Augmented Reality Assisted Factory Layout Planning and Analysis for a Flexible Manufacturing Cell

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Yun Suen Pai
Keio University

Hwa Jen YAP
University of Malaya

Chang Siow-Wee
University of Malaya

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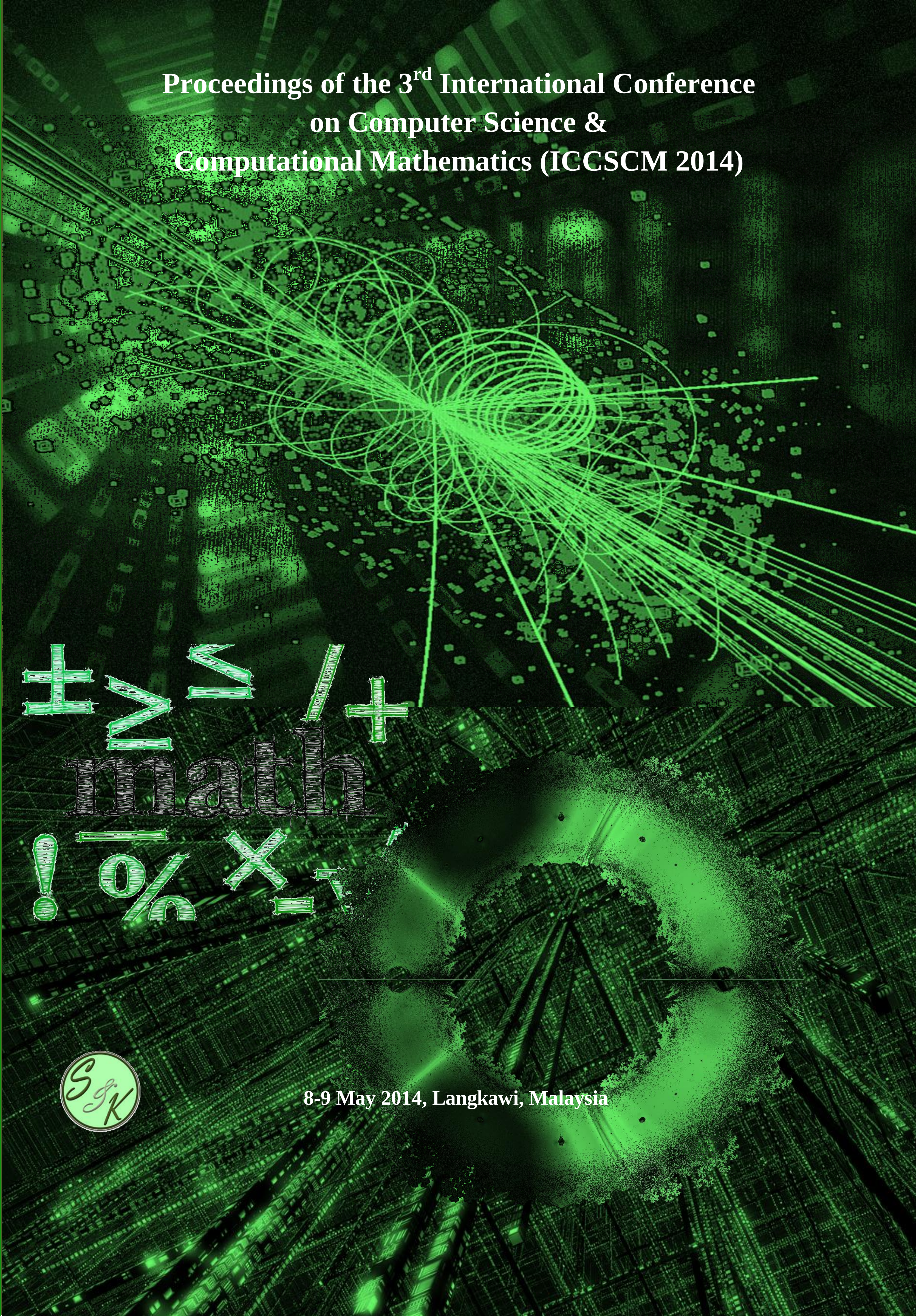

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Yun Suen PAI[1], Hwa JenYAP[1],S. RAMESH[1], Siow-Wee CHANG[2], and Kok Leong Royston CHEONG[1]

[1]Department of Mechanical Engineering, Faculty of Engineering,
University of Malaya, 50603 Kuala Lumpur, Malaysia.
[2]Bioinformatics and Computational Biology, Institute of Biological Sciences, Faculty of Science,
University of Malaya, 50603 Kuala Lumpur, Malaysia.
yspai1412@gmail.com, {hjyap737, ramesh79, siowwee}@um.edu.my, cheongkl.royston@gmail.com

Abstract: Factory layout planning can be a daunting task when optimizing the best route possible for material travel distance, processing time, and so on, especially if a poor form of visualization exists. This study incorporates augmented reality (AR) to aid in the development of a flexible manufacturing cell (FMC) by superimposing 3D models of machines into the physical environment while taking into consideration spatial constraints and collision detection. Four layout types are analyzed, namely the straight line, U-shaped, S-shaped (serpentine), and semi-circle-shaped arrangement. A data structure in extensible markup language (XML) is then developed to record the information regarding spatial relationship, material travel distance, area occupied, processing time, and sequence of operation. This data is used in the line balancing calculation of the actual cycle time of an operation to determine the effects of the layout arrangement to the initial cycle time computed. A case study conducted proves that the program is able to effectively analyze the aforementioned factors for the operator to evaluate on the best possible factory layout.

Keywords: Factory Layout Planning, Augmented Reality, Flexible Manufacturing Cell, Material Travel Distance, Cycle Time, Line Balancing.

1. Introduction

The design of a facility layout is associated with the allocation of machines, work cells, and departments that play a role in ensuring an efficient and effective operation[1]. Many researches have been conducted in developing simulation models in the manufacturing system design, as engineers need to reduce any uncertainties present, such as assessment errors which are hard to determine in traditional facility layouts. A survey was conducted to establish the factors that contribute to several problems still present in today's layout planning process[2]. Firstly, a static and dynamic layout needs to be clearly distinguished. A static layout considers the material to be constant over an extended period of time, whereas a dynamic layout considers a possible change in material flow after a period of time. Characteristics like product variety and volume, facility dimensions, material handling, multi-floor layouts, the need for backtracking, as well as pick-up and drop-off locations greatly impact the overall planning process. It was suggested that graphical tools create a more efficient as well as attractive environment that has the potential to replace existing planning processes, though the criteria of a good layout simulation must first be clear. Since layout planning is a collaborative activity, the perspective and opinion of different departments contribute to the criteria required. It was found that among the main functionalities, besides drawing a layout or modifying them, is to create 3D digital models with proper annotations and information, as well as a support to import and export files from generic formats[3]. The increasing trend towards simulation can be seen in recent published articles, where operational decision-making tools are becoming main stream[4]. Therefore, it is only natural to continuously improve this by pushing the visualization aspect of layout planning and simulation.

1.1 Flexible Manufacturing System.

Since flexible manufacturing system (FMS) is a system that integrates its elements tightly, the relation between them is often hard to compute[5]. Therefore, there is a demand for an analysis method that avoids any substantial loss in labour time, money, and resources. It has been found that when comparing between three different techniques; Awesim, Bottleneck, and Petrinet, more deviations exist for the mathematical-based technique which is Bottleneck. A simulation technique is a better alternative especially in evaluating a more complex system.Additionally, through stochastic modeling, it was found that a reliable FMC has a great impact to the overall production line, and proper planning can do well in minimizing failure rates and maximizing productivity[6]. This implies that scheduling does in fact directly influence the reliability of an FMS. To create an intuitive FMS, a user interface that is interactive, robust, and flexible is a necessity[7]. By using AR as a form of user interface, any user will be able to freely manipulate the overall layout design on a table-top, which is extremely user-friendly. 3D models are usually managed by a database which stores them, as well as calls them depending on the program. ARToolKit was used to achieve this since it supports a wide array of hardware and does not require a powerful workstation. Similarly, the proposed system in this paper further expands the toolkit's capabilities by implementing stereolithrography (STL) instead of virtual reality modeling language (VRML) files.

1.2 AR and VR Application.

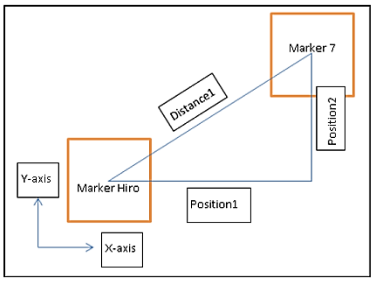
A 2D view of a system is often not easy to understand and evaluate. Therefore, virtual reality (VR) -assisted systems offer a depth perspective that is not possible for a 2D view while at the same time, provides the ability to re-layout existing factory layouts[8]. However, it needs to be mentioned that an AR system can achieve all of the aforementioned benefits as well, as shown in this study, without the additional computing cost. A recent study utilized VR technology for a factory planning system that offers a simultaneous visualization, analysis, and investigation approach[9]. A collaborative system involves social interaction, navigation, annotation, and model manipulation, either among humans or with machines. When implementing this, three stages are taken into account. In the first stage, it is important for both users to store all the data in their respective systems to ensure a collision-free interaction. The second stage only requires the master user to own the complete data set, with the freedom to interact being exclusive only to him or her. The third stage is when multiple models are involved. This collaborative platform, with the aid of VR, is a great tool for factory planning.

VR simulation is more well-known among industries, but the broad scope of which AR can be applied cements the technology as a form of visualization for engineers to implement into almost any system. As of this moment, AR technology has found a place in collaborative design work, maintenance, assembly, robot path planning, computer numerical control (CNC) simulation, and of course, plant layout planning[10]. VR was initially the preferred choice in factory layout planning, but due to the tedious design process and the loss of flexibility in a virtual environment, this limits the productivity overall. With proper tracking and registration, AR eliminates these problems and offers a more robust solution. Representation of a factory layout in the planning stage is crucial in succeeding an effective material flow simulation[11]. Due to poor representation, defects will occur that will directly affect the cost of re-planning. In this aspect, an AR system stands out in that it is able to enhance an existing environment, preserving the usage of the actual working environment while reducing the cost of generating a virtual one. The automotive industry in particular, has been pushing for the development of an AR-based factory planning. In 2003, Volkswagen Group Research and Metaio have collaborated to produce an AR-based prototype for factory planning which proved effective[12]. It was broken up to three development stages, which are web-based application for client-server interaction, a high performance stationary system that streams the output video, and a mobile system based on photos. The project was then dubbed Roivis, which is the final result of the iterative development. A reliability of up to 98% was achieved, making it a valuable planning tool.

Mixed reality is an extension of AR where a virtual object interacts with a physical one like a 2D image of a factory[13]. This essentially further cuts down the virtual content, though tracking and registration needs to be even more precise. Normally, visualization with AR utilizes markers, but a recently developed system uses safety signs present at a factory image instead. Therefore, the system is able to overlay 2D images with 3D virtual objects, while taking into account collision detection and a constrained path movement of the virtual object. This concept proves to be interesting, though immersion does degrade due to the lack of a physical environment. Adding on to the virtual simulation process is the implementation of both VR and AR into a system. The combination of these two forms of visualization creates a system that is compatible with every modeling stage, from analysis to experiments, evaluations, and presentation, since it utilizes the strength of both methods to achieve a desirable simulation[14]. However, the underlying problem with most systems that can handle every stage is that it is not particularly excellent in any, with compromises existing especially in the overall cost.

2. Methodology

The layout planning program is developed using C++ programming with the aid of ARToolKit for tracking and registration. Since the position of each marker in the system is critical in computing the relative distance between them, an algorithm that can find and total up the material distance is required. The first marker placed serves as the world coordinate, as well as the first machine in the production line. Every subsequent marker will act as the next machine, and the distance between that marker and the previous one before it will be the relative distance that exist between each virtual machine, as shown in Figure 1. In other words, when each of these distances is totaled up, the final value is equivalent to the total material travel distance or operator travel distance.



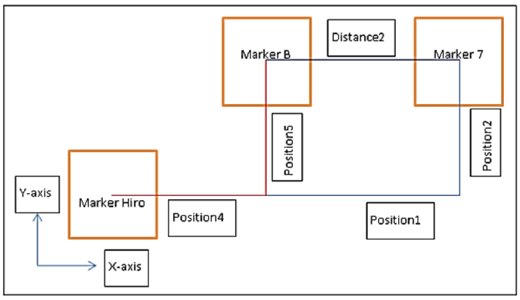


Figure1. The “Hiro” marker is treated as the world coordinate to calculate the total distance

Additionally, since the area required is also taken into consideration, the program must be able to identify which marker has the longest distance relative to the world coordinate or reference marker. By doing so, the system knows the largest possible area that the work cell will require, assuming the space given is rectangular or square in shape. Figure 2 illustrates the proposed system.

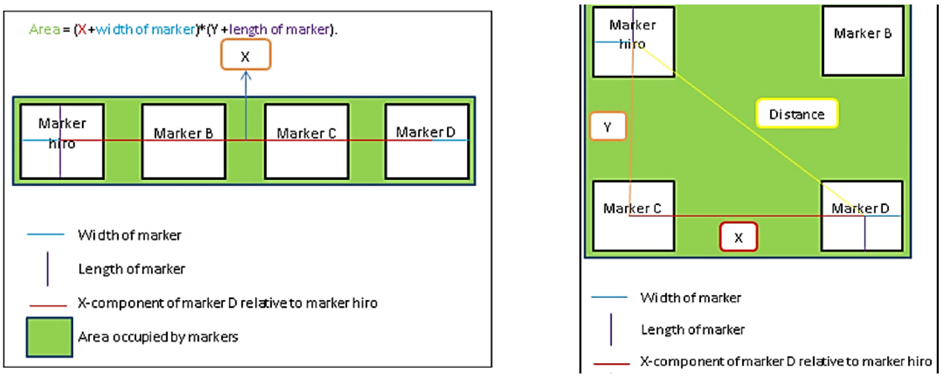


Figure2. Area calculation to determine total space required

The three major components of the system are importing 3D models into the system as an STL file, collision detection between machines while considering the safety zones, and facilitating material travel time and spatial constrainsby generating the results into a universal data structure as an XML file.

2.1. Importing 3D Models.

Each of the 3D models of the virtual machines are designed with a 3D CAD modeling software and exported in the form of an STL file[15]. This is because this format is universally supported in various engineering tools like rapid prototyping and computer integrated manufacturing. The STL models are then rendered with OpenGL into the program and called out according to its assigned marker.

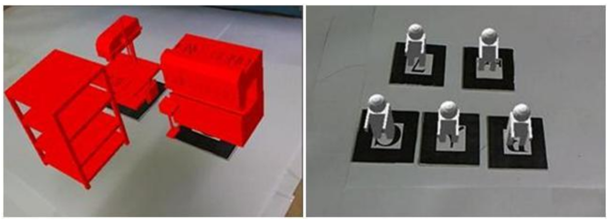


Figure3.STL models generated and placed on markers

2.2. Collision Detection.

The collision detection system calculates the relative distance between each machine to determine the individual safety zones. A colour change is used to indicate collision, where the 3D virtual objects turn red when colliding. Figure 4 depicts two virtual cubes that collide when placed closer than the designated safety zone stated in the program.

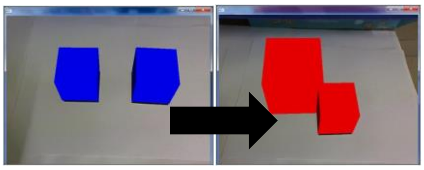


Figure 4. Colour change of virtual cube during collision

2.3. Data and Output Structure.

The data in XML format is saved in an external output directory, where the first part consists of operation information, parameters, relation between markers and machines, as well as colour coding of the 3D models. These data are treated as references during the planning stage. The second part of the XML file is the actual saved data which are the distances between the factory elements, total material travel distance, and the area occupied by the layout.

2.4. Line Balancing.

Line balancing is the key method in designing the most efficient process that is in line with the expected volume or demand of a product, but it rarely takes into account the time required for materials to move between stages, and how this effects the cycle time which focuses on processing time [16]. In fact, line balancing is computed by finding the required number of stages based on the cycle time. Cycle time, by definition, is the time taken for a product to emerge from a stage. The formula below shows the calculation of cycle time.

$$t_1 = \frac{t_a}{d} \tag{1}$$

Where t_1= cycle time, t_a = available time, and d = demand, or quantity to be processed.

The value of $t_a$and d is input by the user based on their specific requirements. The next step is then for the user to input the number of operations required in making the product. For example, producing a mechanical pencil may require around 10 operations, ranging from machining the body to assembling the pencil cap. Each operation has its specific time required to complete it, depending on the operation's complexity and requirements. The addition of each of the time required for all the operations is equivalent to the total work content. Therefore, the calculation of the number of stages required can be seen in the formula below

$$S = \frac{t_{operation\ 1} + t_{operation\ 2} + t_{operation\ 3} + \ldots\ldots + t_n}{t} = \frac{T_n}{t} \tag{2}$$

Where S = number of stages, n = number of operations, and T_n = total work content.

If S is equal to a decimal number, which is impossible given that it represents quantity, the program will automatically round it up to the higher integer value. The obtained number of stages is transferred to the AR environment, where each machine is treated as a stage. The AR system then computes the material travel distance, where travel speed is decided by the user. Therefore, the material travel time, $t_m$can be found, which is the time taken for the material to move from the first stage to the last stage.T_m can then be added back into T_n to obtain the total operation time. The formula is as stated below

$$t_2 = \frac{T_n + t_m}{S} = \frac{T_{operation}}{S} \tag{3}$$

Where t_2 = new cycle time, and $T_{operation}$ = total operation time.

t_2 represents a more accurate value of the cycle time, since it considers the summation of total work content with the material travel time. This allows engineers to carefully consider which layout arrangement is most suited for their required operations because inclusion of standard time for material flow reduces the risk of late delivery of the final product [17].

3. Case study

To test the actual application of the proposed system, a case study is conducted based on the manufacturing and assembly of a computer case. For ease of calculation, input values are kept at the lower range to reduce the computed value of the number of stages, since it can range from 0 to 100 stages in an actual production line. For this particular case study, t_a = 8 hours/day, d = 800 units/day and n = 6 operations. Since each operation has its own required time, $t_{operation\ 1}$ = 45 seconds, $t_{operation\ 2}$ = 18 seconds, $t_{operation\ 3}$ = 22 seconds, $t_{operation\ 4}$ = 32 seconds, $t_{operation\ 5}$ = 20 seconds and $t_{operation\ 6}$ = 43 seconds.The program uses these values to find $t_1$and S, which is equal to 36 seconds and 5 stages respectively. This means that one of the stages perform two operations while the rest performs one.The stage sequence is detailed in Figure 5 along with the line balancing program, where a sheet metal from the inventory is processed by a Numerical Control (NC) punch machine, and then sheared. The metal will then undergo drilling and bending before being sent back to the inventory.

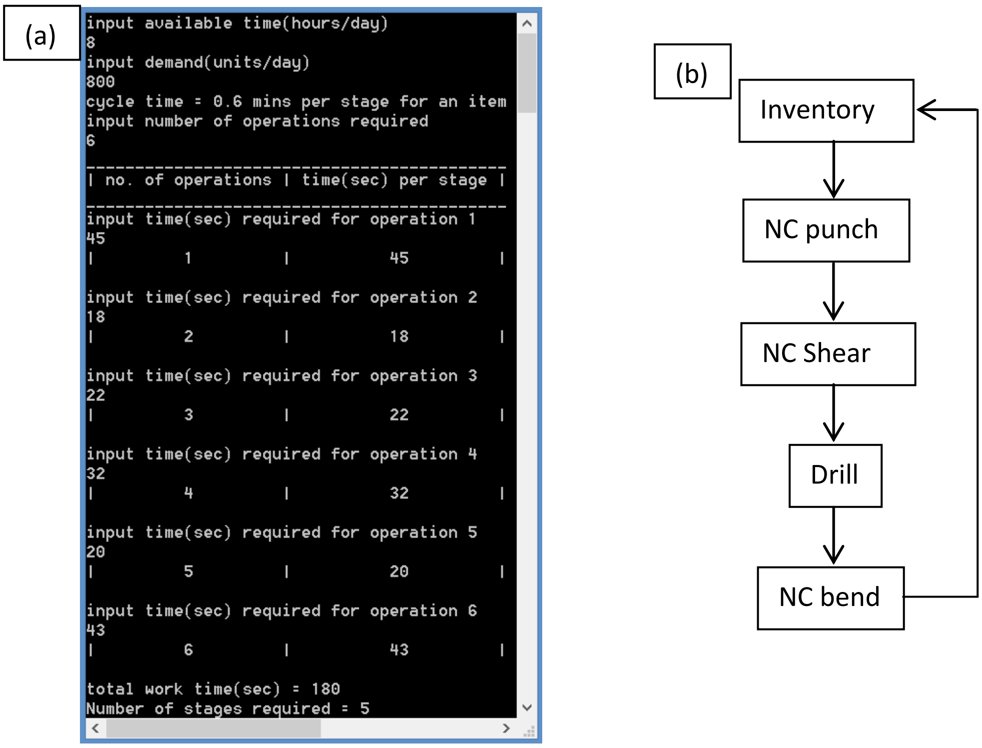


Figure 5.(a) Line balancing program and (b)sequence of operation in the case study

The goal of this case study is to acquire the best possible route with minimum material flow distance and the least space required. Several line shapes were evaluated, that includes the straight-line, S-shaped, U-shaped, and semi-circle as shown in Figure 6. Furthermore, two approaches are used to find the travel distance, which are machine-center oriented and operator-center oriented. In general, machine-center is for automated lines, while operator-center is for manual tasks. Both these orientations are based on the location of the machine and operator respectively.

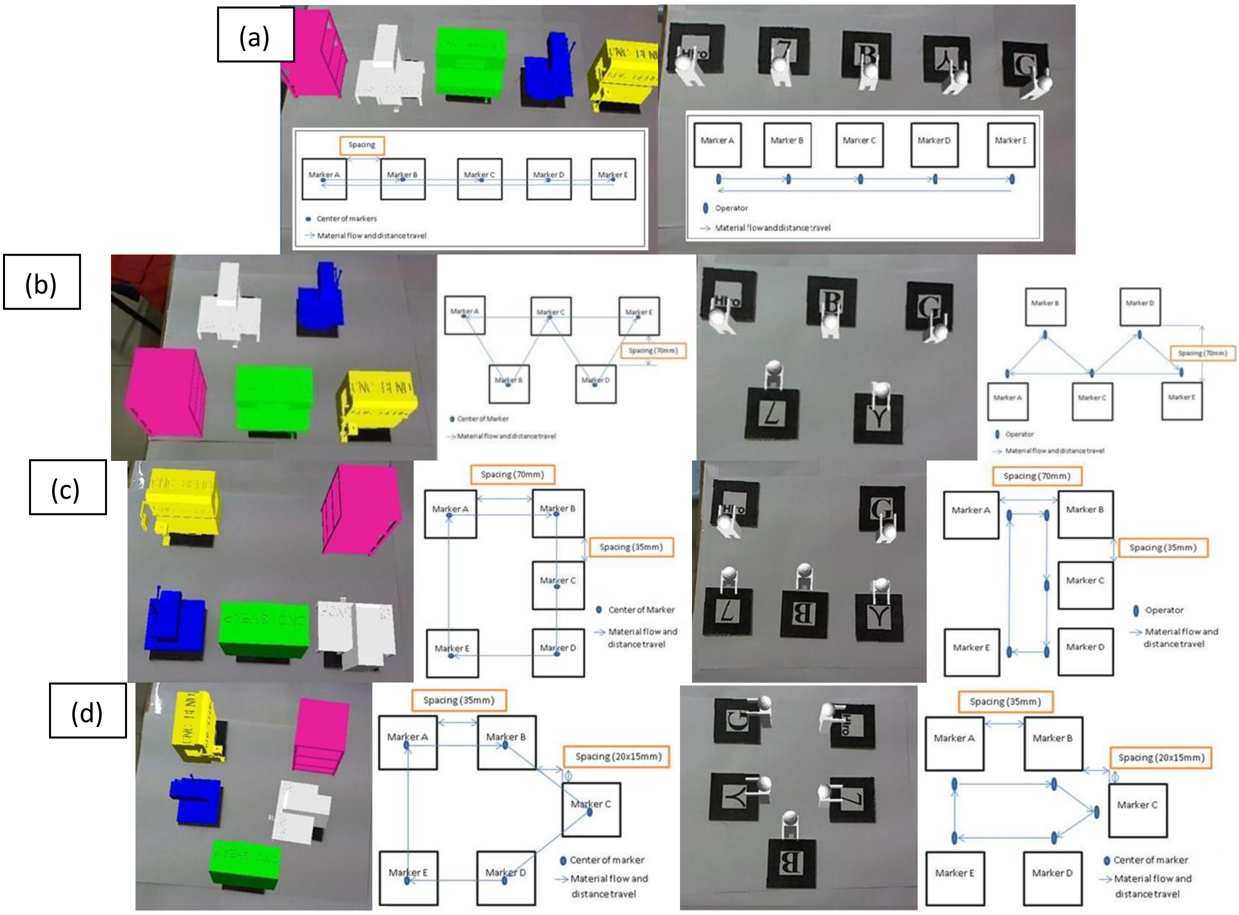


Figure6. Virtual layout of machine and operators with various arrangements, starting with (a) straight line arrangement, (b) S-shaped arrangement, (c) U-shaped arrangement, and (d) Semi circle-shaped arrangement

The straight line arrangement is applied typically when the machines are arranged according to a certain sequence. For the S-shaped, or serpentine arrangement, the machines face inwards while the operators are located back-to-back. The U-shaped arrangement, as the name implies, places the machines in a U-shape with the operators facing back-to-back as well. Finally, the semi-circle arrangement is similar to the U-shaped arrangement, except that more machines are placed horizontally instead of vertically, when viewed from the top.

All the results for the total distance and area are summarized in Table 1.

Table 1.

Layout Arrangement	Total Distance Travel (m)		Total Area (m^2)
	Machine center	Operator	
Straight	662.61	671.74	19833.14
S-Shaped	696.79	494.58	43655.28
U-Shaped	553.71	432.40	34225.45
Semi-circle Shaped	476.26	328.52	31472.27

The lowest value of the total distance traveled is at 328.52m, which is the operator-oriented method for a semi-circled shaped arrangement. Additionally, this particular arrangement also scores the least distance traveled for a machine-center oriented operation. With this value, and assuming the speed to be 0.33m/second, this equals to a travel time of 108.4 seconds. We can then find the t_2, according to equation (3).

$$t_2 = \frac{180 + 108.4}{5} = 57.68 \text{ } seconds$$

Therefore, 57.68 secondsisa more accuraterepresentation of cycle time for this case study using the semi-circle shaped arrangement.For the total area required, the straight line layout requires the least area, at 19833.14m^2. A smaller space that is taken up would obviously be favorable, but this also depends on other factors like the amount of space originally given, as well as the space required for other work cells.

4. Conclusion

The developed layout planning program has proven useful in evaluating layoutswith the aid of effective visualization. In the future, this study can be further improved by adding a more dynamic simulation between the elements present, creating a 2D information overlay, adding high-resolution cameras for increased coverage and accuracy, and finally the actual application of this system into a real factory and comparing it to the traditional layout planning process.

5. Acknowledgements

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