field and test other options, with the possibility to revert easily if they turn out not to be better. While using a CAD tool in the first place would also allow this, the collaboration options would be restricted according to the participants, as only the one in front of the computer would effectively do the planning. Furthermore, in this case, the advantage of having an easily understandable and usable tool for decision-makers (as occurs with the tangible objects) would be lost.

Further Feature Requests

As none of the participants of our initial expert interviews had any experience with a digitally enhanced planning solution, it is not surprising that additional feature requests were formulated in the semi-structured interview after using our prototype for the first time:

- Information from the virtual world should be continuously projected onto the real world, e.g. a projected floor plan true-to-scale would ease the object placement.
- Assistance should be given for translating sizes between the real and the virtual world, e.g. a scale conversion tool.
- The system should provide the possibility to import arbitrary 3D models. Objects that are not physically present should then be projected during the planning session.
- For visualizing concepts, e.g. material flow, objects such as arrows, besides the tapes, should be recognizable.

CONCLUSION AND OUTLOOK

Using the insights from initial interviews with planning experts from two large manufacturing companies, we present a tangible rough layout planning tool that combines the advantageous aspects of both physical and digital models typically used in such planning scenarios. Styrofoam blocks can be quickly created while planning and can be arranged together with adhesive tape to support rapid prototyping in a collaborative fashion and to increase spatial awareness. These arbitrarily shaped physical models are then automatically digitized to offer functionality that is currently restricted to digital solutions, e.g. saving and loading of planned layouts. In an evaluation with planning experts, we learned that the features introduced are much appreciated, especially the easy testing of completely different approaches and the automatic digitization where the quality was perceived as sufficient to be used for further planning steps. We also received insights about possible extensions to facilitate the planning process and how we can improve the current state of our system.

As a next step, we will integrate the feedback from the evaluation. Since the features of our system are not specific to the factory layout domain, we believe that the approach will also facilitate the planning process in other rough layout planning scenarios such as urban planning. Therefore, we will evaluate the system's usefulness in other domains in future studies.

ACKNOWLEDGMENTS

This research was funded in part by the German Federal Ministry of Education and Research (BMBF) under grant number 01IS13015 (project SmartF-IT).

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