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A Systems Approach for Selection Between Manual and Automated Work Zones Within Assembly Lines

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A SYSTEMS APPROACH FOR SELECTION BETWEEN MANUAL AND AUTOMATED WORK ZONES WITHIN ASSEMBLY LINES

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ABSTRACT

Manufacturing firms are continuously looking forward to improve and optimize their processes to meet the requirements of mass production and product customization. In order to meet these demands, the operations on the assembly line need to be allocated with the right level of automation, such that neither the human nor the machine is underutilized With such an emphasis being put on assembly operations within manufacturing enterprises, there is a need for a systematic procedure that helps in identifying appropriate levels of automation (LoA) within different resolutions, such as at the workstation, and the band scales. Based on a literature review, it was seen that the research done within the area of LoA is not abundant, and the few methodologies that discuss about this aspect have their own benefits and limitations. The main aim of this thesis research is to develop a systematic methodology/approach that can help determine the appropriate at a systems level, by looking at various factors such as production volume, production flow, the no. of variants and other factors.

To arrive at this, a set of requirements are defined that can be used to judge the most suitable method from the existing literature. The most suitable method would be a method that satisfies all the requirements and helps in determining the appropriate LoA at workstation and band scales. Two methods: 1) B&D method and 2) Dynamo method partially satisfy most of the requirements and are combined together in order to form a new integrated method that can help in determining the appropriate levels of automation to be applied at workstation and band scales.

Both the methods are validated based on 4 individual case studies performed at 2 different manufacturing firms. Based on the results obtained both the methods are useful at the workstation level but fail to determine the appropriate LoA at the band level. The integrated method is then applied to the operations at one of the manufacturing firms, to suggest possible improvements within the levels of automation currently being implemented at the firm.

DEDICATION

This thesis is dedicated to my parents, Nitin Dhulia and Vandana Dhulia, and my sister, Megha Dhulia. The constant support and affection provided by them has given me the motivation needed to finish this thesis. Without my family, I would not have had this wonderful opportunity for higher education.

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I would like to thank all members of the CEDAR lab. Discussions and collaboration with the member of CEDAR helped me further advance my education outside of the classes, and helped me form the basis for my research.

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TABLE OF CONTENTS

Table of Contents (Continued)

Page

LIST OF TABLES

Page

List of Tables (Continued)

Page

LIST OF FIGURES

Page

List of Figures (Continued)

Page

List of Figures (Continued)

Page

List of Figures (Continued)

Page

List of Figures (Continued)

Page

List of Figures (Continued)

Page

Chapter One
MOTIVATING LEVEL OF AUTOMATION RESEARCH

1.1 Motivation behind the research

In a modern manufacturing enterprise, the assembly work accounts for 20–70% of the total production work with an average of 45% [1] .Furthermore, assembly costs play a significant role in overall production and often account for more than half of all the direct cost involved in manufacturing [1]. This shows the importance given to assembly operations within any manufacturing enterprises. Also, in the recent times the rise in the demand for customized products has led to an increase in product complexity [2]. In order to meet these demands, there has been an upsurge in complex production systems and the level and extent of automation being employed within the industry [3].

Furthermore, Decisions made during the conceptual stages of design have a major effect on the subsequent stages. In fact, more than 70% of a manufacturing cost of a product is defined at the conceptual stage [4] including the assembly cost which is also determined at the design stage [5]. Thus determining the assembly method during the design phase of the system can help the manufacturer avoid unnecessary costs in making design changes to the product features or making changes to the assembly line at a later stage. To advocate for this, there is a need for a systematic procedure that helps in identifying appropriate levels of automation (LoA) within different resolutions, such as at the workstation, band, or plant scales depending on product complexity. Previous research within the area of determining the appropriate level of automation primarily focuses on analyzing the effects of change in automation on cognitive factors such as human performance, situation awareness and mental workload [6–9]. Majority of the previous research makes use of psychomotor experiments with visual simulation tasks in order to analyze how change in the level of automation being employed effects the human performance. However, as compared to a visual simulation task, the operators may or may not experience the same type of conditions while performing a mechanical assembly task. Also, there has been little focus [5,10,11] on determining what level of automation would be suitable at desired scales of resolution and what factors play a crucial role in the decision of determining the accurate level of automation in terms of an assembly line. Therefore, the main aim of this research is to develop a systematic method that can help determine the appropriate level of automation at different scales of resolution, by considering various factors such as production volume, production flow, number of variants, and cost of maintenance.

1.2 What is Level of Automation (LoA)?

Before defining the term level of automation (LoA) it would be beneficial to define the term "automation" as will be used within the context of this research. The reason for this being that, the term automation has different interpretations within different fields of study. As mentioned in the Michigan Business review [12], in automation we have a word that is not yet used with very much consistency. For example, within the field of bionics, automation can be defined as *the science or study of how man and animals perform tasks and solve certain type of problems involving use of* *the body*[1]. However, within the field of cybernetics, automation can be defined as *the comparative study of complex electronic devices and the nervous system in an attempt to understand better the nature of the human brain*[2]. Within the scope of manufacturing, automation can be defined either as *the automatic operation or control of equipment, a process, or a system* or *the techniques and equipment used to achieve automatic operation or control*[3]. It can be seen here that, within the scope of manufacturing, there is a slight difference between the definitions of automation. While the 1st definition primarily talks about automating a task by use of machines in order to achieve a particular result. The 2nd definition would be more apt in order to build a machine that can be used to automate a task. Consequently, for the purpose of this research, we will be primarily looking at different definitions of automation within the field of manufacturing. According to The Oxford English dictionary (2006), automation in the field of manufacturing can be defined as,

1) Automatic control of the manufacture of a product through a number of successive stages,

2) The application of automatic control to any branch of industry or science,

3) By extension, the use of electronic or mechanical devices to replace human labor.

However, these definitions indicate that there might be a possibility to regard automation as a binary feature i.e. you either have it or do not have it [11]. There is no

[1] Source: http://www.thefreedictionary.com/automation (Accessed: 2015.07.07)
[2] Source: http://www.thefreedictionary.com/automation (Accessed: 2015.07.07)
[3] Source: http://www.thefreedictionary.com/automation (Accessed: 2015.07.07)

evidence within these definitions for possibilities of partial automation. Clearly, automation does have its own benefits, and many complex human-machine systems cannot be operated successfully without it [13]. Automation has proven to be of use to humans in various situations, such as in hazardous environments, in scenarios where the human has to deal with a vast amount of mental work load. For example, in the aircraft industry, where the operators at the Air Traffic Control (ATC) tower have to give directions to manage multiple airplanes at the same time, automation has proved to be a blessing in disguise. Still, having completely autonomous systems has its disadvantages as well. Poorly designed automation can lead to an increase in the number of accidents, decrease in situation awareness and increase in mistrust in automation. Thus, a definition that would consider the possibility of partial automation would be helpful. Parasuraman *et al.* [6] define automation as *a device or a system that accomplishes (partially or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator*.

This definition of automation would be considered apt to further define the level of automation as it also considers the possibility of implementing partial automation. Since this definition considers the possibility of partial automation, automation can vary across a continuum of levels ranging from the lowest level of fully manual performance to the highest level of full automation [6]. The levels ranging in between fully manual and fully automated allow for partial automation. Accordingly, this can be considered one of the definitions of LoA.

There are various other definitions for LoA within the existing literature that can be built upon in order to create an updated definition for LoA, to be used in a generic manner. LoA can be defined as the allocation of physical (mechanical processes) and cognitive (informational processes) tasks between humans and technology [11], as ranging from totally manual to totally automatic. As per this definition of LoA, the allocation of tasks between human and machine is done based on a reference scale ranging from one to seven, with one being completely manual and 7 being completely automatic. The intermediate values in the reference scale result in partial automation with the human or the machine having a certain amount of authority depending on the value of physical and cognitive LoA.

LoA can also be defined as the portion of automated functions of a system in relation to the complete function of the system [14]. Each level of automation here is associated with a certain amount of manufacturing costs such as costs associated with personnel, costs associated for operating material, costs associated for information. Depending on these costs an appropriate level of automation can be chosen to be employed. Fasth and Stahre [15] define LoA as

The allocation of physical and cognitive tasks between humans and/or technology, described as a continuum ranging from totally manual to totally automatic.

This definition allows for the possibility of partial automation by allowing for the possibility of task allocation between human and technology. For the purpose of this research, Level of automation (LoA) will be defined as:

The allocation of tasks between humans and/or machines, where the tasks can be performed ranging from completely robotic execution to completely manual execution.

As shown in Figure 1.1, the highest level of automation is shown as a robot, i.e. the robot has complete authority to take decisive actions and performs all necessary operations to achieve the desired result. Likewise, the lowest level of automation can be considered as one where the operator uses their own knowledge to take decisive actions and uses their own physical strength without the aid of any tools to perform necessary operations. The intermediate LoA's involve split distribution of authority and control between human and machine. Similarly, for achieving the mechanical tasks, the human operator might be provided with some form of aid such as manual tools, semi-automated tools or probably the operations might be performed using dedicated machines.

Figure 1.1: Levels of Automation

1.3 Literature review in the field of Level of automation

In this section of Chapter 1, we will be discussing about the existing literature within the area of determining the appropriate levels of automation in the field of manufacturing.

1.3.1 Methodology developed by Parasuraman and Sheridan [6]

According to the methodology developed by Parasuraman and Sheridan, automation refers to the full or partial replacement of a function previously carried out by the human operator [6]. Sheridan and Verplank's objective was to define 'who' (the human or computer) has control in a more definitive sense and not to explicitly describe how an operator and automation might share core information processing functions in complex system control [9]. Therefore this methodology provides a possibility to partially automate the tasks. The automation can vary across various levels of automation such as the lowest level of fully manual performance to highest level of completely automated performance. The authors develop a 10 point scale (Figure 1.2), based on a previously proposed scale [16], where the computer (automation) has the higher authority as the level of automation increases and the human (manual) has the higher authority as the level of automation decreases.

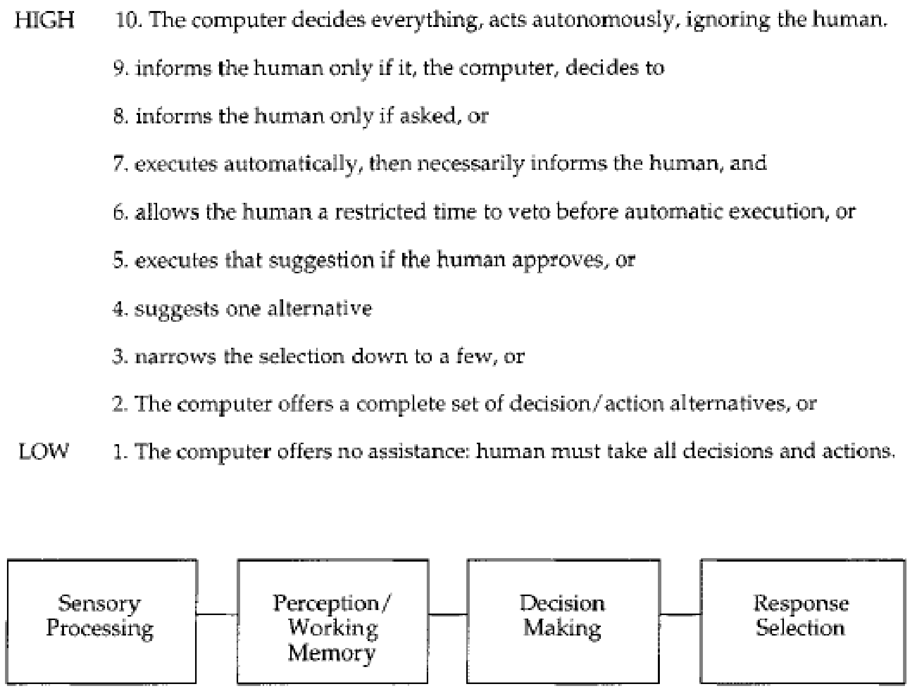

Figure 1.2: LoA taxonomy developed by Sheridan and Parasuraman (2000) [6]

Furthermore, the levels of automation within this methodology are to be assigned into two different aspects of automation:

1) Decision Automation (Informational): As can be seen from Figure 1.2, the sensory processing, working memory and decision making are all elements of decision automation. The decision automation comes into picture with respect to the processing of information. For instance, an operator has to make a decision about installing a nut within the assembly with 4 different types of nuts available. If the decision automation is assigned a value of one, then the operator will have to choose the correct nut for installation based on their own knowledge or experience, but if the decision automation was assigned a value of 5, then the computer selects one nut from the 4 available nuts but will only allow the human/machine to install the nut if the operator approves of it.

2) Action automation (Physical or Mechanical): The last element in Figure 1.2 i.e. the Action execution is an element of Action automation. The automation of this stage involves different levels of machine execution of the choice of action, and typically replaces the hand or voice of the human [6]. For instance, in a mechanical assembly task involving fastening a screw, the task can be done completely manually or in a partially automated manner. If the action automation is assigned a value of one, then the operator will have to install the nut completely manually, but if the action automation is assigned a value of seven, then the machine performs the operation on its own and only then informs the human.

While this methodology acts as a good tool to assign levels of automation to tasks involving decision making within a manufacturing enterprise, there is still not enough evidence within the methodology to appropriately allocate the right level of mechanical automation. This is due to the reason that, the method provides insufficient evidence to help determine what process to automate and what not to automate. A good method should be accurately able to predict the type of machine/ tools that need to be used to perform an assembly operation, i.e. whether to use manual tools? Whether to use semi-automated tools? Whether to employ a robot?

Besides this, the method also does not consider aspects like production volume, the number of parts within the assembly, process flow and other such information that may be of prime importance for to appropriately determine the right level of automation. However this method can serve as good tool to assign appropriate level of decision automation.

1.3.2 Methodology developed by Kapp [17]

The USA principle is an abbreviation for “Understand-Simplify-Automate”. This principle was developed in order to develop an effective way to perform Enterprise Resource Planning (ERP) [17]. The methodology primarily consists of three stages that are to be performed in a sequential manner before a decision is made to automate or not. The three stages of the methodology are:

Understand- This step involves in depth analyzing and understanding the process that needs to be automated. For instance if a certain section of a process needs to be automated, it is important to first understand the process flow and its characteristics, the inputs and outputs coming and going out of the system. By understanding this beforehand, it becomes easier to determine the factors that will be affected by implementing the change.

Simplify- The next stage of the methodology involves simplifying the operations to the maximum extent as possible. This step can be often executed with the help of checklists and questioning the existing process to check if each operation on the process is currently being performed in the simplest manner that it can be performed. If not, then how the respective steps can be simplified further? This step can help in determining what steps require automating and what steps can still be kept manual.

Automate- Once the process has been understood and simplified to the maximum extent possible then, the necessary operations can be automated, based on the manufacturer’s strategy.

An advantage of this methodology is that it provides importance to understanding the process and trying to simplify the process before considering automation. Many a times, operations on an assembly line can probably be performed in a simpler manner, without the need for automation. However, this depends on how much knowledge the person responsible for automating the operations, has about the current process.

The method also has a few limitations in a way that it does not explicitly help in determining what process to automate and what not to automate. This again solely depends upon the manufacturer's strategy and their knowledge about the functioning of the process. Another limitation within the methodology is that, it does not allow the possibility for partial automation, because according to the method, after the simplification, the result is either automat or do not automate.

1.3.3 Methodology developed by Endsley and Kaber [9]

Building on the work of Sheridan and Verplank [16], this methodology was developed during the year 2004, and involves a ten level LoA taxonomy used to provide wider applicability to a range of cognitive and psychomotor tasks within various domains including air traffic control, advanced manufacturing and teleoperations [9]. The ten level taxonomy are based upon four generic functions particular to these domains. The generic functions considered for the construction of the taxonomy are comparable to the functions within the methodology developed by Parasuraman et al [6]. The four generic functions are:

1) Monitoring – This function includes activities that are related to perceiving the system status in order to arrive at a decision.

2) Generating – Based upon the perceived system status, the different alternatives or options that can be used to achieve the task are generated within this function.

3) Selecting – Depending on the various alternatives produced during the generating function, the best alternative to achieve the task is selected in this function.

4) Implementing – To achieve the goal, this function is used to execute the chosen alternative through controlled actions at an interface.

Compared to the method developed by Parasuraman et al [6], the monitoring function is comparable to sensory processing, the generation function is analogous to perception/working memory, the selection function is equivalent to decision making and the implementation function is similar to response selection. The ten levels of automation developed in this methodology are shown in Figure 1.3.

	Roles			
Level of automation	Monitoring	Generating	Selecting	Implementing
(1) Manual control	Human	Human	Human	Human
(2) Action support	Human/computer	Human	Human	Human/computer
(3) Batch processing	Human/computer	Human	Human	Computer
(4) Shared control	Human/computer	Human/computer	Human	Human/computer
(5) Decision support	Human/computer	Human/computer	Human	Computer
(6) Blended decision making	Human/computer	Human/computer	Human/computer	Computer
(7) Rigid system	Human/computer	Computer	Human	Computer
(8) Automated decision making	Human/computer	Human/computer	Computer	Computer
(9) Supervisory control	Human/computer	Computer	Computer	Computer
(10) Full automation	Computer	Computer	Computer	Computer

Figure 1.3: LoA taxonomy developed by Endsley and Kaber [9]

The LoA taxonomy developed here has a scale of one to ten with one being completely manual and 10 being completely automated. The intermediate LoA share the performance of tasks between the human and the computer. A benefit of using this LoA taxonomy would be that, it allows us to apply the LoA at different levels of information processing, such as monitoring, generating or selecting. Depending on which area within the task operation needs to be automated, the LoA for the responsible generic function can be modified.

However, the limitations within this methodology lie in terms of the resolution given to the LoA for informational and mechanical tasks. Looking at Figure 1.3, it can be seen that the allocation of LoA is such that the task is done either by a human or a computer, whereas there is no collaboration between the human and the computer in any scenario. This shows that there is no consideration given to the possibility of partial automation. Also there is no possible way to trace the analysis of the decision for future modification purposes.

1.3.4 Methodology developed by Boothroyd & Dewhurst [5]

The methodology developed by Boothroyd and Dewhurst, explicitly does not consist of a LoA taxonomy in particular but provides the users with a step by step approach to determine the appropriate assembly method for a particular station depending on certain product and production parameters.

The product parameters consist of number of parts design changes during the 1st three years with regard to the total number of parts (ND), number of different product styles to be assembled (NP) [18] , total number of parts in the complete assembly (NA), total number of parts required to build different product styles (NT). The production parameters consist of the annual production volume per shift (VS), the potential for investment in automation (RI), the fluctuations in demand, the number of shifts (SH), the annual salary of an assembly operator (WA).

Based on these parameters, that need to be defined before the analysis, the appropriate assembly method can be determined. Once the parameters are known, the analysis is done by calculating the annual production volume, the potential for investment in automation and calculating the ratio of total number of parts required to build different product styles to the number of parts in the complete assembly. Depending on the values obtained from these calculations, the appropriate assembly method can be determined by maneuvering within the table shown in Table 1.1.

The benefits of this method are that provides consideration for cost minimization and profitability by considering the manufacturer's strategy and provides the manufacturer freedom to decide whether to invest in automation or not depending on the results provided by considering the risk investment potential. Also, it considers production volume as one of the important factors in choosing the assembly method. The consideration of the production volume is important, because if the production volume is low, investment in automation may lead to significant losses, unless the nature of the operations being performed call for the necessity of automation.

One of the limitations within this methodology is that, it does not consider process flow as one of the parameters before calculating the decision, due to which this method may be helpful for determining the assembly method for individual stations but may not be helpful to determine assembly methods at the band scale. Also, as compared to the other methods that provide significance to informational automation, this method openly does not consider any aspects of information processing.

Table 1.1: Selection table for appropriate assembly method (reproduced from [5])

			0	1	2	3	4	5	6	7	8	9
			NP = 1 (Single product without significant variations in demand)								Variety of diff but similar products	Variety of products
			(NT) < 1.5 (NA) ***and*** (ND) < 0.5 (NA)				(NT) ≥ 1.5 (NA) ***or*** (ND) ≥ 0.5 (NA)					
			RI ≥ 5	5>RI> 2	2 ≥RI≥ 1	RI < 1	RI ≥ 5	5 >RI> 2	2 ≥RI≥ 1	RI < 1		
			0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
VS > 0.65 million assemblies per shift annually	NA ≥ 16	**0**	AF	AF	AF	MM (AF)	AP	AP	AP (MM)	MM	MA (AP)	MA
	15 ≥ NA ≥ 7	**1**	AF	AF (AI)	AI (AF)	MM(AI)	AP	AP	MM (AP)	MM	MA	MA
	NA ≤ 6	**2**	AI	AI	AI	AI	AI	AI (AP)	MM	MM	MA	MA
0.65 ≥VS> 0.4 million assemblies per shift annually	NA ≥ 16	**3**	AP	AP	MM (AP)	MM	AP	AP	AP	MA (MM)	MA	MA
	15 ≥ NA ≥ 7	**4**	AI	AI	AI	MM	AP	AP	MM (AP)	MA (MM)	MA	MA
	NA ≤ 6	**5**	AI	AI	MM (AI)	MM	AI (MM)	MM	MM	MA (MM)	MA	MA
0.4 ≥VS> 0.2 million assemblies per shift annually	NA ≥ 16	**6**	AP	AP	MM	MM	AP	AP	AP	MA	MA	MA
	15 ≥ NA ≥ 7	**7**	AI (MM)	MM	MM	MM	AP	MM	MA (MM)	MA	MA	MA
	NA ≤ 6	**8**	MM	MM	MM	MM	MM	MM	MA (MM)	MA	MA	MA
VS ≤ 0.2 million assemblies per shift annually		**9**	MM	MM	MM (MA)	MM	MM	MA	MA	MA	MA	MA

1.3.5 Methodology developed by Fasth and Stahre [15] [19]

The Dynamo methods developed by Fasth and Stahre were developed at the Chalmers University of Technology in Sweden over a period of three years from 2007 to 2010. The methods are used to optimize the levels of automation on an assembly line by assignment of a minimum and a maximum LoA for each station on the line. The assignment of minimum and maximum LoA are done based on reference scales developed for mechanical and informational LoA shown in Figure 1.4. Once the assignment of minimum and maximum LoA is done for the task / station, a Square of

Potential Improvement (SoPI) (Figure 1.5) is developed for each station / task, which can help in showing the flexibility available to automate or de-automate.

Levels	Mechanical	Information
1	Totally manual	Totally manual
2	Static Hand tool	Decision giving
3	Flexible hand tool	Teaching
4	Automatic hand tool	Questioning
5	Static work station	Supervising
6	Flexible workstation	Interventional
7	Totally automatic	Totally automatic

Figure 1.4: Reference scales for LoA developed by Fasth and Stahre (reproduced from [15]**)**

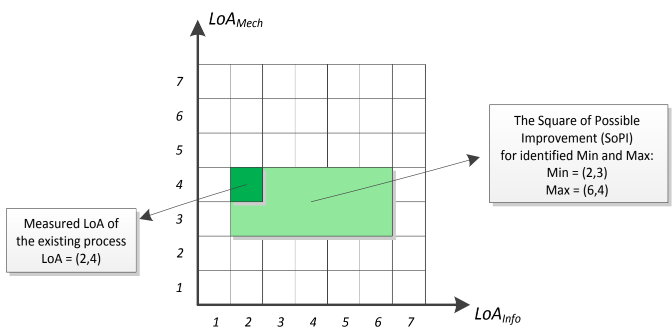

Figure 1.5: Square of potential improvement (from [18]**)**

The 1st method developed by the authors is called the Dynamo (abbreviation for Dynamic levels of automation) and consists of 4 phases in particular to optimize the level of automation. The 1st phase of the method is the Pre-study phase, where in operation instructions are requested from the company and pre-assessment of LoA is done, after which the documentation of the current process flow is performed along with calculating the current LoA being implemented. The 2nd phase is the measurement phases, where in the documented production flow is analyzed and the tasks within the current tasks are broken down using Hierarchical Task analysis [20]. The 3rd phase is the analysis phase, where the assignment of minimal and maximal LoA is done depending upon the nature of the tasks and the required production volume. This phase also involves the construction of the SoPI for each station or task to analyze the flexibility available to automate or de-automate. After the construction of the SoPI for each station / task, the final phase involves the implementation of the suggested decisions.

The 2nd method is the almost similar to the 1st method and will be called the Dynamo ++ for ease of understanding. The Dynamo++ includes all the phases involved in the Dynamo method, with a few additional steps that involve Value stream mapping within the production flow to identify flow and time parameters and following up with the company after implementation of the suggested decisions.

One of the most important benefits of this method is that, unlike the previous methods it provides significance to process flow, which was only considered till now in the USA principle [17]. Also, as compared to the previous LoA taxonomies, this method consists of an LoA taxonomy that has levels of automation providing equal importance to mechanical and informational automation. Consequently, by developing a SoPI, the manufacturer does not have to adhere to a rigid decision, but is given the freedom to choose from a potential area of automation levels.

Although a minor limitation within the methodology is that, unlike the methodology developed by Boothroyd and Dewhurst [5] there is no explicit importance given to parameters related to the products design, but since it considers the process flow the product design parameters maybe implicitly considered within the process.

1.3.6 Methodology developed by Ross [21]

The main aim of this methodology is to economically determine the optimal LoA within assembly operations. To determine this LoA, the method considers product information such as the total amount of quantity that has to be assembled, the features of the parts going into the assembled product and the types of fastening operations that go into completing the assembly [21]. The 1st step within the methodology is to evaluate the technical efforts required to economically automate the joining and fastening operations of the assembly processes [22]. Based on this evaluation, the result of each assembly operation is called an “effort value”. This effort value is then compared to threshold values present in the company’s database based on analyses that may have been done earlier. If the effort value is less than the threshold value, then the possibility to automate can be considered, but if the effort value is more than the threshold value then automation cannot be considered. A potential benefit of comparing the effort value to the threshold value is that, if more effort is going into the joining and assembly operations by making the necessary changes then it would still be beneficial to perform the operations according to the threshold value itself. In a similar manner, the steps shown in Figure 1.6 can be followed to decide whether to automate or not.

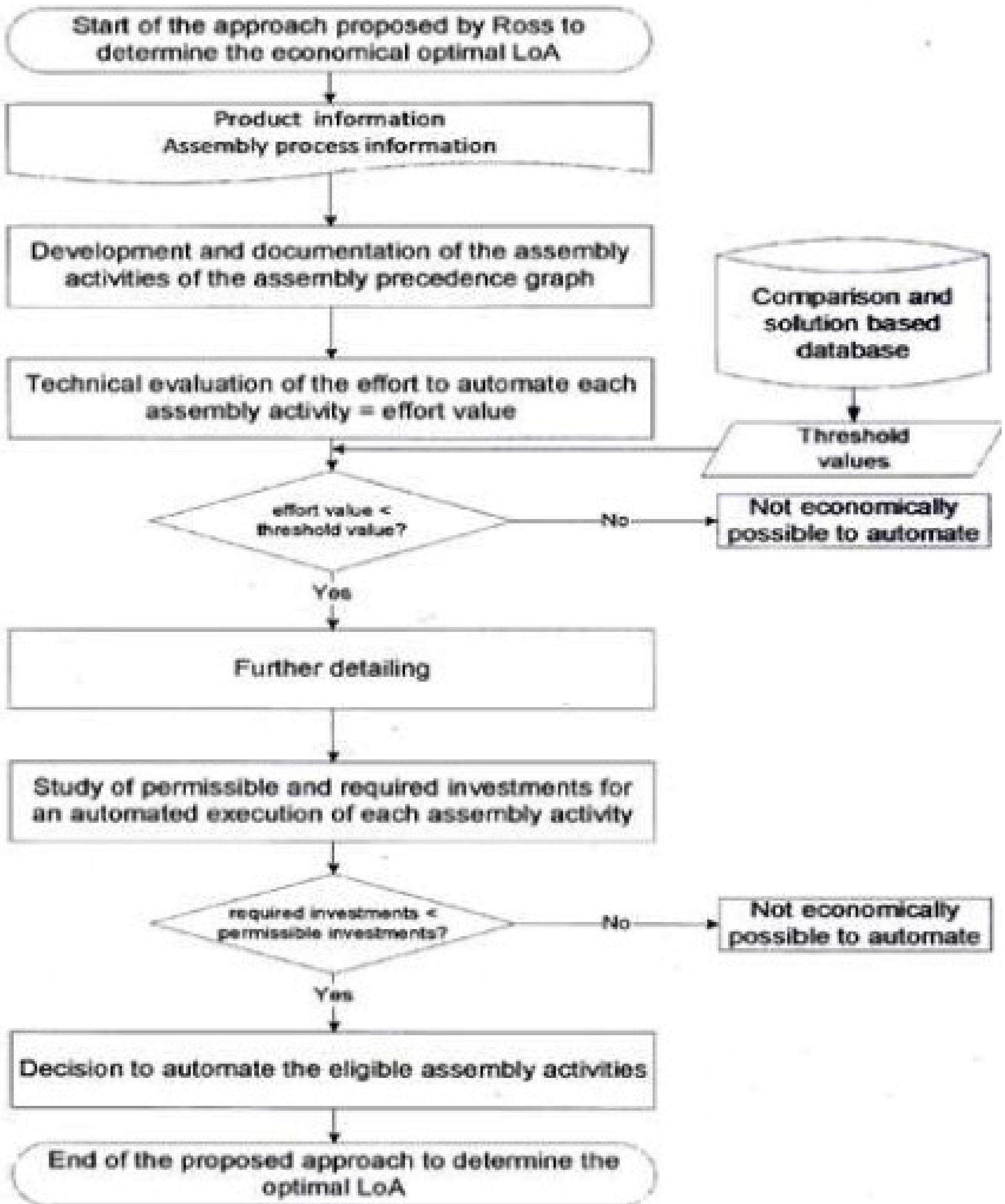

Figure 1.6: Sequential steps within methodology developed by Ross [21] [22]

The benefit of using this method is that important parameters associated with a real time production such as part features, production volume and level of difficulty associated with performing the tasks are considered. However, there is no definitive solution about the particular level of automation that needs to be assigned, by using this method, due to which the method yet does not prove to be a satisfying method for the purpose of this research.

1.3.7 Methodology developed by Lindstrom and Winroth [23]

The methodology developed by Lindstrom and Winroth seeks to make use of the Dynamo methodology in order to align manufacturing strategies of a manufacturer with the levels of automation suggested by the Dynamo methodology. By aligning these together, an automation strategy is formed which secures a desired direction of the firm and also supports the robustness and reliability of the manufacturing system [23].

The methodology consists of a sequence of 5 steps with the inclusion of the steps involved in Dynamo. The 1st step of this methodology, involves the formulation of a plan to execute the methodology. The 2nd step involves setting up a meeting with the company executives to discuss and understand the manufacturing strategy that the company is willing to implement. For example, if the manufacturing strategy of the company is to automate as many operations as possible, then the approach considered while assigning minimal and maximal LoA in the Dynamo methodology would be different compared to the approach taken if the firm is looking to de-automate. Once the manufacturing strategy has been discussed and agreed upon, then the 3rd step is the execution of the Dynamo method to determine respective LoA currently being implemented at the company. After this, the 4th step is the assignment of minimum and maximum LoA can be done to align with the company's manufacturing strategy. Finally, the 5th step involves the documentation of the results obtained within Steps 2 - 4. These documented results can then be discussed with the company to see if accurately aligns with the firm's manufacturing strategy or any changes are required.

This methodology helps in including another aspect of aligning manufacturing strategies with levels of automation, to the Dynamo methodology. This can be helpful in a way that, if the company's investment potential isn't too high, then obviously the company would not be looking to automate to a great extent. In this manner, the respective LoA for the tasks / stations can be assigned in a controlled manner, keeping the firm's manufacturing strategy in mind.

1.3.8 Methodology developed by Konold and Reger [24]

The LoA methodology developed by Konold and Reger consists of 4 levels of automation as shown below:

- Manual assembly where the sequence of workstations are not mechanically chained (Transfer of product by hand)
- Manual assembly where the sequence of workstations are mechanically chained (Automated transfer of product)
- Hybrid assembly consisting of manual and automatic assembly stations
- Automated assembly consisting of automatic assembly stations

The methodology follows a question and an answer approach with a set of seven questions in the form of a flow chart, where depending on the answer to each question, the flow chart directs the user to the next step. The questions seek to answer questions such as the quantity of production, the difficulty of tasks, period of time that is available until start of mass production, work content per product or assembly and the time after which the product may undergo changes. These steps shown in Figure 1.7 finally lead to a potential assembly system that can be applied to achieve the assembly operations.

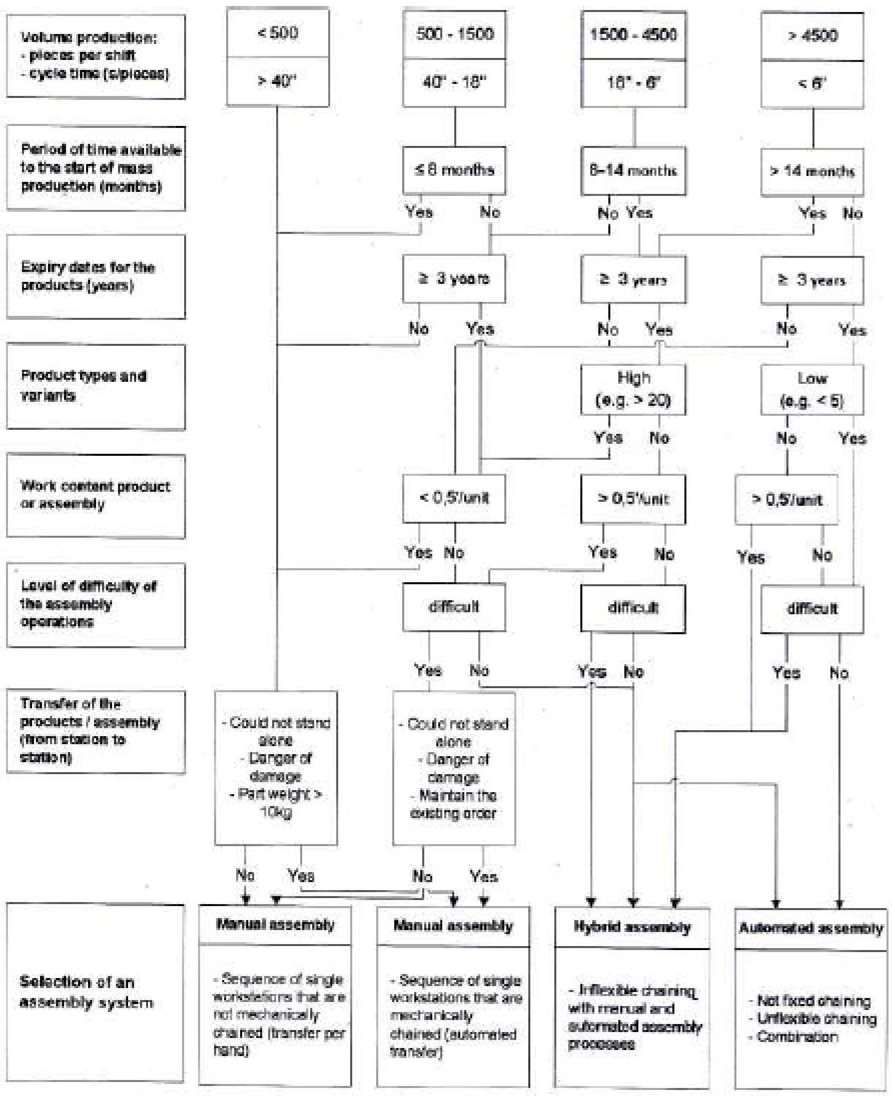

Figure 1.7: Methdology developed by Konold and Reger [24] [22]

This is the 1st method among the methods reviewed until now that considers the aspect of the part weight. If the part is too heavy, it may cause injuries to the human operator in the short or long run, due to which the part may have to be transferred using automated means. Also, similar to the method developed by Boothroyd and Dewhurst, this method also provides importance to product criteria and production criteria. Furthermore, the method also allows for the possibility of partial automation.

However this method can only probably be used to design the transfer mechanism involved within the assembly line since it considers the aspect of part weight. A limitation within the methodology is that, it contains only four levels of automation that do not specifically consider the aspect of decision making. Subsequently, there is also no measure of what types of tools should be used within the suggested assembly system. For instance, within the two levels of automation consisting of manual assembly systems, there is no indication of the usage of manual tools or semi-automated tools. Also, in hybrid assembly systems, there is no depiction about the percentage of assignment done between the human and the machine.

1.3.9 Methodology developed by Almannai et al [25]

Almannai et al developed a decision support tool incorporating techniques of Quality function deployment (QFD) and Failure Mode and Effects Analysis (FMEA) that can be used for selection of manufacturing automation technologies. Within this methodology the QFD technique is used to link the automation objectives with technology, organization and people evaluation to select the best alternative [25] (Figure 1.8) whereas the FMEA technique is used to help the management identify any potential risks involved with the selected alternative and can be used to eliminate the risks [25] (Figure 1.8).

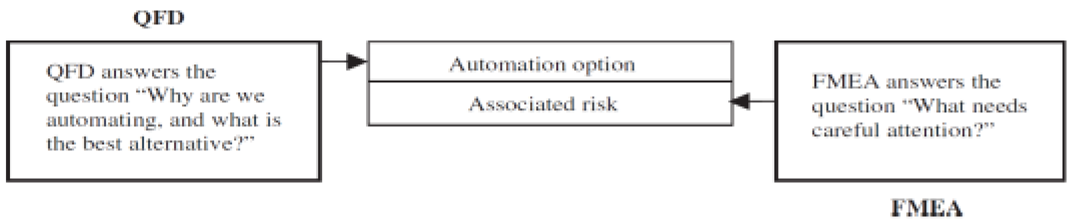

Figure 1.8: Use of QFD and FMEA within the decision support tool developed by Almannai et al [25]

It can be seen in Figure 1.8, that the use of QFD within this methodology, slightly resembles the USA principle discussed earlier in section 1.3.2. Since QFD and FMEA are tools that are typically used within the product development process, for the purpose of this methodology some aspects of QFD and FMEA had to be omitted to allow for the usage of these techniques within process development.

Then methodology consists of three stages (Figure 1.9) over which the selection of automation technologies takes place.

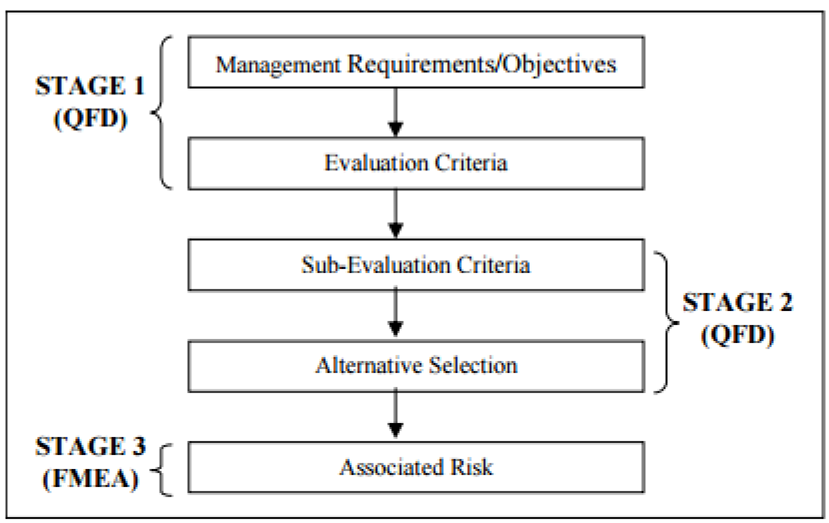

Figure 1.9: Decision-making framework developed by Almannai et al [25]

The 1st stage involves linking the automation objectives to the manufacturer's strategy and the management's needs. The gathered data is then entered into the QFD matrix to establish the relationships between the needs and the evaluation criteria. The process of identifying the evaluation criteria and sub-evaluation criteria involves compiling a list of the elements that could be related to technology, organization, and people in manufacturing systems selection and design literature [22]. The 2nd stage involves the selection of the best alternatives using the sub-evaluation criteria and the final stage involves calculating the risk associated with the best alternative.

This methodology shows us an aspect that was never considered in the earlier methodologies in the form of calculating the risk associated with the chosen automation alternative. Also using a quantified approach to select from the multiple alternatives can be advantageous. However, this method again does not help in assigning an accurate level of automation that can depict information at the system level, such as the tools that need to be used, the distribution of tasks between operator and machine in case of a hybrid assembly.

1.3.10 Methodology developed by Windmark et al [26]

Windmark et al have constructed an economic model that aims to identify the part costs associated with different types of discrete batch manufacturing systems and the different levels of automation used in these manufacturing systems. In order to achieve this goal, the economic model consists of several factors such as product materials costs, cycle time , downtime rates, rejects, rate losses, material waste, total material costs of a batch, maintenance cost, salary costs per hour considering the number of operators and the average salary cost per hour, equipment cost per hour, production series size or the batch size, the production setup time, the planned life time of the equipment, the planned renovation of the equipment during its planned lifetime, the basic investment, the cost per year for space the equipment occupies considering the size of the space and the cost per square meter, and other factors [26].

In this method the LoA is indirectly defined as a factor depending on the equipment costs per hour and the salary costs per hour, as shown in Equation 1.1.

$$x_{af} = \frac{k_{CP}}{k_{CP} + k_D} \qquad \textbf{Equation 1.1}$$

Where,

x_{af} = Automation factor,

k_{CP} = Equipment costs per hour for production on a given machine or line

k_D = Salary costs per hour

The automation factor varies in the value between 0 and 1.0, depending on the values of k_{CP} and k_D. The production is entirely manual when the automation factor is zero, as the equipment costs are negligible. Similarly the production is completely unmanned when the automation factor is equal to one, since the salary costs are entirely negligible. Similarly, if the value of the automation factor lies in between 0 and 1.0, then the level of automation would be on the lines of a hybrid assembly.

The automation factor x_{af} is not a clearly defined variable since, for any given production system, it varies, depending on where the production takes place [26]. The method acts a good tool to determine the level of automation in terms of costs associated with various factors throughout a manufacturing enterprise but, the method does not show a range of automation that can be applied if the value of automation factor lies between 0 and 1.0 and this is what is required within the scope of this research.

However, the method can be used to calculate the part costs once the appropriate level of automation has been determined.

1.3.11 Methodology developed by Gorlach and Wessel [10] [14]

According to Gorlach and Wessel, level of automation represents the portion of automated functions of a system in relation to the complete function of the system and each level of automation is associated with certain costs [14]. This method was developed in the form of a comparative study performed at three Volkswagen production plants at three different locations respectively. The authors consider 5 levels of automation within the methodology to assign LoA to the respective tasks, with level 1 being completely automatic and level 5 being completely manual. The levels of automation are decided based on manufacturing costs (costs for personnel, costs for operating material, costs for material, and costs for information), quality indices, productivity indices, and the manufacturing strategies of the manufacturing firm.

If every created level of automation is provided with costs, the result will be the representation of all relevant costs that are differentiated to resources depending on the different levels of automation [14]. Based on the sum of all the total unit costs of each assembly station and the total unit cost of the whole assembly, the specified level of automation can be determined. However, the analysis also includes the calculation of the quality indices, as quality is a crucial factor among majority of automotive plants.

The method is helpful in terms of including the manufacturing costs associated within a production plant and also beneficial as it considers the quality aspect, which was not considered in any of the previously discussed methods except for the method developed by Boothroyd and Dewhurst. Yet, even in the Boothroyd and Dewhurst method, the quality aspect is considered in terms of the quality of the parts provided to the station, but not the quality of the tasks being performed.

A limitation of this method is that since this method makes use of a comparative study, hence in order to optimize the LoA for an assembly line at any plant, there needs to be an another plant where the same operations are being performed in a better manner. Also, since the layouts, space availability and manufacturing strategy within each plant maybe different, this method may not prove to be worthwhile. Besides, this another limitation that can be noted is that, this method can only be used for the redesigning of an assembly line and cannot be used for the construction of a new assembly line as majority of the factors considered within this method are generally available only after the launch of an assembly line.

1.3.12 Methodology developed by Boothroyd [27]

Boothroyd developed a systematic procedure to calculate the costs associated with the assembly of a product for three types of assembly systems: Manual assembly systems, robotic systems, special purpose assembly systems. For each possible assembly system, the unitary product assembly cost is to be calculated based on the economic formulas developed by Boothroyd in [27]. The formulas provide consideration to the required feed rate, estimated costs associated with the time for handling and inserting a part according to the parts dimensions and characteristics, costs associated with feeders in case of automatic or robotic assembly systems and the cost of basic machines (estimated by

Boothroyd). There are various other factors that go into performing the economic calculation.

A potential benefit of this methodology is that, by performing an economic cost calculation, firstly the result can be obtained using a quantitative approach and secondly consideration is provided to cost minimization and profitability. This way the manufacturer can align their respective manufacturing strategy to analyze which type of assembly system would provide maximum profitability.

However, the assignment of handling and insertion times is generally subjective, varying from person to person, due to which the analysis may tend to give different results for different persons. Additionally, there has been no consideration been given to process flow due to which this methodology may only be useful for design of assembly systems for stations and not for the complete assembly line.

1.3.13 Methodology developed by Salmi et al [18, 22]

Salmi et al developed a modelling language in the year 2013 known as the Assembly Sequence Modelling Language (ASML) that can be used to model assembly operations on an assembly line and can aid in determining the appropriate level of automation. The assembly language makes use of a standardized set of vocabulary to define the operations being performed on the assembly line. The standardized set of vocabulary can be seen in FiguresFigure 1.10Figure 1.11.

In order to model assembly operations on an assembly line, ASML uses a specific set of symbols and rules that have to be used. The different types of symbols used within ASML can be seen in Figure 1.12.

Standardized Verbs list			
S. No	Verb	Definition	Example
1	**Align**	Accurate Positioning of a part or tool over another part	Align bumper to BIW
2	**Apply**	Putting on a medium on an object with or without the aid of a tool	Lubricate headlight seal initial
3	**Attach**	Setting or binding two parts with each other using only the features on each part	Attach hook to ARB
4	**Clean**	Includes all performances, to clean an object with a tool.	Clean windshield with wipe
5	**Connect**	Includes all activities to connect/ locking or unlocking a cable, with or without tool.	Connect cable to harness
6	**Disengage**	Unlocking a fixture or removing a part from the fixture or tool.	Disengage the fixture / Remove Jig
7	**Engage**	Locking a fixture or engaging a tool onto a part.	Engage a fixture or clamp.
8	**Exchange**	Involves exchanging empty bins containing parts and supplies with full bins.	Exchange container nuts
9	**Get**	Picking up a part or tool from around 1 m or does not necessitate getting up or walking from position.	Get torque tool
10	**Handstart**	Screwing in 2 rounds, the bolt or nut by hand or with the aid of tools, to set it in position.	Handstart first screw on tool holder at lift assist
11	**Insert**	Includes all activities to assemble clips with hands and/or tool	Insert clip to Y-strut
12	**Inspect**	Carrying out a check on a part or process, in order to make a decision.	Inspect bumper for damages
13	**Lay**	Laying a cable by hand and/or fastening exactly	Route Bowden cable
14	**Move**	Moving with/without a part/tool around the car or actions like bending down, squatting.	Move to front bumper
15	**Open (Preparatory)**	Includes all activities to handle packaging, separating layers and opening package to take contents.	Open bag with tool
16	**Operate**	Operating is to getting control over adjusting elements with a hand or foot and performing a single operation or a combined operation.	Operate to lower EMS onto hook

Figure 1.10: Standardized vocabulary list for ASML [22]

17	**Place**	Position a part or tool that is already in hand and requires no additional walking	Place ems hanger on third coil
18	**Press (Switch/button)**	Pushing a button or switching on a control to operate a tool.	Press button to release
19	**Push**	Manipulating a tool or part to align or start motion.	Push seat into place
20	**Read**	Reading information carrier, data cards to comprehend the information.	Read option list
21	**Remove (Preparatory)**	Includes all activities to handle packaging, separating layers and opening package to take contents.	Remove flex layer
22	**Remove**	Take a part off an assembly or piece of a part.	Remove a round cut out
23	**Restock**	Refilling storage containers, toolboxes and/or containers.	Restock rivets to carts
24	**Restrict**		Restrict cables.
25	**Scan**	Includes all activities to mark an object with a marking device or to document an object with a scanner.	Get scanner and scan label on IP skin
26	**Screw in**	Involves screwing in a bolt or nut completely with hand.	Screw in by hand total depth
27	**Secure**	Securing a cable with stationary or moveable fastening elements. With or without tools.	Secure cable for foglight
28	**Snap**	Clipping in parts with clips and onto other parts	Snap I-Panel Finisher into console stack
29	**Tighten**	Fastening screws and bolts with manual tools or torque tools.	Tighten 4 off screws with torque tool.
30	**Unscrew**	Unscrewing bolts/nuts manually or with help of a tool.	Unscrew adjuster 3 half turns 3mm gap
31	**Walk**	Walk from car body to car body or supply area without picking up part or any action. (and) Walk to supply area to pick up a part.	Walk to cart and back
32	**Identify**	Identify the right element to use from organized or mixed and disorganized package	Identify the wanted screw to use
33	**Wait**	Wait for a previous condition validation or for ASML rules respect	Wait for the availability of a needed part

Figure 1.11: Standardized vocabulary list for ASML (Contd…)[22]

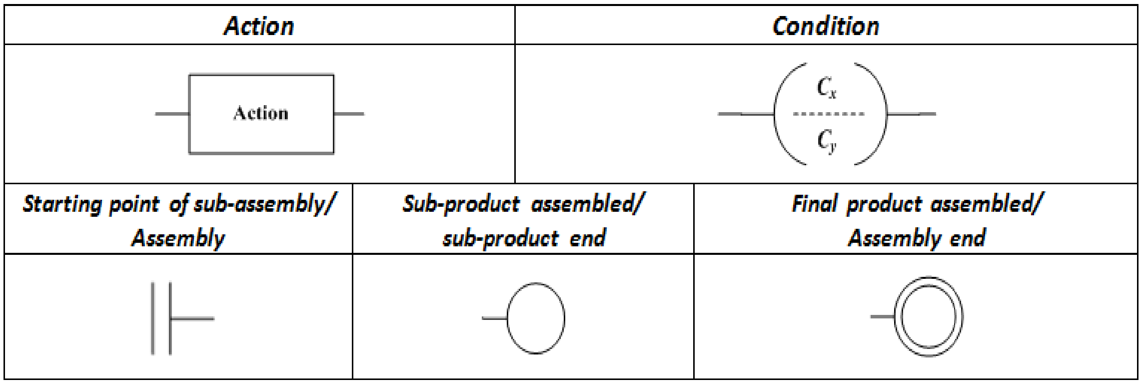

Figure 1.12: Symbols used within ASML [18]

The action symbol is used to depict the operations elementary assembly motions using the standardized vocabulary. The Condition symbol consists of two conditions within the symbol as seen in Figure 1.12, where C_x represents information about the completion of the previous action and C_y represents the tools or parts that are required to perform the next action. The condition symbol is supposed to be used as a transition step between two action steps. The start of an assembly model has to be represented using the "starting point" symbol. In case the assembly involves presence of sub-products, there is also a symbol provided for representing a sub-product. If all the operations within the assembly sequence have been performed then the end of the assembly can be represented using the "assembly end" symbol. Using these symbols, an assembly sequence can be created for an assembly station or for a complete assembly line.

The ASML has a particular set of rules and guidelines that need to be followed to represent the assembly sequence. The 1st rule is that, no two action steps can come in sequence or no two condition steps can come in sequence. An action step has to be followed and preceded by a condition step. This is to allow for proper resource allocation and to verify that the next action step is only performed once the previous action step has been completed. The 2nd rule is that only the standardized vocabulary list can be used to describe the assembly operations within the ASML.

In order to allow for the possibility of parallel operations to be executed at the same time the ASML has a defined set of AND/OR convergence and divergence representation, where the AND divergence/ convergence is used if all the parallel operations running together have to be performed. The OR convergence/divergence is used when only some of the operations within the model have to be performed. The AND/OR convergence and divergence rules can be seen in Figure 1.13. A more detailed explanation of these rules can be seen in [28].

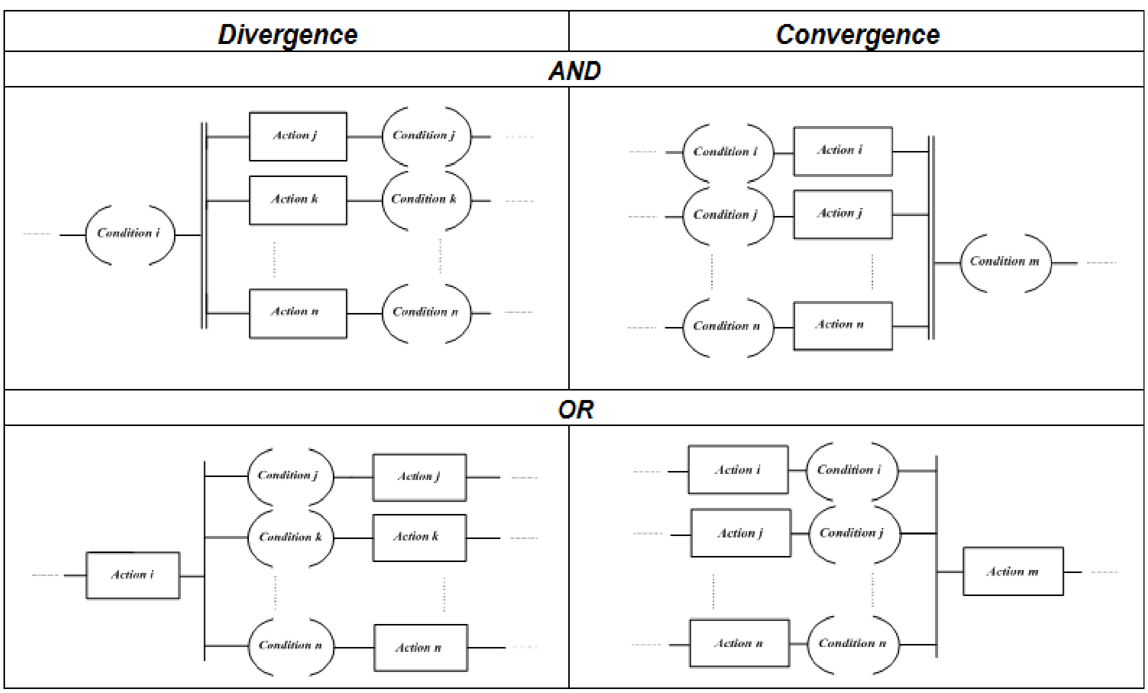

Figure 1.13: AND/OR convergence and divergence in ASML [28]

The ASML modelling can also be used to execute assembly time estimation depending on the type of the verb in the action step and how the action is performed (manually, semi-automatically or automatically). Also the shape, size and weight play an important role in the estimation of assembly time. A set of rules apply to estimating the time for assembly operations as well. If the assembly sequence has operations in the form of a series, then the time estimation of the complete assembly is determined by adding the time values of each motion in the sequence. If there are assembly sequences that are arranged in a parallel manner then the time estimation of the completely assembly is determined by considering the largest time taken among all the parallel sequences.

This method can be used a good tool to depict the process flow at station level as well as at the band level. Another advantage of the ASML is that it considers resource allocation within the modelling due to which the resources can be remodeled or rearranged in case of a change in the assembly system during a later stage. The time estimation aspect can be used to determine how much time each operation takes and help in deciding whether a particular operation needs to be automated if it is taking too long for a human operator to perform that respective operation.

1.4 Conclusion

In this chapter, first the different definitions of level of automation were defined to show the subjectivity related to the definition and then a definition of level of automation was built for the purpose of this research, by analyzing the various definitions.

A brief overview about the different LoA methodologies present within the existing literature is discussed. While some of the methodologies gave prime importance towards the decision making aspect of automation, some methodologies gave primary importance to the costs involved with different levels of automation and some methodologies gave importance to optimizing the level of automation by providing the user the flexibility to choose their own level of automation. It was seen that each LoA methodology had its own potential benefits and limitations compared to the other methodologies, but none of the methodologies completely satisfy the purpose to accurately determine the level of automation at the station scale as well as the band scale.

In order to judge each methodology by its strengths and weaknesses, a set of requirements will be defined in the next chapter. A good LoA methodology should be able to satisfy all the requirements in order to act as a good tool to determine the appropriate level of automation at different scales of resolution.

Chapter Two
DEFINING REQUIREMENTS FOR A SUITABLE METHOD

In this section, requirements are defined that are used to select a method among the various available methods. The method, or methods, that satisfies the most number of requirements is considered as a potential method for determining the level of automation within assembly lines. In order to verify if the methods selected based on the requirements provides valid results, the methods are be analyzed on an industrial case study problem to compare the predicted results with the current industrial implementation. These requirements describe a suitable LoA selecting method for the assembly processes. The requirements (*Ri; i=1...6*) are as follows:

2.1 *Requirement 1 (R1):* A Flexible process

Flexibility is needed in assembly production systems because product life cycles are getting shorter, lot size is getting smaller and there are many variants [29]. Besides these factors, companies employing assembly systems have to deal with short term fluctuations in demand [29]. Hence, flexibility within the process is considered as one of the more important requirements that the method needs to satisfy. The method is considered flexible if it can handle assemblies of different products with a variable demand. A production per batch is required within any industry, due to which the production volume has to be considered. It might be possible that the parts being assembled on the assembly line may have multiple variants due to which the method should be able to provide a solution that supports the possibility of handling different types of variants to be assembled within the product.

2.2 *Requirement 2 (R2):* An Analytic Approach

The approach leading to the decision should have a low level of granularity, involving a detailed view of the assembly system describing the processes in an efficient manner, area by area. Also, the use of a graphical modelling representation would be very beneficial as it helps to represent the assembly sequence in a structured manner.

2.3 *Requirement 3 (R3):* Possibility of Partial Automation

As assembly lines generally consist of multiple stations, each station may need to have a different level of automation depending on the type of operations being performed on the stations. For example, an assembly line consisting of multiple stations may have a station where the operations are such that it would be economical to perform a particular task manually rather than automating it. Similarly, another station may have an operation that requires the task to be automated rather than to perform the task manually. Hence, the method should allow the possibility of deciding where to automate exactly and where not to automate throughout the process. Automation should be suggested based on work areas rather than a global solution of type 'manual', 'automated', or 'hybrid'.

2.4 *Requirement 4 (R4):* Consideration of Cost Minimization and Profitability

A survey conducted in Sweden during 2005 among production experts showed that 53 of the 62 respondents believed that policies regarding choice of manufacturing processes should be considered to a very high degree when formulating manufacturing strategies [23]. Consequently, from a manufacturing point of view, cost minimization and profitability are constraints imposed by the manufacturer. Therefore these constraints should be taken into account by the decision method that will be used for deciding the level of automation.

2.5 *Requirement 5 (R5):* Consideration of manufacturing strategies

As the manufacturer has a better idea about the processes being executed on the assembly line as well as throughout the plant, the decision method considered should give the manufacturer complete freedom to align his manufacturing strategies along with the method. The method should consider the manufacturer's specificities and strategic information of his planned production.

2.6 *Requirement 6 (R6):* Traceability of the decision

The method should be able to track the deciding procedure and executed steps in order to be able to justify and argue why and how a solution was opted with an appropriate documentation and justification. Having traceability within the decision method would also aid in analyzing each area individually. Also, short term fluctuations in demand tend to influence the company parameters, hence having traceability within the decision method would help in modifying the decision if there are any changes within company parameters.

The six defined requirements will now be used to compare the different LoA deciding methods to see which methods satisfy the most number of requirements. Table 2.1 shows the comparison of the different LoA methods mentioned within Chapter One with C_i (i=1…4) being the class to which the method belongs and R_i (i=1…6) being the number of requirements.

Table 2.1: Fulfilment of requirements by LoA methods

LOA METHODS		REQUIREMENTS					
		R1	R2	R3	R4	R5	R6
M1	[21]	-	X	X	X	-	-
M2	[24]	X	-	-	-	X	-
M3	[17]	-	X	X	-	-	-
M4	[6]	-	-	X	X	X	-
M5	[23]	-	X	X	-	X	X
M6	[15] [19]	-	X	X	-	X	X
M7	[25]	-	-	X	-	X	X
M8	[5]	X	-	-	X	X	-
M9	[26]	-	-	X	X	-	X
M10	[27]	-	X	-	X	-	X
M11	[14]	-	X	X	X	X	-
M12	[9]	-	-	X	-	-	-

*(**X**): Current method fulfills with satisfactory manner the given requirement*
(-): *The method is not satisfactory with regard to the given requirement*

As can be seen from the Table 2.1 above, the maximum number of requirements by a method is four, but none of the methods fulfill all of our defined requirements. A method that could fulfil all of the six defined requirements would be considered as an ideal method for the purpose of this research. Hence, the solution proposed within this research is to form a new method by a combination of the different methods shown above, such that the proposed new method fulfils all of the defined requirements and can be further enhanced and improved.

By focusing on Table 2.1 it can be seen that only two methods (M2 and M8) fulfill the requirement R1 (process flexibility) which is given the highest priority among all the requirements. Methods M2 and M8, will be consequently combined with the other remaining methods one by one in order to find a complementary method allowing fulfilment of all the requirements. Considering just M2 and M8, independently, as first members of the combination will avoid the need to consider other useful combinations because no other methods fulfill R1. The results of the combinations are shown in Table 2.2.

Table 2.2: Combination of methods in order to fulfill the defined requirements

COMBINED METHODS	REQUIREMENTS					
	R1	R2	R3	R4	R5	R6
M2 & M1	X	X	X	X	X	-
M2 & M3	X	X	X	-	X	-
M2 & M4	X	-	X	X	X	-
M2 & M5	X	X	X	-	X	X
M2 & M6	X	X	X	-	X	X
M2 & M7	X	-	X	-	X	X
M2 & M8	X	-	-	X	X	-
M2 & M9	X	-	X	X	X	X
M2 & M10	X	X	-	X	X	X
M2 & M11	X	X	X	X	X	-
M2 & M12	X	-	X	-	X	-
M8 & M1	X	X	X	X	X	-
M8 & M3	X	X	X	X	X	-
M8 & M4	X	-	X	X	X	-
M8 & M5	X	X	X	X	X	X
M8 & M6	X	X	X	X	X	X
M8 & M7	X	-	X	X	X	X
M8 & M9	X	-	X	X	X	X
M8 & M10	X	X	-	X	X	X
M8 & M11	X	X	X	X	X	-
M8 & M12	X	-	X	X	X	-

(X): The combination fulfills with satisfactory manner the given requirement
(-): The combination is not satisfactory with regard to the given requirement

It can be observed in Table 2.2 , that only a combination of M8 with M5 (DYNAMO) or M6 (DYNAMO++) allow fulfillment of all the requirements.

In addition, by focusing on methods M2 and M8 in detail, which are the only two methods that consider the aspect of flexibility and handling of different products styles (requirement R1), it can be observed that in method M8, which is the B&D method [5], this method satisfies requirement R1 more than method M2. In fact the B&D method considers various different parameters that impact flexibility in the decision process with the different parameters being: ‘number of product styles’, ‘kinds of products to assemble’, ‘annual production volume per shift’, ‘fluctuations in demand’, and ‘market life’ [5]. These criteria are significant in most of industries involved with assemblies of products. M8 also considers the number of similar parts to assemble compared to the total number of parts as a criterion during the decision. This criterion is also significant in the automotive industry where in several parts are common for different models of vehicles and this represents a good indicator for consideration of flexibility. While for method M2, the flexibility aspect is represented only by a decision switching criterion that categorizes the product types and variants either into ‘high’ or ‘low’. Thus, based on these factors, it can be said that flexibility is consequently less developed in M2 than in M8. This makes the choice and preference of M8 for the proposed method more arguable than will also help avoid other types of possible combinations such as combinations of more than two methods.

The two methods M5 and M6 that successfully complement the combination with M8 in order to fulfill the requirements are methods defined from the same project: a Swedish project named DYNAMO where M5 represents the original DYNAMO method, and M6 is the DYNAMO modified or DYNAMO++.

After a deep study and analysis, the two methods can be practically combined in order to solve the problem defined by the six requirements. DYNAMO (M5) and DYNAMO++ (M6) are quite similar where in DYNAMO++ adds some steps and improved reasoning and strategy. This method (M6), which is more recent, will be consequently used for the case study because it considers additional information than M5, provides an improved analysis and a better understandability of the process with use of some tools which will be presented in further chapters.

Chapter Three
BOOTHROYD AND DEWHURST METHOD

Determining the type of assembly system that a company needs to adopt while still in the initial stages of design helps save on excessive cost. Furthermore it eliminates the need for repetitive iterations to be performed until a satisfying assembly method is obtained to build the assembly. The Boothroyd and Dewhurst (B&D) method [5] is a method applicable for assembly workstations in order to determine, the best alternative or technology allowing the assembly of parts with respect to different information concerning the assembly characteristics and the planned production. As compared to the popular assembly time estimation method [30] developed by Boothroyd and Dewhurst, the method to determine the appropriate assembly method is hardly referenced within the literature. In fact, 80% of the design for assembly handbook [5] is used to describe assembly time estimations for manual or automated assemblies, whereas only 20% of the content is used to explain the method used to determine the correct assembly method. A reason for the lack of references could be that the method was published in the year 1983 and has not been updated to accommodate the recent technological advances. Another reason could be that the method may not have been successful in real time applications, but there is no documented proof for this. Subsequently, the assembly time estimation method has constantly been used throughout the years due to which it may be referenced more often. However, this is not the case with the method that will be discussed in the further sections.

3.1 Parameters considered in the B&D Method

Both of product and production criteria involve flexibility aspect of the lines to be proposed as a solution. The company parameters that help in deciding an appropriate assembly method are described in Table 3.1.

Table 3.1: Company parameters to choose assembly method (adapted from [5])

Parameter	Definition
VS	The production volume that the manufacturer desires to have annually.
NA	Total number of parts required to build the complete assembly
NT	Total number of parts required to build different product styles
ND	Number of parts whose design changes during the first three years necessitating a new feeder/ work head
NP	Number of different products to be assembled using the same basic assembly system during the first three years
QE	Capital Expenditure allowance to replace one operator on one shift
SH	Number of shifts worked per day
WA	Annual cost of a single assembly operator
RI	Risk investment factor
PF	Parts quality factor

If a manufacturer wants to identify what type of assembly system would be the most efficient with respect to the parameters, the manufacturer needs to have all the parameters ready beforehand. A detailed explanation of each of the parameter is provided below.

- VS: The required production volume (VS) is the production volume that the manufacturer desires to have annually.
- NA and NT: The concept of (NA) and (NT) can be better explained using an example. For instance, a manufacturer wants to assemble a product consisting of 20 parts. This implies that the total number of parts within the complete assembly (NA) would be equal to 20. If the manufacturer wants to assemble 4 different variants of the product with all the variants having 16 parts in common, but each variant has 4

different parts respectively within the assembly, this implies that, the total number of available parts to build different product variants (NT) = 32 (=16 + 4×4).

- ND: It is generally considered that automatic assembly machines would only be economic for mature products whose design is not likely to change for several years. As per the B&D method, it is feasible to consider automatic assembly machines if the product does not under go any major changes for at least a period of three years. If a part is undergoing significant design changes very frequently, then for each design change within the parts of the product a new automatic assembly machine may be required, which will lead to increasing costs. This problem does not arise within programmable assembly systems using robots [5], possibly because the machine may only need to be reprogrammed or because of the use of reconfigurable grippers, which may not have a significant impact on the cost as compared to building a completely new machine. Thus, in order to advocate this, a factor (ND) is used to check the number of parts that undergo design changes during the 1st 3 years, within the product, which might necessitate a new workhead/feeder.
- NP: High speed automatic assembly systems are generally used to assemble the same product style in large number of volumes. Thus, if multiple product styles are being built on the same assembly line, having a highly manual or a programmable assembly line might be much more economical than having a high speed automatic assembly line, in order to achieve flexibility within assembling. Although, even if a programmable assembly system is being used to assemble the various product styles, the different parts that are being assembled on the line to build different product

styles, must be of approximately of the same size so that the transfer device being used to transfer the parts can be the same, but each part will need to have its own workhead, feeders and grippers [5]. Thus, to consider this, a factor NP is used within the table to check the number of different product styles that need to be built using the same basic assembly system.

- QE: In the initial stages itself, the company needs to determine how much capital is the company willing to spend on replacing an assembly operator on a single shift. This might include replacing the assembly operator by a machine. Thus to analyze this, a factor QE is considered within the method. If an assembly operator is being replaced by a machine and the machine is working a single shift then the economic cost of the equipment would be QE. If the machine is working two shifts, then the economic cost of the equipment would be (2 x QE).
- SH: Depending on the required production volume the manufacturer has to make a decision as to how many no. of shifts (SH) will be needed per day/ per week to meet the predicted production volume. For example, when the demand for the product rises, the required production volume also has to be increased and in order to achieve this rise in the production volume, the manufacturer might have to increase the number of shifts worked by the operators or the assembly machines. Similarly, if the demand for the product falls, then it does not seem logical to continue with the same number of shifts, as this will result in the production of more than required products, in turn resulting in excessive storage costs. Generally, when the demand for the product rises, the number of shifts worked is limited to a maximum of three shifts.

- RI: The risk investment factor (RI) helps us to determine whether investment in automation should be encouraged or discouraged. The risk investment factor can be defined (RI) as the ratio of ‘the number of production shifts’ multiplied by ‘the capital expenditure allowing replacing by using machine(s) or automation an equivalent of one operator on one shift’ to ‘the annual cost of one assembly operator including overheads’. The risk investment factor can be calculated using Equation 3.1.

$$\boldsymbol{RI = \frac{SH \times QE}{WA}} \qquad \text{Equation 3.1}$$

Where:

RI is the risk investment factor,

SH is the number of shifts,

QE is the capital expenditure, and

WA is the annual salary of typical operator.

As per this method, investment in automation is encouraged when the value of RI ≥ 3 and investment in automation is discouraged if the value of RI < 3.

The product design criteria considered consists of: the number of parts with design changes during first three years with regard to the total number of parts (changes requiring a new feeding device and workheads for automatic machine). Another criterion that can be considered as a product design criterion is the number of product styles to be assembled, expressed by the ratio of the number of parts available to the number of parts in the assembly. A third criterion is the parts quality. The parts quality is also a factor taken into consideration, where in the percentage of defective parts being delivered to the assembly line is taken into account.

For the production information criteria, the method considers the kinds of products to assemble: assembly of a ‘single’ product, ‘variety of different but similar products’, or a ‘variety of different products’. The method also considers the annual production volume per shift, the number of parts in the assembly, fluctuations in demand, product market life and investment in automation.

3.2 Levels of Automation

As per this method, assembly systems can be classified into three different categories namely:

1) Manual assembly systems

2) Special purpose assembly systems

3) Adaptable or programmable assembly systems

Manual assembly systems are those systems where majority of the tasks are performed by the human operator with little or no assistance from a machine. Special purpose assembly systems are systems that are specifically developed to assemble a specific product in large quantities. Programmable assembly systems are similar to special purpose assembly systems i.e. can be used to assemble a specific product in large quantities but can also be used to manufacture other products. The difference between these systems lies in the degree of flexibility and adaptability. Special purpose assembly systems have very low flexibility and adaptability as they are specifically designed to build a particular product containing the same parts every time a new product is being assembled. Programmable assembly systems have a high degree of flexibility and adaptability compared to special purpose assembly systems as these systems can be programmed to assemble different varieties of products. Nonetheless, manual assembly systems have the highest amount of flexibility and adaptability, due to the flexible nature of humans. In order to understand the differences between the three assembly systems a relative comparison among the features of the three assembly systems can be seen in Table 3.2.

Table 3.2: Comparison among features of different assembly systems

Assembly System / Features	Manual assembly system		Special Purpose assembly system		Programmable assembly system	
	MA	**MM**	**AI**	**AF**	**AP**	**AR**
Adaptability and flexibility	Highest adaptability and flexibility		Low adaptability and flexibility		High adaptability and flexibility	
Downtime due to defective parts	Negligible		High unless parts are of good quality		High unless parts are of good quality	
Assembly cost	Relatively constant		Depends on production volume		Depends on production volume	

Each assembly system is further divided into two different assembly methods, with each assembly method having a different degree of automation. The breakdown and the definitions of each level of automation will be discussed in the current section. Within this method the assembly systems consist of different levels of automation ranging from a completely manual assembly method to a completely robotic assembly method. The manual assembly system consists of two LoA's termed MA and MM respectively. MA is defined as a Multi-station assembly line with free-transfer machines where the product is assembled manually by the operator [5]. MM is defined as a multi-station assembly line that contains devices like feeders in the form of mechanical assistance [5], but the assembly is still performed by the human operator. The special purpose assembly systems are categorized into two different LoA's namely AI and AF. Within AI, automated assembly machines provided with special purpose indexing mechanisms, work heads and automatic feeders are used for assembly [5]. Within AF, automated assembly machines provided with special purpose free transfer mechanisms, work heads and automatic feeders are used for assembly [5]. The only difference between these two lies within the mechanism used for transferring the product. Similar to the other two assembly systems the programmable assembly system is also categorized into two different levels of automation. The first LoA being AP, which consists of automated assembly machines containing free transfer machines with programmable workheads and manually loaded part magazines [5]. The second LoA being AR, which consists of automated assembly machines containing two armed robots with special purpose grippers and manually loaded part magazines [5]. All the six different LoA's are scattered within the B&D table depending upon the parameters discussed in Table 3.1. The working of the B&D table for the selection of the appropriate LoA will be discussed in the upcoming section.

3.3 Selection Table

The B&D table is used to select an appropriate assembly system based on different company parameters. Table 3.3 shows a reproduction of the original table as defined by Boothroyd and Dewhurst within the design for assembly handbook. The working of the table will be discussed subsequently within this section.

Table 3.3: B&D table for selecting the appropriate level of automation (from [5])

			NP = 1 (Single product without significant variations in demand)								Variety of diff but similar products	Variety of products
			(NT) < 1.5 (NA) ***and*** (ND) < 0.5 (NA)				(NT) ≥ 1.5 (NA) ***or*** (ND) ≥ 0.5 (NA)					
			RI ≥ 5	5>RI> 2	2 ≥RI≥ 1	RI < 1	RI ≥ 5	5 >RI> 2	2 ≥RI≥ 1	RI < 1		
			0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
VS > 0.65 million assemblies per shift annually	NA ≥ 16	**0**	AF	AF	AF	MM (AF)	AP	AP	AP (MM)	MM	MA (AP)	MA
	15 ≥ NA ≥ 7	**1**	AF	AF (AI)	AI (AF)	MM(AI)	AP	AP	MM (AP)	MM	MA	MA
	NA ≤ 6	**2**	AI	AI	AI	AI	AI	AI (AP)	MM	MM	MA	MA
0.65 ≥VS> 0.4 million assemblies per shift annually	NA ≥ 16	**3**	AP	AP	MM (AP)	MM	AP	AP	AP	MA (MM)	MA	MA
	15 ≥ NA ≥ 7	**4**	AI	AI	AI	MM	AP	AP	MM (AP)	MA (MM)	MA	MA
	NA ≤ 6	**5**	AI	AI	MM (AI)	MM	AI (MM)	MM	MM	MA (MM)	MA	MA
0.4 ≥VS> 0.2 million assemblies per shift annually	NA ≥ 16	**6**	AP	AP	MM	MM	AP	AP	AP	MA	MA	MA
	15 ≥ NA ≥ 7	**7**	AI (MM)	MM	MM	MM	AP	MM	MA (MM)	MA	MA	MA
	NA ≤ 6	**8**	MM	MM	MM	MM	MM	MM	MA (MM)	MA	MA	MA
VS ≤ 0.2 million assemblies per shift annually		**9**	MM	MM	MM (MA)	MM	MM	MA	MA	MA	MA	MA

3.3.1 Selection Table Steps

The table consists of ten rows and ten columns, throughout which different assembly methods discussed in Section 3.2 are scattered. The appropriate selection of the assembly method depends on the quantitative value of the parameters. The first step for the selection of the assembly method is to determine in what range the annual production volume per shift lies. If the annual production volume per shift (VS) is greater than 0.65 million assemblies per year, then the solution would lie in the top three rows. If VS is between 0.65 and 0.41 million assemblies per year then the solution would lie within rows 3, 4, or 5. Similarly, when VS is between 0.4 and 0.21 million assemblies per year, the solution would lie within rows 6, 7, or 8. Finally, if VS is less than or equal to 0.2 million assemblies per year then the solution would lie in the lower most row.

Once the range within which the annual production volume of the manufacturer lies is determined, then the search is restricted to the set of rows associated with the particular range. For example, if the manufacturer wishes to produce 0.56 million assemblies of a certain product per year with two shifts being worked per day then the solution would be restricted within rows 6, 7 or 8 as 0.28 million assemblies would be produced per shift annually.

In the next step, the number of parts in the complete assembly is determined and is checked for within the selected production volume range to restrict the search to a single row. Considering an example, if the manufacturer's product contained fifteen parts within the completed assembly then as NA =15, the search would be restricted to row seven.

A similar approach is used to restrict the column search to a single column too. The first step involves analyzing the number or product styles being built and whether there is any similarity between different product styles and variants being manufactured and analyzing the market life of the product(s). Depending on this, the solution would exist either within columns (0, 1, 2….,7) (NP=1) or column 8 (NP>1 and requires no manual fitting) or column 9 (NP>1 and fluctuations in demand occur). If the result lies within columns 0 to 7 then, the search can be restricted by looking at the ratio of NT (total number of parts available to build different product styles) v/s NA (number of total parts required to build the completed assembly). Another aspect that can be used to restrict the column search is by measuring the ratio of ND (Number of parts whose design changes during the first three years necessitating a new feeder/ work head) v/s NA (Total number of parts required to build the complete assembly). If $\{(NT) < 1.5\ (NA) \cap (ND) < 0.5\ (NA)\}$ then the result is restricted within columns zero to three and if $\{(NT) \geq 1.5\ (NA)\ U\ (ND) \geq 0.5\ (NA)\}$ then the result lies within columns four to seven. Once the particular range of columns are selected the final column is selected based on the value of RI. Also, what can be noticed within the table is that some cells within the table have two solutions within the same cell with one solution being in parentheses. The systems indicated in the parentheses are no more than 10% less economical than the optimum assembly system in the same cell [5].

3.3.2 Example Use of B&D Selection Table

An illustrative example is provided below to provide a better sense of understanding of how the table works.

A manufacturer wants to assemble 450,000 assemblies with each assembly consisting of twenty parts each. There are four different variants of the product with an 80% overlap of parts. The number of shifts worked throughout the year is two shifts per day and a single assembly operator costs $60,000 annually to perform the assembly operations, including wages, benefits, and taxes. Assuming, the manufacturer is willing to invest $45,000 on a machine to replace one operator on one shift, then the recommendation is found in the cell (3, 6) (where 3 = row number and 6 = column number) of Table 3.3 which is programmable assembly system (AP). The calculations used are as follows:

Since each assembly consists of twenty parts in total, hence, the total number of parts required to build the complete assembly is,

$$NA = 20$$

Also, there are totally 4 different variants of the product with an 80% overlap of parts. Consequently, this can be used to calculate the total number of parts required to build different product styles (NT). Let *'p'* be the common parts within each variant of the product, then,

$$p = 20 \times 80\% = 16$$

Let the different variants of the product be represented using V_i, such that variant 1 is V_1, variant 2 is V_2 and so on. With each variant of the product having 16 parts in common, the remaining 4 parts out of the 20 parts in the assembly are different for each variant. Henceforth, V_1 would have 4 different parts of its own besides the 16 common parts within the assembly. Similarly V_2, V_3 and V_4 each respectively have 4 different parts within the complete assembly. Thus,

$$NT = 16 + 4 + 4 + 4 + 4 = 32$$

VS = 450,000

NT/NA = 32/20 = 1.6

Number of shifts/ day (SH) = 2

Annual cost of an assembly operator (WA) = $60000

Capital Expenditure allowance to replace one operator on one shift (QE) = $45000

$$\mathbf{RI} = \frac{\mathbf{SH \times QE}}{\mathbf{WA}} = \frac{\mathbf{2 \times 45000}}{\mathbf{60000}} = \mathbf{1.5}$$

Table 3.4: B&D table logic explanation

NP=1 (single product without major variation in demand)						
(NT) ≥ 1.5 (NA) U (ND) ≥ 0.5 (NA)						
			RI ≥ 5	5>RI>2	2≥RI≥1	RI > 1
			4	5	6	7
0.65 ≥VS> 0.4 million assemblies per shift annually	NA≥16	3	AP	AP	AP	MA (MM)
	15 ≥ NA ≥ 7	4	AP	AP	MM (AP)	MA (MM)
	NA ≤ 6	5	AI (MM)	MM	MM	MA (MM)

3.4 Sensitivity of the decision towards the number of shifts (SH) and total number of parts required to build different product styles (NT)

In this section, the sensitivity of the decision will be analyzed towards change in the number of shifts (SH), to see how the decision method and the decision itself is impacted by varying these parameters. Firstly, the number of shifts are varied all the other factors are kept constant to see how sensitive the decision is towards the number of shifts (SH). Although, practically the number of shifts that are worked in a day within any company is restricted to a maximum of 3 shifts / day, the method is analyzed for up to 7 shifts / day in order to have an enhanced idea about the sensitivity of the decision.

Based on the analysis within Table 3.5 it can be seen that as the number of shifts increase, the decision tends to incline towards automated solutions. The reason for this being, as the number of shifts increase, the total overall cost for employing operators on shifts begins to rise as well, thus it would be more feasible to employ a machine to perform the job in case of a large number of shifts. Thus it can be assumed that the higher the number of shifts, the greater is the opportunity to implement automation [5]. Also, the larger the (NT/NA) ratio, the lesser is the flexibility, due to which the solution tends to incline towards either manual or programmable assembly systems. This can be seen within Table 3.5 and Table 3.6 that as the (NT/NA) ratio increases from 1.3 to 1.6 the solution starts shifting from high speed assembly systems (AF) to Programmable/Manual assembly systems (AP or MM). Also, for instance at the start of the production, if the manufacturer runs only 1 shift, the predicted result is MM (AF) and assuming the manufacturer implements an MM assembly system, but in case of an increase in demand if the shifts have to be increased then the predicted result changes to AF, due to which the manufacturer may have to redesign the complete system again. This shows that the decision is clearly sensitive to the number of shifts and the decision suggested by the method is not very robust.

Table 3.5: Sensitivity of decision towards number of shifts (SH) (NT=26)

PRODUCTION VOLUME =0.7 MILLION (90% OVERLAP OF PARTS) (ALL FACTORS KEPT CONSTANT, VARYING SH)							
NA	NT	WA	SH	QE	RI= (SH × QE)/WA	NT/NA	ASSEMBLY METHOD
20	26	65,000	1	50,000	0.76	1.3	MM(AF)
20	26	65,000	2	50,000	1.52	1.3	AF
20	26	65,000	3	50,000	2.28	1.3	AF
20	26	65,000	4	50,000	3.04	1.3	AF
20	26	65,000	5	50,000	3.8	1.3	AF
20	26	65,000	6	50,000	4.56	1.3	AF
20	26	65,000	7	50,000	5.32	1.3	AF

In order to determine the robustness of the decisions being suggested by the B&D method, the sensitivity of the decision is analyzed again in Table 3.6 with an increased number of parts required to build different product styles (NT = 32). As compared to the previous analysis, by just increasing NT by a total of 6 parts, we can see that the recommended solutions change to a great extent. While previously, the result was either MM or AF, after an increase in NT leads to a result of either MM or AP. A change by a small factor of 6 parts leads to an increased variability due to which the result may have changed from AF to AP. Similar to the previous analysis (Table 3.5), the sensitivity of the decision can be seen here as well, as for an increase in the number of shifts from one to three the result changes from MM to AP. However once the number of shifts start to rise from three to seven (shifts four to seven are represented in gray as there are just hypothetical scenarios) the decision remains the same, based on which it can be said that there is a saturation point after which an increase in the number of shifts does not affect the decision.

Table 3.6: Sensitivity of the decision towards number of shifts (SH) (NT=32)

PRODUCTION VOLUME =0.7 MILLION (80% OVERLAP OF PARTS) (ALL FACTORS KEPT CONSTANT, VARYING SH)							
NA	NT	WA	SH	QE	RI= (SH × QE)/WA	NT/NA	ASSEMBLY METHOD
20	32	65,000	1	50,000	0.76	1.6	MM
20	32	65,000	2	50,000	1.52	1.6	AP(MM)
20	32	65,000	3	50,000	2.28	1.6	AP
20	32	65,000	4	50,000	3.04	1.6	AP
20	32	65,000	5	50,000	3.8	1.6	AP
20	32	65,000	6	50,000	4.56	1.6	AP
20	32	65,000	7	50,000	5.32	1.6	AP

3.5 Sensitivity of the decision towards Capital Expenditure to replace One Operator on One Shift (QE)

Now that we know, how sensitive the decision is towards the number of shifts, in this section the sensitivity of the decision will be analyzed with respect to the capital expenditure to replace on operator on one shift (QE). The analysis for this section can be seen within Table 3.7. To perform this analysis, all the other company parameters are kept constant and only QE is varied. Again it can be seen that, the higher the value of QE, the greater is the opportunity for employing automation[5]. Similar to the previous section it can also be seen here that as the (NT/NA) ratio increases the decision starts shifting towards programmable or manual assembly systems, due to reduced flexibility and increase in variance among the parts. It can be seen in the sensitivity analysis that even though the value of QE increases fivefold from 60,000 to 300,000 the decision is not impacted much as it just fluctuates between AF and AI, which is not a major change. Hence it can be said that the decision is comparatively not as sensitive to QE as compared to SH.

Table 3.7: Sensitivity of the decision towards change in capital expenditure to replace one operator on one shift (QE)

PRODUCTION VOLUME =0.7 MILLION (90% OVERLAP OF PARTS) (ALL FACTORS KEPT CONSTANT, VARYING QE)							
NA	NT	WA	SH	QE	RI= (SH × QE)/WA	NT/NA	ASSEMBLY METHOD
10	13	60,000	1	50,000	0.83	1.3	MM(AI)
10	13	60,000	1	60,000	1	1.3	AI(AF)
10	13	60,000	1	70,000	1.16	1.3	AI(AF)
10	13	60,000	1	80,000	1.334	1.3	AI(AF)
10	13	60,000	1	90,000	1.5	1.3	AI(AF)
10	13	60,000	1	100,000	1.66	1.3	AI(AF)
10	13	60,000	1	120,000	2	1.3	AF(AI)
10	13	60,000	1	140,000	2.33	1.3	AF(AI)
10	13	60,000	1	160,000	2.667	1.3	AF(AI)
10	13	60,000	1	180,000	3	1.3	AF(AI)
10	13	60,000	1	200,000	3.33	1.3	AF(AI)
10	13	60,000	1	250,000	4.16	1.3	AF(AI)
10	13	60,000	1	300,000	5	1.3	AF

Chapter Four
DYNAMO METHOD

Dynamo [15] and Dynamo++ [15] methods were developed in the same Swedish automation project called Dynamo as 'Dynamic Levels of Automation for Robust Manufacturing Systems' by Chalmers University of Technology since 2007 to 2010 and consists consequently in the most recent methods. The Dynamo method was developed during the period of 2004-2007 by performing seven different case studies using a single case study method in sequence [11] while the Dynamo++ is an improvisation of the existing Dynamo method. The next section would discuss in detail about the different steps involved in the Dynamo and Dynamo++ methods.

4.1 Dynamo ++ steps

The Dynamo method consists of eight steps which will be discussed in this section. The first step of the methodology involves defining the goal and the purpose of the measurement and to check the delimitations of the goal within the production flow [11]. The goal, for example could possibly be a hypotheses/theory which is being analyzed to check for its validity within a manufacturing enterprise. The goal could also be to increase or decrease the level of automation depending upon the requirements of the company. Also, during this step the operation instructions are requested from the company before going on-site, to pre-judge the LoA based on operation instructions. Once the goal/purpose of the experiment has been defined the second step involves determining the production flow of the whole process which is being analyzed. Determining the number of parts which go into building a model, making note of the different variants of models, purpose of each operator/machine, identifying work organization is all done within this step. Once all this information is available, this information is documented, which would be used in the further steps. The third step comprises of performing a walk through within the manufacturing firm to document the parts and various models that go through each cell/station. Also, information regarding the number of operators assigned to each station/cell is documented within this step.

The 4th step encompasses determining the main task within each station/cell. This is where the documentation that was generated in the earlier steps comes into play. As per the authors, the main task is identified by visualizing the document, and looking at the work flow, but it would be advisable to interview executives or operators to check whether the main task identified from the documents is the appropriate one before proceeding to the subsequent steps. In the fifth step, identification of sub- tasks is done by observing how the main task is achieved, which is done by breaking down the task until it reaches a level of operations, where only the human or the technology can be solely responsible for achieving the task [11]. Within this method, reference scales have been developed for two different types of LoA, namely: Mechanical LoA and Information LoA. The scales show varying degrees of automation that can be assigned to tasks. The reference scales developed are shown in Table 4.1. Within the 6th step, based on the sub-tasks identified in the previous step each sub-task is assigned a LoA value from the reference scale seen in Table 4.1. The seventh step consists of identifying a minima and maxima to each LoA judged in the previous step.

Table 4.1: Reference scales within the DYNAMO method (from [11])

LoA	Mechanical and Equipment	Information and control
1	**Totally manual** – Totally manual work, no tools are used, Operator only uses their own muscle power	**Totally manual** – Operator creates their own understanding of the situation and develops their own course of action based on their experience & knowledge
2	**Static Hand Tool** – Manual work by the operator with the help of a static tool. Ex: Screw Driver	**Decision giving** – Operator gets information on what to do, or proposal on how the task can be achieved. Ex: Work order
3	**Flexible Hand Tool** – Manual work with support of flexible tool. Ex: Adjustable spanner	**Teaching** – Operator gets instructions on how the task can be achieved. Ex: Checklists, manuals
4	**Automated Hand tool** – Manual work with support of automated tool. Ex: Hydraulic Bolt driver	**Questioning** – The system questions the execution if the execution deviates from what the system considers being suitable. Ex: Verification before action
5	**Static Machine/workstation** – Automatic work by machine that is designed for a specific task. Ex: Lathe	**Supervision** – System calls for the operator's attention and directs it to the present task. Ex: Alarms
6	**Flexible machine/workstation** – Automatic work by machine that can be reconfigured for different tasks. Ex: CNC machine	**Intervene** – System takes over and corrects the action if the execution deviates from what the system considers suitable. Ex: Thermostat
7	**Totally Automatic** – Completely automatic work, the machine solves all problems that occur. Ex: Autonomous systems	**Totally automatic** – All information and control is handled by the system. Ex: Autonomous systems

This decision is taken along with the help of a production technician or an expert from within the manufacturing enterprise who is well versed with the production flow, because they have a much better understanding of how the production flow works and may provide reasoning towards some of the limitations that may occur. The final step involves analyzing the maxima and minima judged in the previous step. A graph diagram is drawn with the mechanical LoA on Y-axis and the information LoA on X-axis as shown in Figure 4.1. Drawing horizontal and vertical lines for the respective maxima and minima of mechanical and information LoA's an area is formed which defines the potential area of automation. Placing the LoA value from the observed LoA value as a black dot in the Mechanical-Information-LoA diagram for all documented sub-task gives the current LoA being applied. Also, the LoA values estimated from the operation instructions are placed on the graph. Plotting preliminary and observed LoA helps show the actual flexibility and dynamics of automation.

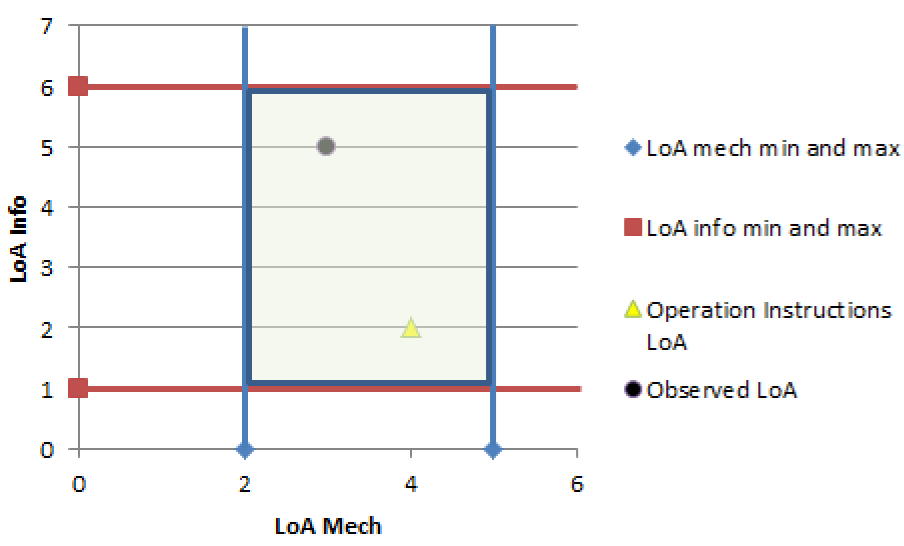

Figure 4.1: Graph diagram for constructing potential area of automation

Dynamo++ offers a structured guideline supporting in how to proceed in manufactories for sake of actual process LoA measurement and possibilities of improvement studies and analyses by following a certain number of defined steps and template documents for better organization and traceability of the decision process. Dynamo++ is based on 12 steps shown in Table 4.2 that can be divided into 4 phases: pre-study, measurement, analysis, and implementation. The pre-study phase includes the first three steps (Off site study, walking the process, documenting production flow) of the dynamo method. The measurement phase includes step four and step five of the dynamo i.e. identifying main tasks, sub tasks and documenting the results. The analysis phase includes steps six, seven and eight of the Dynamo method where a particular LoA is assigned to each task as well as minimum and maximum LoA are assigned to each task. The assignment of minimum and maximum LoA leads to the construction of the square of possible improvements. The steps seven and eight concerning respectively Square of Possible Improvements (SoPI) design (Figure 4.2) and analysis represent important steps and characterize the Dynamo methods. One of the limitations of the dynamo method is that, there hasn't been much emphasis on the analysis after the SoPI has been constructed and this is what is shown as an improvisation within the dynamo++ method. The dynamo++ emphasizes on the analysis post implementation of the results to check if the assessed LoA's meet the goal defined within the first step or there needs to be a certain change made.

Table 4.2: Dynamo++ methodology steps (from [15]**)**

Steps	Phase	Description
Step 1	**Pre-Study**	Identify the system to improve onsite
Step 2		Walk the process
Step 3		Identify flow and time parameters by Value Stream Mapping (VSM) building
Step 4	**Measurement**	Identify main operations and subtasks for selected area by Hierarchical Tasks Analysis (HTA) designing
Step 5		Measure LoA using the LoA mechanical and information scales
Step 6		Results documentation
Step 7	**Analysis**	Decide min and max LoA for the different tasks by Workshop
Step 8		Design Square of Possible Improvements (SoPI) based on workshop results
Step 9		SoPI analysis
Step 10	**Implementation**	Write / visualize the suggestions of improvements
Step 11		Implementation of the decision suggestions
Step 12		Follow-up when the suggestions have been implemented and analyses their effects on time and flow

4.2 Square of Possible Improvements (SoPI)

The Square of Possible Improvements (SoPI) consists in drawing in a 2D axis (LoA Mechanical or Physical, LoA Information or Cognitive) the minimum and maximum levels according to studies, observations, discussions, interviews, workshops, and results that should have been already established in previous steps of the Dynamo method. The mechanical LoA (LoAmech) is plotted on the Y-axis, while the information LoA (LoAinfo) is plotted on the X-axis. To construct a SoPI for a particular station/task, firstly two horizontal lines are drawn from the points corresponding to minimal and maximal LoAmech parallel to the x-axis. Similarly, two vertical lines are drawn corresponding to the minimal and maximal LoAinfo parallel to the y-axis. The two horizontal and two vertical lines intersect with each other to form the square of potential improvements as seen in Figure 4.2. The SoPI offers a good visibility about the span of the possible solutions that can be opted for the process improvement. The boundaries created by the minimal and the maximal LoA help the company with regards to future improvements in automation based on demand. Another benefit of having a SoPI is, it gives us an idea of regions or sections that can be automated or de-automated.

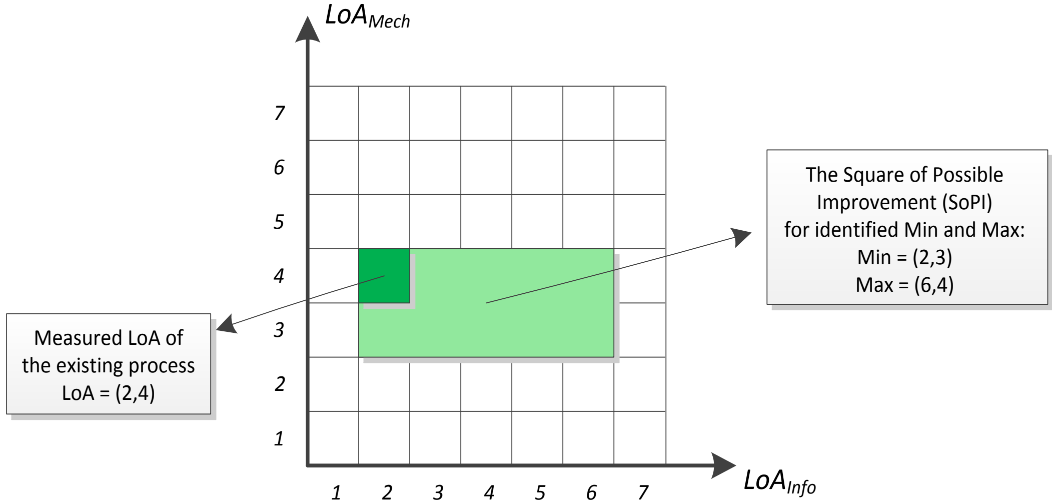

Figure 4.2: Square of Possible Improvements (SoPI)

Chapter Five
VALIDATION OF B&D METHOD BASED ON CASE STUDIES

Following the explanation of the B&D and DYNAMO methods in the previous chapters, the B&D method is applied to two separate assembly lines at two different industries in this chapter. The purpose of applying the B&D method to these case studies is to validate whether the method accurately predicts what is currently being applied at the individual assembly lines.

The data for this analysis has been gathered by requesting operation instructions from the companies and then performing an extensive walk through of the assembly lines to get a better idea of the operations being performed on the assembly lines. Although the data could have been gathered without requesting operation instructions from the company, however having operation instructions beforehand aids in understanding the process better. Furthermore, this reduces the time needed to perform the walkthrough. In order to gather the data during the walk through, a template is created which is used in gathering information for the B&D method as well as the Dynamo method. Appendix A: has the template that is created to gather information for the case studies.

5.1 B&D Case Study I

The first company studied is a major automotive manufacturer located in South Carolina, USA. The assembly line being analyzed in this company is used for the assembly of the door subsystems. In order to collect the data, the operation instructions for line are requested, with the operation instructions separated from station to station. The operation instructions consist of various different types of instructions such as instructions concerning quality, instructions for getting parts and instructions for performing assembly steps. The instructions that are of prime importance are the assembly instructions that describe the assembly operation being performed.

Once the operation instructions have been received from the company, the operation instructions are studied to have a preliminary knowledge of the assembly operations being performed at each individual station. After the operation instructions have been studied, the next step includes performing a detailed walkthrough of the assembly line to observe the process and fill up the data collection template. For Case Study I, the assembly line consists of 31 stations throughout which various operations are performed to assemble parts within the door. The assembly line is shaped in the form of a U-Shape with 17 stations in line along a stretch and then the line curves to make a U-shape after which station 18 to station 33 lie along a single stretch. Figure 5.1 illustrates the representation of the stations and the layout of the current line.

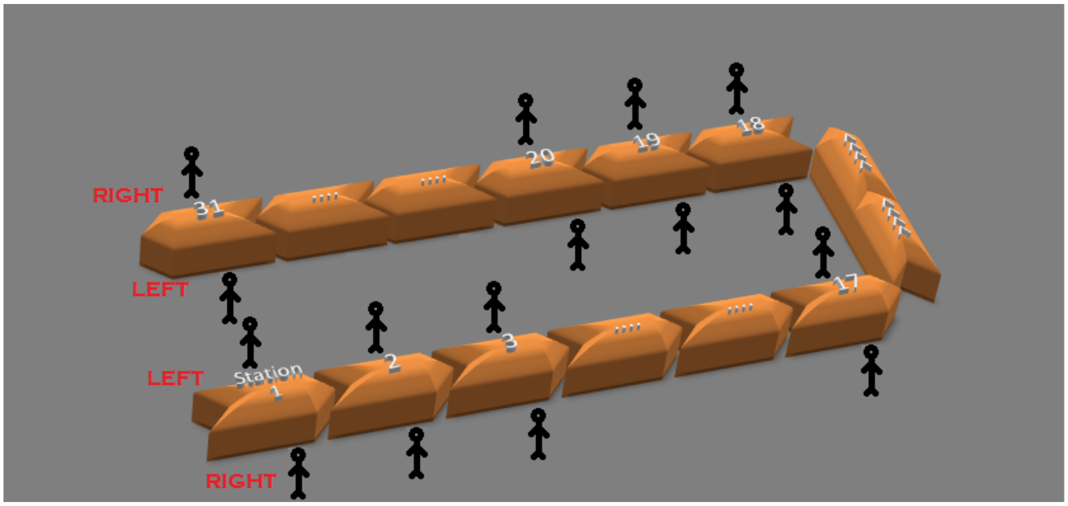

Figure 5.1: Representation of the current layout of the door line (Case Study I)

Besides Station 7, each station on the assembly line has operations being performed on both sides (left and right). Station 7 has operations being performed only on the left side of the station. This could be due to the reason that just having one side of the station performing operations within this station is sufficient to meet the required target. Furthermore, the stations that have operations being performed on both sides of the station have operations assigned in such a manner that both the sides of the stations follow the same operation instructions. Essentially, most of the operations are mirrored on both the sides.

In order to avoid confusion and for convenience the sides of the station are considered into two different cells, even though operations being performed on each side are the same. The left side of the station is represented with an 'L' beside the station number and the right side of the station is represented with an 'R' beside the station number. Thus, for example, the left side of station XX would be represented as XXL and the right cell of station one would be represented as XXR. The left doors of the car are presented to the XXR whereas the right doors of the car are presented to XXL. Figure 5.2 can be used to understand the station representation in a better manner.

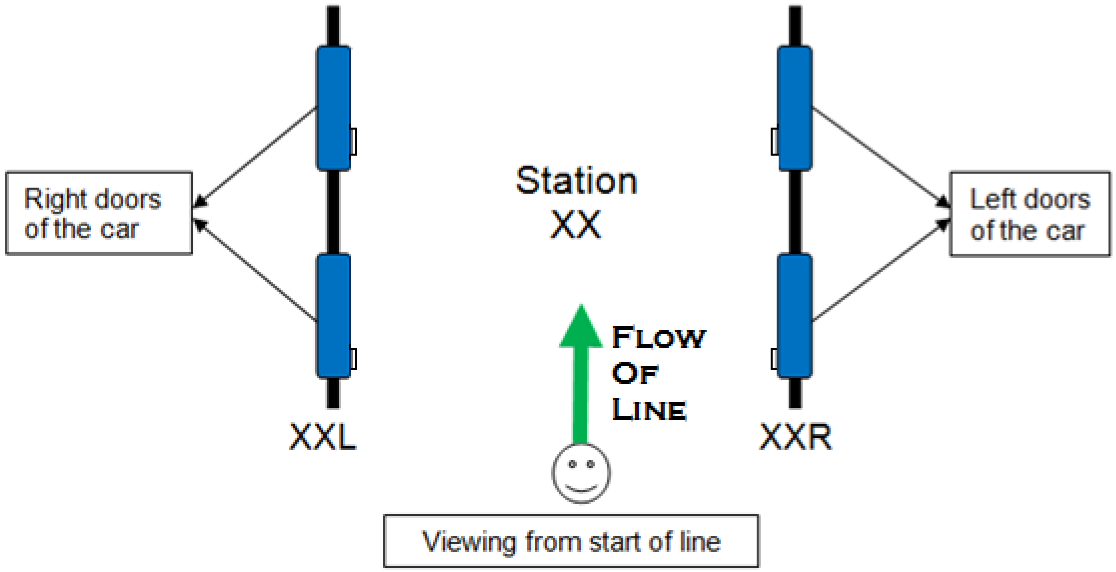

Figure 5.2: Station representation for B&D case study I

The data required to be filled in the data collection template is gathered by interviewing a company employee, while doing the walk through simultaneously. Based on the interview, the door line is used to assemble parts on doors of two variants of cars. Each shift has to meet a target of assembling doors for 350 vehicles / shift, which implies that the total number of doors assembled per shift is equal to 350 vehicles / shift X 4 doors = 1400 doors/shift. The company runs two shifts per day for six days a week. Consequently, the number of shifts (SH) = 2 shifts / day. Also, the annual production volume / shift can be calculated as,

$$VS = 1400\ \frac{doors}{shift} \times 6\ \frac{days}{week} \times 52\ \frac{weeks}{year} = 436{,}800\ \frac{doors}{shift}\ annually$$

Thus, it can be said that the annual production volume of doors/shift (VS) is 436,800 doors per shift annually. However, since each station has two cells, thus the production volume will be split into two different cells, resulting in the left side of the line producing 218,400 doors per shift annually and the right side of the line producing 218,400 doors per shift annually as well.

Furthermore, every station consists of two operators with each side allocated with its own respective operator. Each operator is approximately paid an annual salary of $40,000, but including overhead costs the total cost for employing an assembly operator almost adds up to $75,000. Accordingly, the annual cost of a single assembly operator (WA) is $75,000.

Based on the operation instructions and the walk through at the assembly plant, it was observed that three of the stations between Station 1 to Station 17 employed sealing robots to apply seals onto windows and doors. By performing an online market research, the price of a door seal robot varies between $70,000 to $120,000[4], thus in order to attain a value for the capital expenditure allowance to replace one operator on one shift (QE), an average of these two values is considered and QE is assigned a value of $95,000.

Table 5.1 shows the validation of the B&D method for case study I. The analysis is done for each station individually as well as for an overall section of the line (station 1 to station 17). From the analysis, it can be seen that, for each station the method estimates MM (Manual assembly with mechanical assistance) as the predicted solution. As already discussed within section 3.2, MM is defined a multi-station assembly line that contains devices like feeders in the form of mechanical assistance, but the assembly is still performed by the human operator. The authors provide a very little information about any other type of mechanical assistance besides feeders within solution MM; however any

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[4] Source: http://www.robotics.org/content-detail.cfm/Industrial-Robotics-Industry-Insights/Robotic-Sealing-Automation-for-Smaller-Industrial-Operations/content_id/1348 (accessed 2015.06.17)

device that aids the human operator in performing the assembly can be considered as a form of mechanical assistance. Thus devices such as feeders and semi-automated devices such as torque drivers, welding guns, would be considered as a part of MM assembly systems.

Table 5.1: Validation of B&D method on Case study I

Station	Annual VS/Shift	NA	NT	SH	WA	QE	NT/NA	RI	Decision	Current implementation
1	218400	8	8	2	75000	95000	1.00	2.53	MM	MA(Manual + manual tools)
2	218400	13	15	2	75000	95000	1.15	2.53	MM	MA (Manual + manual tools)
3	218400	1	2	2	75000	95000	2.00	2.53	MM	AR (Manual + Door seal robot)
4	218400	1	2	2	75000	95000	2.00	2.53	MM	AR (Manual + Door seal robot)
5	218400	15	20	2	75000	95000	1.33	2.53	MM	MM (Manual + SA tools)
6	218400	13	21	2	75000	95000	1.62	2.53	MM	MM (Manual + manual tools + SA tools)
7	218400	9	17	2	75000	95000	1.89	2.53	MM	AR (Manual +Window seal robot)
8	218400	12	17	2	75000	95000	1.42	2.53	MM	MM (Manual + manual tools + SA tools)
9	218400	9	1034	2	75000	95000	114.89	2.53	MM	MM (Manual + SA tools)
10	218400	8	2048	2	75000	95000	256.00	2.53	MM	MM (Manual + SA tools)
11	218400	8	84	2	75000	95000	10.50	2.53	MM	MM (Manual + SA tools)
12	218400	7	137	2	75000	95000	19.57	2.53	MM	MM (Manual + SA tools)
13	218400	6	12	2	75000	95000	2.00	2.53	MM	MM (Manual + SA tools)
14	218400	12	18	2	75000	95000	1.50	2.53	MM	MM (Manual + manual tools + SA tools)
15	Inspection									
16	218400	5	14	2	75000	95000	2.80	2.53	MM	MM (Manual + SA tools)
17	218400	7	18	2	75000	95000	2.57	2.53	MM	MM (Manual + SA tools)
Total	**218400**	**134**	**3467**	**2**	**75000**	**95000**	**25.87**	**2.53**	**MM**	AR (Manual + overhead conveyor + sealing robots)

where, SA tools = Semi-Automated tools

5.1.1 Station level of automation

From Table 5.1, it can be seen clearly seen that besides a few stations, the method accurately predicts what is currently being implemented within the process. The few stations that are not predicted accurately are shaded in light gray and dark gray. The rows highlighted in dark gray represent stations for which the predicted solution and the current implementation are not even closely related. The rows highlighted in light gray represent stations for which the predicted solution is at least closely related to the current implementation. MA represents manual assembly systems, where the assembly process is broken down into individual tasks performed in sequence by assembly operators, where an individual operator continually repeats the same operation or limited series of operations [5]. Since, the design for assembly handbook has very less information about the types of tools used within MA assembly systems; it will be assumed that the tools requiring a human operator to apply their own physical strength on the tool to execute the operation will come under MA assembly systems. Tools such as screw drivers, wrenches, push nut installation tools, come under manual assembly systems.

As can be seen in Table 5.1, the Stations 1 and 2, which are highlighted in yellow, have a predicted solution of MM, whereas the current implementation is completely manual with all the operations performed on these stations using only manual tools with the operator using their own physical strength to perform the operations. The deviation from the current implementation could be due to the way the table is structured. By observing Table 3.3, it can be seen that the predicted solution exists within cell (7, 1). However, by looking around the row 7 and column 2 it can be seen that cell (9, 2) consists of solution MM (MA). The predicted solution may be different from the current implementation due to the current production volume (VS) and the value of the Risk investment factor (RI). Owing to this deviation from the current implementation, the Dynamo method can be used to improve the predicted solution further.

Also, within some stations (Stations 9 and 10), the total number of parts is relatively very high, due to the possibility of various types of configurations. Even though the station receives only one of the configurations for the assembly, the all the possible configurations have to be considered as a part of NT. Similarly for Station 12, it can be seen that the NT value is as high as 137. This is due to the various options of colors available for door handles and door handle cover caps.

Compared to stations 1 and 2, where the predicted solution is relatively close to current implementation, the predicted solution within stations 3, 4 and 7 is completely different from the current implementation. The current process employs an operator on each side of station 3 and station 4 whereas station 7 consists of a single operator only on the left side of station 7. Each side of station 3 and 4 consists of a door seal robot on both the sides of the station to apply seals onto the doors arriving at the station. The responsibility of the operators at these stations is to apply the correct variant of seal on to the door seal robot depending on the model of the door arriving at the station. The door seal robot then applies the seal onto the door. For station 7, the main task of the operators is to prepare the triangle glass for the window seal robot. The window seal robot identifies whether the triangle glass sent in by the operator is the right model of triangle glass depending on the variant of the door coming into the station, applies glue onto the triangle glass and applies the right variant of seal onto the triangle glass.

Compared to station 1 and 2, the deviation within these stations occurs due to the type of operation being performed. There could be many possible reasons due to which the stations 3, 4 and 7 need to employ sealing robots instead of a human operator performing the operation. A few of the reasons could be that, the glue being applied onto the seal maybe harmful for humans, or a human operator may take too long to assemble the seal onto the door, resulting in an increase in the takt time or it could be an issue related to quality. However, due to the existence of such scenarios and to further improve the predicted solution, the necessity for the inclusion of Dynamo method can be justified.

5.1.2 Band level of automation

According to B&D analysis, the suggested level of automation at the band level is MM, but the current implementation makes use of an overhead conveyor that follows an inline indexing mechanism (AI). This shows that the method could not predict the right solution for the level of automation for the complete band. One of the reasons for this could be that the method does not consider the part size, shape and weight as one of its parameters.

5.2 B&D Case Study II

The second company studied is a major manufacturer of rolling element bearings for automotive and industrial uses, located in South Carolina, USA. The assembly line being analyzed within this company is used for the assembly of pistons. Before performing the walk-through of the assembly line, similar to case study I operation instructions were requested from this company as well. The operation instructions were reviewed to gain a good understanding of the line before performing a walk-through of the assembly line. Compared to the previous case study the assembly line at this plant consists of very few stations. The complete assembly line consists of a series of six stations with the operations at majority of the stations performed using high speed automatic assembly machines.

To aid for a better understanding of the working of the assembly line, the layout of the current process is shown within Figure 5.3.

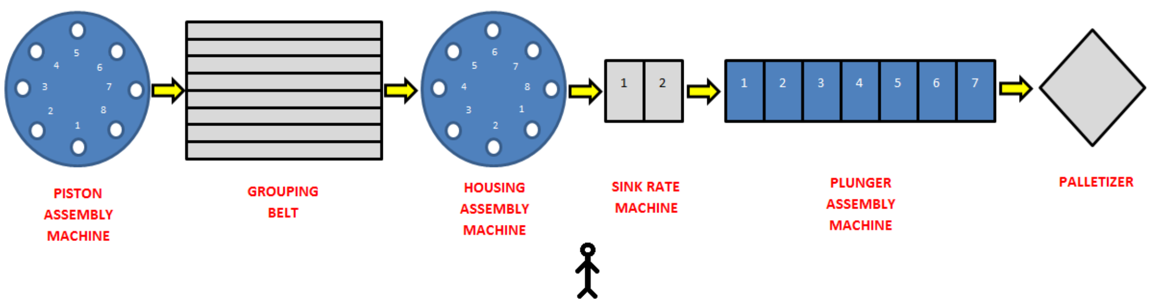


Figure 5.3: Representation of the current layout of the piston line (Case Study II)

The 1st machine on the line is the piston assembly machine and its primary task is to assemble a valve cap, spring and a ball bearing onto the piston. The machine in itself consists of eight individual stations over which different assembly operations and tests take place. Furthermore, there are a total of eight different varieties of pistons, but all of them have the same variants of the valve cap, spring and the ball bearing installed onto them. The primary difference between the different variants of pistons lies within the outer diameters of the pistons. Subsequently, once all the parts have been installed onto the piston, the piston is delivered onto Station 7. From Station 7, the pistons are delivered to the 2nd machine; the grouping belt, where the pistons are grouped into different lanes based on the outer diameter of the piston.

The 3rd machine on the line is the housing assembly machine and is used to assemble housings and return springs onto the pistons. Similar to the piston assembly machine, the housing assembly machine also consists of eight individual stations over which various assembly operations and functional tests are performed. The return spring is fed to the housing at Station 3 before the housing is assembled onto the piston at Station 4. Also, there are eight different varieties of housings available to be assembled onto the eight different types of pistons, with each piston having its respective housing. Based on the variant of housing fed to Station 1, the grouping belt delivers the appropriate piston to Station 4, where the housing is assembled onto the piston. The remaining stations of the housing assembly machine are used to perform different types of functional tests. The final housing assembly machine is then sent from Station 8 to the sink rate machine.

The 4th machine on the assembly line is the sink rate machine, which is used to lubricate the pistons, perform a sink rate check and a compression check over the pistons. The 5th machine is the plunger assembly machine, which consists of seven individual stations in-line within the machine. The main task of this machine is to perform the assembly of a plunger over the housed piston. Besides this, a variety of different functional tests are performed within the different stations of the machine that help in determining the functionality of the piston before it is sent to be palletized at the Palletizer, which is the final machine on the assembly line. The primary task of the palletizer is to palletize the pistons onto a pallet, after which the pallet can be sent out for delivery.

The plant runs a total of 3 shifts throughout the day with each shift required to meet a target volume of 9500 piston assemblies/shift. Thus, the number of shifts (SH) = 3. Based on an interview done with an engineer at the plant, it is known that the plant runs for 6 days/week for a total of 355 working days throughout the entire year. From this information the annual production volume per shift (VS) can be calculated as

$$VS = 9500\ \frac{assemblies}{shift} \times 1\ \frac{shift}{day} \times 355\ \frac{days}{year} = 3{,}372{,}500\ \frac{assemblies}{shift}\ annually$$

Contrary to the previous case study, where in each station had two operators to perform the respective operations on each side of the station, this assembly line consists of only a single operator for the complete line. The responsibilities of the operator are to restock the machines with parts and to take appropriate actions in case of machine failures. Hence the operator does not perform any assembly operations within the assembly line.

Since this plant is also located in South Carolina, USA, the annual salary of an assembly operator is assumed to be equal to \$75,000, which includes the cost for overhead plus benefits. Therefore the annual cost of a single assembly operator (WA) = \$75,000 (Table 5.2). However, since the value of WA is assumed, an analysis is done for a lower annual cost of \$60,000 as well, to check if the assumed value leads to a different array of results (Table 5.3).

The capital expenditure allowance to replace a single assembly operator on one shift (QE) would be equal to the cost of each machine at each station. The costs for each machine can be seen in Table 5.2. These costs were obtained based on the interview done with the manufacturing engineer during the walk through.

Table 5.2: Validation of B&D method on Case Study II (WA = $75,000)

Station	VS/Shift	NA	NT	SH	WA	QE	NT/NA	RI	Decision	Current Implementation
1	3372500	4	11	3	75000.00	307708.44	2.75	12.31	AI	AI (Rotary indexing machine)
2	Material Handling								-	
3	3372500	3	17	3	75000.00	258674.82	5.67	10.35	AI	AI (Rotary indexing machine)
4	Material Handling								-	
5	3372500	18	18	3	75000.00	281058.73	1.00	11.24	AF	AI (In-line indexing machine)
6	Material Handling								-	
Total	**3372500**	**15**	**36**	**3**	**75000.00**	**400000.00**	**2.40**	**16**	**AP**	AI (In-line indexing machine)

Table 5.3: Validation of B&D method on Case Study II (WA = $60,000)

Station	VS/Shift	NA	NT	SH	WA	QE	NT/NA	RI	Decision	Current Implementation
1	3372500	4	11	3	60000.00	307708.44	2.75	12.31	AI	AI (Rotary indexing machine)
2	Material Handling								-	
3	3372500	3	17	3	60000.00	258674.82	5.67	10.35	AI	AI (Rotary indexing machine)
4	Material Handling								-	
5	3372500	18	18	3	60000.00	281058.73	1.00	11.24	AF	AI (In-line indexing machine)
6	Material Handling								-	
Total	**3372500**	**15**	**36**	**3**	**60000.00**	**400000.00**	**2.40**	**20**	**AP**	AI (In-line indexing)

5.2.1 Station level of automation

Firstly, by comparing Table 5.2 and Table 5.3, it can be noticed that changing the value of WA from $75,000 to $60,000 does not impact the decision in any manner. This signifies that the decision is not very sensitive to change in the annual salary of an assembly operator. Although for larger changes to the value of WA, the method may have an increased level of sensitivity, which may lead to a different array of results.

Furthermore, compared to the previous case study, the method helps in determining the appropriate assembly method more accurately within this case study. Three out of the four assembly stations are predicted accurately by the method; with the only exception being Station 5, which is highlighted in light gray, as the predicted result is almost close to the current implementation. At Station 5, the method predicts the result as AF (automated assembly machines provided with special purpose free transfer mechanisms, work heads and automatic feeders) where as in reality the assembly line employs an AI machine (automated assembly machines provided with special purpose indexing mechanisms, work heads and automatic feeders). A free transfer machine may be employed within an assembly line to accommodate for variations in the production due to rise or fall in demand. However, since the stations before and after station 5 follow an indexing principle, thus the input to station 5 is indexed as well as the output from station 5 has to be indexed. This may be the reason due to which the Station 5 may currently be employing an indexed mechanism.

5.2.2 Band level of automation

As compared to the previous case study, the method at least comes close to determining the level of automation that is currently being implemented at the band scale on the piston assembly line. This could be due to the production volume being so large, the decision was bound to be automated, but yet the method does not accurately determine the correct level of automation at the band level.

5.3 B&D Discussion

For the 1st Case Study, the method accurately predicts the assembly methods currently being employed for 13/16 stations, whereas within the 2nd case study, the method accurately predicts the assembly methods for 3/4 stations. Based on the two case studies, it can be said that the B&D method can prove to be a very helpful tool in giving a preliminary idea to decide the appropriate assembly method within stations of an assembly line. The consideration of flexibility is one of the major advantages of the method, as it considers the variance and overlap between the number of parts in the assembly and the number of parts required to build different product styles (NT). Another benefit of the method is that it studies the aspect of cost minimization and profitability by considering the manufacturer's investment potential. For example, if the demand for a certain product falls, the manufacturer can consider lowering his/her RI potential by varying QE, SH or WA and analyze which of the decisions would be more profitable.

However, besides these advantages, the method also has some drawbacks. One drawback being, the method does not consider process flow, due to which the method may only be applicable to workstations, while it may be hard to design a complete band as seen in Section 5.1.2. Also, there seems to be no consideration provided to ergonomic factors within the method. An evidence for this could be seen in B&D Case Study I where in station 3 and 4 involved applying seals on doors. The sealant being used may be harmful for humans, due to which door seal robots are currently being used for the application. The door seal robots may also be used to meet a certain level of quality; another aspect that has been very vaguely discussed within the method.

Chapter Six
VALIDATION OF DYNAMO METHODOLOGY BASED ON CASE STUDIES

Based on the validation of the B&D method on the two case studies in the previous chapter, it can be noted that the B&D method acts as a good tool to determine the appropriate assembly method at the station level. However, since the B&D method does not explicitly consider the process flow, it is difficult to determine the appropriate level of automation at a band level. Thus, the case studies will now be validated based on the Dynamo methodology. This method should be able to act as a worthy tool to select appropriate level of automation over the complete band, since process flow is one of its crucial elements.

6.1 Dynamo Case Study I

The same door line that was analyzed within B&D Case Study I is analyzed for this case study. First, based on the operation instructions received from the company, preliminary mechanical and informational LoA were assigned to each station. Conducting a preliminary LoA measurement is useful to gain an understanding of how the tasks are intended to be conducted [11]. The LoA measurement is performed by two voluntary participants from the Clemson Engineering Design and Applications Research (CEDAR) lab at Clemson University, SC. The 1st participant (P1) is a PhD student at Clemson University in the Department of Mechanical Engineering and has worked on multiple projects within the company being studied for Case Study I. The 2nd participant (P2) is a Master's student who has sufficient knowledge about the door line being studied at the company for Case Study I having spent seven days (~50 hours) studying the door line process in question. The preliminary LoA is then assigned to each station based on the reference scales seen within Table 4.1.

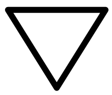
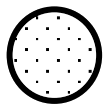
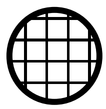
The next step includes performing the walk through of the door line and then assigning minimum and maximum LoA to each station based on the process flow. The data collection template is again used in order to gather detailed information about the process. An example of the filled data collection template is shown in Figure 6.1.

The different operations achieved, with corresponding Section/ cell number, and techno executing = how (machine, human, robot, ...)	Operation description	Corres. Nb Cell (Ci)	Techno: if machined then type of the machine, its age, maintenance, particularities	Nb operators	Tasks of the operators
	O1- Wait time	All		2	
	O2-Door Emblem Clean on the left front door	01002 RF	1xWipes	2	Clean with wipes
	O3-Door gap seal b-pillar surface clean with a new wipe	01002 RR	1xWipes	2	Clean with wipes
	O4-Triangle glass adhesive area clean with a new wipe	01002 RR	1xWipes	2	Clean with wipes
	O5- Door Gap seal install	01002 RR	1XB pillar Gap seal	2	Check model F15/F16, Get B-pillar gap seal, Remove liner and do not touch adhesive surface or let it touch door, Apply the seal and press it
	O6-Emblem install	01002 RF	Emblem, Emblem Fixture tool	2	If vehicle has option 320, no emblem will be installed. Place emblem in fixture, Remove backing to expose glue, Place backing in trash, Align emblem fixture

Figure 6.1: Example of filled data collection template

Once all the information about the complete process flow over the complete band is gathered within the data collection template, the next step is to document the production flow by means of symbols [11]. This method consists of three types of symbols that are used to document the production flow. These symbols and their interpretation can be seen in Table 6.1.

Table 6.1: Symbols used to document the production flow

Symbol	Interpretation
	Buffer (Used to represent the buffer zone in between stations)
	Workstation / Cell with operation instructions
	Workstation / Cell without operation instructions

For each of the sixteen stations, the process flow is documented using the data collection template and the symbols shown in Table 6.1. The documentation of the process flow for the all the sixteen stations can be seen in Appendix B: Figures 1-9. After the process flow has been documented, the main task within the station is broken down into further sub-tasks by using the hierarchical task analysis (HTA) approach developed by Kirwan and Ainsworth, 1992 [20]. The primary purpose of breaking down the main task into sub-tasks is to define the tasks in such a manner that either a human or a machine should be able to perform the task. Henceforth, the main tasks for the sixteen stations are broken down into sub-tasks. The breakdown of tasks for each station can be seen within Appendix B: . The next step includes analyzing the observed LoA and assigning minimal and maximal LoA's using the reference scales for mechanical and informational LoA. Based on the information received during the walk through as well as using the documented production flow, the observed LoA is calculated and the minimal and maximal LoA are assigned.

6.1.1 Station level of automation

The primary reason why two participants are chosen to perform the LoA measurement is to examine how the results vary with respect to the knowledge and the experience of the participant with regards to the process being analyzed.

From the SoPI analysis for Station 1 (Figure 6.2), it can be seen that both the participants assign the same values for maximal and minimal mechanical LoA and Information LoA. However there occurs a slight difference in the values for Operation Instructions LoA, where P1 assigns a value of 1 for Mechanical LoA and P2 assigns a value of 2. This could be due to the reason that P1 has less knowledge about the current processes on the door line than P2. However, both the participants assign the same maximal and minimal LoA's and it can be seen that the Observed LoA lies within the Square of potential improvement. Thus, if the manufacturer decides to automate the station 1, the station could possibly be automated until the Mechanical LoA 5 (Static Machine/Workstation). However, there seems to be no potential to increase the informational LoA since it is already at the maximum.

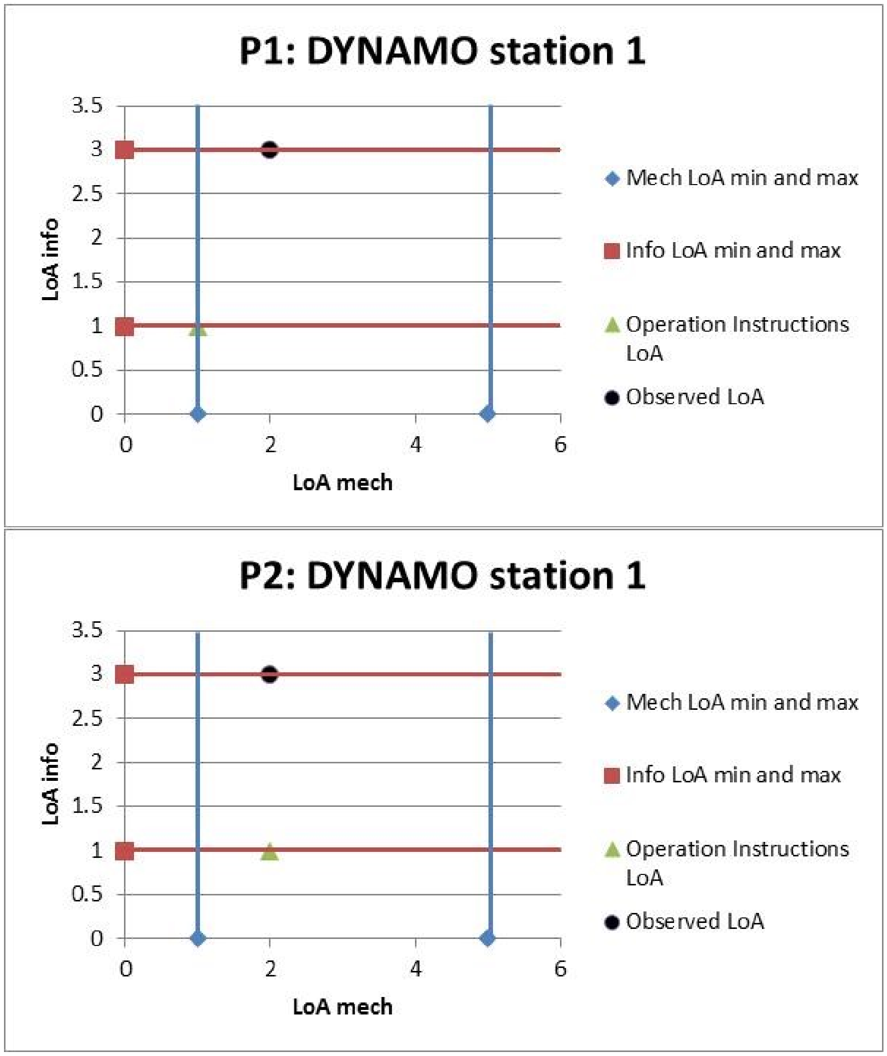


Figure 6.2: SoPI's for Station 1 (P1 and P2)

For Stations 2, 3 and 4 (Figure 6.3, Figure 6.4, Figure 6.5), it can again be seen that there is slight or no difference between the operation instructions LoA. However, in these stations, the maximal and minimal LoA's assigned by P1 differ compared to the maximal and minimal LoA's assigned by P2. It can be noticed that in all three stations, P1 comparatively assigns lower maximums for Informational LoA as compared to P2. Again, this could possibly depend on the participant's knowledge of the process or how conservative or liberal the participant is while assigning the values for LoA.

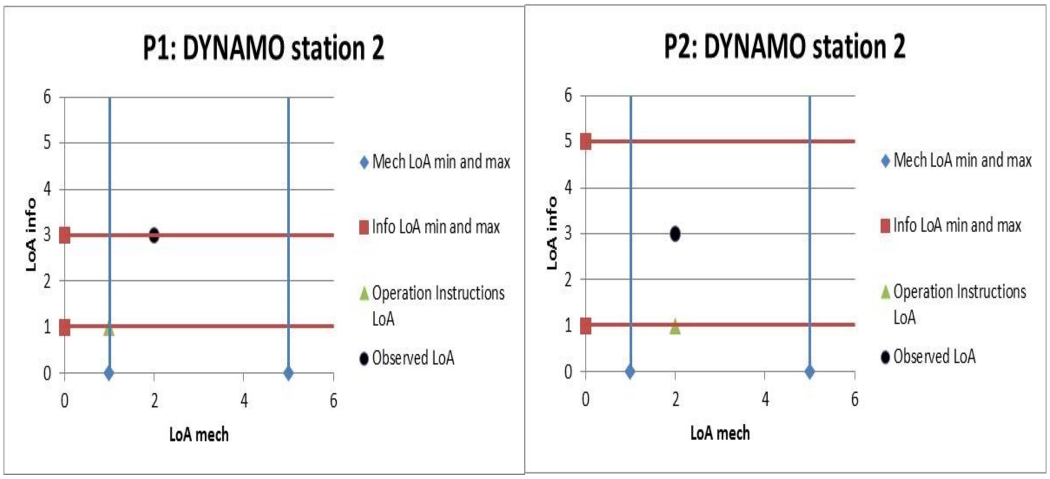


Figure 6.3: SoPI's for Station 2 (P1 and P2)

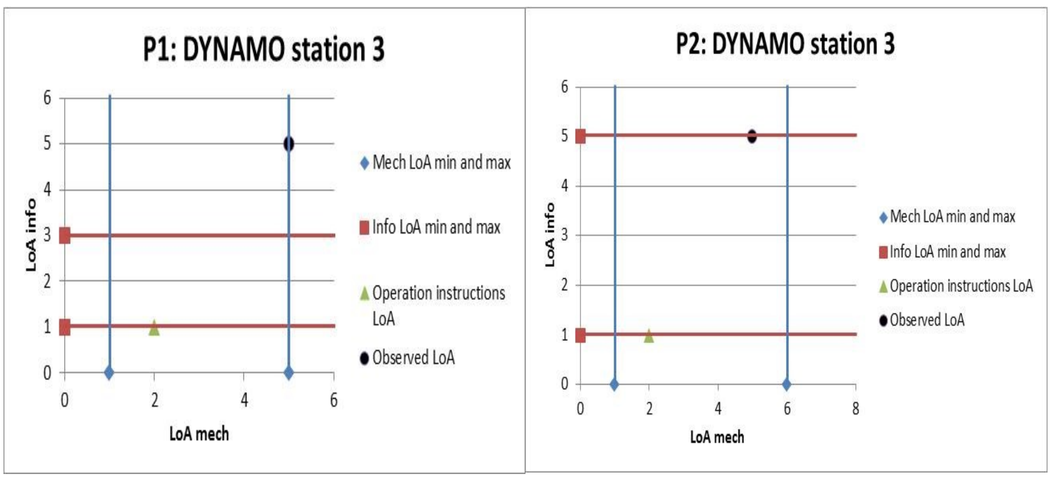


Figure 6.4: SoPI's for Station 3 (P1 and P2)

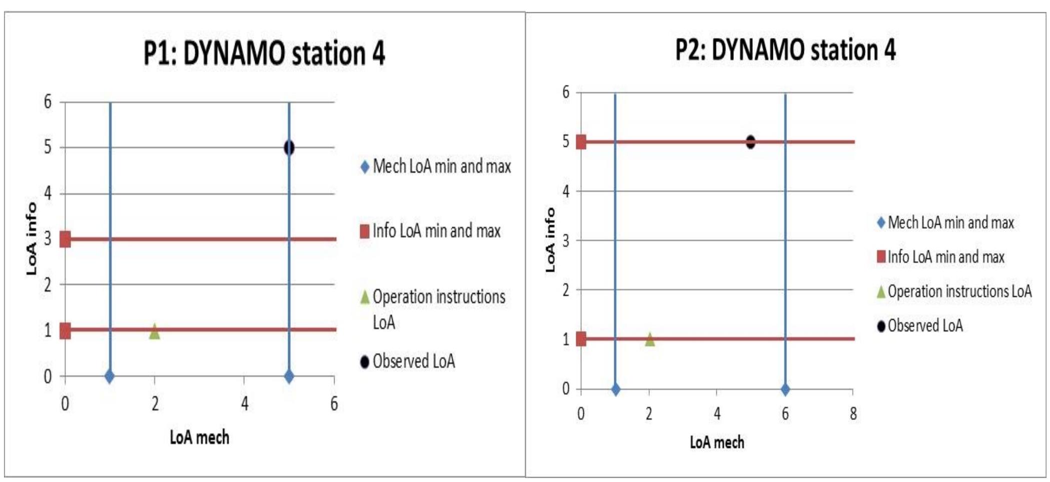


Figure 6.5: SoPI's for Station 4 (P1 and P2)

Nevertheless, an advantage of constructing a square of potential improvement is that it gives an idea of how much the LoA can be decreased or increased for improving the process. Also, plotting the preliminary and observed LoA within the SoPI shows the actual flexibility and dynamics of automation. This can be seen within the SoPI of participant P1 for Station 5 and 6 (Figure 6.6, Figure 6.7), where there seems to a big gap between the LoA assigned for the operation instructions to what is currently being applied. This also makes it evident that performing a walkthrough of the assembly line before assigning LoA's to the stations is a crucial step in the determination of Level of Automation.

Similar to the previous stations, a comparison of SoPI's of the two participants is done for the remaining stations on the assembly line which can be seen in Figures Figure 6.8, Figure 6.9, Figure 6.10, Figure 6.11, Figure 6.12, Figure 6.13, Figure 6.14, Figure 6.15, Figure 6.16 and Figure 6.17.

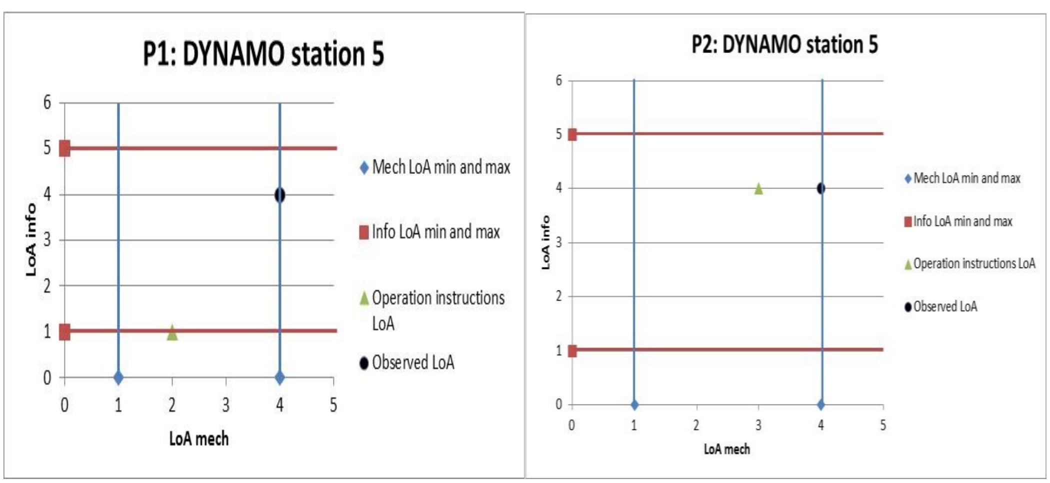


Figure 6.6: SoPI's for Station 5 (P1 and P2)

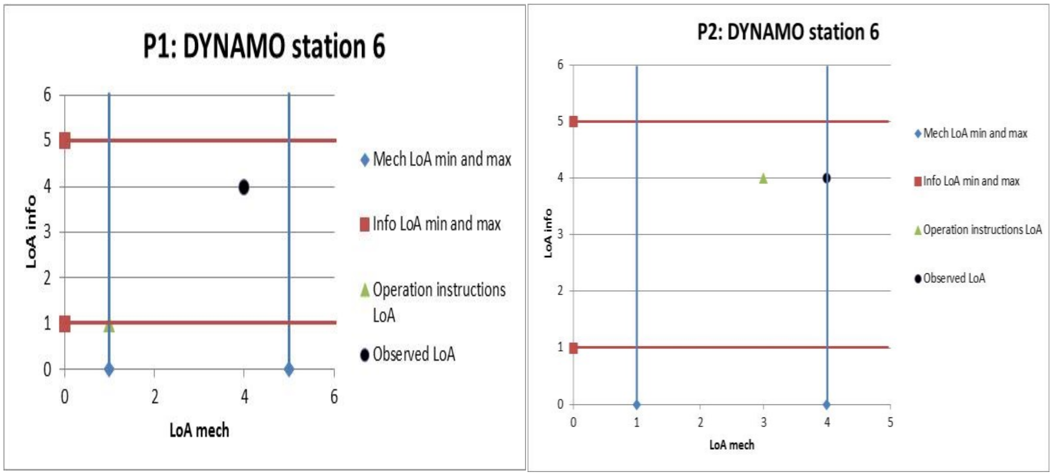


Figure 6.7: SoPI's for Station 6 (P1 and P2)

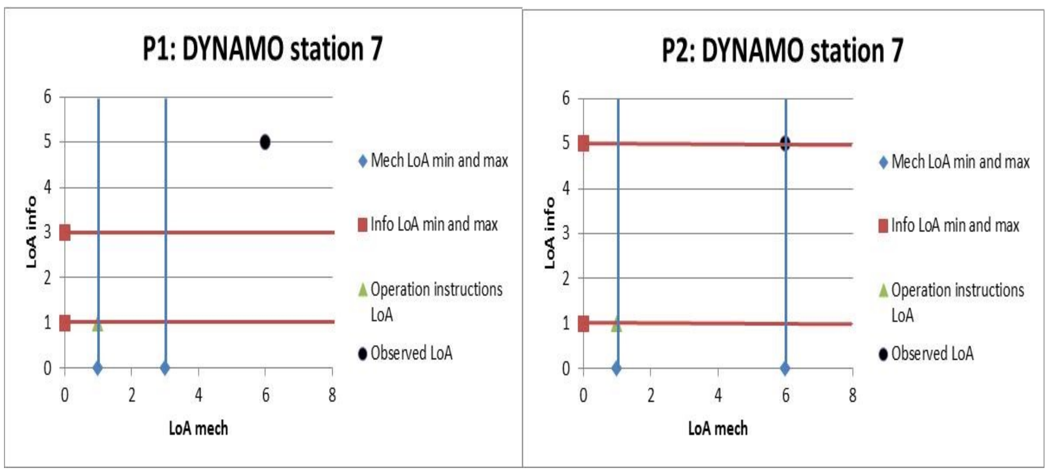


Figure 6.8: SoPI's for Station 7 (P1 and P2)

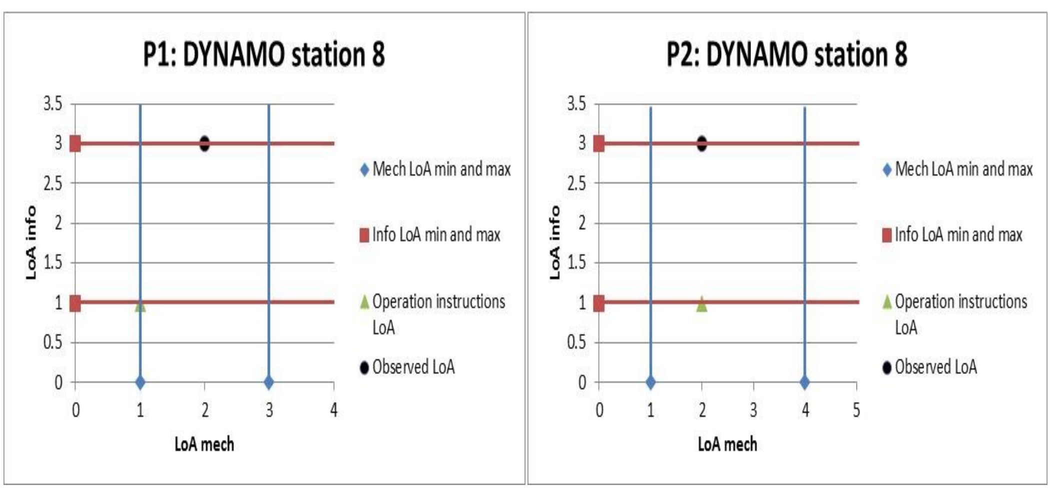


Figure 6.9: SoPI's for Station 8 (P1 and P2)

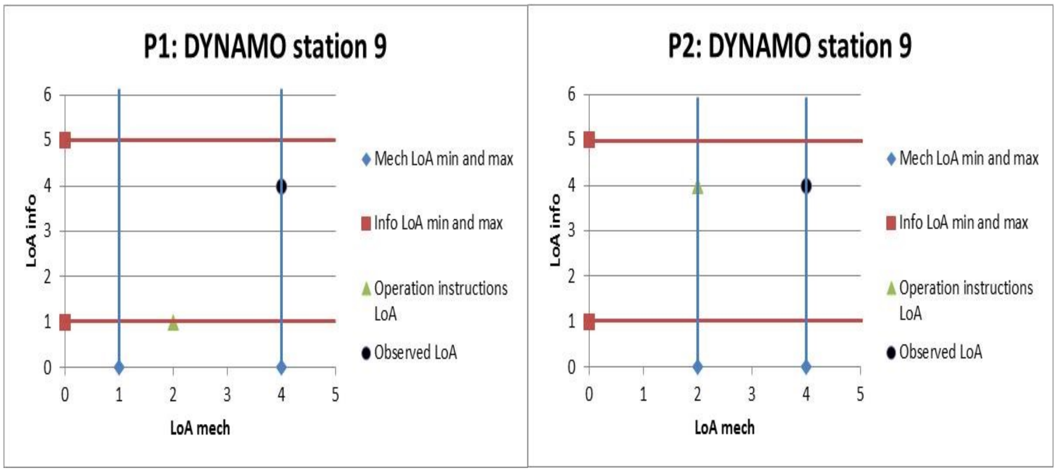


Figure 6.10: SoPI's for Station 9 (P1 and P2)

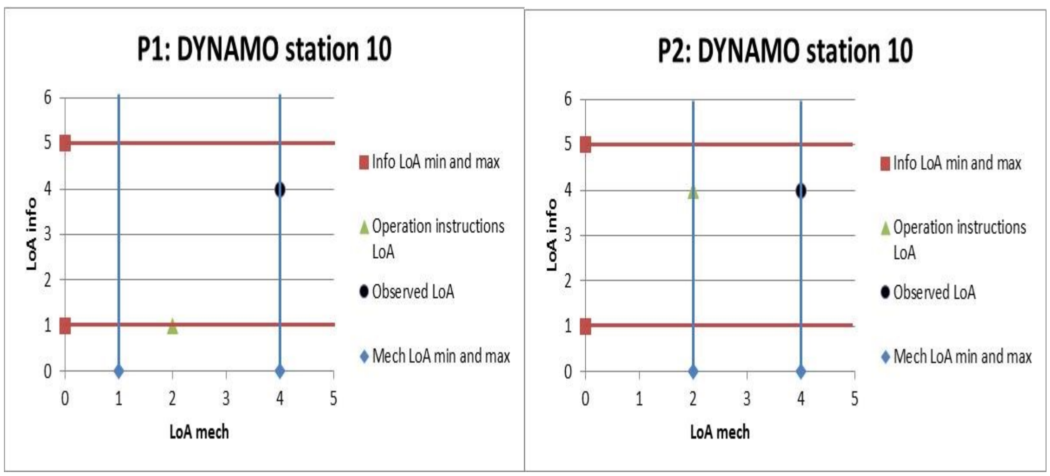


Figure 6.11: SoPI's for Station 10 (P1 and P2)

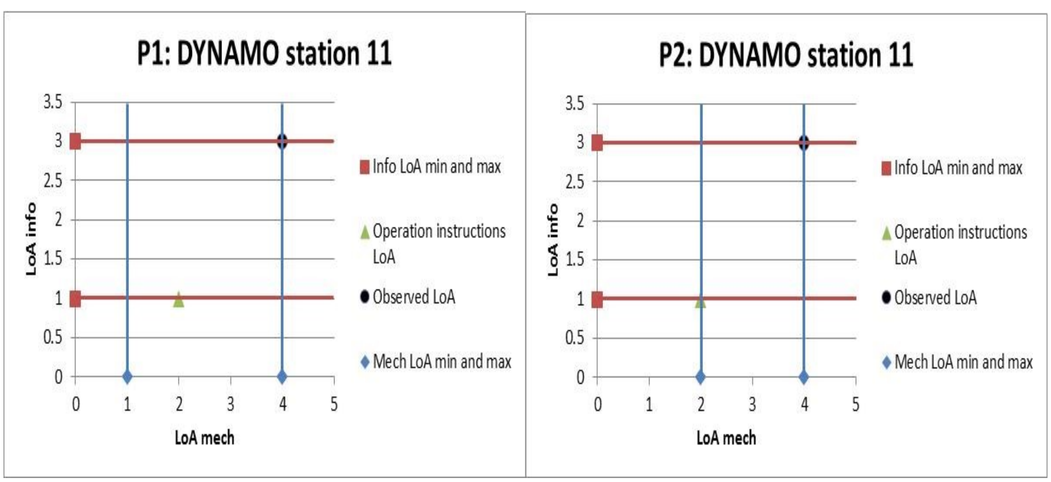


Figure 6.12: SoPI's for Station 11 (P1 and P2)

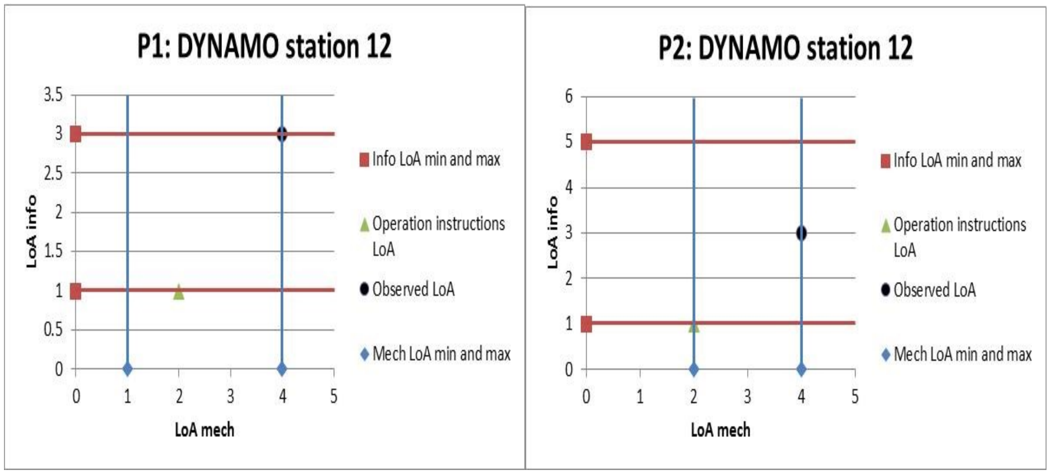


Figure 6.13: SoPI's for Station 12 (P1 and P2)

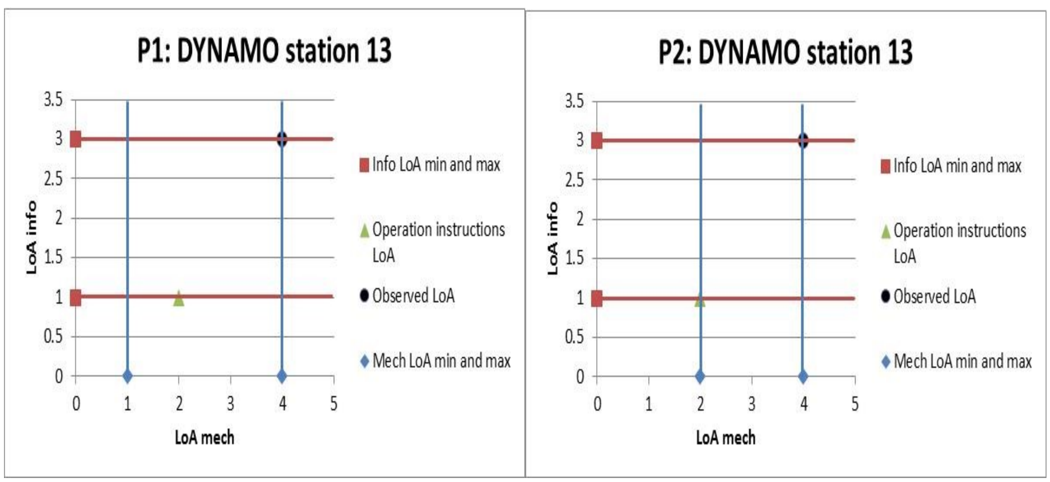


Figure 6.14: SoPI's for Station 13 (P1 and P2)

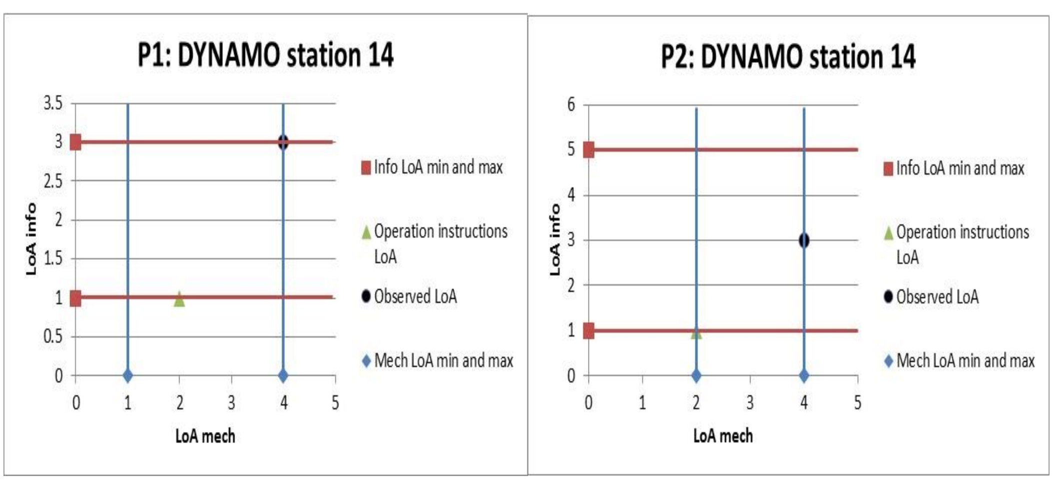


Figure 6.15: SoPI's for Station 14 (P1 and P2)

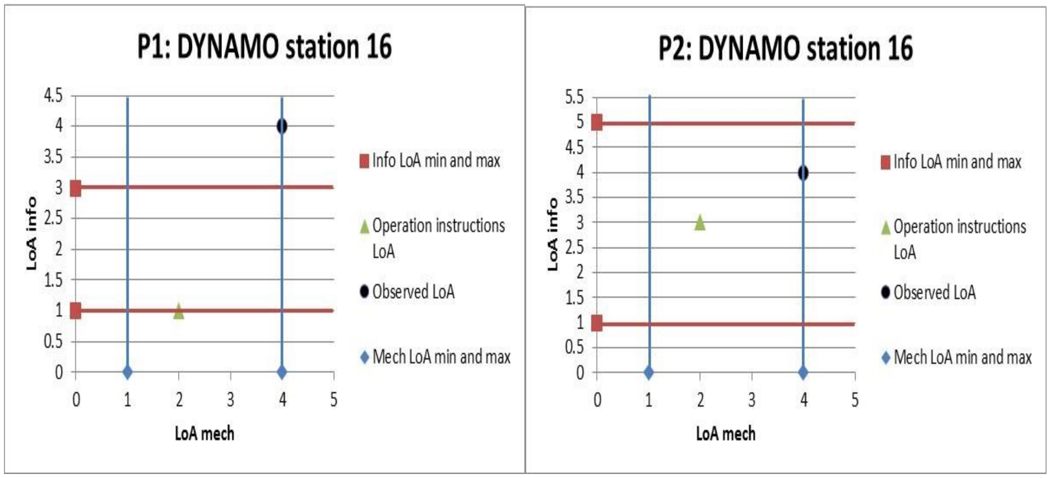


Figure 6.16: SoPI's for Station 16 (P1 and P2)

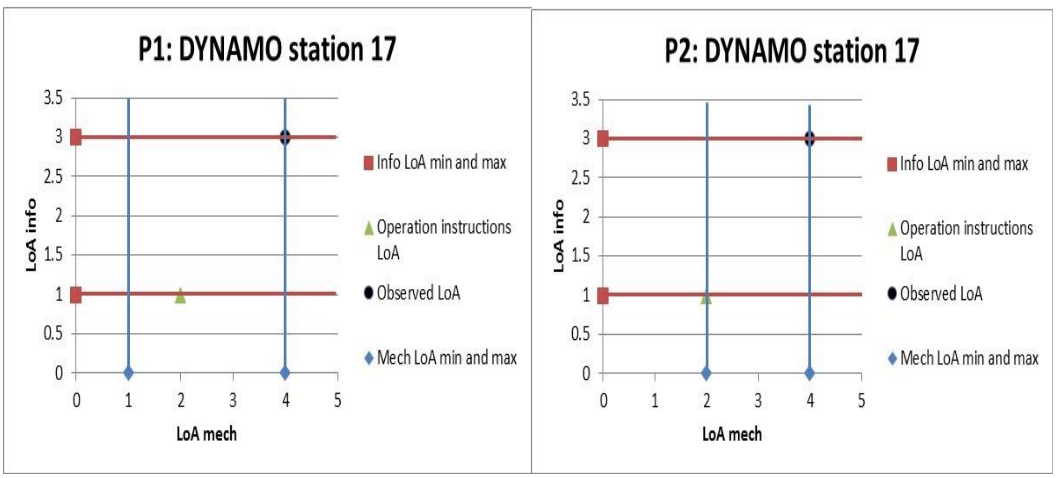


Figure 6.17: SoPI's for Station 17 (P1 and P2)

As can be seen within the comparison of majority of the SoPI's, the mechanical LoA value and the informational LoA value assigned for the operation instructions is generally very low. This could be due to the fact that the annual production volume of doors within this company is less than 500,000 doors / shift annually. This implies that, annually less than 250,000 doors are being assembled per cell within each station. Due to the annual production volume being so low, the participants may have felt that there might not be a need to employ automation for such a low volume. However once the walk through was performed, there might have been certain operations that would require or can employ automation, thus resulting in considerably high “maximal LoA values”.

6.1.2 Band level of automation

Contrary to the assumption that was made earlier, this method also does not allow for the assignment of tasks at a band level, as the LoA scales developed within this method are suitable only for tasks that involve assembly operations and cannot be used to assign minimal and maximal LoA for tasks involving transfer operations.

6.2 Dynamo Case Study II

For this Case Study, the piston assembly line that was studied within B&D Case Study II is analyzed using the Dynamo Method. As per the 1st step within the Dynamo method, firstly the operation instructions were requested from the company in order to perform a preliminary LoA measurement before performing the walk through. However the company did not have any formalized set of operation instructions, hence the operation instructions had to be created based on data gathered during the walk through. The operation instructions created based on the walk through are shown in Table 6.2.

Table 6.2: Operation Instructions for the piston assembly line

OPERATION INSTRUCTION
INSERT PISTON ONTO STATION
INSPECT PISTON HEIGHT
INSERT VALVE CAP, SPRING AND BALL BEARING ONTO PISTON
INSPECT PISTON FOR SPRING ALIGNMENT
INSPECT PISTON FOR AIR LEAKAGE
INSPECT VALVE FUNCTIONING
INSPECT PISTON OD AND GROUP PISTON FOR NEXT STATION
REMOVE PISTON IF DEFECTIVE
ALIGN PISTON BASED ON PISTON OD
RESTOCK PISTONS IF BUFFER IS EMPTY
INSERT HOUSING AND INSPECT HOUSING OD
INSPECT HOUSING BORE AND HEIGHT
INSERT RETURN SPRING ONTO HOUSING
INSERT PISTON ONTO HOUSING
INSPECT PISTON FOR PRESENCE OF LUBRICATION HOLE
INSPECT PISTON FOR COMPRESSED LENGTH AND MOUNTING SIZE
REMOVE PISTON IF DEFECTIVE
INSERT PISTONS ONTO CARRIAGES
APPLY LUBRICATION OIL TO PISTONS
INSPECT PISTON FOR SINK RATE AND COMPRESSION
APPLY LUBRICATION OIL TO PISTONS AND INSERT PLUNGER ONTO PISTON
INSERT SNAP RING INTO THE PISTON
INSPECT PLUNGER FIT USING PRESSURE TEST
INSPECT PLUNGER FIT USING PRESSURE TEST
INSPECT PLUNGER MOVEMENT USING COMPRESSION TEST
INSPECT PLUNGER MOVEMENT USING COMPRESSION TEST
INSPECT PLUNGER MOVEMENT USING COMPRESSION TEST
PLACE PISTONS ONTO PALLET

The operation instructions were created based on the formatted structure to create operation instructions developed within [31]. From the developed operation instructions, it can be seen that there are few value added assembly steps (7) as compared to the various amounts of inspection steps (14) that go into checking the functioning of the piston. Once the operation instructions are created, a preliminary LoA assessment is done on the operations. The further steps within the method involve walking the assembly line to document the process flow by the use of symbols shown in Table 6.1. The documented process flow for the piston assembly line can be seen in Appendix B: . After the process flow for the complete assembly line has been documented the different main tasks for each station are broken down into sub-tasks using HTA analysis, which can also be seen in Appendix B: After the main tasks have been broken down into sub-tasks such that each operation can be performed either by a machine or by a human operator, the maximum and the minimum LoA values are assigned to each station along with the current observed LoA. The SoPI's for each station of the piston assembly line can be seen below. As compared to the B&D Case Study I, where the analysis was done by two participants, in this case study the analysis is done by only 1 participant.

6.2.1 Station level of automation

Station 1 in itself consists of eight different stations over which the piston is transferred using a rotary indexing mechanism. Station 1 within the piston assembly line is used for the assembly of a valve cap, spring and a ball bearing into the piston. While these are the only assembly steps within Station 1; the remaining stations within Station 1 are used to inspect the functioning of the piston. The SoPI for Station 1 can be seen within Figure 6.18. Compared to the SoPI's within Dynamo Case Study I, the SoPI within this case study has the operation instructions LoA considerably close to the actual implementation. As the production volumes for this assembly line are as large as 3,372,500 assemblies per shift annually; in order to meet the demand for such a large volume the LoA values assigned tend to be more inclined towards automation. Due to this reason even the minimal values of Mechanical LoA and Informational LoA for Station 1 are as high as (4, 3).

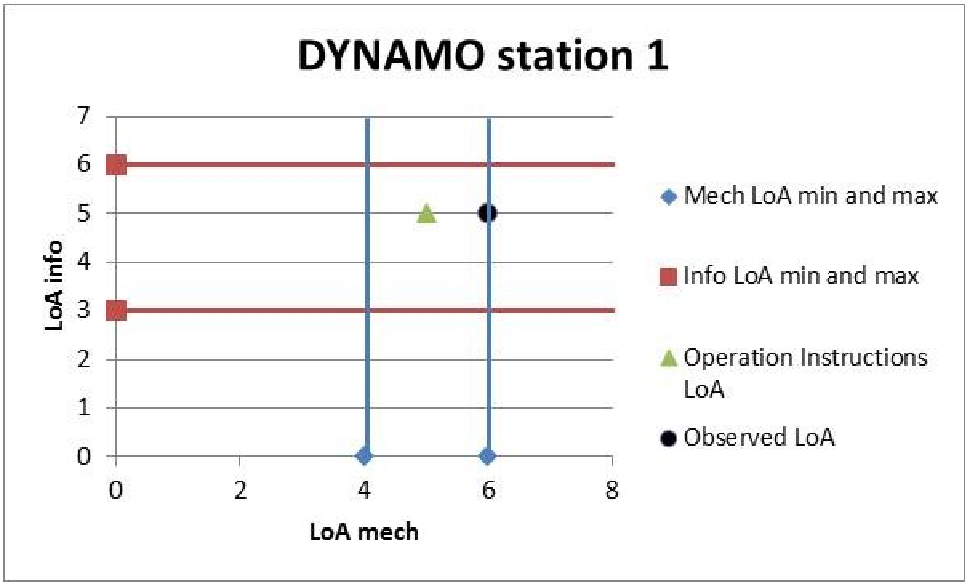


Figure 6.18: SoPI for Station 1 (Case Study II)

The main purpose of Station 2 is to group the pistons according to their respective outer diameters (OD's) in order to prepare pistons to be assembled with housings at Station 3. The annual production volume of pistons is one of the reasons that the minimal and the maximal LoA values assigned are high (Figure 6.19). Besides this, another reason that both the Mechanical and Informational LoA are high is that, since the pistons need to be grouped and the outer diameter of the pistons vary in the order of millimeters or microns, there would be a need for advanced tools even if the operation is being performed by a human operator. Nonetheless, the operation would need to be employ automation under any circumstances to decrease the occurrences of errors and to meet the required demand of pistons desired annually.

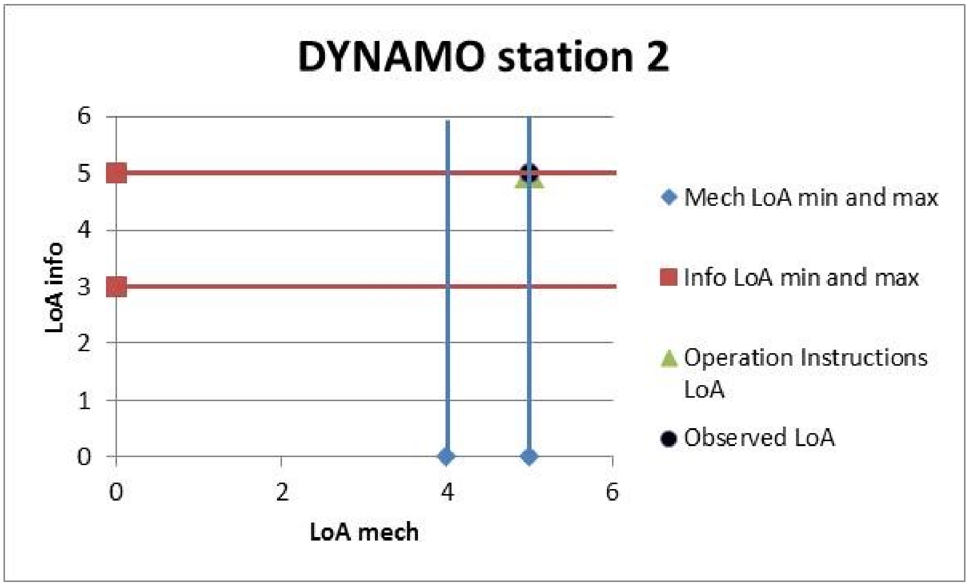


Figure 6.19: SoPI for Station 2 (Case Study II)

Station 3 of the piston assembly line is similar to Station 1, where in there are 8 stations incorporated with a rotary indexing mechanism. The main purpose of this station is to assemble housings over the piston. Since there are 8 different varieties of pistons with different OD's, there are also 8 different types of housings with different inner diameters (ID's). Again the minimal and maximal LoA are relatively high so that the demand for the large production volume can be met. The SoPI for Station 3 can be seen in Figure 6.20.

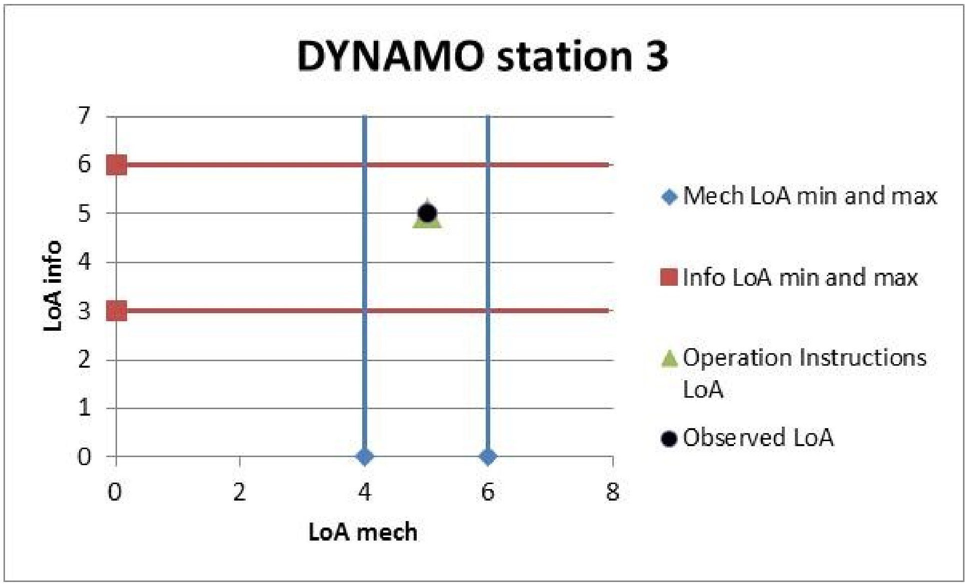


Figure 6.20: SoPI for Station 3 (Case Study II)

The main purpose of Station 4 of the piston assembly line is to apply oil to the pistons for lubrication and perform a sink rate and a compression check to verify the functioning of the piston. Upon interviewing one of the operators on the assembly line it was found out that the sink rate and the compression check for the piston is performed in order to inspect the backlash velocity, measure the time-distance relationship, measure the time-speed relationship and measure the power-distance relationship. The SoPI for Station 4 can be seen in Figure 6.21. Although the lubrication of the pistons can be done manually, but since the other function of the station is to perform the sink rate and compression check, it was assumed that advanced tools (if operation is performed by an operator) or a dedicated machine would be required to perform this operation, resulting in minimum and maximum Mechanical LoA values of (4, 5) within the SoPI.

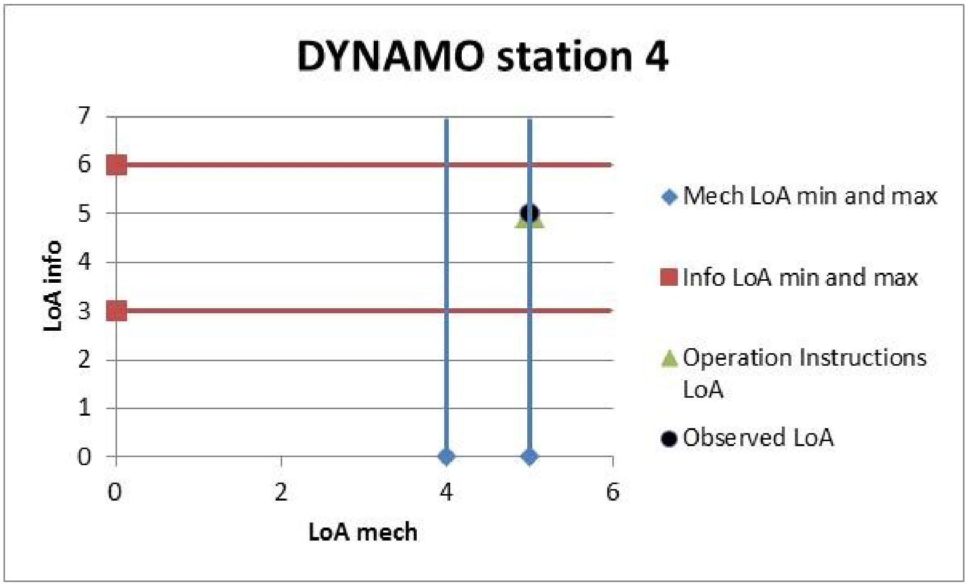


Figure 6.21: SoPI for Station 4 (Case Study II)

Station 5 in itself consists of 7 stations that are connected using an in-line indexing mechanism, out of which one of the stations is used to assemble a plunger into the piston and another station is used to assemble a snap ring into the piston. The remaining stations of Station 5 are used to check the fitting of the plunger along with the piston by means of pressure tests and compression tests. The minimum level of mechanical LoA assigned here is two (Figure 6.22) since it was assumed that the plunger and the snap ring can be installed using a manual punch. The fitting of the plunger can be checked using manual tools that can be punched in and pulled to check the fitting of the plunger. However, this can only be possible if the annual production volume decreases to a large extent. Subsequently, in order to accommodate for an annual production volume in the range of 3,000,000 it would be more feasible to consider automation due to which the maximum mechanical LoA assigned is 5.

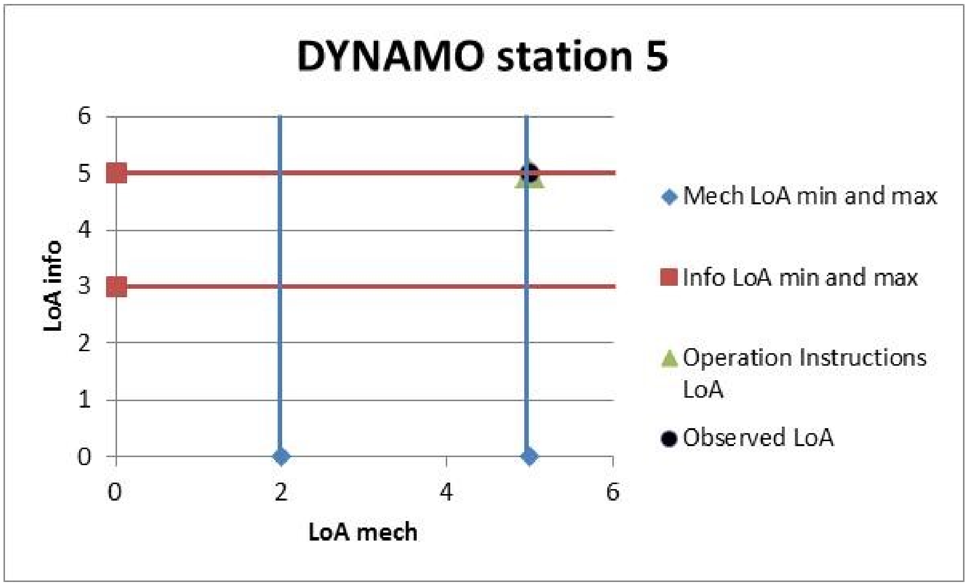


Figure 6.22: SoPI for Station 5 (Case Study II)

Station 6 of the piston assembly line is used to palletize the assembled pistons into pallets. The operation instructions LoA and the observed LoA in the SoPI for Station 6 (Figure 6.23) lie on complete extremes. It could be possible that all the pistons can be arranged into a pallet using a human operator due to which the preliminary LoA for the operation instructions was assigned a value of (1, 3) where Mechanical LoA = 1 and Informational LoA = 3. However, incorporating a human operator might cause in increase in the cycle time due to the remaining stations being completely automated, due to which station 6 might be employing a dedicated machine. Nevertheless, if the annual production volume declines considerably, then a human operator can be used to perform this operation without the aid of any tools, due to which the minimal mechanical LoA is assigned a value of one.

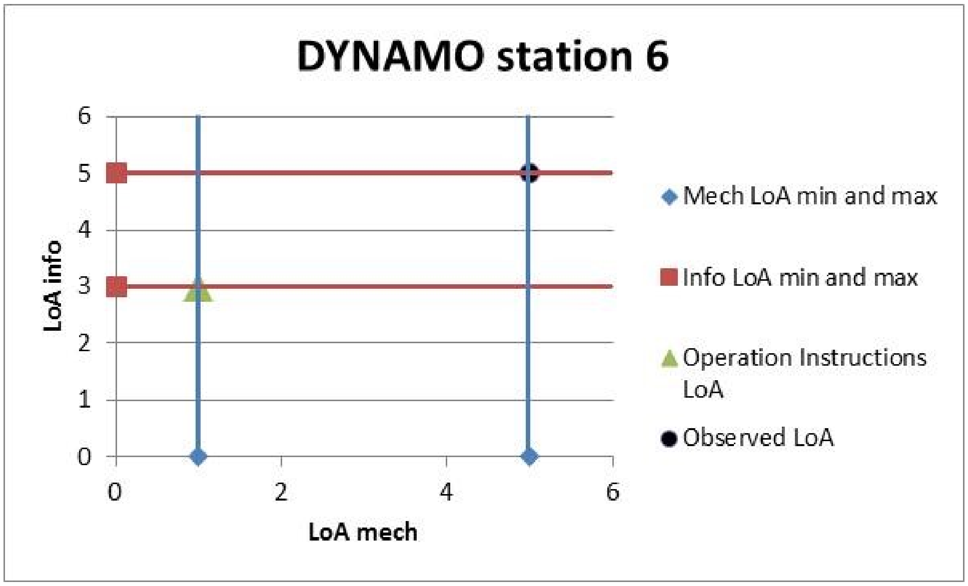


Figure 6.23: SoPI for Station 6 (Case Study II)

6.2.2 Band level of automation

Again, this method cannot be used to determine the appropriate level of automation for a complete band due to the inadequacy of the level of automations required to express transfer mechanisms.

6.3 Dynamo Discussion

Based on the comparisons done between the SoPI's in Dynamo Case Study I, it is seen that the knowledge and the experience of the person responsible for assigning the LoA to the station plays a very crucial role in improving the process. Also, as compared to the B&D method, which does not consider walking the process as one of the factors before determining the assembly method, this method provides significant importance to the process flow. Another benefit of this method is that, by the construction of a SoPI it provides the manufacturer with flexibility to choose between different options that can be considered within the limits of the minimal and maximal LoA.

Furthermore, an interesting aspect is noticed within the construction of SoPI; Based on the construction of SoPI's within the 2 case studies (Dynamo Case Study I and Dynamo Case Study II), it can be seen that the potential area is narrower in the SoPI's within Case Study II in comparison to Case Study I. Can it be said that the production volume plays an important role in narrowing down the potential area for improvement? There is no concrete evidence to support this, but it can be assumed that as the production volume increases, the tendency to employ automation increases as well. As the tendency to employ automation increases, the minimal and the maximal LoA within mechanical or informational LoA may gradually start getting closer, due to which the potential area for improvement may start narrowing down.

A few of the limitations of the Dynamo method are:

1) As compared to the B&D method, the Dynamo method is much more time consuming as it involves factors such as documenting the complete process flow and breaking down the tasks into sub-tasks. However these factors are crucial to make an optimal decision.

2) As already mentioned earlier, to a certain extent the results within the method depend on the familiarity of the observer with the process and the experience of the observer in the field of manufacturing as well.

3) Unlike the B&D method that helps in arriving at a rigid solution using a quantitative analysis, the Dynamo method yet does not provide an accurate level of automation that can be applied. The method does act as a good tool to provide a potential

zone within which the level of automation for a respective station can be assigned, but does not provide an accurate level of automation.

Chapter Seven
INTEGRATED PROPOSED METHOD

As seen in the previous chapters, the B&D method and the Dynamo method both have a few disadvantages but act as good tools to arrive at a viable result. Thus, the aim of the new proposed method is to take the benefits from each of these methods and combine them to form a new integrated method that can further help in determining the appropriate Level of Automation.

The B&D method can be useful in terms of meeting the requirement concerning a flexible process. Also the method considers cost minimization and profitability as a crucial element by bearing in mind the Risk investment factor which is associated with the company's investment potential. As seen in the two case studies within Chapter Five, the B&D method almost accurately predicts the right choice of assembly method for any particular station if the parameters explained in Section 3.1 are known beforehand. Although the B&D method shows very less evidence of considering the process flow while determining the appropriate level of automation. This gap can be concealed by incorporating the B&D method within the Dynamo method, since consideration and documentation of the process flow one of the important steps of the Dynamo method. Thus, it can be said that the B&D method would be helpful for the design of a new process, since the process flow isn't known, whereas the Dynamo method can be helpful for the redesign of a process, because the process flow is known.

7.1 The Integrated Proposed Method with ASML modelling

In this section, a new proposed method will be defined that combines the B&D method and Dynamo Method along with ASML modelling. As already explained in Section **Error! Reference source not found.**, the ASML (Assembly Sequences Modelling Language) is a graphical modelling language used to represent assembly sequences and processes [28]. Although the Dynamo method already has a symbolic language that is used to represent the process flow, modelling the existing process using the ASML can be of benefit here because it uses specific rules for modelling. The method that is proposed by combining the two methods with ASML modelling is divided into seventeen steps that can be seen in Table 7.1.

The 1st six steps within the proposed method are the same as the 1st six steps of the Dynamo + + method which involve the pre-study (Steps 1-3) and the measurement (Steps 4-6) phase. However, within the proposed method, before the analysis is done for the construction of SoPIs, Step 7 involves modelling the process using the ASML modelling and Step 8 involves applying the B&D method to different workstations independently. A benefit of using ASML modelling at this stage is that it gives the observer another outlook at the process being studied. Also, another advantage of using the ASML modelling is that, the modelling involves conditional steps before each action step to describe the tools required for the next operation and whether or not the previous action has been completed. Also, since ASML makes of a standard vocabulary list developed by [31], the modelling of the process tends to be more objective as only a standard set of verbs and adjectives can be used to represent the process. However, within the Dynamo method as there is no standard vocabulary list used, the modelling can make use of general language and can lead to different interpretations by different people. A short example of an ASML model is shown in Appendix C: Figure 1 in comparison with the modelling used in the DYNAMO method.

Moving forward, after Step 8 has been performed; the analysis phase (Step 9-12) of the Dynamo++ method can be executed to develop SoPIs. Step 9 involves the assignment of minimal and maximal LoA by considering the values obtained in the B&D analysis as preliminary solutions. Step 10 involves designing the square of possible improvements and Step 11 consists of conducting an analysis on the SoPIs developed within the previous step. Though, before implementing the suggested results derived within the analysis phase, a few more steps are added in the integrated method. Within Step 13, different reconfigurations within workstations are tried by reallocating the resources available, to see if the system can be improved in a further better manner. If better reconfigurations exist, then Step 14 involved repeating the steps are from Step 8 and this loop goes on until a satisfactory result is achieved. Step 15 includes the discussion of the different alternatives in terms of various SoPIs due to various configurations by conducting a workshop at the manufacturing enterprise. Once the workshop has been conducted, the next step is to implement the best alternative which is then followed up by monitoring the suggestion and analyzing its effects on time and flow within the process.

Table 7.1: The proposed integrated method combining B&D method, Dynamo method and ASML modelling (adapted from [18])

Steps	Description	Source	Phase
Step 1	Identify the system to improve onsite	*Step 1 Dynamo++*	*Pre-study*
Step 2	Walk the process	*Step 2 Dynamo++*	
Step 3	Identify flow and time parameters by Value Stream Mapping (VSM) building	*Step 3 Dynamo++*	
Step 4	Identify the main operations and subtasks for selected area by Hierarchical Tasks Analysis (HTA) designing	*Step 4 Dynamo++*	*Measurement*
Step 5	Measure LoA using the LoA mechanical and information scales	*Step 5 Dynamo++*	
Step 6	Results documentation	*Step 6 Dynamo++*	
Step 7	Process ASML modelling with resources corresponding to different workstations identified	*ASML modelling*	*Process modelling*
Step 8	Apply B&D to the different workstations one by one independently	*B&D*	*Prel. solution*
Step 9	Decide min and max LoA for the different tasks by Workshop considering B&D as preliminary solutions	*Step 7 Dynamo++*	*Analysis*
Step 10	Design Square of Possible Improvements (SoPI) based on workshop results	*Step 8 Dynamo++*	
Step 11	SoPI analysis	*Step 9 Dynamo++*	
Step 12	Write / visualize the suggestions of improvements	*Step 10 Dynamo++*	
Step 13	Try other reorganizations/ reconfigurations of the workstations by other resources allocations in the ASML model if other feasible alternatives exist, else Go to step 15	*New*	*Other reconfigurations and alternatives*
Step 14	Loop: Go to step 8	*New*	
Step 15	Discuss the different alternatives and SoPIs (workshop with experts) and keep the best	*New*	*Discussion*
Step 16	Implementation of the decision suggestions	*Step 11 Dynamo++*	*Implementation*
Step 17	Follow-up when the suggestions have been implemented and analyses their effects on time and flow	*Step 12 Dynamo++*	

7.2 Application of the Integrated Proposed Method

To measure how well the proposed method works, the integrated method will be applied to the door line assembly studied within previous case studies (B&D Case Study I and Dynamo Case Study I). The method will be applied in a step by step manner depending on the steps mentioned within the integrated method in Table 7.1. The 1st phase within the integrated method is the Pre-Study phase.

PRE-STUDY PHASE:

Step 1: Identify the system to improve onsite

7.2.1 As the analysis is being done for the door line assembly, this can be considered as the system that can be further be improved or optimized.

Step 2: Walk the process

One of the most crucial elements of the Dynamo method is walking the process, in order to see how the operations on the assembly line exactly take place. As mentioned earlier, the door assembly line consists of 16 stations with 2 cells for each station (the right cell and the left cell). Every cell except for Stations 3, 4 and 7 are assigned with an operator for each cell, henceforth summing up to two operators per station respectively. The data collection template acts as a helpful tool to gather important information about how the operations are performed, the type of tools that are used to perform the operations and how the process flows.

Step 3: Identification of flow and time parameters by Value Stream Mapping

When the data has been gathered in the data collection template, the flow of operations being performed on the line can be documented by using value stream mapping. Using Value Stream Mapping (VSM) to identify the flow and time parameters can be helpful at a later stage if the decision needs to be modified or reconsidered. Furthermore, documenting the process flow using this model can help in the traceability of the decision at later stages. The process flow for the door line is documented using the symbols shown in Table 6.1. Each station starts and ends with a buffer to accommodate for down times in case one or more of the stations experience any form of machine breakdown or technical problems. The documentation of the process flow for each of the 16 stations within the door line is shown in Appendix B: Figure 1 to Figure 9.

MEASUREMENT PHASE:

7.2.2 *Step 4: Identifying the main operations and sub-tasks for a selected area by Hierarchical Task Analysis (HTA)*

Within any industry, each station within an assembly line may or may not have multiple operations being performed at the station. If multiple operations are being performed on a respective station, then the HTA method can be used to identify the main tasks and break down the main task into sub-tasks to an extent such that the operation can be performed either by a human or a machine individually, so that it becomes easier to assign an appropriate LoA to the task or to the overall station. The HTA breakdowns for each of 16 stations on the door line assembly are shown in Appendix B: .

Step 5 and Step 6: Measure LoA using the mechanical and informational LoA scales and results documentation

This step of the proposed method consists of measuring the current mechanical and informational LoA for each respective station on the assembly line. The mechanical and informational LoA values are assigned based on the scale developed by [11]. The reference scales (Table 4.1) for both mechanical and informational LoA are split into seven levels of automation with LoA = 7 being completely automated and LoA = 1 being completely manual. The observed mechanical and informational LoA for each station on the assembly line can be seen in Table 7.2.

Table 7.2: Mechanical and Informational LoA for current implementation on Stations 1-17

Station #	Mechanical LoA	Informational LoA
1	2	3
2	2	3
3	5	5
4	5	5
5	4	4
6	4	4
7	6	5
8	2	3
9	4	4
10	4	4
11	4	3
12	4	3
13	4	3
14	4	3
16	4	4
17	4	3

As per Figure 7.1, majority (10/16) of the stations on the assembly line currently have a mechanical LoA value of four. Similarly half (8/16) stations on the assembly line currently have an informational LoA value of three. This implies that the currently the process is fairly manual where the operators perform assembly operation with the help of flexible tools such as torque drivers and take decisions based on manuals/checklists given to the operator.

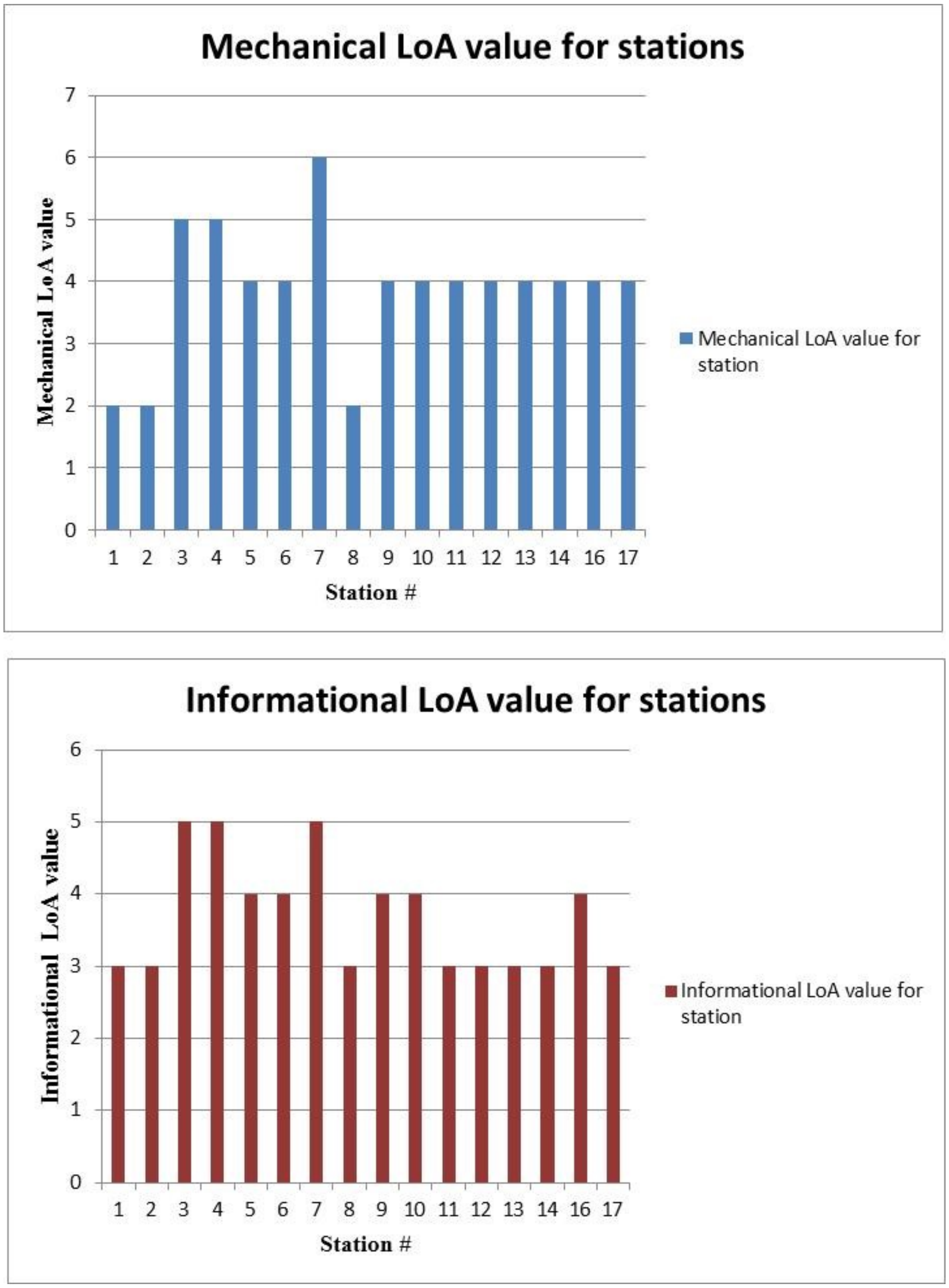


Figure 7.1: Graph depicting mechanical and informational LoA for each station

Hence if the process needs to be optimized further, the stations currently having manual assembly could possibly be automated. This would greatly depend on the process flow as some operations could probably be reconfigured in order to make the tasks easier to be automated.

7.2.3 PROCESS MODELLING PHASE:

Step 7: Identify resources needed at each station and perform ASML modelling for each station within the process

The data collection template is used for gathering information that may be helpful in identifying the resources needed to perform the operations. A benefit of ASML modelling is that a conditional step is present which has to be satisfied before the action step is executed. The conditional step consists of two types of conditions: 1) The previous action step has to be completed before the next action step can be initiated, 2) The tools/parts required to perform the next action step already have to be available before the action step is executed. Having conditional steps aids in reducing the chances of errors occurring due to handling various operations at the same time and it also reduces the downtime that will be caused to other stations on the line if the human/machine forgets to get any tool or part required to perform the assembly operation. The ASML models for each station on the assembly line are shown in Appendix C.

7.2.4 PRELIMINARY SOLUTIONS:

Step 8: Application of B&D method to different workstations independently

The next step involves application of the B&D method to each station independently, as the solution determined by the B&D method will be utilized as a preliminary solution in the upcoming steps. The application of the B&D method to each workstation independently is done earlier in B&D Case Study I: Table 5.1. As per the integrated proposed method, since the results of the B&D analysis will be used as the preliminary LoA in the Dynamo methodology, a comparison is done between the levels of automation of these 2 methods, which can be seen in Table 7.3. Although, since B&D

method does not give prime importance to informational LoA, this table could probably only be used to compare the mechanical LoA of Dynamo with the LoA of B&D.

From Table 7.3, the assembly method MA from B&D is equivalent to Level of automation 1 in the Dynamo method. MM assembly method within B&D method is defined as a multi-station assembly line that contains devices like feeders in the form of mechanical assistance [5], but the assembly is still performed by the human operator. Henceforth, LoA 2, 3 and 4 from Dynamo would be equivalent to MM as these three levels of automation consist of tools that aid the human operator in performing the assembly. Likewise, AI and AF are comparable to the LoA 5 of the Dynamo method. Subsequently AP and AR would be analogous to LoA 6. Although, the B&D method does not consider the universal assembly center within the selection table, but it is considered as a hypothetical machine that can solve any problem on its own without requiring any assistance from the human operator. Hence this can be considered similar to LoA 7.

Table 7.3: Comparison of LoAs between B&D method and Dynamo method

B & D METHOD	DYNAMO METHODOLOGY		
ASSEMBLY METHOD	**LOA**	**MECHANICAL AND EQUIPMENT**	**INFORMATION AND CONTROL**
MA	**1**	**Totally manual –** totally manual work, no tools are used, operator only uses their own muscle power	**Totally manual** – operator creates their own understanding of the situation and develops their own course of action based on their experience & knowledge
MM	**2**	**Static hand tool** – manual work by the operator with the help of a static tool. Ex: screw driver	**Decision giving** – operator gets information on what to do, or proposal on how the task can be achieved. Ex: work order
	3	**Flexible hand tool** – manual work with support of flexible tool. Ex: adjustable spanner	**Teaching** – operator gets instructions on how the task can be achieved. Ex: checklists, manuals
	4	**Automated hand tool –** manual work with support of automated tool. Ex: hydraulic bolt driver	**Questioning** – the system questions the execution if the execution deviates from what the system considers being suitable. Ex: verification before action
AI	**5**	**Static machine/workstation** – automatic work by machine that is designed for a specific task. Ex: lathe	**Supervision** – system calls for the operator's attention and directs it to the present task. Ex: alarms
AF			
AP	**6**	**Flexible machine/workstation** – automatic work by machine that can be reconfigured for different tasks. Ex: cnc machine	**Intervene** – system takes over and corrects the action if the execution deviates from what the system considers suitable. Ex: thermostat
AR			
UNIVERSAL ASSEMBLY CENTER	**7**	**Totally automatic** – completely automatic work, the machine solves all problems that occur. Ex: autonomous systems	**Totally automatic** – all information and control is handled by the system. Ex: autonomous systems

7.2.5 ANALYSIS PHASE:

Step 9: Decide minimum and maximum LoA for each station by considering the solution from B&D analysis as the preliminary solution

In this step, the solution given by the B&D method for each station in Table 5.1 is considered as the preliminary solution before the assignment of maximum and minimum LoA is done for each station. The min and max LoA are then decided for each station based on the preliminary solution of B&D, the process flow and the type of operations being performed at the station. Since the B&D method does not explicitly consider the aspect of decision automation, the B&D solutions can only be used to assign the minimal and the maximal mechanical LoA, while the informational LoA will have to be decided based on the type of operations being performed. Table 7.4 shows the assignment of minimum and maximum LoA for each station. The values represented in parentheses beside "MM" show the corresponding level of automation to which the MM value would be comparable to, in the Dynamo method. These values in the parentheses are different for each station due to the nature of the operations being performed at that particular station. For example, at a particular station it may be possible that screws can be tightened using a Manual screw driver; hence the corresponding LoA value for MM in the parentheses would be equal to two. However, it may also be possible that a particular station may require the screws to be tightened to a meet a certain degree of quality. In such cases it would be better to use a semi-automated screw driver; with a LoA value of four.

Table 7.4: Minimum and Maximum LoA for each station considering B&D results as preliminary solutions

Station #	Preliminary solution according to B&D	Mechanical LoA		Informational LoA	
		Min	Max	Min	Max
1	MM (LoA = 2)	2	5	2	3
2	MM (LoA = 2)	2	5	2	4
3	MM (LoA = 3)	3	6	3	5
4	MM (LoA = 3)	3	6	3	5
5	MM (LoA = 4)	2	4	3	5
6	MM (LoA = 4)	2	4	3	5
7	MM (LoA = 2)	2	5	1	5
8	MM (LoA = 2)	2	5	3	5
9	MM (LoA = 4)	2	4	2	5
10	MM (LoA = 4)	2	4	2	5
11	MM (LoA = 4)	2	4	2	3
12	MM (LoA = 4)	2	4	2	4
13	MM (LoA = 4)	2	4	2	4
14	MM (LoA = 4)	2	4	3	5
16	MM (LoA = 4)	2	4	2	5
17	MM (LoA = 4)	2	4	2	3

Step 10: Design of Square of Possible Improvements (SoPI)

Based on the B&D solutions, within the previous step, minimum and maximum LoA are assigned to each station on the assembly line. From the minimum and maximum LoA assigned, the SoPI for each station can now be constructed for each station with the preliminary solutions (B&D preliminary solution) and the current implementations (Observed LoA) marked within the SoPI. The SoPI for station 1 can be seen in Figure 7.2, while the SoPIs for the remaining stations are seen in Appendix C: . Since the B&D method does not explicitly consider decision automation, the B&D solutions always lie on the X-axis (Mechanical LoA) within the graph.

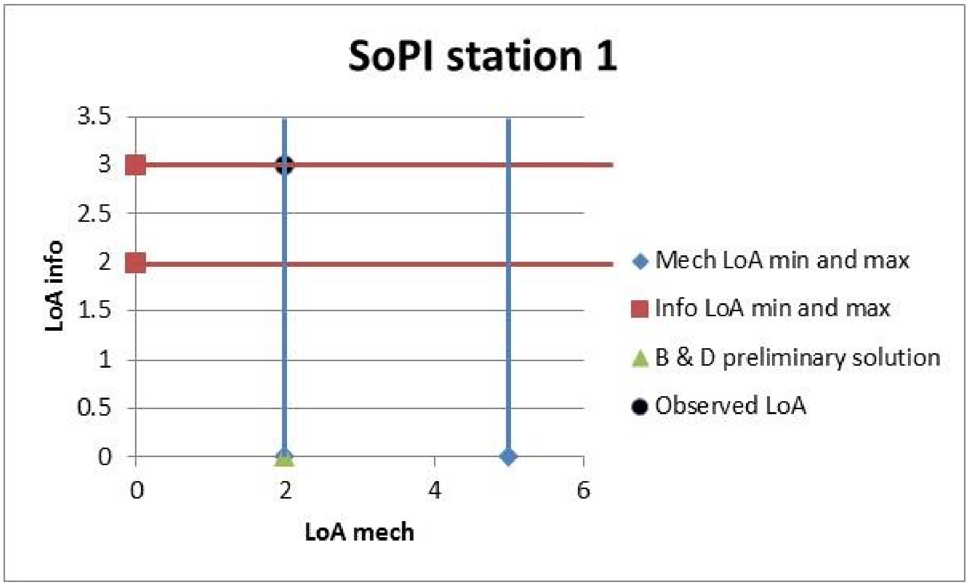


Figure 7.2: SoPI for Station 1

Step 11: SoPI analysis

Assigning the values of minimal and maximal LoA, based on the preliminary solutions of B&D, it can be seen that within the SoPIs for all the sixteen stations, the potential area of improvement comparatively narrows down in comparison to the SoPIs developed in the Dynamo Case Study II. By analyzing the SoPI for station 1, seen in Figure 7.2, the B&D solution accurately predicts the solution that is currently being implemented. The LoA value is relatively at a lower value of (2, 3) at this instance, with the mechanical LoA equal to two and the informational LoA equal to three. This could probably be due to the annual production volume being low and also due to the nature of the operations. However, in the future if the demand rises and the annual production volume has to be increased to an extent of 10 million, then the LoA can potentially be increased to a maximum of (5, 3) with the mechanical LoA = 5 and the informational

LoA = 3. Similarly, the LoA for the remaining stations can be increased or decreased depending on their individual SoPIs.

Step 12: Write / visualize the suggestions of improvements

Depending on the SoPI, the LoA value can be optimized anywhere within the SoPI, depending on whether the LoA satisfies two requirements. The 1st requirement being that the assigned LoA has to be able to meet the target of the required annual production volume. The 2nd requirement is that the respective LoA should be able to accurately perform the operations depending on the nature of the operations. For instance, for Station 1, the current major operations involve exchanging empty kits with full kits, inserting clips and grommets into the door and cleaning the doors with wipes. Currently all these operations are performed by a human operator with or without the aid of manual tools. The exchanging of kits is performed without the aid of any manual tools; the cleaning of doors with wipes is done without the aid of manual tools. However for inserting clips and grommets, the operator is aided with manual tools. Based on the SoPI for station 1 (Figure 7.2), the operations requiring manual tools can also be performed with a semi-automated tool, to meet a certain degree of quality or if there is a considerable increase in the production volume. If the production volume increases to a great extent, then a dedicated machine / robot can be used to perform these operations, with parts being fed using devices like feeders.

For Station 2 also, the some of the operations such as cleaning of doors and insertion of screw clips, applying emblem on door can be performed by a robot in case of increase in production volume. However there are some operations such as insertion of finishers that would require to be performed by a human, due to the aspect of aligning the finisher at the right position.

Stations 3 and 4 are already highly automated and make use of door seal robots to apply seals onto doors. However, the seal is applied onto the robot by a human operator. If the robot can be configured to choose the right seal on its own and apply the seals onto the door automatically, then the need for a human operator at these stations can be eliminated.

Similarly, for the other stations, depending on the SoPI for each station, the use of manual tools, semi-automated tools, dedicated machines or robots can be chosen accordingly.

7.2.6 OTHER CONFIGURATIONS AND ALTERNATIVES

Step 13: Try other reconfigurations of workstations by varying resource allocation in the ASML model to determine if other feasible alternatives exist

From Figure 7.1 it can be seen that the mechanical LoA value for Stations 1, 2 and 8 is relatively low compared to the other stations. Also, Station 3, 4 and 7 are highly automated compared to other stations. This step can be used to remodel the operations within some of these stations such that some of the operations can be automated to an extent or can be remodeled to be performed in the same station. However, since the stations 3, 4 and 7 incorporate robots that are used for different types of automated operations, these stations are not considered for remodeling. In order to automate some of the operations, remodeling for Stations 1, 2 and 8 lead to the following ASML models [Figure 7.3, Figure 7.4, Figure 7.5, Figure 7.6, Figure 7.7, Figure 7.8, Figure 7.9].

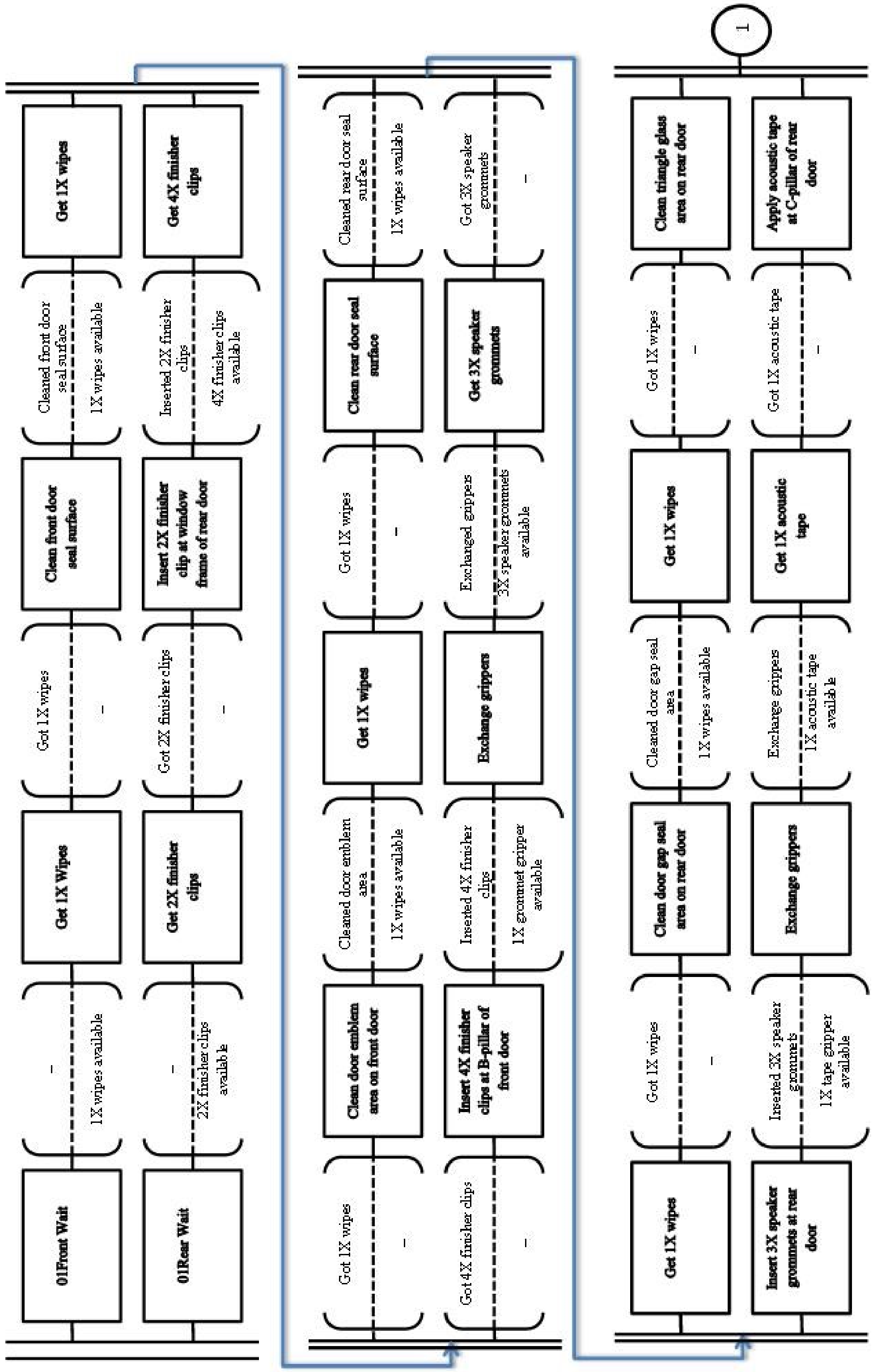


Figure 7.3: Remodelled assembly sequence for Station 1 using ASML

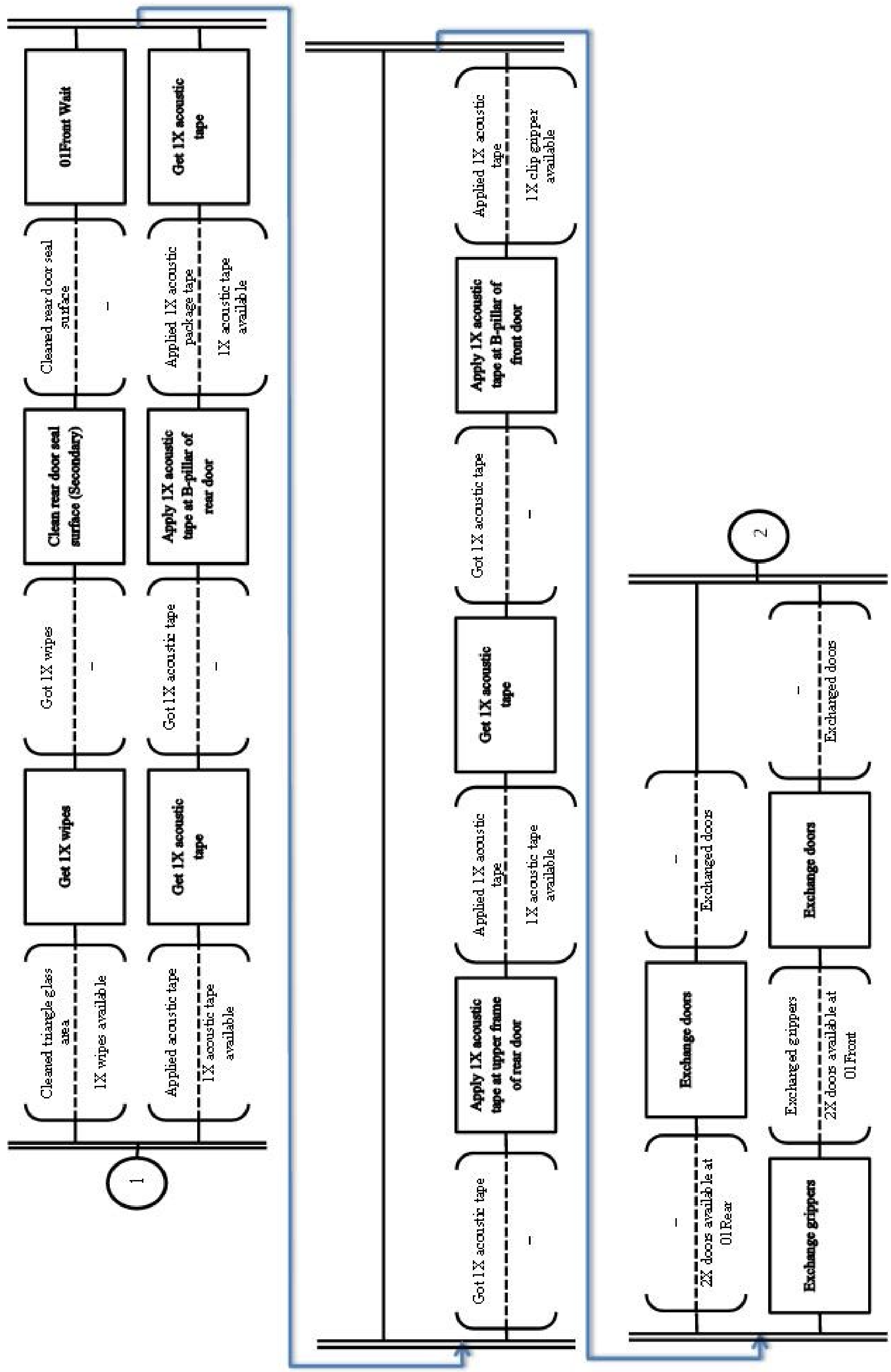


Figure 7.4: Remodelled assembly sequence for Station 1 using ASML (Contd…)

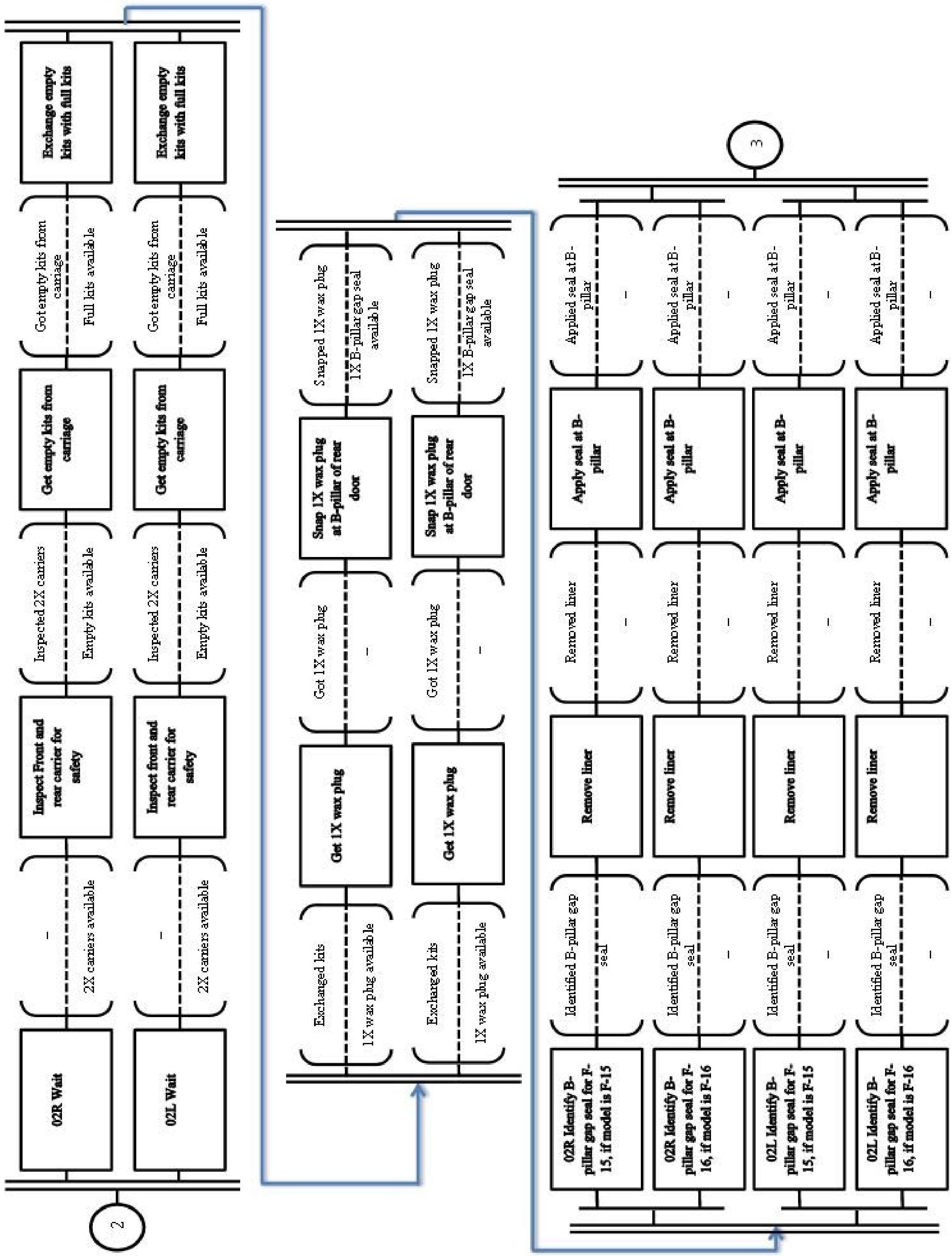


Figure 7.5: Remodelled assembly sequence for Station 2 using ASML

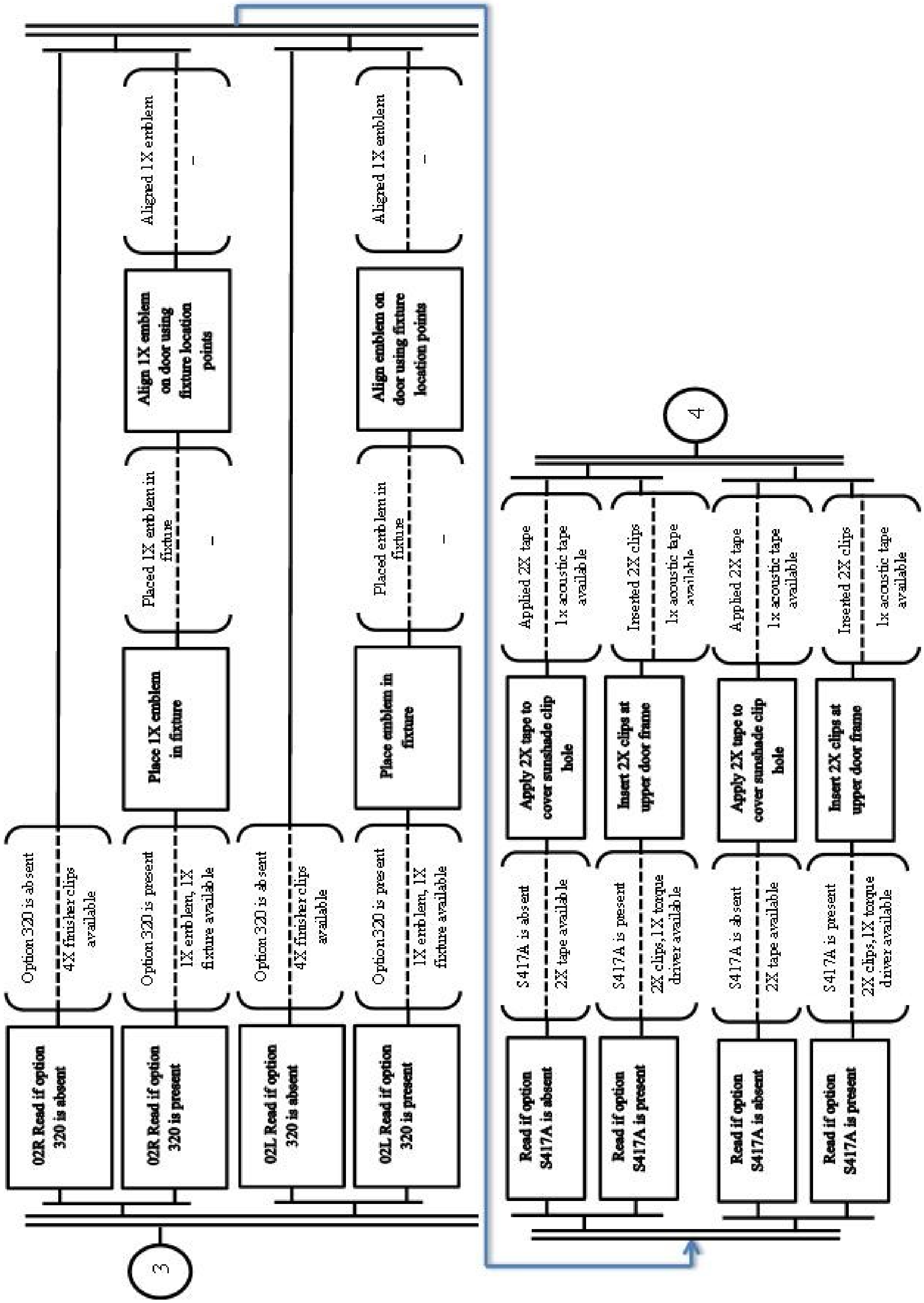


Figure 7.6: Remodelled assembly sequence for Station 2 using ASML (Contd…)

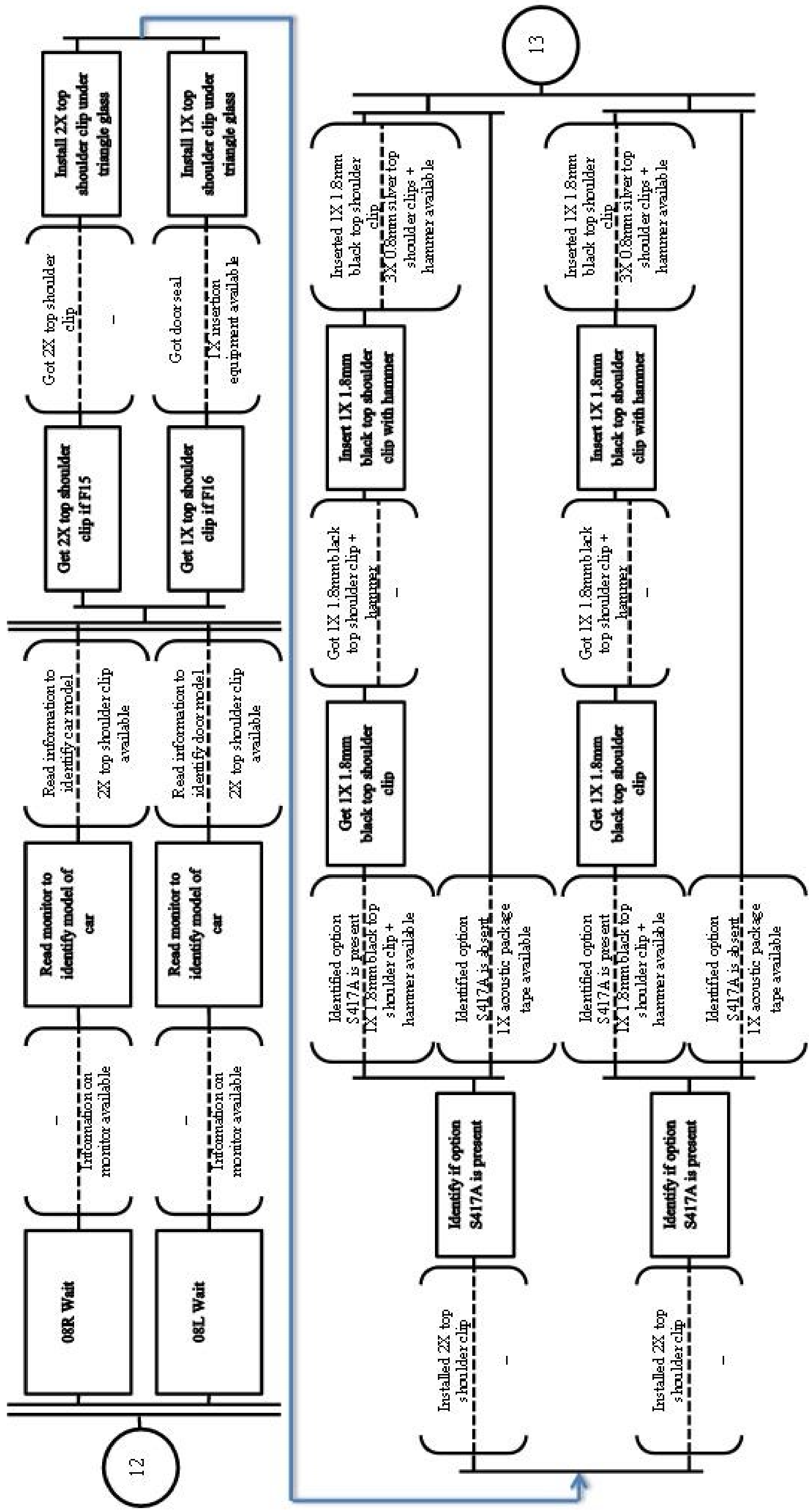


Figure 7.7: Remodelled assembly sequence for Station 8 using ASML

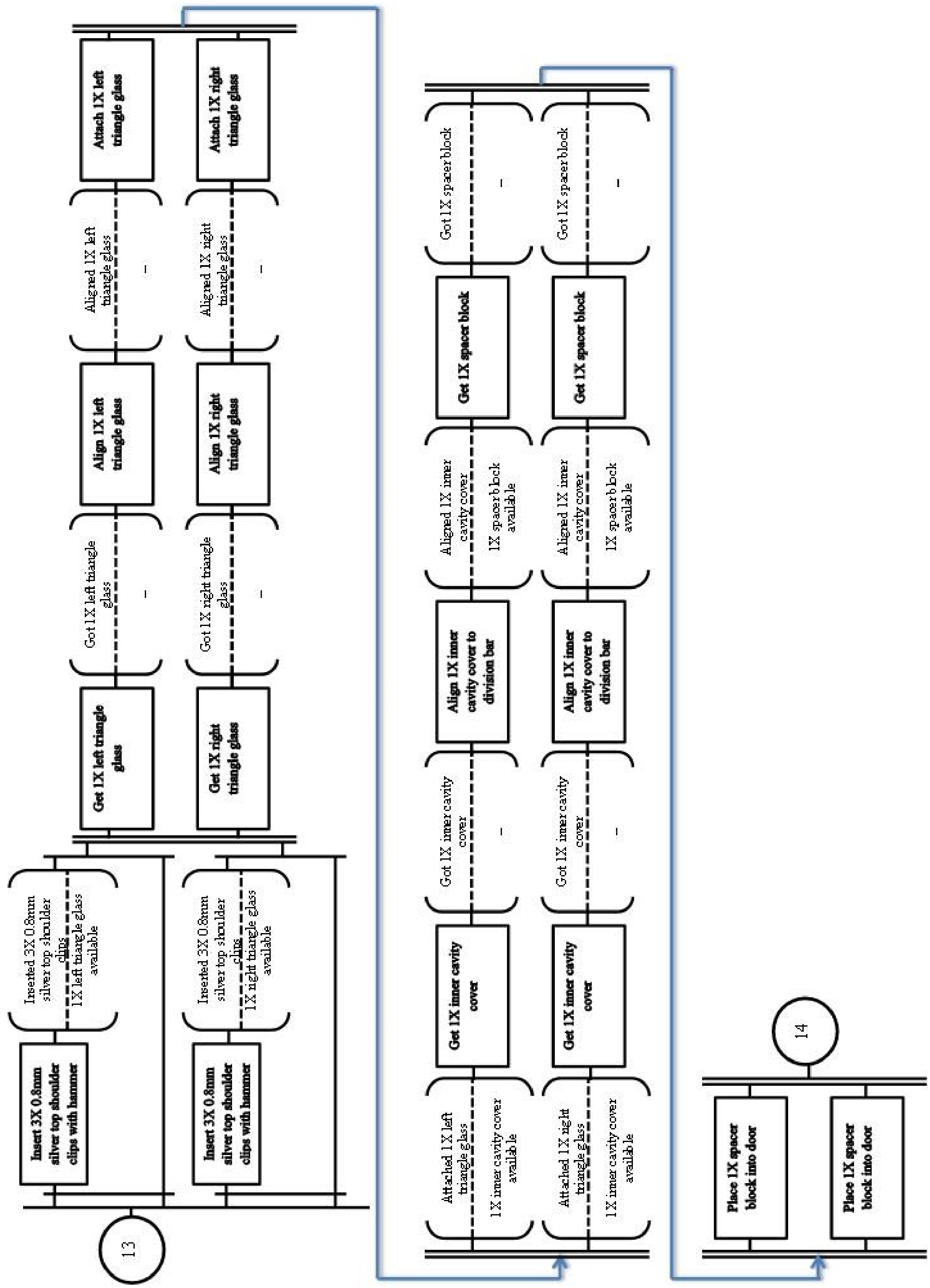


Figure 7.8: Remodelled assembly sequence for Station 8 using ASML (Contd…)

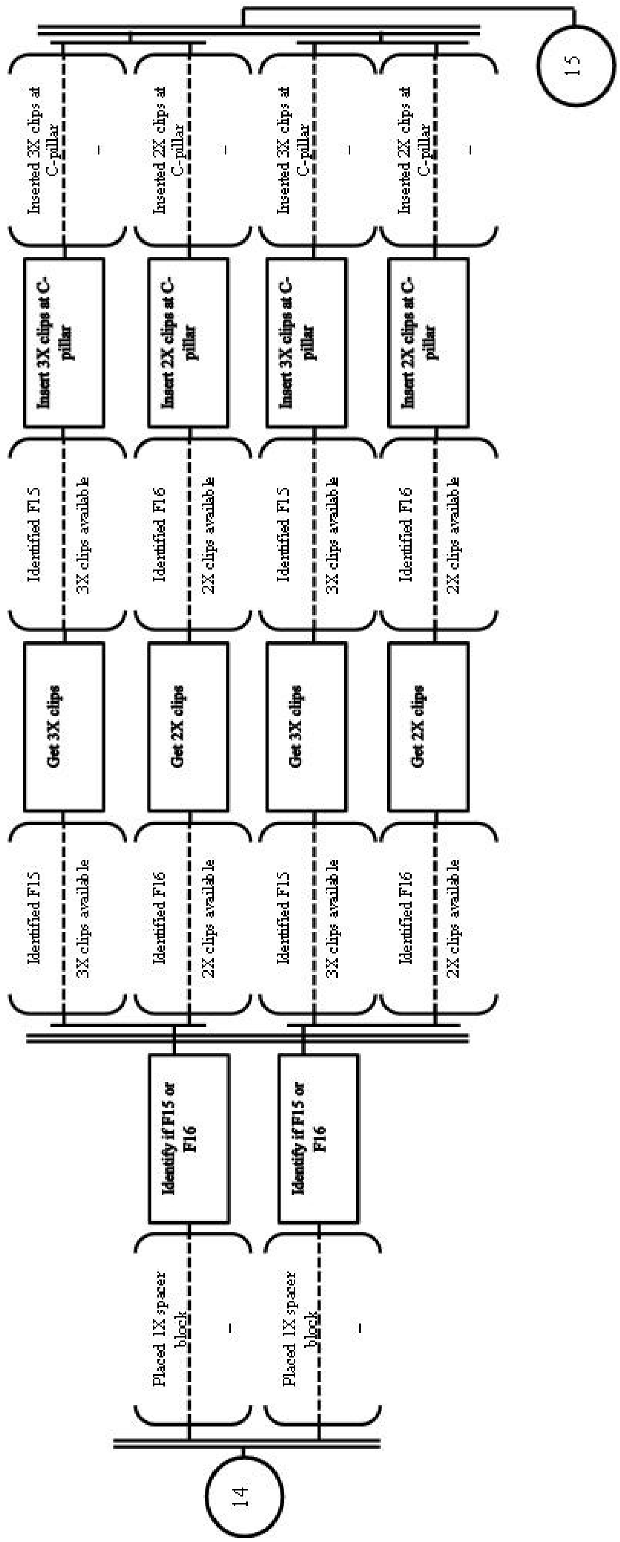


Figure 7.9: Remodelled assembly sequence for Station 8 using ASML (Contd…)

Step 14: Go to Step 8 (2): Apply B&D to different workstations independently

Since Stations 1, 2 and 8 have undergone remodeling; the B&D analysis needs to be redone for each of these stations as there has been a change in the number of parts within each station. The results of the B&D analysis for these three stations can be seen in Table 7.5.

Table 7.5: B&D analysis for remodeled stations

Station Number	Annual VS/Shift	NA	NT	SH	WA	QE	NT/NA	RI	Decision
01F	218400	6	6	2	75000	95000	1.00	2.53	MM
01R	218400	13	13	2	75000	95000	1.00	2.53	MM
2	218400	7	12	2	75000	95000	1.71	2.53	MM
8	218400	10	15	2	75000	95000	1.50	2.53	MM

Previously, as the operations were mirrored on both sides of the stations, the analysis for one side of the station was enough, as the same results would apply for the other side of the station as well. Similarly, in the remodeled analysis, Station 2 and Station 8 have mirrored operations, but Station 1 does not have mirrored operations on the two sides, due to which a separate analysis (01F and 01R) is done for Station 1. Within Station 1, 01F means 01Front and 01R means 01Rear. The reason for this assignment would be discussed in the coming steps.

Nonetheless, even with the remodeled operations the recommended solutions by B&D yet do not change and the result for each station is still MM. A major reason for this could be the production volume, as at lower production volumes, the Table 3.3 mostly contains of only MM or MA as recommended solutions, except in a few cases when RI≥5 or 5> RI > 2. In any case, these recommended solutions would be reconsidered as the preliminary LoA in the further steps.

Step 9 (2): Decide Min and Max LoA for the remodeled stations by considering B&D solutions as preliminary solutions

Within this step the minimum and maximum LoA for the remodeled stations are reassigned as the operations for these stations have been altered, due to which there might be a need for a new SoPI. The min and max LoA for the remodeled stations can be seen in Table 7.6.

Table 7.6: Min and Max LoA for remodeled stations considering B&D results as preliminary solution

Station #	Preliminary solution according to B&D	Mechanical LoA		Informational LoA	
		Min	Max	Min	Max
1	MM (LoA = 2)	2	6	2	5
2	MM (LoA = 2)	1	5	2	5
8	MM (LoA = 4)	2	5	3	5

Step 10 (2): Design of Square of Possible Improvements (SoPI) for remodeled stations

Based on the assignment of minimum and maximum LoA for the remodeled stations in Table 7.6, for each station a new potential SoPI is constructed, with the B&D results assigned as the preliminary solution in the graph. Also, assigned within the graph is the suggested LoA instead of the current observed LoA. The SoPIs for Station 1, Station 2 and Station 8 can be seen in Figure 7.10, Figure 7.11 and Figure 7.12 respectively.

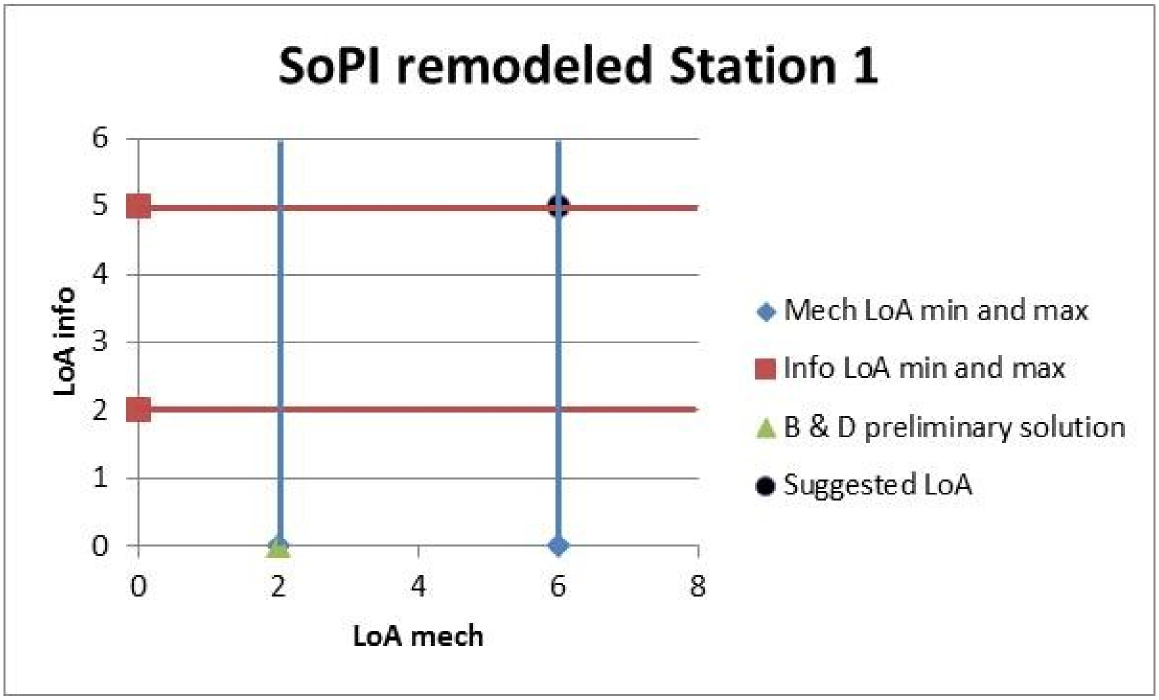


Figure 7.10: SoPI for remodeled Station 1

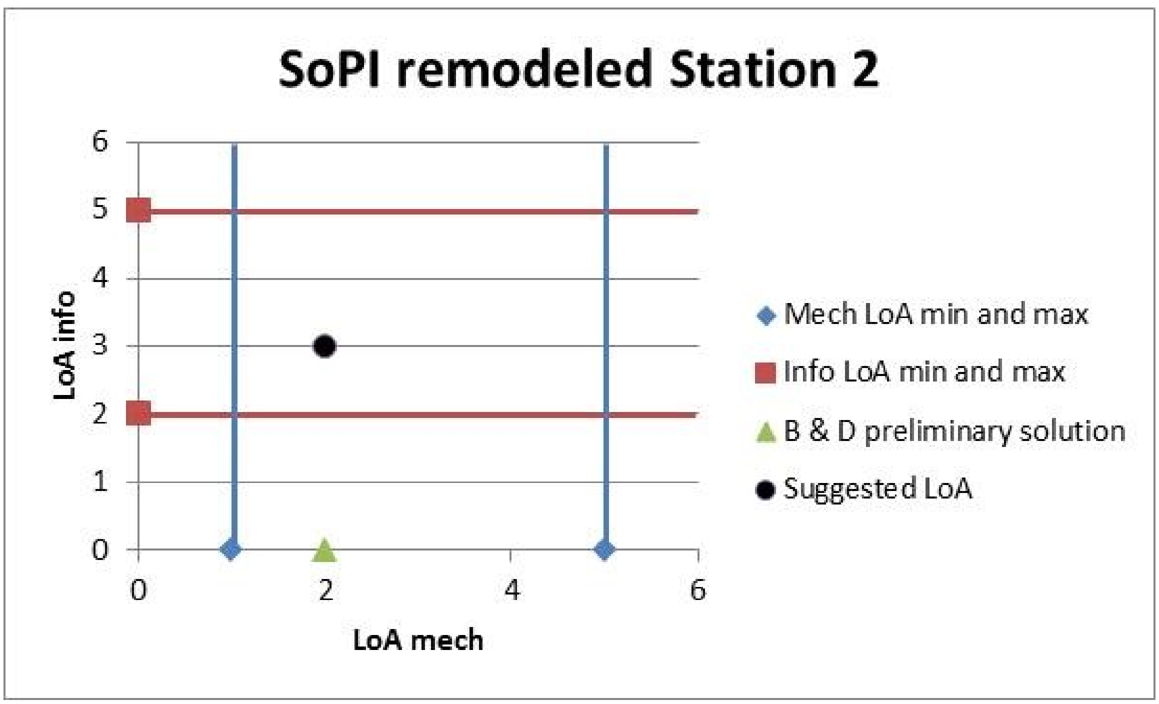


Figure 7.11: SoPI for remodeled Station 2

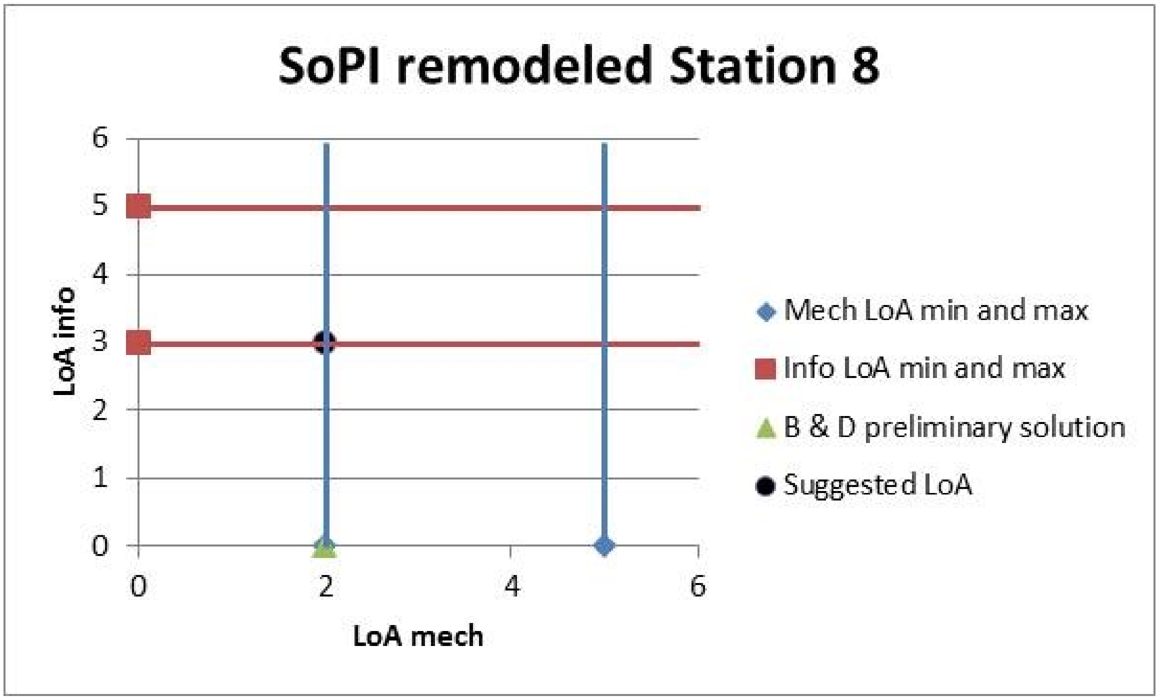


Figure 7.12: SoPI for remodeled Station 8

Step 11 (2): SoPI analysis for remodeled stations

For Station 1, the B&D solution predicts a mechanical LoA of one. However, as the remodeled station only consists of operations that require fastening of clips or that require cleaning of doors, the suggested LoA has been boosted to a mechanical LoA of 6 and an informational LoA of 5 as there are no complex decisions that need to be taken by the robot and the fastening of clips can be done using robots. Further information about how the operations on this station can be performed will be discussed in Step 12 (2).

For Station 2, there isn't much change in the SoPI. A few of the operations from Station 1 were interchanged with operations from station 2, so that at least one of these stations can be automated to a higher degree. Nonetheless, even after remodeling Station 2 does not undergo any LoA changes and still remains at an LoA value of (2, 3) with two being the mechanical LoA and three being the informational LoA.

Since only 2 of the operations were removed from Station 8 and assigned to Station 1, the LoA value of Station 8 is not impacted radically and even station 8 retains the same LoA that was maintained earlier.

DISCUSSION

7.2.7 *Step 12 (2) / Step 15: Write/ visualize the suggestions of improvements / Discuss the different alternatives*

Based on the remodeling of the stations and the assignment of minimal and maximal LoA, one of the crucial changes the assembly line can implement is within Station 1. The operations being executed at Station 1 after remodeling can be seen in Table 7.7.

Table 7.7: Operations being executed at Station 1 after remodeling

	After remodeling
01F	Wait time
	Clean front door seal surface
	Clean rear door seal surface
	Clean door emblem area on front door
	Clean door gap seal area on rear door
	Clean triangle glass area on rear door
	Secondary clean rear door seal surface
01R	Install 3X finisher clips at window frame
	Install 4X finisher clips at B-pillar
	Install 3X speaker grommets
	Install acoustic tape at rear door C-pillar
	Install acoustic tape at rear door B-pillar
	Install acoustic tape at rear door upper frame
	Install acoustic tape at front door B-pillar

Based on the SoPI for Station 1, seen in Figure 7.10, the remodeled station is suggested a LoA of (6, 5) with six being the mechanical LoA and five being the informational LoA. The manner, in which the operations can be performed at Station 1, can be better explained with the aid of a rough sketch shown in Figure 7.13.

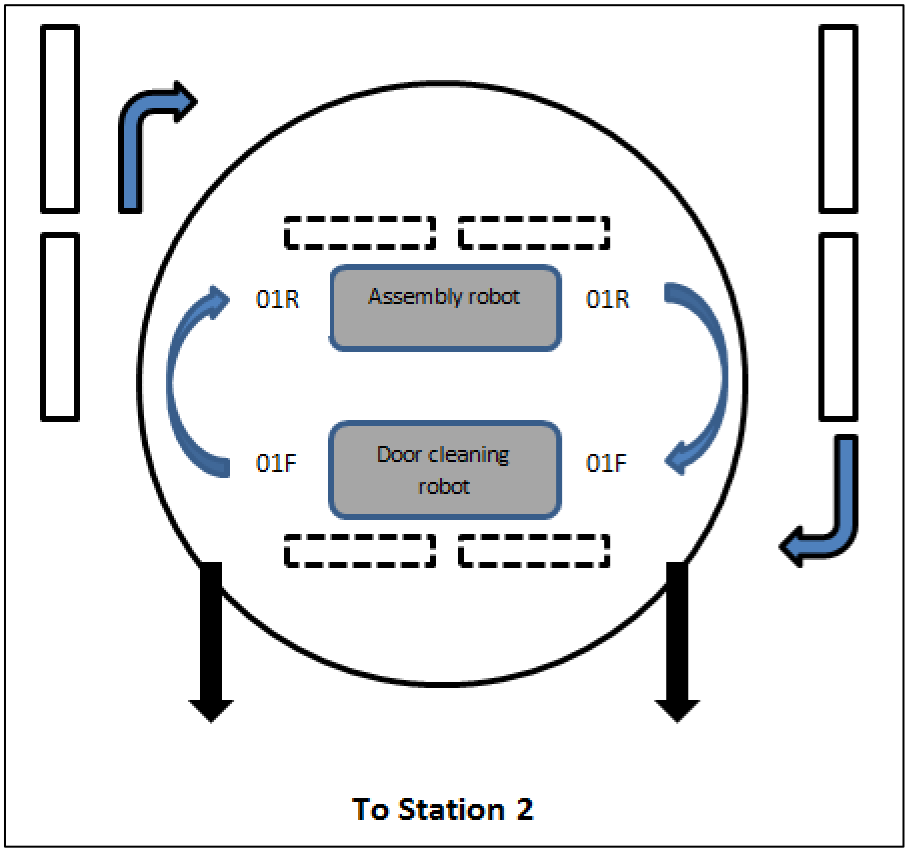


Figure 7.13: Working of operations for remodeled Station 1

For the operations at remodeled Station 1 to be automated, the station needs to employ two robots, with one robot assigned for assembly operations and the other robot assigned for door cleaning operations. The zones within Station 1 are represented as 01F (01 Front) and 01R (01 Rear). The door cleaning robot is present at 01F whereas the assembly robot is present at 01R. Based on the operations assigned to Station 1 in the ASML remodeling for Station 1 (Figure 7.3 and Figure 7.4), the station needs to employ a rotary indexing mechanism through which the doors can be exchanged between 01R and 01F. The doors arrive in sets of two (left front & left rear or right front & right rear) at each cell within each station. First, when the doors arrive (assuming right doors arrive) at 01R, the door cleaning robot begins cleaning operations at the respective locations on the door, based on the sequence generated within the ASML. Simultaneously at the same time, the left doors arrive at 01F, and the assembly robot begins assembly operations onto the door depending on the assembly sequence generated according to the ASML. Since station 1 contains different types of assembly operations such as insertion of clips, insertion of speaker grommets and application of acoustic tape, therefore the assembly robot should be equipped with the possibility of changing grippers as each type of assembly operation may require a different type of gripper. The delivery of parts to the cell 01F can be done by means of feeders. If the operations at 01F are completed before the operations at 01R or vice-versa, then the doors wait at the respective cell until the operations at the other cell are not completed. Once the operations on 2 sets of doors are completed for each cell, then the cells interchange doors, i.e. 01R sends the cleaned doors to 01F for performing assembly operations and 01F sends the assembled doors to 01R for performing cleaning operations. After the assembly operations as well as cleaning operations are completed on all the 4 doors then the doors are transferred onto Station 2.

As compared to the current implementation, where the operations on Station 1 are completely manual, by the use of ASML and remodeling the operations accordingly, Station 1 can be completely automated, where an operator may necessarily be required only in case of a machine break down.

Although the operations were remodeled for Station 2 and partially for Station 8 as well, the potential of automating these stations is less, due to a difference in the values of NA and NT, hence it would be beneficial to let these stations be operated manually. Also since the current production volume of doors is as low as 436,800 doors / shift annually, it may still be beneficial to assign manual assembly to Station 1, but it may be profitable to automate Station 1 in case of an increase in production volume or to reduce the risk of fatigue caused to human operators due to repeatability of operations.

IMPLEMENTATION

7.2.8 *Step 16 & Step 17: Implementation of suggestions and following up when decisions have been implemented to analyze the effect on time and flow*

Since the current proposal of automating Station 1 is just a hypothetical scenario, the true effect of the decision can only be validated upon implementation at the company studied for this Case Study. Upon implementation, the effect of the decision on time and flow has to be analyzed to make further changes to the potential solution in order to optimize the process further.

Chapter Eight
CONCLUSIONS AND FUTURE WORK

Based on the lack of a definitive LoA methodology within the existing literature, there was a need to define a new method to determine the appropriate level of automation at the station and the band scale. From the literature review, the benefits and limitations of different LoA methodologies were determined, after which six requirements were defined to determine the most suitable method. Since none of the existing methodologies satisfied all the six requirements, a proposal to combine two (B&D method and Dynamo method) of the existing methods together was made to satisfy all the requirements.

The B&D method was validated based on two different case studies within two different companies. Two case studies were performed at two different companies to validate the method on different types of assembly lines. While one of the assembly lines (door line) was almost completely manual, the other assembly line (piston assembly line) was completely automated. The validation of the B&D method on these two case studies showed that the method can almost accurately predict the type of assembly system at the station level. However, since the B&D method does not consider any form of process flow, the method may or may not predict the level of automation at the band scale accurately.

Additionally, as mentioned earlier in Chapter Three , in comparison to the time estimation method by Boothroyd and Dewhurst which has constantly been used throughout the years and updated within the software, the method for selection of assembly method has not been revisited since 1983. To align with the advancements in robotic and automated technologies over the years, the data used within the method may need to be revisited for validation within the current industrial settings.

The Dynamo method was also validated on two different case studies at the same two different companies. One case study was performed on the door line assembly and the other case study was performed at the assembly line for pistons. Although the Dynamo method does not provide us with a fixed solution, the method helps in developing a potential area over which the operations can either be automated or de-automated, thus providing the manufacturer flexibility to choose from multiple level of automations present between the minimal and the maximal LoA. Although, the consideration of the process flow by Dynamo was considered beneficial to determine LoA at a band scale, the method does not help us in determining the appropriate LoA for the transfer of the product over the whole band. A potential reason for this could be that none of the methods consider the part size, shape and weight as one of the parameters due to which an appropriate assembly system cannot be determined at the band scale.

Since B&D provides an almost accurate result and the Dynamo provides a potential area of improvement, these two methods were combined together into an integrated proposed method. The integrated proposed method also considers the modelling approach used within ASML, as the ASML can serve as a good tool for appropriate resource allocation and modelling of the process flow

The integrated proposed method was applied onto the door line assembly to potentially automate some of the operations, if possible. After the initial analysis, Stations 1, 2 and 8 were found to have the least level of mechanical automation due to which the operations on these stations were reconfigured to automate some of the operations. After the reconfiguration of operations, the suggested improvements show that Station 1 can be completely automated to an LoA value of (6, 5) as compared to the current implementation having an LoA value of (2, 3), whereas Station 2 and Station 8 still undergo the same level of automation as the current implementation. However, some of the clip insertion operations and cleaning operations from Station 2 were rearranged within Station 1 due to which the risk of injuries such as carpal tunnel syndrome or tendonitis can be reduced.

As already discussed within Section 1.3.13, the ASML modelling can also serve as a useful tool for assembly time estimation. Due to a time constraint during the walk through of the door line assembly, time estimation could not be performed for the assembly operations being performed at the door line. In order to better allocate the levels of automation to different tasks, a time study analysis can be performed to calculate the time for each elementary motion within the ASML modelling of the door line. Based on the times obtained during the time study analysis, the operations for the different stations on the door line can be reconfigured and new potential SoPIs can be developed.

Since the integrated proposed method could not determine the appropriate level of automation at the band level, the next step within the method can consider the aspect of part size, shape and weight and integrate the methodology developed by Konold and Reger [24] since the methodology developed by them can be primarily used for designing of transfer mechanisms.

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APPENDICES

APPENDIX A: DATA COLLECTION TEMPLATE

Data to gather for every workstation throughout the Assembly lines

The data below has to be gathered in the level of each workstation, as if each one is completely independent from the others. There will be then a sheet for every workstation.

The method	*The parameter*		*To gather*
B&D	Annual production volume per shift (VS)		
	Number of parts in the 'complete' assembly (NA)		
	Number of different products to be assembled using the same basic system during the first three years (NP)		
	Number of parts whose design changes during the first 3 years (major changes, e.g. imposing new feeders/workheads) (ND)		
	Total number of parts available for building different product styles (NT)		
	Company Investment potential or Investment ratio: RI = SH*QE/WA	SH: Number of shifts.	
		QE: Capital equivalent for 1 assembly worker (capital allowing replacing an equivalent 1 operator on 1 shift by using machine(s) or automation).	

Figure 1: Data Collection Template

		WA: Annual cost of employing 1 assembly worker	
	A variety of different but similar products is produced by the workstation (A)		Yes / No
	A variety of different products is produced by the workstation (B)		Yes / No
DYNAMO	Main purpose of the station		
	Specify where the production flow starts and where ends		
	Purpose of the production: assembly for delivery, assembly for next workstation, with quantities specifying (per day, per month...)		
	Number of assemblies to achieve (per day, month...)		
	Number of variants to be produced in the same line (the product mix within the production flow)		
	Number of shifts (per day, month,etc)		
	The different Cells or Sections identifying within the production flow (in the correct order / else specify how organized in the flow if parallelisms, etc..)		C1-
			C2-
			C3-
			C4-
			C5-
			C6-
			C7-

Figure 2: Data Collection Template (Contd…)

		Operation description	Corres. Nb Cell (Ci)	Techno: if machined then type of the machine, its age, maintenance, particularities, type of tools used	Nb operators	Tasks of the operators and/or machines
	The different operations achieved, with corresponding Section/ cell number, and techno executing = how (machine, human, robot, ...)	O1-				
		O2-				
		O3-				
		O4-				
		O5-				
		O6-				
		O7-				
		O8-				
		O9-				
		O10-				
		O11-				
		O12-				

Figure 3 – Data collection template (Contd…)

APPENDIX B: DYNAMO CASE STUDY DOCUMENTS

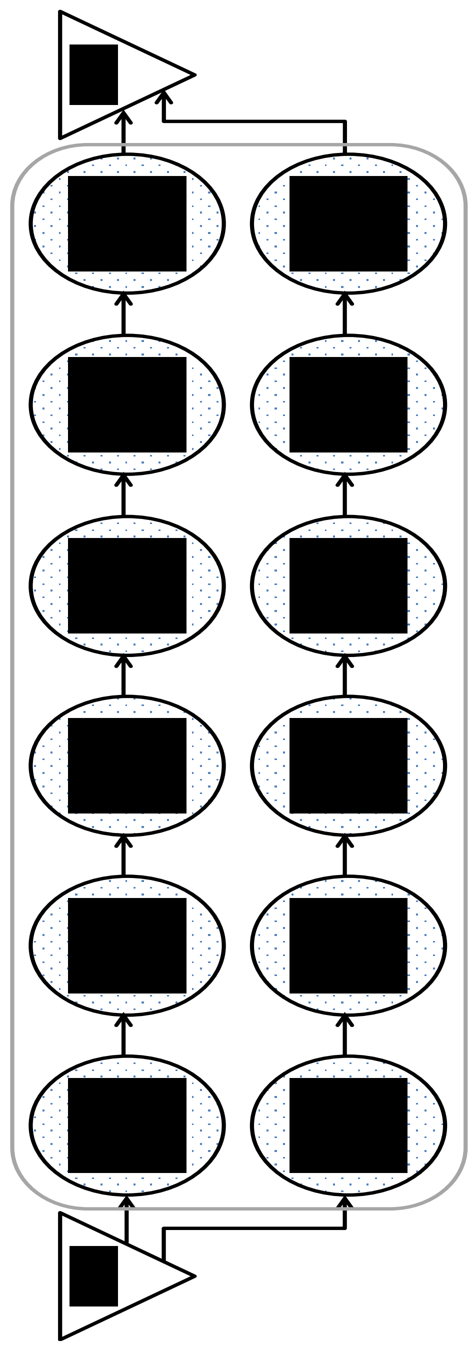

Figure 1: Process documentation for Case Study I - Station 1

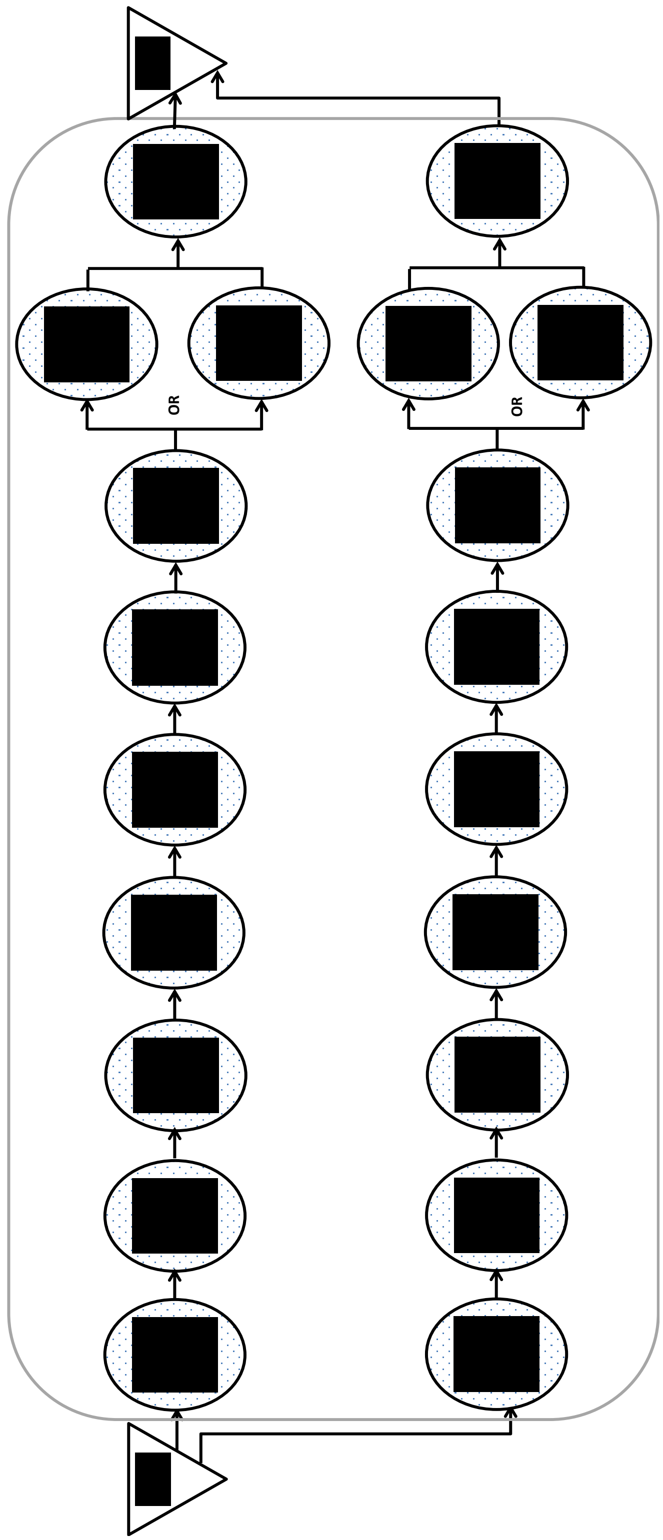

Figure 2: Process documentation for Case Study I - Station 2

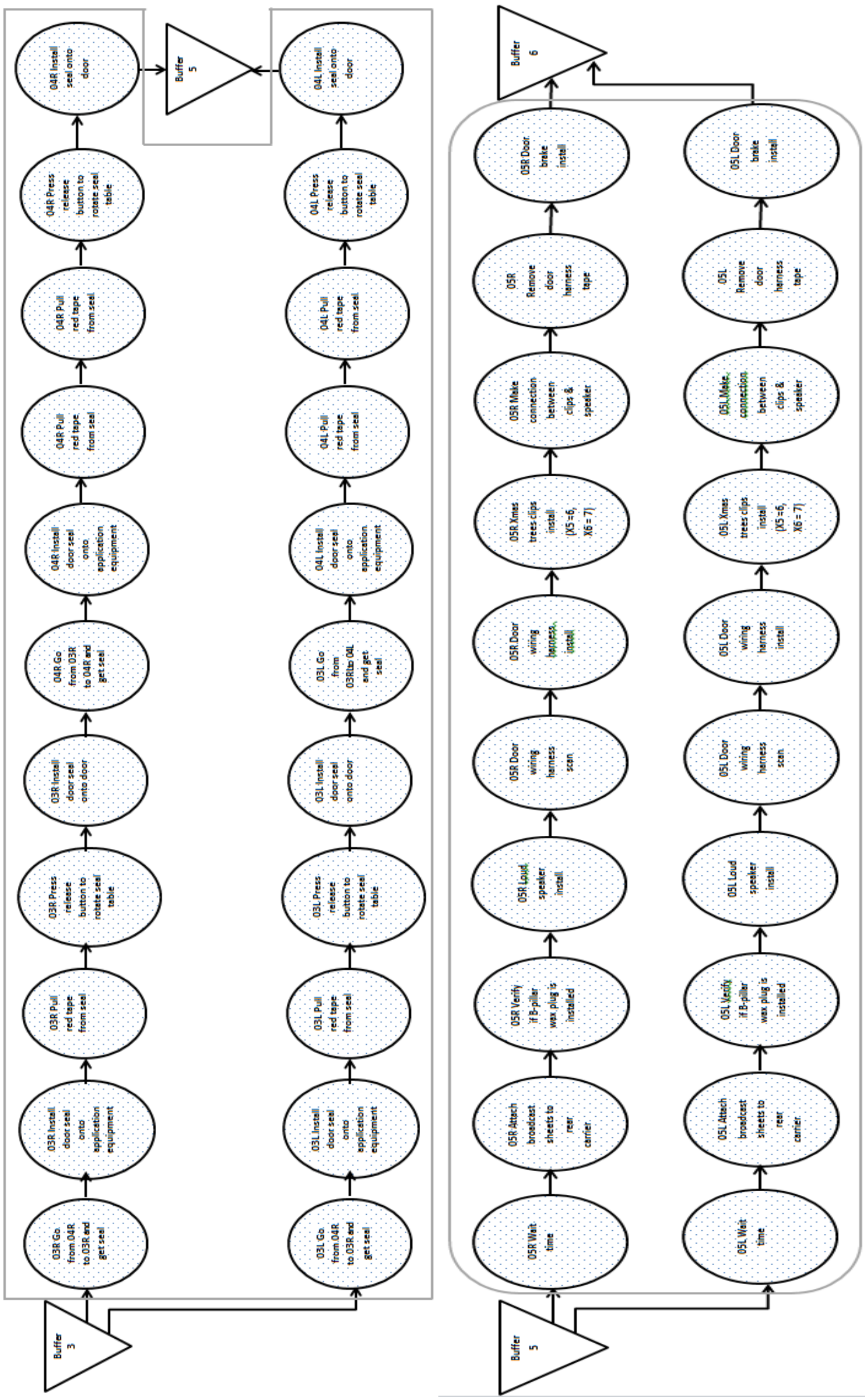

Figure 3: Process documentation for Case Study I – Station 3, 4 and 5

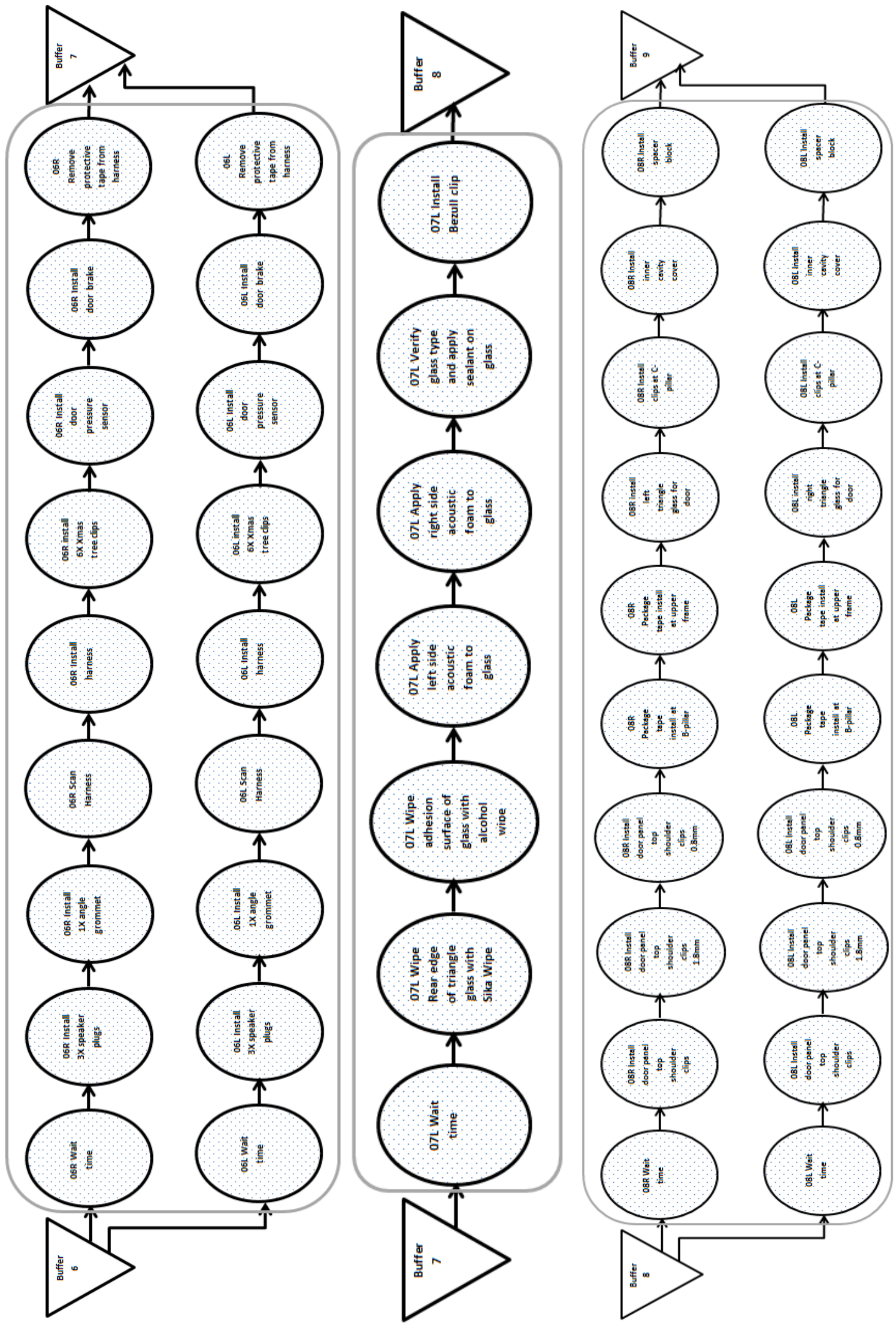

Figure 4: Process documentation for Case Study I - Station 6, 7 and 8

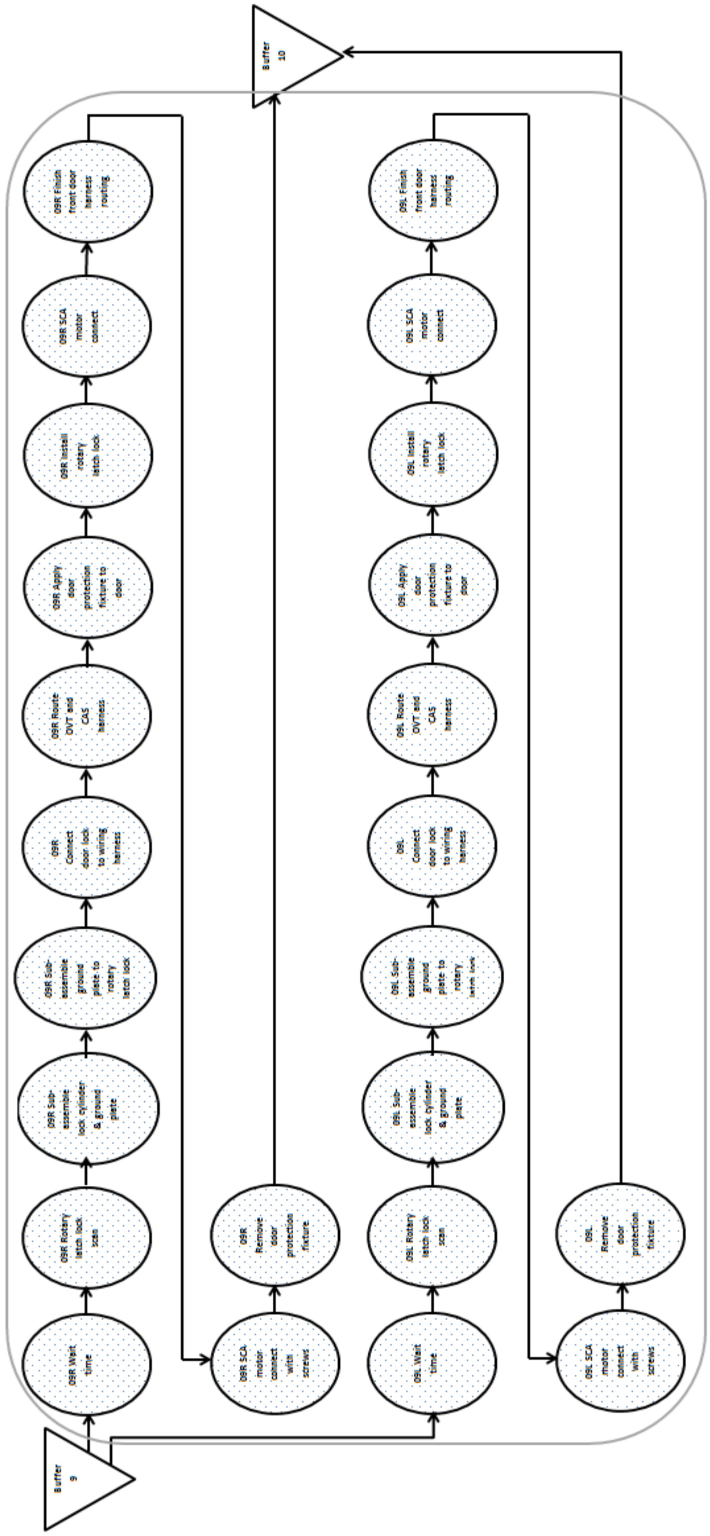

Figure 5: Process documentation for Case Study I - Station 9

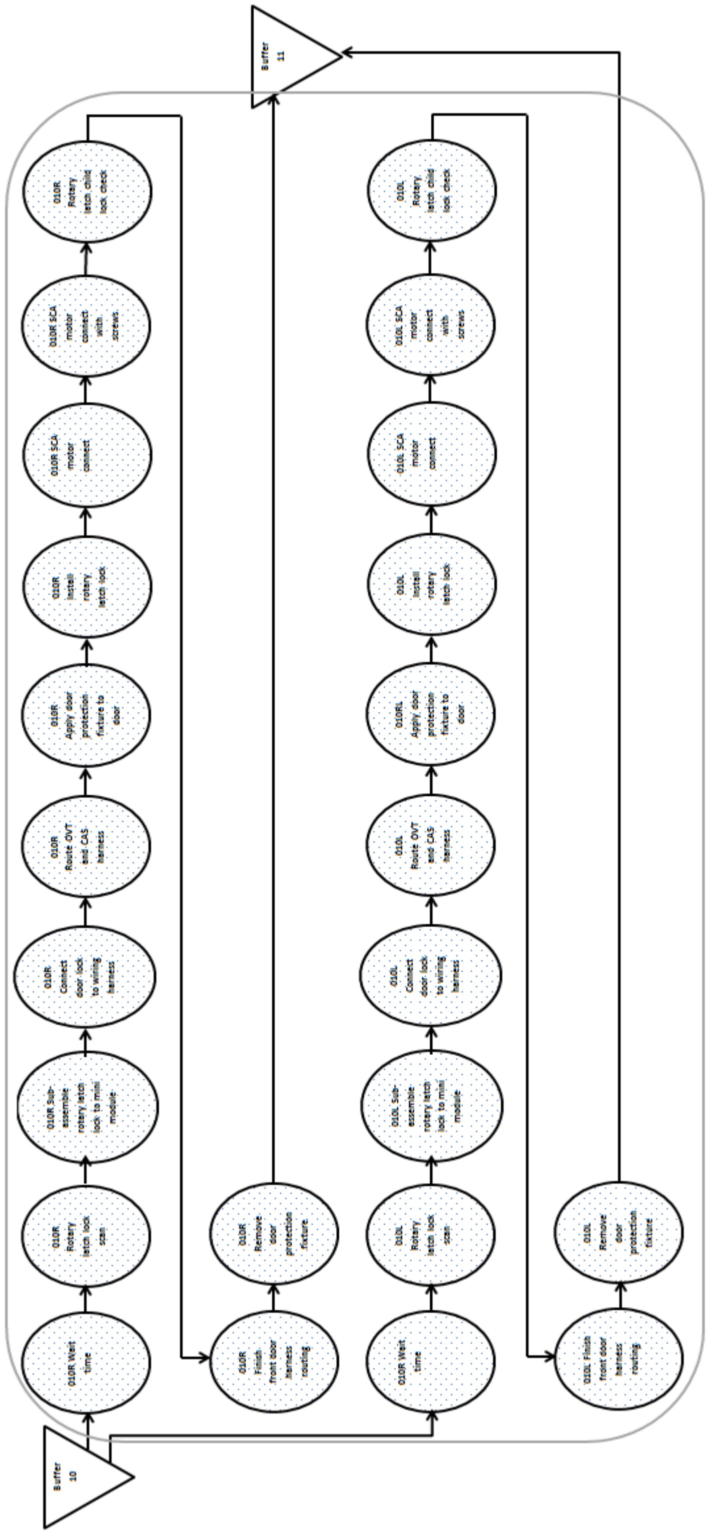

Figure 6: Process documentation for Case Study I- Station 10

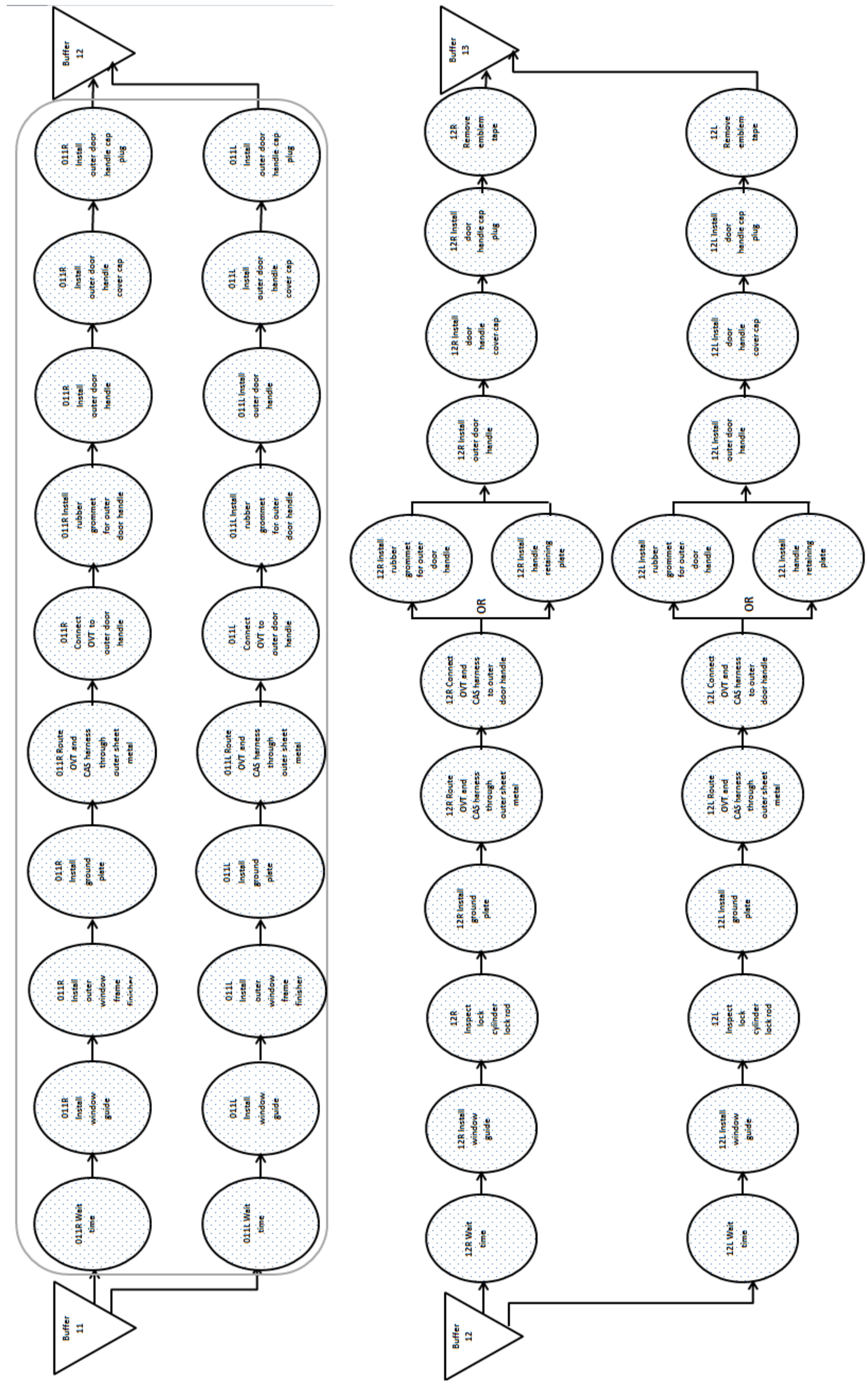

Figure 7: Process documentation for Case Study I- Station 11 and 12

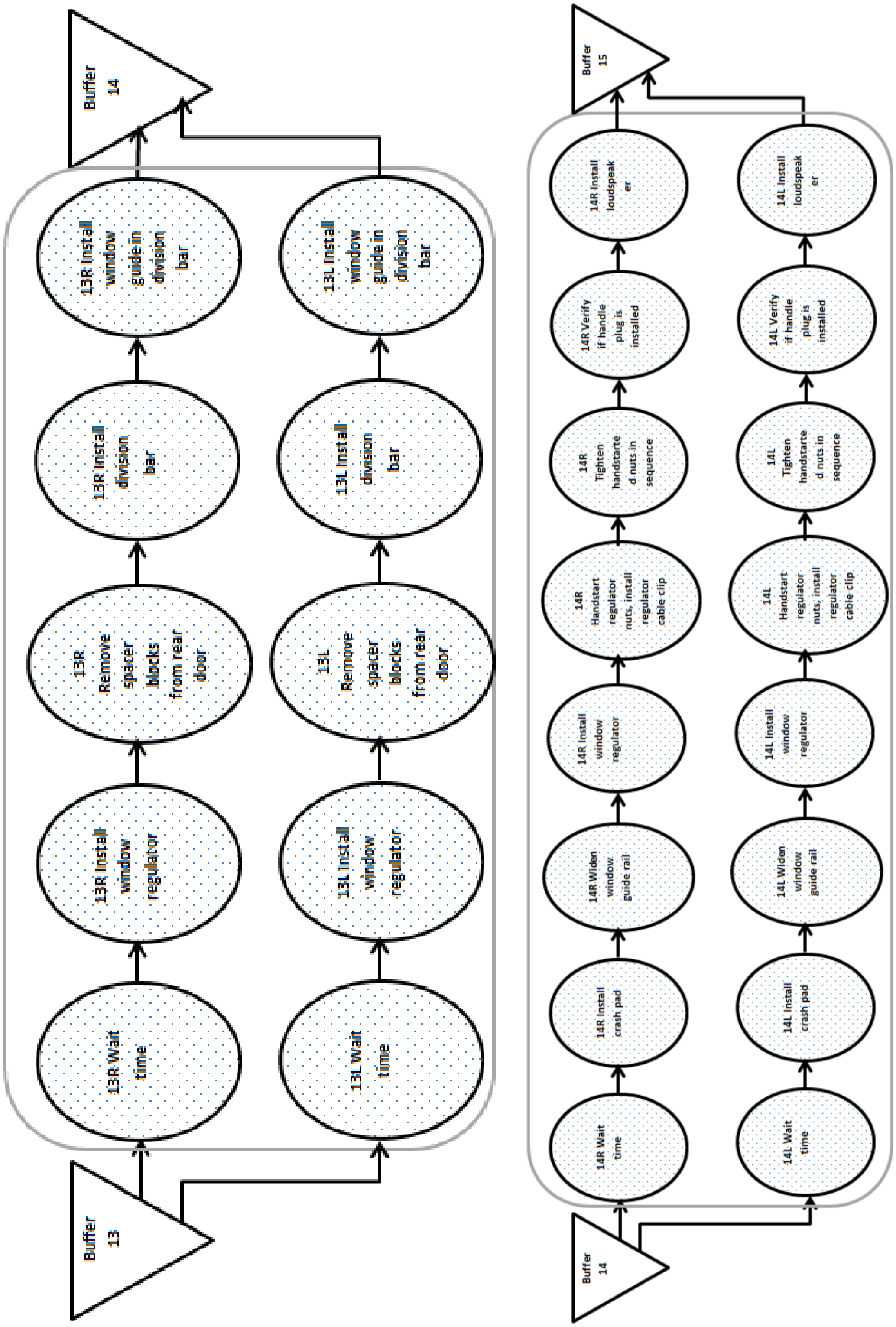

Figure 8: Process documentation for Case Study I - Station 13 and 14

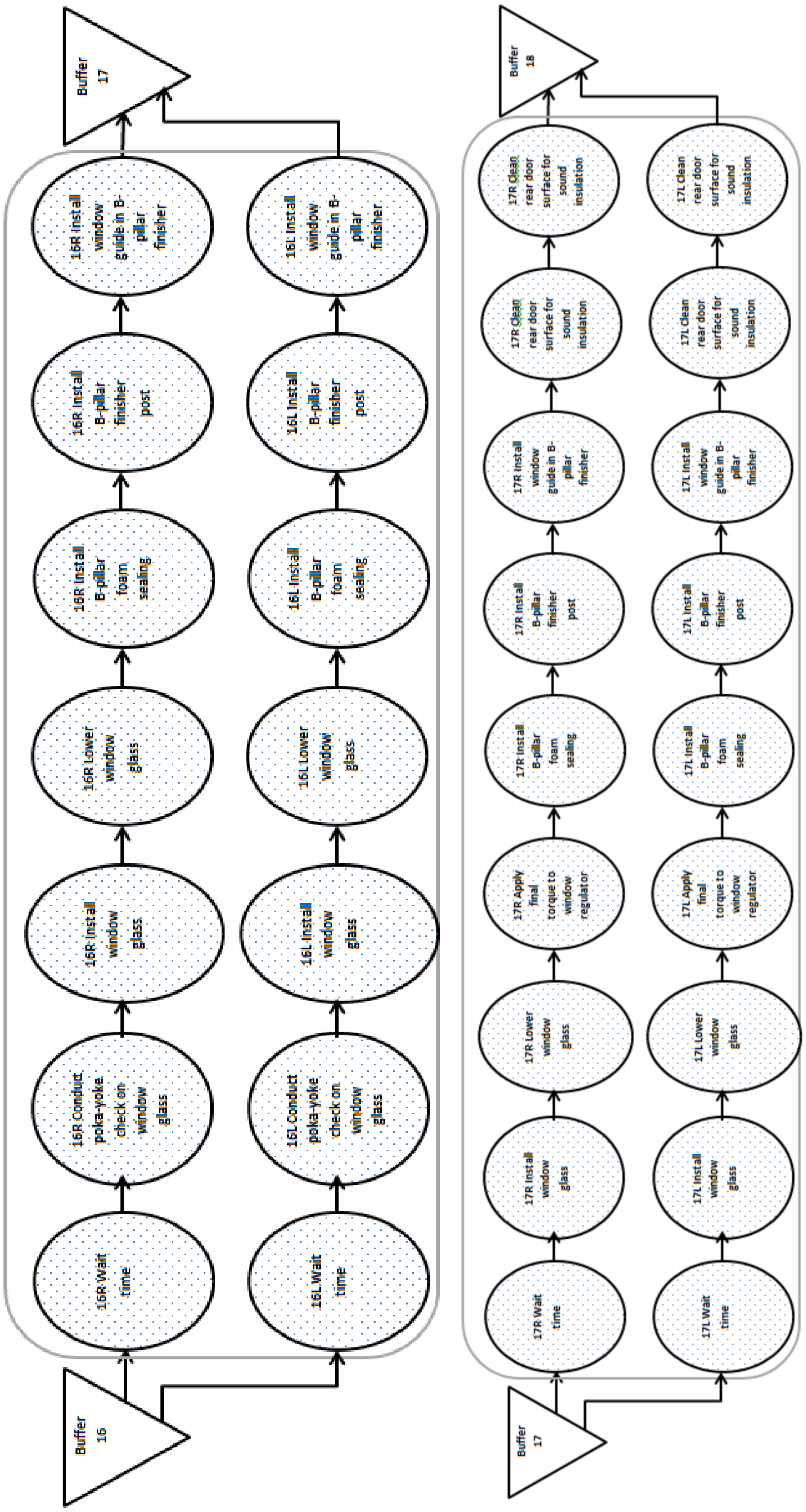

Figure 9: Process documentation for Case Study I- Station 16 and 17

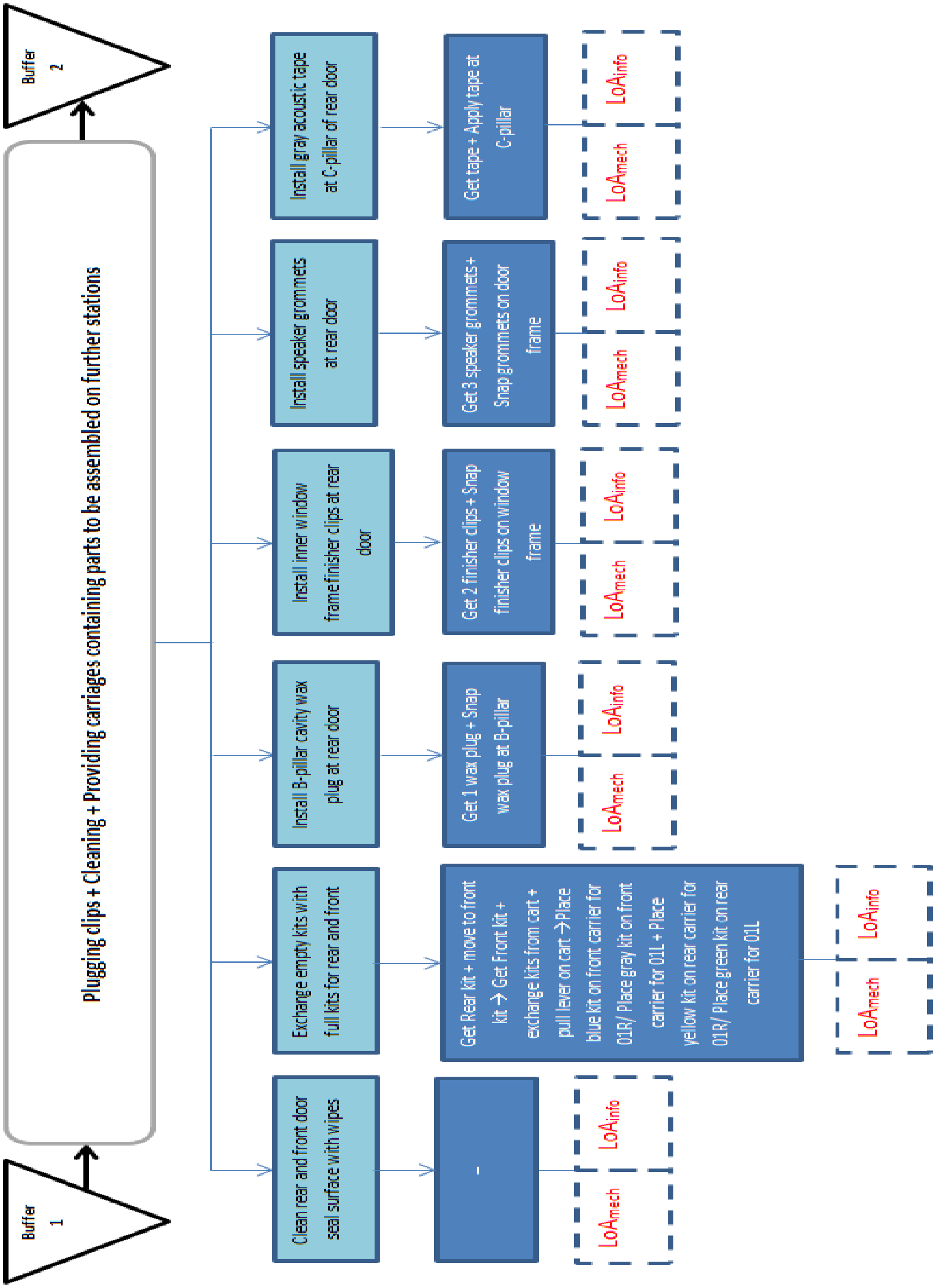

Figure 10: Breakdown of tasks for Case Study I – Station 1

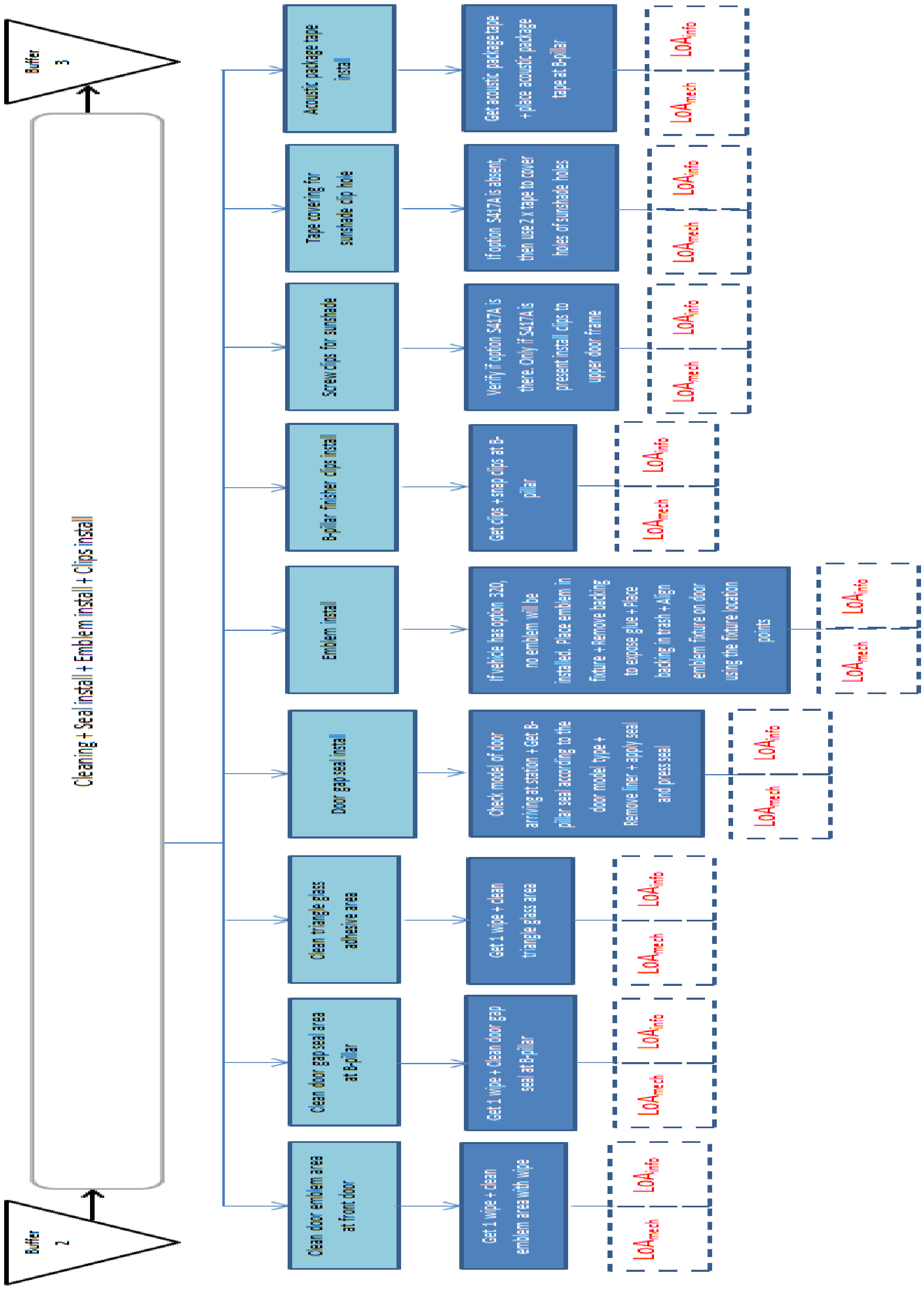

Figure 11: Breakdown of tasks for Case Study I – Station 2

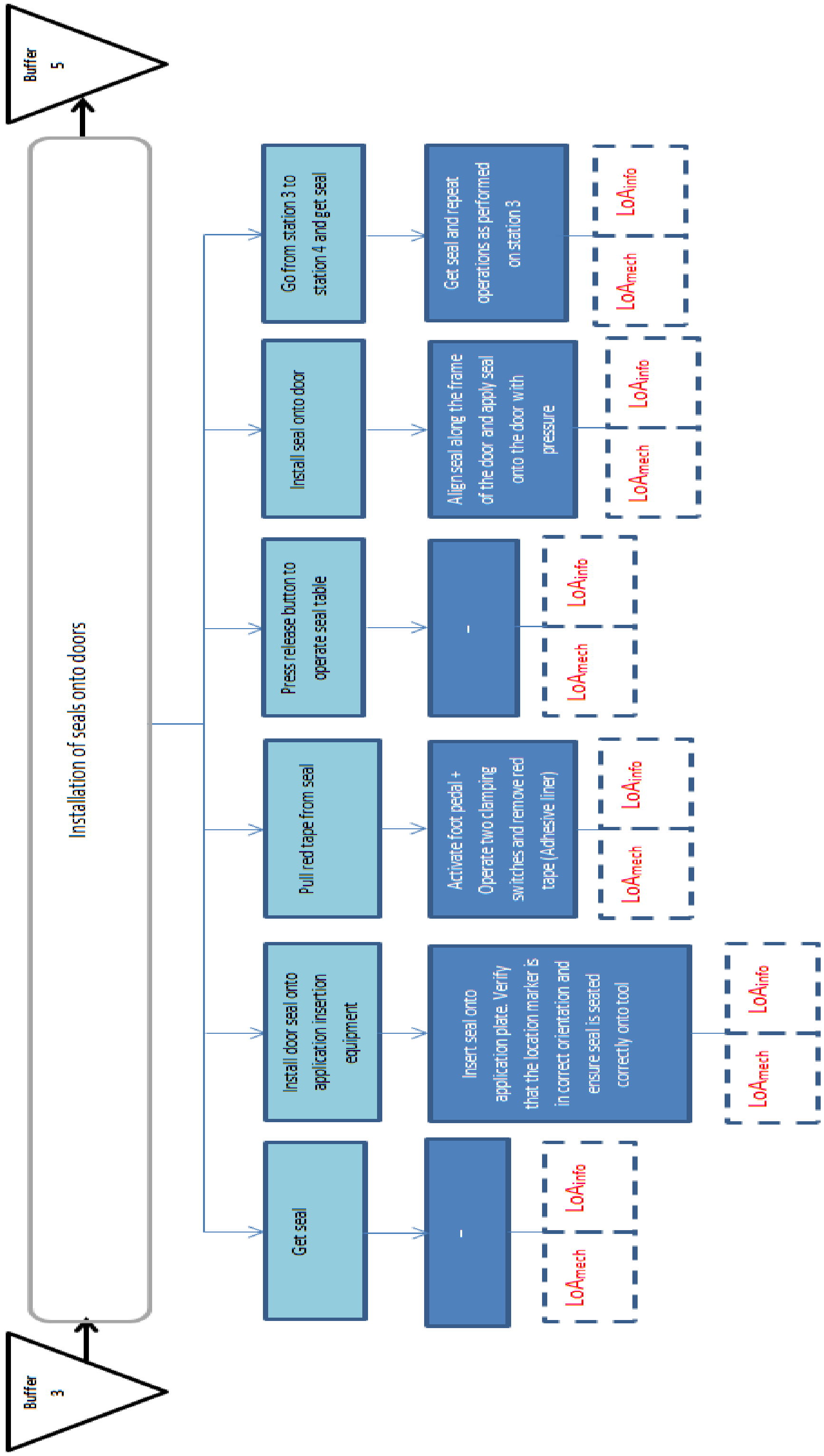

Figure 12: Breakdown of tasks for Case Study I – Station 3 and Station 4

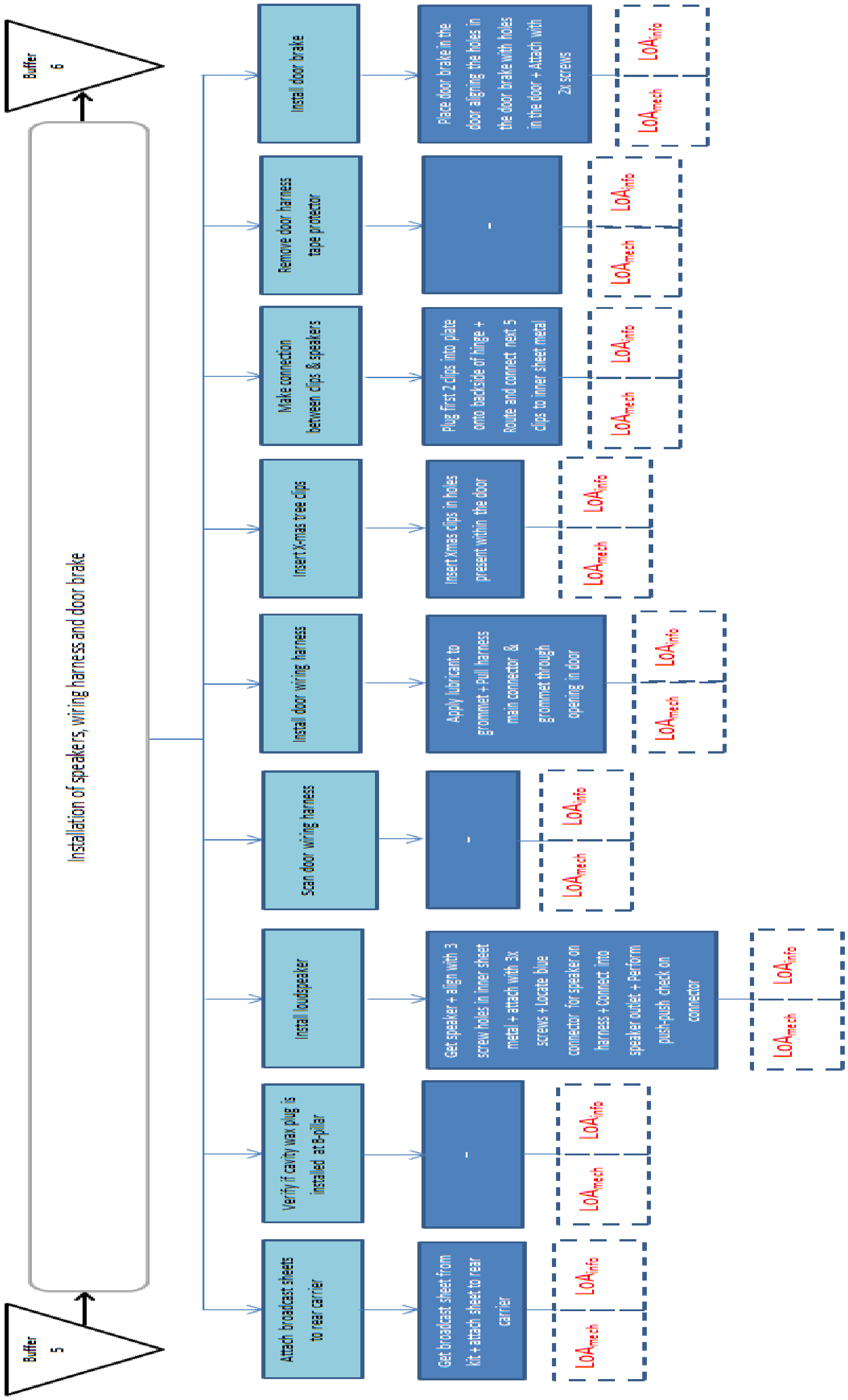

Figure 13: Breakdown of tasks for Case Study I – Station 5

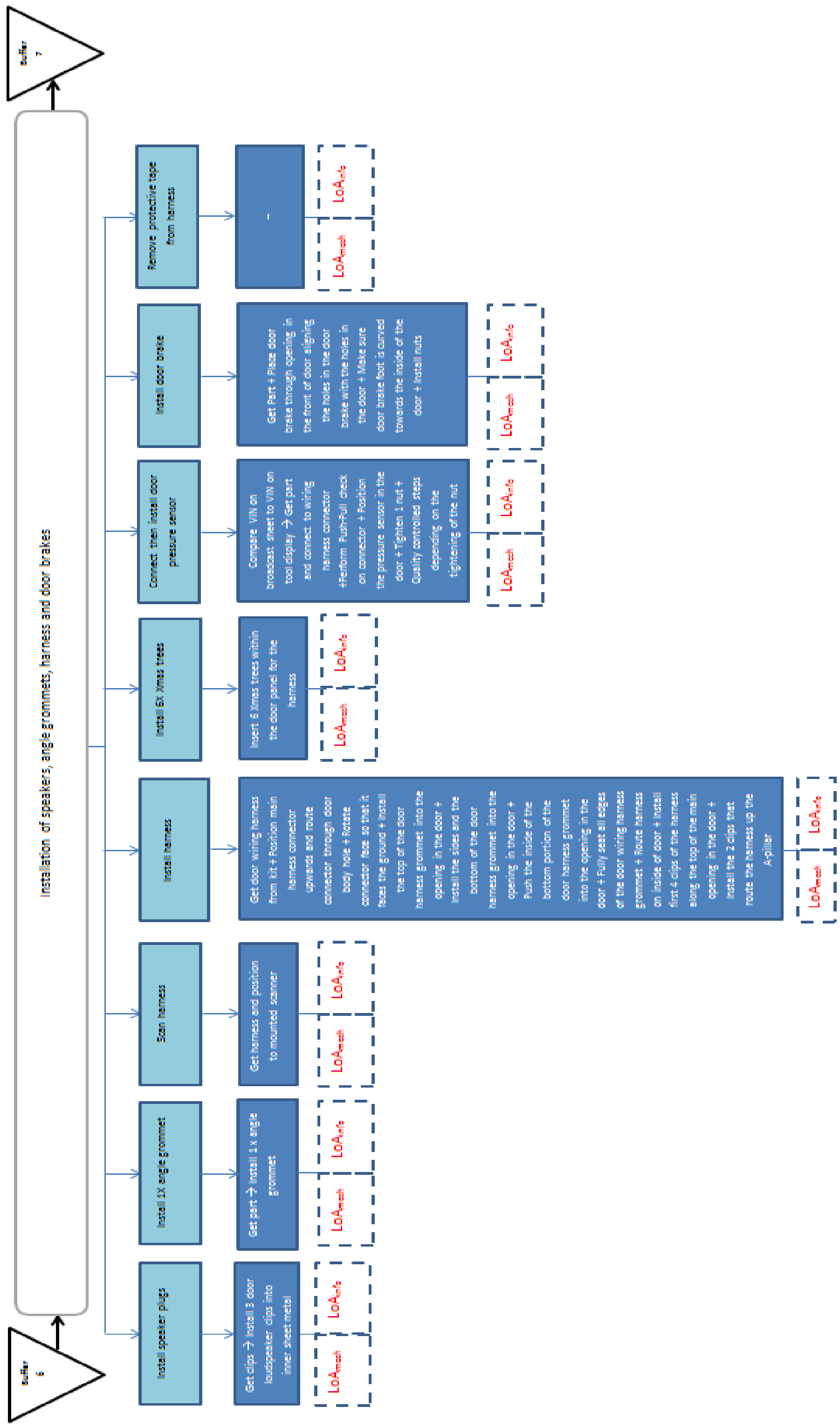

Figure 14: Breakdown of tasks for Case Study I – Station 6

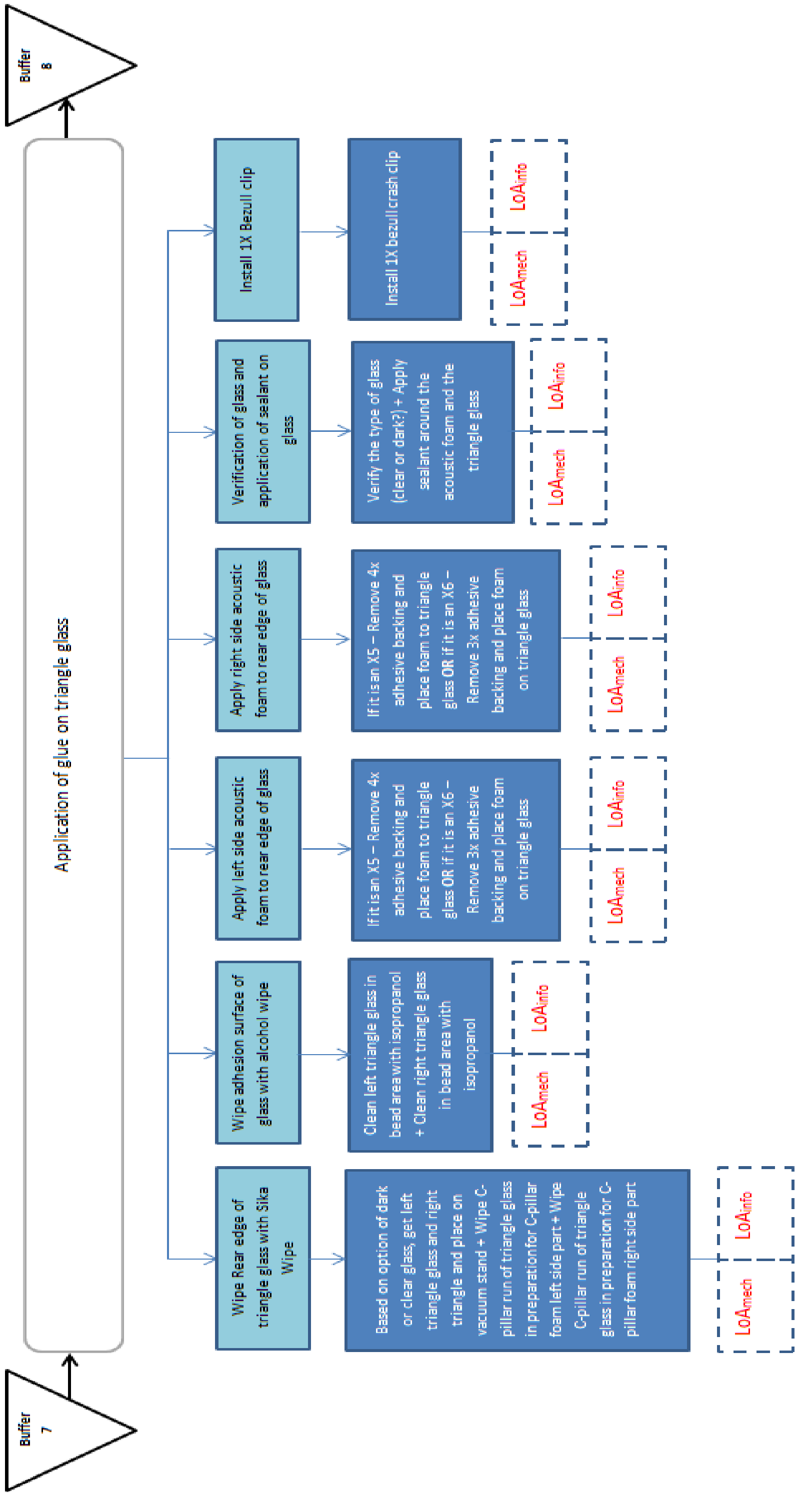

Figure 15: Breakdown of tasks for Case Study I – Station 7

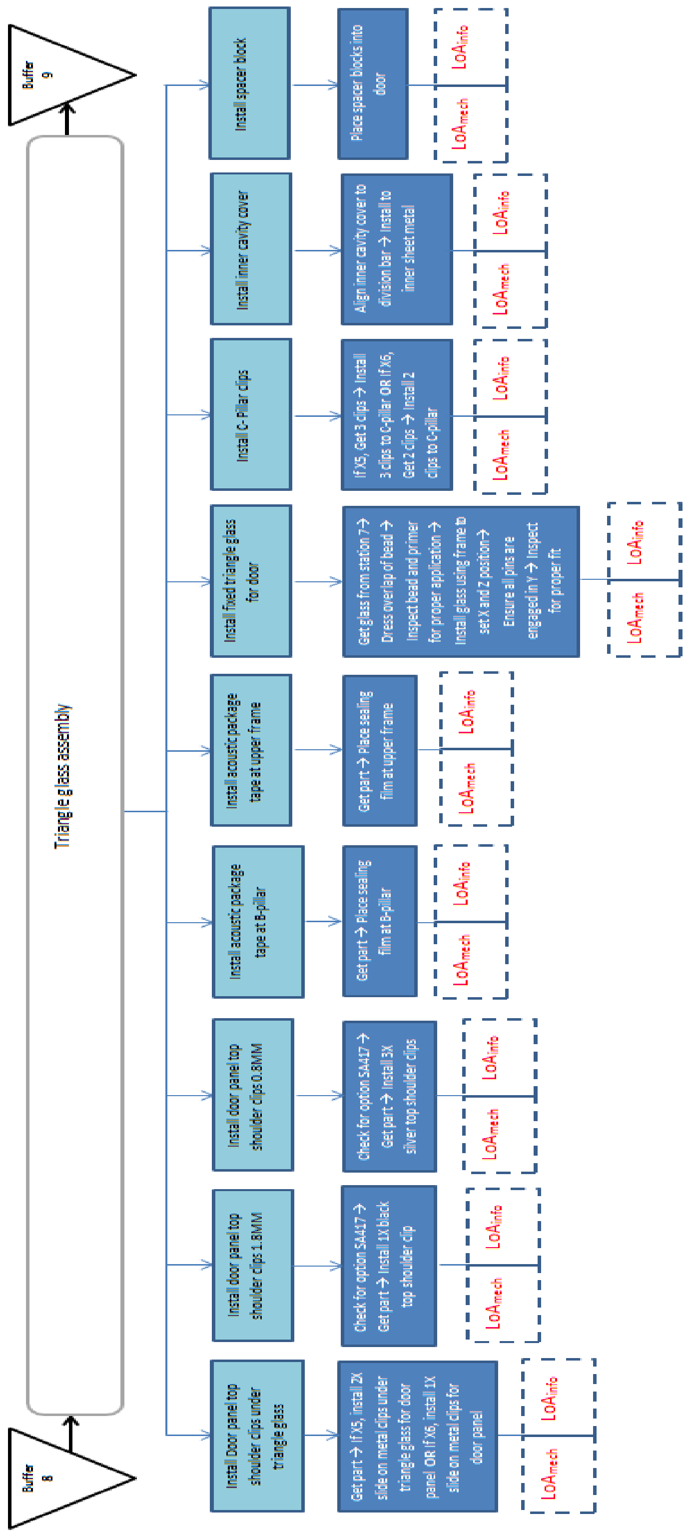

Figure 16: Breakdown of tasks for Case Study I – Station 8

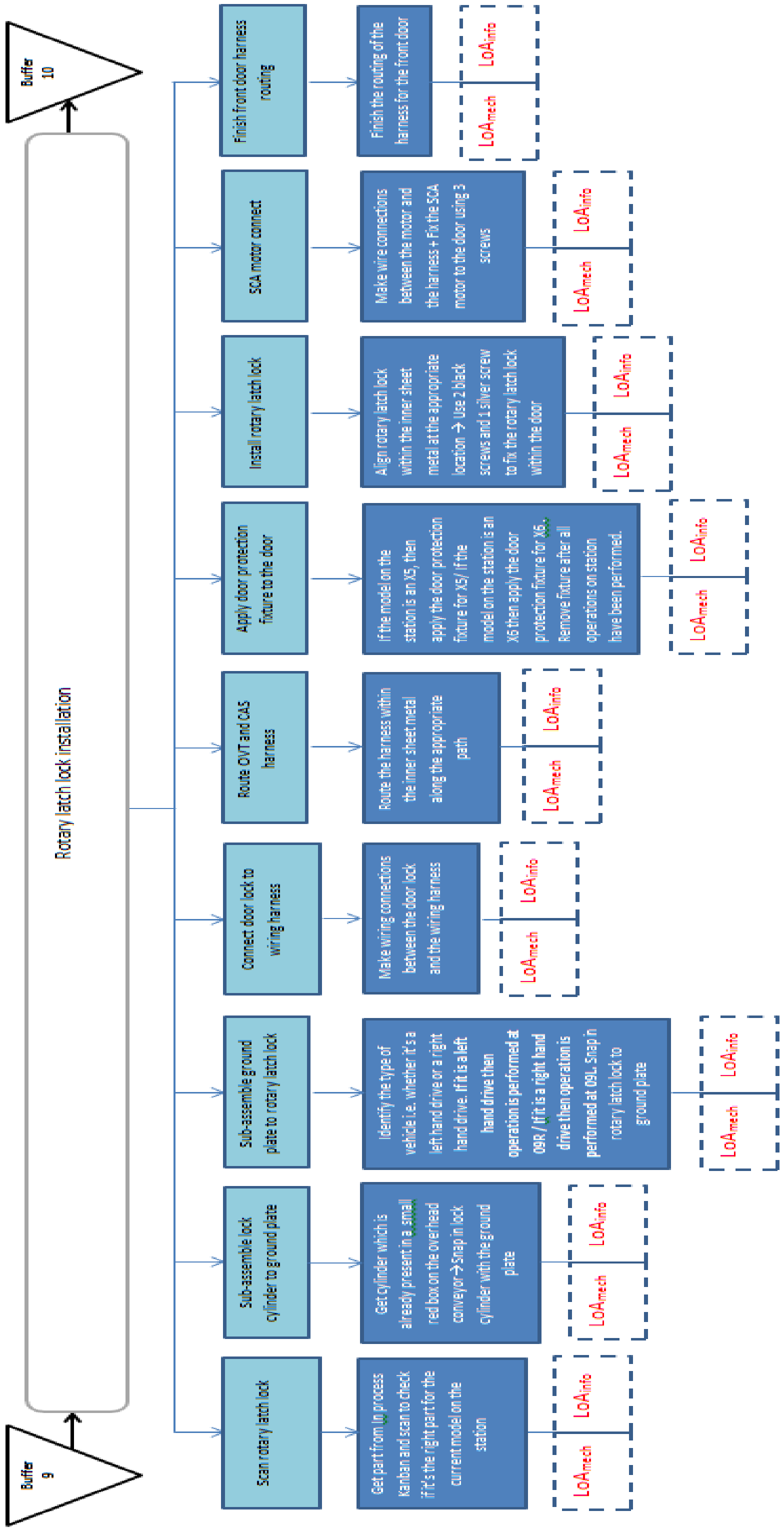

Figure 17: Breakdown of tasks for Case Study I – Station 9

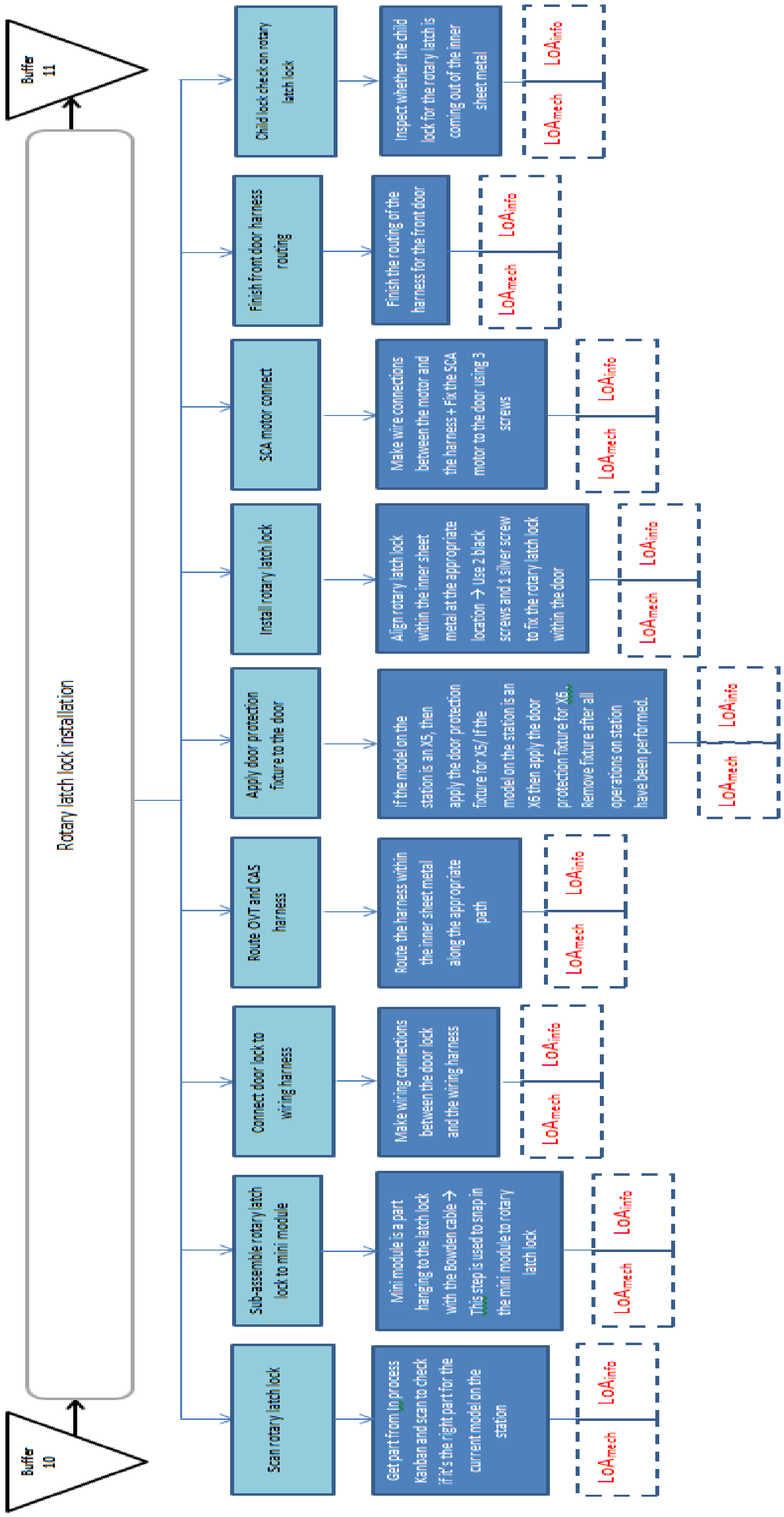

Figure 18: Breakdown of tasks for Case Study I – Station 10

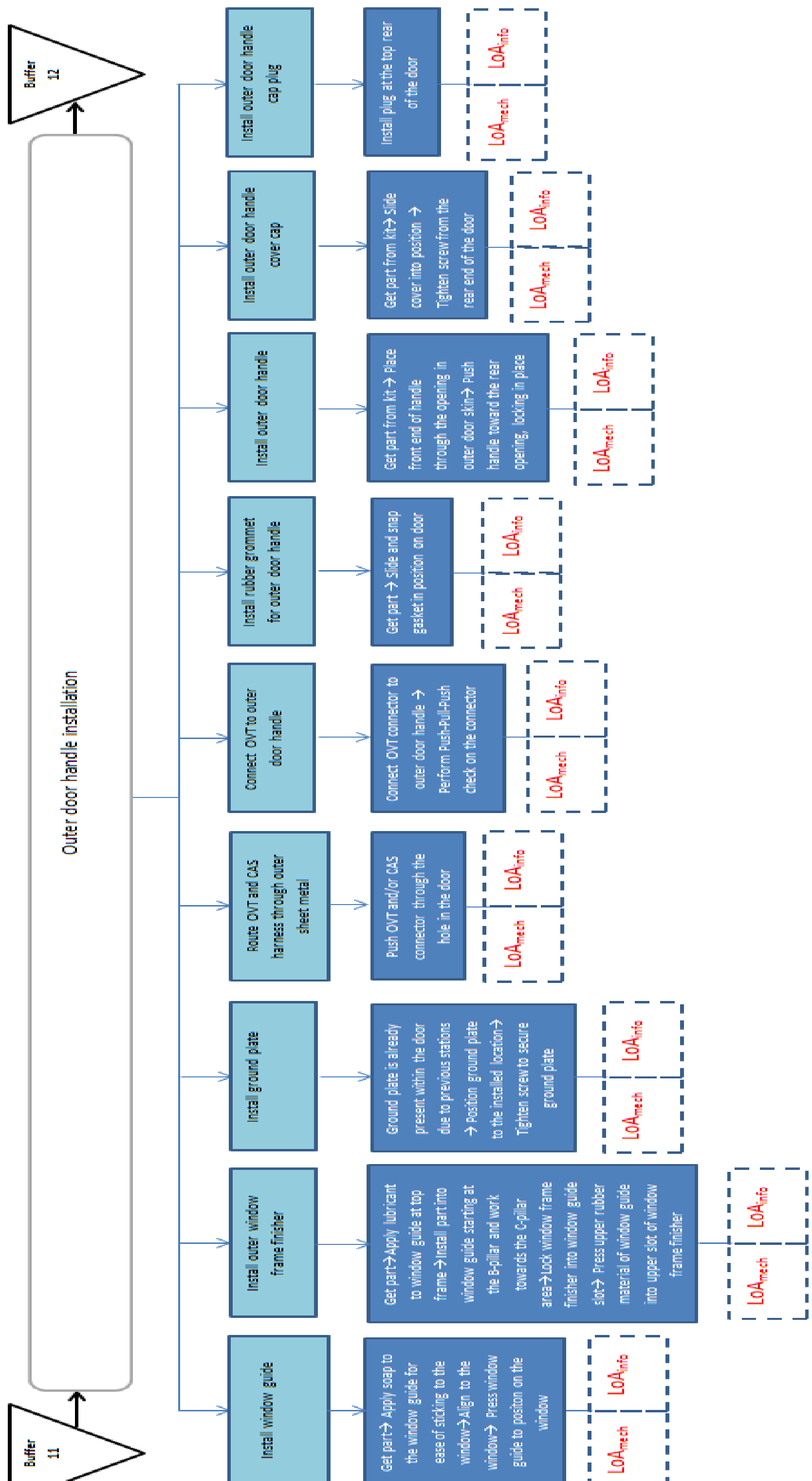

Figure 19: Breakdown of tasks for Case Study I – Station 11

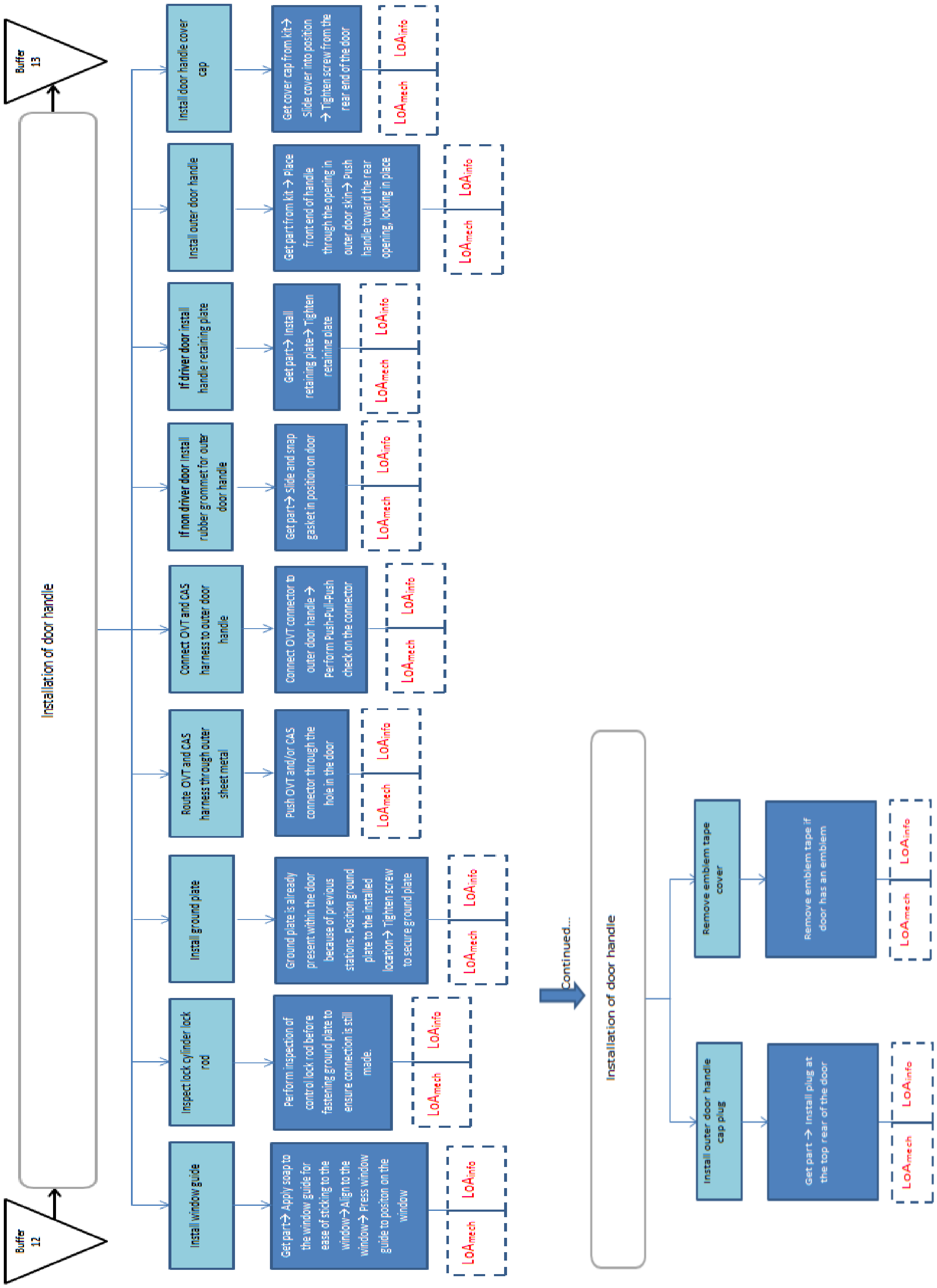

Figure 20: Breakdown of tasks for Case Study I – Station 12

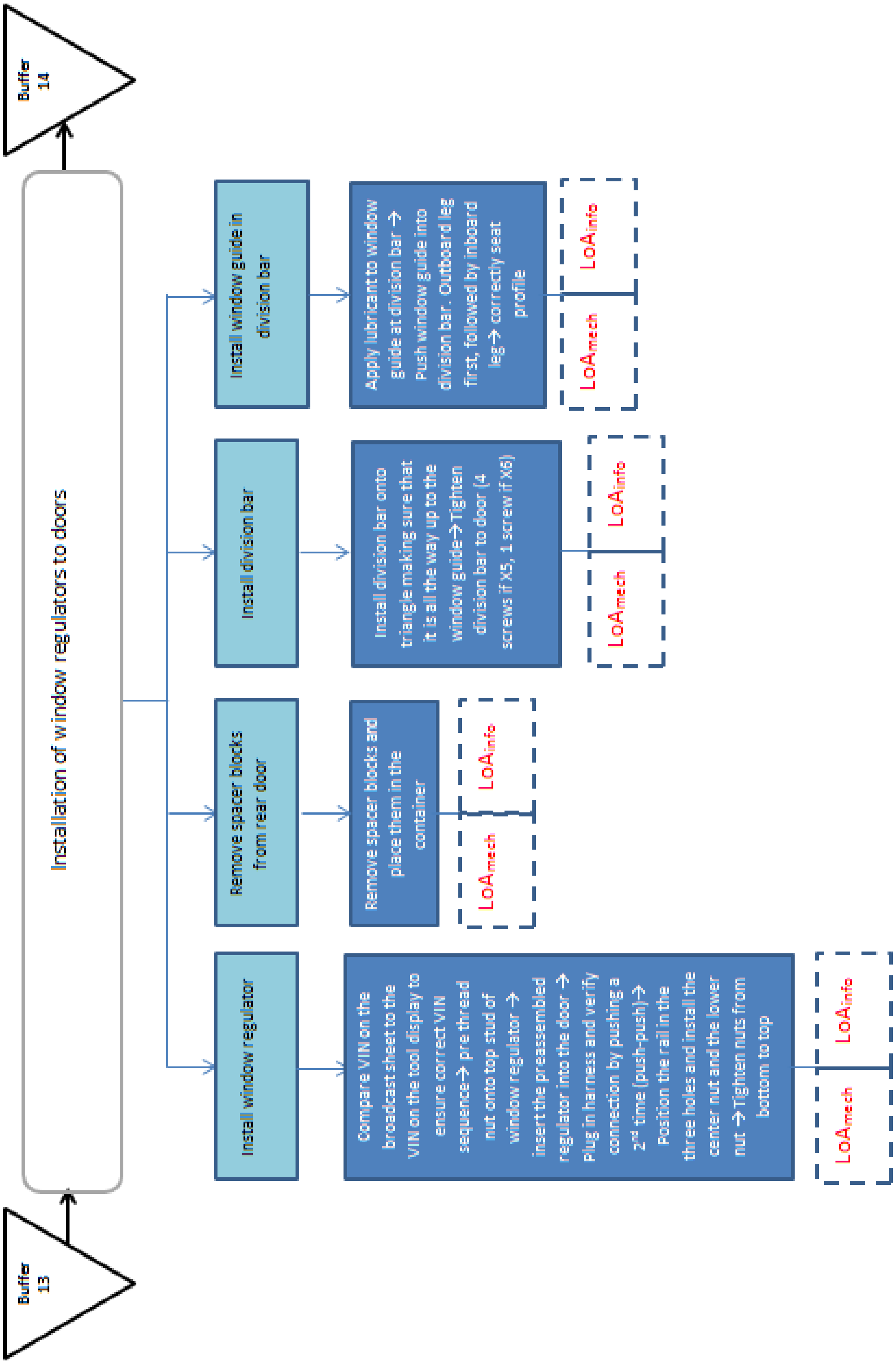

Figure 21: Breakdown of tasks for Case Study I – Station 13

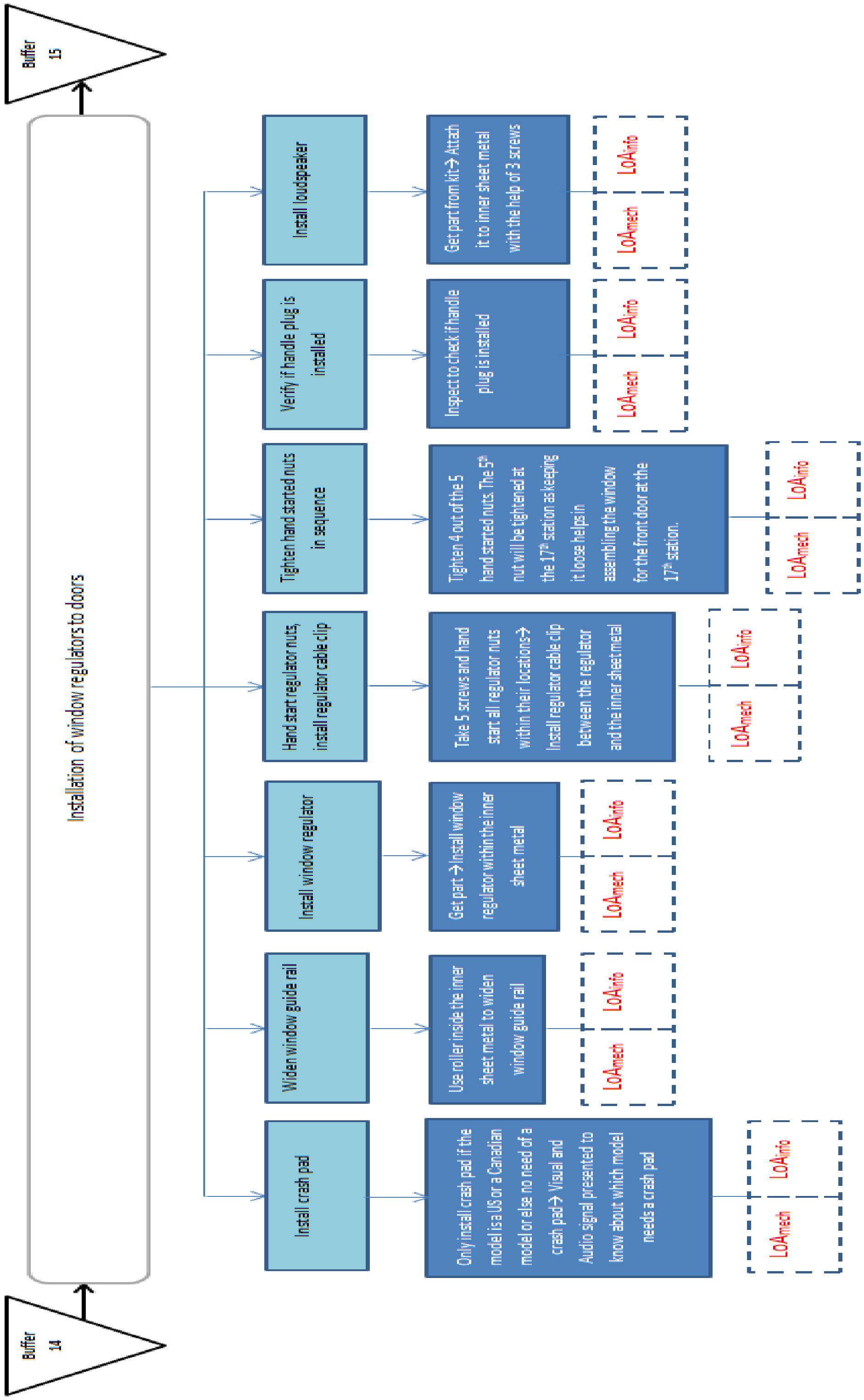

Figure 22: Breakdown of tasks for Case Study I – Station 14

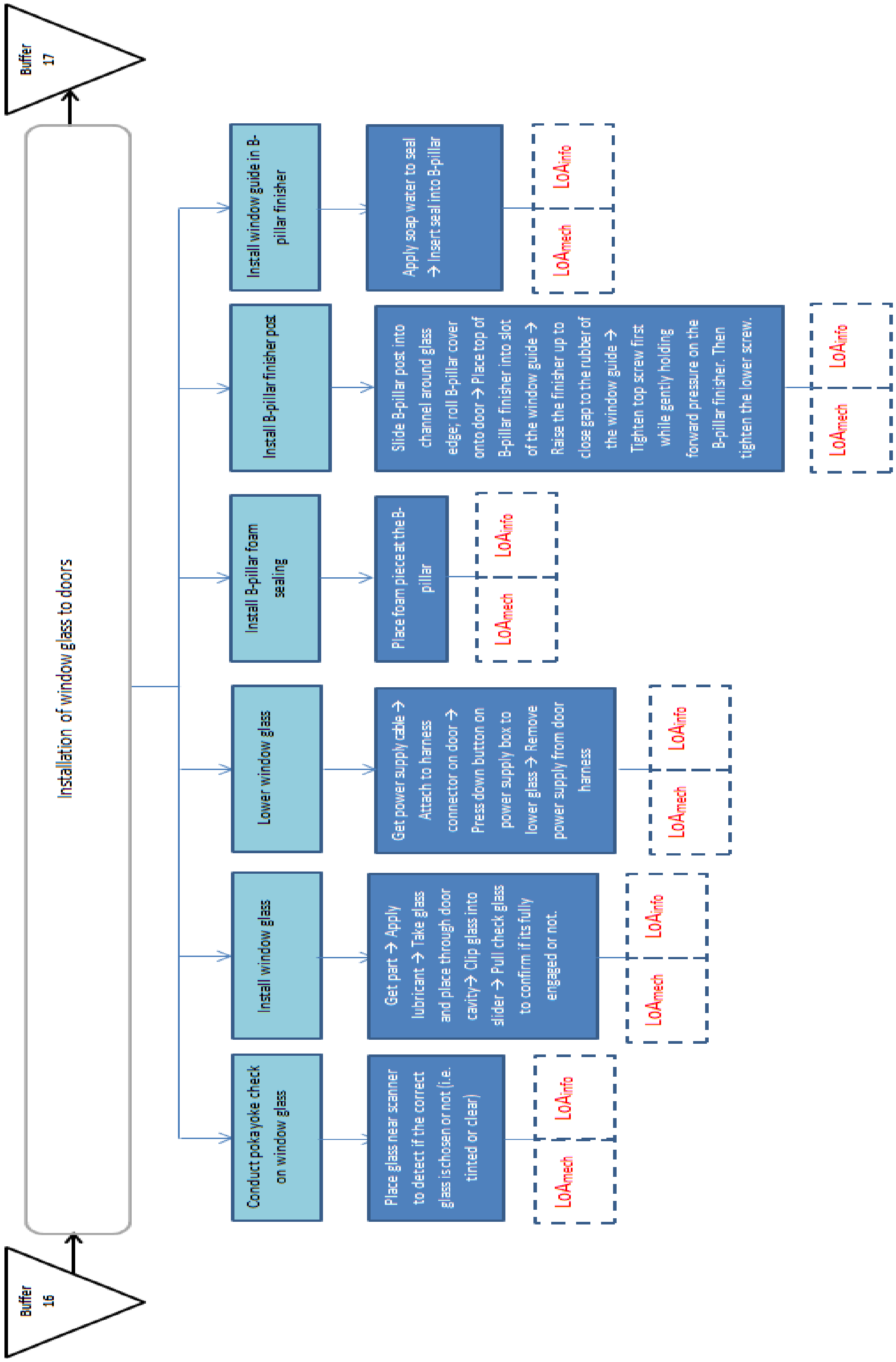

Figure 23: Breakdown of tasks for Case Study I – Station 16

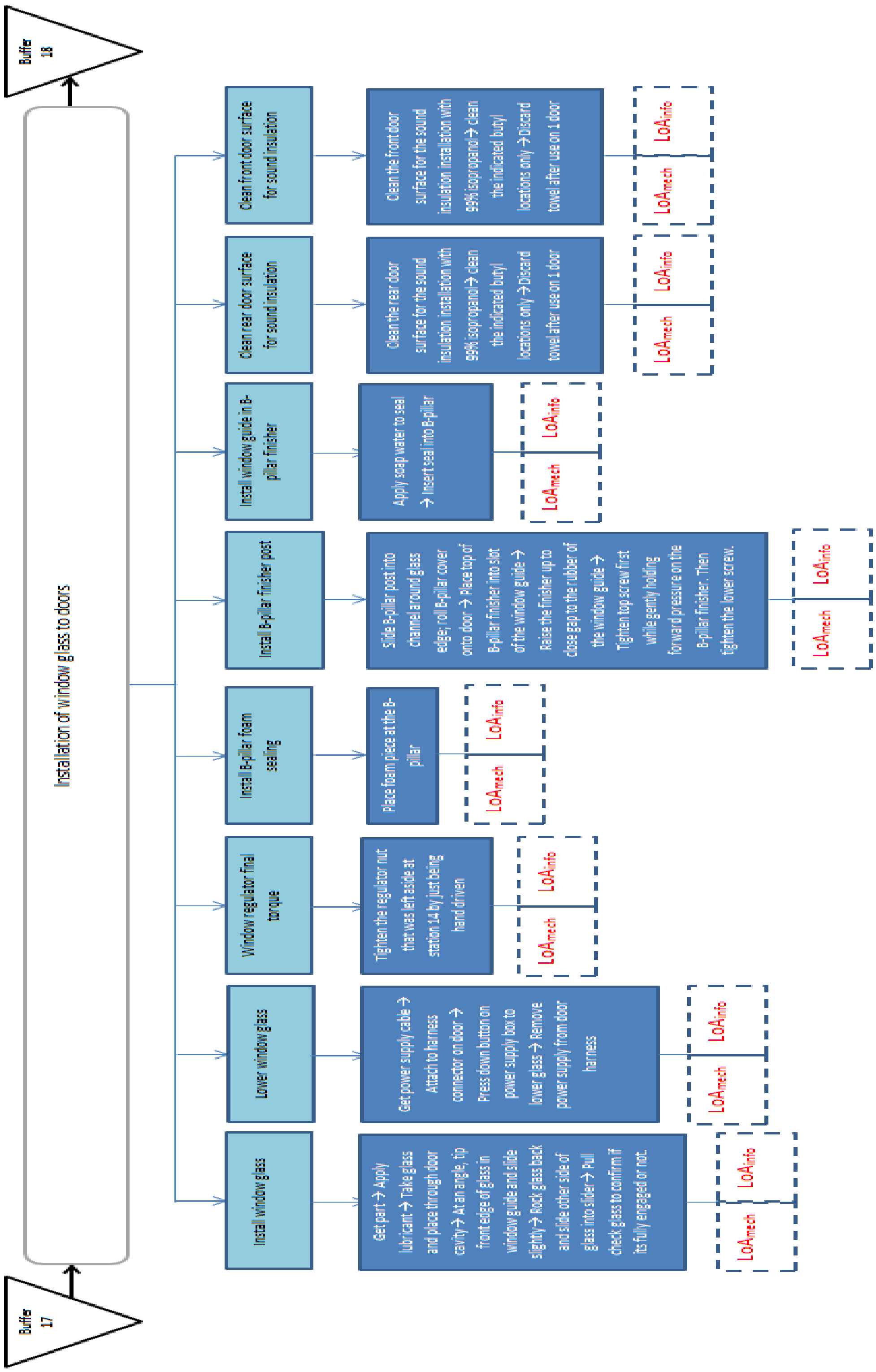

Figure 24: Breakdown of tasks for Case Study I – Station 17

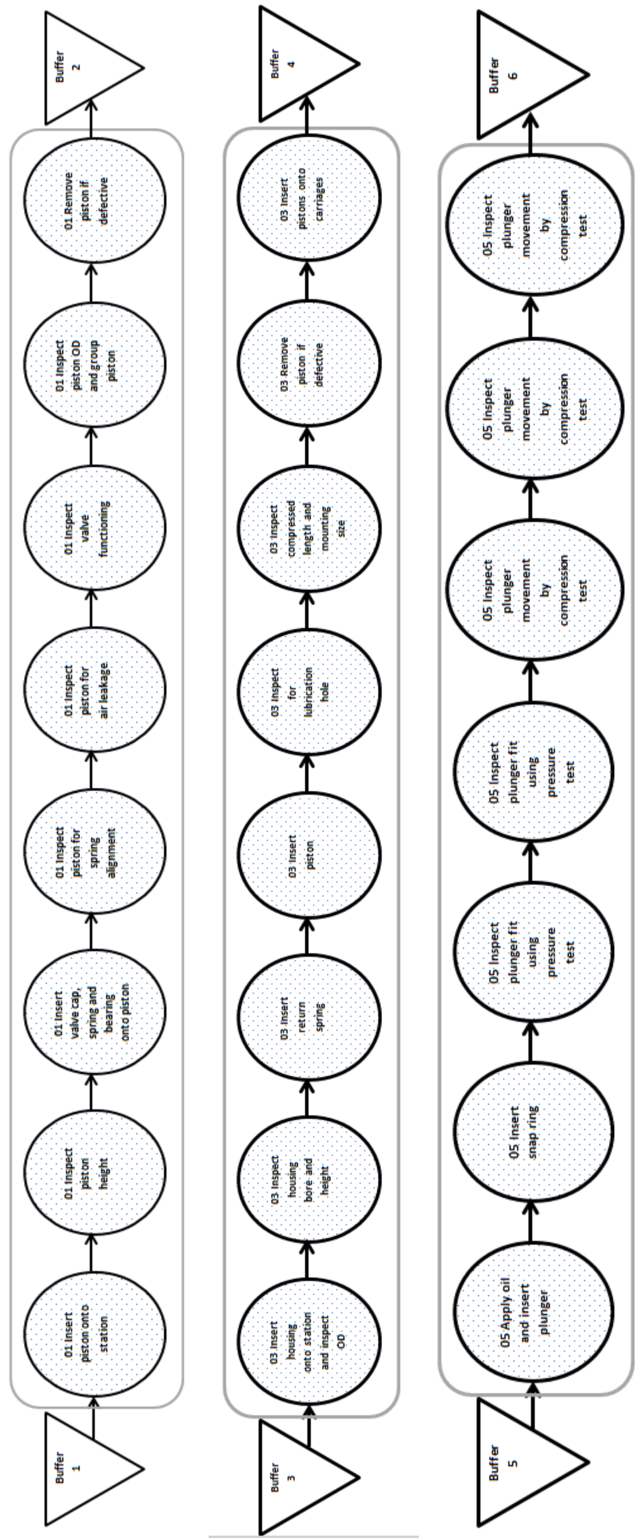

Figure 25: Process documentation for Case Study II – Stations 1, 3 and 5

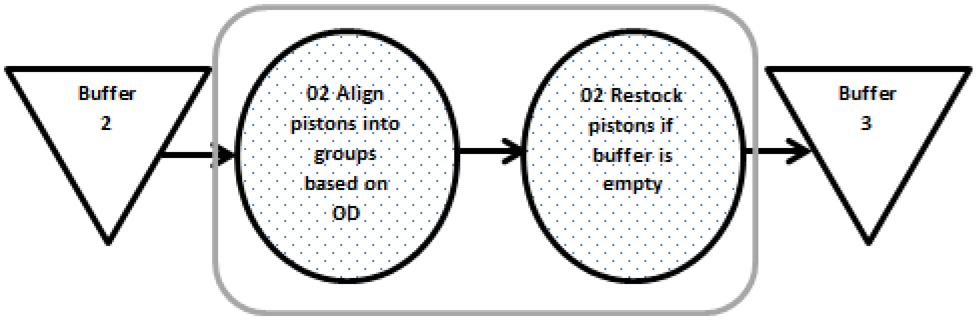

Figure 26: Process documentation for Case Study II – Station 2

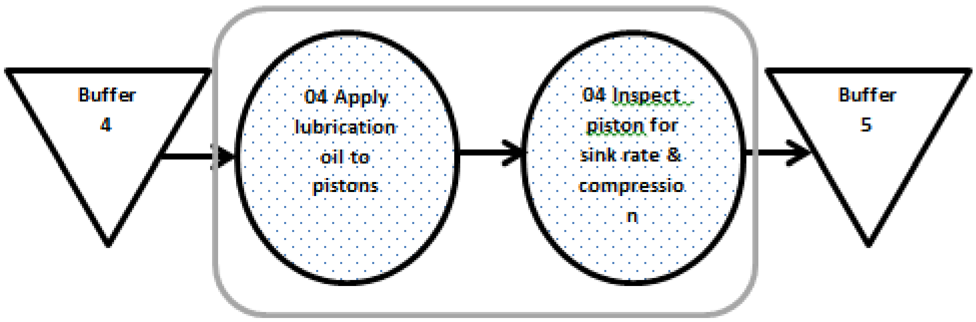

Figure 27: Process documentation for Case Study II – Station 4

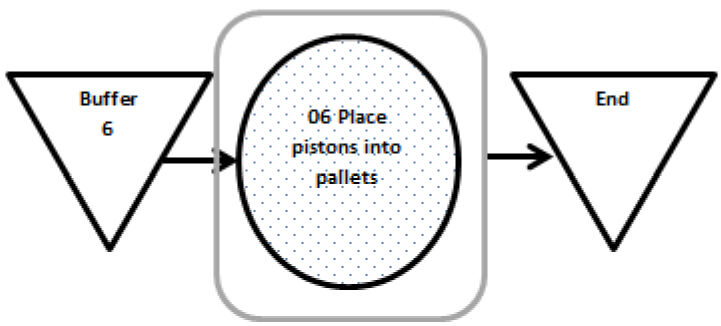

Figure 28: Process documentation for Case Study II – Station 6

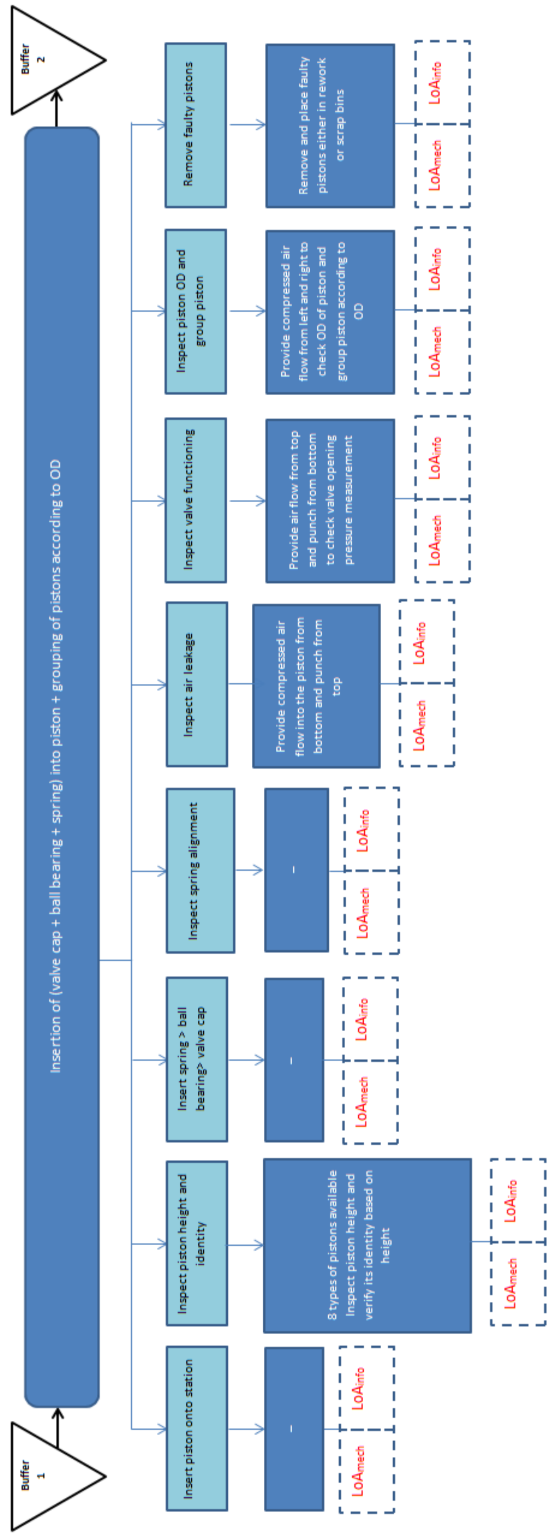

Figure 29: Breakdown of tasks for Case Study II –Station 1

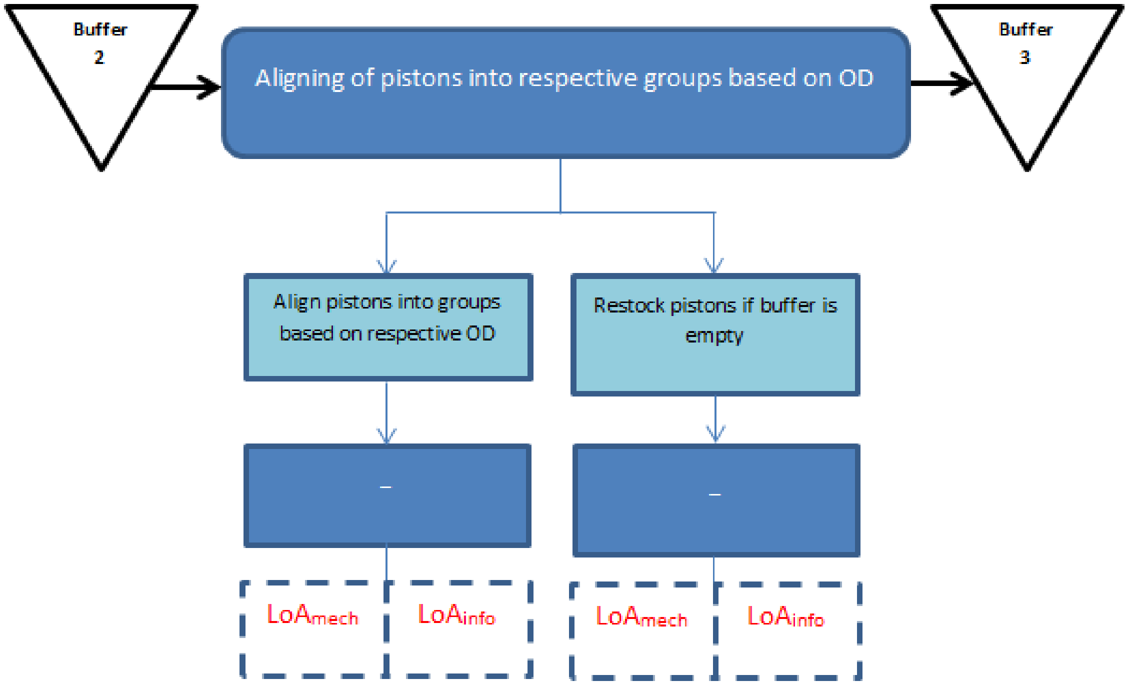

Figure 30: Break down of tasks for Case Study II – Station 2

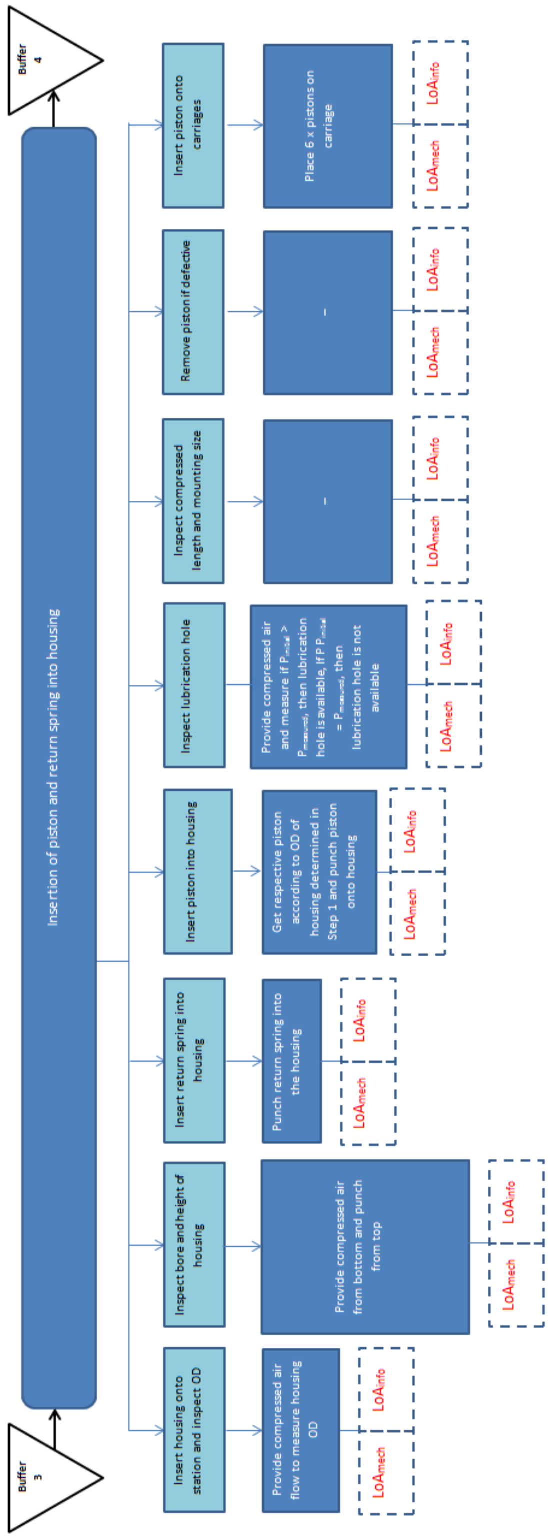

Figure 31: Breakdown of tasks for Case Study II – Station 3

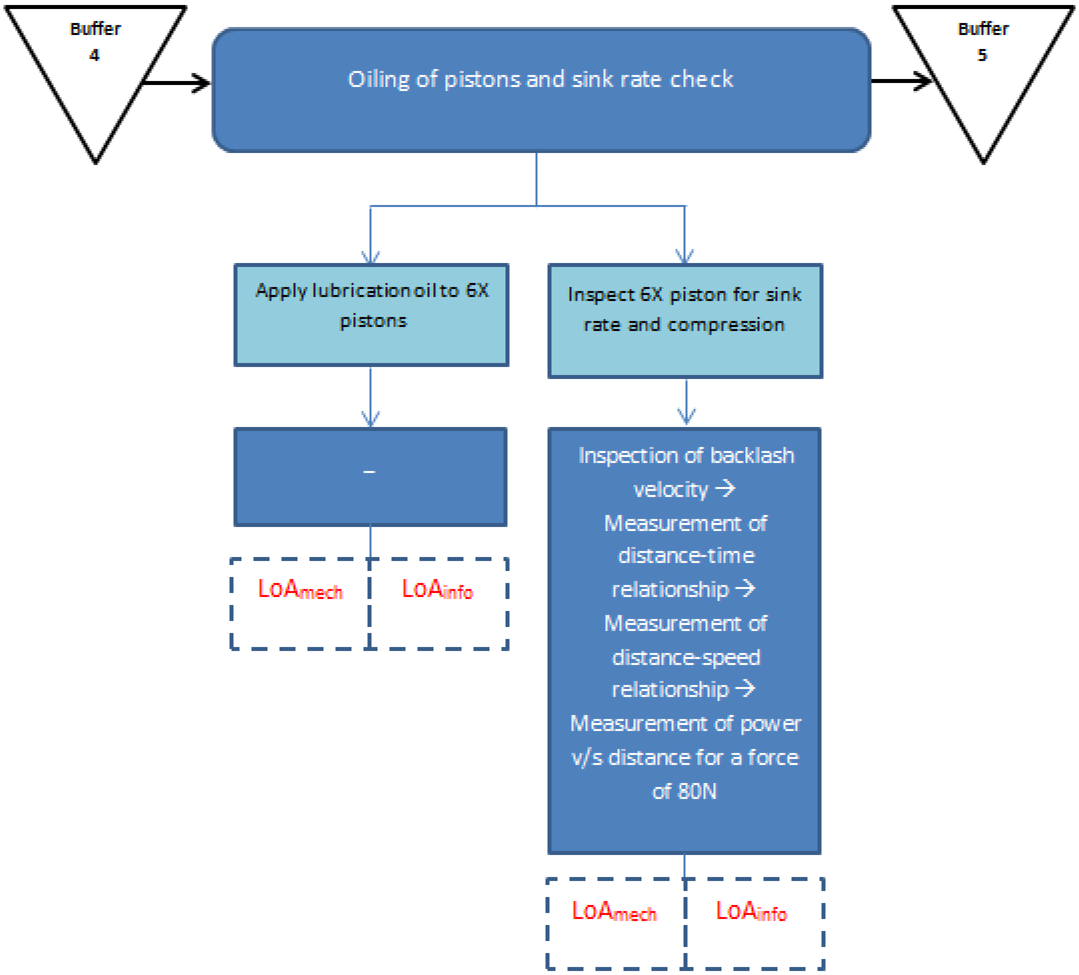

Figure 32: Break down of tasks for Case Study II – Station 4

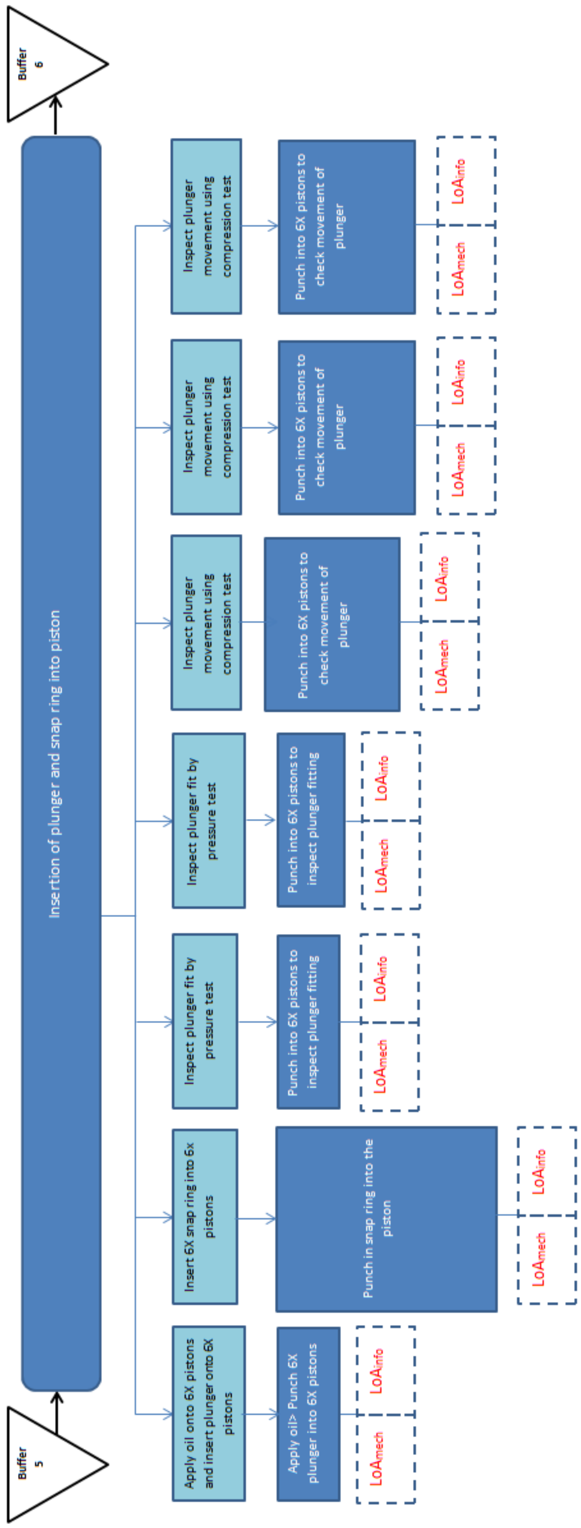

Figure 33: Break down of tasks for Case Study II – Station 5

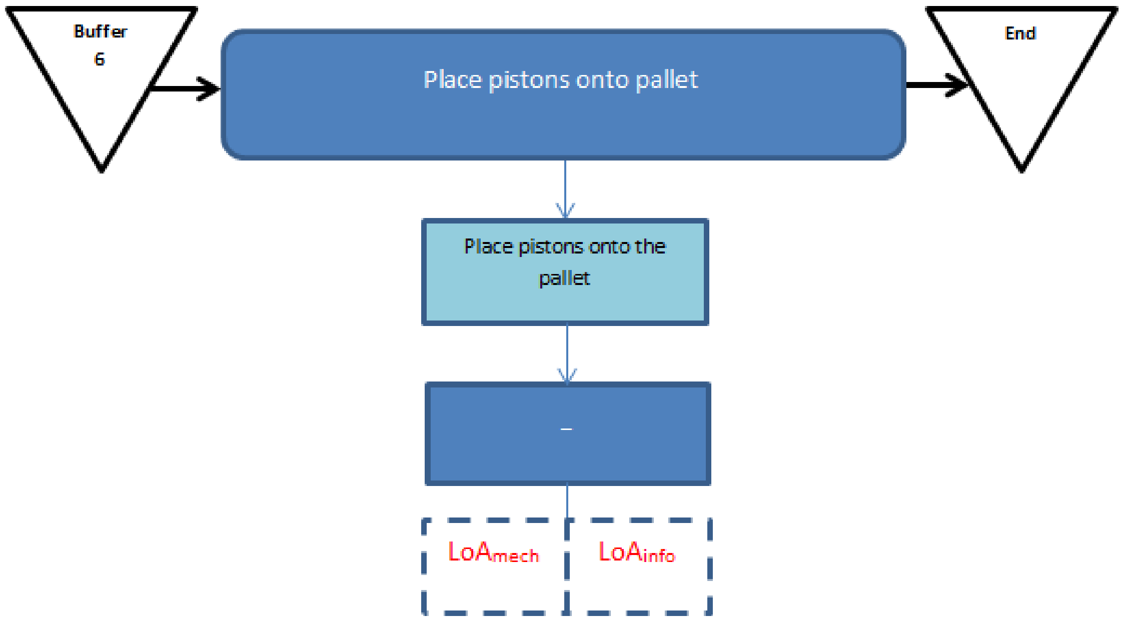

Figure 34: Break down of tasks for Case Study II – Station 6

APPENDIX C: INTERGRATED PROPOSED METHOD DOCUMENTS

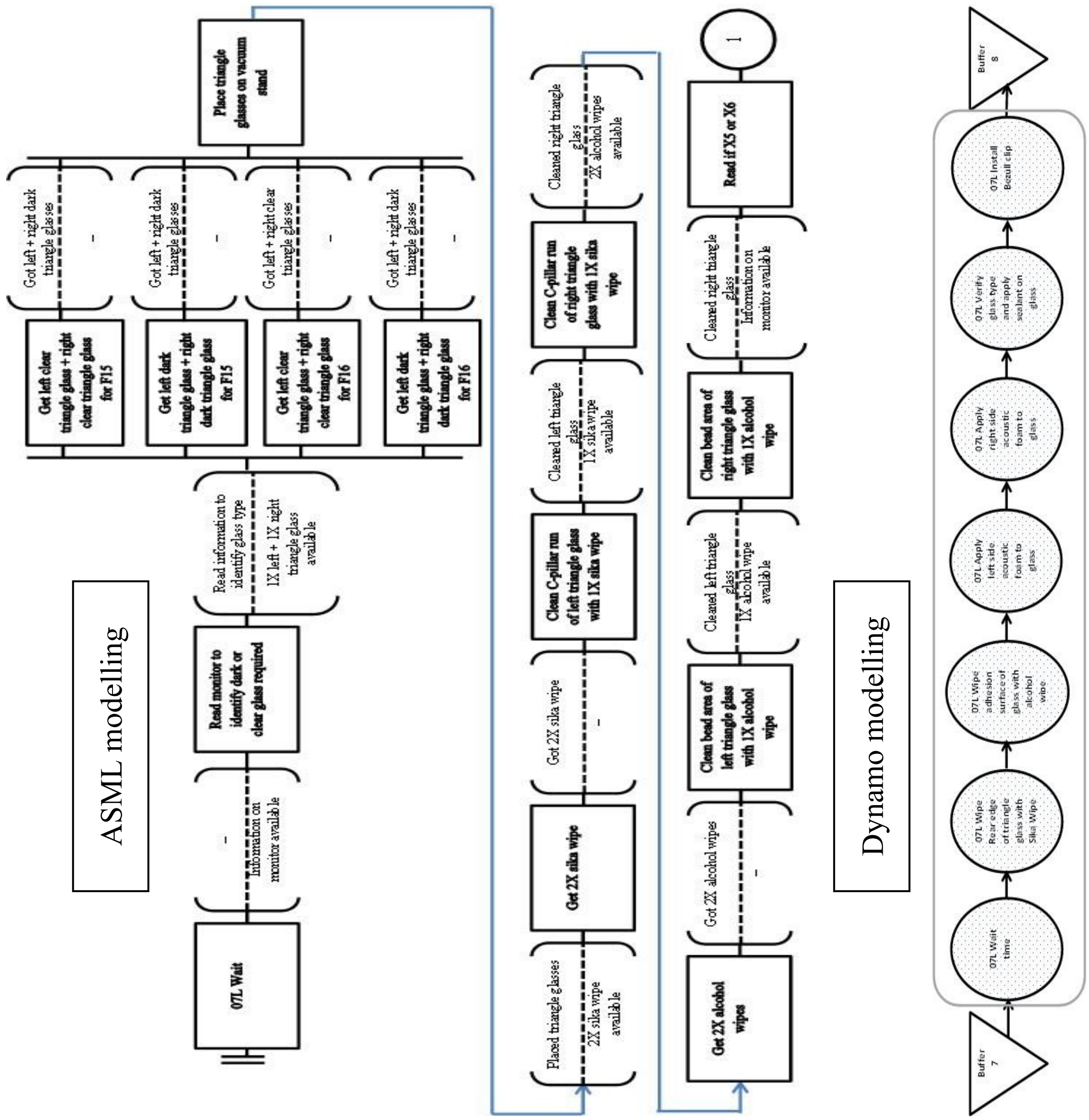

Figure 1: Comparison between ASML modelling and Dynamo modelling

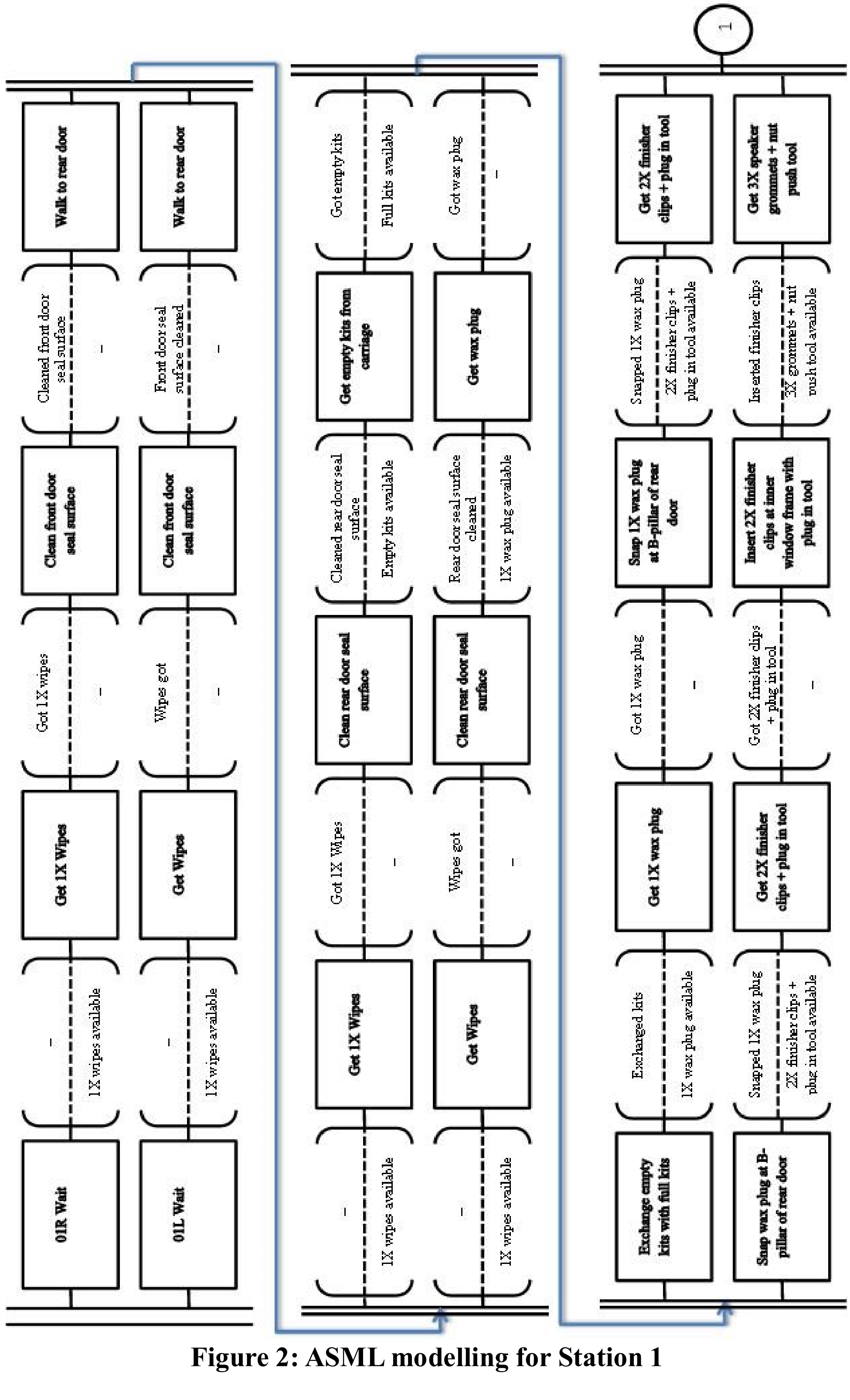

Figure 2: ASML modelling for Station 1

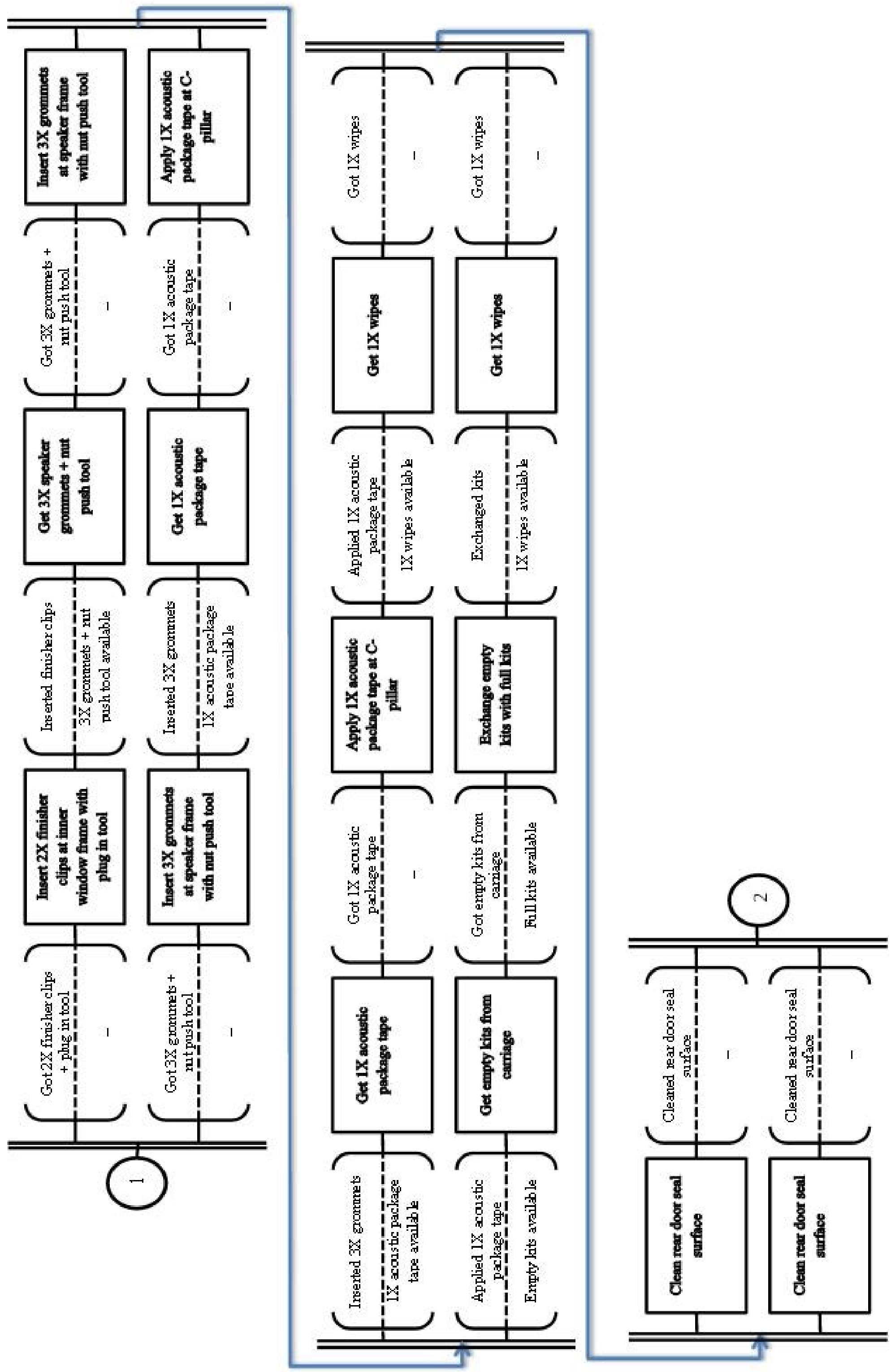

Figure 3: ASML modelling for Station 1 (Contd...)

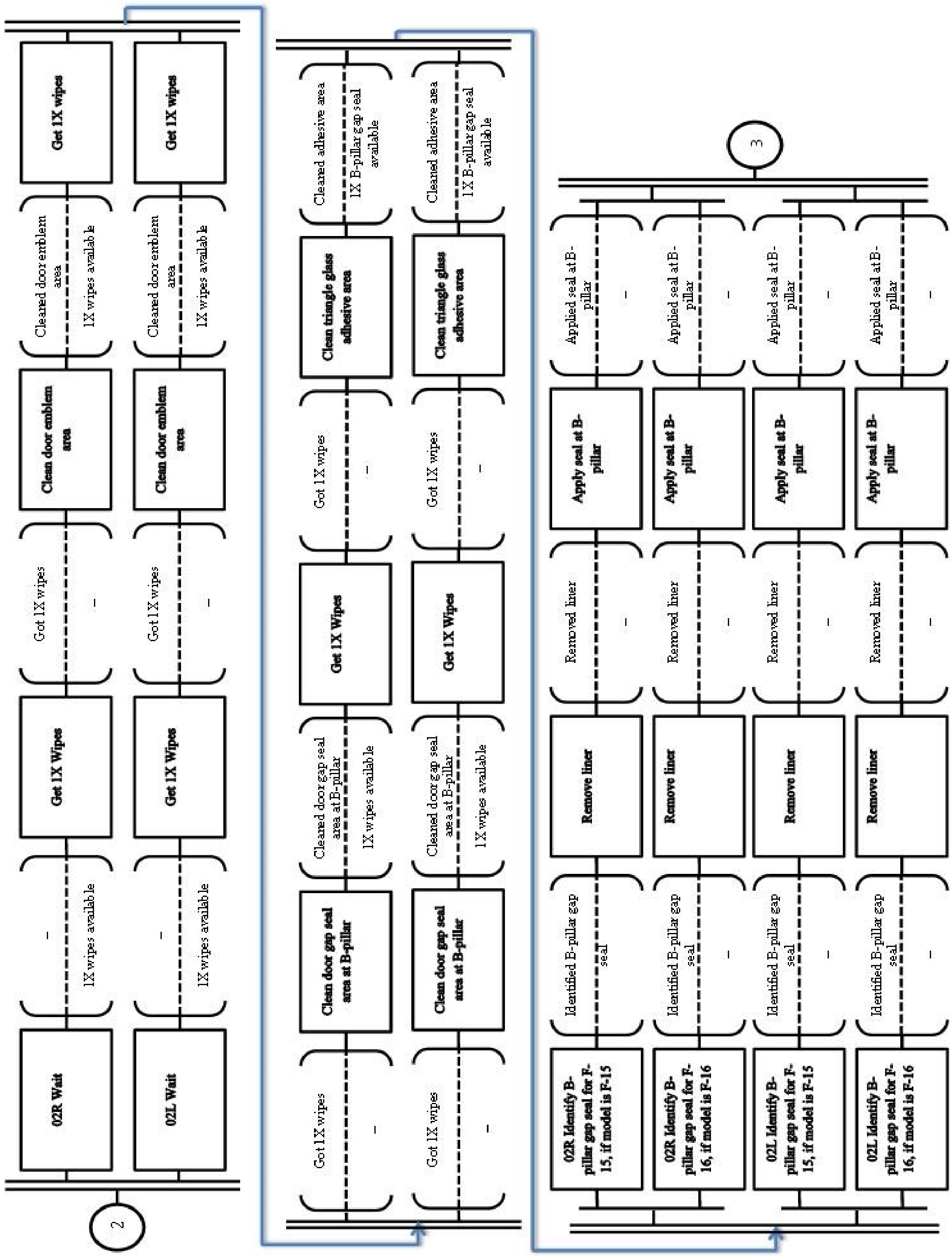

Figure 4: ASML modelling for Station 2

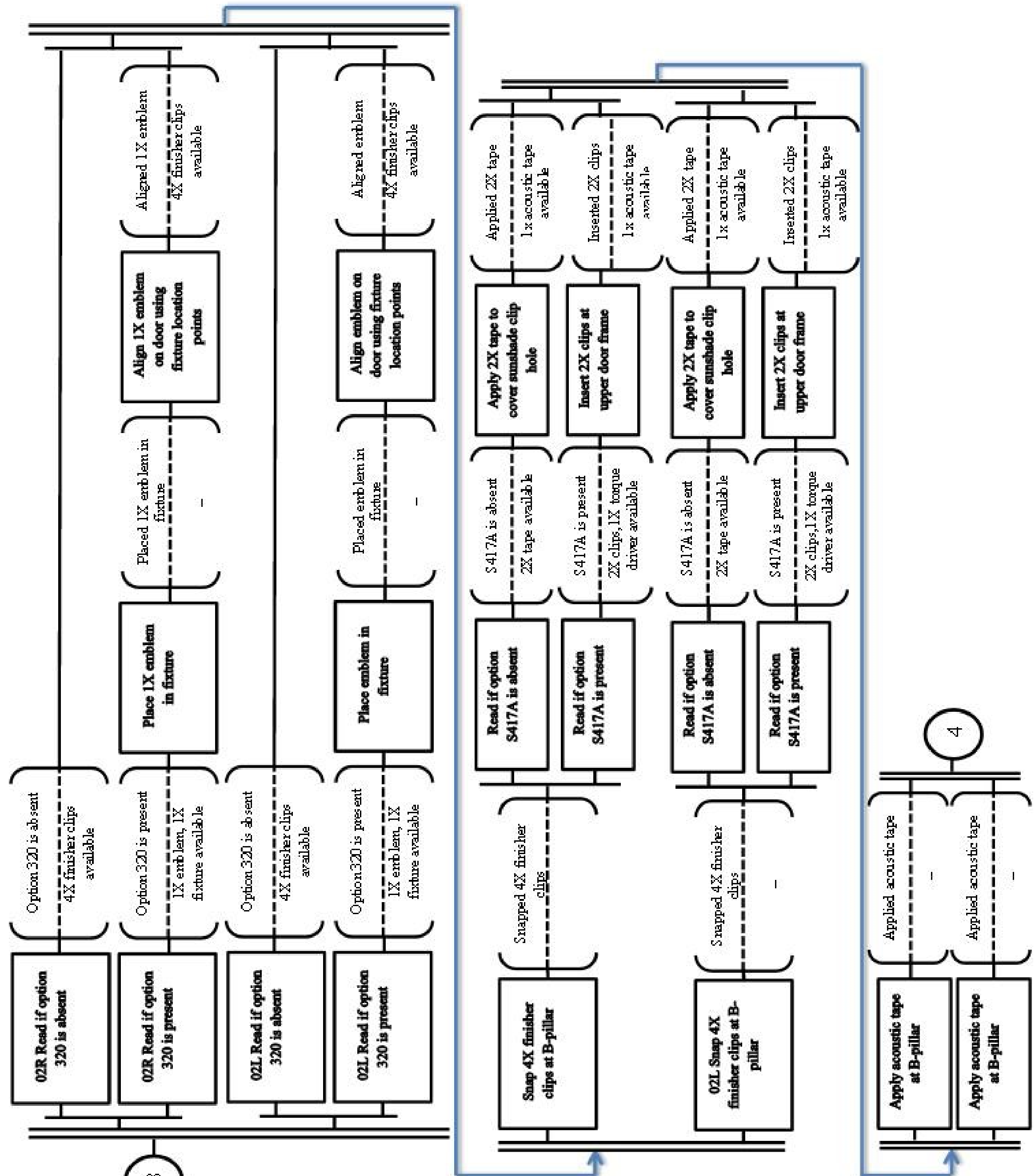

Figure 5: ASML modelling for Station 2 (Contd…)

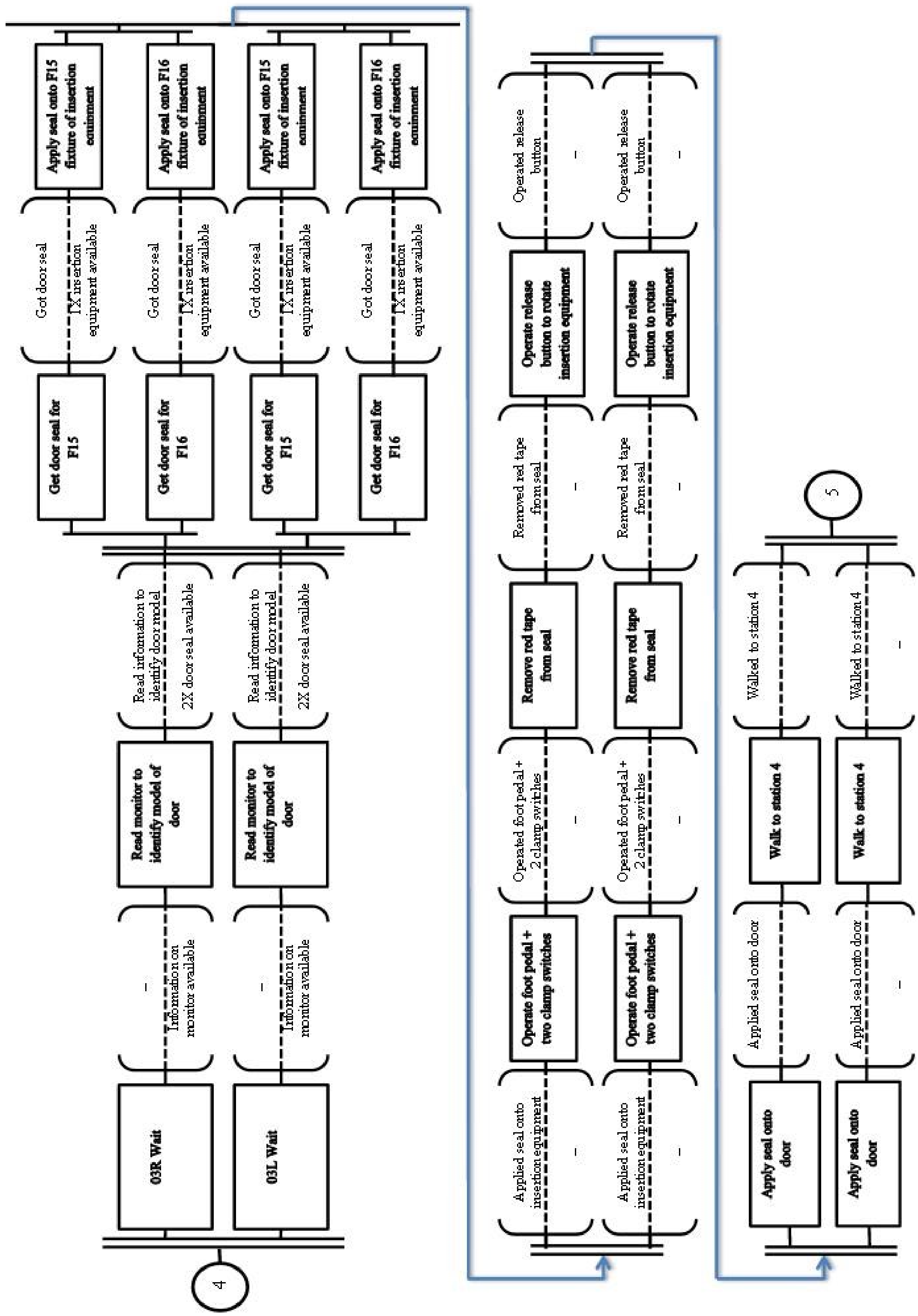

Figure 6: ASML modelling for Station 3

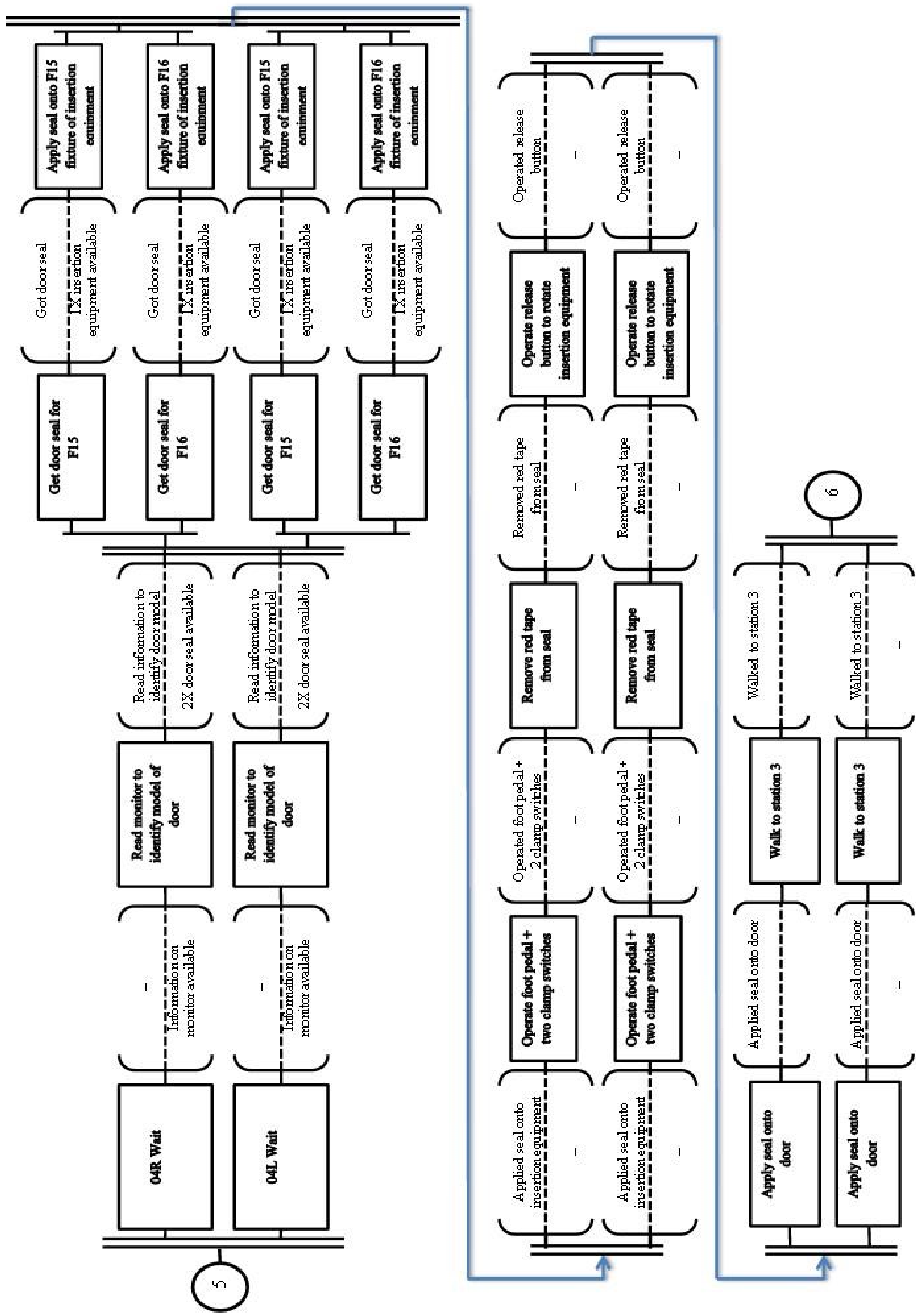

Figure 7: ASML modelling for Station 4

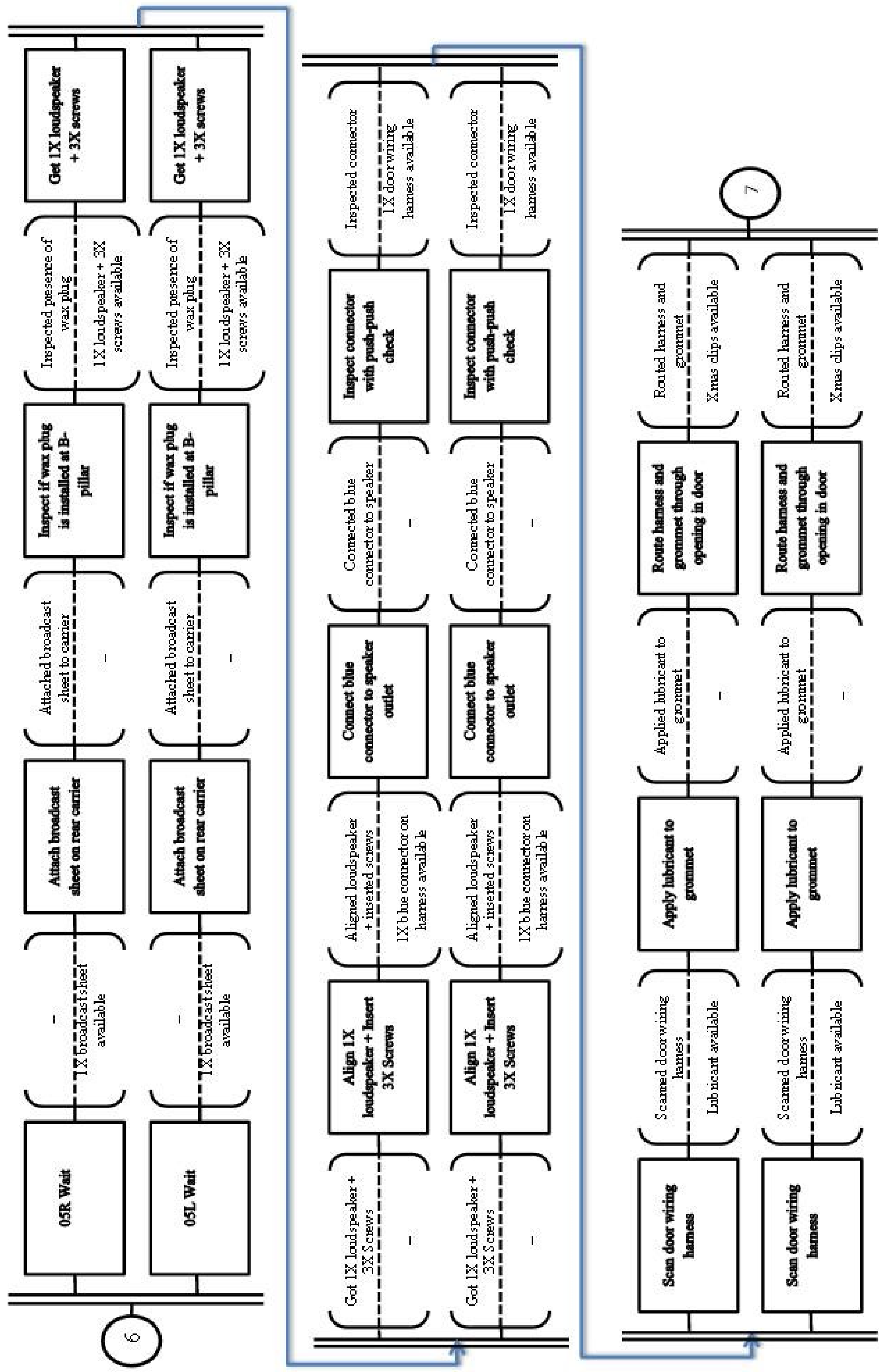

Figure 8: ASML modelling for station 5

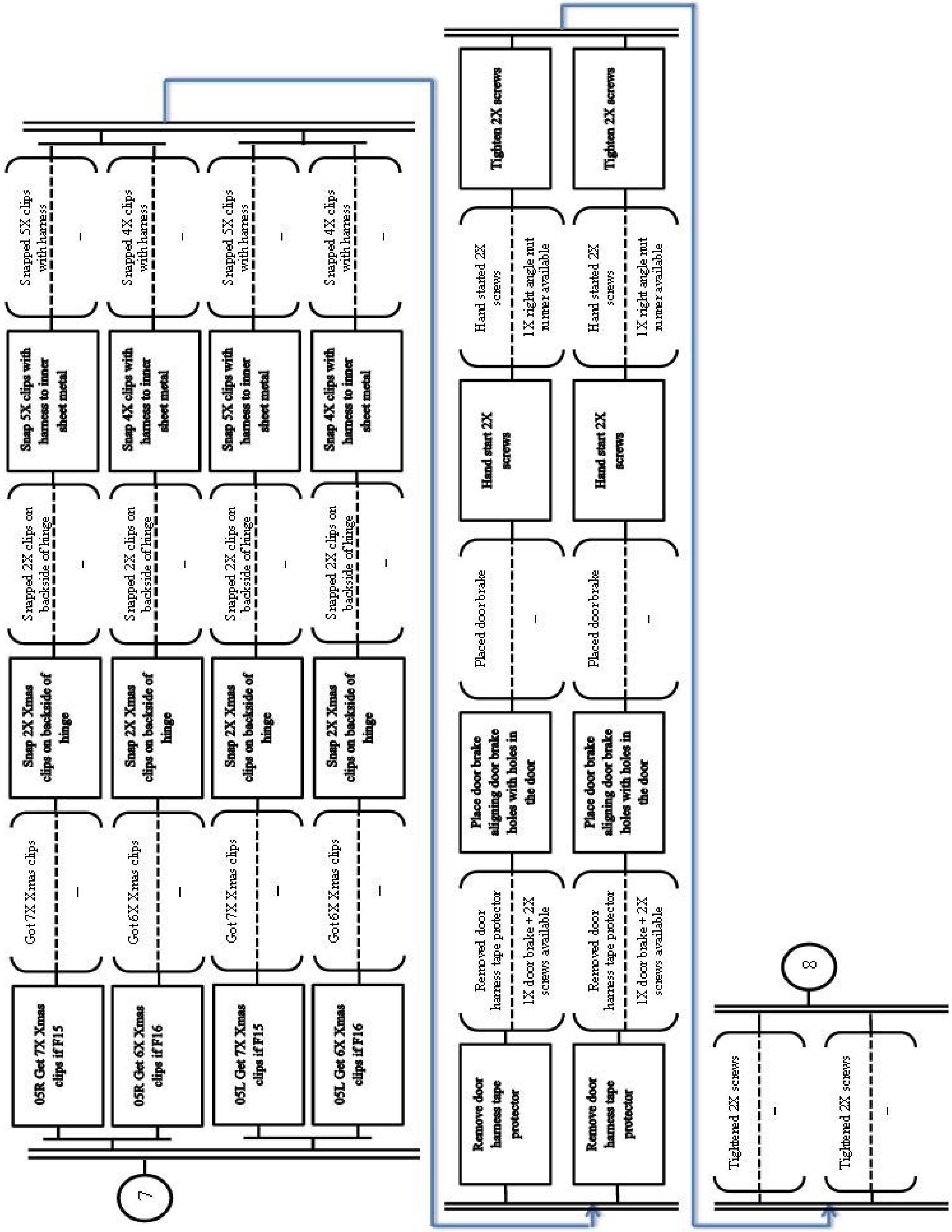

Figure 9: ASML modelling for Station 5 (Contd…)

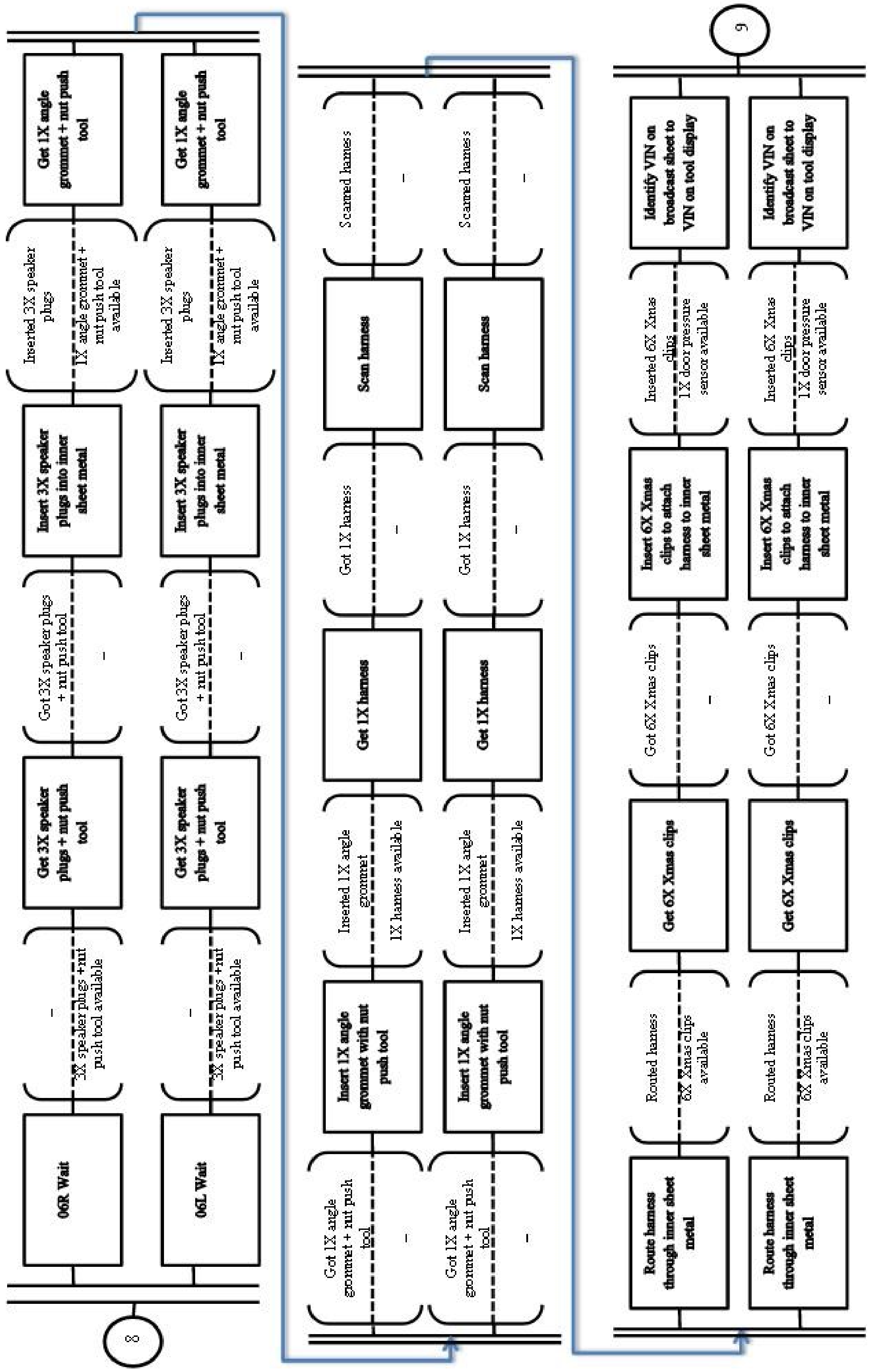

Figure 10: ASML modelling for Station 6

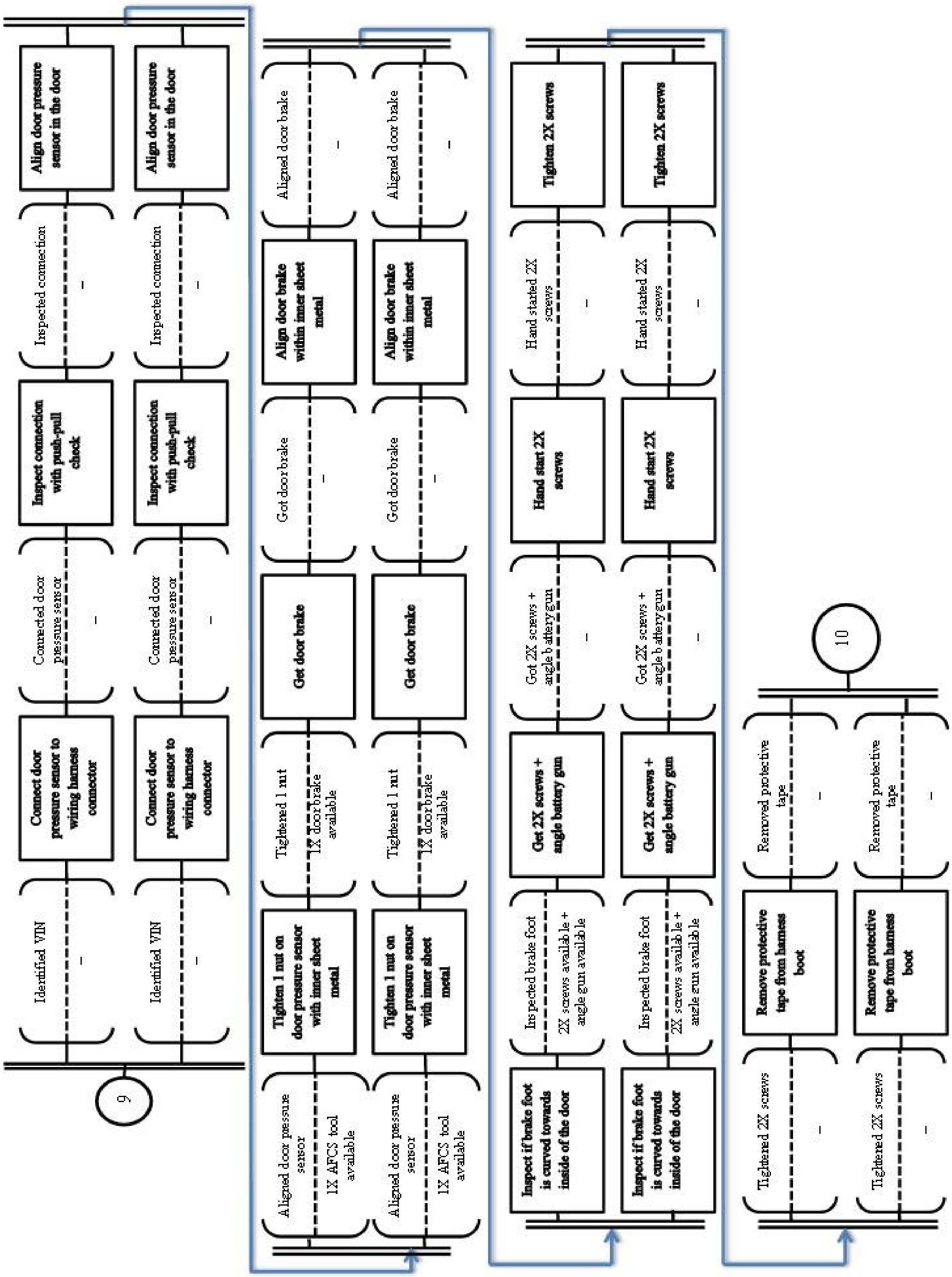

Figure 11: ASML modelling for Station 6 (Contd…)

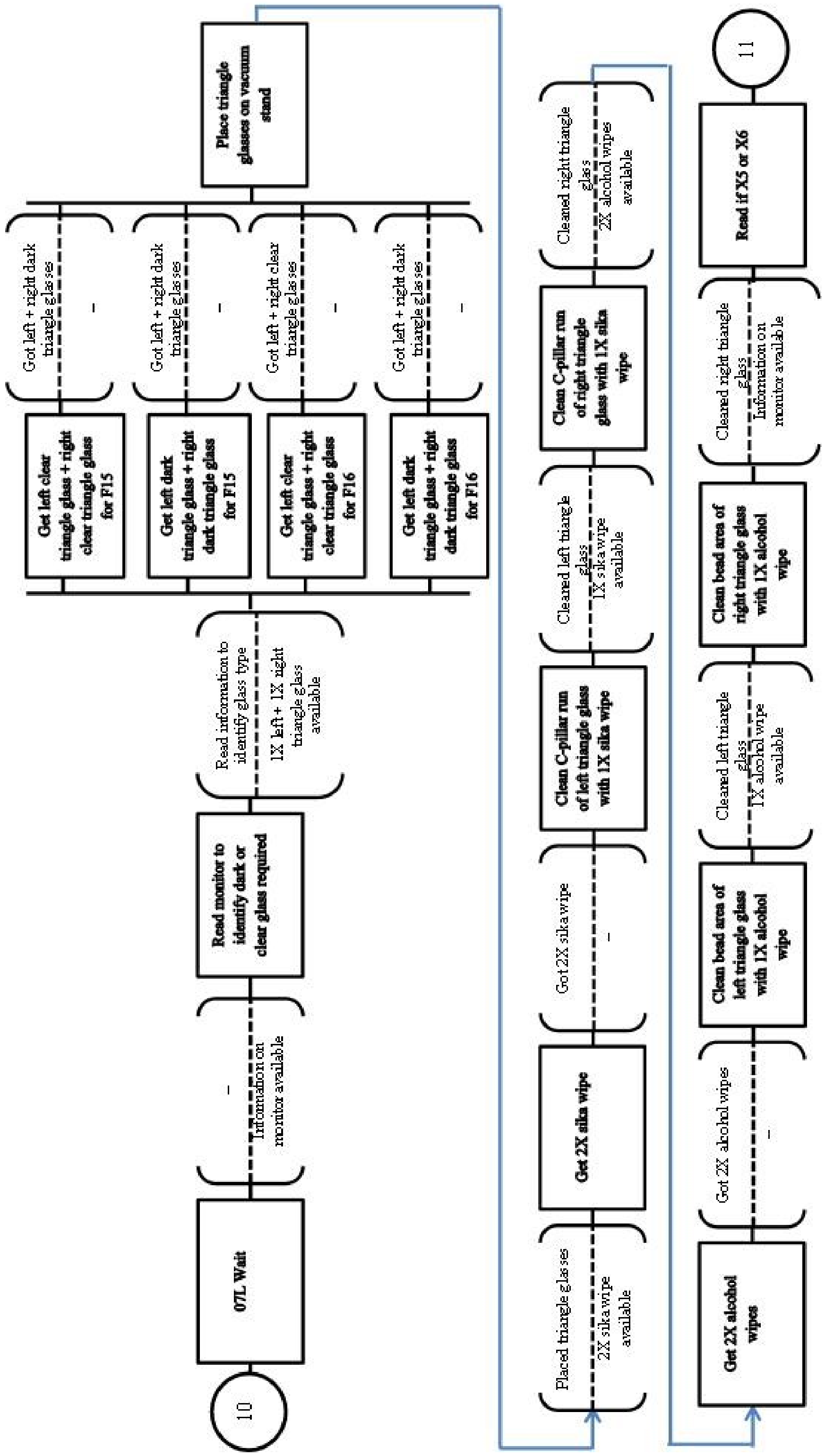

Figure 12: ASML modelling for Station 7

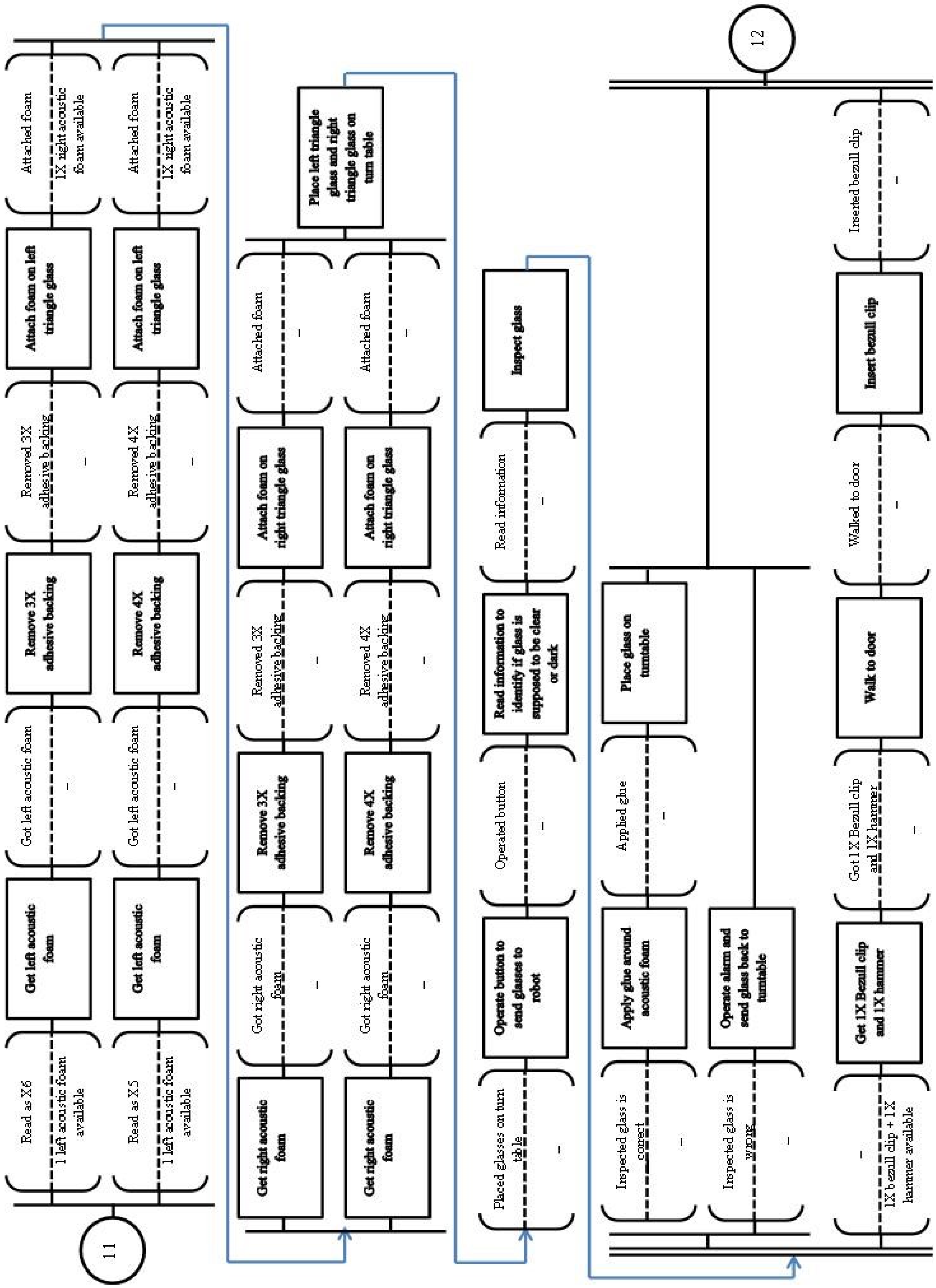

Figure 13: ASML for Station 7 (Contd…)

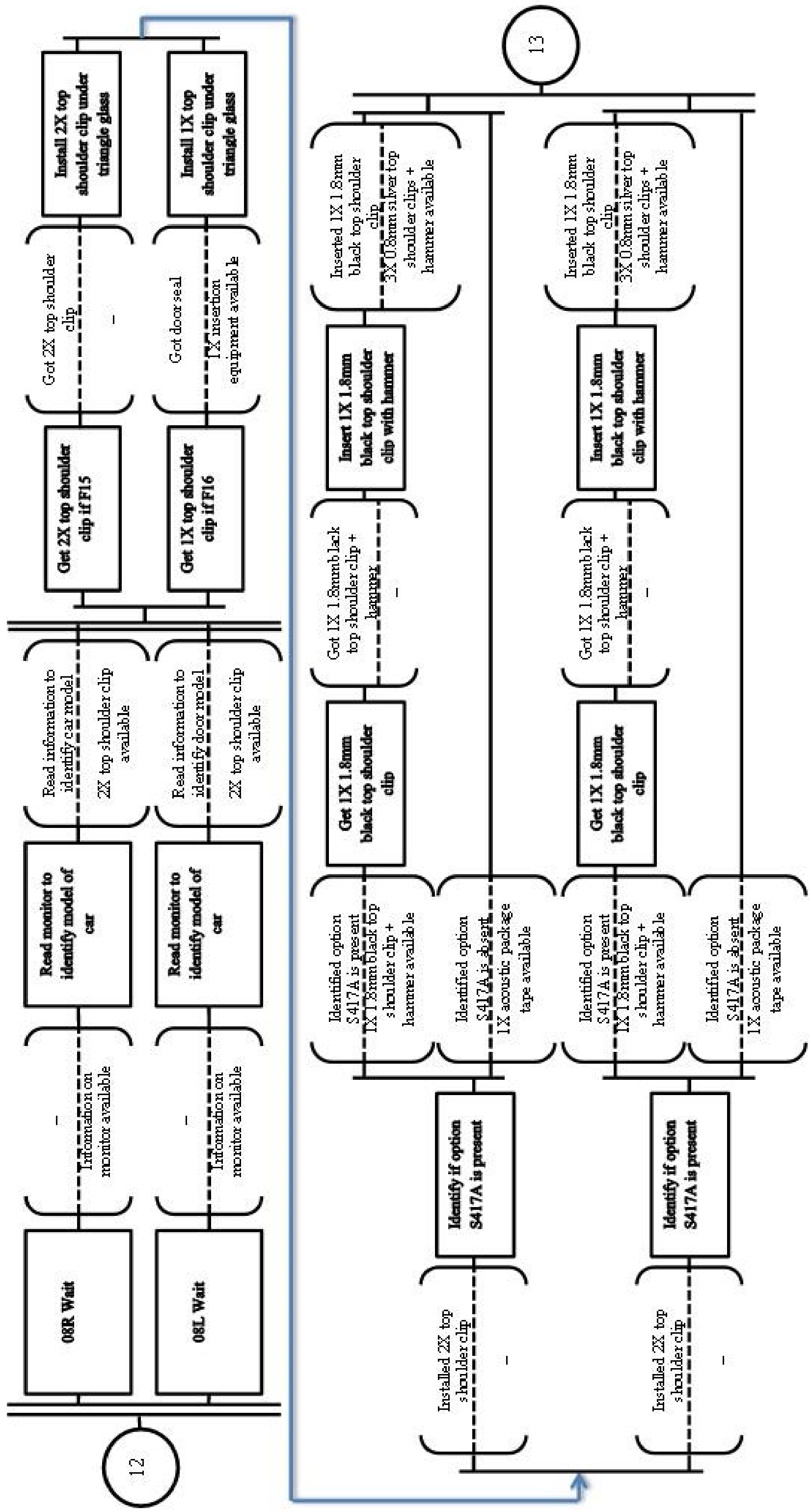

Figure 14: ASML modelling for Station 8

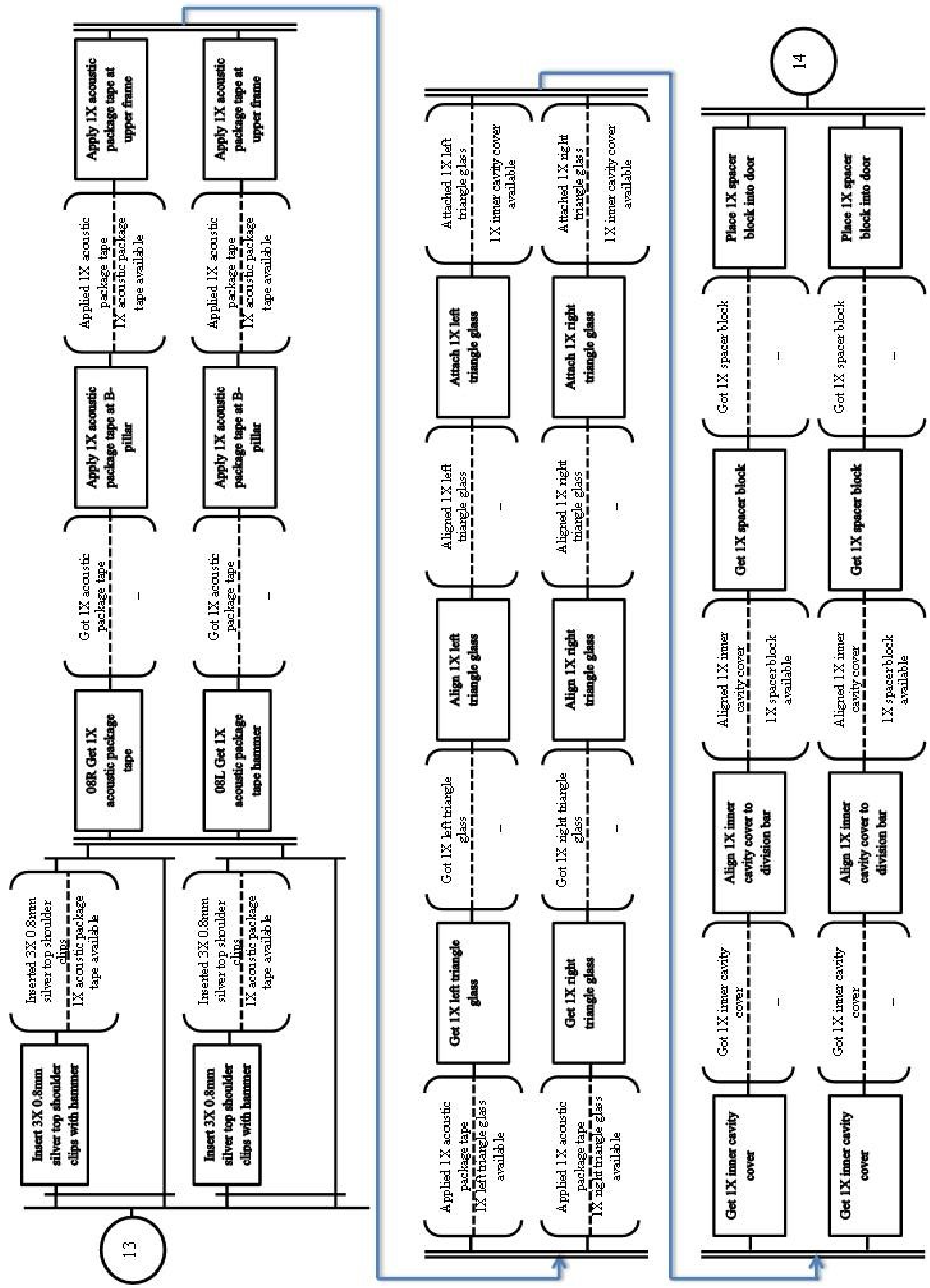

Figure 15: ASML modelling for Station 8 (Contd…)

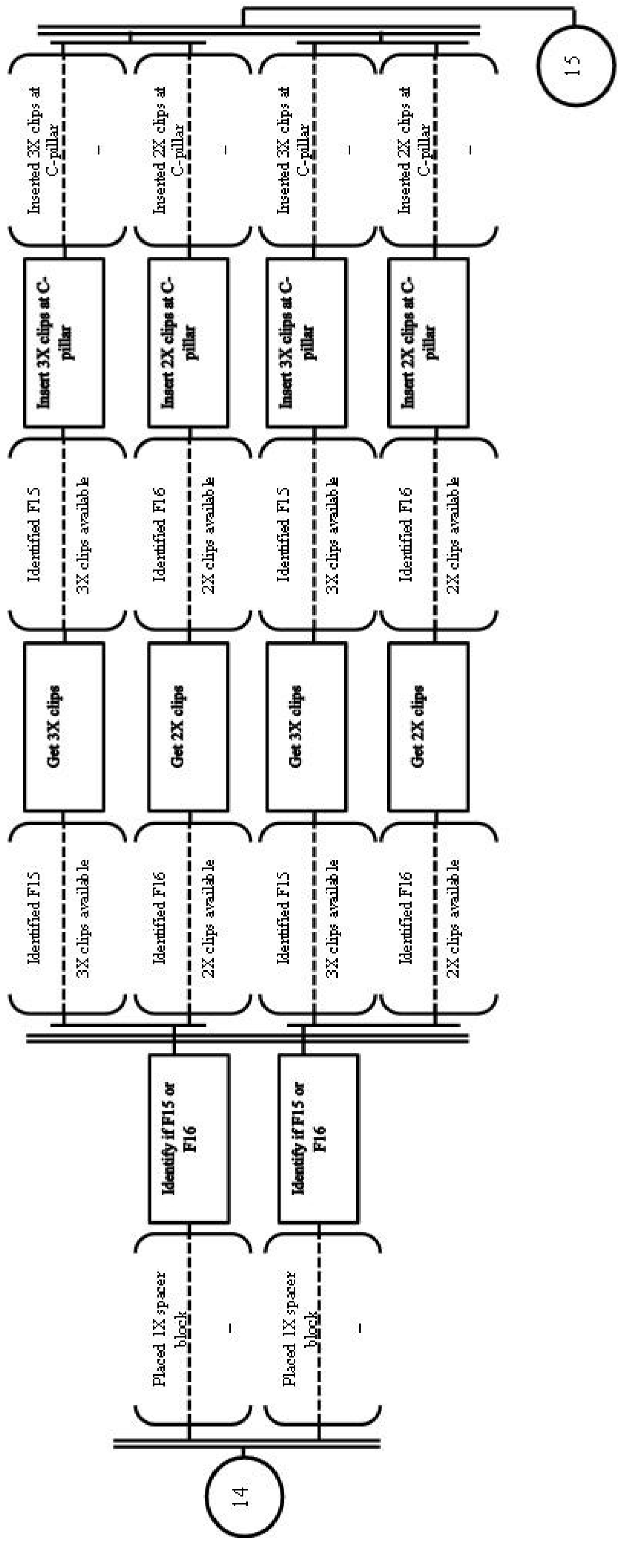

Figure 16: ASML modelling for Station 8 (Contd…)

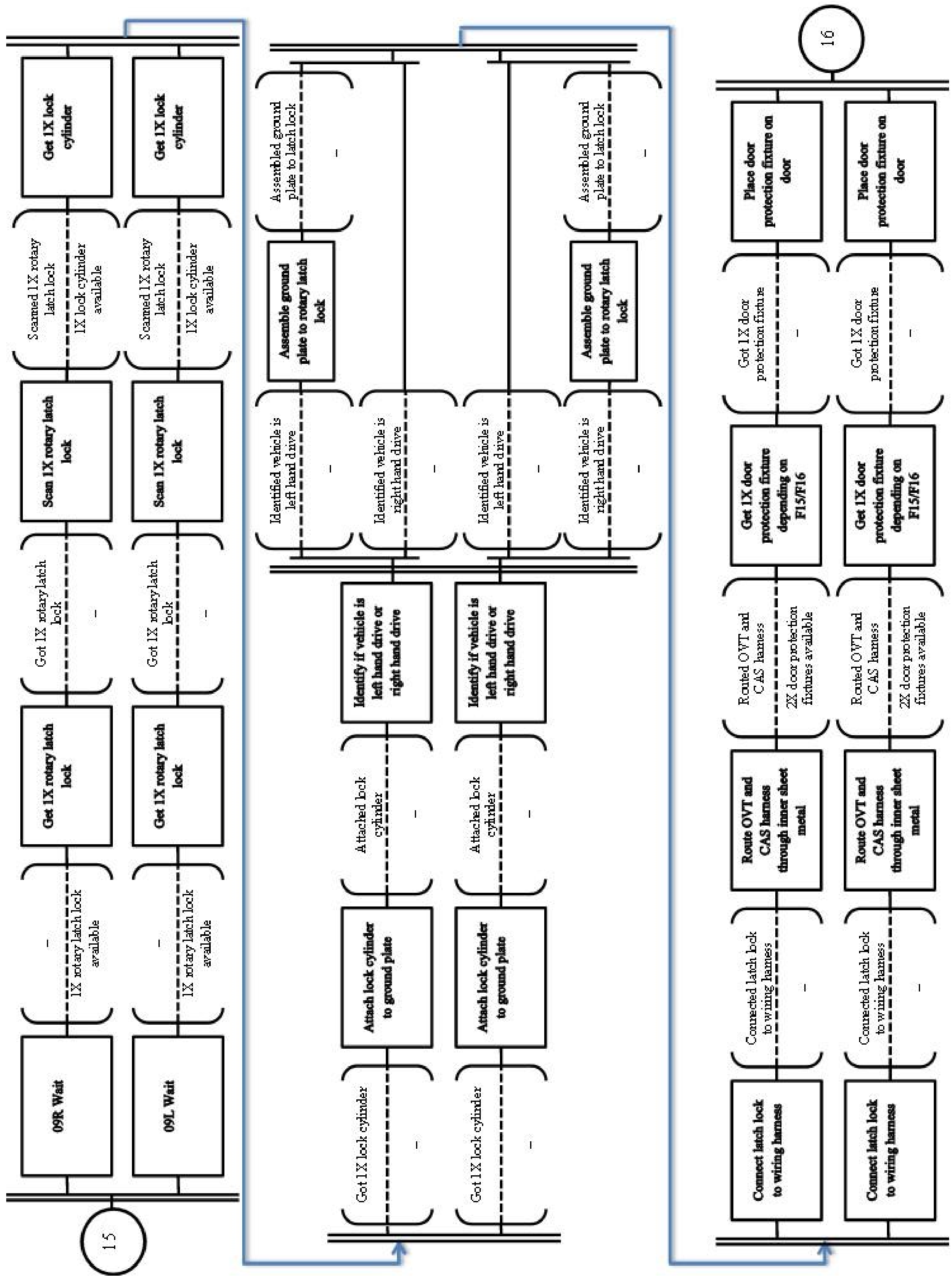

Figure 17: ASML modelling for Station 9

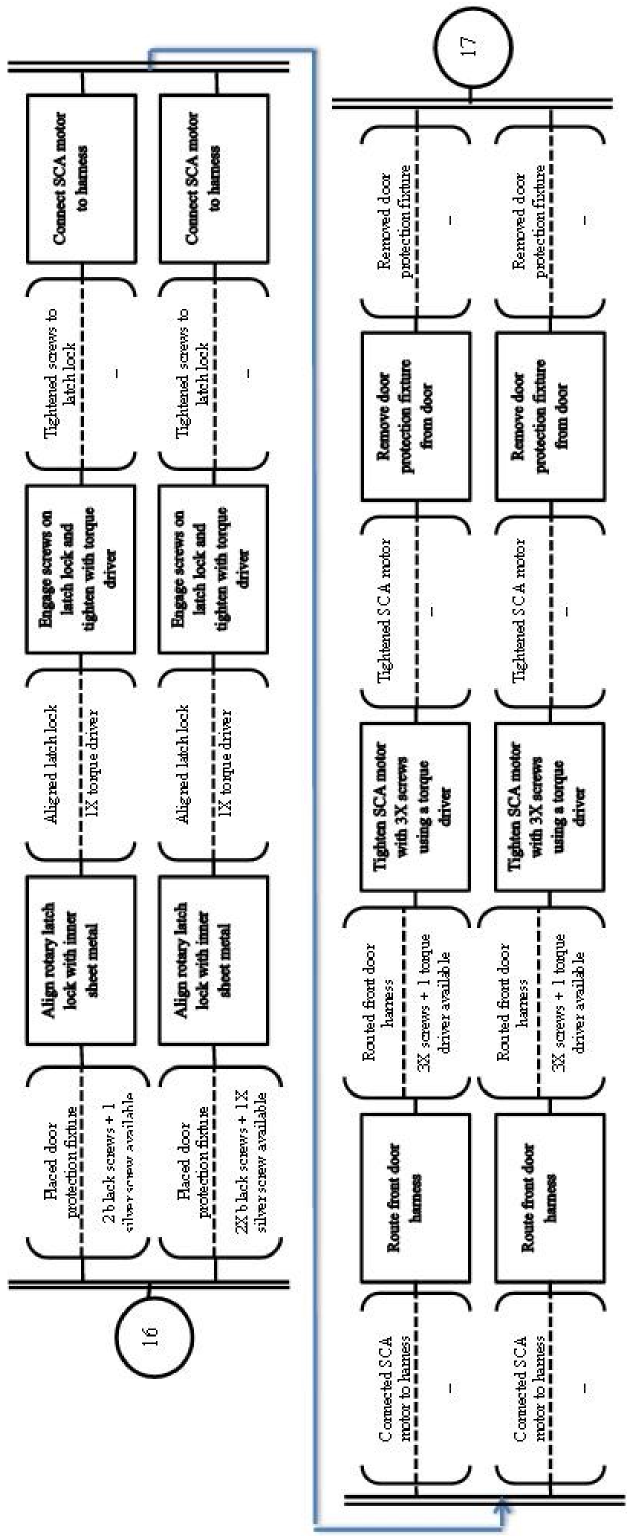

Figure 18: ASML modelling for Station 9 (Contd…)

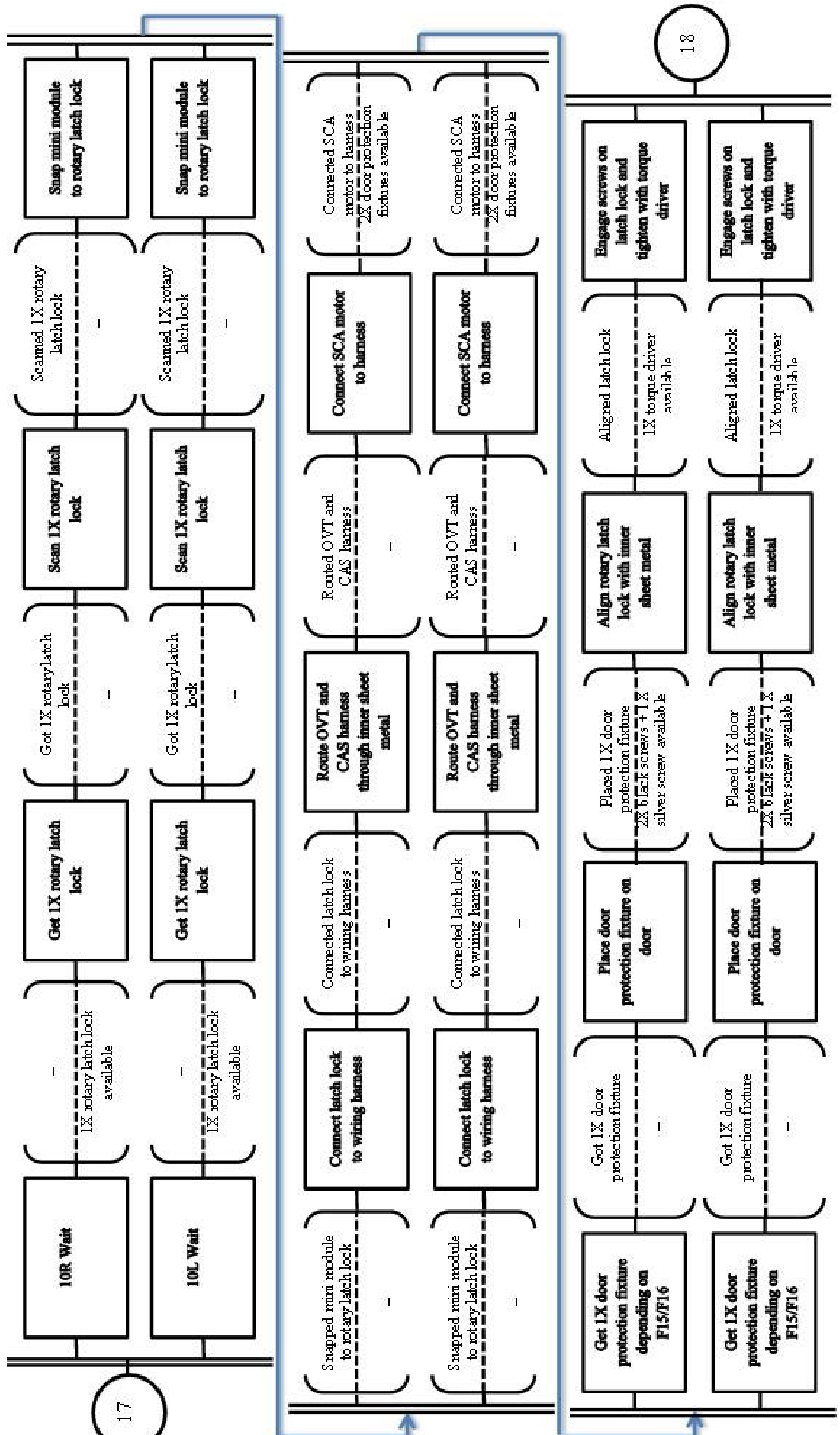

Figure 19: ASML modelling for Station 10

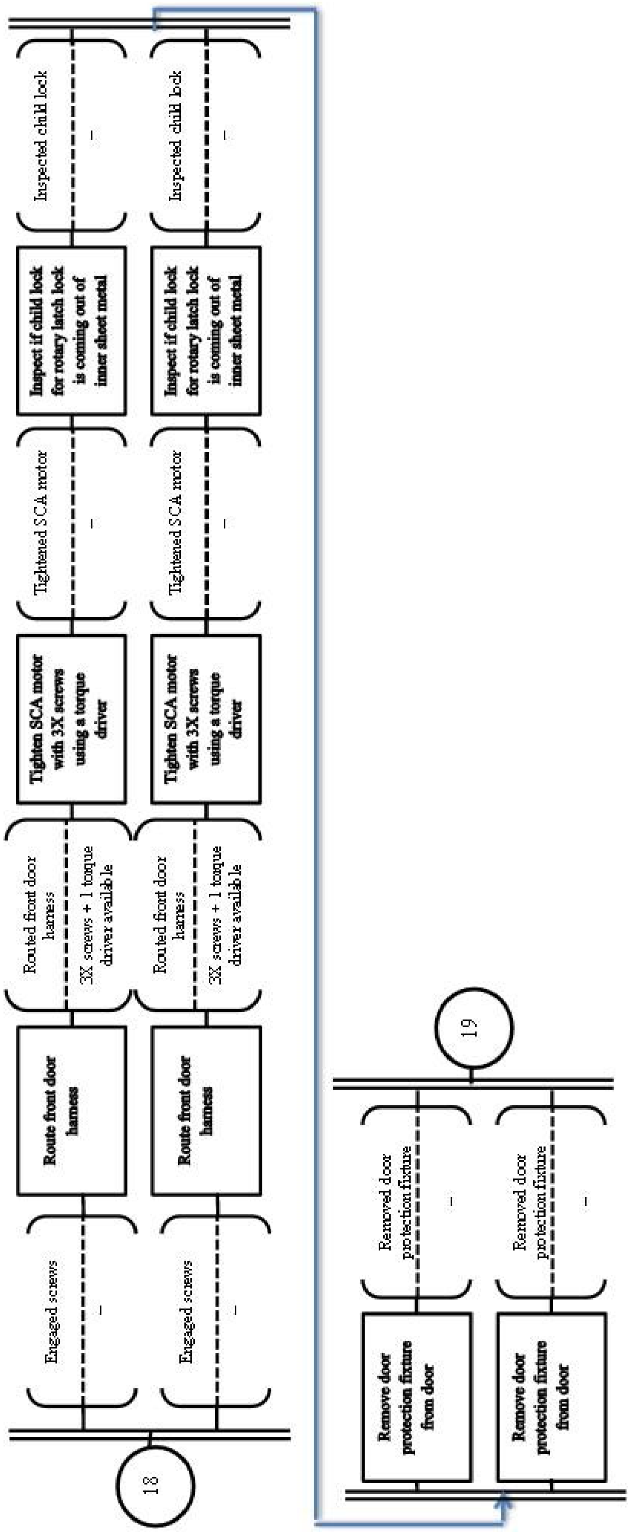

Figure 20: ASML modelling for Station 10 (Contd…)

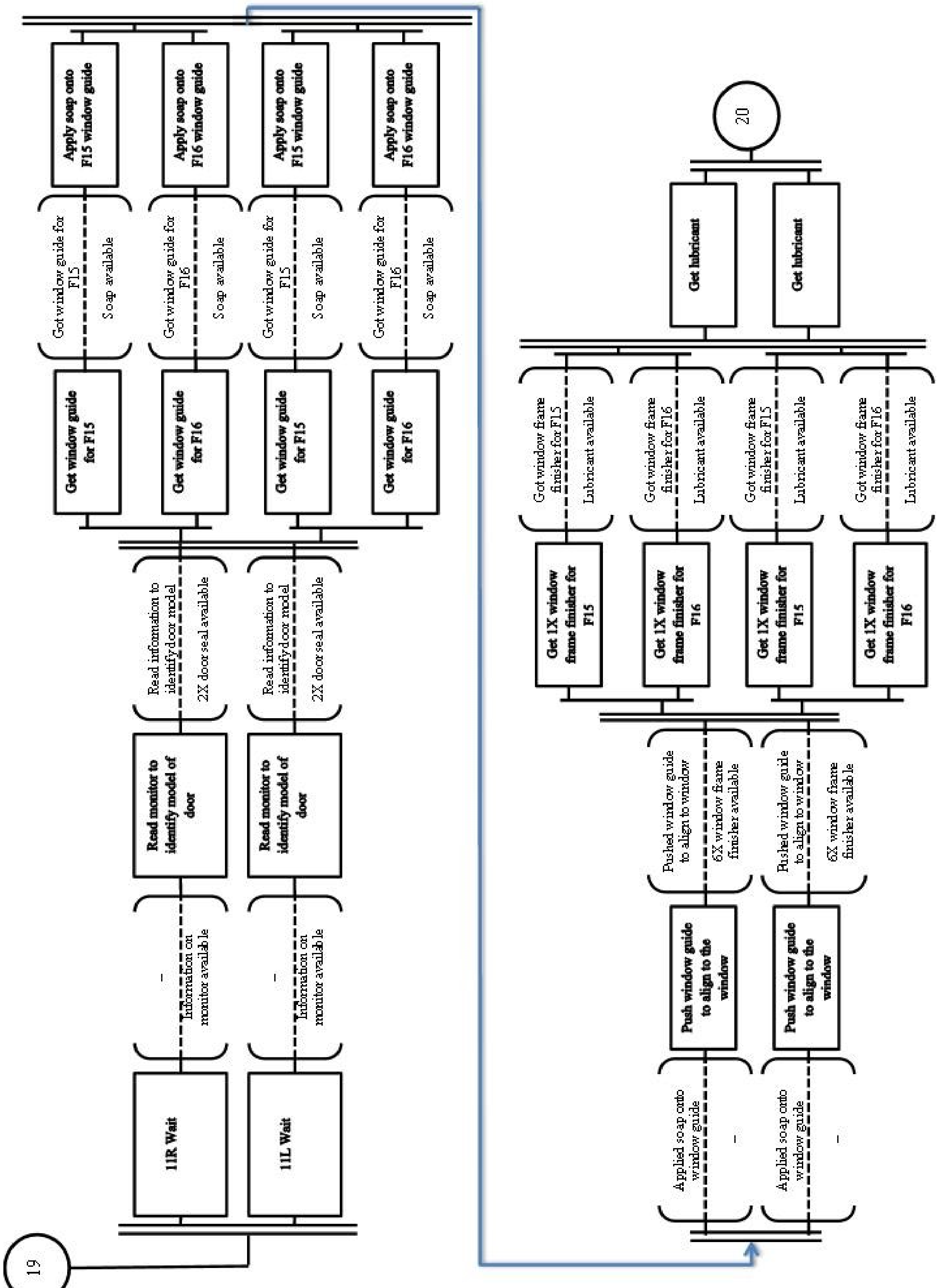

Figure 21: ASML modelling for Station 11

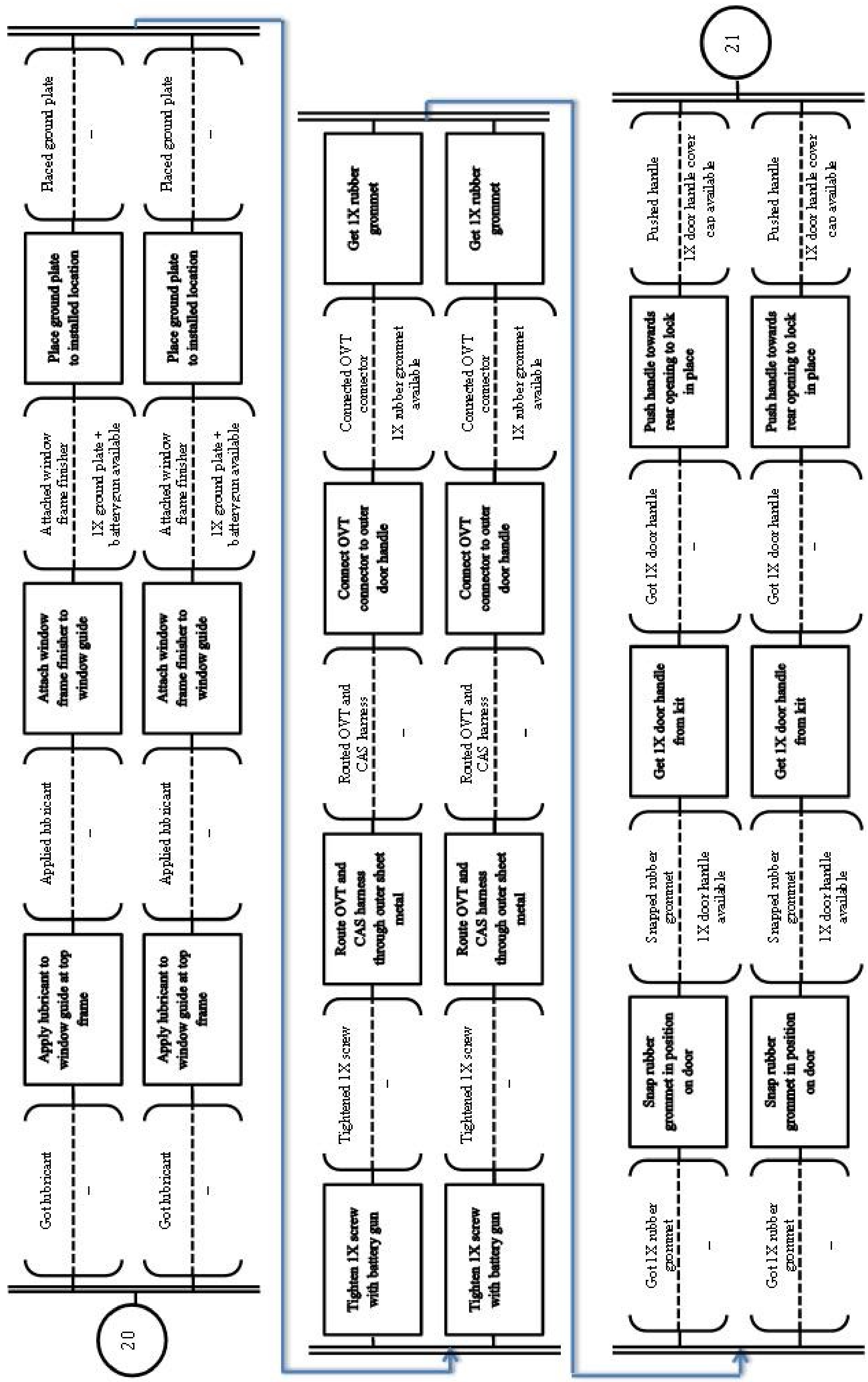

Figure 22: ASML modelling for Station 11 (Contd…)

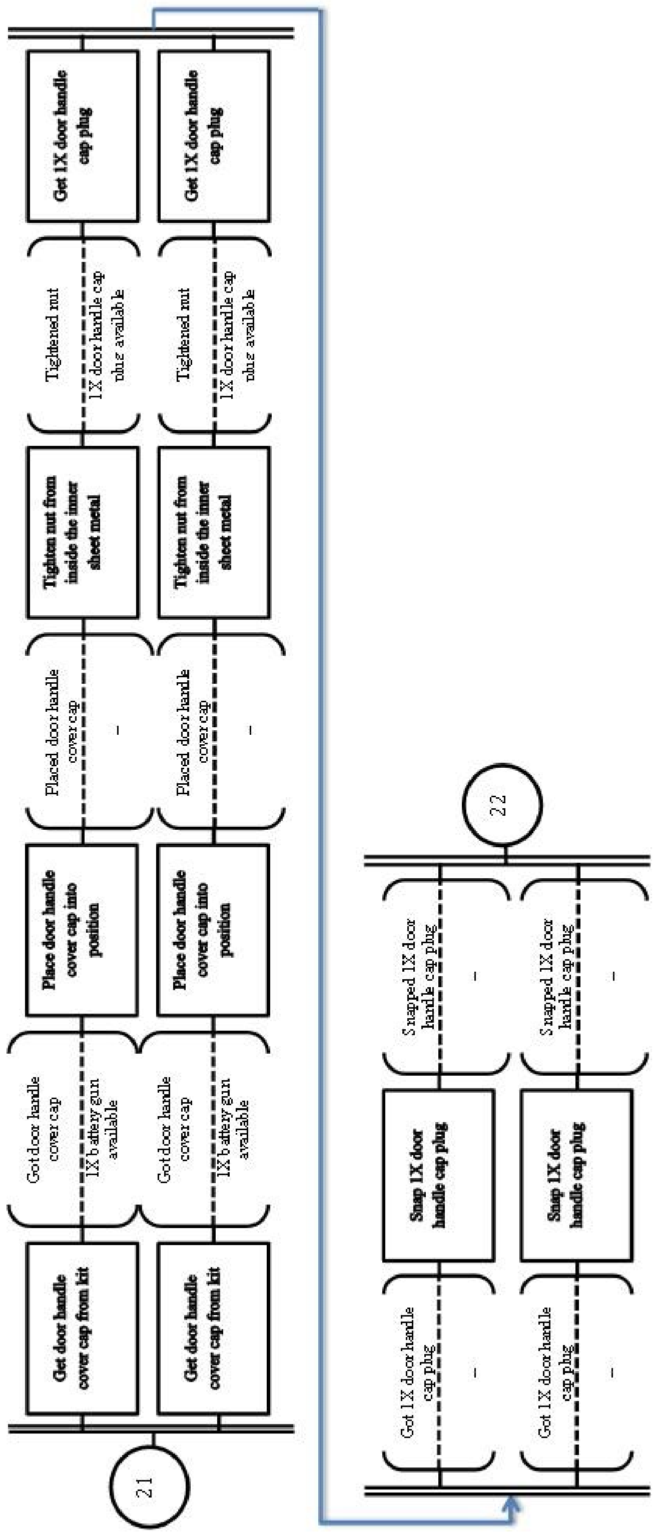

Figure 23: ASML modelling for Station 11 (Contd…)

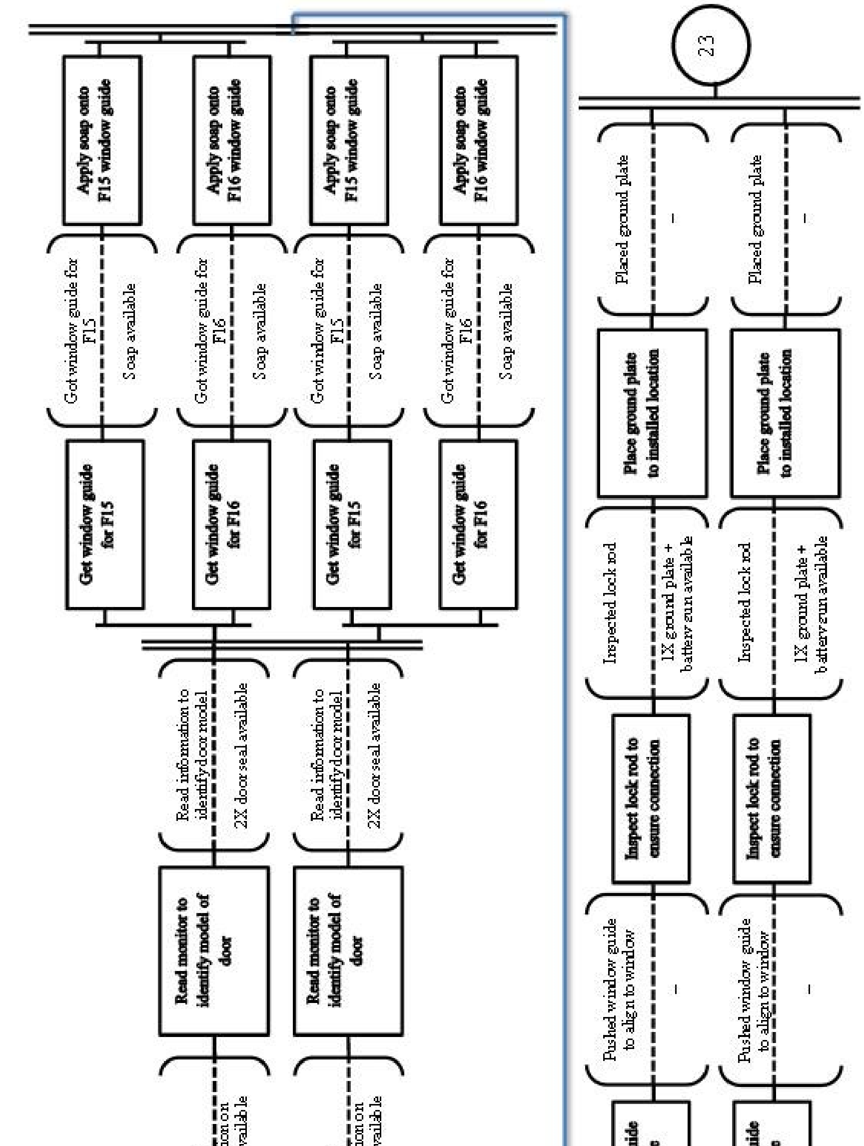

Figure 24: ASML modelling for Station 12

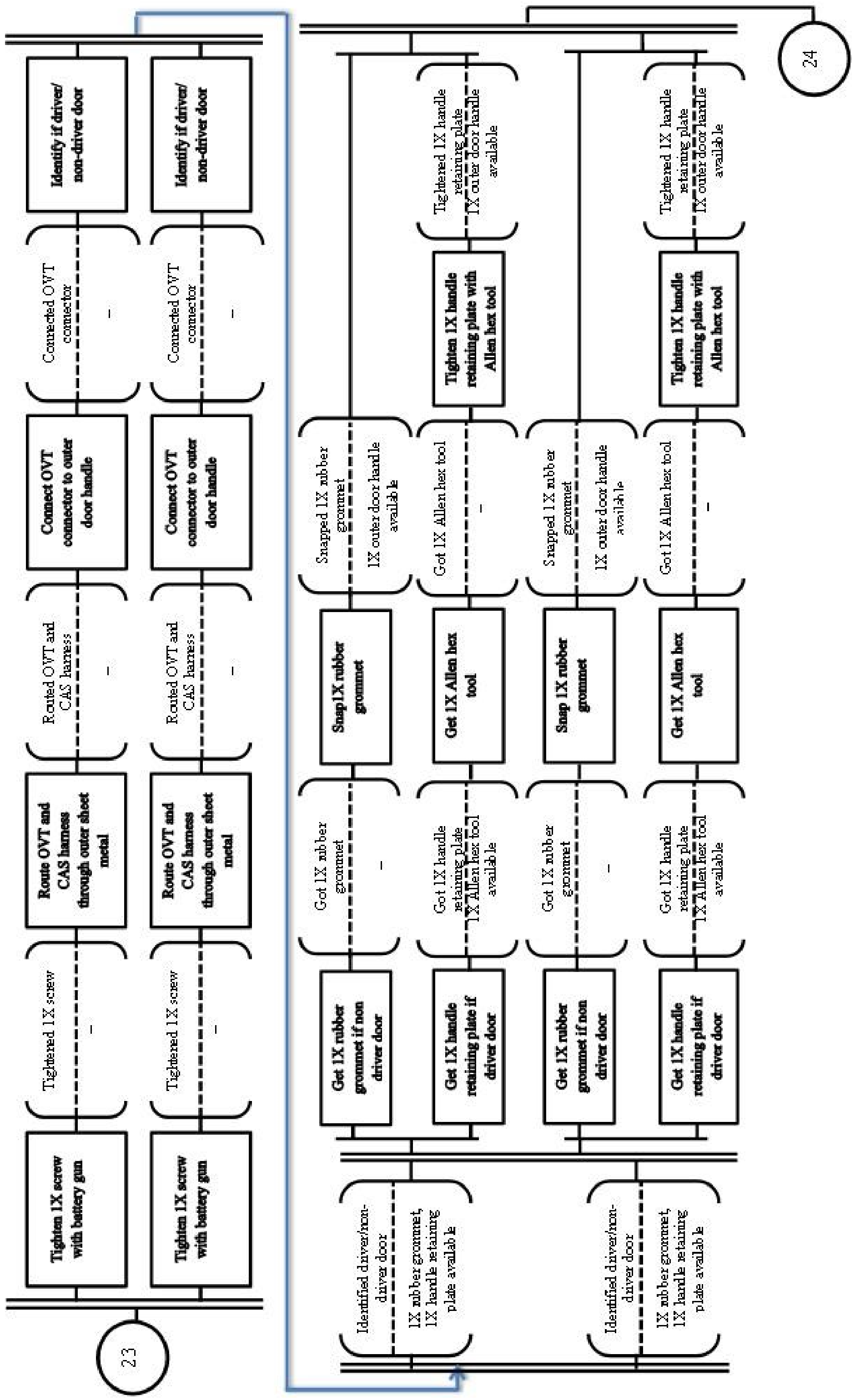

Figure 25: ASML modelling for Station 12 (Contd…)

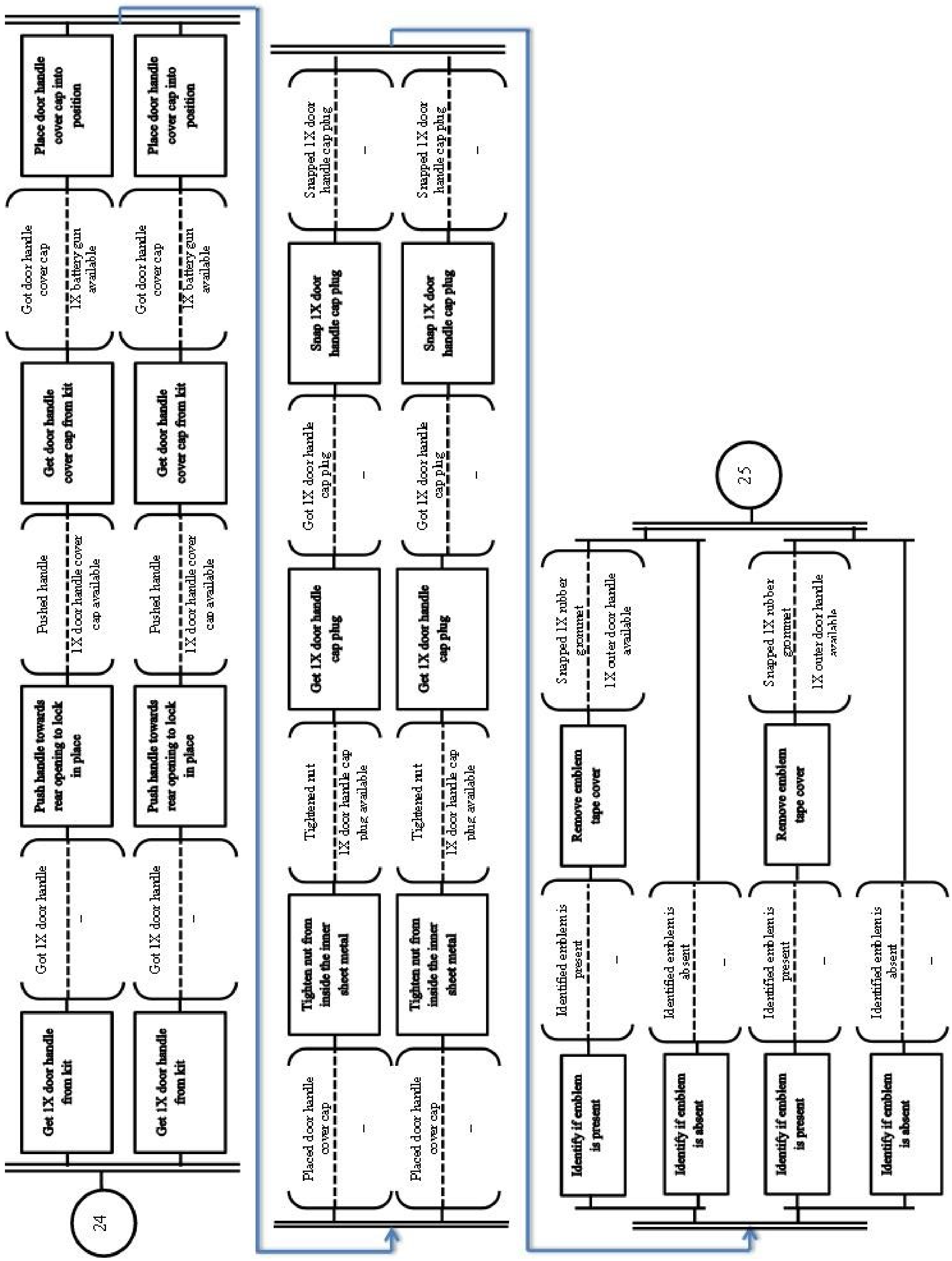

Figure 25: ASML modelling for Station 12 (Contd…)

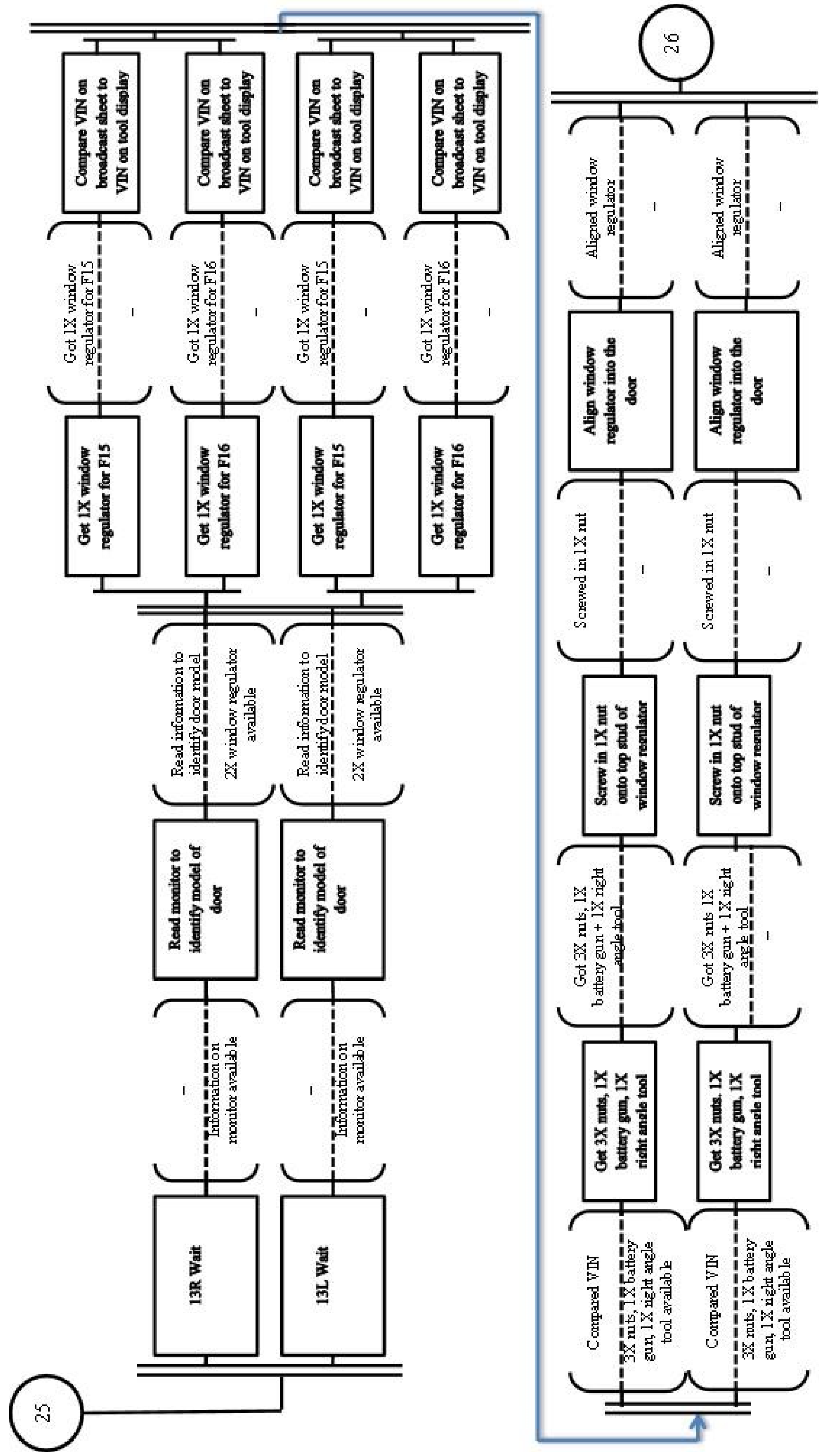

Figure 26: ASML modelling for Station 13

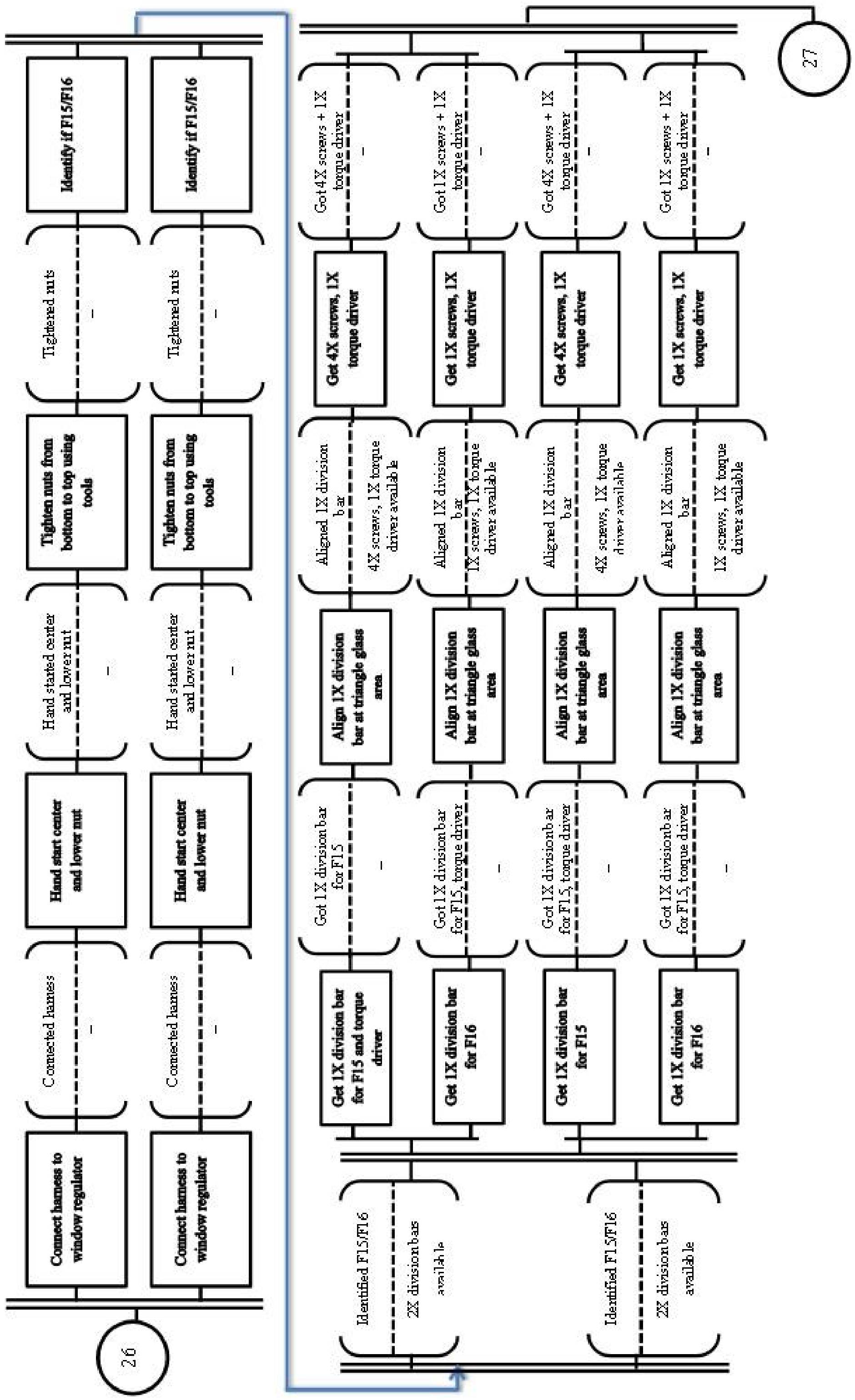

Figure 26: ASML modelling for Station 13 (Contd…)

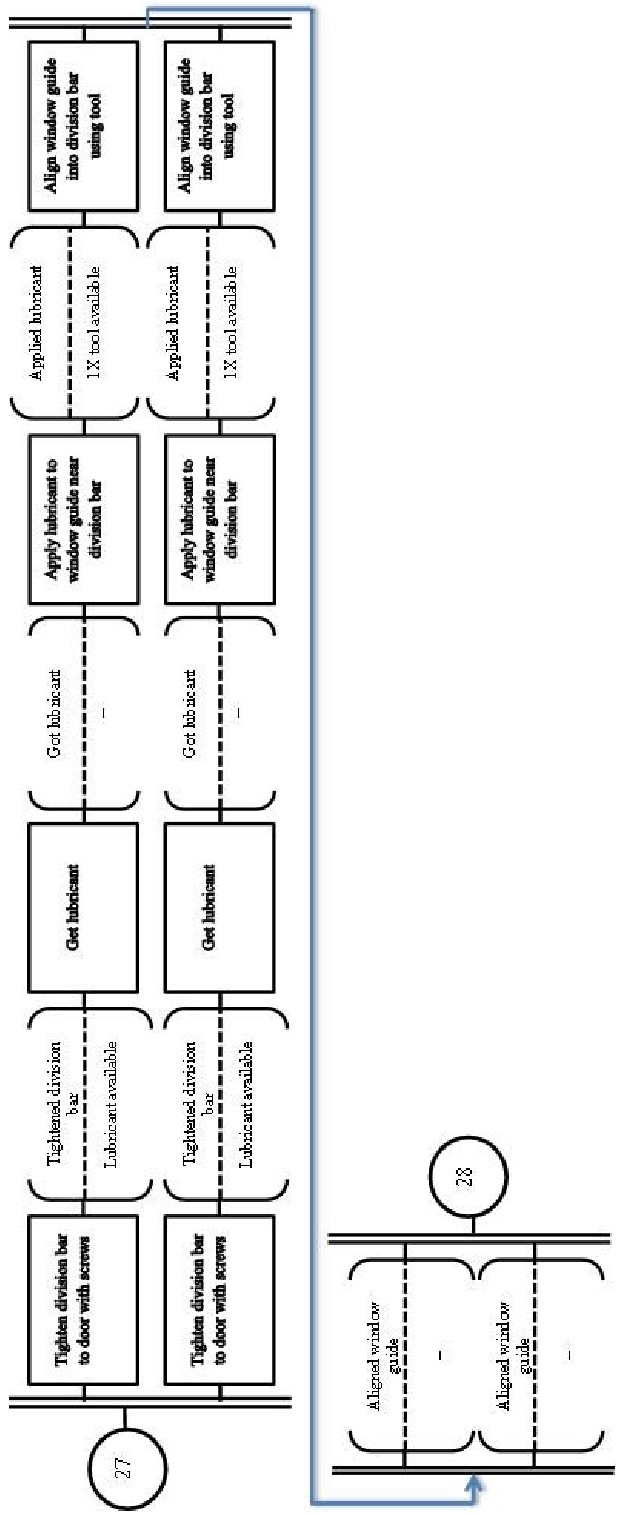

Figure 27: ASML modelling for Station 13 (Contd…)

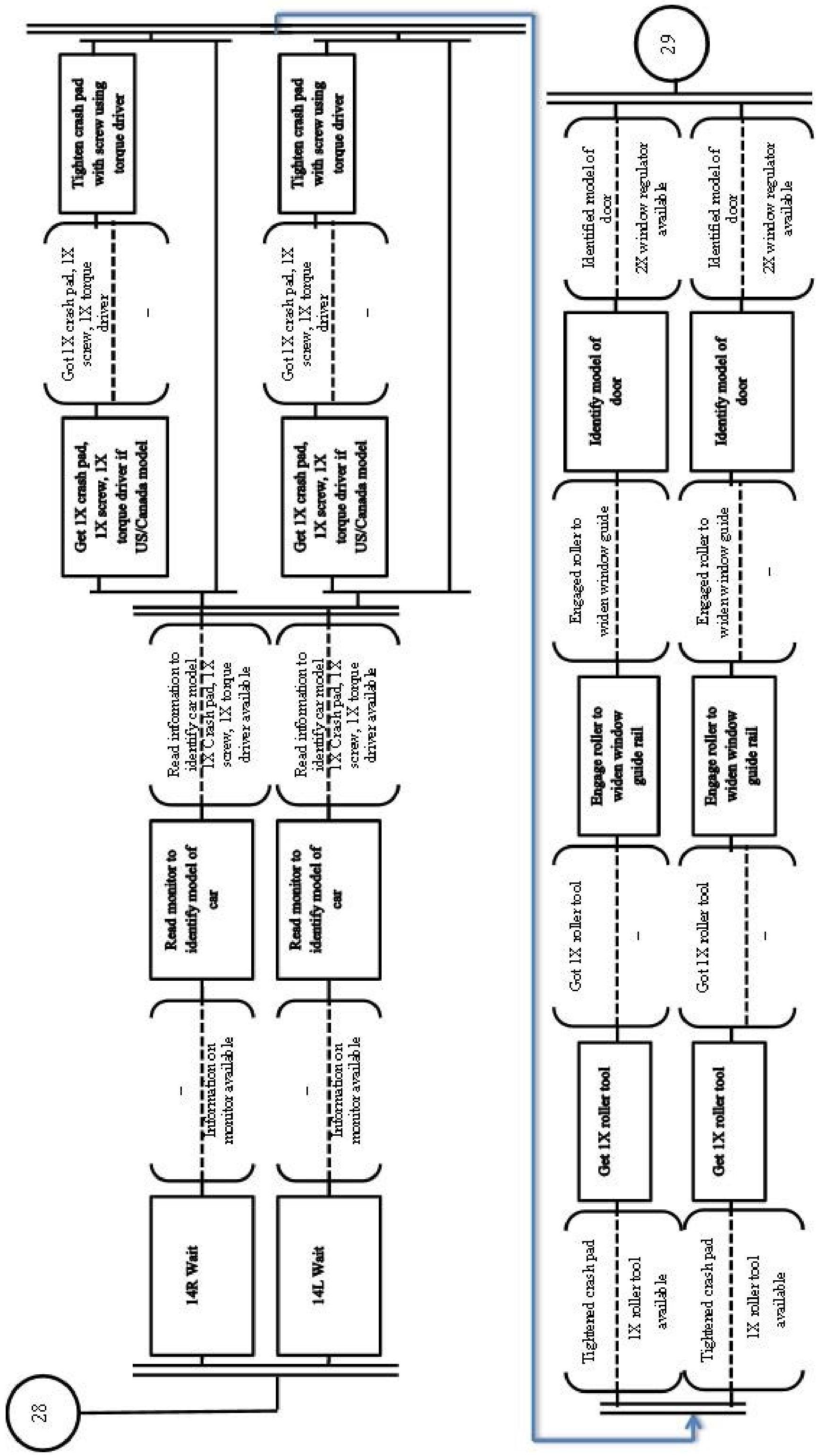

Figure 28: ASML modelling for Station 14

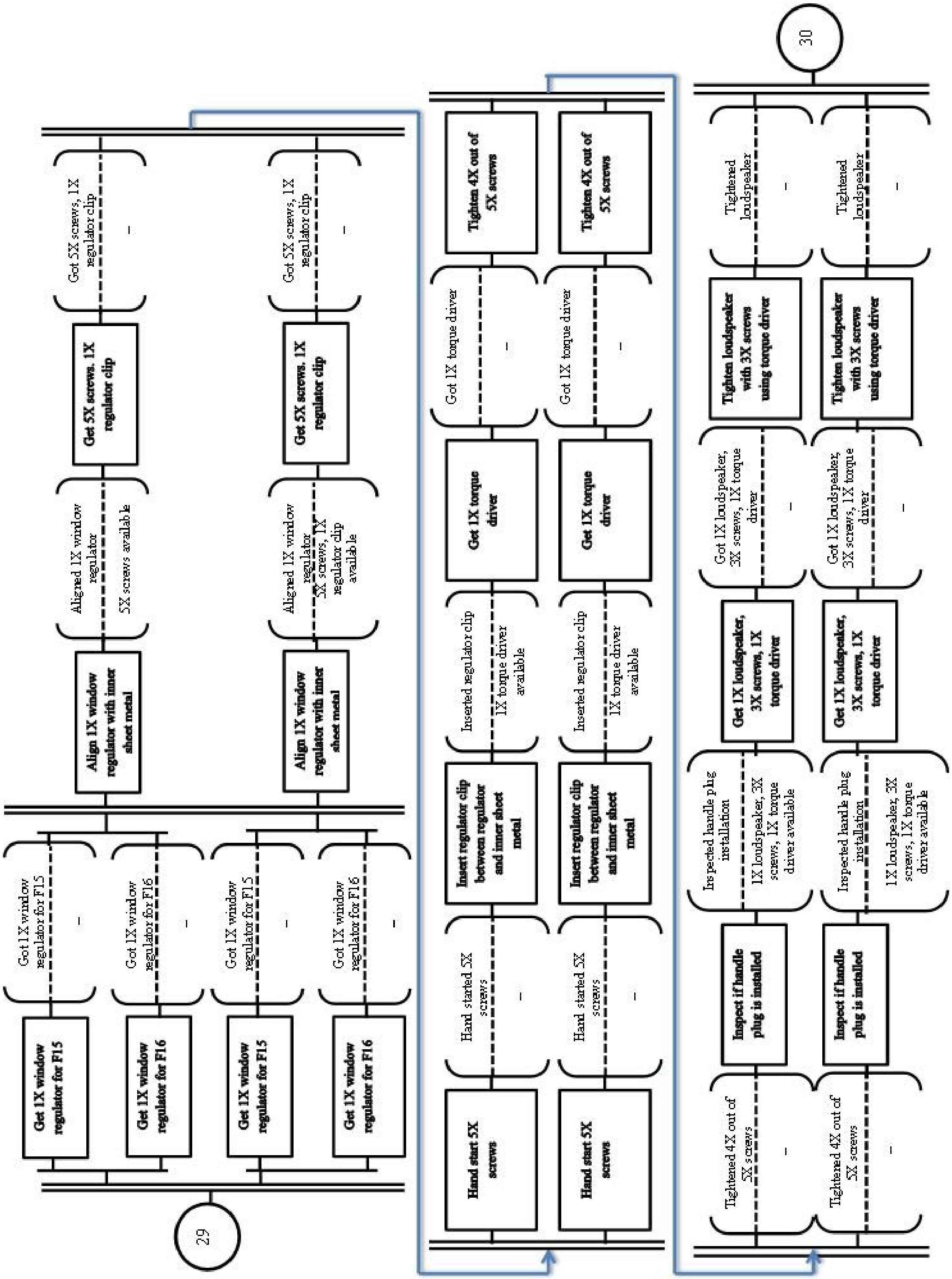

Figure 29: ASML modelling for Station 14 (Contd…)

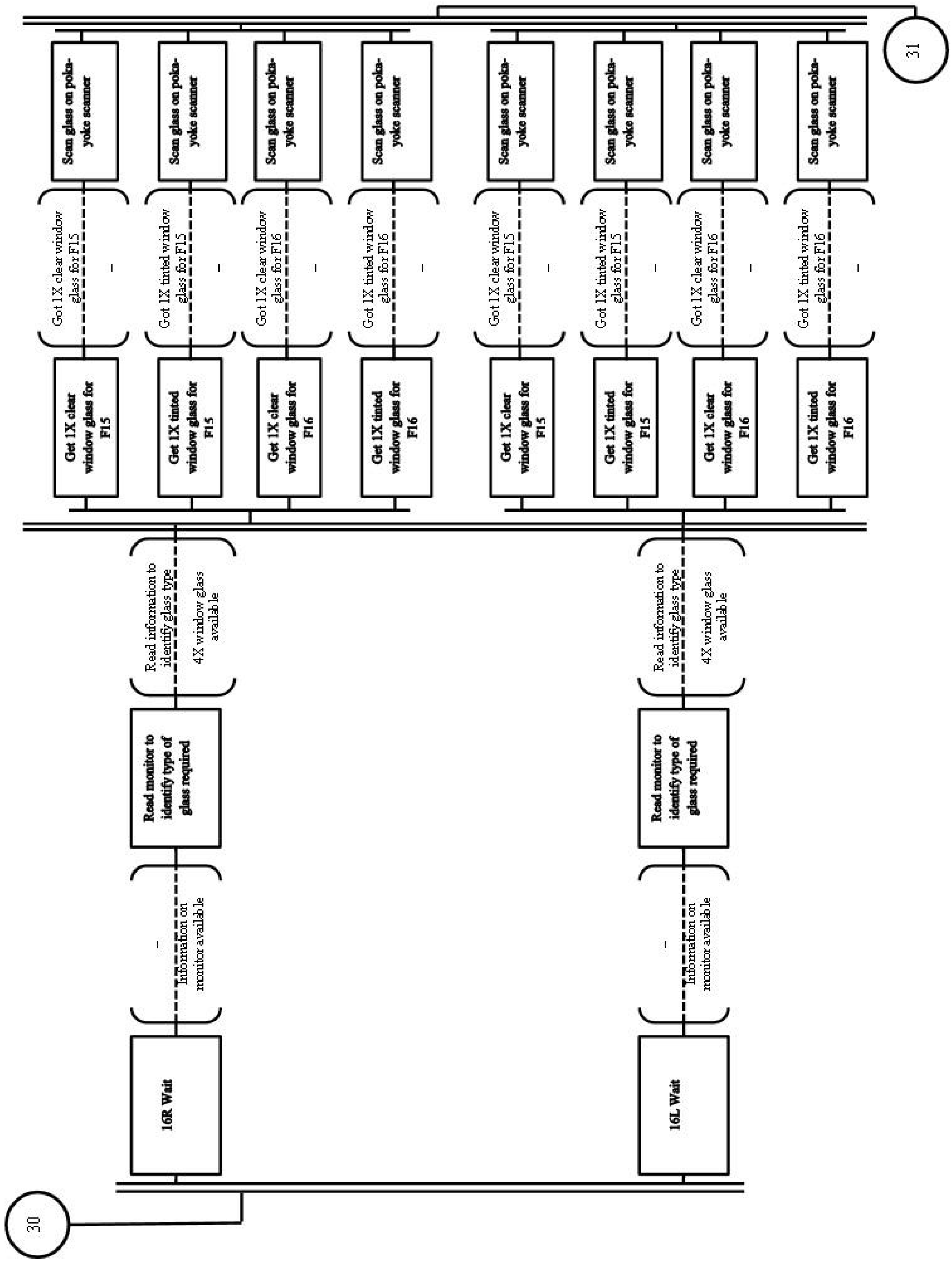

Figure 30: ASML modelling for Station 16

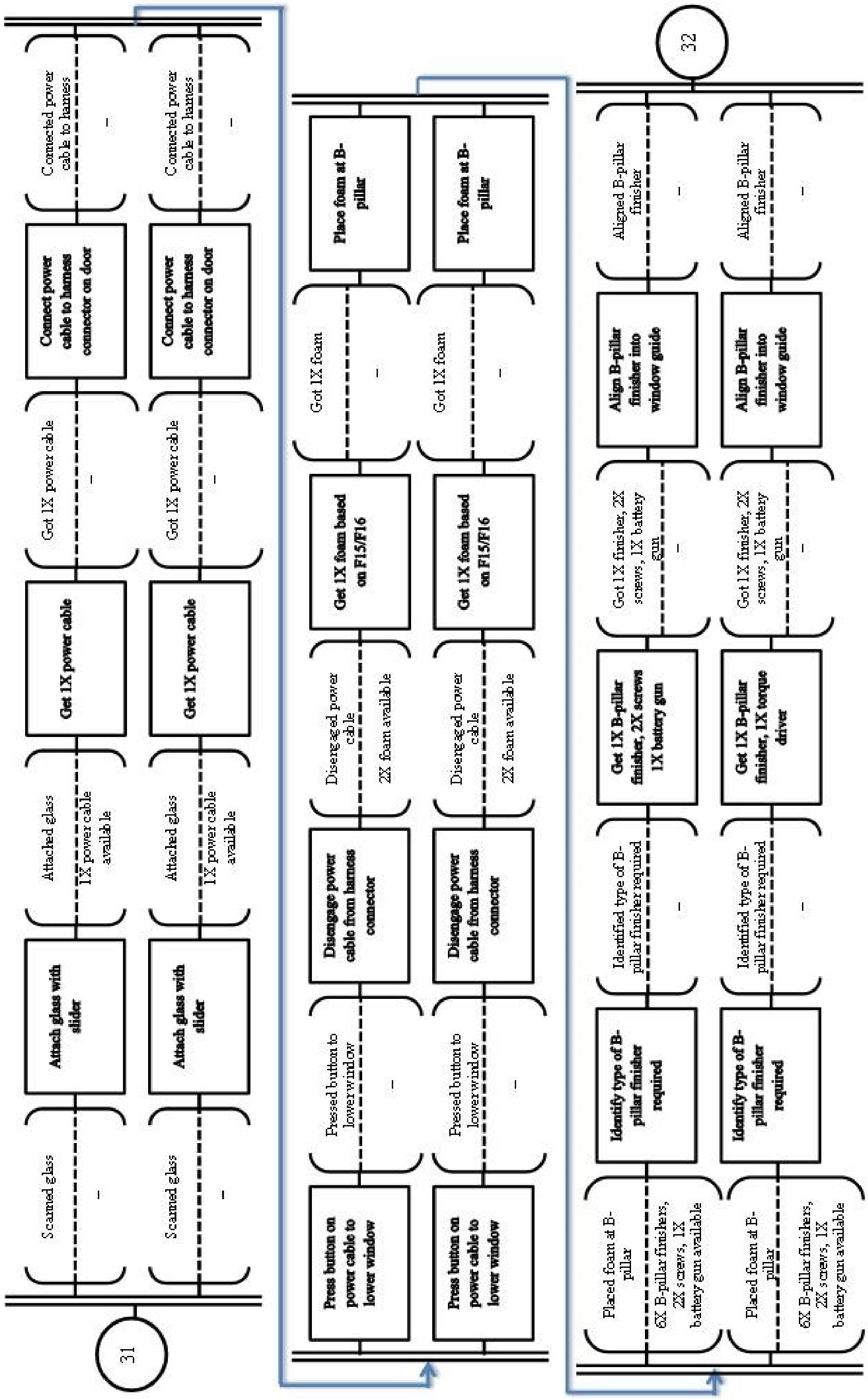

Figure 31: ASML modelling for Station 16 (Contd…)

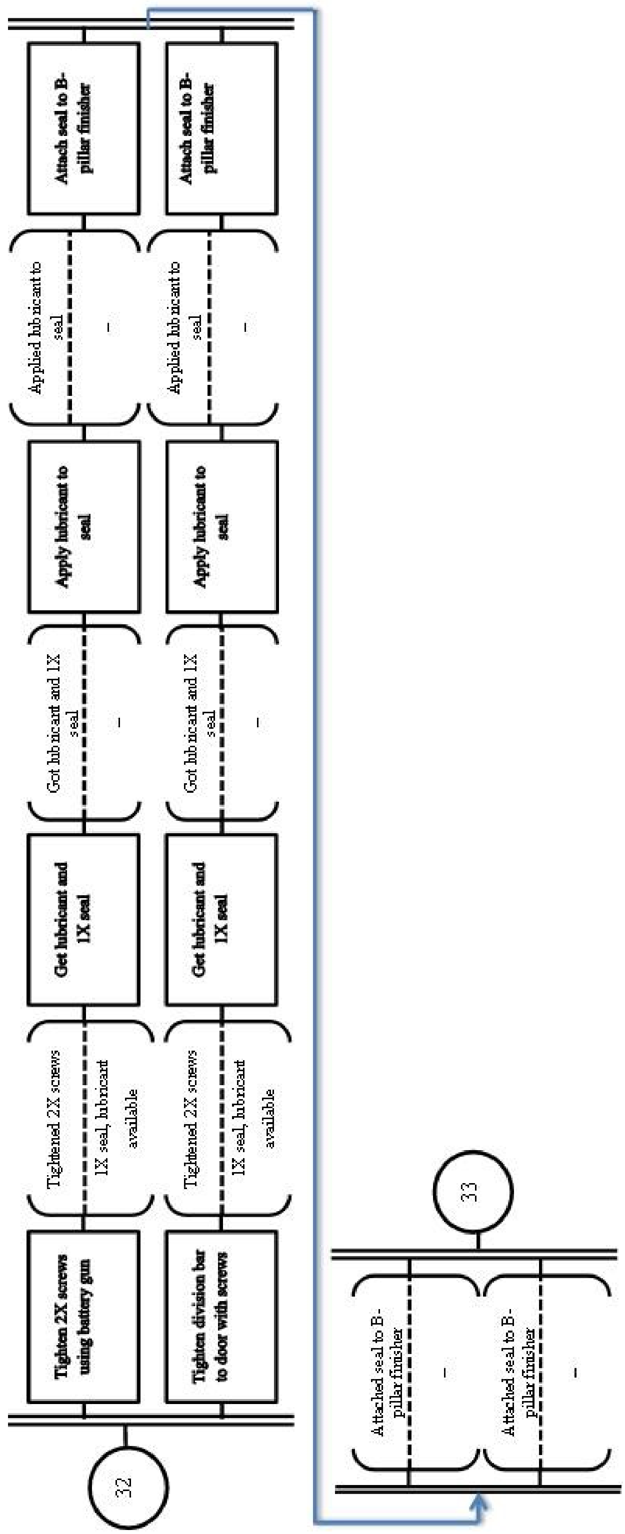

Figure 32: ASML modelling for Station 16 (Contd…)

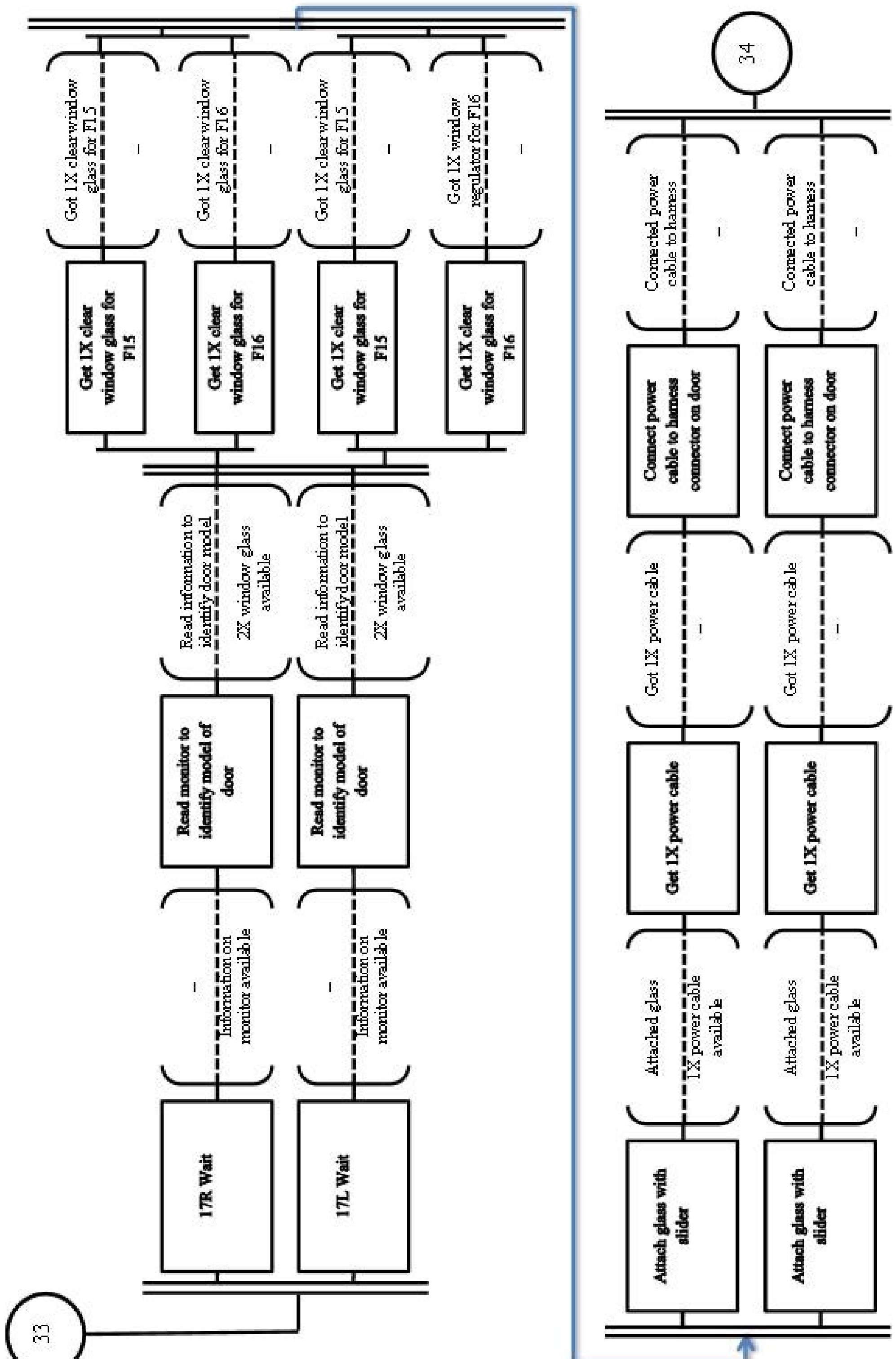

Figure 33: ASML modelling for Station 17

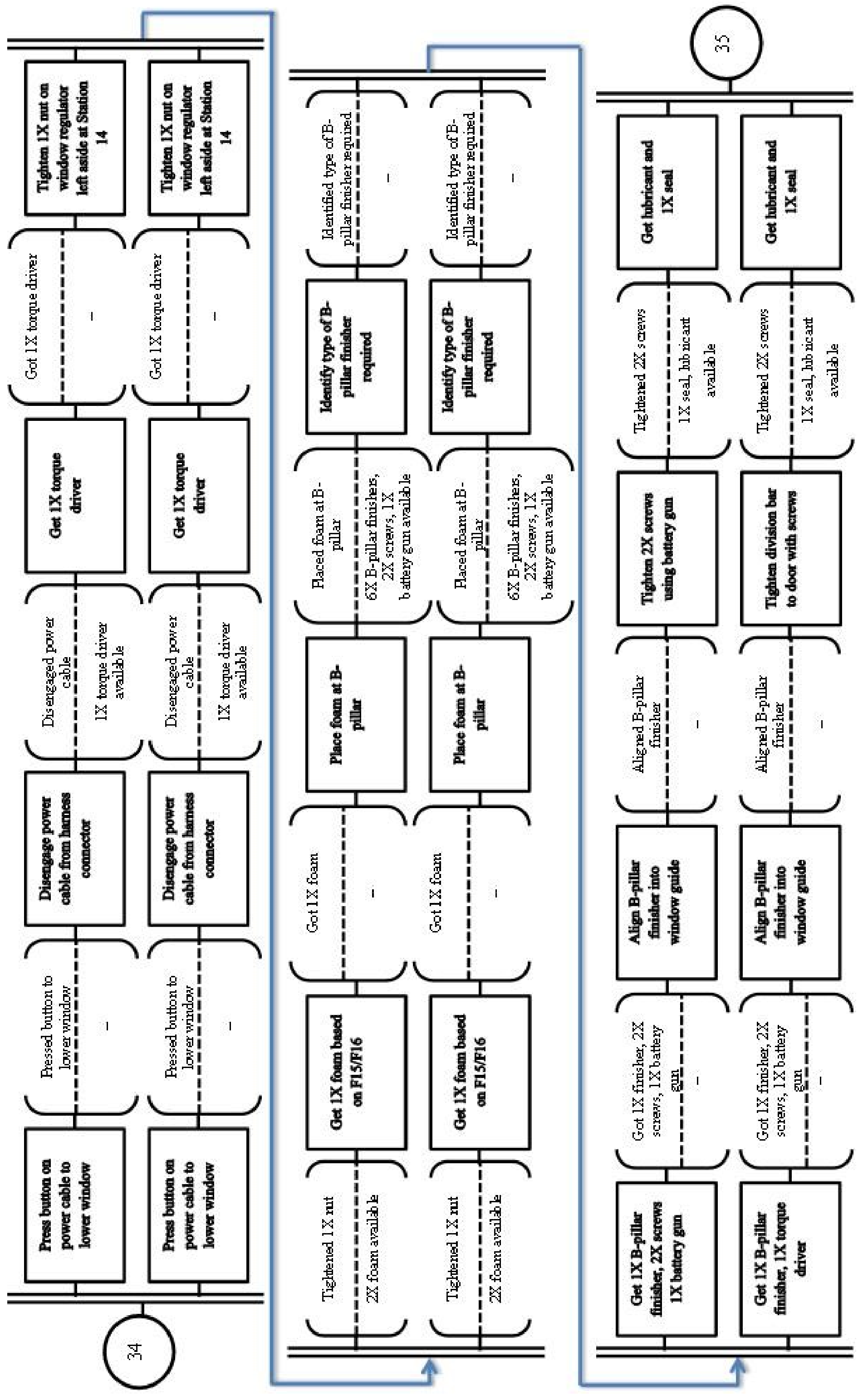

Figure 34: ASML modelling for Station 17 (Contd…)

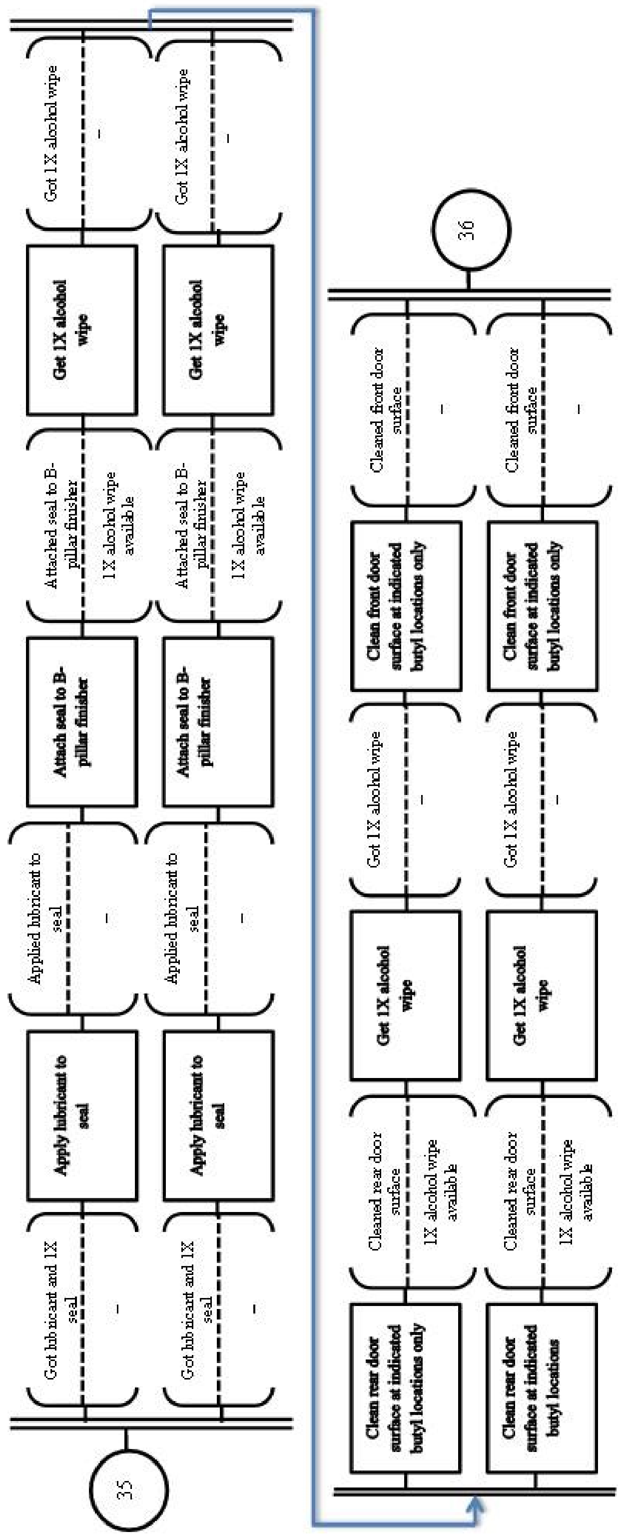

Figure 35: ASML modelling for Station 17 (Contd…)

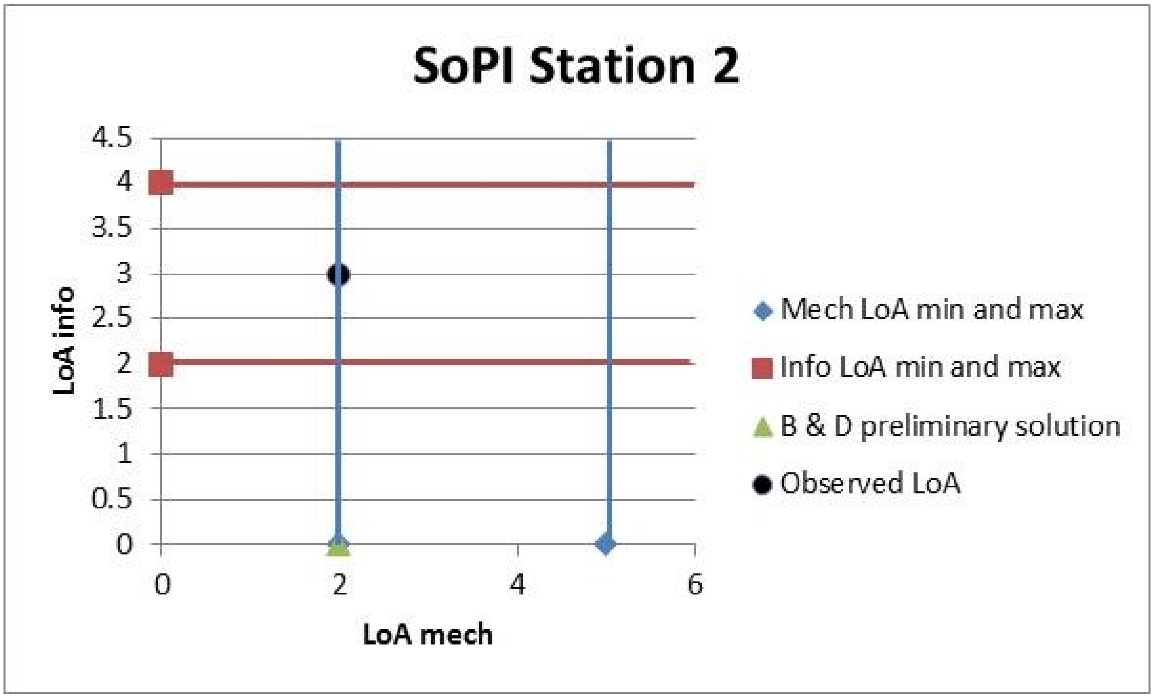

Figure 36: SoPI for Station 2

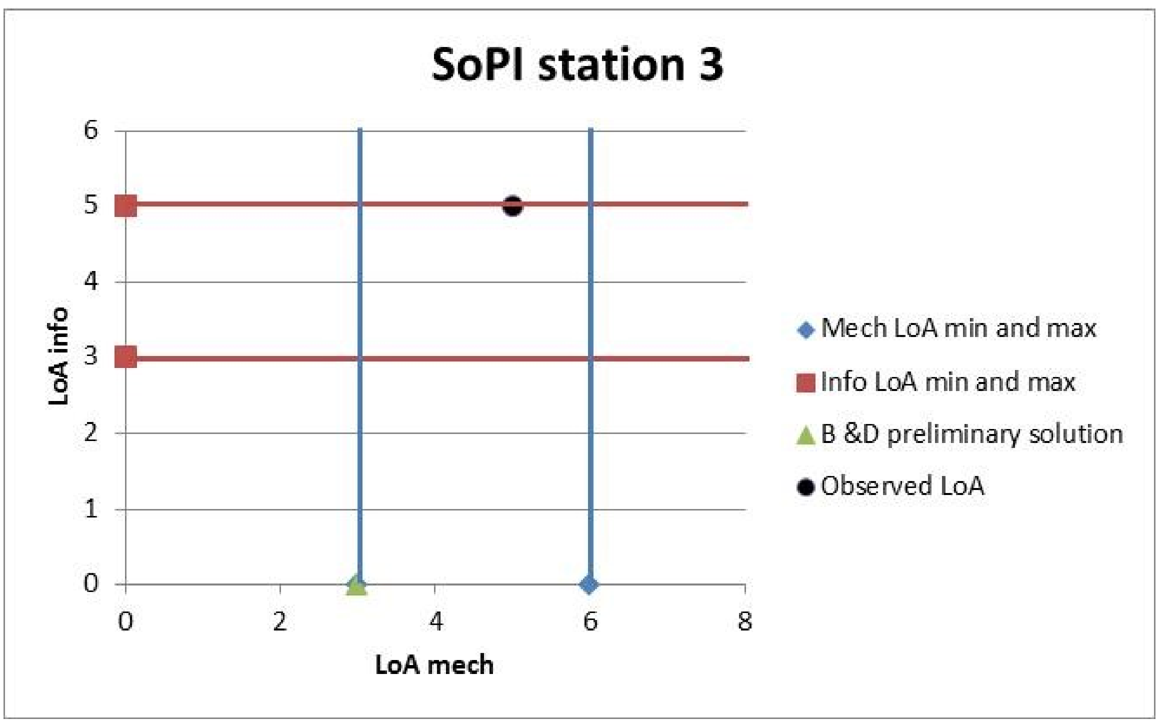

Figure 37: SoPI for Station 3

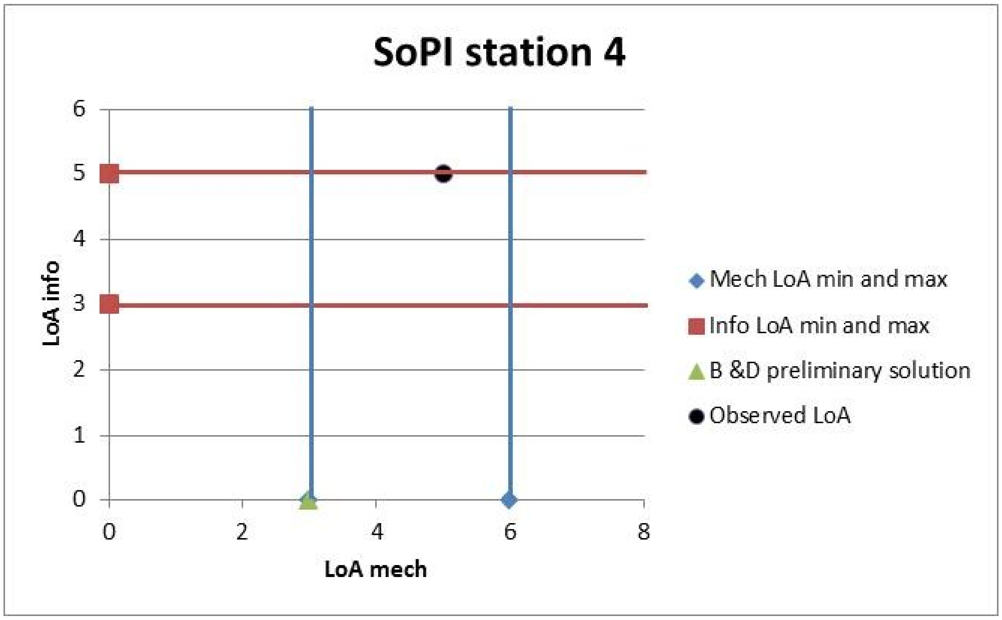

Figure 38: SoPI for Station 4

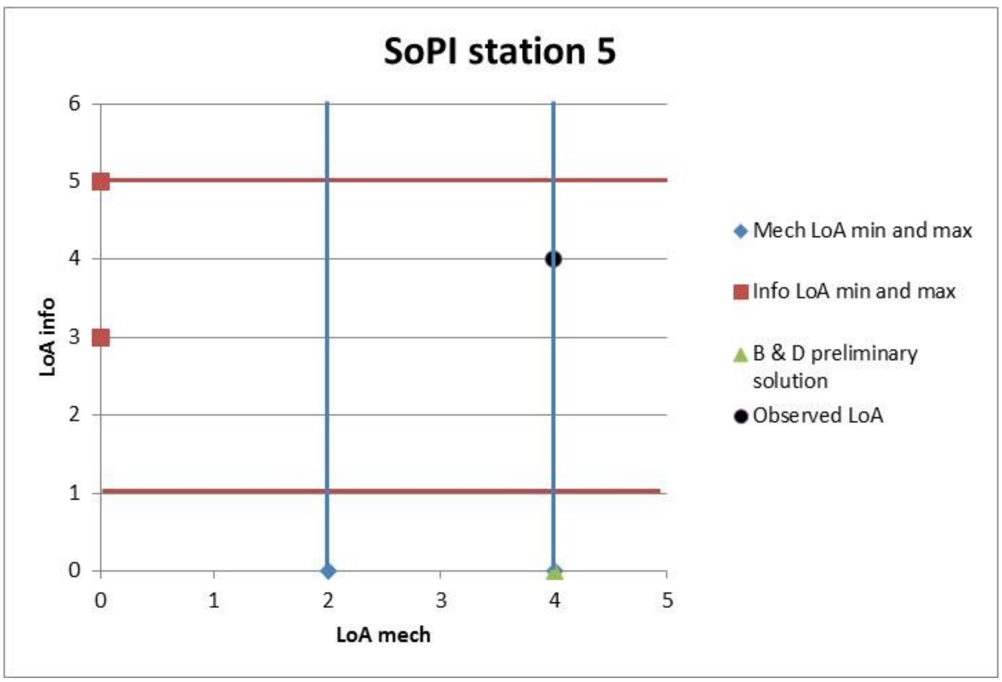

Figure 39: SoPI for Station 5

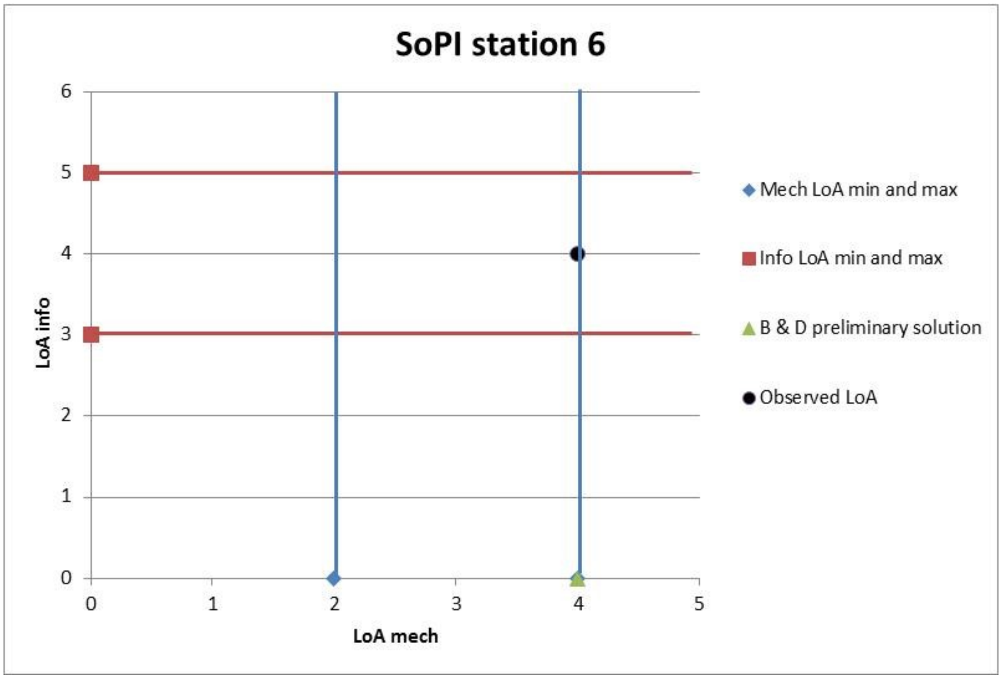

Figure 40: SoPI for station 6

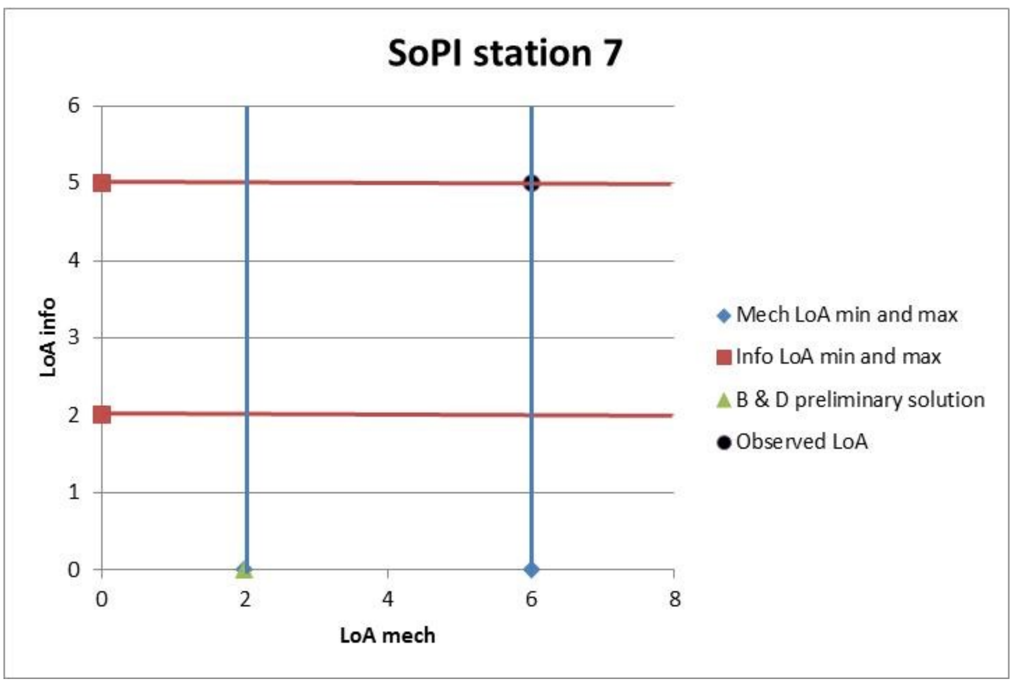

Figure 41: SoPI for Station 7

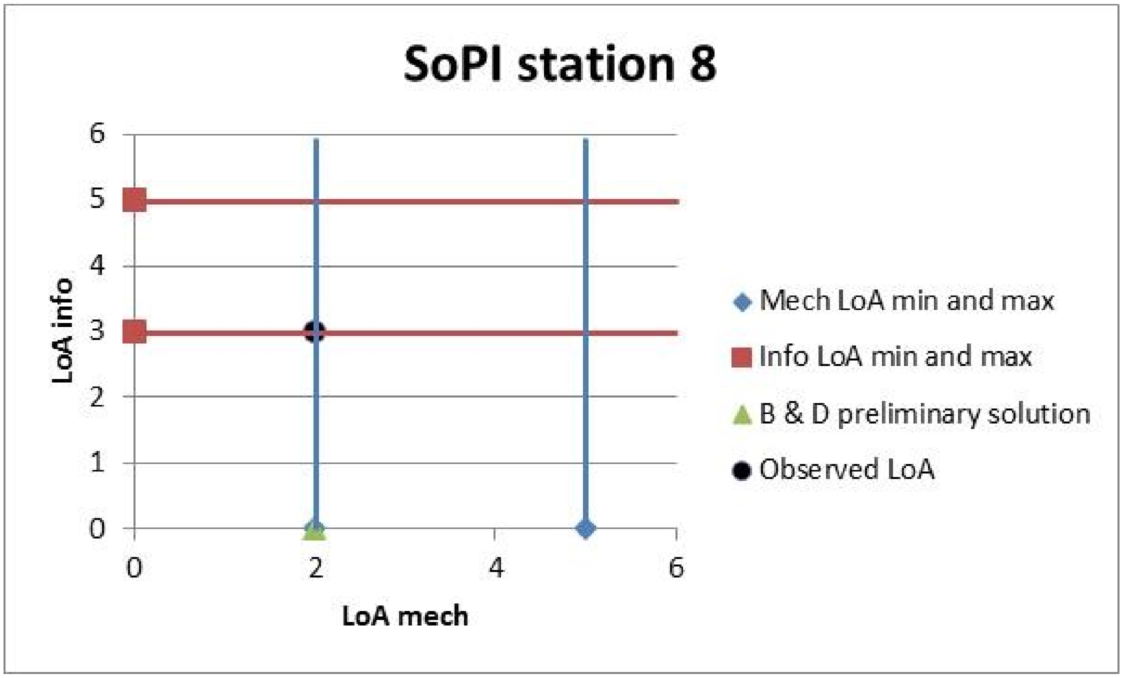

Figure 42: SoPI for Station 8

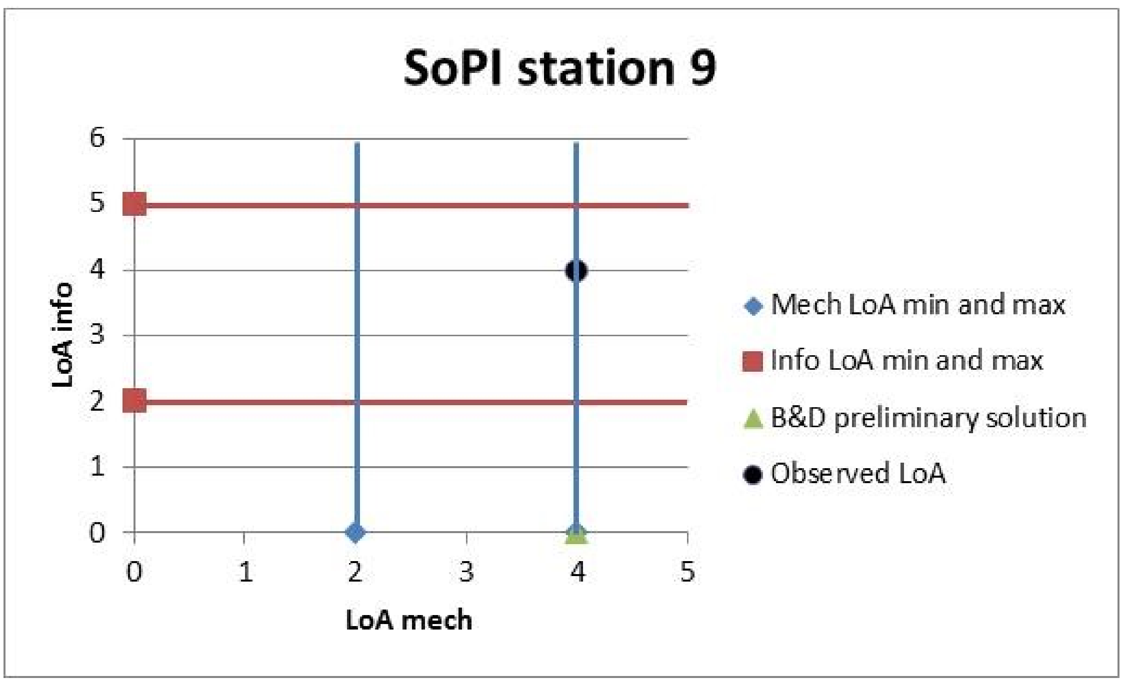

Figure 43: SoPI for Station 9

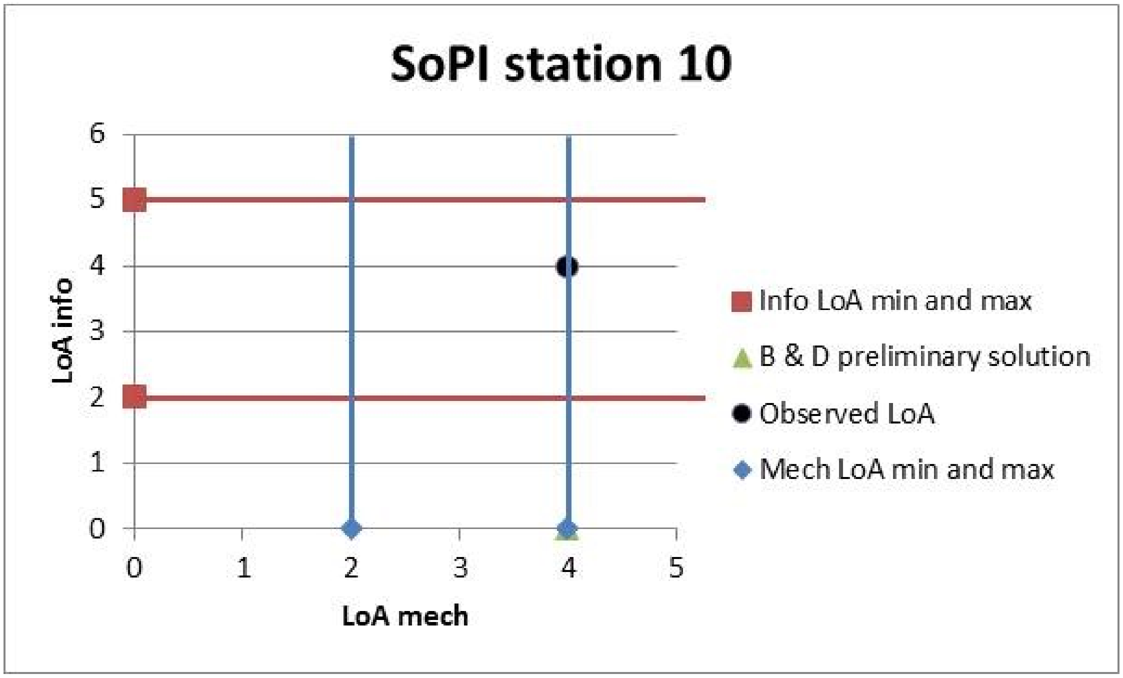

Figure 44: SoPI for Station 10

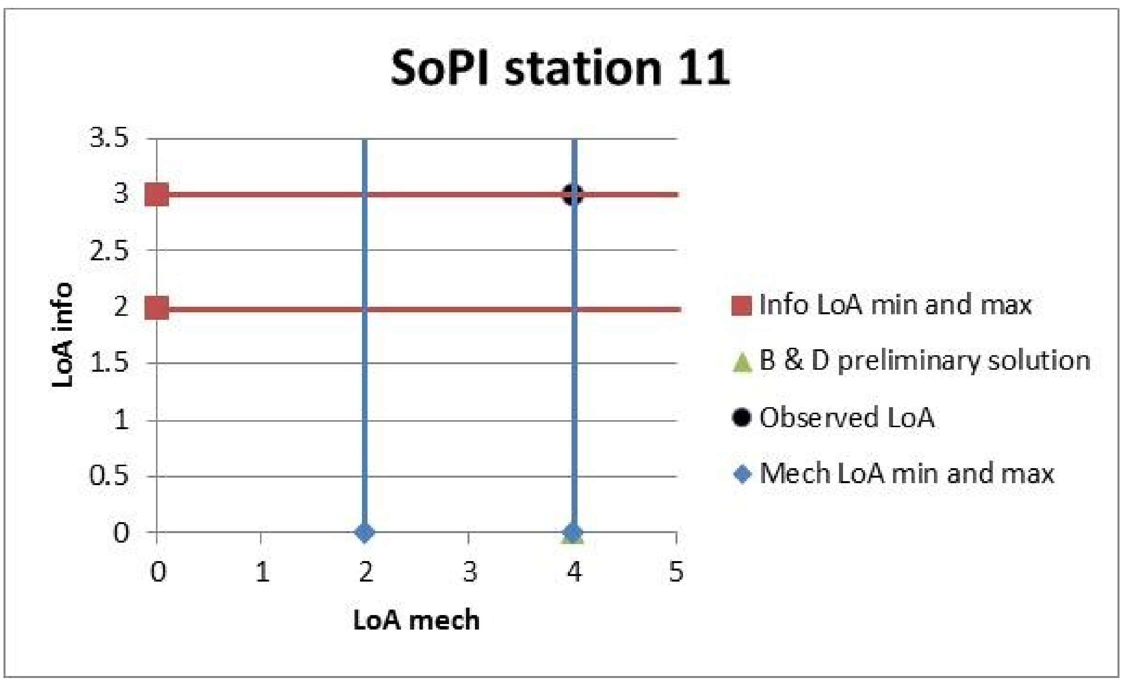

Figure 45: SoPI for Station 11

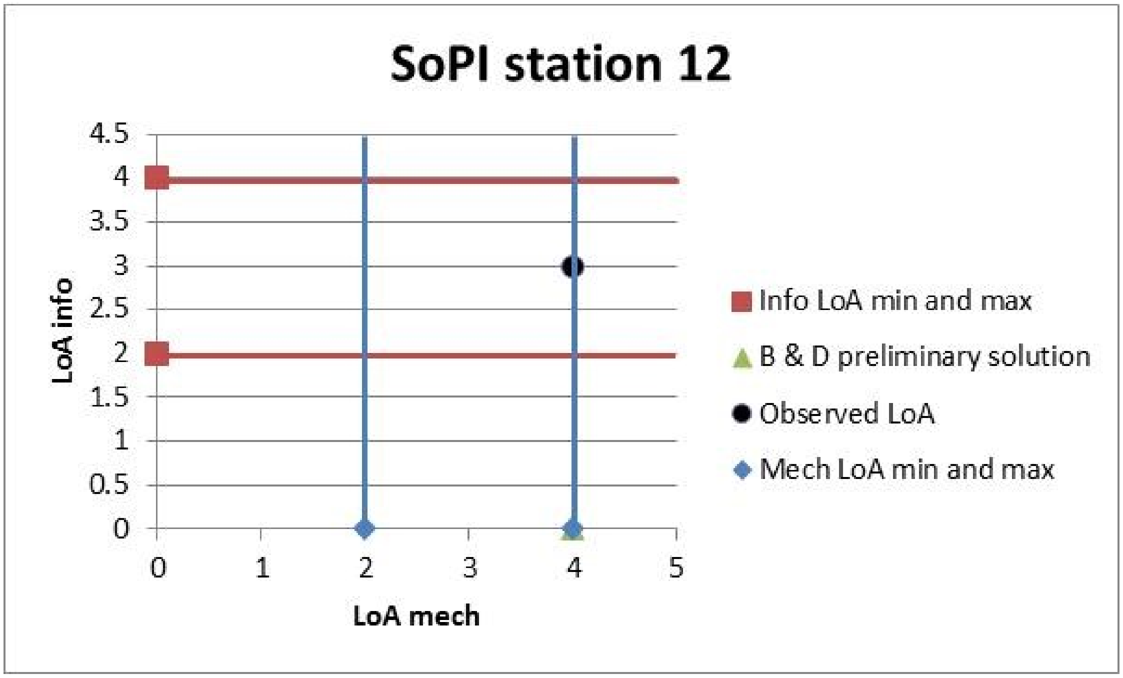

Figure 46: SoPI for Station 12

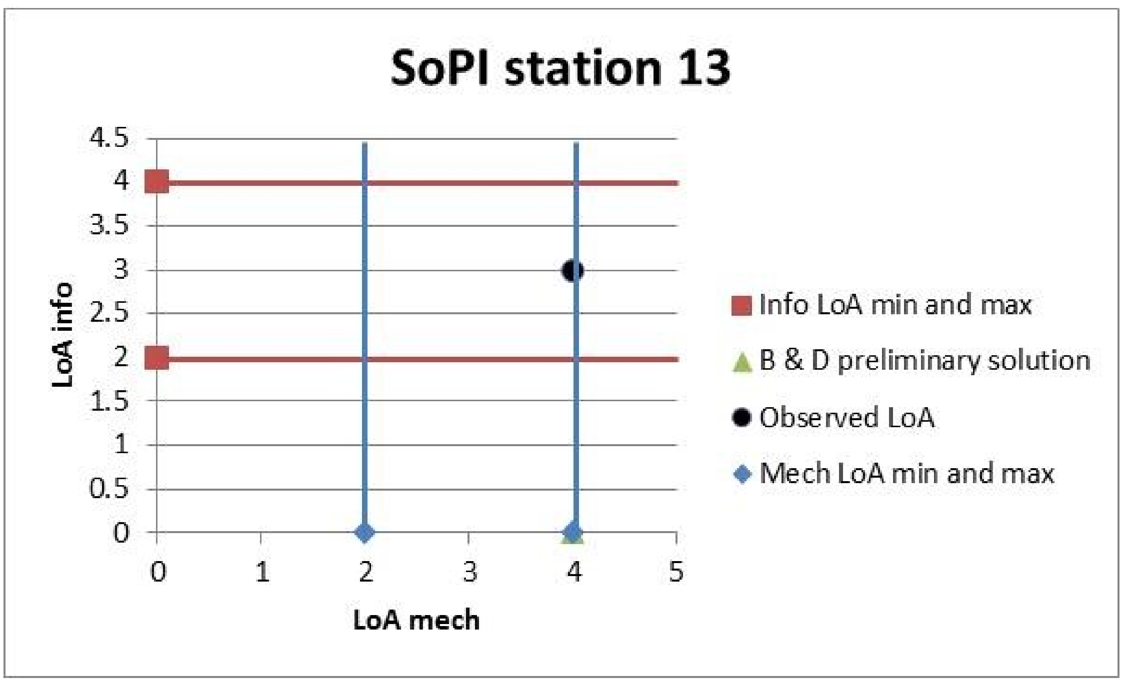

Figure 47: SoPI for station 13

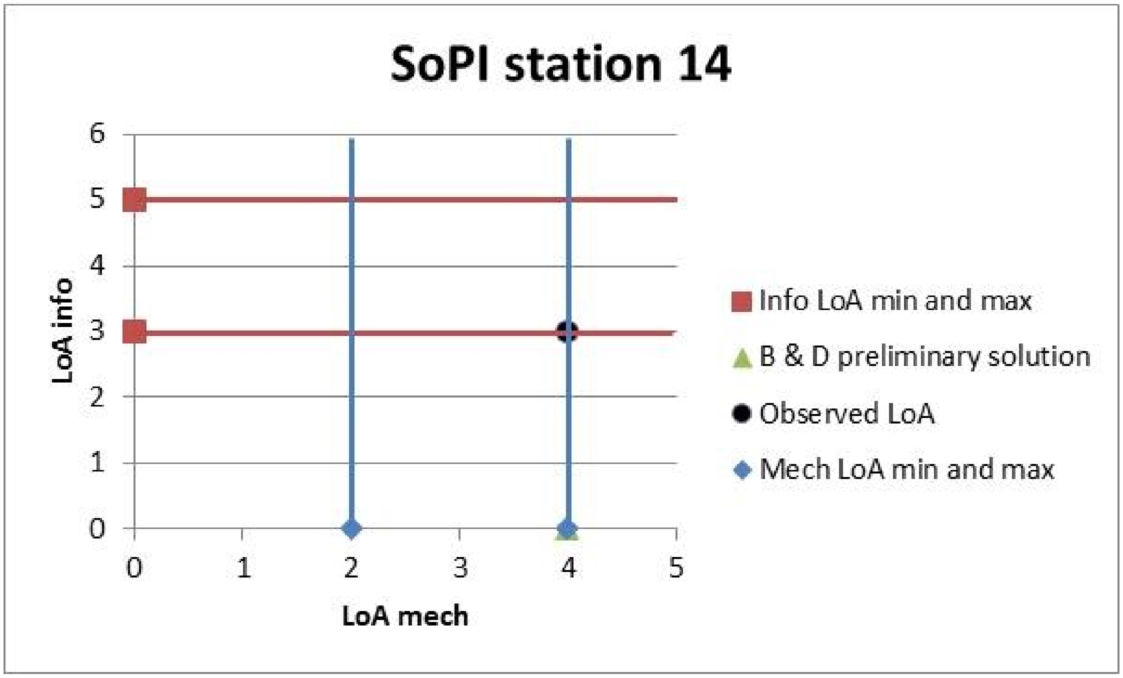

Figure 48: SoPI for Station 14

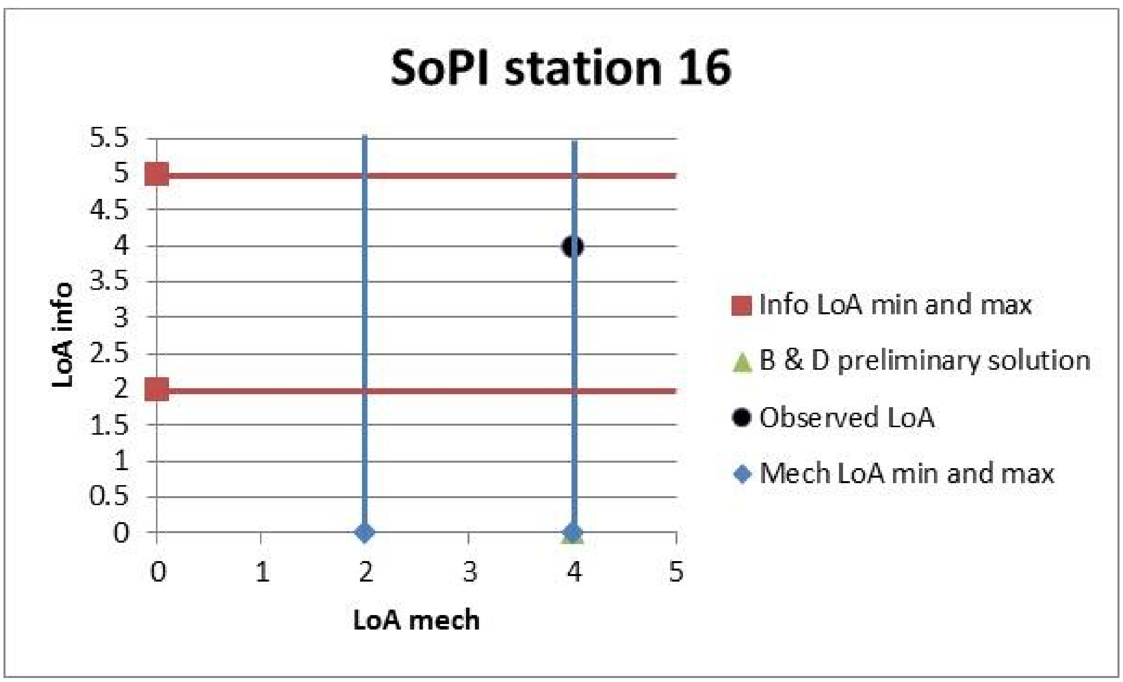

Figure 49: SoPI for Station 16

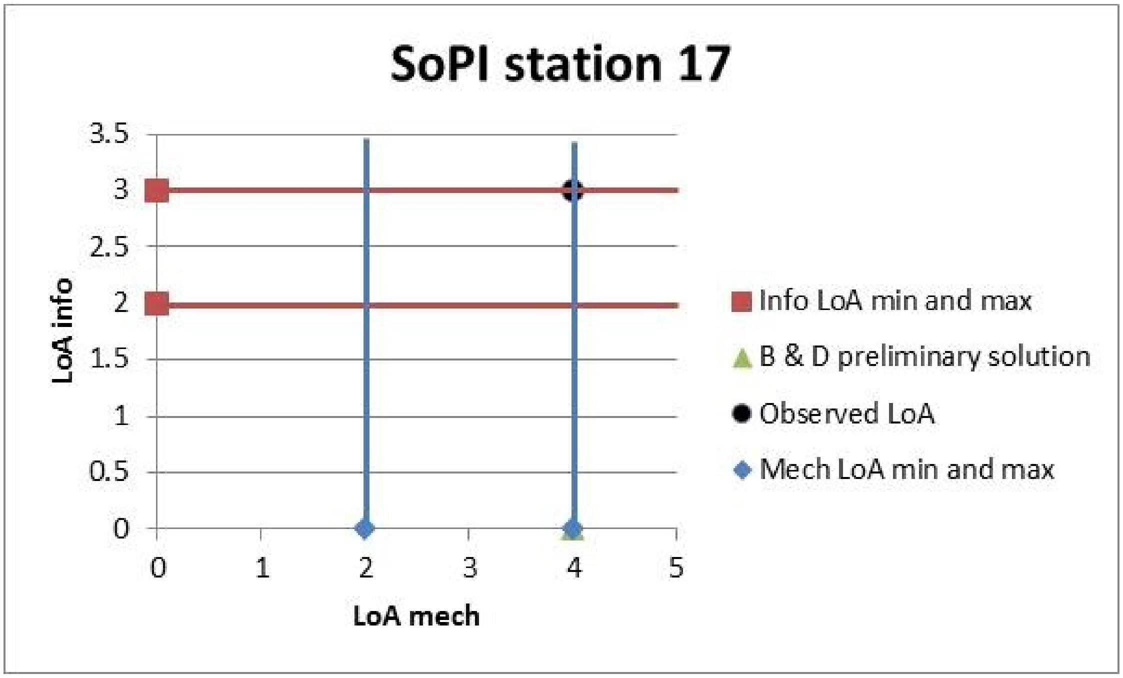

Figure 50: SoPI for Station 17