Collaborative Assembly Sequence Planning (CASP) for On-site Assembly of a Photovoltaic Power Station Considering Data Analysis

Pedro Vélez-Aristizabal*, Gilberto Osorio-Gómez

EAFIT University, Product Design Engineering Research Group, Medellín, Colombia

* Corresponding author. email: pveleza@eafit.edu.co.

Manuscript submitted August 19, 2022; revised January 18, 2023; accepted March 10, 2023; published July 3, 2023.

doi: 10.12720/sgce.12.3.73-80

Abstract: Assembly Sequence Planning (ASP) plays a fundamental role in estimating assembly resources since having a precise and identified amount of associated data will provide a more approximate vision of the on-site assembly and commissioning of the product. This would allow for optimal assembly work and cost reduction through better use of resources such as time, personnel, and equipment. Expert staff usually carry out ASP, making decisions based on experience and previous knowledge of the product and the manufacturing context. This article presents a collaborative procedure for the generation of assembly sequences of a case study of a renewable energy project through geometrical reasoning and logical reasoning with information related to sub-assemblies, constraints, limitations, and information on the precedence of sub-components. This approach allows for determining how this information influences the designation of resources (human and machinery) and cost and time estimation associated with each assembly task.

Key words: Assembly, assembly sequence planning, solar charging station, metadata, renewable energy.

1. Introduction

For the assembly of a product, there are many ways to plan the assembly sequence, from the use of Design for Assembly (DFA) software to the empirical approach or based on previous knowledge of the designer. Having precise and identified data as much as possible at the design formulation stage will be helpful at the time of assembly by making better use of resources and reducing product costs, making products more affordable, and, therefore, increasing the potential demand of new customers.

In the assembly process, many implicit variables are accompanied by data and figures that provide sufficient information to complete a correct assembly. This is executed in the best way (less time and fewer resources). Most of these data are reflected in the available resources that must be allocated when making the installation. The most common and relevant data could be time and costs. Still, associated with these, there may be limitations due to requirements, standards, available space, storage, tools, geographical location, shipping transfers, geometry shapes, loads to support, etc. Such information is open to the assembly staff and the engineering group developing the project, allowing the opportunity to propose a Collaborative Assembly Sequence Planning (CASP) approach, where people with different knowledge and points of view could present sequences and identify overlooked aspects.

Concerning the high demand for renewable energy sources in cities, there is a need to implement solar charging stations to power electric vehicles and devices. This opens opportunities to strengthen the development of on-site installation strategies to solve assembly problems of this type of device. According to this, the assembly of a solar charging station has been proposed as the case study for this research.

2. Related Work

Several authors present advances in Assembly Sequence Planning (ASP) corresponding to the assembly of products in industrial lines.

Tseng *et al.* made a "change" in the traditional graphing method, where the connectors related to the assembly of parts contain information such as combination, direction, tool, and cycle time. They use genetic algorithms to solve the layout of the connectors by finding similarities between them and the selection of the stations of the line, thus defining an assembly sequence [1]. Dong *et al.* used the assembly tree method based on the semantics of connections, demonstrating a knowledge-based approach that, through geometric information and non-geometric knowledge, can drastically reduce the complexity of planning assembly sequences [2].

Subsequently, Tseng *et al.* presented a particle swarm optimization (PSO) method, in which assembly and disassembly sequences are evaluated simultaneously to minimize the total costs of these operations [3]. At the same time, Demoly *et al.* defined the assembly sequence in the preliminary design phases by introducing and applying knowledge of the assembly process and context with a product life cycle management approach. They presented an algorithm based on a mathematical model that integrates boundary conditions related to DFA rules, engineering decisions, and product structure [4]. Wang *et al.* proposed a method for decomposing an assembly into sub-assemblies to reduce the difficulty of planning the assembly sequence of complex products, considering geometry, topology, and process constraints [5]. Thomas *et al.* presented an approach for planning feasible assembly sequences using AND/OR graphs, which considers geometrical, physical, and mechanical, as well as work cell-specific, constraints [6]. Finally, Su *et al.* proposed a multi-agent evolutionary algorithm for assembly sequence planning using the particle swarm optimization algorithm, using a varied population strategy which improves the efficiency and capacity of the evolution of the PSO algorithm. They also used evaluation indicators to construct a fitness function and achieve multi-objective optimization [7].

In summary, many ASP approaches consider the experience of designers and optimization algorithms. Still, all of them are based on one person or a specific group of experts and the available information for the approach. Then, it is possible to analyze a collaborative approach for ASP where different knowledge and points of view could be considered.

3. Collaborative Assembly Sequence Planning (CASP) Proposal

Usually, Assembly Sequence Planning (ASP) activities are carried out by production or industrial engineer with the knowledge and experience of the tools and resources available in a company, as well as the definition of properties according to the product. Most of these sequences are performed to solve assembly balances in industrial lines. The objective of this approach is to propose an activity where a group of engineers analyses a case of an on-site assembly project and how, using geometric-logical reasoning added to the metadata inherent to the assembly of components, they associate and generate data that can be crucial at the time of planning the assembly.

Geometric reasoning consists of how a person interprets images, while logical reasoning starts from information such as data on dimensions, weights, and descriptions of component precedence. Both conclude in the same "global" logic that is also supplied with data about available resources and limitations. Fig. 1 illustrates how data plays a crucial role in the reasoning stage of ASP.

The abovementioned metadata consists of attributes or elements necessary to describe a given resource, functioning as an identifier. It intends to provide the minimum information to identify a resource. Considering this definition, the context, content, and control information, the cataloging scope can be regarded as a process of metadata generation [8].

These data can be divided into two blocks: part data and context data.

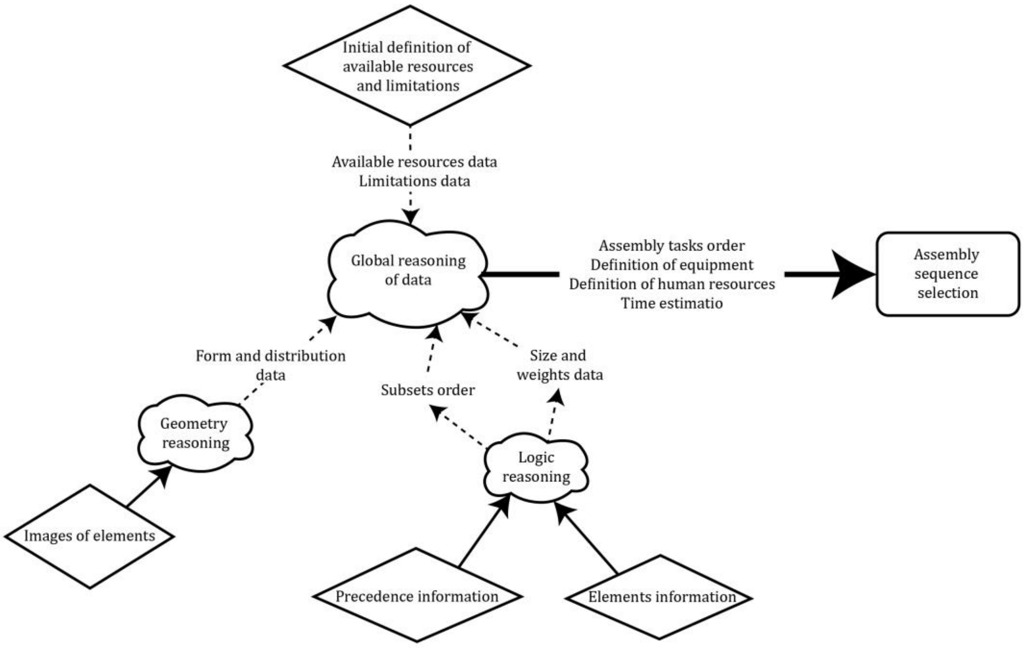


Fig. 1. Collaborative Assembly Sequence Planning (CASP) scheme.

3.1. Part data

This data refers to information about the physical properties and shapes of the product. For these, it is crucial to provide the planner with sufficient images to identify the parts.

Providing the weight of the components makes it possible to determine how to handle the element in terms of transportation and assembly. With this, it is possible defining if an operator can support the load of the component or if, on the contrary, it requires a tool for manipulation.

The location of the parts or sub-components within an assembly provides information on where it will be located and perhaps the function it fulfills in conjunction with the other parts of a product. This data informs if the part requires previous joints, post-processes, if fasteners are needed for its assembly, and indicates the correct assembly position. Using images of the part and the assembled product is advantageous to provide component location data. Once the locations of the components are precise, it is essential to define their assembly precedence since there are parts that must be assembled before others or subassemblies that require assembly priority to form an assembled product. This information benefits the person in charge of planning the assembly sequence and can be conveyed through illustrations and descriptions.

3.2. Context data

Most of the information is found in the context data since the human, tools, and economic resources must be mentioned, and constraints, cost, and assembly time could be estimated.

The assembly tools must be available when assembling components and include the elements required to perform the correct assembly of parts of a product. Consider whether the operator must be trained for the operation, the condition of the machinery or tool, the operating manual, or the datasheet. The assembly tool can be defined by the weight of the elements to be handled and the specific assembly requirements and complexity.

Human resources are essential since they will oversee performing the assembly tasks or operating machinery to carry out this work and ensure that the product is correctly assembled. It is crucial to determine the level of training that the person making the assemblies must have in terms of the product and the handling of tools or machinery. Human resources can be defined by the number of parts to be assembled, the weight of the components, the equipment to be used for the assembly, and the desired time.

Having these resources defined, the costs limiting the capacity to purchase or contract both assembly equipment and human resources can be determined. Costs can be represented in two ways: fixed costs which remain constant whether it is executed, and variable costs, which fluctuate over time or according to the resources.

Also, it is possible to define the activity times and total execution time, which depend significantly on the previous knowledge or experience of the operators in charge of carrying out the assembly or assemblies of specific components. It also depends on the operation times of the tools, the distances to be covered, or the paths to be followed for the assembly activity.

4. Case Study: Assembly on-site of a solar charging station

The case study presented in this article corresponds to a photovoltaic charging station with a single-axis tracking system. The station's function is to supply hybrid or electric vehicles, or smaller devices, with the energy required for their operation.

A group of 14 mechanical, mechatronics, physical, electrical, and product design engineers was convened for this exercise. In the execution of the activity, the engineers had to define an assembly sequence for the charging station using all the sub-elements that compose it and considering their dimensions, weights, and which group of parts they are assembled to identify the assembly times, observations, human resources required for assembly, tools needed and possible risks when performing the assembly.

Each participant was given a brochure containing all the necessary information for the installation. A slide showed the objective, the expected results, and the restrictions and limitations for the assembly of the components, accompanied by an image of the fully assembled station. The information provided in the slide is presented next.

4.1. Objective

Define an assembly sequence for the charging station using all the elements and considering their dimensions, weights, to which component they are assembled, assembly times, observations, and possible tools required.

4.2. Expected results

Assembly Sequence of components, Assembly time, Remarks, Human resources required for installation, Tools for assembly, Possible risks during assembly.

4.3. Restrictions and limitations

The maximum load weight of an operator is 20 kg; elements will be available in place at the assembly moment; there are four operators available; cranes, forklifts, slings, scaffolding, and ladders are available, as well as hand tools. There is the availability of a working area around the foundation, 50 m^2.

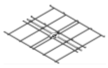
On the brochure, there was a table providing the following information:

Element name | Image | Nomenclature | Size | Weight.

The images associated with the sizes and weights gave participants a more precise idea to describe the expected activity results in greater detail, as seen in Table 1.

Besides, an isometric view and an internal exploded view of the station, shown in Fig. 2, were included to provide the information required to perform geometric reasoning.

Table 1. Metadata for each component.

Component data				
Component	Image	Nomenclature	Measures	Weight
Base		A	High: 1m Diameter: 2m	196kg
Bench		B1, B2, B3 & B4	Diameter: 1m wall thickness: 5cm	70kg each
Cover plate		C1 & C2	Diameter: 1,5m	23kg each
Shell		D1, D2, D3 & D4	High: 1m	15kg each
Control cabinet		E	High: 90cm Long: 60cm Wide: 35cm	30kg
Power cabinet		F	High: 90cm Long: 60cm Wide: 35cm	40kg
Battery rack		G1 & G2	High: 65cm Long: 60cm Wide: 26cm	17kg each
Pole		H	High: 4m Diameter: 35cm	196kg
Actuator		I	Long: 74cm	8kg
Solar panels		J1, J2, J3, J4, J5, J6, J7 & J8	High: 2,3m Long: 4,4m Wide: 4cm	30kg each
Panel frame		K	High: 4,6m Long: 44,4m Wide: 30cm	190kg
Batteries		L1, L2, L3 & L4	High: 50cm Long: 20cm Wide: 20cm	70kg each

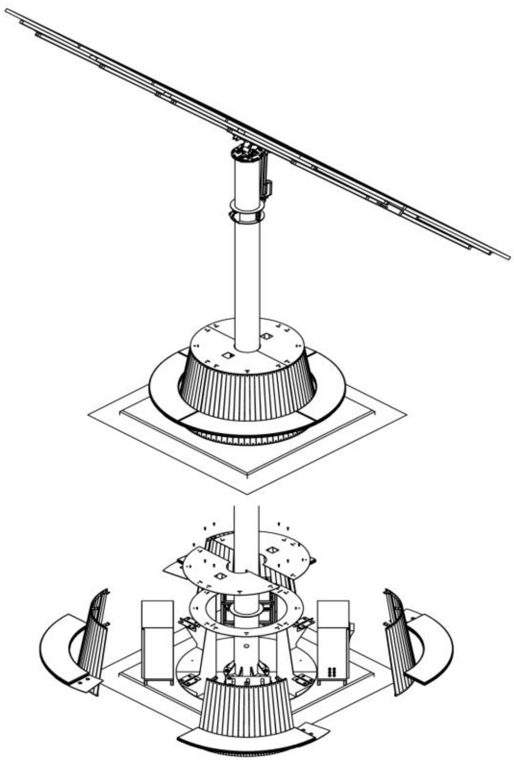


Fig. 2. Image of views of the station.

Fig. 3 shows the images of each component (sub-assemblies) with their respective nomenclature. This is to get an idea of the geometries and, together with the information illustrated as a reference in Table 1, define how to manipulate each of these elements.

Precedence information indicated which component was attached to another element and the required fasteners. Fig. 3 shows that the panels were not assembled in any order, so they were assembled in the desired order.

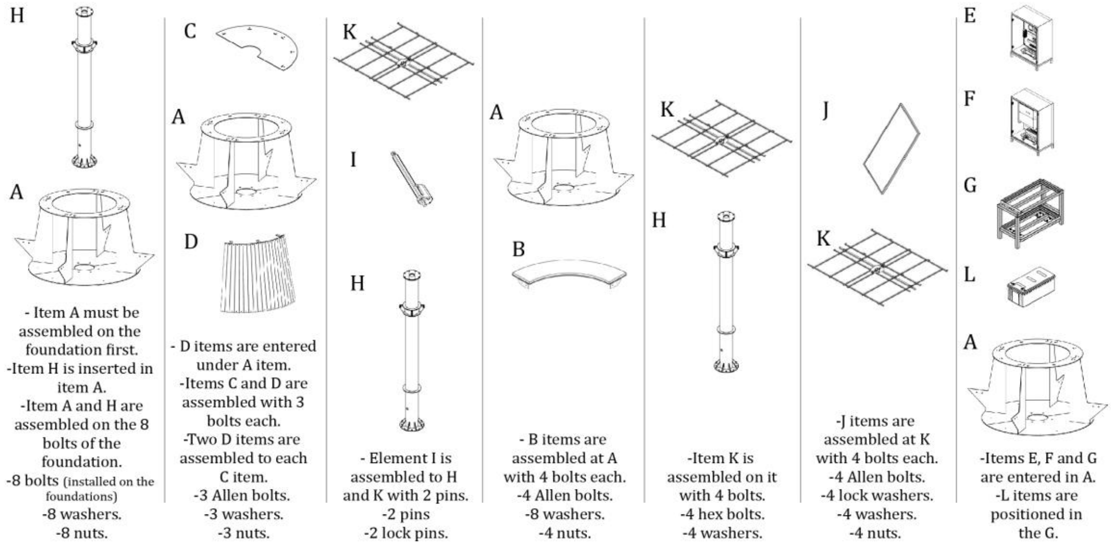


Fig. 3. Assembly conditions and precedence.

In addition, there is a table to fulfill, as shown in Table 2. Finally, there was a space where the risks identified during the assembly stage could be expressed.

5. Results

Each engineer defined an assembly sequence with the associated metadata for this exercise. The 14 plans were effective as they presented a logical order of assembly. These results reflect that 57 % of the sequences tend to assemble the heaviest, bulky components and those requiring work at height first with the use of the crane, slings, and scaffolding and with the coordination of operators to perform the orientation and unloading of the elements.

In the 14 assembly sequences in general, two main feasible ways were observed; the first way, more marked by 57% of the sequences, the panels are installed on the support structure on the ground, and already then, this structure is hoisted and installed on the pole. In a second way, the support structure of the panels is first assembled to the pole, and then the panels are installed.

Analyzing the results, an average execution time of 443 minutes with a deviation of 175 minutes was defined. Considering that the working day of an operator is 8 hours a day, then the installation of all the components could be carried out in only one working day with the collaboration of 4 operators. These sequences showed that the installation of all the parts would involve an average of 22 assembly activities with a deviation of 5 activities. This means that in all the sequences proposed, parallel assembly processes were considered since if a serial assembly had been carried out, the number of steps would have equaled the number of parts. Some of the variables identified in the activity results that are not generally identified in ASP are Alignment, Falling elements, Weather, Available tools, and Work area conditioning.

Table 2 shows an assembly sequence with 26 steps that fit the average obtained from all the sequences. This corresponds to the sequence proposed by a mechanical engineer. The assembly sequence starts with the assembly of the heaviest and bulky components that require work at height and must be lifted.

Table 2. Result of the assembly sequence proposed in the activity.

Assembly sequence											
No.	Components	Time	Observations	Human Resources	Equipment / Tools	No.	Components	Time	Observations	Human Resources	Equipment / Tools
1	A	20	Place on foundation	2	Crane						
2	H-A	50	Locate the post on the base, Place 8 H-washers, Tighten 8 H-nuts.	4	Crane and handheld tool	16	L2-G1	10	Place L2	3	
3	I-H	10	Install lower pin in I with H	2	handheld tool	17	L3-G2	10	Place L3	3	
4	K-H	60	Lift and position K at H, Insert 4 hex bolts, Insert 4 washers and Tighten 4 hex nuts.	4	Crane and handheld tool	18	L4-G2	10	Place L4	3	
5	I-K	10	Connect upper pin of I with K	1	handheld tool	19	E-A	10	Place E	2	
6	J3-K	30	Place J3, lock washer assembly, AR, TR	3	handheld tool	20	F-A	10	Place F	2	
7	J6-K	30	Place J6 , lock washer assembly, AR, TR	3	handheld tool	21	D1-A	10	Place D1	1	handheld tool
8	J7-K	30	Place J7, lock washer assembly, AR, TR	3	handheld tool		D2-A		Place D2	1	handheld tool
9	J2-K	30	Place J2, lock washer assembly, AR, TR	3	handheld tool		D3-A		Place D3	1	handheld tool
10	J4-K	30	Place J4,lock washer assembly, AR, TR	3	handheld tool		D4-A		Place D4	1	handheld tool
11	J5-K	30	Place J5, lock washer assembly, AR, TR	3	handheld tool	22	C1-A	10	Place C1	2	handheld tool
12	J8-K	30	Place J8, lock washer assembly, AR, TR	3	handheld tool		C2-A		Place C2	2	handheld tool
13	J1-K	30	Place J1, lock washer assembly, AR, TR	3	handheld tool	23	B1-A	10	Place B1	4	handheld tool
14	G1-A	10	Locate G1	1		24	B2-A	10	Place B2	4	handheld tool
	G2-A		Locate G2	1		25	B3-A	10	Place B3	4	handheld tool
15	L1-G1	10	Place L1	3		26	B4-A	10	Place B4	4	handheld tool

6. Conclusions

According to the results presented by the activity, it is determined that when performing collaborative work with several engineers, different resource management considerations are obtained on the same assembly sequence, which generates valuable complementary information at the time of making an ASP.

As the solar charging station is installed on-site, the entire assembly procedure of the components belonging to the project must be previously planned and verified by the occupational safety entity. This has established a guideline with norms and requirements for the installation and assembly services suppliers to comply with.

An analysis of the activity results shows that the participants' approach to resource allocation was linked entirely to geometric-logical information plus constraints and requirements. This was sufficient to present feasible assembly sequences. As mentioned in the results, 57% of the participants decided to do an assembly sequence of the parts, starting with the panels assembling on the structure and then lifting this sub-assembly to fix it to the post. In some of these sequences, risks of working at heights and lifting components were identified, which indicate that they prefer to avoid working at heights, thus reducing the chances of being considered dangerous work and the additional costs involved in having an equipment service for working at heights.

It is expected to develop a method that integrates product components, item descriptions and characteristics, precedence and requirements, constraints and limitations, and available resources to plan feasible assembly sequences, including sufficient information to carry out a product assembly in the field.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Both authors conducted the research, analyzed the data, and wrote the paper.

Acknowledgments

This research has been developed in the framework of the “ENERGETICA 2030" Research Program, with code 58667 in the “Scientific Colombia” initiative, funded by The World Bank through the call “778-201 Scientific Ecosystems”, managed by the Colombian Ministry of Science, Technology, and Innovation (Minciencias), with contract No. FP44842-210-2018.

References

[1] Tseng, H. E., and Tang, C. E. (Jan. 2007). A sequential consideration for assembly sequence planning and assembly line balancing using the connector concept. *http://dx.doi.org/10.1080/00207540500250606*, 44(1), 97–116, doi: 10.1080/00207540500250606.

[2] Dong, T., Tong, R., Zhang, L., and Dong, J. (May 2006). A knowledge-based approach to assembly sequence planning. *The International Journal of Advanced Manufacturing Technology, 32(11)*, 1232–1244, doi: 10.1007/S00170-006-0438-1.

[3] Tseng, Y. J., Yu, F. Y., and Huang, F. Y. (Apr. 2011). A green assembly sequence planning model with a closed-loop assembly and disassembly sequence planning using a particle swarm optimization method. *The International Journal of Advanced Manufacturing Technology, 57(9)*, 1183–1197, doi: 10.1007/S00170-011-3339-X.

[4] Demoly, F., Yan, X. T., Eynard, B., Rivest, L., and Gomes, S. (Feb. 2011). An assembly oriented design framework for product structure engineering and assembly sequence planning. *Robotics and Computer-Integrated Manufacturing, 27(1)*, 33–46, doi: 10.1016/J.RCIM.2010.05.010.

[5] Wang, Y. and Liu, J. (Feb. 2013). Subassembly identification for assembly sequence planning. *The International Journal of Advanced Manufacturing Technology, 68(1)*, 781–793, doi: 10.1007/S00170-013-4799-Y.

[6] Thomas, U., Stouraitis, T., and Roa, M. A., (Oct. 2015). Flexible assembly through integrated assembly sequence planning and grasp planning, *IEEE International Conference on Automation Science and Engineering*, vol. 2015-October, pp. 586–592, doi: 10.1109/COASE.2015.7294142.

[7] Williams J. *Narrow-band analyzer*. Ph.D. dissertation. Department of Electrical Engineering, Harvard University. Cambridge, MA; 1993.

[8] Su, Y., Mao, H., and Tang, X. (Jan. 2021). Algorithms for solving assembly sequence planning problems. *Neural Computing and Applications*, 33(2), 525–534, doi: 10.1007/S00521-020-05048-6/FIGURES/4.

[9] Agudelo Benjumea, M. M. (s.f.) Los metadatos. Recuperado de http://aprendeenlinea.udea.edu.co/lms/men/docsoac3/0301_metadatos.pdf