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Computer-Aided Assembly Sequence Planning For High-Mix Low-Volume Products In The Electronic Appliances Industry

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Abstract

Electronic appliance manufacturers are facing the challenge of frequent product orders. Based on each product order, the assembly process and workstations need to be planned. An essential part of the assembly planning is defining the assembly sequence, considering the mechanical product's design, and handling of the product's components. The assembly sequence determines the order of processes for each workstation, the overall layout, and thereby time and cost. Currently, the assembly sequence is decided by industrial engineers through a manual approach that is time-consuming, complex, and requires technical expertise. To reduce the industrial engineers' manual effort, a Computer-Aided Assembly Sequence Planning (CAASP) system is proposed in this paper. It compromises the components for a comprehensive system that aims to be applied practically. The system uses Computer-Aided Design (CAD) files to derive Liaison and Interference Matrices that represent a mathematical relationship between parts. Subsequently, an adapted Ant Colony Optimization Algorithm generates an optimized assembly sequence based on these relationships. Through a web browser-based application, the user can upload files and interact with the system. The system is conceptualized and validated using the CAD file of an electric motor example product. The results are discussed, and future work is outlined.

Keywords

Assembly sequence; production planning; computer-aided assembly planning; industry 4.0; High-Mix Low-Volume

1. Introduction

Assembly planning describes the planning of bringing individually machined parts into a final product of higher complexity [1]. It incorporates the planning of the assembly tasks and required tools, the sequence, the layout, and resources [2]. Due to the market demands for product versions and models, smaller batch runs, and shorter concept-to-market lead times, the effort of assembly planning is rising [3–5]. The importance of assembly planning is high as assembly accounts for up to 70% of the production costs [1]. The assembly sequence planning (ASP) is a fundamental step of the assembly planning process. It has a significant impact on the assembly process, such as the assembly line layout and the operations at each workstation, and thereby production efficiency and cost [6]. It is complicated to find the optimal assembly sequence out of the vast number of possibilities [7]. ASP remains a manual task due to complexity reasons and the impact on the assembly process. The automatization of ASP has been examined in research as one of the main drivers for assembly optimization [8].

It can be observed that especially electronic appliances contract manufacturers with a high-mix low-volume production strategy can profit from an automated ASP solution because of the high need and feasibility. The need to automate ASP arises on the one side due to the increasing assembly planning effort. Electronics contract manufacturers apply the high-mix low-volume production method as a reaction to market demands, wide client base and a need to increase profitability [9]. High-mix low-volume is characterized by low unit volumes and high diversity, resulting in increased assembly planning effort [10]. Besides, contract manufacturers are under constant pressure to reduce costs [9]. Finally, the ASP for contract manufacturers is complicated by the limited connection between product design and assembly planning [11]. On the other side, the feasibility of an automated ASP is high. ASP can be automated more easily because of the increasing uniformity of products due to digitization, that help contract manufacturers serve various customers while still achieving economies of scale. This is especially relevant for electronic products, as the parts are primarily standard parts like resistors, capacitors, memory chips, which are assembled in many different product configurations [12,13]. Also, it can be derived that the high share of manual assembly operations supports the feasibility. Electronic appliance assembly mainly consists of the final product assembly which is dominated by manual operations [14]. The planning complexity and resulting costs of manual assembly are lower in contrast to automated assembly systems [15].

Whilst theoretical approaches have been outlined in scientific literature, practical industry solutions for an automated ASP remain limited [16,17]. For instance, common CAD software offer minimal support in determining the assembly sequence [18]. The paper describes an approach, named Computer-Aided Assembly Sequence Planning (CAASP), for high-mix low-volume products in the electrical appliances contract manufacturers industry. An overview of related work in assembly sequence planning is given (section 2). The solution approach is presented (section 3), and the solution is validated by an electric motor assembly example (section 4). Finally, a conclusion is derived, and future work is outlined (section 5).

2. Related work

The related work on ASP can be structured regarding practical and theoretical approaches [19], which are described in more detail in the following sections.

2.1 Practical approaches

There are different practical approaches for assembly sequence planning. Such technological solutions must be applicable in the industry and pursue the goal of facilitating assembly sequence planning for the industrial engineer. Existing practical approaches are explained below. Based on the necessary information for the assembly sequence planning, precedence rules and graphs can be generated [20,21]. These approaches are further developed, for example by *Hao et al.* [22] using a genetic algorithm combined with the simulated annealing algorithm to search for the disassembly sequence planning. However, these approaches have in common that they require the intervention of assembly planners to gather further information such as additional precedence relations of subassemblies. [19] Due to the increasing use of CAD systems, the extraction of information from CAD files to generate an assembly sequence emerged as a field of research. However, such approaches as those of *Mathew et al.* [23] are still characterized by manual efforts, e.g., in the form of manual labelling or quality problems of the results. To further reduce manual efforts *Hadj et al.* [24] developed an add-in for the CAD-software SolidWorks that is used in the design phase to increase the efficiency of product development processes by exclusively considering feasible assembly sequences. However, applicability in terms of consideration of other CAD software and convenience for users are not the focus of these approaches. *Gulivindala et al.* [25] concludes that the information distribution of assembly sequences and the practical feasibility is not given. Based on these findings, a cloud-based solution for automatic disassembly planning with a genetic algorithm is developed, which results can be efficiently distributed to Internet of Things devices. However, since this research does not focus on the assembly sequence problem during the product development phase and the corresponding use for assembly planners, the previously mentioned problems of using different CAD software and the usability for assembly planners remain. It appears that so far no sufficiently practicable approach has been found that meets today's requirements for user-centeredness and system independence. To achieve practicability, the CAASP is based on a system-independent architecture without installation effort and an intuitive user interface.

2.2 Theoretical approaches

Currently, methods for generating assembly sequences can be mainly divided into two categories – mathematically based and artificial intelligence (AI) based. Mathematically based methods use diagrams, graphs, or matrices to generate assembly sequences, while AI methods are used to generate optimal assembly sequences. On the one hand, precedence diagrams [26,27] and liaison diagrams [28,29] were originally used to describe part relationship in generating assembly sequences. However, those diagrams need to be generated manually. The manual work of creating the matrices was automatized. This was supported by use of CAD software, where part and assembly information is available in digitized data format. This provides foundation to automatically generate mathematical models and opens new era for assembly sequence planning. *Gu and Yan* present an approach that automatically disassembly sequences based on connectivity diagrams using CAD data from a feature-based data base [30]. *Hadj et al.* used mating data extraction and collision analysis to generate assembly sequences automatically, directly integrated in CAD software by using its application programming interface [19]. Although the manual effort could be reduced tremendously, mathematical methods can only generate feasible assembly sequences, it cannot generate optimal assembly sequences and lacks practical usage which hasn’t been tested on complex products.

On the other hand, AI methods, e.g., genetic algorithm [22], neural networks [31], particle swarm optimization [32], artificial immune systems [33] have been used for automatic assembly sequence planning. *Lu* and *Yang* [34] used ant colony algorithm for ASP, but it needs human intervention as assembly task priority diagram needs to be generated manually. *Huang* and *Xu* [6] combined mathematical methods with AI methods to use integrated disassembly interference matrix, connection matrix, integrated support matrix and Ant Colony Optimization (ACO) to solve assembly sequence problems. However, the matrices are generated manually and require human intervention. *Pan et. al* proposed an automatic way for assembly sequence planning which firstly introduced input as STEP CAD files [35]. The method extracts geometrical information for interference-free matrices which represents interference relationships between assembly components and then automatically generate assembly sequences with minimum number of assembly direction reorientations. However, it has only been tested for products with less than 5 components and for complex products with large number of components, the performance cannot be guaranteed.

Although new ear of automatic assembly sequence planning method opens, fully automatic assembly sequence planning system with user interface which can be applied to complex products still needs to be developed. Therefore, in this paper, a fully automatic assembly sequence planning system which doesn’t need human intervention together with user interface is proposed to show the advance. It combines and adapts existing methods. The automatic assembly sequence planning system shall reduce manual work in assembly sequence planning, and the generated assembly sequence shall provide vast support to the industrial engineers for assembly planning work which in the end can save time and improve efficiency in a production environment.

3. Computer aided-assembly sequence planning (CAASP) system

In the following, the CAASP system is described. It handles the flow of information starting from the user upload, see Figure 1. The relevant product data is extracted (phase 1), described in section 3.1. The geometrical constraints are modelled (phase 2) the optimal assembly sequence is generated (phase 3), described in section 3.2. Finally, the results are visualized to the user.

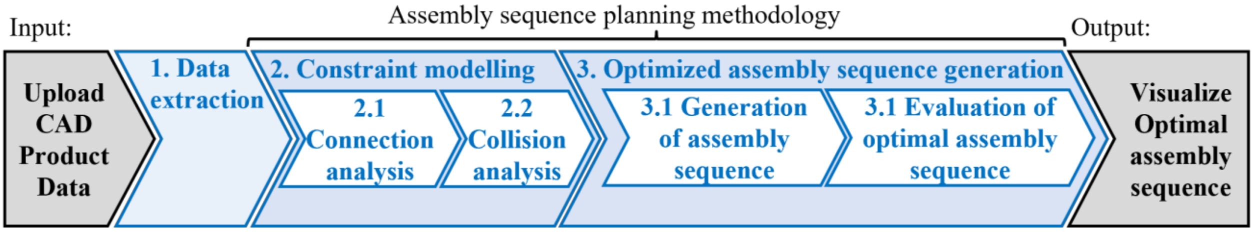

Figure 1: CAASP system flow of information

3.1 CAASP software system description

The ASP methodology is embedded in the ASP algorithm in the CAASP system to facilitate the usage by the user, e.g. an industrial engineer. The process is shown in a system diagram in Figure 2, modelled in the Unified Modelling Language (UML) [36]. The user uploads a CAD file in a web-based and user-centred application. This file is stored in a database with file management capabilities, along with additional information such as the date the file was uploaded. The database assigns a task ID to this file which is used as a unique identification number for the backend. The middleware is a backend component which communicates between database and CAD software. The middleware automatically extracts additional data necessary for assembly sequence planning from the CAD file by connecting to CAD software using application programming interfaces (APIs). Hence, manual effort to collect necessary data for assembly sequence planning can be significantly reduced. The data extraction was developed for the common STEP format, the Standard for the Exchange of Product model data [37]. The STEP format opens the opportunity to use various CAD software for the data extraction purpose and thus realize an agnostic and vendor independent approach. After extraction the data is validated and stored in the database. The ASP algorithm accesses this data and generates an assembly sequence, see section 3.2. The results are stored in the database so that the optimal assembly sequence results can be accessed by continuous pull requests from the frontend and displayed in a practical way for the user, referred to as the component name.

3.2 Assembly sequence planning methodology

The detailed methodology, consisting of two phase is presented in Figure 3. The first phase is the modelling of the geometric constraints as input for the optimization. The CAD input data is enriched to derive geometrical constraints like spatial data, part relationships, and collision information. In the CAASP system, the liaison matrix is applied to analyse the connections (step 2.1), while the interference matrices are utilized to analyse the collisions between the parts CAD file (step 2.2), see Figure 3. The liaison matrix represents contact information between two parts in an assembly and is produced by examining the connections between every part in a file [23]. The connected parts have a value of '1', while '0' indicates no connection between two parts. An interference matrix is also produced from the assembly file using collision analysis [19]. The assembly parts that interfere with other parts along the +x, -x, +y, -y, +z, and -z axes are identified. The information along the six axes is stored in six different binary matrices with values ‘0’ and ‘1’ where '0' indicates that there is no collision and ‘1’ indicates collision [38]. Step 3.1 follows, which is the generation of assembly sequences. These are produced by generating a disassembly sequence, which is then reversed to produce an optimal assembly sequence. For more complex assemblies with sub-assemblies, optimal sequences are generated for each of the subassemblies, after which a sequence is generated for the entire assembly.

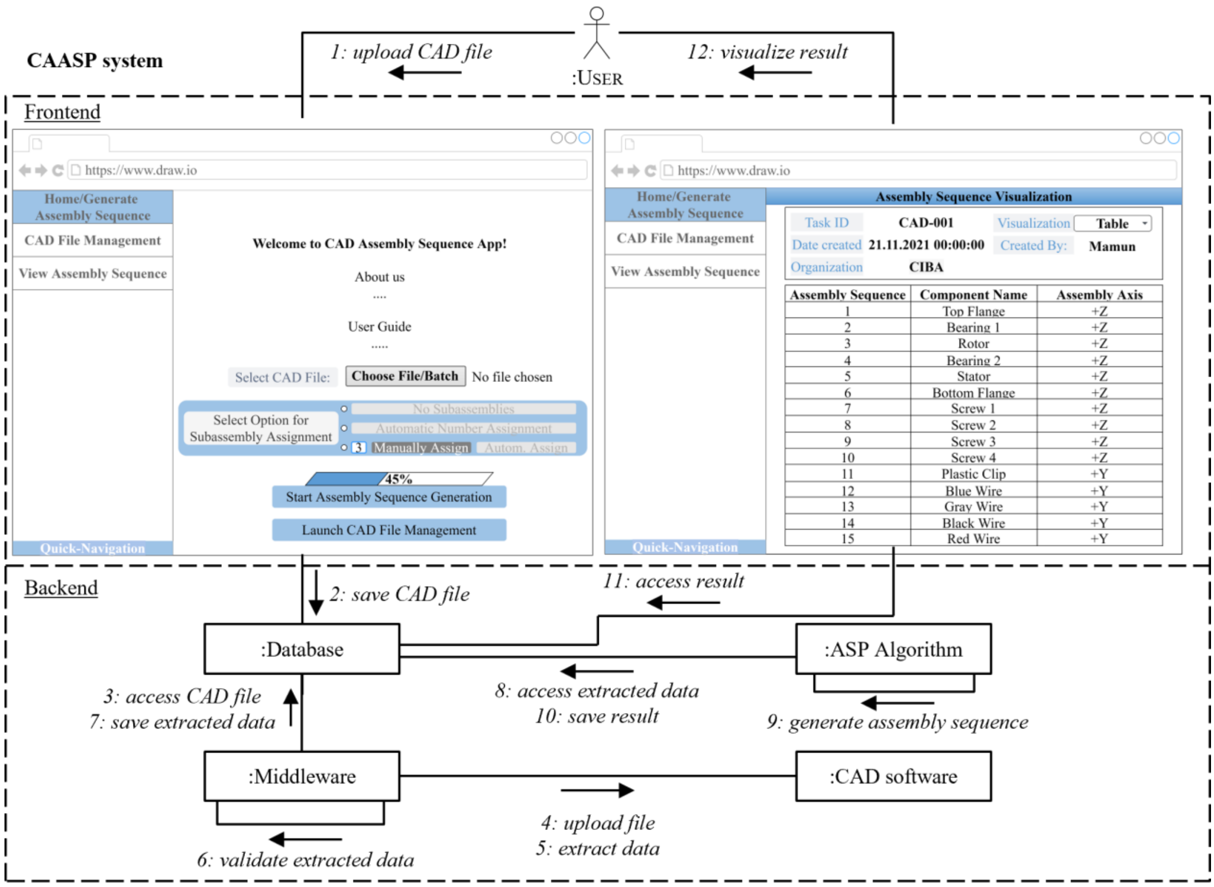

Figure 2: Frontend and backend of CAASP system

The ASP problem is first converted into a graph with nodes and edges as mentioned in Figure 3, step 3.1. The nodes are created by combining a part number and potential orientations along the six axes. For example, part 1 would have the nodes (1, '+x'), (1, '-x'), (1, '+y'), (1, '-y'), (1, '+z'), and (1, '-z') [39]. For the purpose of this research, minimal orientation change between parts has been identified as the primary requirement of an optimal assembly sequence. Each edge is initialized with a weight based on orientation change between two nodes that connect the edge. Angular changes of 0°, 90°, and 180° will results in a weight initialization of 1, 5, and 10 respectively. For example, an edge connecting (1, '+x') and (4, '+x') has a weight of 1, (1, '+x') and (4, '-y') has a weight of 5, and (1, '+x') and (4, '-x') has a weight of 10. Since the ASP problem can be represented as a graph with nodes and edges, the ACO method can be utilized to obtain a solution. Based on the logic of the algorithm, pheromone levels between all nodes are initialized with a concentration level The potential starting points for a sequence are identified by searching for rows with all zeroes in the interference matrix (step 3.1). All zeroes in a row of a part implies that the part is not blocked by other parts during disassembly. The number of ants is initialized to the number of starting points, and the ants are randomly placed at these points.

The following step is to identify the next feasible disassembly node for the ant. Out of the remaining components to be disassembled, parts that are not blocked by any of remaining components are selected using the interference matrix. The liaison matrix is then used to isolate parts from the selection that are in contact with the remaining components. If no parts are in contact, then the components chosen based on the interference matrix are directly utilized. Node selection from these potential nodes is done using the ACO probability formula as in [40]. The heuristic component in the algorithm becomes the weights, which are based on orientation initialized in the graph. Once the next part is selected based on the probability function, the algorithm checks if all the parts have been visited by each ant. If there are parts that still need to be visited by each ant, the node selection process is repeated. When all the parts have been visited, the pheromone levels for each path is incremented using the pheromone updating formula [40]. Once all the ants have completed an iteration, the best sequence of the iteration is selected based on the least number of reorientations (step 3.2). Subsequently, the pheromone evaporation is performed on all the edges using the evaporation formula in [40]. If iterations are still to be completed, the entire process is repeated. The optimal sequence is selected based on the global pheromone levels after all the iterations have been completed.

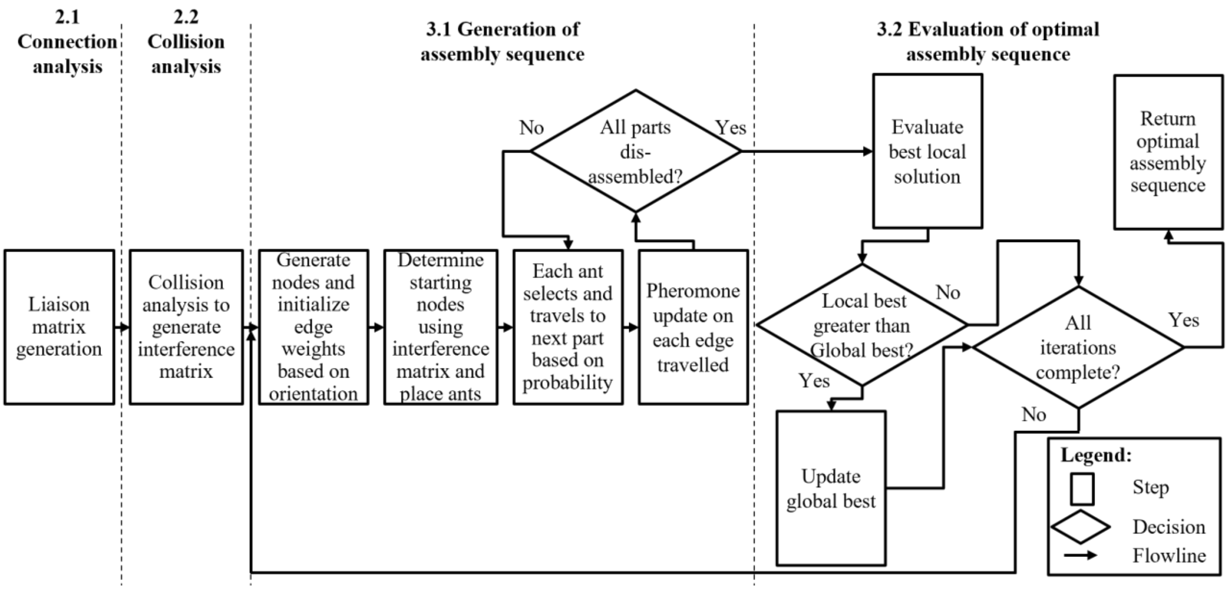

Figure 3: Detailed view of ASP methodology

4. Validation

The CAASP system is currently set up to automate the data processing between the user upload and the presentation of the result. To verify the practicability and accuracy of the methodology discussed, a 3D STEP file motor consisting of 15 components was chosen for validation [41] of the ASP methodology described in section 3.2. Figure 4 shows the CAD model, which represents a typical product in the Electronics Appliance Industry produced by contract manufacturers. The model contains 15 components that each have various contacts in the liaison matrix and multiple collisions along axes in the interference matrices. This model should ideally be assembled by dividing its components into two groups that are assembled along two different axes. Therefore, this motor model provides a relevant opportunity for the ASP methodology to optimize the assembly sequence by considering the minimization of component orientation changes during the assembly process.

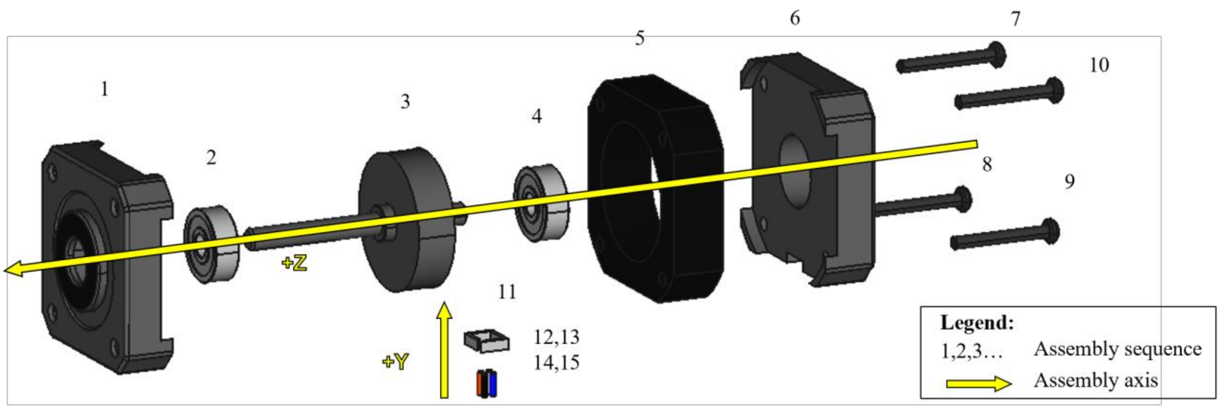

Figure 4: Labelled assembly sequence with directional axes (example)

The integrated system has been utilized to process a STEP file as input for the analysis. After the file is read, the system automatically calculates the liaison matrix, six collision matrices, and generates an optimal assembly sequence. The liaison matrix and collision matrix results are shown in Figure 5. Although there is one matrix for each of the 6 axes produced in the collision analysis results, only the +Z axis matrix is shown below for reference. The values in the first row and column ranging from 1 to 15 represent the components of the motor assembly, which can be referenced in the “Component Number” row of Table 1. The Component Number is used in this section for convenience of associating the values in the matrices with component numbers in the generated assembly sequence.

Liaison Matrix:

$$
\begin{array}{cc}
 & \begin{matrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \end{matrix} \\
\begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ 12 \\ 13 \\ 14 \\ 15 \end{matrix} &
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\
1 & 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\end{array}
$$

Interference Matrix: +Z Axis

$$
\begin{array}{cc}
 & \begin{matrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 \end{matrix} \\
\begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ 12 \\ 13 \\ 14 \\ 15 \end{matrix} &
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\end{array}
$$

Figure 5: Liaison matrix and one interference matrix in the +Z axis

It should be mentioned that although every assembly sequence generated by CAASP system is mechanically feasible, a minor number of generated sequences is not practical since bolts or screws are chosen as the first component of the sequence. The focus of the following is on most sequences that are both feasible and practical. A noteworthy aspect to discuss is how the CAASP system created one group of components to be sequentially assembled in the +Z direction and one group of components to be sequentially assembled in the +Y direction, as shown in Table 1. Figure 4 provides a visual representation for the labelled assembly sequence of each component along the assembly axes (example result). The results shown represent one variation out of many similar, potential optimal assembly sequences. Since the ASP algorithm attempts to optimize the assembly sequence by minimizing assembly axis orientation changes, the assembly sequence first consists of components from the +Z group, followed by components from the +Y group, thus resulting in an assembly sequence with minimum orientation changes. Based on the optimization criteria, when comparing the algorithm-generated assembly sequence to the known optimum assembly sequence, it can be shown that both sequences achieve the same level of optimization from a feasibility and assembly orientation perspective.

Table 1: Assembly Sequence Result (example)

Category	Output														
Assembly Sequence	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Component Number	9	8	4	6	7	10	5	13	15	3	12	1	2	14	11
Assembly Axis	+Z	+Z	+Z	+Z	+Z	+Z	+Z	+Z	+Z	+Z	+Y	+Y	+Y	+Y	+Y

The total runtime for the entire calculation takes 5.3 minutes on average. It should be noted that the liaison matrix calculation and optimized assembly sequence planning only require 15 seconds in total to complete, while the remaining 95% of runtime is spent on collision analysis for calculation of the liaison matrices. This highlights the need for further optimizations in the collision analysis method in future works.

5. Discussion and future work

The research work outlines a feasible solution for contract manufacturers to support the industrial engineers' planning of assembly sequences. The solution fulfils user-centeredness by a web-based frontend. System dependencies are reduced by a backend architecture that can be deployed company-internally or cloud-based. CAASP supports STEP format to build a vendor-agnostic solution. The methodology automates the ASP of contract manufacturers with minimal human intervention. The validation of the methodology shows the feasibility of the approach exemplified in the ASP of an electronic motor. Presently, the limitations are seen in the execution of CAASP as a high amount of computation time is needed for analysing part collisions. In the electronic motor example, this leads to a calculation time of 5.3 minutes for 15 parts in the liaison matrices. The industrial applicability of the approach is restrained by using the minimal orientation change between parts as a solemn optimization criterion. In the electronic motor assembly, this can result in proposing feasible but impractical sequences (minor cases). For example, the plastic clip precedes the wire assembly – although feasible, it is not practicable in an actual industrial setting. Future research aims at increasing the practicability of CAASP. It shall handle various optimization criteria and algorithmic constraints common in the electronic appliance industry. The CAASP system will be applied to several product types, models, and variants to adjust the system for wide usage in the industry. Furthermore, application engineering shall be conducted for seamless integration into business processes and high compatibility with state-of-the-art software vendors.

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