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A novel tool for optimization and verification of layout and human logistics in digital factories

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Abstract

We introduce a novel digital factory layout tool that optimizes both the layout of machines and the corresponding ergonomic logistics considering space constraints. A model is constructed by tangible properties on machines and environment, regions on the floor and by ranking their mutual relations. An optimized layout is then computed based on the model, the relations and an ergonomic score for the human work tasks, which are automatically computed by digital manikins. The result is an optimized layout, visualized in 3D, with improved logistic routes. The layout tool has been implemented and successfully tested on a relevant industrial case.

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Keywords: Virtual Manufacturing; Digital human modeling; Facility layout planning; Logistics; Optimization; Simulation

1. Introduction and background

Regardless if it is a new installation or a redesign of an already existing layout, there are several aspects that need to be considered in the layout planning process [1,2]. For instance, all the logistics related to the production system regarding human workers, carriers, material and product handling needs to be considered and there will be a need for media supply, such as water, electricity and ventilation, as well as the possibility to perform larger maintenance routines and future expansions of the factory.

One way to optimize the layout is to utilize simplified systematic layout planning, also known as Muthers method, which is a graphical pen and paper based method [3]. However, the method is time consuming, especially for larger layouts and the result may be hard to interpret for non-experts.

With a virtual layout planning tool, it is possible to visualize the layout in 3D and involve multidisciplinary competences in order to identify flaws and evaluate different layout concepts [4,5]. Moreover, it is possible to address these aspects already in an early stage of the layout planning process, which reduces the need of late design changes, shortens the ramp-up time and creates an efficient and sustainable production system [6].

To support the virtual layout process, we introduce a novel digital factory layout tool that optimizes both the layout of machines and the corresponding ergonomic logistics considering space constraints. The ergonomic logistics is calculated using the IMMA manikin [7–9], which automatically performs collision-free assembly operations and creates collision-free walking routes.

A model is constructed by tangible properties, such as connections and displays on the machines and in the environment. The space requirement of a property is defined by regions. They may, for instance, be created around machines and on the floor in the workshop environment in order to represent the space needed for work, service, transportation and by legal requirements.

All entities in the model and their mutual relations are first ranked and then used to compute an optimized layout that considers the both relations and the space requirements. In the next step, the digital manikins are assigned tasks, which upon success yields an ergonomic score. The layout is then further optimized with respect to the logistic walking routes, which are created when the manikins performs their tasks. The result is an optimized layout with improved logistic routes that may be visualized in 3D.

2. Intelligent Moving Manikins (IMMA)

The ergonomic evaluation is calculated using IMMA, which is based on a bio-mechanical skeleton that is constructed as a simplified skeleton with 82 joints and more than 162 degrees of

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freedom [10].

When an IMMA manikin is instructed to perform a task, it automatically computes the ergonomically sound motions that are needed to accomplish the task. Moreover, the motions also consider the balance, which includes the weights of the different human body segments, the objects being carried as well as exterior forces and torques from the environment. The manikin also automatically avoids collision with itself and objects in the environment [11,12]. The logistic walking routes are automatically computed to consider both the clearance to the surrounding and the shortest collision-free walking distance.

All simulations in IMMA are made with batches of manikins, called families that may easily be created to cover the majority of a population [13,14]. The manikin families are instructed by a high-level language [15]and each member of the manikin family tries to perform the instructions with as good ergonomics as possible throughout the simulation.

3. Systematic layout planning

The systematic layout planning is a method used to construct layouts based on the interactions between the activities that occurs among the functionalities in the plant and the method may be applied to arbitrary layouts applications such as office layouts, grocery stores and workshops [16]. The layout planning method is built around three fundamentals; *chart* the relationships, *document* the space requirements and *adjustment* to achieve a feasible of the layout [16].

In this work, the simplified systematic layout planning method has been implemented. It is a pen and paper method, derived from the systematic layout planning and it consists of the following six steps [3]:

1. Identify and chart the relationships between resources, obstacles and environment based on for instance the material flow, service and environmental factors such as noise.
2. Establish and document the space requirement and the necessary media supply for each resource in the layout.
3. Draw a relationship graph in order to create a graphical representation of the relationships that were defined in the first step. The nodes in the graph represents the resources and the edges the relations. Different types of edges may be used to visualize the different relations.
4. Draw space relationship layouts based on both the relationships and on the space requirements of the resources, obstacles and the environment.
5. Evaluate the alternatives by considering the importance between the different criteria used in the evaluation.
6. Detail the selected layout and make minor adjustments, in order to ensure proper functionality such as facility maintenance and to add the auxiliary equipment needed in order to create an total overview of the actual layout.

4. Virtual layout planning

The optimized layout is based on a model constructed from the different resources used in the layout. The resources are general and might represent tangible objects and functionality on the equipment and in the environment, such as drains, displays and machines.

Moreover, a resource may also contain additional properties, such as a location and space regions. The location is used to determine if a resource is fixed or movable, whereas the regions are used to represent the required space for a machine or to allocate claims on the workshop floor. This way it is possible to include the space needed in order to work and to walk around a machine, to perform a service, the logistic transportations and to ensure that the legal requirement are fulfilled in the layout. Fig. 1 shows how properties of the facility are modelled as resources whereas a machine is modelled in Fig. 2.

Fig. 1. A workspace visualized by a point cloud where an electric service station (blue), a door (red) and a ventilation shaft (orange) has been modelled as resources that requires regions on the floor to ensure proper functionality and maintenance work. Courtesy by GKN.

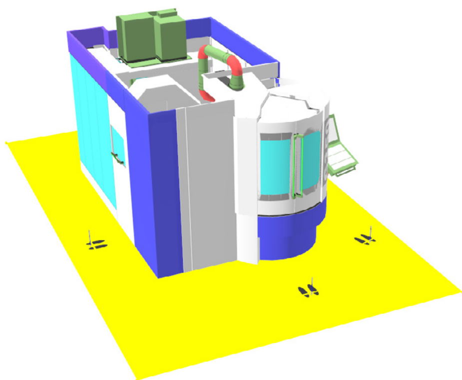

Fig. 2. A CNC machine that has been modelled as a resource with a working region (yellow) and three footings to mark entry points that guides the manikins to different functionalities of the resource. Courtesy by GKN.

Furthermore, the regions may also contain different preferences for the manikin which may be utilized by the logistic path planner in the computation of the walking routes since. A region may for instance be preferred, non-preferred or even forbidden to walk across. Fig. 3 shows how the walking route is changes when the region changed from avoid to forbidden.

An entry point is defined for each position of a resource where a manikin shall enter when to perform a task such as interact with a machine or to pick parts from a shelf.

The regions, their properties and the entry points will affect the walking routes and new walking routes needs to be computed for each update of the layout. Thus, the walking routes allows an easy visualization of the different routes needed to perform the instructions in a certain layout. An example of a

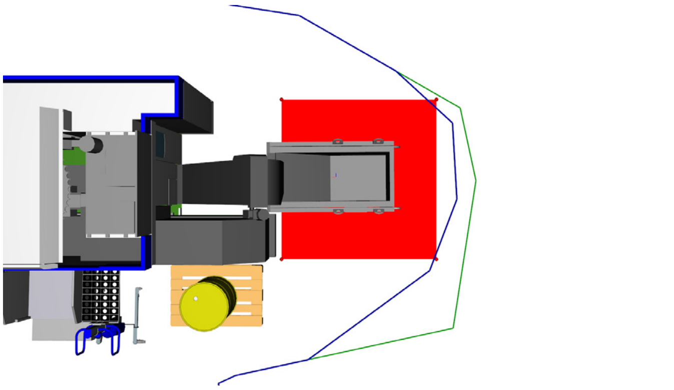

Fig. 3. The logistic path planner utilizes the regions of the resources in order to create collision-free walking routes are for the digital manikins. The blue path shows the path used before the red region increased the walking penalty and the green the path after the penalty update. Courtesy by GKN.

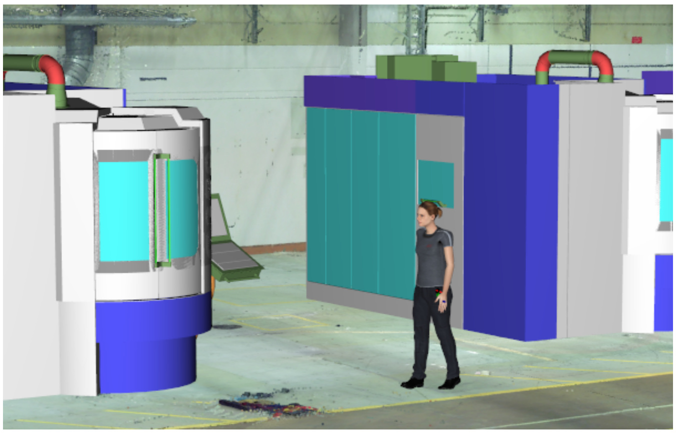

Fig. 4. A manikin that performs a collision-free walking route in an environment mixed with point clouds and CAD geometries. Courtesy by GKN.

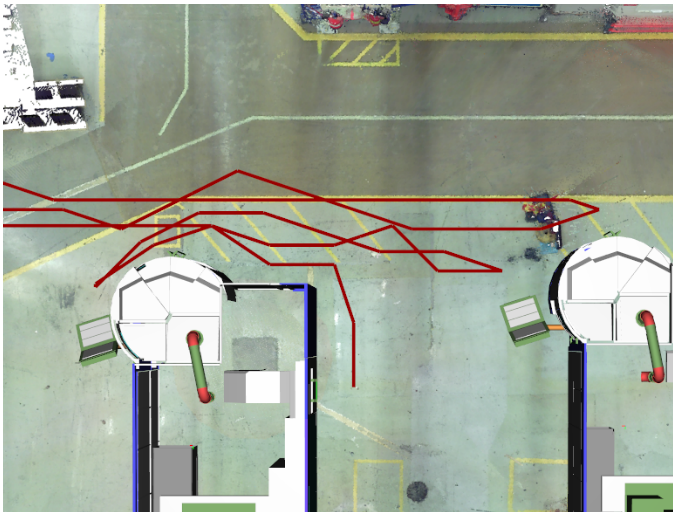

Fig. 5. An overview of the logistic walking routes used when performing a set of instructions. Courtesy by GKN.

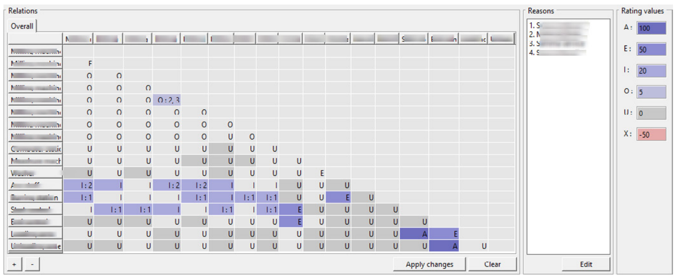

Fig. 6. The relationship chart with the mutual relations among the resources. The relations are weighted according to the simplified systematic layout planning method shown to the right.

walking manikin is shown in Fig. 4 whereas an example of a walking route is shown in Fig. 5.

All entities in the model are included in a matrix and their mutual relations ranked by the user, see Fig. 6. A score is then computed based on the current relations and the layout. Fig. 7 shows the relations of a layout where the different weights are represented by line width, pattern and color. A change in the layout or of a weight will instantly compute a new score. This enables real-time modelling of layouts.

An optimized layout is then computed based on these relations and it is then further optimized with respect to the logistic walking routes, see section 5.3.

The digitalized systematic layout planning has been implemented in the Industrial Path Solutions (IPS) software tool [17].

5. Layout optimization

The layout score is computed as

$$f(L) = f(D, S) = \sum d_{i,j} s_{i,j} \tag{1}$$

where $d_{i,j}$ is the distance between the center of the objects and $s_{i,j}$ is the relation weight. The resources are placed in the environment without colliding with regions in the environment or other resources. The layout is then calculated using the following three step optimization procedure. First, an initial layout is constructed and then optimized in a second step. Finally, the layout is improved with respect to the logistic walking routes.

5.1. Initial layout construction

Initially, a grid surface is constructed based on the size of the factory, which includes the regions for fixed resources, such as supplying media and transportation isles. Next, all movable resources are sequentially placed on the grid based on a rank computed from the relation chart and their closeness. More specifically, k resources are selected at each step of the algorithm and the closeness and score to all assigned resources are computed. The resources with the highest score is first selected to a position in the grid, followed by the resource with the lowest closeness value. Equalities are resolved using randomization.

There are two algorithms for placing the resource onto the grid; *evaluate all placing orders* and *evaluate all local combinations*. In the first each of the k resources are placed at the position that yields the lowest layout score, whereas in the second, all positions and rotations for each of the k resources are evaluated and the layout which yields the lowest score is chosen.

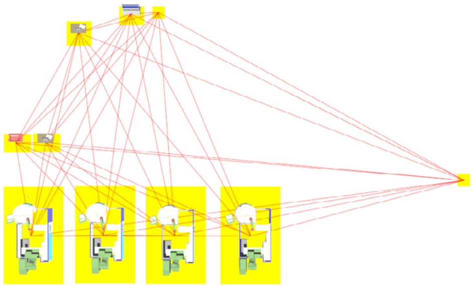

Fig. 7. Visualization of the relations in a layout. Courtesy by GKN.

5.2. Optimize a layout

Different algorithms have been proposed in order to optimize the layout. During the optimization, only the position of the resource in the grid and a 90° rotation of the resource is considered. The rotation point of a resource is located in the center and hence a 180° rotation of the resource will be redundant.

5.2.1. k-Exchange

The exchange algorithm selects $k \geq 2$ resources randomly and evaluates all possible combinations. If $k = 2$ they exchange positions and the two rotations are evaluated. If the exchange yields an improvement, the layout is preserved. When $k > 2$, all the possible combinations, including the positions and rotations are evaluated for a fixed number of iterations.

5.2.2. Hill climbing

The algorithm is iteratively constructing neighbour solutions from the current layout state by manipulating the resources. A resource may be manipulated by a rotation and a perturbation in the $x-$ and $y-$axis. and the manipulation that yields a minimum to the layout score is defined as the neighbour solution. Initially, a set of neighbour solutions is created from the manipulation of resources and the algorithm then iteratively creates and evaluates the neighbour solutions for k-random selected and manipulated resources until an optimum is found.

5.3. Logistic walking routes optimization

The logistic optimization is an additional step, applied to an existing solution $f(l_e)$, that tries to find a layout l_w such that $\alpha f(l_e) \leq f(l_w) \leq f(l_e)$ for $\alpha \in [0, 1]$.

The manikin is instructed to perform tasks and for each of task there exists an entry point, see example en Fig. 2. When the instructions have been performed, the work flow of an existing layout will be revealed and quantified with a score. The following algorithms has been used to improve the logistic walking routes:

5.3.1. Rotation

In order to improve the ergonomics, each resource is moved to a new location in the grid. However, compared to the previous optimizations, where only a 90° rotation was considered for each of the resource, all four directions of the resources must now be included in the optimization since a rotation of a resource may enable, disable or affect the length of the routes.

However, the computation of the logistic walking routes is time consuming and instead of testing all possible rotations for all of the resources, the following algorithm is proposed in order to reduce the number of computations needed. Define $k \in \mathbb{N}$. For n steps, randomly select k resources. Rotate all the selected resources 180°. Let each improvement of the rotation define the current layout and let $k = k - 1$. Repeat until $k = 1$.

5.3.2. Exchange position

In similarity to the exchange algorithm in section 5.2.1, k resources exchange position. However, instead of searching for the best exchange, a layout produced by an exchange that fulfils $\alpha f(l_e) \leq f(l_w) \leq f(l_e)$ for $\alpha \in [0, 1]$ is randomly selected. In the next step, all the selected exchange layouts are evaluated with all possible rotations. The algorithm runs for fixed number of iterations and the layout with the best ergonomic score is chosen as the final layout.

6. Test case and result

The layout tool is tested on a relevant industrial test case that includes four CNC machines, a control station a computer station, washing and a tool service station. Fig. 8 and Fig. 9 show an overview and all the resources used in the layout respectively.

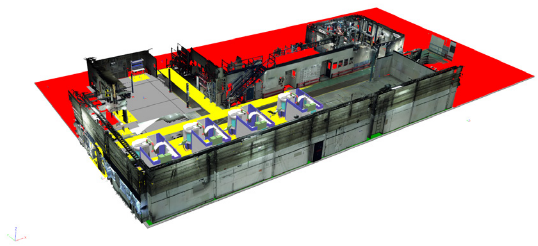

Fig. 8. The facility used in the layout. Courtesy by GKN.

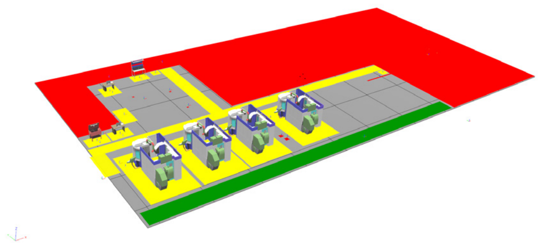

Fig. 9. The resources used in the layout. Courtesy by GKN.

6.1. Layout construction

The construction algorithm has been tested on two scenarios. One with no position constraints and with one resource in a fixed location. Fig. 10 shows the result when the two algorithms, *evaluate all placing orders* and *evaluate all local combinations* are used on the test case without any position constraints. In Fig. 11, the washing machine has been locked at a fixed location before the execution of the algorithms.

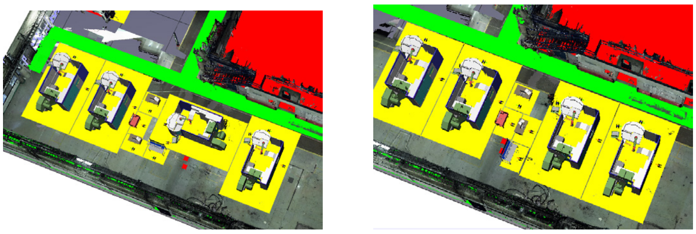

Fig. 10. The results from (a) the *all placing orders* and; (b) the *evaluate all local combinations* algorithms. Courtesy by GKN.

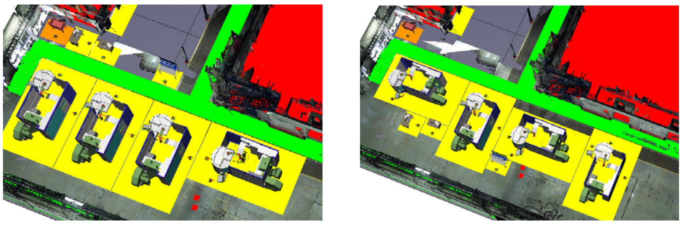

Fig. 11. The result of fixating the position of a resource (orange) before executing the (a) *all placing orders* and; (b) *evaluate all local combinations* algorithms on the test case. Courtesy by GKN.

6.1.1. k-Exchange

Fig. 12 shows the results after executing the k-Exchange algorithm with $k = 4$.

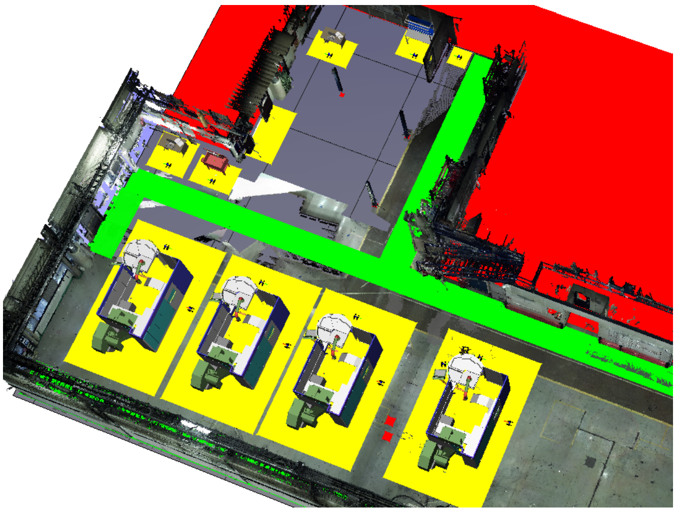

Fig. 12. The k-Exchange algorithm executed with four resources per exchange. Courtesy by GKN.

6.1.2. Hill climbing

The results of the hill climb optimization where three and two resources have been used to generate the neighbour solutions are shown in Fig. 13.

6.2. Improving the walking routes

The initial layout, see Fig. 14, is achieved from the first optimization step in 6.1 and the deviation from the initial score is defined with $\alpha = 95$. Moreover, since not all directions of the resource have been considered in the layout optimization, see section 5, there exist no feasible walking route in the initial layout to this optimization step.

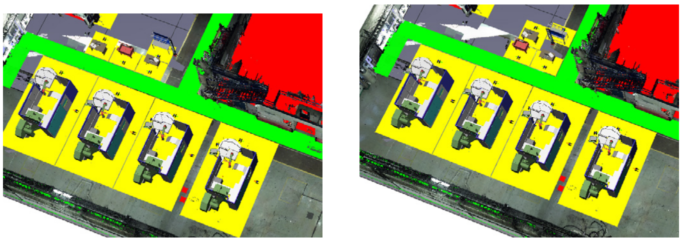

Fig. 13. The results of executing the hill climb optimization where (a) two and (b) three resources has been used to generate the neighbour solutions. Courtesy by GKN.

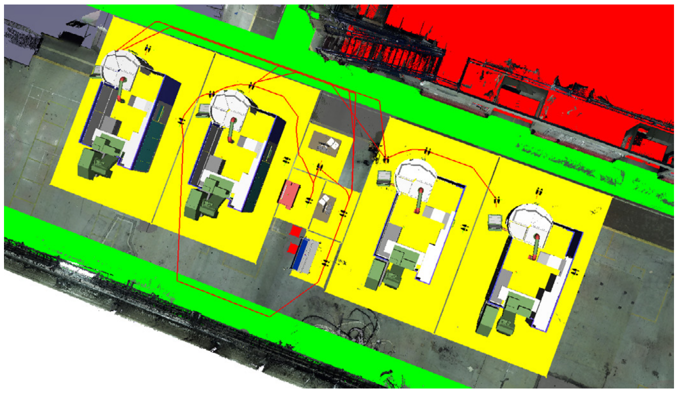

Fig. 14. The initial layout used for improving the walking routes. Note, this solution lacks a feasible walking route. Courtesy by GKN.

6.2.1. Rotation

The result from the rotation algorithm is shown in Fig. 15, which contains a feasible walking route.

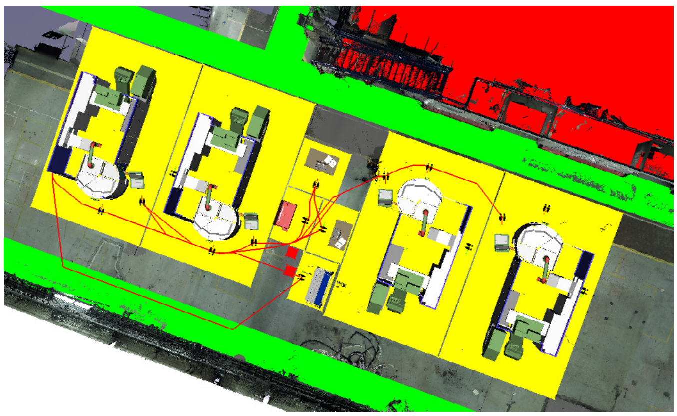

Fig. 15. The rotation algorithm creates a layout with a collision-free walking route based the initial solution. Courtesy by GKN.

6.2.2. Exchange position

Fig. 16 shows the layout with a feasible walking route that has been found by the exchange position algorithm.

7. Discussion

The result shows that our digital layout tool succeed with creating optimized layouts that also consider the logistic walking routes. Note, there exist no feasible walking route in the layout solution from the first optimization step. However, this

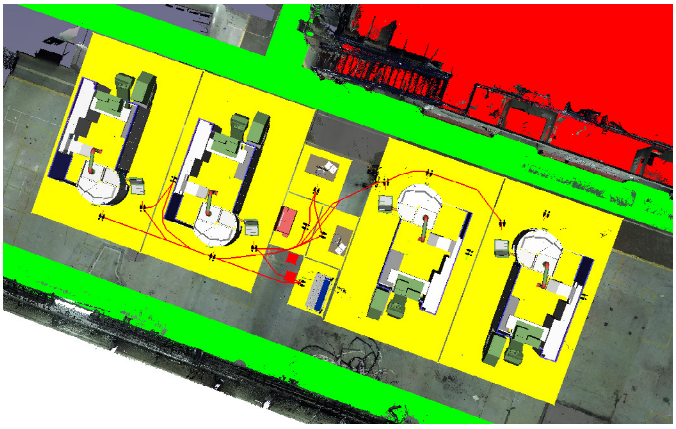

Fig. 16. A layout with a collision-free walking route has been created by the exchange position algorithm from the initial solution. Courtesy by GKN.

is corrected in the final optimization step and it emphasizes the importance of including the logistic walking routes in the layout optimization.

The computation of the layout is based on the weighted relations of the resources in the model. Thus, all aspects that shall be considered in the layout need to be expressed as a resource in the model. Moreover, the distances are located in the center of the resources. This may not always be an adequate approximation that prevents the possibility to for instance model that a certain side of a resource shall face a certain direction. However, since the tool provides real-time updates of manual layout changes, there is always a possibility for the users to edit the solutions and to include an aesthetic view of a layout.

The layout tool allows scanned point cloud to be used to visualize the status of the facility and to provide information of available resources and their positions when the layout model is constructed as well as improving the 3D visualization of the different layout concepts. Moreover, the automatic computation of the manikin motions is not limited to simulation of logistic walking routes and whole assembly sequences as well as other tasks, such as maintenance, will be simulated in the future work. This will result in more realistic simulations that may, for instance, consider the ergonomics of a certain layout of the workshop throughout a day. Finally, the tool is not limited to manufacturing and it would be interesting to evaluate the tool on other fields of application, as well as in large scale layouts.

8. Conclusion and future work

The digital factory layout tool, which optimizes the layout of machines and the corresponding ergonomic logistics, has successfully been implemented and tested on an industrial relevant case. The tool makes it possible to easily create and visualize different layout concepts in 3D in order to provide a clear view of the layout that may easily be shared with non-expert users of the software tool.

In our future work, the tool will be extended to simulate more complex scenarios, both regarding the layout and the performed task. Moreover, an in-depth investigation of the optimization algorithms will be made as well as further improvement of the computations of the collision free walking routes.

The tool will be further extended with functionalities to support, for instance multiple manikins, carriers and automatized equipment in order to simulate larger production systems.

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