UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola d'Enginyeria de Barcelona Est

BACHELOR THESIS

Bachelor's degree in Industrial Electronics and Automatic Control Engineering

ROOF ASSEMBLY ON A CAR BODY

Descriptive Memory

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Resum

El present treball de fi de grau explica el funcionament i automatització darrere d'una moderna línia d'assemblatge de sostres en un centre de manufactura d'automòbils. Les seqüències automàtiques de la línia d'assemblatge són analitzades amb l'ajuda de gràfics GRAFCET elaborats sobre la base de les observacions i treball de l'autor en aquesta línia de muntatge. Un capítol està dedicat a discutir les comunicacions entre els tres controladors lògics programables que governen el procés d'assemblatge, mentre que un altre capítol exposa el maneig dels procediments de seguretat, tant físics com programables. Es desenvolupa una interfície home màquina dissenyada per a assistir al monitoratge de la seguretat durant producció, i dues estacions automatitzades orientades a millorar l'acompliment de la línia. Una breu anàlisi ambiental sobre les deixalles d'alumini generats durant el procés d'assemblatge també es duu a terme, així com una anàlisi econòmica. Finalment, es fa una avaluació de les millores fetes a l'acompliment de la producció.

Resumen

El presente trabajo de fin de grado explica el funcionamiento y automatización detrás de una moderna línea de ensamblaje de techos en un centro de manufactura de automóviles. Las secuencias automáticas de la línea de ensamblaje son analizadas con la ayuda de gráficos GRAFCET elaborados en base a las observaciones y trabajo del autor en dicha línea de montaje. Un capítulo está dedicado a discutir las comunicaciones entre los tres controladores lógicos programables que gobiernan el proceso de ensamblaje, mientras que otro capítulo expone el manejo de los procedimientos de seguridad, tanto físicos como programables. Se desarrolla una interfaz hombre máquina diseñada para asistir al monitoreo de la seguridad durante producción, y dos estaciones automatizadas orientadas a mejorar el desempeño de la línea. Un breve análisis ambiental sobre los desechos de aluminio generados durante el proceso de ensamblaje también se lleva a cabo, así como un análisis económico. Finalmente, se hace una evaluación de las mejoras hechas al desempeño de la producción.

Abstract

The present bachelor thesis explains the functioning and automatization behind a modern roof assembly line in a car manufacturing center. The assembly line's automatic sequences are analyzed with the aid of GRAFCET charts elaborated based on the author's observations and work on said line. A chapter is dedicated to discussing the communications between the three programmable logic controllers that govern the assembly process, while another chapter exposes the handling of safety procedures, both physical and programmable. A human machine interface is developed and designed to aid in the monitoring of safety during production, and two automated stations which aim to improve the line's performance. A brief environmental analysis concerning the aluminum waste generated during the assembly process is also put together, as well as an economic analysis. Finally, an evaluation of the improvements made on the production performance is made.

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1. Introduction

The assembly line concept in industrial manufacturing as we know it today had its origin post-industrial revolution in the early 20th century, developed by the Ford Motor Company to be able to satisfy the high demand for automobiles. Soon, competitors had to adopt this system to be able to compete with the efficiency and high production output that this method represented.

By modern standards, a production line in the automotive industry is divided into physical stations each with a specific task. Stations are controlled by programmable logic controllers, *PLCs* from now on, which divide the complex manufacturing process into sequences. Sequences are subsequently divided into steps, each describing the state in which the different components in the station must be in order to advance into the next step, once all steps are complete then into the next sequence, and consequently the next station, as programmed by the PLC programmer.

1.1. Objective

The objective of this document, is to be able use the knowledge acquired throughout the duration of the industrial electronics and automatic control engineering course and apply it to be able to understand in a detailed fashion the functioning of an assembly line, the automated roof assembly on a car body in this case. Profiting from this knowledge, improvements to the assembly line production potential are made and evaluated.

1.2. Scope of the Project

The automatic sequences of each station and safety procedures are interpreted in GRAFCET charts to better help understand how they work. A human machine interface designed to aid in the safety monitoring of the line. In order to demonstrate the functioning of this application, a code has been programmed to emulate the behavior of the line under different safety scenarios. In the same manner as the rest of the stations, the improvement stations sequences are described accordingly. Simplified electric schematics for the assembly line's hardware are included in the annexes.

2. The Assembly Line

In the second chapter it will be explained what an assembly line consists of and how the roof assembly line analyzed in this project works, explaining sequence per sequence throughout the whole process from the moment the car body enters the line to when it exits the line with the roof mounted, including the handling of the actual roof part before it is mounted into the body.

The roof assembly line consists of 20 stations and 19 robots arranged into seven safety areas, monitored by 16 HMIs, controlled by three PLCs from the Rockwell Automation brand, which communicate with each other via an ethernet network. It is designed to work in a fully automatic manner without the need for operators, except for the loading of parts and scrap removal. It is designed to produce at least 30 cars per hour and is among the first in the world to achieve this level of automatization for a roof assembly line in the automotive industry, while also pioneering the use of linear synchronous motor technology for the transport of the vehicles along the line. In the factory, the roof line is fed by a conveyor which brings the car bodies from the upper framer where bodysides are welded into the underbody. Once the roof is assembled, the line feeds the cladding line where the doors, trunk and hood are assembled manually by operators.

2.1. How the Line Works

Initially, the vehicle enters from station 690 from the conveyor 9, which is located above ground in an upper level into the station 10 lifter, which is waiting in the up position. Once the vehicle enters, it is lowered to ground level, where the roof assembly line is located. It is then transported by the buffer station 20 into the station 30 glue station. Here, robots put glue into the upper section of the car body, which is then forwarded by the station 40 buffer into station 50, where the most time-consuming sequence takes place, the placement of the roof part, regardless of its type, by the 280R gripper robot into the body. The robots on station 50 first measure that the part falls within the tolerance measurements to proceed into an initial riveting process.

Once the station 50 sequence is finished, the vehicle advances through the station 60 buffer first into station 70, where a couple robots apply a riveting program according to the roof type, either moon roof or fixed roof. The vehicle then enters station 80 which operates in the same way as the previous station, robots applying the adequate re-riveting program to the body according to type. Afterwards the vehicle will endure a measuring inspection by the robots in station 90, which determine whether the vehicle's measurements fall within tolerance. Finally, the vehicle exits to conveyor 10 back to the upper level, via the station 100 lift station. The car body looking as the picture below, depending on the variant.

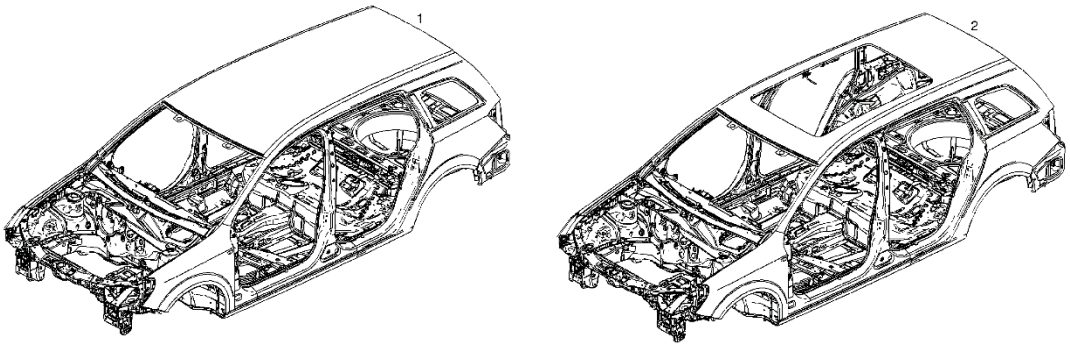

Figure 2.1. Car body, fixed rood type 1 (left), and moon roof type 2 (right). Source: [1]

Roof parts are inserted in to the assembly line loaded in the same racks which are also used for transport, meaning the parts are loaded into the racks and delivered by the parts supplier. Once on site, racks are loaded manually by operators with the aid of forklifts. There are four rack stations, two of each type, since roof parts are different according to type, as shown in the following illustration.

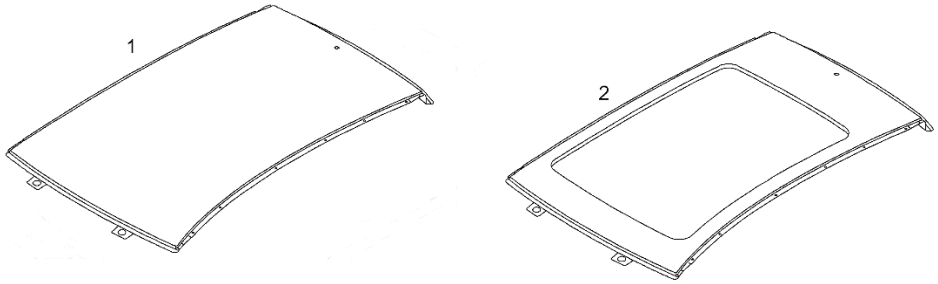

Figure 2.2. Roof part, fixed rood type 1 (left), and moon roof type 2 (right). Source: [2]

In the case of moon roof parts, although parts come pre-cut from the supplier, because of its aluminum composition and thin geometry, the part's opening is not large enough as it would complicate transport due to an increased risk of the part becoming bent and deformed. Therefore, the final cut is made in the assembly line just before being placed on the car body. Parts are placed on rack stations 242 and 243, where they are picked up by gripper robot 240R, which places the part on fixture station 282 for it to later be picked up by gripper robot 200R. Said robot will then place the part at the press station 275, where once the part is pressed its placed on fixture station 281. Finally, gripper robot 280R will pick up the piece and place it on the car body in station 50.

For fixed roof parts, the process is simplified since the supplier provides the parts ready to be directly placed on the car body. Parts are loaded into rack stations 201 and 202, waiting for gripper robot 200R

to pick them and place them on fixture station 281, where the gripper robot 280R will then pick the piece and finally place it on the car body in station 50.

To better understand the whole process, the diagrams in the next two pages show the layout of the stations and how the car body and the roof parts flow through them. Additionally, the control areas of the PLCs are specified as well as the location of safety roller doors. The functioning of each station is explained in detail in the following sections of this chapter.

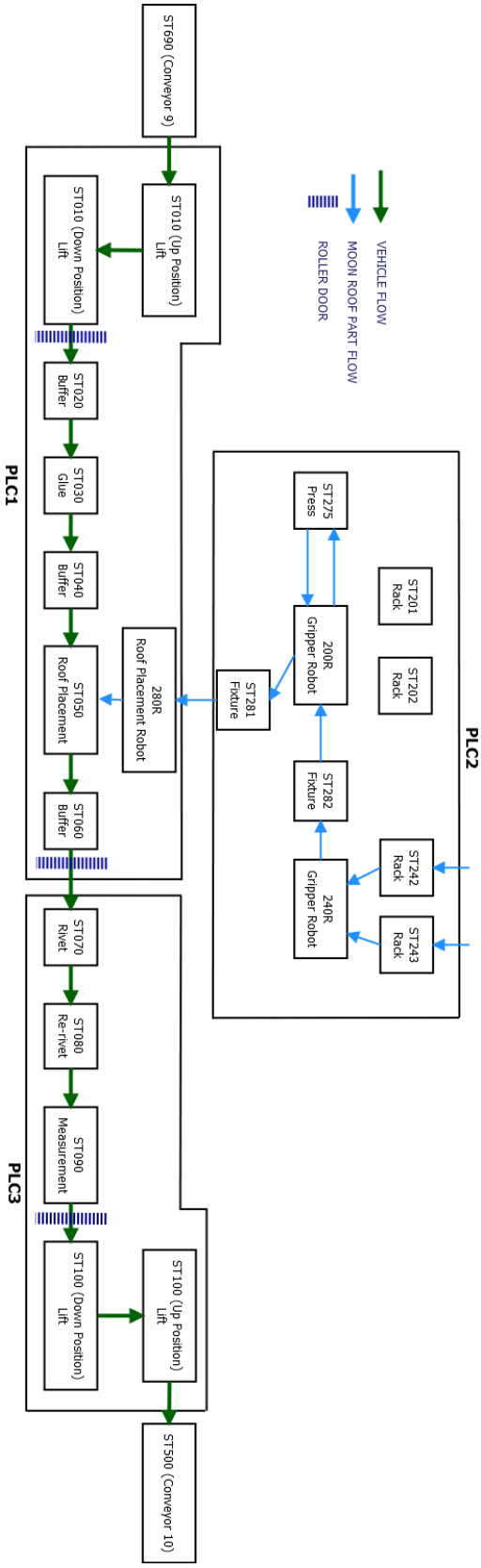

Figure 2.3. Roof Line Flowchart for Moon Roof Type Vehicle

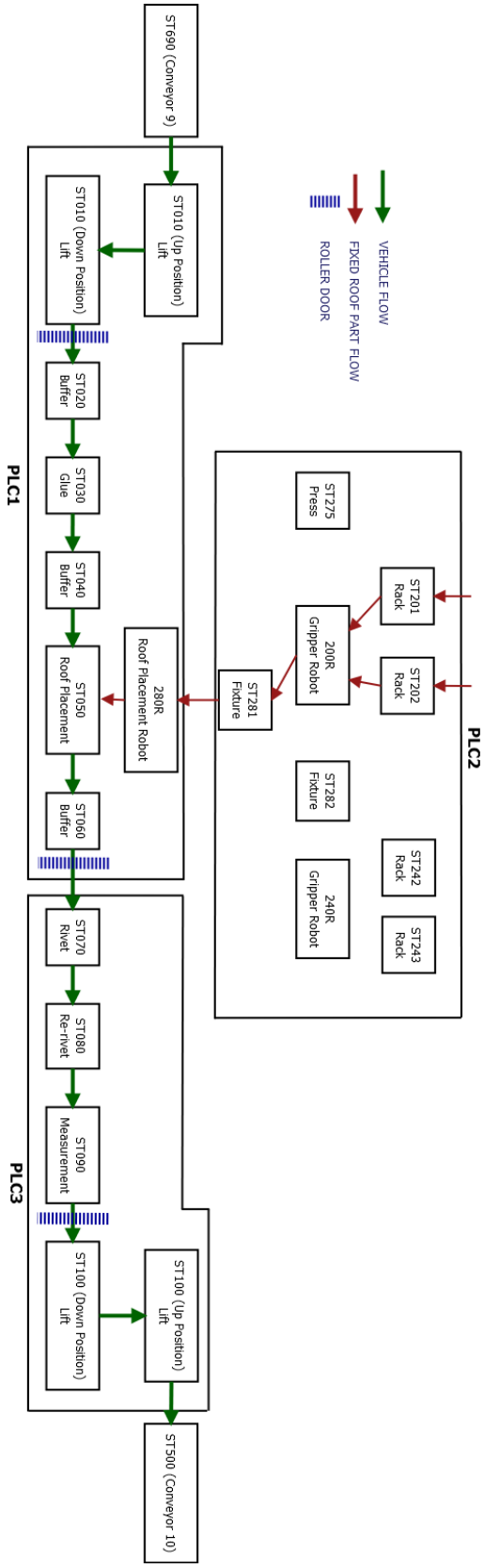

Figure 2.4. Roof Line Flowchart for Fixed Roof Type Vehicle

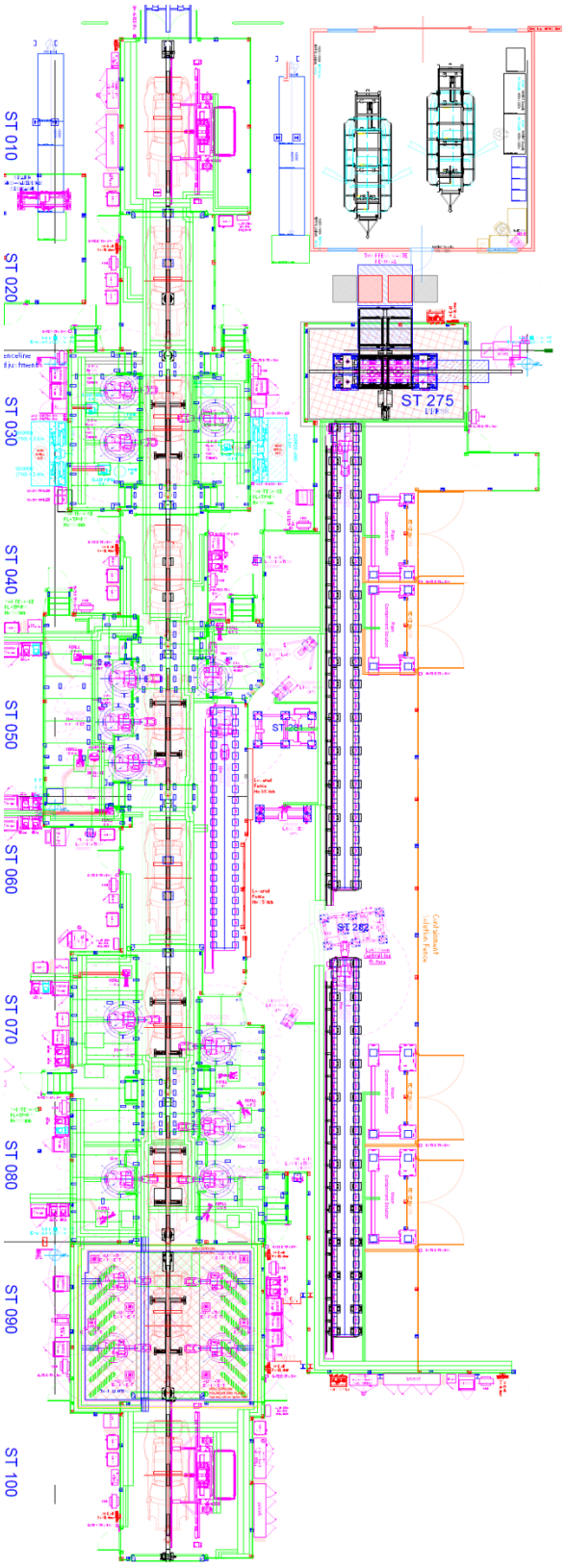

Figure 2.5. Roof Line Floorplan

2.2. PLC1

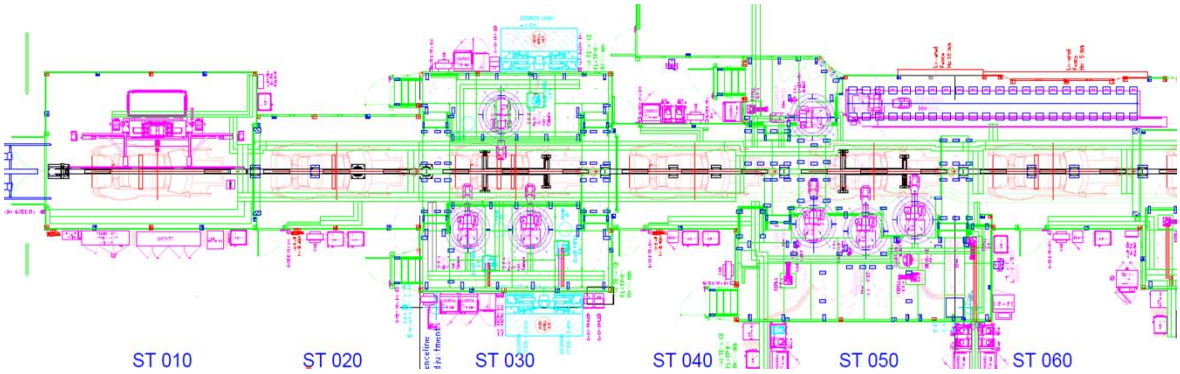

Figure 2.6. PLC1 Floorplan

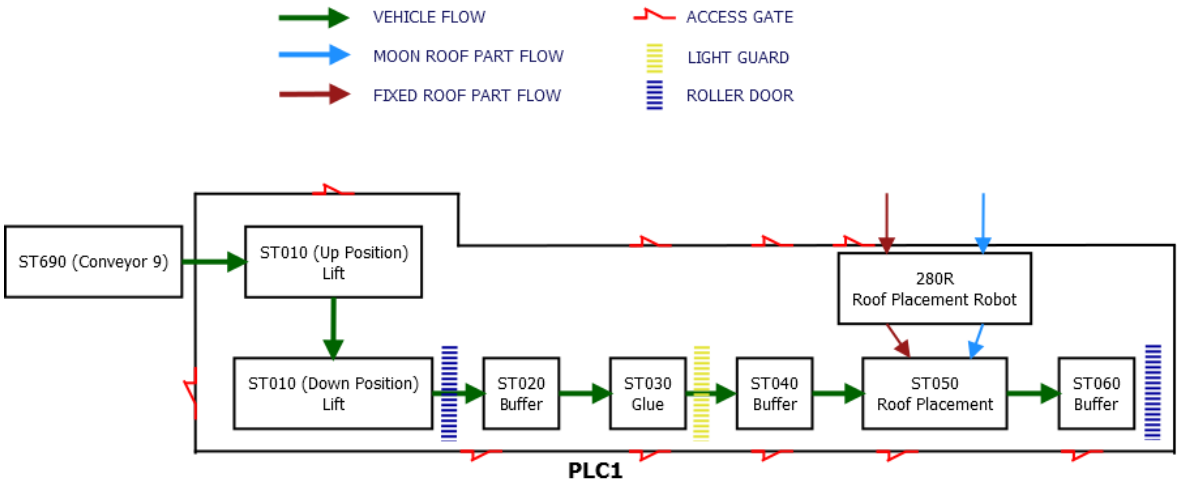

Figure 2.7. PLC1 Area Flowchart

The first PLC controls a total of seven stations and eight robots, arranged into seven sequences and three safety areas. This PLC is monitored by seven HMIs.

2.2.1. ST010 Lifter

The lifter is initially waiting in the up position, with the pallet stopper in the rest position, to allow the incoming vehicle to enter, and the latch in rest position to secure the lift into the conveyor. Once a vehicle approaches and enters the lift, its data type is transferred from the previous line PLC and the pallet stopper goes in to work position to physically prevent more vehicles from coming in. The vehicle is then secured by the pallet lock to ensure it is properly fastened to the rail. Only then, the latch will retract to the work position, allowing the lift's driver to move the rail into the down position.

When the down position is reached, the latch expands again to fasten to the station 20 rail while at the same time the radio frequency identification *RFID* reader reads the vehicle's data from its tag. The RFID transponder employed in the line is a SICK RFU 620-10100, which is a mid-range write/read device with integrated antenna, a frequency range between 860 *MHz* ~ 960 *MHz*, and ethernet communication. The vehicle type being confirmed, it is transferred to the PLC2 robots 200R and 240R First In First Out databases *FIFO,* which will allow the PLC2 to operate as intended depending of the vehicle variant being built. The pallet lock goes into rest position and once the roller door gate is checked to be opened, the vehicle is then allowed to leave the station.

Figure 2.8. SICK RFU 620-10100 RFID transponder used in the line. Source: [3]

With the station now empty, the latch will retract for the driver to move the rail back to the up position, expand once again to fasten to station 690, and the pallet stopper will move back to the rest position so the next vehicle may enter.

Table 2.1. ST010 Lifter Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[1].EOC	End of Cycle
BTTOK	_1_A2_31_512BT	Braking Transistor Temperature OK
MECP	_1_A2_31_2526CON_1	Motor Enable Contactor +
MECN	_1_A2_31_2526CON_2	Motor Enable Contactor -

MECF	_1_A2_31_2526CON_F	Motor Enable Contactor Feedback
SACV9OK	CV090_035_5.SA12_OK	Safety Area Conveyor 9 is OK
SA1OK	_SA01_2_SAFETY_AREA_OK	Safety Area 1 is OK
SA2OK	_SA02_2_SAFETY_AREA_OK	Safety Area 2 is OK
Rel2	zzSeq[1].Release.2	Station 10 to Station 690 (Conveyor 9) Enter Reverse Acknowledge Release
VIP	zzSeq[1].InPos[50].1	Vehicle In Position
HESOK	zzSeq[1].InPos[50].7	Hall Effect Sensor is OK
SeqOK	zzSeq[1].TypeOK	Sequence Type is OK
TFR	Type.InStation[1].13	Type Fixed Roof
TMR	Type.InStation[1].12	Type Moon Roof
Dry	Type.InStation[1].28	Type Dry Part
TMM	zzSeq[1].Flag.28	Type Miss Match
PSRest	_010S611B	Pallet Stop in Rest Position
PSWork	_010S611A_OK	Pallet Stop in Work Position
PLRest	010S621B	Pallet Lock in Rest Position
PLWork	_010S621A	Pallet Lock in Work Position
NoVehST20ST10	zzSeq[2].Release.21	No Vehicle Between Stations 20 and 10
NoVehST69ST10	_STN690.Release.7	No Vehicle Between Stations 69 (Conveyor 9) and Station 10
LRest	_010S191B	Latch in Rest Position
LWork	_010S191A	Latch in Work Position
DriveInDownPos	zzSeq[1].InPos[15].1	Lifter Motor Drive in Down Position
GC	_010S361B	RollerGate Closed
GO	_010S361A	RollerGate Open
RFIDOK	_010_RFID.ReadOK	Radio Frequency Identification is OK
FIFO200Rauto	zzSeq[1].Flag.8	FIFO from Robot 200R is in Automatic Mode
FIFO240Rauto	zzSeq[1].Flag.9	FIFO from Robot 240R is in Automatic Mode
FIFO200Req0	zzSeq[1].Flag.20	FIFO from Robot 200R is Zero
Fifo240Req0	zzSeq[1].Flag.22	FIFO from Robot 240R is Zero
FIFO200Rclrdat	zzSeq[1].Flag.10	FIFO from Robot 200R Data is Cleared
FIFO240Rclrdat	zzSeq[1].Flag.11	FIFO from Robot 240R Data is Cleared
Seq0	zzSeq[1].SeqTypeZero	Sequence Type is 0
T0	zzSeq[1].StnTypeZero	Station Type is 0
RFID0	zzSeq[1].Flag.30	Radio Frequency Identification is 0
Rel1	zzSeq[1].Release.1	Station 10 to Station 20 Exit Forward Request Release
DriveInUpPos	zzSeq[1].InPos[15].2	Lifter Motor Drive in Up Position

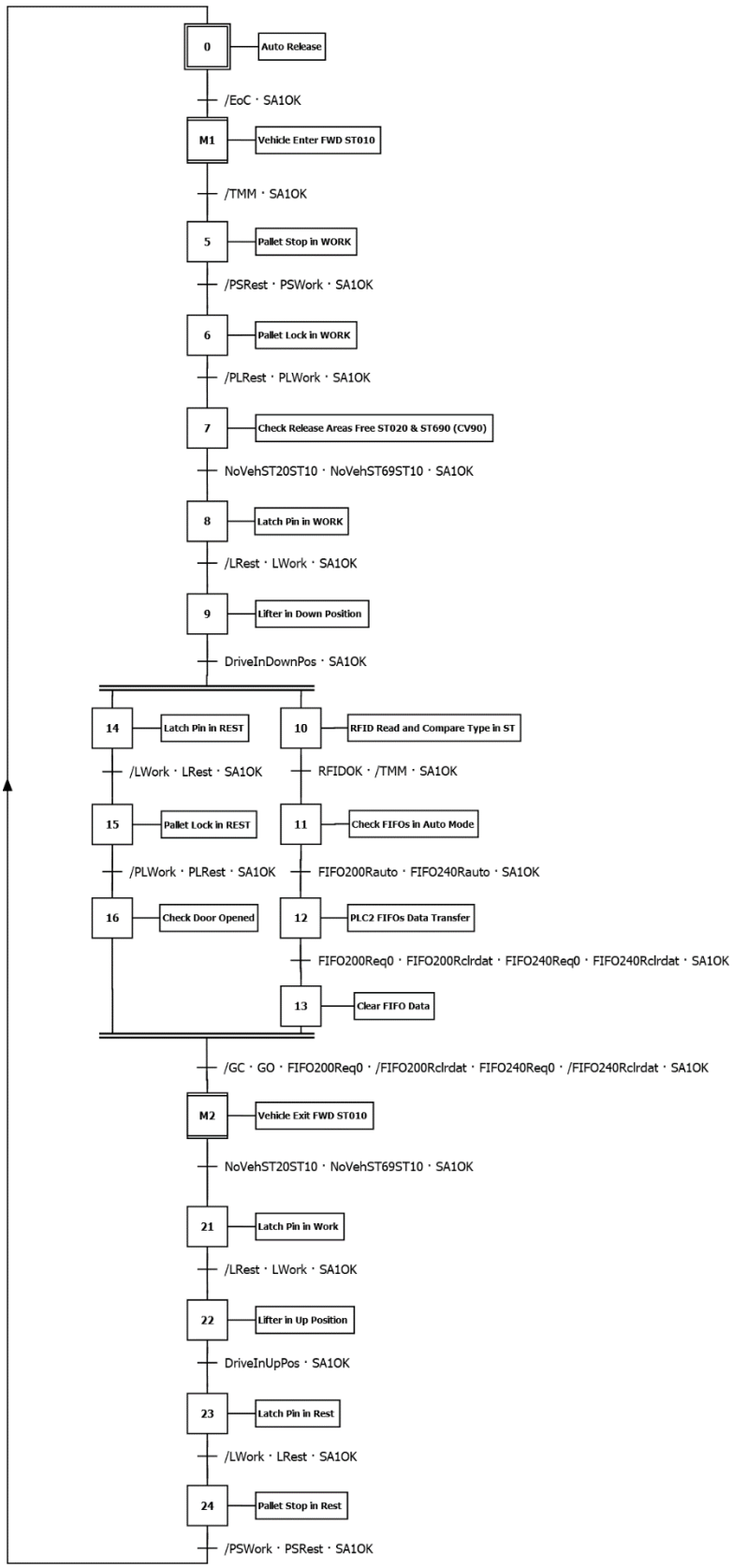

Figure 2.9. ST010 Lifter Sequence GRAFCET

2.2.2. ST020 Buffer

The buffer transports the vehicle from the station 10 lift to station 30. The transfer of vehicles between stations is carried out in three steps by means of linear synchronous motor technology instead of traditional roller beds. On the first step, the station is waiting for a vehicle to enter. In said step, initial conditions are verified. These include the motors not presenting any faults, a vehicle not being present in the station, and because of the location of this buffer, the lift's safety area not being perturbed. More details on how safety areas and the general safety concept works is provided in chapter 3.

The second step is reached when the release acknowledging permission for the vehicle to enter the station is active, which occurs when initial conditions are met and there is a vehicle awaiting to enter in the previous station. In the third step, the vehicle has reached the station. Once its correct position is verified by the motors sensors, type information is transferred from the previous station and is then verified with the actual type on the station on the following step to look out for a possible mismatch.

The exit process is the same in an inversed manner, waiting on step 5 in case the next station is blocked and releasing the vehicle in step 6 once conditions in the following station are adequate for entering. In step 7, the type information is cleared from the station as there is no longer a vehicle on it.

Table 2.2. ST20 Buffer Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[2].EOC	End of Cycle
BTTOK	_1_A2_32_512BT	Braking Transistor Temperature OK
MECP	_1_A2_32_2526CON_1	Motor Enable Contactor +
MECN	_1_A2_32_2526CON_2	Motor Enable Contactor -
MECF	_1_A2_32_2526CON_F	Motor Enable Contactor Feedback
NoVehST20ST10	zzSeq[2].Release.21	No Vehicle Between Stations 20 and 10
SA1OK	_SA01_2_SAFETY_AREA_OK	Safety Area 1 is OK
SA2OK	_SA02_2_SAFETY_AREA_OK	Safety Area 2 is OK
Rel2	zzSeq[2].Release.2	Station 20 to Station 10 Enter Forward Acknowledge Release
VIP	zzSeq[2].InPos[50].1	Vehicle In Position
HESOK	zzSeq[2].InPos[50].7	Hall Effect Sensor is OK
SeqOK	zzSeq[2].TypeOK	Sequence Type is OK
TFR	Type.InStation[2].13	Type Fixed Roof
TMR	Type.InStation[2].12	Type Moon Roof
Dry	Type.InStation[2].28	Type Dry Part
TMM	zzSeq[2].Flag.28	Type Miss Match
Rel1	zzSeq[2].Release.1	Station 20 to Station 30 Exit Forward Request Release
Seq0	zzSeq[2].SeqTypeZero	Sequence Type is 0
T0	zzSeq[2].StnTypeZero	Station Type is 0

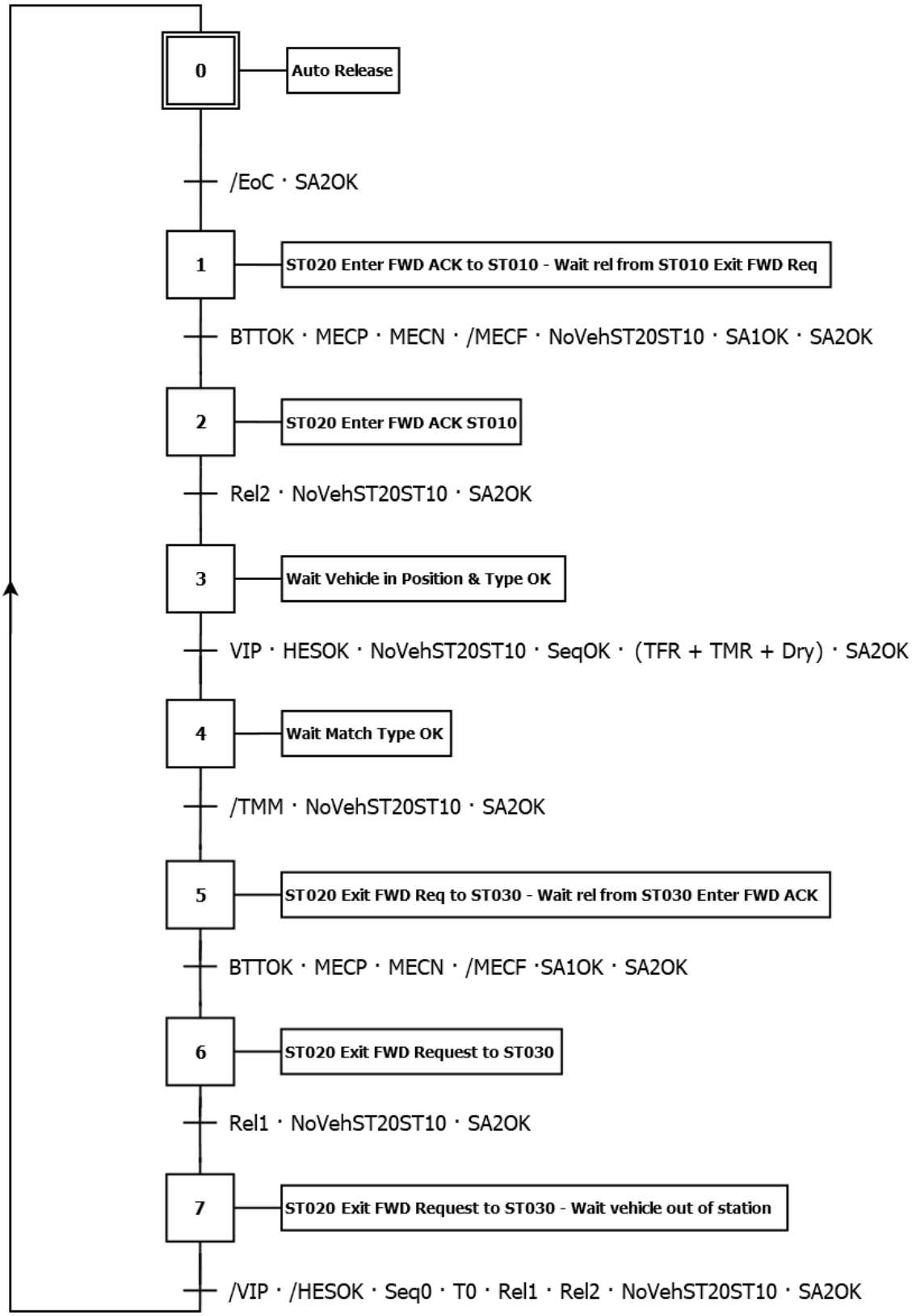

Figure 2.10. ST020 Buffer Sequence GRAFCET

2.2.3. ST030 Glue Station

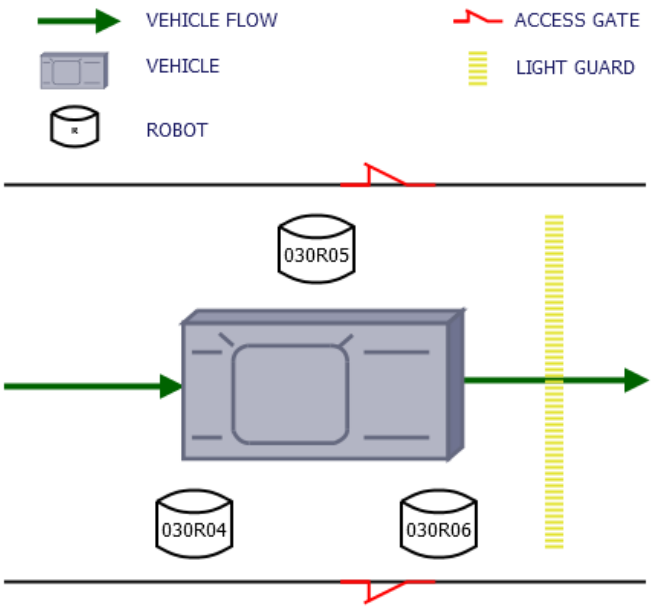

Figure 2.11. ST030 Layout

The station has three six-axis robots that put glue into the upper car body via an SCA SYS6000 adhesive bonding system. While the robots work on the vehicle, it is secured by a pallet lock which prevents movement that may be caused by the contact of the car body and the robot during the sealing process. Depending on the vehicle type, the robots apply a different sealing program, since the fixed roof variant body requires a larger surface area to be applied with glue.

Table 2.3. ST030 Glue Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[3].EOC	End of Cycle
BTTOK	_1_A2_33_512BT	Braking Transistor Temperature OK
MECP	_1_A2_33_2526CON_1	Motor Enable Contactor +
MECN	_1_A2_33_2526CON_2	Motor Enable Contactor -
MECF	_1_A2_33_2526CON_F	Motor Enable Contactor Feedback
SA2OK	_SA02_2_SAFETY_AREA_OK	Safety Area 2 is OK
SA3OK	_SA03_2_SAFETY_AREA_OK	Safety Area 3 is OK
RJD_4	zzSeq[3].JobDone.4	Robot Job Done 4: 030R04 Sealer Done
RJD_5	zzSeq[3].JobDone.5	Robot Job Done 5: 030R05 Sealer Done
RJD_6	zzSeq[3].JobDone.6	Robot Job Done 6: 030R06 Sealer Done
RJD_8	zzSeq[3].JobDone.8	Robot Job Done 8: 030R04-030R06 Sealer Done

Rel2	zzSeq[3].Release.2	Station 30 to Station 20 Enter Forward Acknowledge Release
VIP	zzSeq[3].InPos[50].1	Vehicle In Position
HESOK	zzSeq[3].InPos[50].7	Hall Effect Sensor is OK
SeqOK	zzSeq[3].TypeOK	Sequence Type is OK
TFR	Type.InStation[3].13	Type Fixed Roof
TMR	Type.InStation[3].12	Type Moon Roof
Dry	Type.InStation[3].28	Type Dry Part
TMM	zzSeq[3].Flag.28	Type Miss Match
PLRest	_030S601B	Pallet Lock in Rest Position
PLWork	_030S601A	Pallet Lock in Work Position
R_In(1,0)_7	Rob_In[1,0].7	030R04 in Home Position
R_In(2,0)_7	Rob_In[2,0].7	030R05 in Home Position
R_In(3,0)_7	Rob_In[3,0].7	030R06 in Home Position
R_In(1,0)_10	Rob_In[1,0].10	030R04 Program Request
R_In(2,0)_10	Rob_In[2,0].10	030R05 Program Request
R_In(3,0)_10	Rob_In[3,0].10	030R06 Program Request
R_In(1,1)_25	Rob_In[1,1].25	030R04 Cycle Complete Request
R_In(2,1)_25	Rob_In[2,1].25	030R05 Cycle Complete Request
R_In(3,1)_25	Rob_In[3,1].25	030R06 Cycle Complete Request
R_In(1,1)_10	Rob_In[1,1].10	030R04 Job Ready: Seal
R_In(2,1)_10	Rob_In[2,1].10	030R05 Job Ready: Seal
R_In(3,1)_10	Rob_In[3,1].10	030R06 Job Ready: Seal
RTK1	zzRobot[1].TypeOK	Robot 1 Type is OK
RTK2	zzRobot[2].TypeOK	Robot 2 Type is OK
RTK3	zzRobot[3].TypeOK	Robot 3 Type is OK
R_In(1,0)_3	Rob_In[1,0].3	030R04 Robot Fault
R_In(2,0)_3	Rob_In[2,0].3	030R05 Robot Fault
R_In(3,0)_3	Rob_In[3,0].3	030R06 Robot Fault
R_In(1,0)_1	Rob_In[1,0].1	030R04 in Automatic Mode
R_In(2,0)_1	Rob_In[2,0].1	030R05 in Automatic Mode
R_In(3,0)_1	Rob_In[3,0].1	030R06 in Automatic Mode
R_In(1,0)_5	Rob_In[1,0].5	030R04 Program Run
R_In(2,0)_5	Rob_In[2,0].5	030R05 Program Run
R_In(3,0)_5	Rob_In[3,0].5	030R06 Program Run
R_In(1,0)_4	Rob_In[1,0].4	030R04 in Fault
R_In(2,0)_4	Rob_In[2,0].4	030R05 in Fault
R_In(3,0)_4	Rob_In[3,0].4	030R06 in Fault
R_In(1,1)_18	Rob_In[1,1].18	030R04 Area Job Request
R_In(2,1)_18	Rob_In[2,1].18	030R05 Area Job Request
R_In(3,1)_18	Rob_In[3,1].18	030R06 Area Job Request
R_In(1,0)_16	Rob_In[1,0].16	030R04 Area Release Approach
R_In(2,0)_16	Rob_In[2,0].16	030R05 Area Release Approach
R_In(3,0)_16	Rob_In[3,0].16	030R06 Area Release Approach
R_In(1,0)_18	Rob_In[1,0].18	030R04 Area Release Seal
R_In(2,0)_18	Rob_In[2,0].18	030R05 Area Release Seal
R_In(3,0)_18	Rob_In[3,0].18	030R06 Area Release Seal
R_Out(1,0)_16	Rob_Out[1,0].16	030R04 Area Ready Approach

R_Out(2,0)_16	Rob_Out[2,0].16	030R05 Area Ready Approach
R_Out(3,0)_16	Rob_Out[3,0].16	030R06 Area Ready Approach
R_Out(1,0)_18	Rob_Out[1,0].18	030R04 Area Ready Seal
R_Out(2,0)_18	Rob_Out[2,0].18	030R05 Area Ready Seal
R_Out(3,0)_18	Rob_Out[3,0].18	030R06 Area Ready Seal
Rel1	zzSeq[3].Release.1	Station 30 to Station 40 Exit Forward Request Release
Seq0	zzSeq[3].SeqTypeZero	Sequence Type is 0
T0	zzSeq[3].StnTypeZero	Station Type is 0

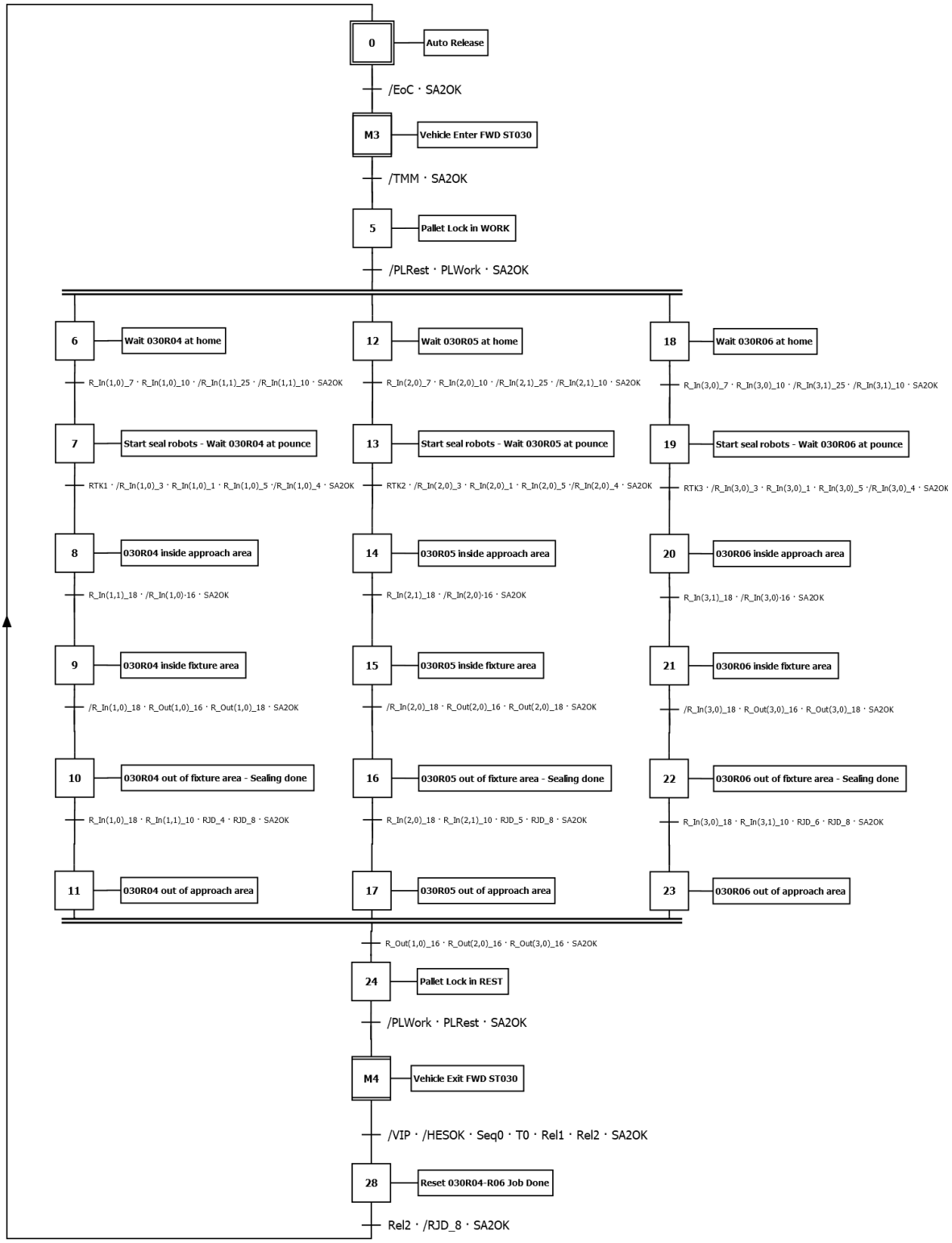

Figure 2.12. ST30 Glue Sequence GRAFCET

2.2.4. ST040 Buffer

This buffer works in the same manner as the one described on section 2.2.2, considering the neighboring safety area 2. It transports the vehicle from the glue station into the roof placement station.

Table 2.4. ST40 Buffer Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[4].EOC	End of Cycle
BTTOK	_1_A2_41_512BT	Braking Transistor Temperature OK
MECP	_1_A2_41_2526CON_1	Motor Enable Contactor +
MECN	_1_A2_41_2526CON_2	Motor Enable Contactor -
MECF	_1_A2_41_2526CON_F	Motor Enable Contactor Feedback
SA2OK	_SA02_2_SAFETY_AREA_OK	Safety Area 2 is OK
SA3OK	_SA03_2_SAFETY_AREA_OK	Safety Area 3 is OK
Rel2	zzSeq[4].Release.2	Station 40 to Station 30 Enter Forward Acknowledge Release
VIP	zzSeq[4].InPos[50].1	Vehicle In Position
HESOK	zzSeq[4].InPos[50].7	Hall Effect Sensor is OK
SeqOK	zzSeq[4].TypeOK	Sequence Type is OK
TFR	Type.InStation[4].13	Type Fixed Roof
TMR	Type.InStation[4].12	Type Moon Roof
Dry	Type.InStation[4].28	Type Dry Part
TMM	zzSeq[4].Flag.28	Type Miss Match
Rel1	zzSeq[4].Release.1	Station 40 to Station 50 Exit Forward Request Release
Seq0	zzSeq[4].SeqTypeZero	Sequence Type is 0
T0	zzSeq[4].StnTypeZero	Station Type is 0

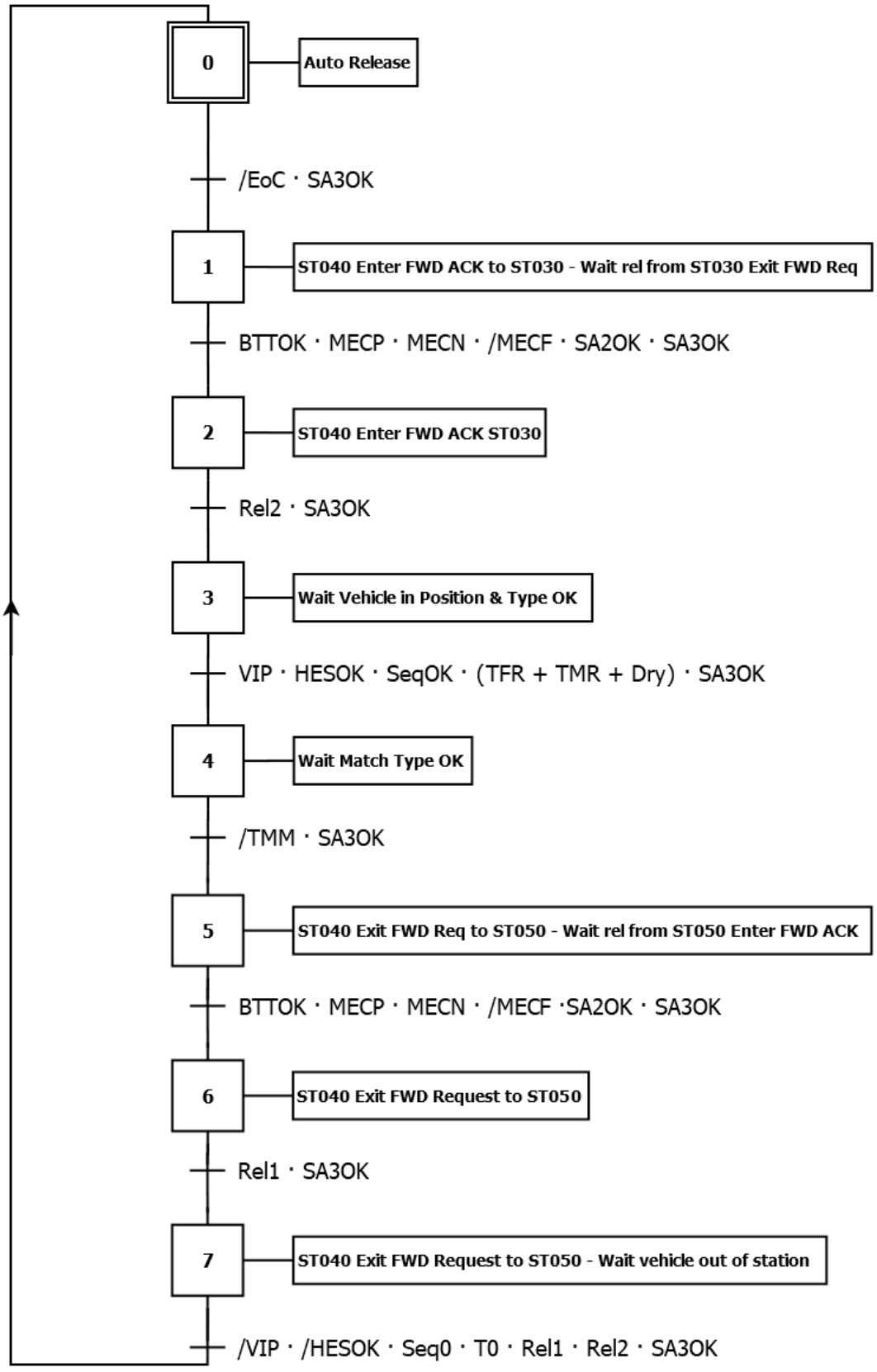

Figure 2.13. ST40 Buffer Sequence GRAFCET

2.2.5. ST050 Roof Placement Station

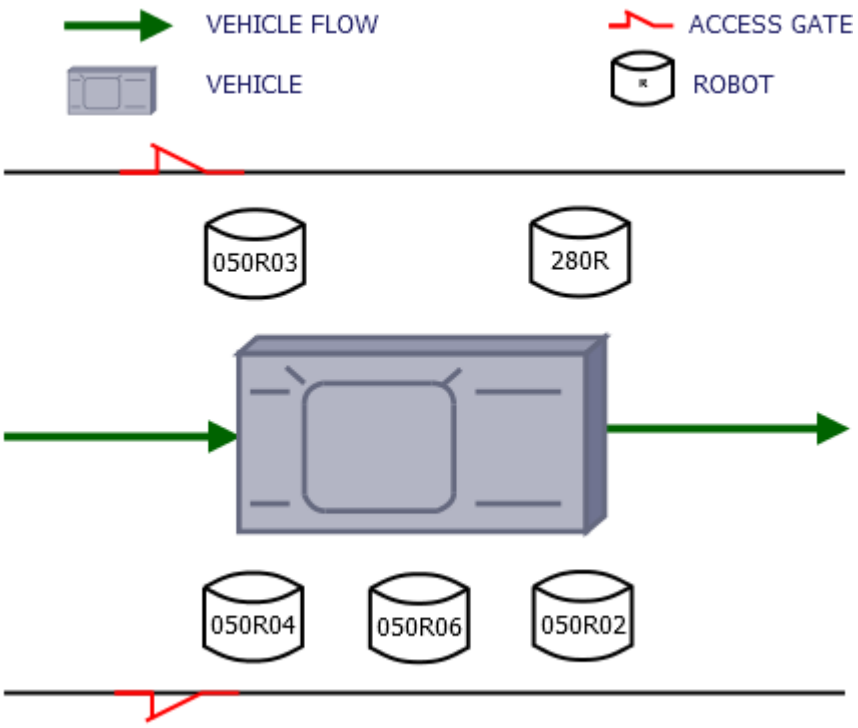

Figure 2.14. ST050 Layout

The roof placement station is the most critical phase in the process, it consists of four six-axis robots which work together with the 280R gripper robot, whose sequence is described in section 2.2.7. The robots perform both tasks of measuring and riveting as described later.

As the vehicle enters the station, its type information is confirmed by both RFID and by barcode. The RFID hardware is the same as the one used in station 30, as specified in section 2.2.3. In addition, identification by barcode is employed. The pallet transporting the vehicle body is fitted with a barcode containing the vehicle's data. It is read by an opto-electronic sensor, specifically a SICK CLV690 device that decodes the barcode and sends the data content to the PLC through an ethernet connection. It is then compared to the RFID and the station data to look for a mismatch.

Figure 2.15. SICK CLV690 barcode reader used in the line. [3]

Once the vehicle's type is confirmed, it is secured in place by the pallet locker. Then, robots 050R03 and 050R04 use their attached cameras to take a picture of the top part of the car body to be analyzed by the ISRA vision system, which has its own PC in the line for image and measuring processing. This picture processing validates that the car body is suitable to receive the roof part by the 280R gripper robot.

After the roof part is placed on the body, the four 050R robots measure the part with attached sensors, the measurements are then processed by the ISRA vision system which checks for possible imperfections on the roof part and its placement which may affect production quality. Once validated, the four robots proceed to rivet the part into the car body applying the adequate program depending on the vehicle variant. Finally, the pallet lock is released and the vehicle advances into buffer station 60.

Table 2.5. ST50 Roof Placement Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[5].EOC	End of Cycle
BTTOK	_1_A2_42_512BT	Braking Transistor Temperature OK
MECP	_1_A2_42_2526CON_1	Motor Enable Contactor +
MECN	_1_A2_42_2526CON_2	Motor Enable Contactor -
MECF	_1_A2_42_2526CON_F	Motor Enable Contactor Feedback
SA3OK	_SA03_2_SAFETY_AREA_OK	Safety Area 3 is OK
RJD_1	zzSeq[5].JobDone.1	Robot Job Done 1: 280R Part Dropped
RJD_2	zzSeq[5].JobDone.2	Robot Job Done 2: 050R02 Part Riveted
RJD_3	zzSeq[5].JobDone.3	Robot Job Done 3: 050R03 Part Riveted
RJD_4	zzSeq[5].JobDone.4	Robot Job Done 4: 050R04 Part Riveted
RJD_6	zzSeq[5].JobDone.6	Robot Job Done 6: 050R06 Part Riveted
RJD_8	zzSeq[5].JobDone.8	Robot Job Done 8: 050R02-050R06 Part Riveted
Rel2	zzSeq[5].Release.2	Station 50 to Station 40 Enter Forward Acknowledge Release

BCROK	zzSeq[5].BCR1.BC.ReadOK	Barcode Read OK
BCRNK	zzSeq[5].BCR1.BC.ReadNOK	Barcode Read Not OK
VIP	zzSeq[5].InPos[50].1	Vehicle In Position
HESOK	zzSeq[5].InPos[50].7	Hall Effect Sensor is OK
SeqOK	zzSeq[5].TypeOK	Sequence Type is OK
TFR	Type.InStation[5].13	Type Fixed Roof
TMR	Type.InStation[5].12	Type Moon Roof
Dry	Type.InStation[5].28	Type Dry Part
RFIDOK	_050_RFID.ReadOK	Radio Frequency Identification is OK
TMM	zzSeq[5].Flag.28	Type Miss Match
PLRest	_050S601B	Pallet Lock in Rest Position
PLWork	_050S601A	Pallet Lock in Work Position
R_In(4,0)_7	Rob_In[4,0].7	050R02 in Home Position
R_In(5,0)_7	Rob_In[5,0].7	050R03 in Home Position
R_In(6,0)_7	Rob_In[6,0].7	050R04 in Home Position
R_In(7,0)_7	Rob_In[7,0].7	050R06 in Home Position
RTK1	zzRobot[4].TypeOK	Robot 1 Type is OK
RTK2	zzRobot[5].TypeOK	Robot 2 Type is OK
RTK3	zzRobot[6].TypeOK	Robot 3 Type is OK
RTK4	zzRobot[7].TypeOK	Robot 4 Type is OK
R_In(4,0)_10	Rob_In[4,0].10	050R02 Program Request
R_In(5,0)_10	Rob_In[5,0].10	050R03 Program Request
R_In(6,0)_10	Rob_In[6,0].10	050R04 Program Request
R_In(7,0)_10	Rob_In[7,0].10	050R06 Program Request
R_In(4,1)_25	Rob_In[4,1].25	050R02 Cycle Complete Request
R_In(5,1)_25	Rob_In[5,1].25	050R03 Cycle Complete Request
R_In(6,1)_25	Rob_In[6,1].25	050R04 Cycle Complete Request
R_In(7,1)_25	Rob_In[7,1].25	050R06 Cycle Complete Request
R_In(4,1)_8	Rob_In[4,1].8	050R02 Job Ready: Measure
R_In(5,1)_8	Rob_In[5,1].8	050R03 Job Ready: Measure
R_In(6,1)_8	Rob_In[6,1].8	050R04 Job Ready: Measure
R_In(7,1)_8	Rob_In[7,1].8	050R06 Job Ready: Measure
R_In(4,1)_10	Rob_In[4,1].10	050R02 Job Ready: Rivet
R_In(5,1)_10	Rob_In[5,1].10	050R03 Job Ready: Rivet
R_In(6,1)_10	Rob_In[6,1].10	050R04 Job Ready: Rivet
R_In(7,1)_10	Rob_In[7,1].10	050R06 Job Ready: Rivet
R_In(4,0)_3	Rob_In[4,0].3	050R02 Robot Fault
R_In(5,0)_3	Rob_In[5,0].3	050R03 Robot Fault
R_In(6,0)_3	Rob_In[6,0].3	050R04 Robot Fault
R_In(7,0)_3	Rob_In[7,0].3	050R06 Robot Fault
R_In(4,0)_1	Rob_In[4,0].1	050R02 in Automatic Mode
R_In(5,0)_1	Rob_In[5,0].1	050R03 in Automatic Mode
R_In(6,0)_1	Rob_In[6,0].1	050R04 in Automatic Mode
R_In(7,0)_1	Rob_In[7,0].1	050R06 in Automatic Mode
R_In(4,0)_5	Rob_In[4,0].5	050R02 Program Run
R_In(5,0)_5	Rob_In[5,0].5	050R03 Program Run
R_In(6,0)_5	Rob_In[6,0].5	050R04 Program Run
R_In(7,0)_5	Rob_In[7,0].5	050R06 Program Run

R_In(4,0)_4	Rob_In[4,0].4	050R02 in Fault
R_In(5,0)_4	Rob_In[5,0].4	050R03 in Fault
R_In(6,0)_4	Rob_In[6,0].4	050R04 in Fault
R_In(7,0)_4	Rob_In[7,0].4	050R06 in Fault
R_In(5,1)_17	Rob_In[5,1].17	050R03 Area Job Request General Photo
R_In(6,1)_17	Rob_In[6,1].17	050R04 Area Job Request General Photo
R_Out(5,0)_17	Rob_Out[5,0].17	050R03 Area Ready General Photo
R_Out(6,0)_17	Rob_Out[6,0].17	050R04 Area Ready General Photo
R_In(5,0)_17	Rob_In[5,0].17	050R03 Area Release General Photo
R_In(6,0)_17	Rob_In[6,0].17	050R04 Area Release General Photo
R_In(5,1)_9	Rob_In[5,1].9	050R03 Job Ready General Photo
R_In(6,1)_9	Rob_In[6,1].9	050R04 Job Ready General Photo
R_In(8,1)_20	Rob_In[8,1].20	280R Area Job Request Measure
R_In(8,1)_12	Rob_In[8,1].12	280R Job Ready Measure
R_In(8,1)_13	Rob_In[8,1].13	280R Job Ready Drop Part
RemRel3	zzSeq[6].Release.3	Fixed Roof Type Remote Release from 280R Sequence
RemRel4	zzSeq[6].Release.4	Moon Roof Type Remote Release from 280R Sequence
Flag_29	zzSeq[5].Flag.29	Match Robot with Station Type Flag
R_Out(8,0)_20	Rob_Out[8,0].20	280R Area Ready Measure
R_In(8,0)_20	Rob_In[8,0].20	280R Area Release Measure
R_In(8,1)_4	Rob_In[8,1].4	280R Tool Request Measure
R_In(4,1)_16	Rob_In[4,1].16	050R02 Area Job Request Measure
R_In(5,1)_16	Rob_In[5,1].16	050R03 Area Job Request Measure
R_In(6,1)_16	Rob_In[6,1].16	050R04 Area Job Request Measure
R_In(7,1)_16	Rob_In[7,1].16	050R06 Area Job Request Measure
R_In(4,0)_16	Rob_In[4,0].16	050R02 Area Job Release Measure
R_In(5,0)_16	Rob_In[5,0].16	050R03 Area Job Release Measure
R_In(6,0)_16	Rob_In[6,0].16	050R04 Area Job Release Measure
R_In(7,0)_16	Rob_In[7,0].16	050R06 Area Job Release Measure
R_In(8,1)_21	Rob_In[8,1].21	280R Area Job Request Drop
R_Out(8,0)_21	Rob_Out[8,0].21	280R Area Ready Drop
R_In(8,0)_21	Rob_In[8,0].21	280R Area Release Drop
R_In(4,1)_18	Rob_In[4,1].18	050R02 Area Job Request Rivet
R_In(5,1)_18	Rob_In[5,1].18	050R03 Area Job Request Rivet
R_In(6,1)_18	Rob_In[6,1].18	050R04 Area Job Request Rivet
R_In(7,1)_18	Rob_In[7,1].18	050R06 Area Job Request Rivet
R_Out(4,0)_18	Rob_Out[4,0].18	050R02 Area Ready Rivet
R_Out(5,0)_18	Rob_Out[5,0].18	050R03 Area Ready Rivet
R_Out(6,0)_18	Rob_Out[6,0].18	050R04 Area Ready Rivet
R_Out(7,0)_18	Rob_Out[7,0].18	050R06 Area Ready Rivet
R_In(4,0)_18	Rob_In[4,0].18	050R02 Area Release Rivet
R_In(5,0)_18	Rob_In[5,0].18	050R03 Area Release Rivet
R_In(6,0)_18	Rob_In[6,0].18	050R04 Area Release Rivet
R_In(7,0)_18	Rob_In[7,0].18	050R06 Area Release Rivet
R_In(4,1)_2	Rob_In[4,1].2	050R02 Tool Request Rivet
R_In(5,1)_2	Rob_In[5,1].2	050R03 Tool Request Rivet

R_Out(4,1)_2	Rob_Out[4,1].2	050R02 Tool Ready Rivet
R_Out(5,1)_2	Rob_Out[5,1].2	050R03 Tool Ready Rivet
Rel1	zzSeq[5].Release.1	Station 50 to Station 60 Exit Forward Request Release
Seq0	zzSeq[5].SeqTypeZero	Sequence Type is 0
T0	zzSeq[5].StnTypeZero	Station Type is 0

Figure 2.16. ST50 Roof placement Sequence GRAFCET

2.2.6. ST060 Buffer

The third buffer of the line works as the rest of the buffers as described in section 2.2.2, taking into account the dividing roller gate, which separates the safety areas controlled by PLC1 and PLC3.

Table 2.6. ST60 Buffer Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[7].EOC	End of Cycle
BTTOK	_1_A2_43_512BT	Braking Transistor Temperature OK
MECP	_1_A2_43_2526CON_1	Motor Enable Contactor +
MECN	_1_A2_43_2526CON_2	Motor Enable Contactor -
MECF	_1_A2_43_2526CON_F	Motor Enable Contactor Feedback
SA3OK	_SA03_2_SAFETY_AREA_OK	Safety Area 3 is OK
SA5OK	EZ22_3_033_1_9.SA05_OK	Safety Area 5 is OK
Rel2	zzSeq[7].Release.2	Station 60 to Station 50 Enter Forward Acknowledge Release
VIP	zzSeq[7].InPos[50].1	Vehicle In Position
HESOK	zzSeq[7].InPos[50].7	Hall Effect Sensor is OK
SeqOK	zzSeq[7].TypeOK	Sequence Type is OK
TFR	Type.InStation[7].13	Type Fixed Roof
TMR	Type.InStation[7].12	Type Moon Roof
Dry	Type.InStation[7].28	Type Dry Part
TMM	zzSeq[7].Flag.28	Type Miss Match
GC	_060S361B	RollerGate Closed
GO	_060S361A	RollerGate Open
Rel1	zzSeq[7].Release.1	Station 60 to Station 70 Exit Forward Request Release
Seq0	zzSeq[7].SeqTypeZero	Sequence Type is 0
T0	zzSeq[7].StnTypeZero	Station Type is 0

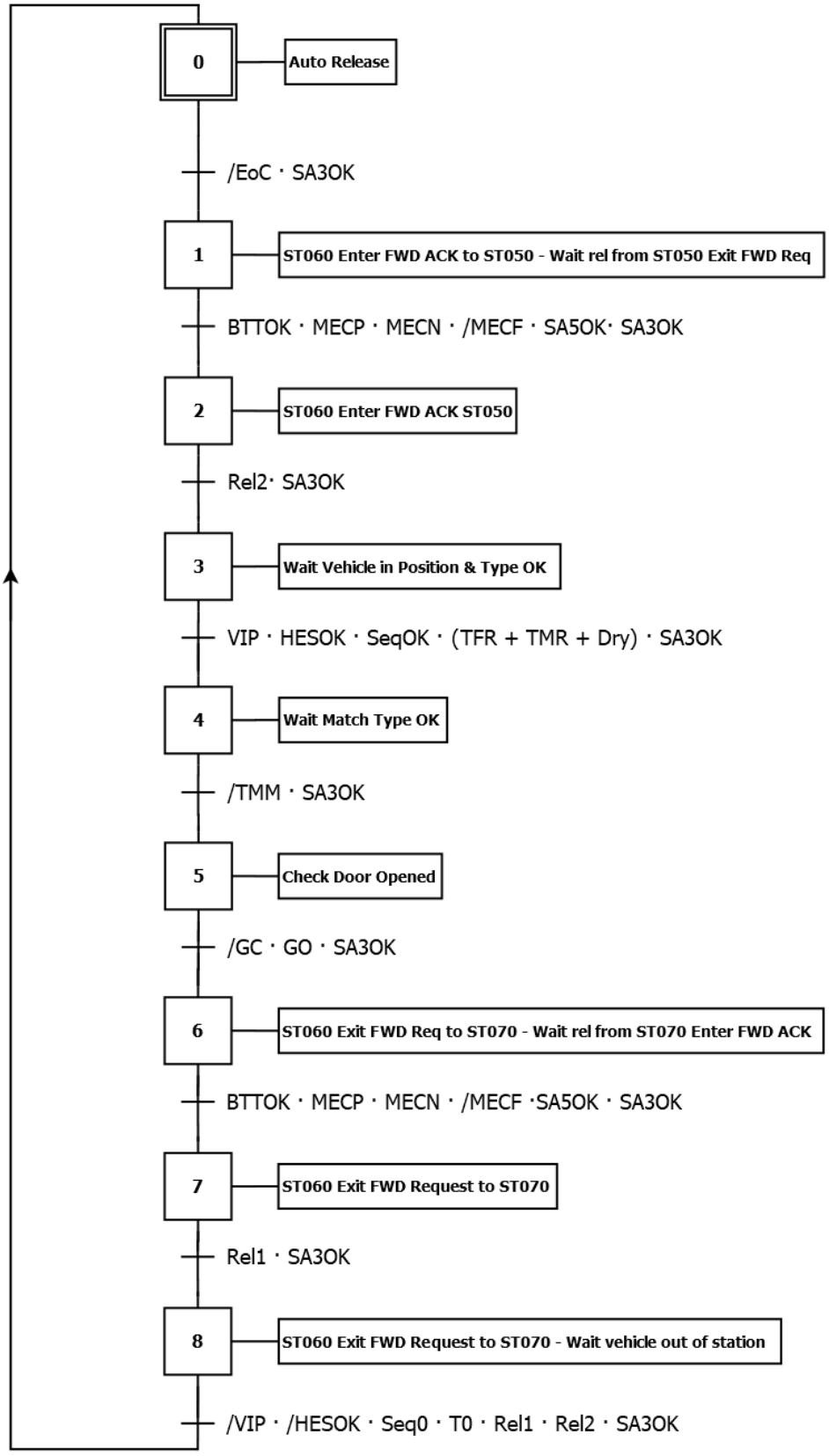

Figure 2.17. ST60 Buffer Sequence GRAFCET

2.2.7. 280R Gripper Roof Placement Robot

The 280R gripper is a six-axis robot with a gripper which enables it to pick and place roof parts. It collects the piece from the fixture station 281 in PLC2 to place it into the car body in station 50 of the PLC1. Since the robot moves between two PLCs and consequently two safety areas, it is affected whenever safety area 3 (PLC1) or 4 (PLC2) are down. When placing the roof on top of the car body, it remains in this position holding the part into the body during all the measuring and riveting processes of the station 50 robots, returning to home position only after the vehicle is ready to leave station 50.

Table 2.7. 280R Gripper Roof Placement Robot Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[6].EOC	End of Cycle
SA3OK	_SA03_2_SAFETY_AREA_OK	Safety Area 3 is OK
R_In(8,0)_7	Rob_In[8,0].7	280R in Home Position
R_In(8,0)_10	Rob_In[8,0].10	280R Program Request
T0	zzSeq[6].StnTypeZero	Station Type is 0
TFR	Type.InStation[6].13	Type Fixed Roof
TMR	Type.InStation[6].12	Type Moon Roof
NTFR	zzSeq[6].Flag.0	Next Type to build Fixed Roof
NTMR	zzSeq[6].Flag.1	Next Type to build Moon Roof
TMM	zzSeq[6].Flag.28	Type Miss Match
RTK	zzRobot[8].TypeOK	Robot Type is OK
R_In(8,0)_3	Rob_In[8,0].3	280R Robot Fault
R_In(8,0)_1	Rob_In[8,0].1	280R in Automatic Mode
R_In(8,0)_5	Rob_In[8,0].5	280R Program Run
R_In(8,0)_4	Rob_In[8,0].4	280R in Fault
R_Out(8,0)_12	Rob_Out[8,0].12	280R Return to Home Position
R_In(8,1)_25	Rob_In[8,1].25	280R Cycle Complete Request
R_Out(8,0)_16	Rob_Out[8,0].16	280R Area Ready Pick STN281
R_Out(8,0)_20	Rob_Out[8,0].20	280R Area Ready Measure
R_Out(8,0)_21	Rob_Out[8,0].21	280R Area Ready Drop
R_In(8,1)_8	Rob_In[8,1].8	280R Job Ready Pick STN281
R_In(8,1)_12	Rob_In[8,1].12	280R Job Ready Measure
R_In(8,1)_13	Rob_In[8,1].13	280R Job Ready Drop ST50

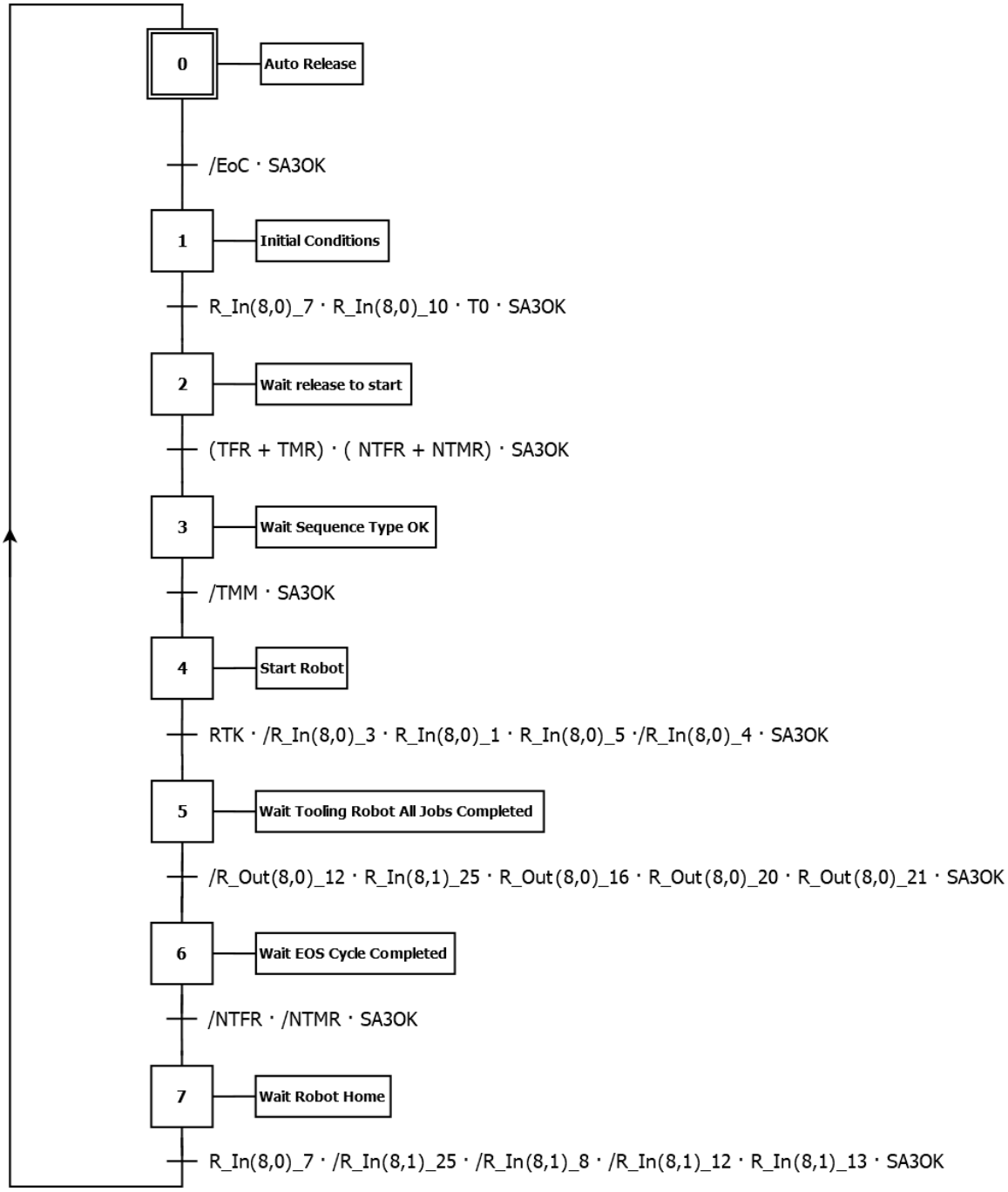

Figure 2.18. 280R Robot Roof placement Sequence GRAFCET

2.3. PLC2

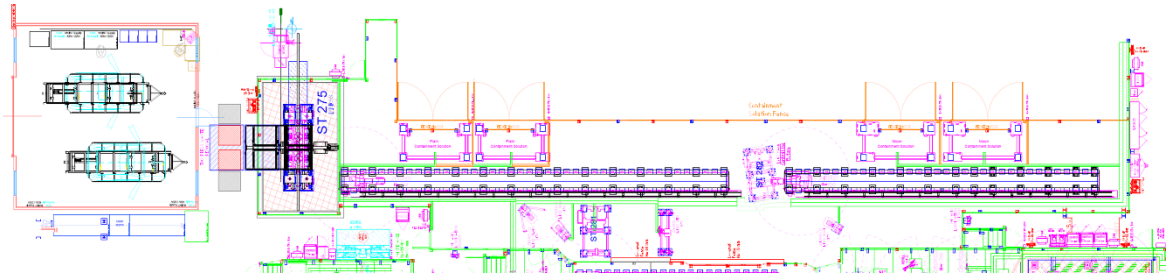

Figure 2.19. PLC2 Area Floorplan

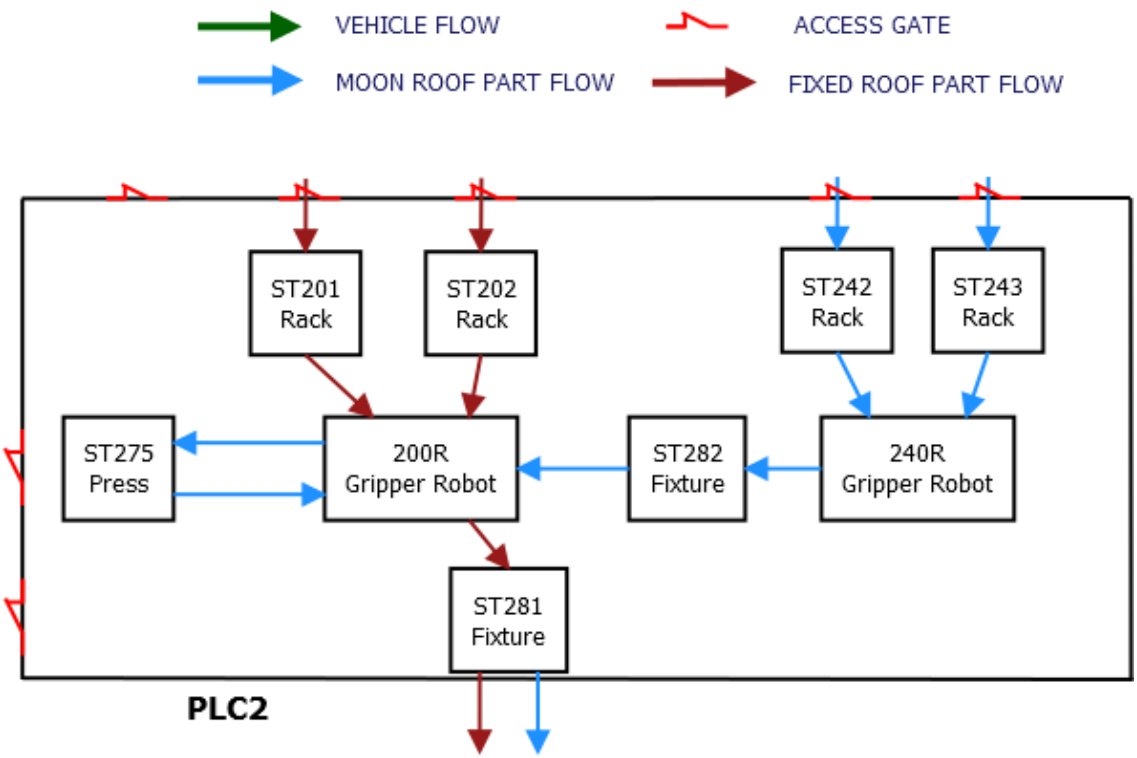

Figure 2.20. PLC2 Area Flowchart

The PLC2 area contains a total of nine stations, seven access gates, two robots and a large single safety area. As explained in section 2.1, fixed and moon roof parts differ and consequently follow a different flow through the stations.

2.3.1. Rack Stations

As it was mentioned in section 2.1, the parts supplier provides the roof parts in transport racks which are mounted into the rack stations. The operator must request to open the rack gate and proceed to

manually load the rack into the station with the aid of a forklift. Once the rack is placed on the station, the operator shall lock the gate to allow for the automatic process to continue. Inductive sensors will detect the rack is present and correctly aligned, which will allow for two vertical location pins to rise into the work position securing the rack in place. As the pins rise, these will also push the rack's transport locks, which hold the roof parts correctly aligned and in place, into the rest position to allow the gripper robots to pick them from the rack. A 5 second timer has been added to secure the transport locks are correctly retracted. The last part in the rack is monitored by a laser sensor, this way the station controls when the rack is empty. When empty, the location pins are lowered to allow for extraction of the rack by the operator with the aid of a forklift.

2.3.1.1. ST201

As a fixed roof rack, parts are picked by gripper robot 200R whenever the alternative fixed roof rack station 202 is not ready for pick. When the rack gate is opened for loading and unloading of racks, it will only affect 200R gripper robot instead of causing the whole safety area to go down.

Table 2.8. ST201 Fixed Roof Rack Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[25].EOC	End of Cycle
SA4OK	_SA04_2_SAFETY_AREA_OK	Safety Area 4 is OK
Rel2	zzSeq[25].Release.2	Station 201 Not Ready for Pick Release
2A520_CH1	_2A520_CH1	Gate 520 Closed Channel 1
2A520_CH2	_2A520_CH2	Gate 520 Closed Channel 2
2A520_GOK	_2A520_GATE_OK	Gate 520 Closed OK
S501	_201S501	Rack Present Sensor 501
S502	_201S502	Rack Present Sensor 502
S521	_201S521	Check last Part in Rack Sensor
LPRest	_201S611B	Left Location Pin in Rest Position
LPWork	_201S611A	Left Location Pin in Work Position
RPRest	_201S612B	Right Location Pin in Rest Position
RPWork	_201S612A	Right Location Pin in Work Position
Tim201	_201TIM_TRLOCK_OPEN.DN	Timer to ensure Transport Lock is Open
LTLWork	_201S601A	Left Transport Lock in Work Position
LTLRest	_201S601B	Left Transport Lock in Rest Position
RTLWork	_201S602A	Right Transport Lock in Work Position
RTLRest	_201S602B	Right Transport Lock in Rest Position
ST202_Rel2	zzSeq[26].Release.2	Station 202 Not Ready for Pick Release
Rel1	zzSeq[25].Release.1	Station 201 Release to Start 200R Release
R_In(1,0)_16	Rob_In[1,0].16	200R Area Release Pick Rack ST201

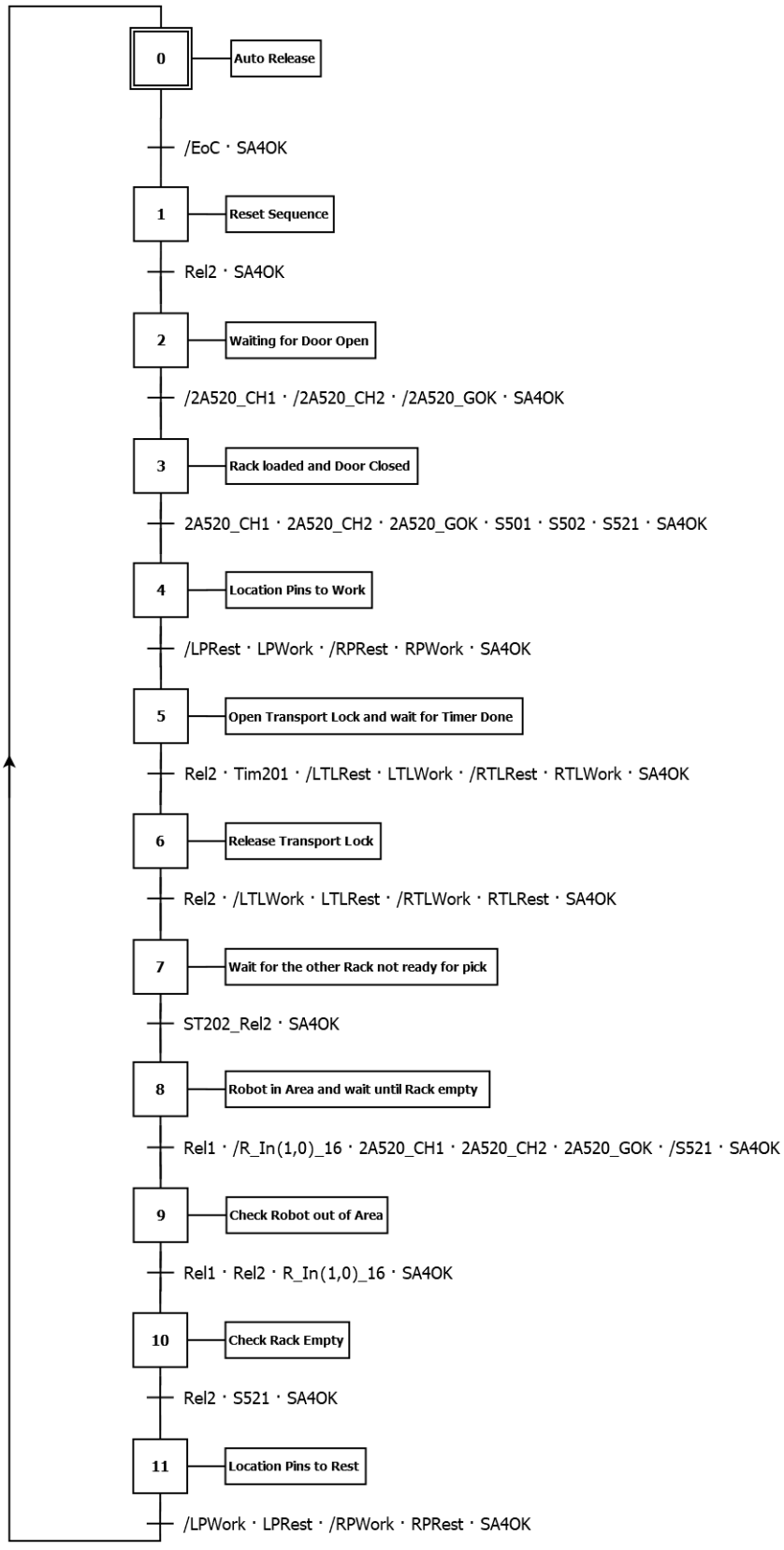

Figure 2.21. ST201 Fixed Roof Rack Sequence GRAFCET

2.3.1.2. ST202

As a fixed roof rack, parts are picked by gripper robot 200R whenever the alternative fixed roof rack station 201 is not ready for pick. When the rack gate is opened for loading and unloading of racks, it will only affect 200R gripper robot instead of causing the whole safety area to go down.

Table 2.9. ST202 Fixed Roof Rack Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[26].EOC	End of Cycle
SA4OK	_SA04_2_SAFETY_AREA_OK	Safety Area 4 is OK
Rel2	zzSeq[26].Release.2	Station 202 Not Ready for Pick Release
2A521_CH1	_2A521_CH1	Gate 521 Closed Channel 1
2A521_CH2	_2A521_CH2	Gate 521 Closed Channel 2
2A521_GOK	_2A521_GATE_OK	Gate 521 Closed OK
S501	_202S501	Rack Present Sensor 501
S502	_202S502	Rack Present Sensor 502
S521	_202S521	Check last Part in Rack Sensor
LPRest	_202S611B	Left Location Pin in Rest Position
LPWork	_202S611A	Left Location Pin in Work Position
RPRest	_202S612B	Right Location Pin in Rest Position
RPWork	_202S612A	Right Location Pin in Work Position
Tim202	_202TIM_TRLOCK_OPEN.DN	Timer to ensure Transport Lock is Open
LTLWork	_202S601A	Left Transport Lock in Work Position
LTLRest	_202S601B	Left Transport Lock in Rest Position
RTLWork	_202S602A	Right Transport Lock in Work Position
RTLRest	_202S602B	Right Transport Lock in Rest Position
ST201_Rel2	zzSeq[25].Release.2	Station 201 Not Ready for Pick Release
Rel1	zzSeq[26].Release.1	Station 202 Release to Start 200R Release
R_In(1,0)_17	Rob_In[1,0].17	200R Area Release Pick Rack ST202

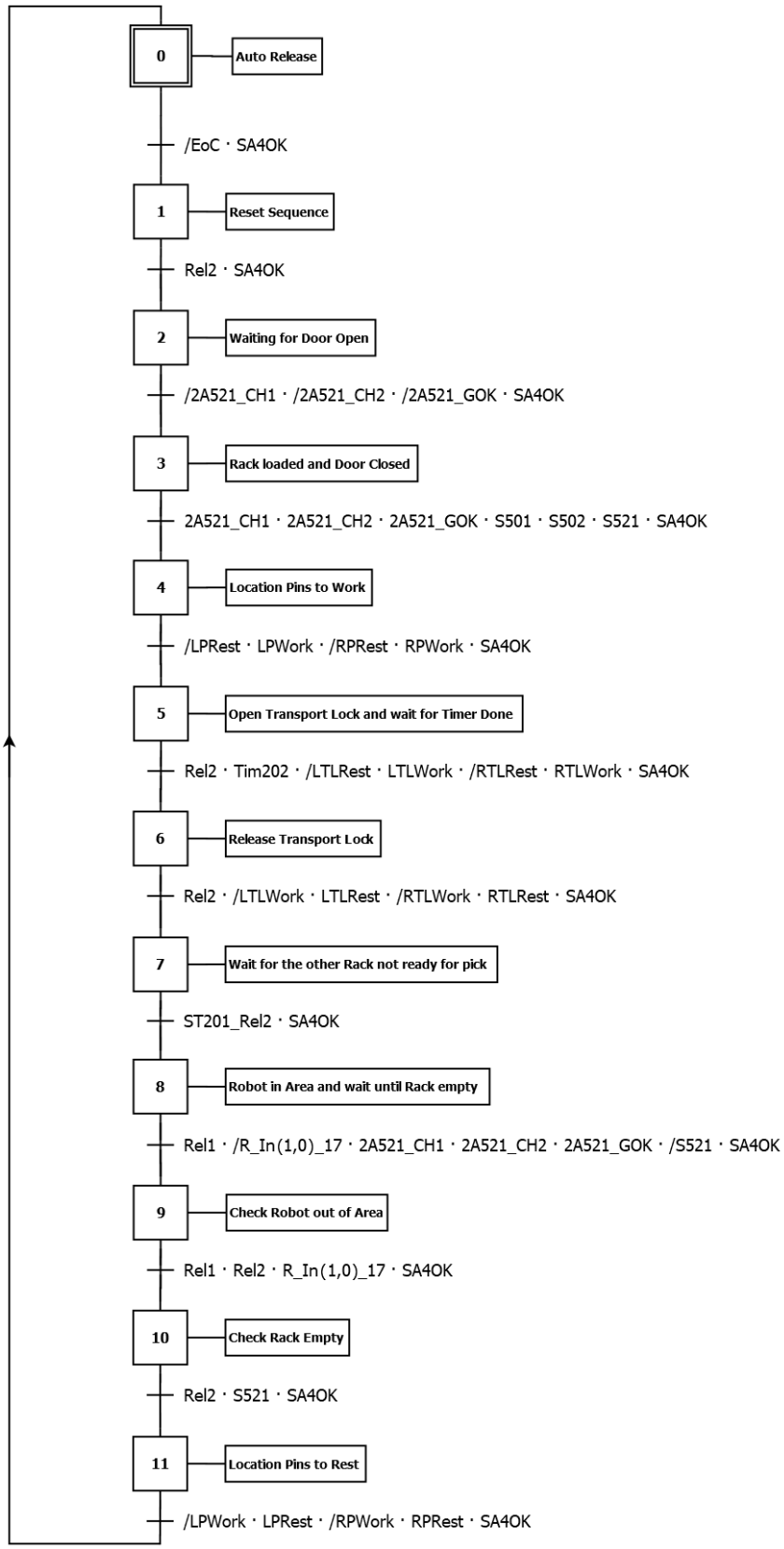

Figure 2.22. ST202 Fixed Roof Rack Sequence GRAFCET

2.3.1.3. ST242

As a moon roof rack, parts are picked by gripper robot 240R whenever the alternative moon roof rack station 243 is not ready for pick. When the rack gate is opened for loading and unloading of racks, it will only affect 240R gripper robot instead of causing the whole safety area to go down.

Table 2.10. ST242 Moon Roof Rack Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[27].EOC	End of Cycle
SA4OK	_SA04_2_SAFETY_AREA_OK	Safety Area 4 is OK
Rel2	zzSeq[27].Release.2	Station 243 Not Ready for Pick Release
2A522_CH1	_2A522_CH1	Gate 522 Closed Channel 1
2A522_CH2	_2A522_CH2	Gate 522 Closed Channel 2
2A522_GOK	_2A522_GATE_OK	Gate 522 Closed OK
S501	_242S501	Rack Present Sensor 501
S502	_242S502	Rack Present Sensor 502
S521	_242S521	Check last Part in Rack Sensor
LPRest	_242S611B	Left Location Pin in Rest Position
LPWork	_242S611A	Left Location Pin in Work Position
RPRest	_242S612B	Right Location Pin in Rest Position
RPWork	_242S612A	Right Location Pin in Work Position
Tim242	_242TIM_TRLOCK_OPEN.DN	Timer to ensure Transport Lock is Open
LTLWork	_242S601A	Left Transport Lock in Work Position
LTLRest	_242S601B	Left Transport Lock in Rest Position
RTLWork	_242S602A	Right Transport Lock in Work Position
RTLRest	_242S602B	Right Transport Lock in Rest Position
ST243_Rel2	zzSeq[28].Release.2	Station 243 Not Ready for Pick Release
Rel1	zzSeq[27].Release.1	Station 242 Release to Start 240R Release
R_In(2,0)_17	Rob_In[2,0].17	240R Area Release Pick Rack ST242

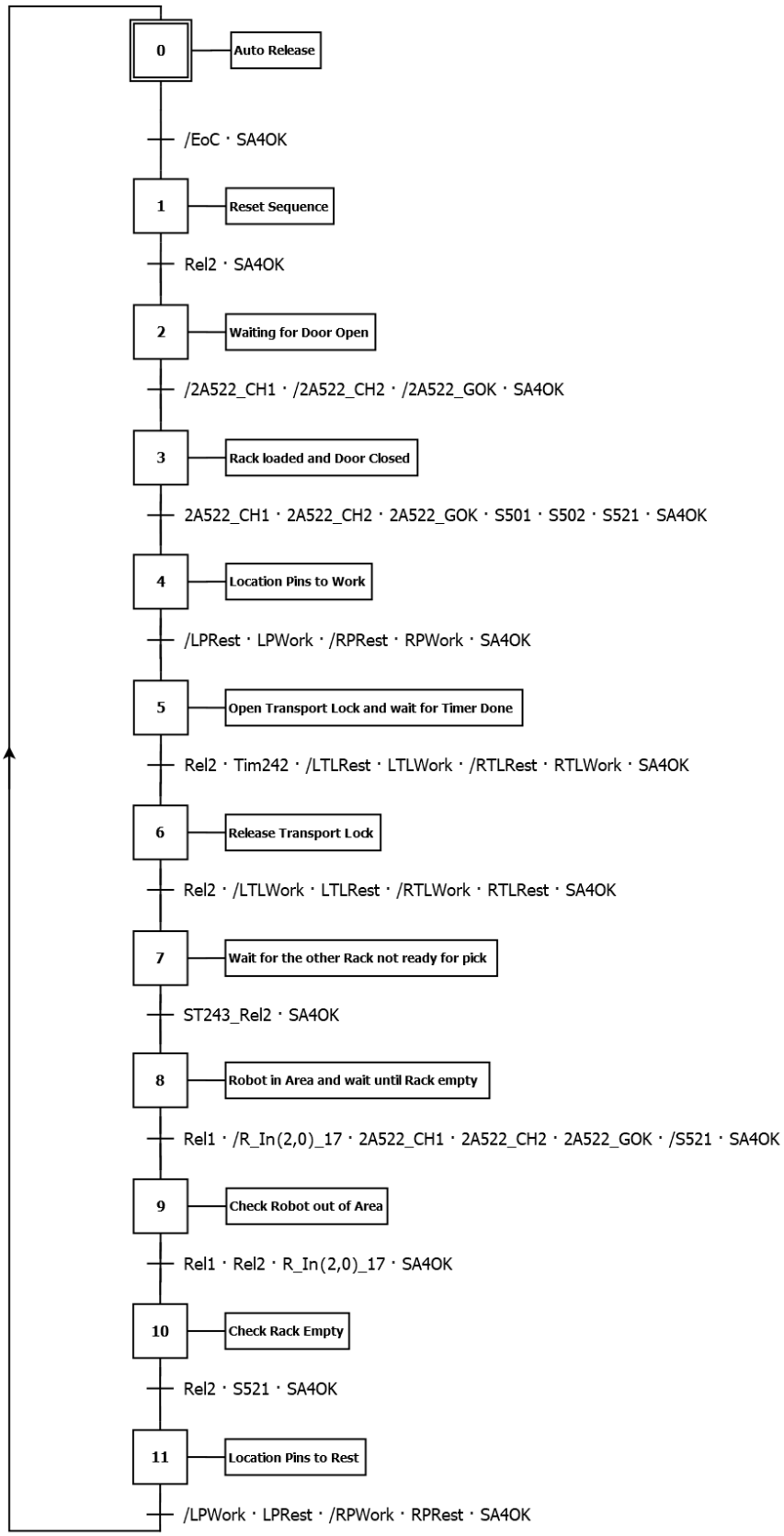

Figure 2.23. ST242 Moon Roof Rack Sequence GRAFCET

2.3.1.4. ST243

As a moon roof rack, parts are picked by gripper robot 240R whenever the alternative moon roof rack station 242 is not ready for pick. When the rack gate is opened for loading and unloading of racks, it will only affect 240R gripper robot instead of causing the whole safety area to go down.

Table 2.11. ST243 Moon Roof Rack Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[28].EOC	End of Cycle
SA4OK	_SA04_2_SAFETY_AREA_OK	Safety Area 4 is OK
Rel2	zzSeq[28].Release.2	Station 242 Not Ready for Pick Release
2A523_CH1	_2A523_CH1	Gate 523 Closed Channel 1
2A523_CH2	_2A523_CH2	Gate 523 Closed Channel 2
2A523_GOK	_2A523_GATE_OK	Gate 523 Closed OK
S501	_243S501	Rack Present Sensor 501
S502	_243S502	Rack Present Sensor 502
S521	_243S521	Check last Part in Rack Sensor
LPRest	_243S611B	Left Location Pin in Rest Position
LPWork	_243S611A	Left Location Pin in Work Position
RPRest	_243S612B	Right Location Pin in Rest Position
RPWork	_243S612A	Right Location Pin in Work Position
Tim243	_243TIM_TRLOCK_OPEN.DN	Timer to ensure Transport Lock is Open
LTLWork	_243S601A	Left Transport Lock in Work Position
LTLRest	_243S601B	Left Transport Lock in Rest Position
RTLWork	_243S602A	Right Transport Lock in Work Position
RTLRest	_243S602B	Right Transport Lock in Rest Position
ST242_Rel2	zzSeq[27].Release.2	Station 242 Not Ready for Pick Release
Rel1	zzSeq[28].Release.1	Station 243 Release to Start 240R Release
R_In(2,0)_18	Rob_In[2,0].18	240R Area Release Pick Rack ST243

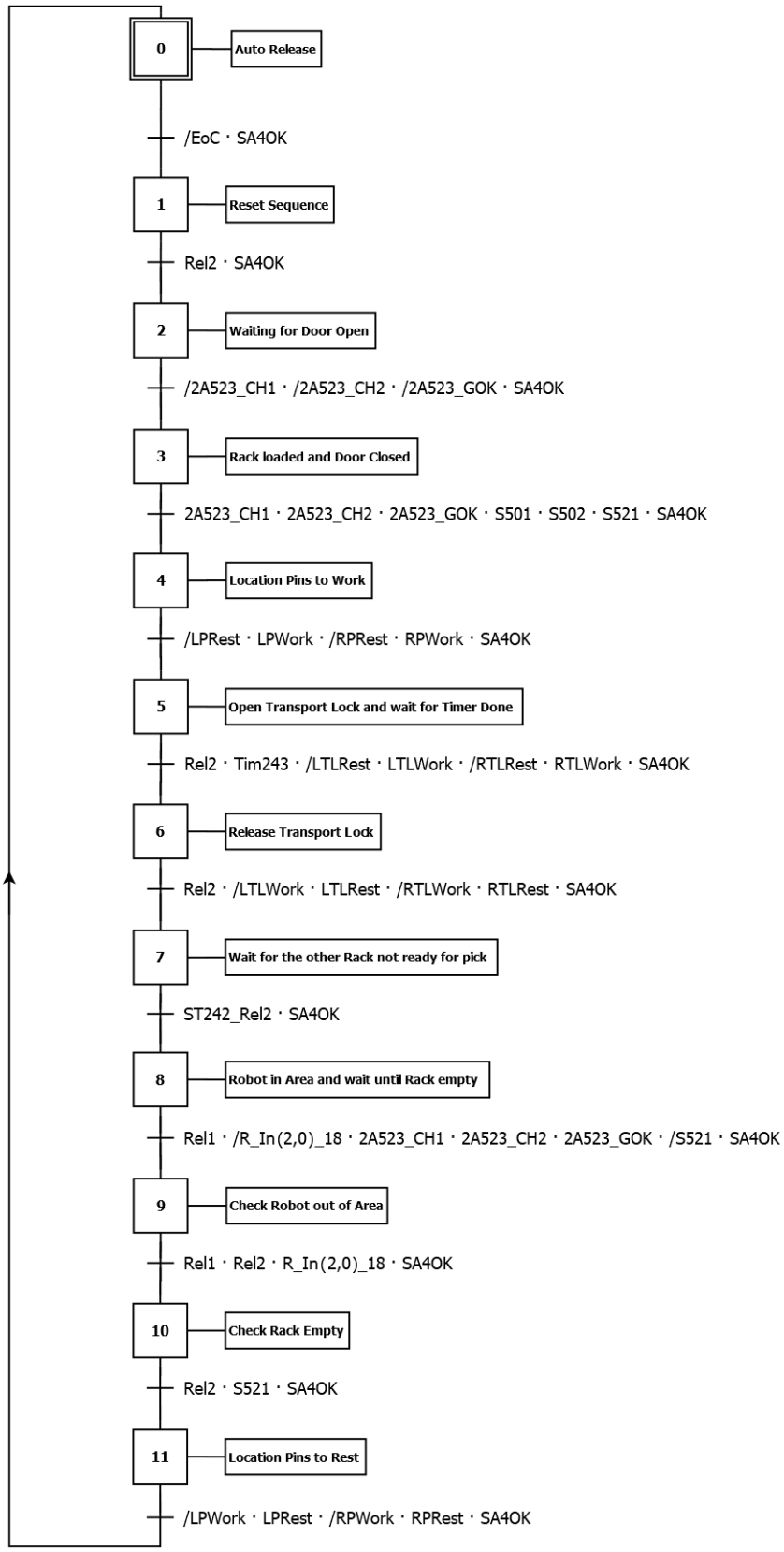

Figure 2.24. ST243 Moon Roof Rack Sequence GRAFCET

2.3.2. Robots

Both gripper robots are six-axis robots mounted on a linear transport belt (which would theoretically give them a 7th axis), which gives them the ability to displace on a single horizontal axis to reach both racks, the fixtures, and in the case of the 200R robot the press.

2.3.2.1. 200R

In the case of fixed roof parts, the gripper robot will pick the roof part from either rack 201 or 202 and place it on the fixture 281. For moon roof parts, it will pick the part from fixture 282 and place it on the press station 275 for it to be cut. Afterwards, it will place the cut part on fixture 281.

Table 2.12. 200R Robot Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[17].EOC	End of Cycle
SA4OK	_SA04_2_SAFETY_AREA_OK	Safety Area 4 is OK
2A520_GOK	_2A520_GATE_OK	Gate 520 Closed OK
2A521_GOK	_2A521_GATE_OK	Gate 521 Closed OK
R_In(1,0)_7	Rob_In[1,0].7	200R in Home Position
R_In(1,0)_10	Rob_In[1,0].10	200R Program Request
T0	zzSeq[17].StnTypeZero	Station Type is 0
ST282rel	zzSeq[21].Release.1	Station 282 release to Start 200R Robot
ST201rel	zzSeq[25].Release.1	Station 201 release to Start 200R Robot
ST202rel	zzSeq[26].Release.1	Station 202 release to Start 200R Robot
NTFR	zzSeq[17].Flag.0	Next Type to build Fixed Roof
NTMR	zzSeq[17].Flag.1	Next Type to build Moon Roof
TMM	zzSeq[17].Flag.28	Type Miss Match
RTK	zzRobot[1].TypeOK	Robot Type is OK
R_In(1,0)_3	Rob_In[1,0].3	200R Robot Fault
R_In(1,0)_1	Rob_In[1,0].1	200R in Automatic Mode
R_In(1,0)_5	Rob_In[1,0].5	200R Program Run
R_In(1,0)_4	Rob_In[1,0].4	200R in Fault
R_Out(1,0)_12	Rob_Out[1,0].12	200R Return to Home Position
R_In(1,1)_25	Rob_In[1,1].25	200R Cycle Complete Request
R_Out(1,0)_16	Rob_Out[1,0].16	200R Area Ready Pick Station 201
R_Out(1,0)_17	Rob_Out[1,0].17	200R Area Ready Pick Station 202
R_Out(1,0)_19	Rob_Out[1,0].19	200R Area Ready Pick Station 282
R_Out(1,0)_20	Rob_Out[1,0].20	200R Area Ready Press Station 275
R_Out(1,0)_21	Rob_Out[1,0].21	200R Area Ready Drop Station 281
R_In(1,1)_8	Rob_In[1,1].8	200R Job Ready Pick Station 201
R_In(1,1)_9	Rob_In[1,1].9	200R Job Ready Pick Station 202
R_In(1,1)_11	Rob_In[1,1].11	200R Job Ready Pick Station 282
R_In(1,1)_12	Rob_In[1,1].12	200R Job Ready Press Station 275
R_In(1,1)_13	Rob_In[1,1].13	200R Job Ready Drop Station 281

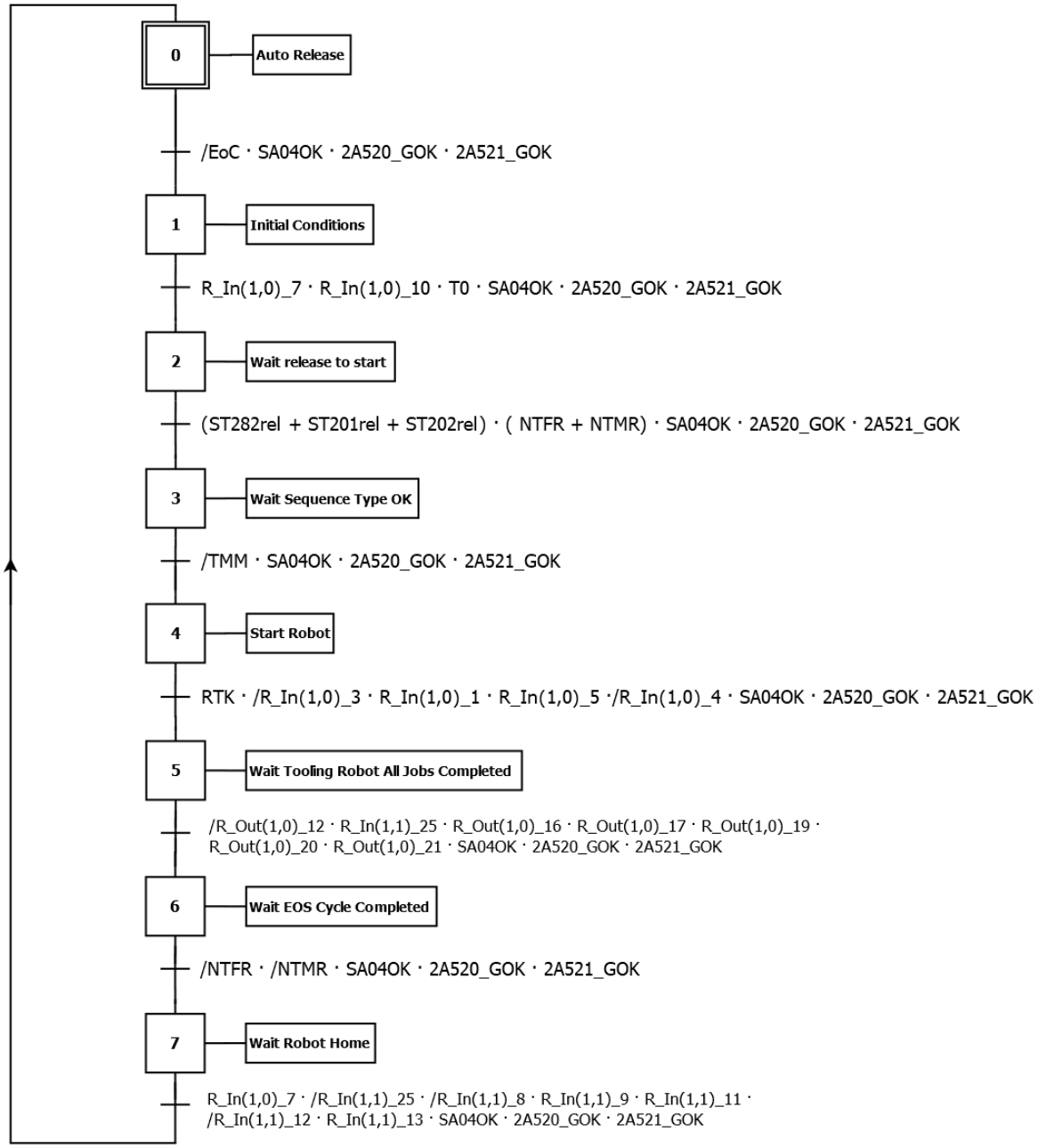

Figure 2.25. 200R Robot Sequence GRAFCET

2.3.2.2. 240R

The 240R gripper robot only works with sunroof parts. It will pick the part from either rack 242 or 243 and place it on fixture 282.

Table 2.13. 240R Robot Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[18].EOC	End of Cycle
SA4OK	_SA04_2_SAFETY_AREA_OK	Safety Area 4 is OK
2A522_GOK	_2A522_GATE_OK	Gate 522 Closed OK
2A523_GOK	_2A523_GATE_OK	Gate 523 Closed OK
R_In(2,0)_7	Rob_In[2,0].7	240R in Home Position
R_In(2,0)_10	Rob_In[2,0].10	240R Program Request
T0	zzSeq[18].StnTypeZero	Station Type is 0
ST242rel	zzSeq[27].Release.1	Station 242 release to Start 240R Robot
ST243rel	zzSeq[28].Release.1	Station 243 release to Start 200R Robot
NTMR	zzSeq[18].Flag.0	Next Type to build Moon Roof
TMM	zzSeq[18].Flag.28	Type Miss Match
RTK	zzRobot[2].TypeOK	Robot Type is OK
R_In(2,0)_3	Rob_In[2,0].3	240R Robot Fault
R_In(2,0)_1	Rob_In[2,0].1	240R in Automatic Mode
R_In(2,0)_5	Rob_In[2,0].5	240R Program Run
R_In(2,0)_4	Rob_In[2,0].4	240R in Fault
R_Out(2,0)_12	Rob_Out[2,0].12	240R Return to Home Position
R_In(2,1)_25	Rob_In[2,1].25	240R Cycle Complete Request
R_Out(2,0)_17	Rob_Out[2,0].17	240R Area Ready Pick Station 242
R_Out(2,0)_18	Rob_Out[2,0].18	240R Area Ready Pick Station 243
R_Out(2,0)_21	Rob_Out[2,0].21	240R Area Ready Drop Station 282
R_In(2,1)_9	Rob_In[2,1].9	240R Job Ready Pick Station 242
R_In(2,1)_10	Rob_In[2,1].10	240R Job Ready Pick Station 243
R_In(2,1)_13	Rob_In[2,1].13	240R Job Ready Drop Station 282

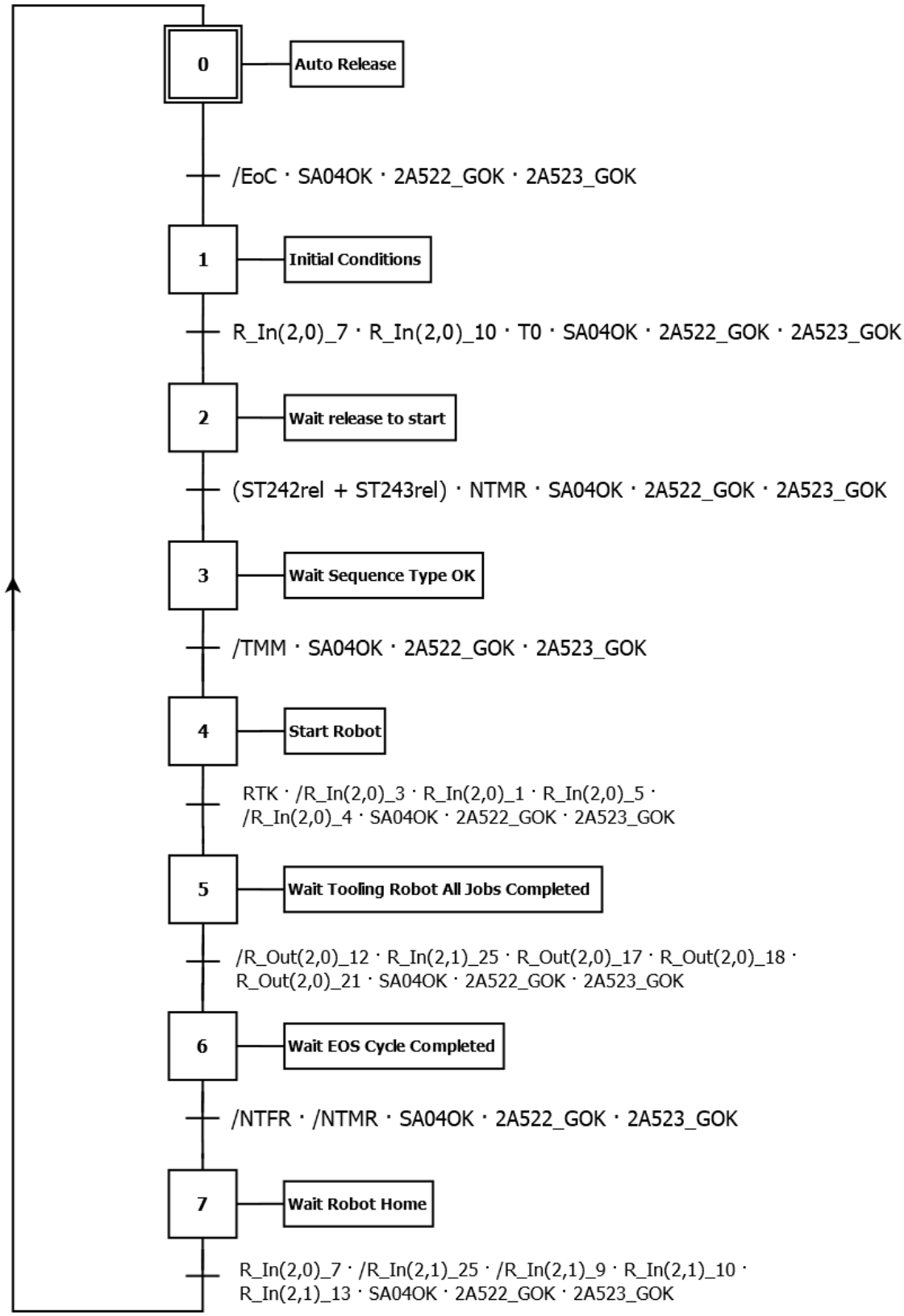

Figure 2.26. 240R Robot Sequence GRAFCET

2.3.3. Fixtures

Roof parts are placed by robots into the fixtures. Once sensors detect a part is present, the fixture will lift the part with a couple location pins to center the part. When the part is lifted and centered, another couple of clamps will secure the part in place waiting for the next robot to pick up the part. The clamps will only release the part once the next robot is in pick position and has already secured the part. Once the sensors detect the piece is no longer present, the lift will retract to the lower position to wait for the next part to be received.

2.3.3.1. ST282

This fixture only receives sunroof parts from robot 240R and are picked up by gripper robot 200R.

Table 2.14. ST282 Fixture Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[21].EOC	End of Cycle
SA4OK	_SA04_2_SAFETY_AREA_OK	Safety Area 4 is OK
JD_1	zzSeq[21].JobDone.1	Job Done 1: 240R Part Dropped
JD_2	zzSeq[21].JobDone.2	Job Done 2: 200R Part Picked
T0	zzSeq[21].StnTypeZero	Station Type is 0
R_In(2,1)_21	Rob_In[2,1].21	240R Area Job Request Drop Station 282
R_In(2,1)_9	Rob_In[2,1].9	240R Job Ready Pick Station 242
R_In(2,1)_10	Rob_In[2,1].10	240R Job Ready Pick Station 243
R_In(2,1)_13	Rob_In[2,1].13	240R Job Ready Drop Station 282
TFR	Type.InStation[21].13	Type Fixed Roof
TMR	Type.InStation[21].12	Type Moon Roof
TMM	zzSeq[21].Flag.28	Type Miss Match
R_Out(2,0)_21	Rob_Out[2,0].21	240R Area Ready Drop Station 282
R_In(2,1)_5	Rob_In[2,1].5	240R Tool Request Drop Station 282
S501	_282S501	Part Present Sensor 501
S502	_282S502	Part Present Sensor 502
S511	_282S511	Part Present Sensor 511
S512	_282S512	Part Present Sensor 512
LRest	_282S601B	Lift in Rest Position
LWork	_282S601A	Lift in Work Position
LCRest	_282S632B	Left Clamp in Rest Position
LCWork	_282S632A	Left Clamp in Work Position
RCRest	_282S631B	Right Clamp in Rest Position
RCWork	_282S631A	Right Clamp in Work Position
Rel1	zzSeq[21].Release.1	Station 282 Release to Start 200R
Rel3	zzSeq[17].Release.3	Robot 200R running Program 1
Rel4	zzSeq[17].Release.4	Robot 200R running Program 2
R_Out(1,0)_19	Rob_Out[1,0].19	200R Area Ready Pick Station 282
R_In(1,0)_19	Rob_In[1,0].19	200R Area Release Pick Station 282
R_In(1,1)_3	Rob_In[1,1].3	200R Tool Request Pick Station 282

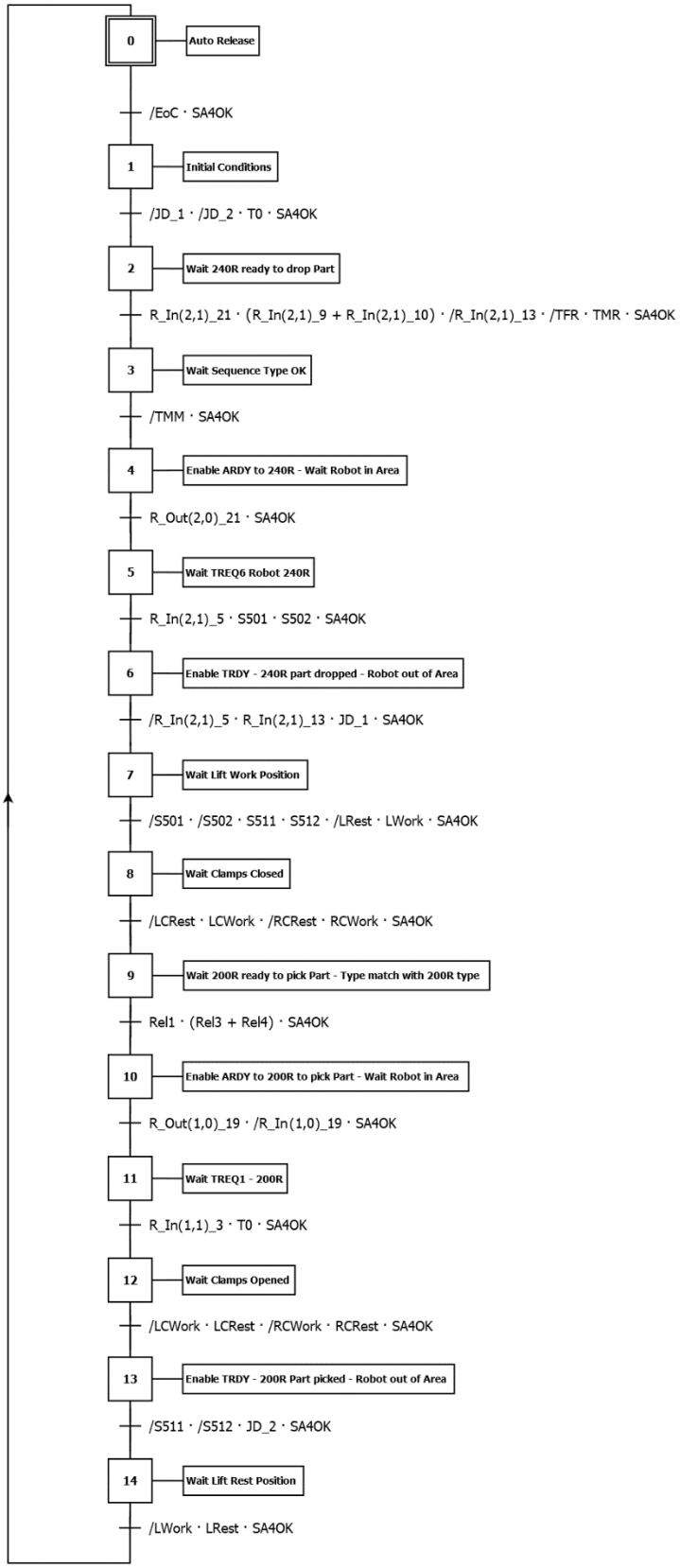

Figure 2.27. ST282 Fixture Sequence GRAFCET

2.3.3.2. ST281

Fixture station 281 receives both fixed and sunroof parts from gripper robot 200R and they are picked up by gripper robot 280R.

Table 2.15. ST281 Fixture Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[20].EOC	End of Cycle
SA4OK	_SA04_2_SAFETY_AREA_OK	Safety Area 4 is OK
JD_1	zzSeq[20].JobDone.1	Job Done 1: 200R Part Dropped
JD_2	zzSeq[20].JobDone.2	Job Done 2: 280R Part Picked
T0	zzSeq[20].StnTypeZero	Station Type is 0
R_In(1,1)_21	Rob_In[1,1].21	200R Area Job Request Drop Station 281
R_In(1,1)_8	Rob_In[1,1].8	200R Job Ready Pick Station 201
R_In(1,1)_9	Rob_In[1,1].9	200R Job Ready Pick Station 202
R_In(1,1)_11	Rob_In[1,1].11	200R Job Ready Pick Station 282
R_In(1,1)_13	Rob_In[1,1].13	200R Job Ready Drop Station 281
TFR	Type.InStation[20].13	Type Fixed Roof
TMR	Type.InStation[20].12	Type Moon Roof
TMM	zzSeq[20].Flag.28	Type Miss Match
R_Out(1,0)_21	Rob_Out[1,0].21	200R Area Ready Drop Station 281
R_In(1,1)_5	Rob_In[1,1].5	240R Tool Request Drop Station 281
S501	_281S501	Part Present Sensor 501
S502	_281S502	Part Present Sensor 502
S512	_281S512	Part Present Sensor 512
S513	_281S513	Part Present Sensor 513
LRest	_281S601B	Lift in Rest Position
LWork	_281S601A	Lift in Work Position
LCRest	_281S622B	Left Clamp in Rest Position
LCWork	_281S622A	Left Clamp in Work Position
RCRest	_281S621B	Right Clamp in Rest Position
RCWork	_281S621A	Right Clamp in Work Position
Rel1	zzSeq[20].Release.1	Start 280R Robot Fixed Program
Rel2	zzSeq[20].Release.2	Start 280R Robot Moon Program
RemRel3	zzPlc1RemoteIn.Release.3	Remote Release 280 Running Program 1 (Fixed)
RemRel4	zzPlc1RemoteIn.Release.4	Remote Release 280 Running Program 2 (Moon)
280RAreaReady	EZ22_3_032_031_280R01.AreaReady.1	280R Robot Area Ready Remote Signal
280RAreaRel	_031_280R01.AreaRelease.1	280R Robot Area Release Remote Signal

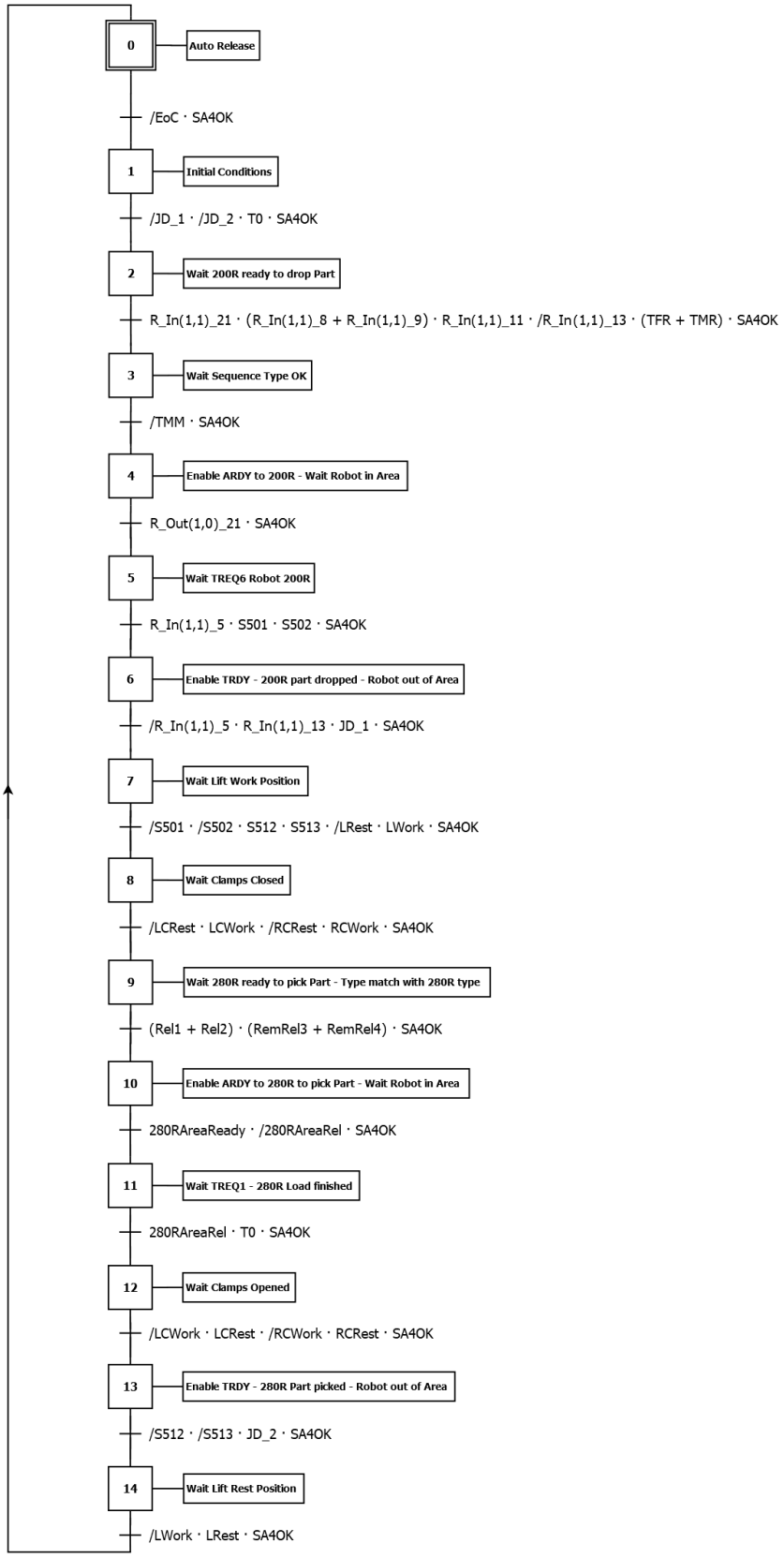

Figure 2.28. ST281 Fixture Sequence GRAFCET

2.3.4. Press

The press is a specific model tailored to the factory's needs by manufacturer TOX Pressotechnik which exerts a press force of up to 964 *kN*. It creates the two holes necessary for sunroof parts to be mounted on the vehicles. The gripper robot 200R holds the part in the cutting position and is also secured by rod clamps. When the press closes, the scrap falls down into a waste trolley below the press. With the press back open after cutting, the rod clamps free the part and the robot 200R retreats with the part from the press area.

Table 2.16. ST275 Press Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[19].EOC	End of Cycle
SA4OK	_SA04_2_SAFETY_AREA_OK	Safety Area 4 is OK
JD_1	zzSeq[19].JobDone.1	Job Done 1: Left side Part Clinching
JD_2	zzSeq[19].JobDone.2	Job Done 2: Right side Part Clinching
JD_8	zzSeq[19].JobDone.8	Job Done 8: Right General Press Process Complete
T0	zzSeq[19].StnTypeZero	Station Type is 0
R_In(1,1)_20	Rob_In[1,1].20	200R Area Job Request Press Station 275
R_In(1,1)_11	Rob_In[1,1].11	200R Job Ready Pick Station 282
R_In(1,1)_12	Rob_In[1,1].12	200R Job Ready Press Station 275
TFR	Type.InStation[19].13	Type Fixed Roof
TMR	Type.InStation[19].12	Type Moon Roof
TMM	zzSeq[19].Flag.28	Type Miss Match
R_Out(1,0)_20	Rob_Out[1,0].20	200R Area Ready Press Process Station 275
LRodL	_275_1S601B	Left Rod Clamp Locked
LRodU	_275_1S601A	Left Rod Clamp Unlocked
RRodL	_275_2S601B	Right Rod Clamp Locked
LRodU	_275_2S601A	Right Rod Clamp Unlocked
LPressO	_275_1S801A	Left side Press Open
LPressC	_275_1S801B	Left side Press Closed
RPressO	_275_2S801A	Right side Press Open
LPressC	_275_2S801B	Right side Press Closed
R_In(1,0)_20	Rob_In[1,0].20	200R Area Release Press Station 275

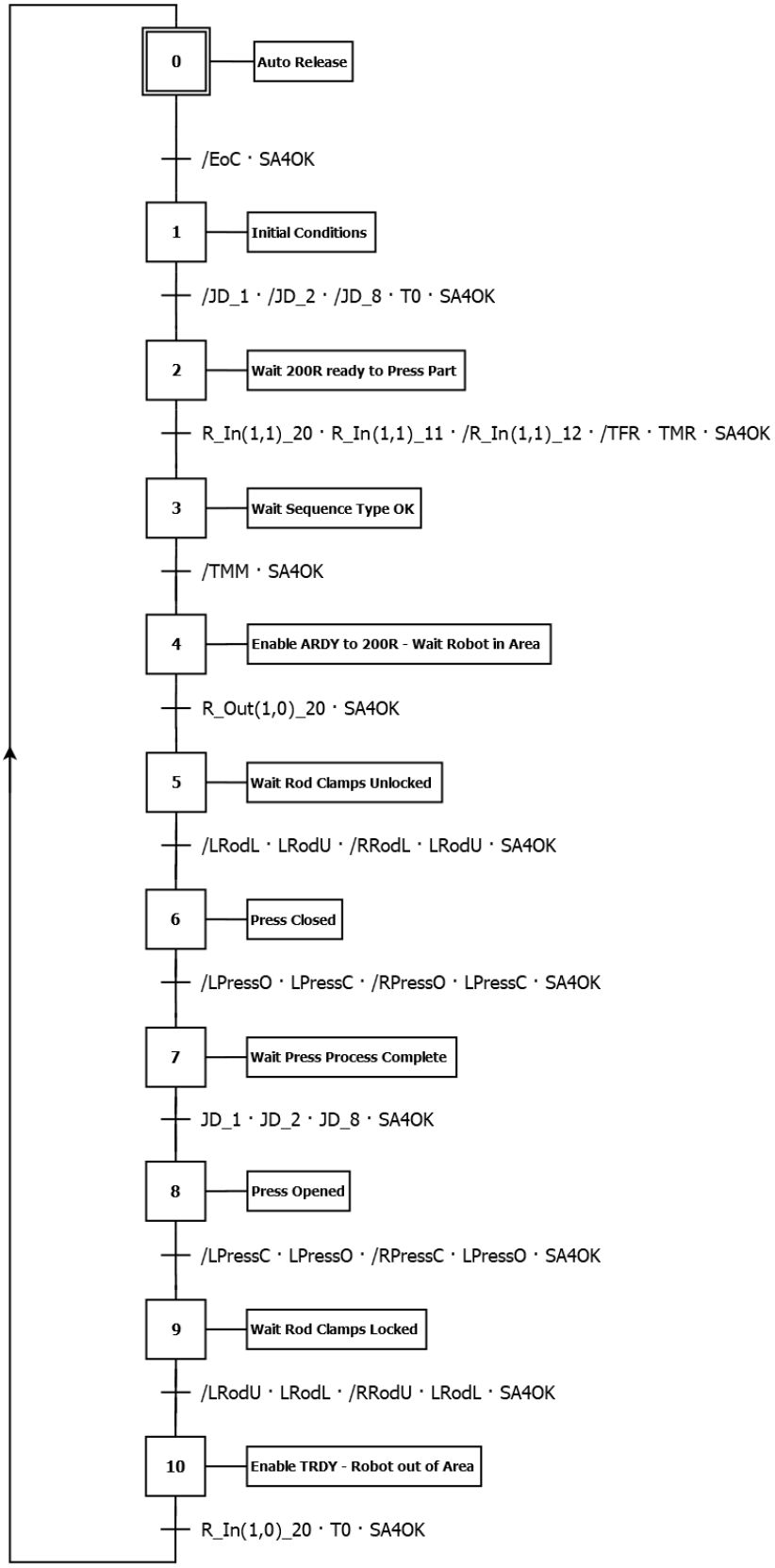

Figure 2.29. ST275 Press Sequence GRAFCET

2.4. PLC3

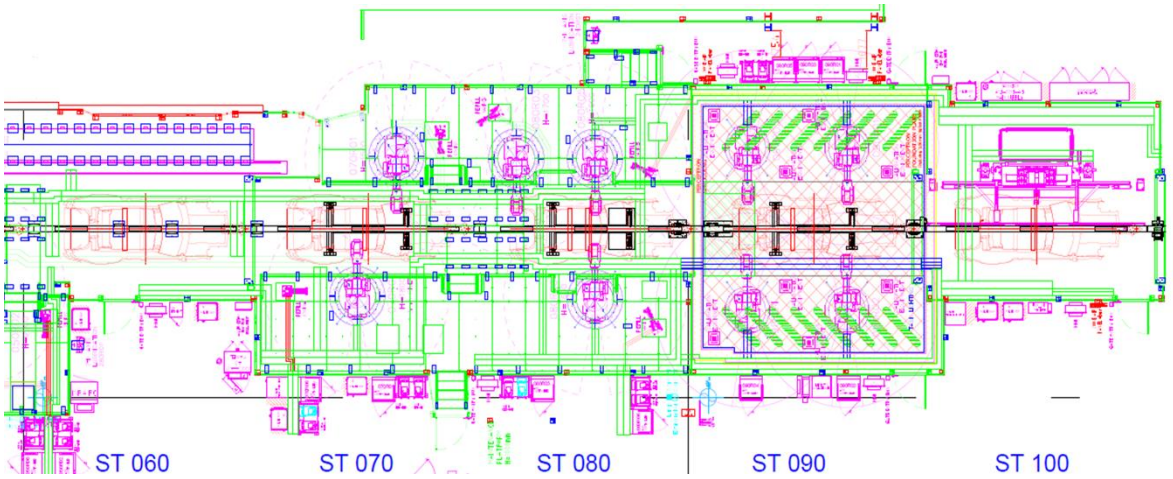

Figure 2.30. PLC3 Floorplan

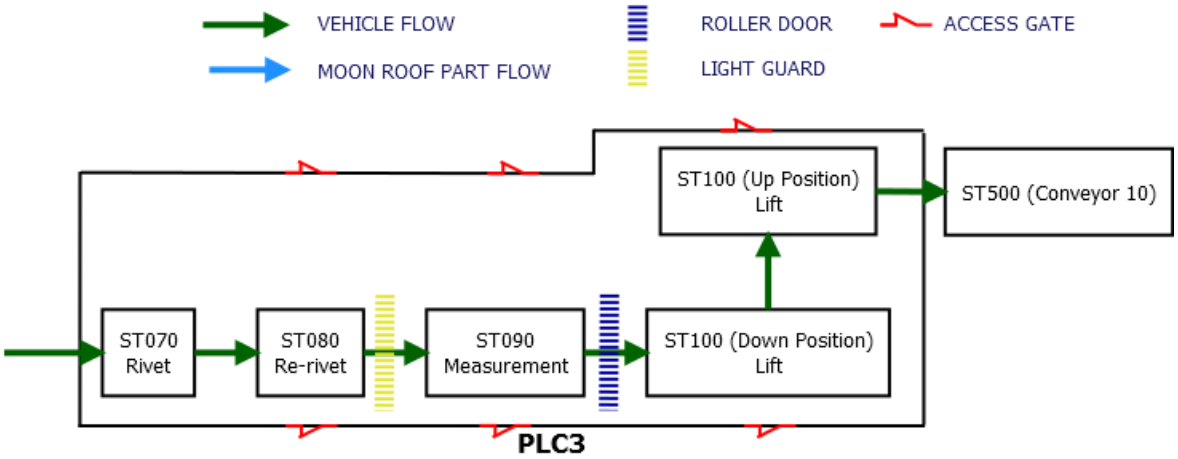

Figure 2.31. PLC3 Area Flowchart

The third PLC controls five stations, nine robots and six access gates which are distributed among three safety areas.

2.4.1. ST070 Rivet Station

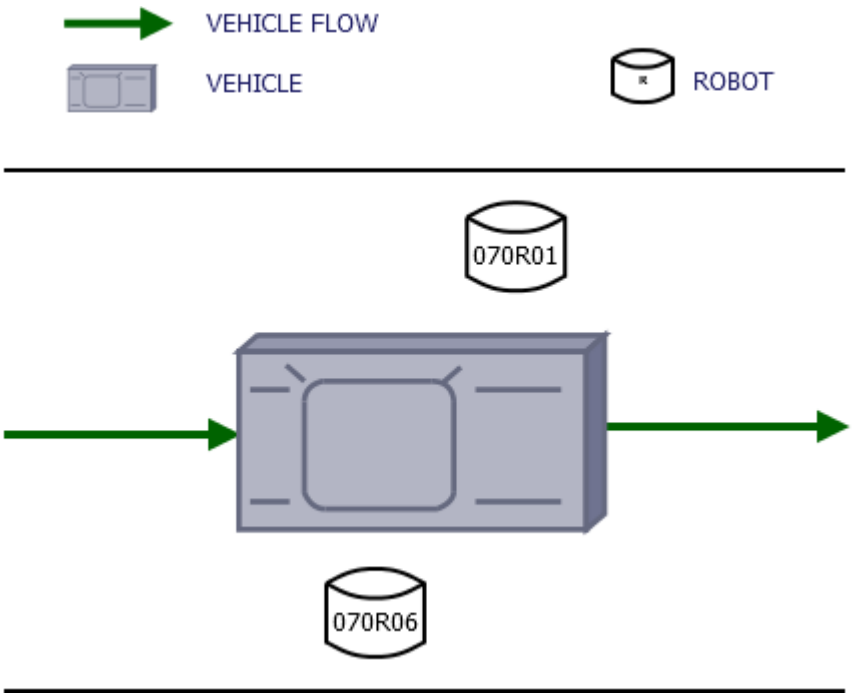

Figure 2.32. ST070 Layout

The rivet station consists of two six-axis robots that rivet the roof into the car body when the vehicle is secured by a pallet lock. The robots apply a different riveting program depending on the type of roof.

Table 2.17. ST70 Rivet Station Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[2].EOC	End of Cycle
BTTOK	_3_A2_31_512BT	Braking Transistor Temperature OK
MECP	_3_A2_31_2526CON_1	Motor Enable Contactor +
MECN	_3_A2_31_2526CON_2	Motor Enable Contactor -
MECF	_3_A2_31_2526CON_F	Motor Enable Contactor Feedback
NoVehST70ST60	zzSeq[2].Release.21	No Vehicle between Station 70 and Station 60
SA3OK	EZ22_3_031_1_1.SA03_OK	Safety Area 3 is OK
SA5OK	_SA05_2_SAFETY_AREA_OK	Safety Area 5 is OK
RJD_1	zzSeq[2].JobDone.1	Robot Job Done 1: 070R01 Rivet Done
RJD_6	zzSeq[2].JobDone.6	Robot Job Done 6: 070R06 Rivet Done
RJD_8	zzSeq[2].JobDone.8	Robot Job Done 8: 070R01-070R06 Rivet Done
Rel2	zzSeq[2].Release.2	Station 70 to Station 60 Enter Forward Acknowledge Release
VIP	zzSeq[2].InPos[50].1	Vehicle In Position
HESOK	zzSeq[2].InPos[50].7	Hall Effect Sensor is OK

SeqOK	zzSeq[2].TypeOK	Sequence Type is OK
TFR	Type.InStation[2].13	Type Fixed Roof
TMR	Type.InStation[2].12	Type Moon Roof
Dry	Type.InStation[2].28	Type Dry Part
TMM	zzSeq[2].Flag.28	Type Miss Match
PLRest	_070S601B	Pallet Lock in Rest Position
PLWork	_070S601A	Pallet Lock in Work Position
R_In(1,0)_7	Rob_In[1,0].7	070R01 in Home Position
R_In(2,0)_7	Rob_In[2,0].7	070R06 in Home Position
R_In(1,0)_10	Rob_In[1,0].10	070R01 Program Request
R_In(2,0)_10	Rob_In[2,0].10	070R06 Program Request
R_In(1,1)_25	Rob_In[1,1].25	070R01 Cycle Complete Request
R_In(2,1)_25	Rob_In[2,1].25	070R06 Cycle Complete Request
R_In(1,1)_10	Rob_In[1,1].10	070R01 Job Ready: Rivet
R_In(2,1)_10	Rob_In[2,1].10	070R06 Job Ready: Rivet
RTK1	zzRobot[1].TypeOK	Robot 1 Type is OK
RTK2	zzRobot[2].TypeOK	Robot 2 Type is OK
R_In(1,0)_3	Rob_In[1,0].3	070R01 Robot Fault
R_In(2,0)_3	Rob_In[2,0].3	070R06 Robot Fault
R_In(1,0)_1	Rob_In[1,0].1	070R01 in Automatic Mode
R_In(2,0)_1	Rob_In[2,0].1	070R06 in Automatic Mode
R_In(1,0)_5	Rob_In[1,0].5	070R01 Program Run
R_In(2,0)_5	Rob_In[2,0].5	070R06 Program Run
R_In(1,0)_4	Rob_In[1,0].4	070R01 in Fault
R_In(2,0)_4	Rob_In[2,0].4	070R06 in Fault
R_In(1,1)_18	Rob_In[1,1].18	070R01 Area Job Request Rivet
R_In(2,1)_18	Rob_In[2,1].18	070R06 Area Job Request Rivet
R_In(1,0)_16	Rob_In[1,1].18	070R01 Area Release Approach
R_In(2,0)_16	Rob_In[2,1].18	070R06 Area Release Approach
R_In(1,0)_18	Rob_In[1,0].18	070R01 Area Release Rivet
R_In(2,0)_18	Rob_In[2,0].18	070R06 Area Release Rivet
R_Out(1,0)_16	Rob_Out[1,0].16	030R04 Area Ready Approach
R_Out(2,0)_16	Rob_Out[2,0].16	030R05 Area Ready Approach
R_Out(1,0)_18	Rob_Out[1,0].18	070R01 Area Ready Rivet
R_Out(2,0)_18	Rob_Out[2,0].18	070R06 Area Ready Rivet
Rel1	zzSeq[2].Release.1	Station 70 to Station 80 Exit Forward Request Release
Seq0	zzSeq[2].SeqTypeZero	Sequence Type is 0
T0	zzSeq[2].StnTypeZero	Station Type is 0

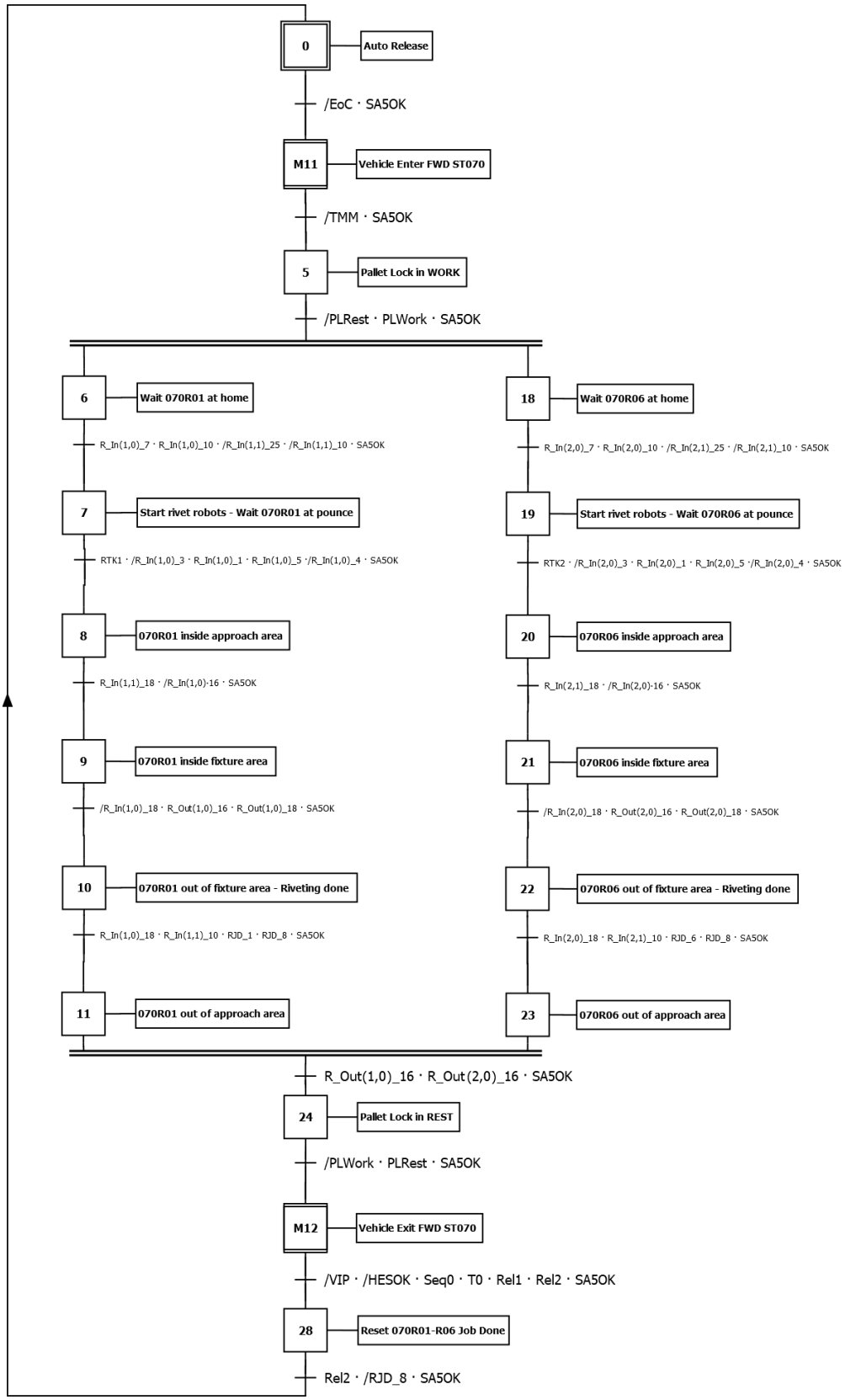

Figure 2.33. ST70 Rivet Sequence GRAFCET

2.4.2. ST080 Re-rivet Station

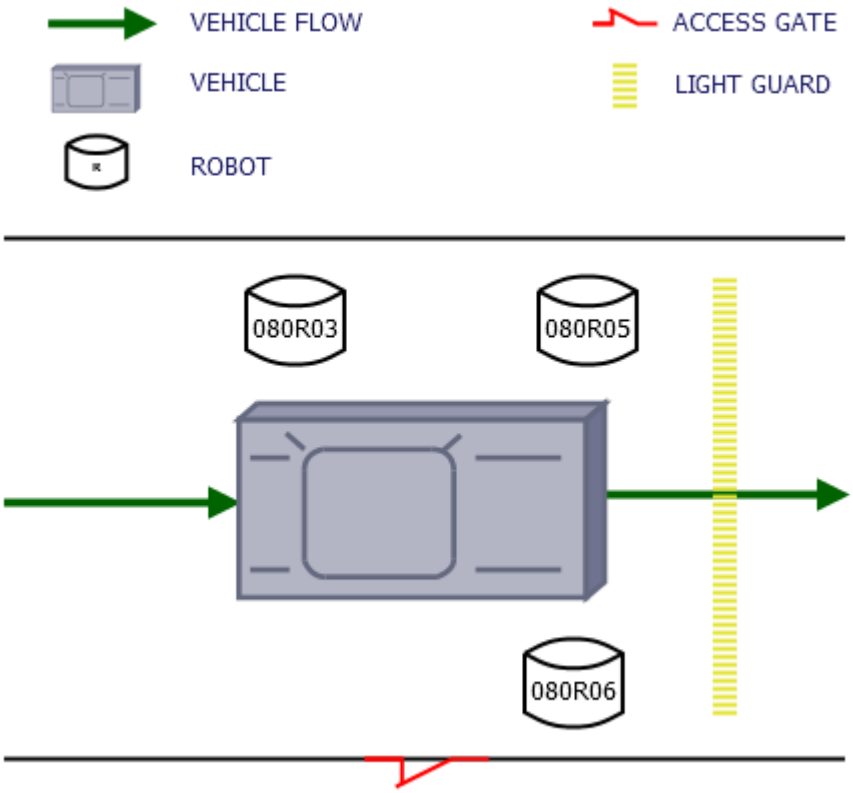

Figure 2.34. ST080 Layout

The re-rivet station is the final riveting station in the line. The corresponding rivet program according to the vehicle's type is applied by three six-axis robots once the vehicle is secured by the pallet lock. This station is also equipped with a light guard to delimit the safety area with the station 90 measurement station.

Table 2.18. ST80 Re-rivet Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[3].EOC	End of Cycle
BTTOK	_3_A2_32_512BT	Braking Transistor Temperature OK
MECP	_3_A2_32_2526CON_1	Motor Enable Contactor +
MECN	_3_A2_32_2526CON_2	Motor Enable Contactor -
MECF	_3_A2_32_2526CON_F	Motor Enable Contactor Feedback
SA5OK	_SA05_2_SAFETY_AREA_OK	Safety Area 5 is OK
SA6OK	_SA06_2_Safety_Area_OK	Safety Area 6 is OK
RJD_3	zzSeq[3].JobDone.3	Robot Job Done 3: 080R03 Rivet Done
RJD_5	zzSeq[3].JobDone.5	Robot Job Done 5: 080R05 Rivet Done
RJD_6	zzSeq[3].JobDone.6	Robot Job Done 6: 080R06 Rivet Done

RJD_8	zzSeq[3].JobDone.8	Robot Job Done 8: 080R04-080R06 Rivet Done
Rel2	zzSeq[3].Release.2	Station 80 to Station 70 Enter Forward Acknowledge Release
VIP	zzSeq[3].InPos[50].1	Vehicle In Position
HESOK	zzSeq[3].InPos[50].7	Hall Effect Sensor is OK
SeqOK	zzSeq[3].TypeOK	Sequence Type is OK
TFR	Type.InStation[3].13	Type Fixed Roof
TMR	Type.InStation[3].12	Type Moon Roof
Dry	Type.InStation[3].28	Type Dry Part
TMM	zzSeq[3].Flag.28	Type Miss Match
PLRest	_080S601B	Pallet Lock in Rest Position
PLWork	_080S601A	Pallet Lock in Work Position
R_In(3,0)_7	Rob_In[3,0].7	080R03 in Home Position
R_In(5,0)_7	Rob_In[5,0].7	080R05 in Home Position
R_In(6,0)_7	Rob_In[6,0].7	080R06 in Home Position
R_In(3,0)_10	Rob_In[3,0].10	080R03 Program Request
R_In(5,0)_10	Rob_In[5,0].10	080R05 Program Request
R_In(6,0)_10	Rob_In[6,0].10	080R06 Program Request
R_In(3,1)_25	Rob_In[3,1].25	080R03 Cycle Complete Request
R_In(5,1)_25	Rob_In[5,1].25	080R05 Cycle Complete Request
R_In(6,1)_25	Rob_In[6,1].25	080R06 Cycle Complete Request
R_In(3,1)_10	Rob_In[3,1].10	080R03 Job Ready: Rivet
R_In(5,1)_10	Rob_In[5,1].10	080R05 Job Ready: Rivet
R_In(6,1)_10	Rob_In[6,1].10	080R06 Job Ready: Rivet
RTK1	zzRobot[3].TypeOK	Robot 1 Type is OK
RTK2	zzRobot[5].TypeOK	Robot 2 Type is OK
RTK3	zzRobot[6].TypeOK	Robot 3 Type is OK
R_In(3,0)_3	Rob_In[3,0].3	080R03 Robot Fault
R_In(5,0)_3	Rob_In[5,0].3	080R05 Robot Fault
R_In(6,0)_3	Rob_In[6,0].3	080R06 Robot Fault
R_In(3,0)_1	Rob_In[3,0].1	080R03 in Automatic Mode
R_In(5,0)_1	Rob_In[5,0].1	080R05 in Automatic Mode
R_In(6,0)_1	Rob_In[6,0].1	080R06 in Automatic Mode
R_In(3,0)_5	Rob_In[3,0].5	080R03 Program Run
R_In(5,0)_5	Rob_In[5,0].5	080R05 Program Run
R_In(6,0)_5	Rob_In[6,0].5	080R06 Program Run
R_In(3,0)_4	Rob_In[3,0].4	080R03 in Fault
R_In(5,0)_4	Rob_In[5,0].4	080R05 in Fault
R_In(6,0)_4	Rob_In[6,0].4	080R06 in Fault
R_In(3,1)_18	Rob_In[3,1].18	080R03 Area Job Request Rivet
R_In(5,1)_18	Rob_In[5,1].18	080R05 Area Job Request Rivet
R_In(6,1)_18	Rob_In[6,1].18	080R06 Area Job Request Rivet
R_In(3,0)_16	Rob_In[3,0].16	080R03 Area Release Approach
R_In(5,0)_16	Rob_In[5,0].16	080R05 Area Release Approach
R_In(6,0)_16	Rob_In[6,0].16	080R06 Area Release Approach
R_In(3,0)_18	Rob_In[3,0].18	080R03 Area Release Rivet
R_In(5,0)_18	Rob_In[5,0].18	080R05 Area Release Rivet

R_In(6,0)_18	Rob_In[6,0].18	080R06 Area Release Rivet
R_Out(3,0)_16	Rob_Out[3,0].16	080R03 Area Ready Approach
R_Out(5,0)_16	Rob_Out[5,0].16	080R05 Area Ready Approach
R_Out(6,0)_16	Rob_Out[6,0].16	080R06 Area Ready Approach
R_Out(3,0)_18	Rob_Out[3,0].18	080R03 Area Ready Rivet
R_Out(5,0)_18	Rob_Out[5,0].18	080R05 Area Ready Rivet
R_Out(6,0)_18	Rob_Out[6,0].18	080R06 Area Ready Rivet
Rel1	zzSeq[3].Release.1	Station 80 to Station 90 Exit Forward Request Release
Seq0	zzSeq[3].SeqTypeZero	Sequence Type is 0
T0	zzSeq[3].StnTypeZero	Station Type is 0

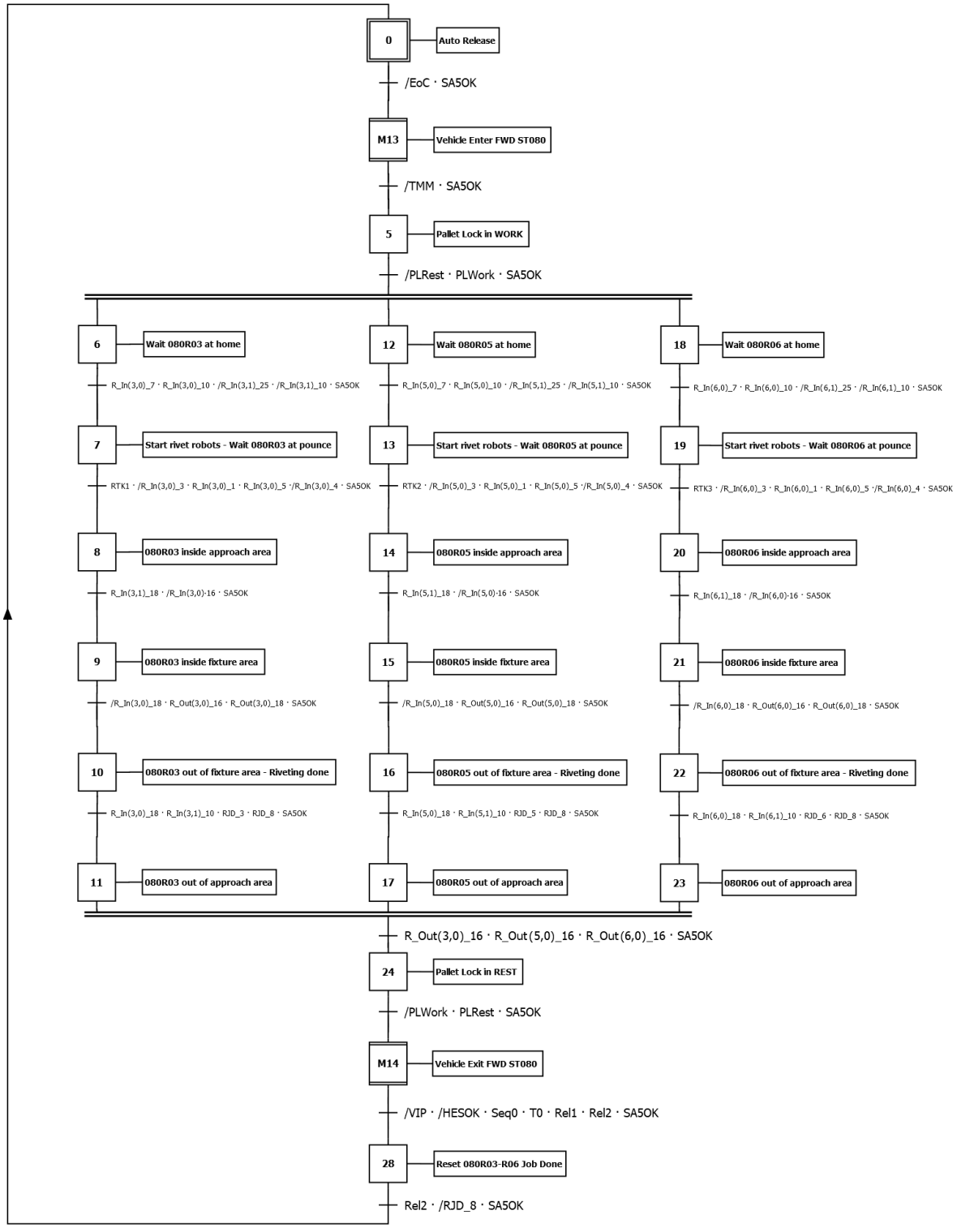

Figure 2.35. ST80 Re-rivet Sequence GRAFCET

2.4.3. ST090 Measurement Station

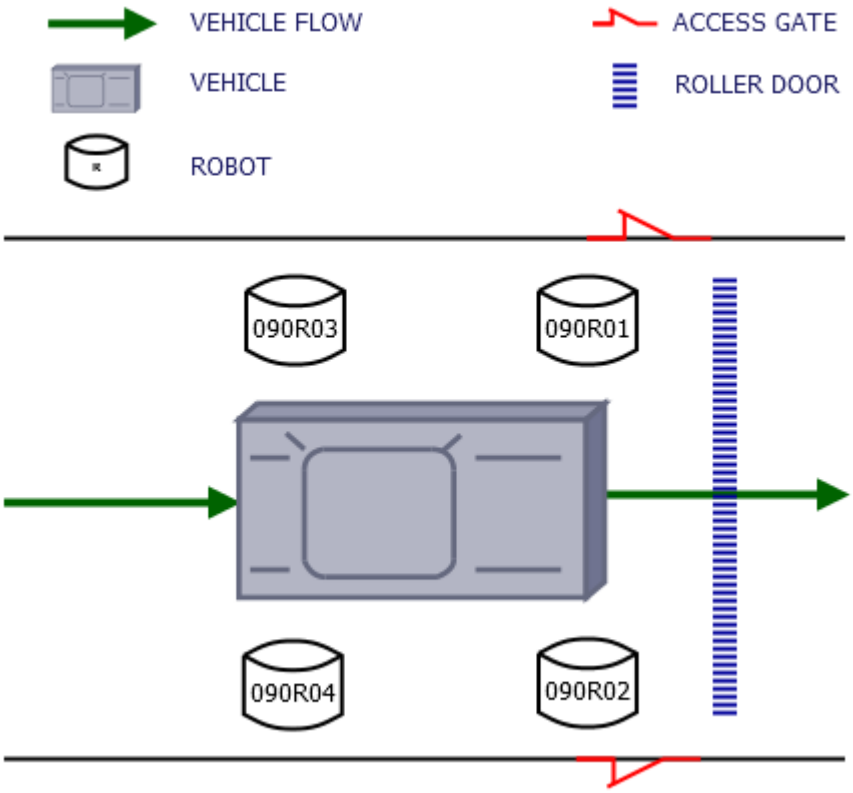

Figure 2.36. ST090 Layout

In this station, because this is the last non-transport only station before the vehicle is transferred to the cladding line, the whole car body is measured by four six-axis robots after the vehicle is secured by the pallet lock. Measurement is carried out by non-contact fully automated dimensional gauging by laser, provided by the manufacturer Perceptron. The manufacturer also provides a PC with metrology software that analyzes the vehicle's measurements and provides the operator with information about anomalies in the car body. Because the next station is a lift, station 90 is provided with a roller door to divide the safety areas.

Table 2.19. ST90 Measurement Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[4].EOC	End of Cycle
BTTOK	_3_A2_41_512BT	Braking Transistor Temperature OK
MECP	_3_A2_41_2526CON_1	Motor Enable Contactor +
MECN	_3_A2_41_2526CON_2	Motor Enable Contactor -
MECF	_3_A2_41_2526CON_F	Motor Enable Contactor Feedback
RJD_1	zzSeq[4].JobDone.1	Robot Job Done 1: 090R01 Measure Done

RJD_2	zzSeq[4].JobDone.2	Robot Job Done 2: 090R02 Measure Done
RJD_3	zzSeq[4].JobDone.3	Robot Job Done 3: 090R03 Measure Done
RJD_4	zzSeq[4].JobDone.4	Robot Job Done 4: 090R04 Measure Done
RJD_8	zzSeq[4].JobDone.8	Robot Job Done 8: 090R01-090R04 Measure Done
Rel2	zzSeq[4].Release.2	Station 90 to Station 80 Enter Forward Acknowledge Release
VIP	zzSeq[4].InPos[50].1	Vehicle In Position
HESOK	zzSeq[4].InPos[50].7	Hall Effect Sensor is OK
SeqOK	zzSeq[4].TypeOK	Sequence Type is OK
TFR	Type.InStation[4].13	Type Fixed Roof
TMR	Type.InStation[4].12	Type Moon Roof
Dry	Type.InStation[4].28	Type Dry Part
RFIDOK	_090_RFID.ReadOK	Radio Frequency Identification is OK
TMM	zzSeq[4].Flag.28	Type Miss Match
PLRest	_090S601B	Pallet Lock in Rest Position
PLWork	_090S601A	Pallet Lock in Work Position
Rel21	zzSeq[4].Release.21	No Vehicle Between Station 90 and Station 100
Rel22	zzSeq[4].Release.22	Start Robots 090R01-090R04
Rel3	zzSeq[5].Release.3	Robots 090R01-090R04 Run Program
Rel5	zzSeq[5].Release.5	Robots 090R01-090R04 Areas Release
GC	_090S361B	Gate Closed
GO	_090S361A	Gate Opened
SA5OK	_SA05_2_Safety_Area_OK	Safety Area 5 is OK
SA6OK	_SA06_2_Safety_Area_OK	Safety Area 6 is OK
SA7OK	_SA07_2_Safety_Area_OK	Safety Area 7 is OK
Rel1	zzSeq[4].Release.1	Station 90 to Station 80 Exit Forward Request Release
Seq0	zzSeq[4].SeqTypeZero	Sequence Type is 0
T0	zzSeq[4].StnTypeZero	Station Type is 0

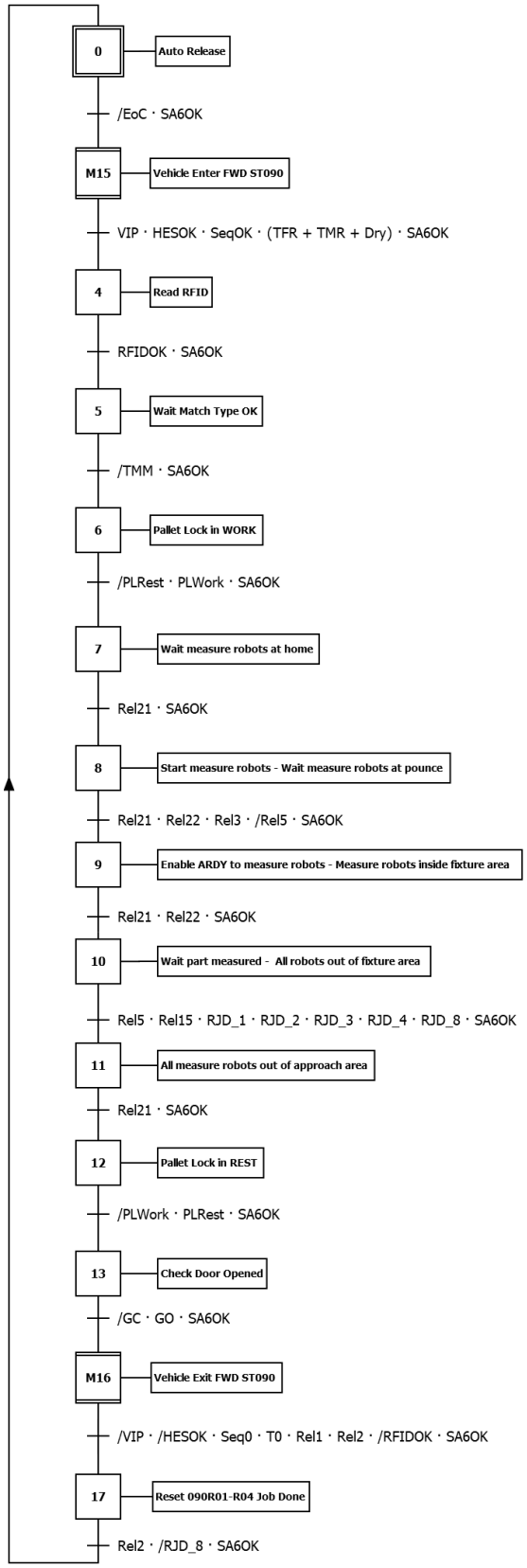

Figure 2.37. ST90 Measurement Sequence GRAFCET

In this case, due to the Perceptron system, the station robots are considered a different sequence apart from the station itself. The operator is notified via the Perceptron PC exactly which points of the vehicle body present anomalies via pink alarms, which pop up when the part is rejected in case the anomalies surpass the specified tolerance. The system also provides a grey alarm in case a sensor error is identified.

Table 2.20. 090R01-090R04 Robots Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[5].EOC	End of Cycle
SA6OK	_SA06_2_Safety_Area_OK	Safety Area 6 is OK
RJD_1	zzSeq[5].JobDone.1	Robot Job Done 1: 090R01 Measure Done
RJD_2	zzSeq[5].JobDone.2	Robot Job Done 2: 090R02 Measure Done
RJD_3	zzSeq[5].JobDone.3	Robot Job Done 3: 090R03 Measure Done
RJD_4	zzSeq[5].JobDone.4	Robot Job Done 4: 090R04 Measure Done
Rel22	zzSeq[4].Release.22	Start Robots 090R01-090R04
R_In(7,0)_10	Rob_In[7,0].10	090R01 Program Request
R_In(8,0)_10	Rob_In[8,0].10	090R02 Program Request
R_In(9,0)_10	Rob_In[9,0].10	090R03 Program Request
R_In(10,0)_10	Rob_In[10,0].10	090R04 Program Request
R_In(7,1)_25	Rob_In[7,1].25	090R01 Cycle Complete Request
R_In(8,1)_25	Rob_In[8,1].25	090R02 Cycle Complete Request
R_In(9,1)_25	Rob_In[9,1].25	090R03 Cycle Complete Request
R_In(10,1)_25	Rob_In[10,1].25	090R04 Cycle Complete Request
R_In(7,1)_10	Rob_In[7,1].10	090R01 Job Ready: Measure
R_In(8,1)_10	Rob_In[8,1].10	090R02 Job Ready: Measure
R_In(9,1)_10	Rob_In[9,1].10	090R03 Job Ready: Measure
R_In(10,1)_10	Rob_In[10,1].10	090R04 Job Ready: Measure
PAc	P4I.Part_Accepted	Part Accepted
PiA	P4I.Part_Rejected	Pink Alarm
GrA	Perc_SensorError	Grey Alarm
RTK1	zzRobot[7].TypeOK	Robot 1 Type is OK
RTK2	zzRobot[8].TypeOK	Robot 2 Type is OK
RTK3	zzRobot[9].TypeOK	Robot 3 Type is OK
RTK4	zzRobot[10].TypeOK	Robot 4 Type is OK
R_In(7,0)_3	Rob_In[7,0].3	090R01 Robot Fault
R_In(8,0)_3	Rob_In[8,0].3	090R02 Robot Fault
R_In(9,0)_3	Rob_In[9,0].3	090R03 Robot Fault
R_In(10,0)_3	Rob_In[10,0].3	090R04 Robot Fault
R_In(7,0)_1	Rob_In[7,0].1	090R01 in Automatic Mode
R_In(8,0)_1	Rob_In[8,0].1	090R02 in Automatic Mode
R_In(9,0)_1	Rob_In[9,0].1	090R03 in Automatic Mode
R_In(10,0)_1	Rob_In[10,0].1	090R04 in Automatic Mode
R_In(7,0)_5	Rob_In[7,0].5	090R01 Program Run
R_In(8,0)_5	Rob_In[8,0].5	090R02 Program Run
R_In(9,0)_5	Rob_In[9,0].5	090R03 Program Run
R_In(10,0)_5	Rob_In[10,0].5	090R04 Program Run

R_In(7,0)_4	Rob_In[7,0].4	090R01 in Fault
R_In(8,0)_4	Rob_In[8,0].4	090R02 in Fault
R_In(9,0)_4	Rob_In[9,0].4	090R03 in Fault
R_In(10,0)_4	Rob_In[10,0].4	090R04 in Fault
R_Out(7,0)_18	Rob_Out[7,0].18	090R01 Area Ready Measure
R_Out(8,0)_18	Rob_Out[8,0].18	090R02 Area Ready Measure
R_Out(9,0)_18	Rob_Out[9,0].18	090R03 Area Ready Measure
R_Out(10,0)_18	Rob_Out[10,0].18	090R04 Area Ready Measure
R_In(7,0)_18	Rob_In[7,0].18	090R01 Area Release Measure
R_In(8,0)_18	Rob_In[8,0].18	090R02 Area Release Measure
R_In(9,0)_18	Rob_In[9,0].18	090R03 Area Release Measure
R_In(10,0)_18	Rob_In[10,0].18	090R04 Area Release Measure
R_In(7,1)_10	Rob_In[7,1].10	090R01 Job Ready Measure
R_In(8,1)_10	Rob_In[8,1].10	090R02 Job Ready Measure
R_In(9,1)_10	Rob_In[9,1].10	090R03 Job Ready Measure
R_In(10,1)_10	Rob_In[10,1].10	090R04 Job Ready Measure
Rel15	zzSeq[5].Release.15	Perceptron Part measured Release
R_In(7,0)_7	Rob_In[7,0].7	090R01 in Home Position
R_In(8,0)_7	Rob_In[8,0].7	090R02 in Home Position
R_In(9,0)_7	Rob_In[9,0].7	090R03 in Home Position
R_In(10,0)_7	Rob_In[10,0].7	090R04 in Home Position

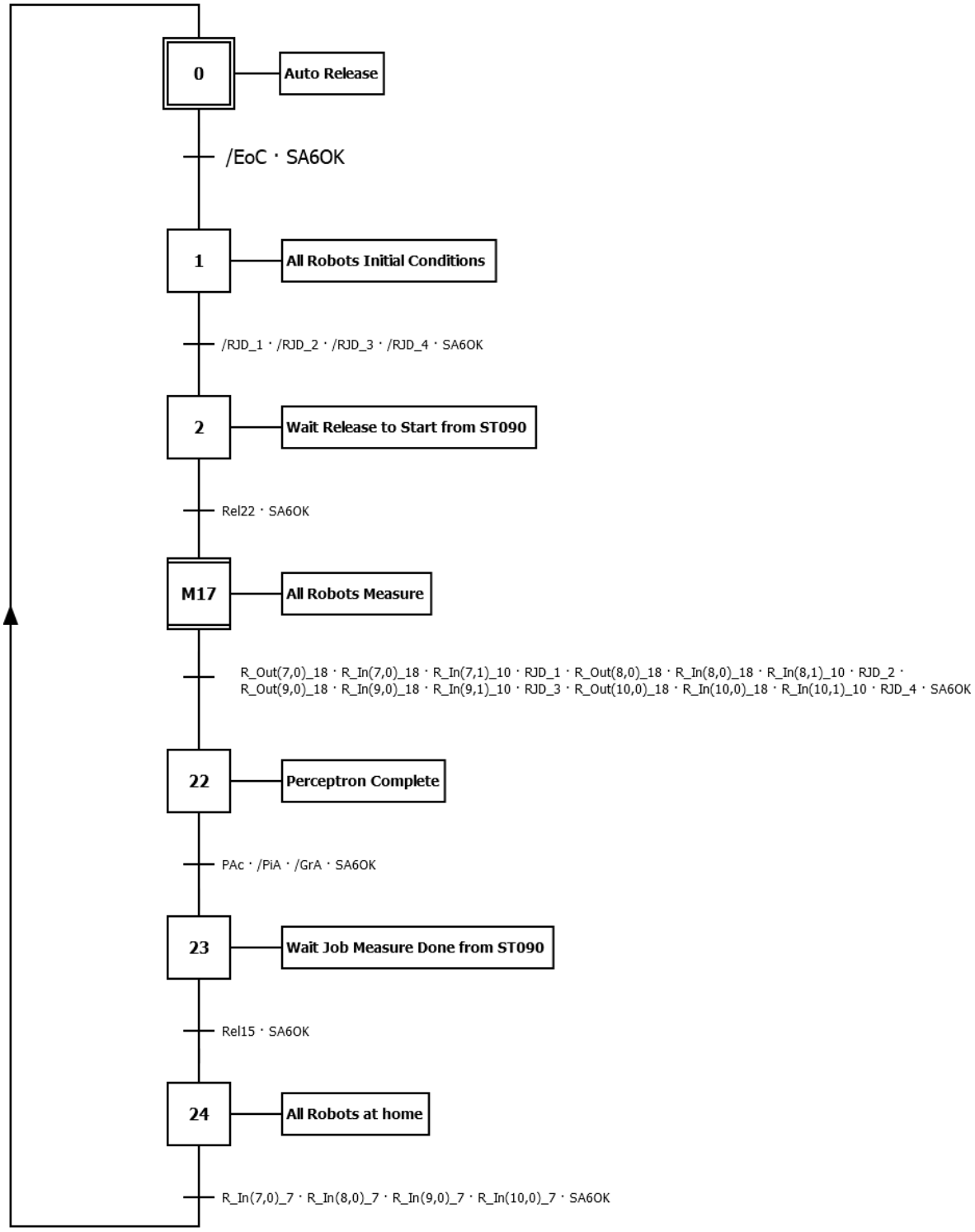

Figure 2.38. ST90 Robots Measurement Sequence GRAFCET

2.4.4. ST100 Lifter

The final station in the line consists of a lifter which works in the same way as the first one described in section 2.2.1 but in an inversed manner. The vehicle is transported from ground level as it exits the station 90 measuring station back to the upper level conveyor which transports it to the cladding line.

Table 2.21. ST100 Lifter Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[6].EOC	End of Cycle
BTTOK	_3_A2_42_512BT	Braking Transistor Temperature OK
MECP	_3_A2_42_2526CON_1	Motor Enable Contactor +
MECN	_3_A2_42_2526CON_2	Motor Enable Contactor -
MECF	_3_A2_42_2526CON_F	Motor Enable Contactor Feedback
SA6OK	_SA06_2_Safety_Area_OK	Safety Area 6 is OK
SA7OK	_SA07_2_Safety_Area_OK	Safety Area 7 is OK
SA8OK	_SA08_2_Safety_Area_OK	Safety Area 8 is OK
Rel2	zzSeq[6].Release.2	Station 100 to Station 90 Enter Forward Acknowledge Release
VIP	zzSeq[6].InPos[50].1	Vehicle In Position
HESOK	zzSeq[6].InPos[50].7	Hall Effect Sensor is OK
SeqOK	zzSeq[6].TypeOK	Sequence Type is OK
TFR	Type.InStation[6].13	Type Fixed Roof
TMR	Type.InStation[6].12	Type Moon Roof
Dry	Type.InStation[6].28	Type Dry Part
TMM	zzSeq[6].Flag.28	Type Miss Match
PSRest	_100S641B	Pallet Stop in Rest Position
PSWork	_100S641A_OK	Pallet Stop in Work Position
PLRest	_100S621B	Pallet Lock in Rest Position
PLWork	_100S621A	Pallet Lock in Work Position
NoVehST100ST90	zzSeq[6].Release.21	No Vehicle Between Stations 100 and 90
NoVehST500ST100	zzSeq[8].Release.21	No Vehicle Between Stations 500 (Conveyor 10) and Station 100
LRest	_100S191B	Latch in Rest Position
LWork	_100S191A	Latch in Work Position
DriveInDownPos	zzLifter[1].In_Pos2	Lifter Motor Drive in Down Position
GC	_100S361B	RollerGate Closed
GO	_100S361A	RollerGate Open
Seq0	zzSeq[6].SeqTypeZero	Sequence Type is 0
T0	zzSeq[6].StnTypeZero	Station Type is 0
Rel1	zzSeq[6].Release.1	Station 10 to Station 20 Exit Forward Request Release
DriveInUpPos	zzLifter[1].In_Pos1	Lifter Motor Drive in Up Position

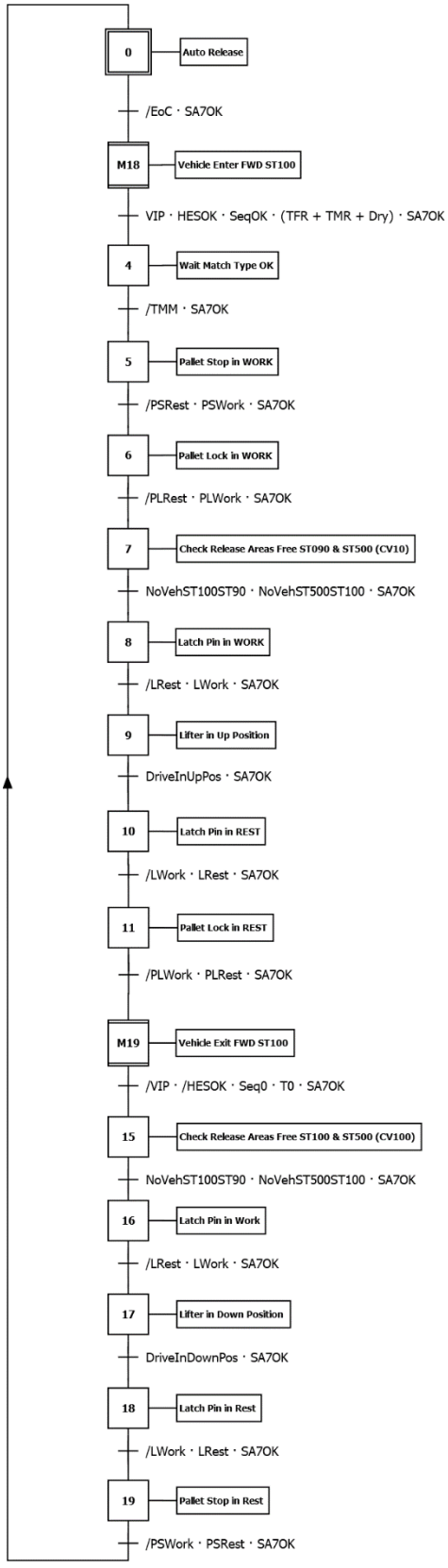

Figure 2.39. ST100 Lifter Sequence GRAFCET

3. Safety

3.1. GuardLogix Software

Guardlogix is a component of the Rockwell Automation Studio 5000 Logix Designer which is the PLC controller software. Guardlogix is the safety component where the safety programs are written and running.

A feature of the software is the safety signature. For the safety PLC, and consequently the whole PLC to operate, the safety signature must be locked. The safety signature is created when writing the safety program, and it must be unlocked every time there is a modification to the program. This way, unwanted or dangerous modifications to the program by unauthorized personnel can be prevented and a change log of the safety program can be kept, which may be used in case that legal responsibilities are sought.

Communication is made using an ethernet/IP 1756-EN2T module which connects the controller to I/O devices, encapsulating messages within standard TCP/ IP protocol.

Programs are contained within a continuous task, with the main program's period limited to a maximum of 500 *ms* by design. In case this period is exceeded the watchdog will trigger a non-recoverable fault to avoid a hazardous situation caused by a slow response by the safety components. Communication between safety components must always be under 20 *ms*, in case this time is exceeded, the safety watchdog will trigger a non-recoverable fault in the same manner as in the continous task.

3.2. Energy Control and Power Lockout

Energy control and power lockout *(ECPL)* safety procedure to enter into the lines in case manual intervention is needed. Because opening a door will cause the safety area to go down and disconnect all the machinery in it, it is enough to lock the door open with a personal padlock to ensure work can be carried out inside safely. Every single person who enters the line must carry and use his or her own padlock, using a single one per group is not tolerable. A tag bearing the name of the owner and his phone number is attached to the padlock. The padlock may only be removed by its owner. In case that the padlock needs to be removed and the person is unavailable, it may only be removed once the number is called to make sure the person is not inside and is unable to come retrieve it, or the site manager authorizes the removal. Not complying with this procedure is considered a severe misdemeanor and may be penalized with expulsion from the factory.

Figure 3.1. ECPL compliant padlock locking equipment. Source: [4]

3.3. Hardware

3.3.1. Safety Controller

The safety controllers in use are Rockwell 1756-L7SP with USB communication ports and a secure digital (SD) memory card.

3.3.2. Light Barriers

Safety light curtains installed are a pair of SICK deTec4 core barriers. The curtains are aligned with each other, one acts as a sender and the other one as a receiver. Whenever the laser beams between them are crossed, the neighboring safety areas will go down. The variant used on site has a resolution of 30 *mm* and a response time of 14 *ms*.

Figure 3.2. SICK deTec4 light barrier. Source: [5]

3.3.3. Roller Doors

Roller doors are installed to separate the lifter safety areas and between PLC 1 and 3. They close when access is requested to neighboring safety areas of the roller doors. This way, personnel access between the safety areas is prevented and therefore the neighboring safety area can continue operating even if the other side of the gate is down. The doors accomplish a closing time of 1.3 *s* and have fire-retardant capabilities.

Figure 3.3. Rapid Roller Door. Open in the left image and closed in the right. Source: Centreline Machine Guards LTD. Source: [6]

3.3.4. Gates

Gates are closed and opened via a Fortress Interlocks amGardpro interlock switch equipped with a 'universal' (factory-wide) safety key. Gates can only be unlocked with a safety key, which will then release a unique grey key. Without inserting the grey key back, the safety key cannot be extracted and thus the gate cannot be locked back. The interlock switch has two redundant safety circuits, this way in case there is a malfunction in one the backup circuit will maintain the correct operation of the switch.

Figure 3.4. Fortress Interlocks amGardpro interlock switch. Source: [7]

The control box attached provides the operator with five buttons. A 'central start' button, which allows the operator to resume production once the adequate conditions are met, it will flash in a white color whenever the conditions are ready to continue. An 'open gate' button, which requests to unlock the gate and allows access once all machinery is disconnected, it will flash once the request is made (when the button is pushed) and remain in solid green color when the gate is electronically unlocked. The 'reset' button acknowledges the error caused by the opening of the gate it pertains to, as well as all alarms and interlocks in the PLC. The 'close gate' button serves to electronically lock the gate if the mechanical conditions are met, it will remain in a solid white lit state whenever the gate is unlocked. And finally, a large emergency stop button which disconnects all electric and pneumatic power to the whole line. Above it the red emergency stop lamp will remain lit for as long as the emergency stop remains latched. The distribution of these is as shown in the following picture.

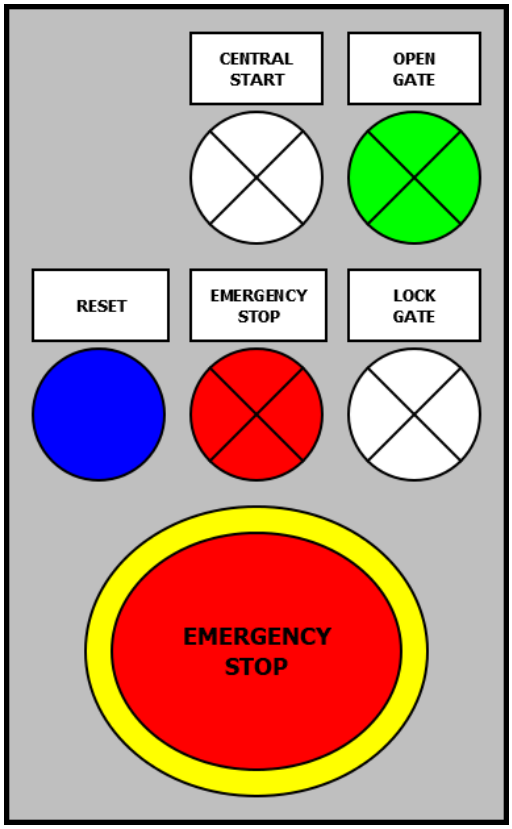

Figure 3.5. Gate control box button distribution.

3.4. Start, Error and Stop Modes

To represent graphically the line's start, error and stop modes, the GEMMA *Guide d'Etudes des Modes de Marches et d'Arrêts* is used.

Table 3.1. GEMMA chart variables.

Variable	PLC Contact	Description
Central Start	zzCentral.StartReq	Central start
Auto	zzCentral.AutoReq	Automatic mode
Interlock	zzseq[XX].IntOk	Interlock
E-stop	_SA00_1_Estops_OK	Emergency stop
EoC	zzSeq[XX].EOC	End of cycle
Reset	zzCentral.Reset	Reset
Initial Conditions	zzseq[XX].Ready	Initial conditions
Manual	zzCentral.ManReq	Manual mode

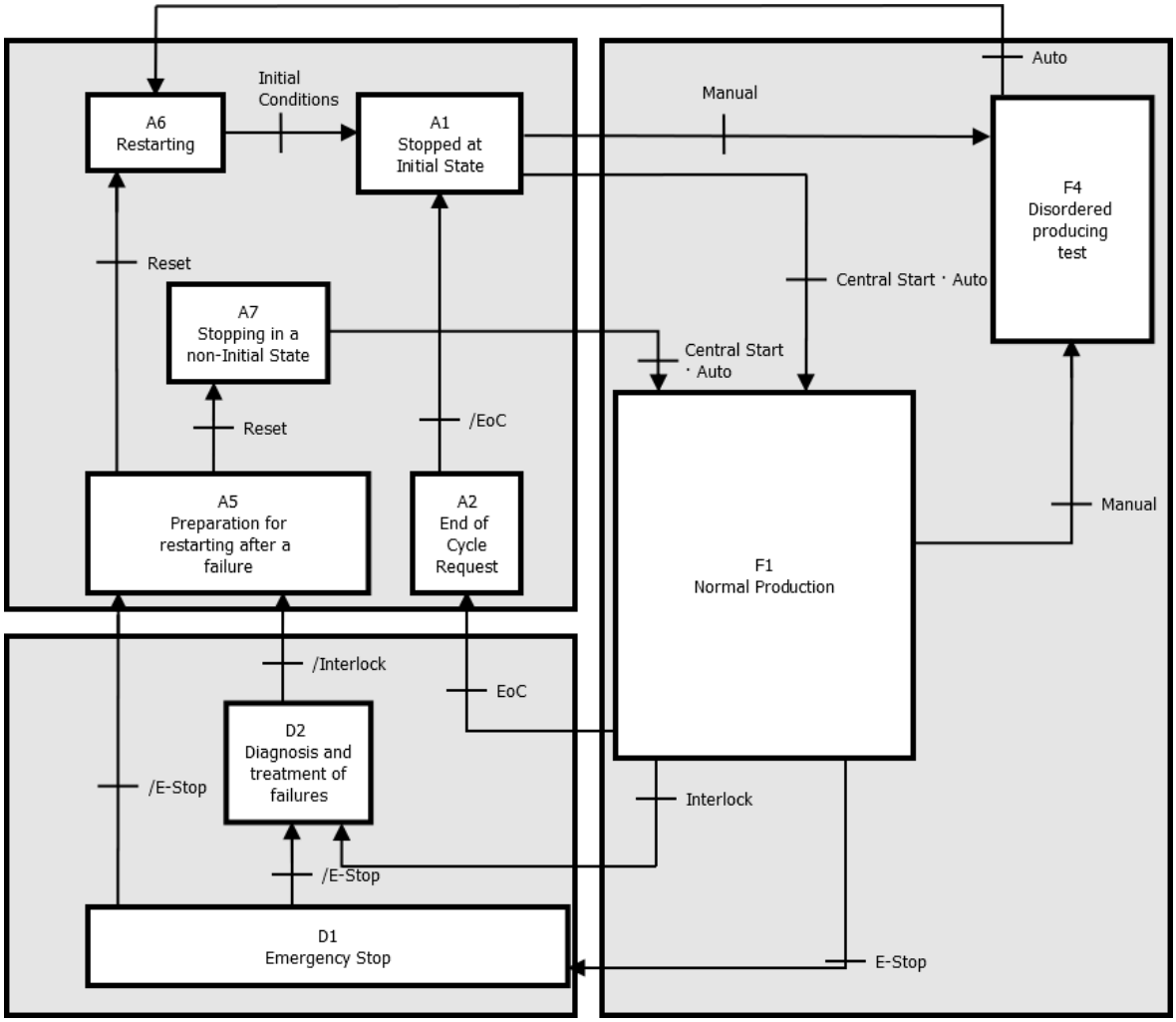

Figure 3.6. GEMMA chart, start, error and stop modes.

Once the initial conditions are met, normal production can start once automatic mode and the central start button are pressed. The automatic and manual modes can be toggled from the HMI interface. The manual mode can be activated during normal production for a disordered producing test, resuming normal production by selecting automatic mode providing initial conditions are met and the central start button is met. In the event of an emergency stop, restarting can be achieved once the emergency stop is unlatched and the reset button is pressed. A similar treatment is followed with interlock failures, with a reset being necessary after the interlock fault is corrected. An end of cycle request can be made through the HMI interface, in which case the station will finish the current cycle and stop at the initial state.

3.5. Safety Areas

A safety area consists of a machine field which is delimited by safety equipment, such as doors and light barriers. When the access gate to a safety area is unlocked, all machinery in said area is disconnected. The distribution of safety areas in the assembly line is described in the following sections.

Because this line uses linear synchronous motor technology to displace vehicles along the line, it has the particularity that whenever a safety area is down in PLC1 and 3, the motors from the neighboring stations go down too, even in the case that the roller doors are down. This happens because the motors are capable of moving the vehicle at high speeds which could rip the roller door and cross the safety area in case of a motor malfunction.

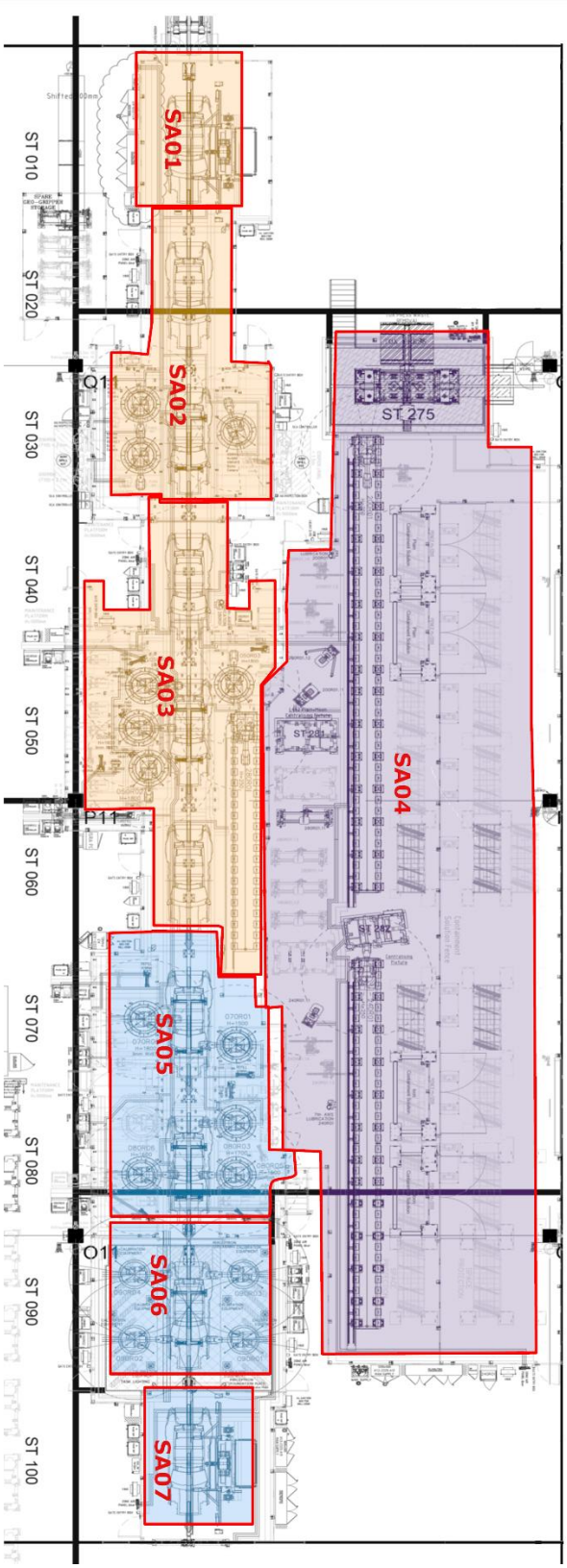

Figure 3.7. Safety area floorplan.

3.5.1. PLC1

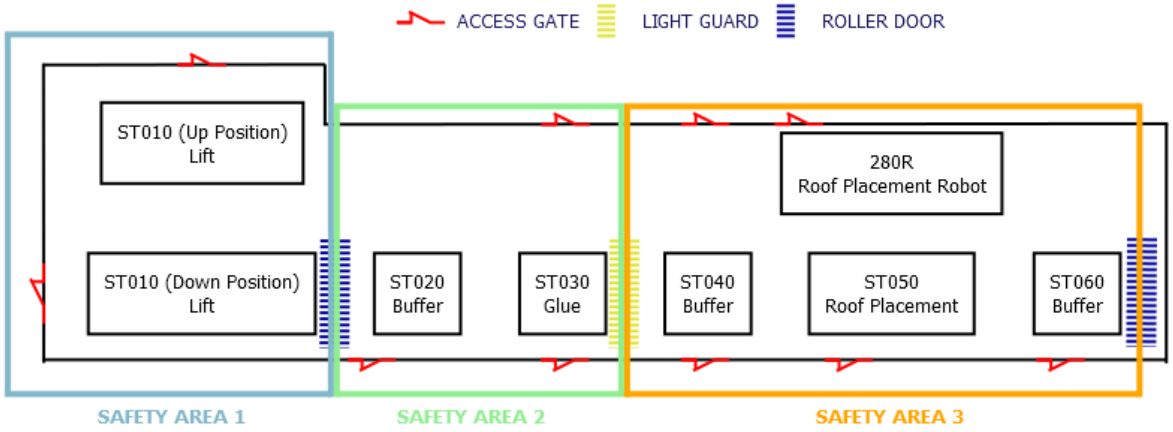

Figure 3.8. PLC1 safety area layout.

A total of three safety areas are controlled by PLC1. A light barrier separates safety area 1 and the conveyor 9 safety area, it is not shown on the layout because this barrier is controlled by the conveyor 9 PLC.

Table 3.2. Safety Area 1 GRAFCET Variables

Variable	PLC Contact	Description
SA1OK	_SA01_2_SAFETY_AREA_OK	Safety Area 1 is OK
E-Stop	_SA00_1_Estops_OK	Emergency Stop
AG1	_1A511_GATE_OK	Access Gate 1
AG2	_1A512_GATE_OK	Access Gate 2

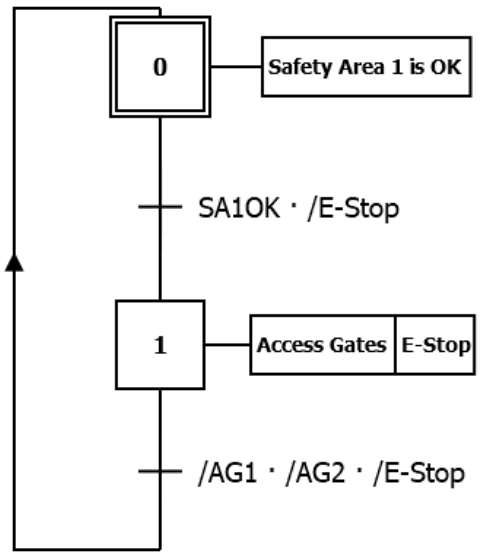

Figure 3.9. Safety Area 1 GRAFCET

Table 3.3. Safety Area 2 GRAFCET Variables

Variable	PLC Contact	Description
SA2OK	_SA02_2_SAFETY_AREA_OK	Safety Area 2 is OK
E-Stop	_SA00_1_Estops_OK	Emergency Stop
LB	SA02_SA03_FenceLine_OK	Light Barrier
AG3	_1A513_GATE_OK	Access Gate 3
AG4	_1A514_GATE_OK	Access Gate 4
AG5	_1A516_GATE_OK	Access Gate 5

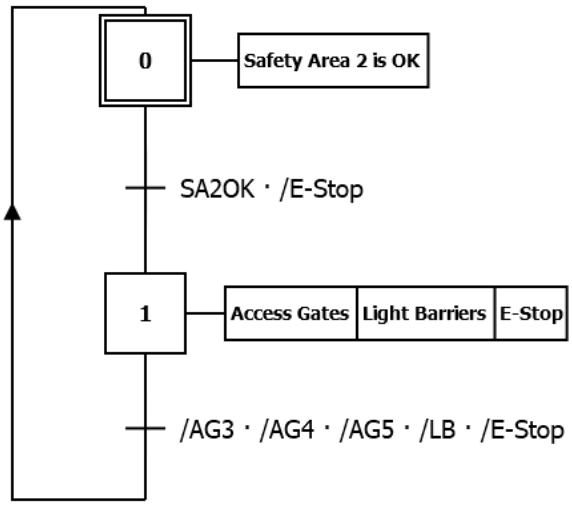

Figure 3.10. Safety Area 2 GRAFCET

Table 3.4. Safety Area 3 GRAFCET Variables

Variable	PLC Contact	Description
SA3OK	_SA03_2_SAFETY_AREA_OK	Safety Area 3 is OK
E-Stop	_SA00_1_Estops_OK	Emergency Stop
LB	SA03_SA02_FenceLine_OK	Light Barrier
AG6	_1A515_GATE_OK	Access Gate 6
AG7	_1A517_GATE_OK	Access Gate 7
AG8	_1A518_GATE_OK	Access Gate 8
AG9	_1A520_GATE_OK	Access Gate 9
AG10	_1A522_GATE_OK	Access Gate 10

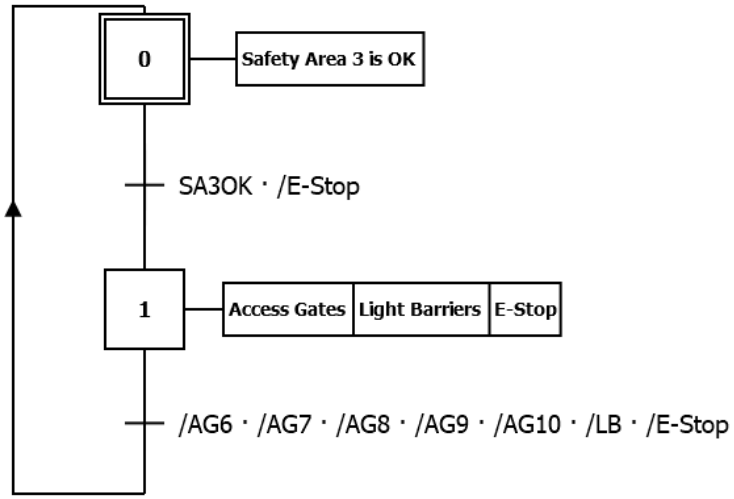

Figure 3.11. Safety Area 3 GRAFCET

3.5.2. PLC2

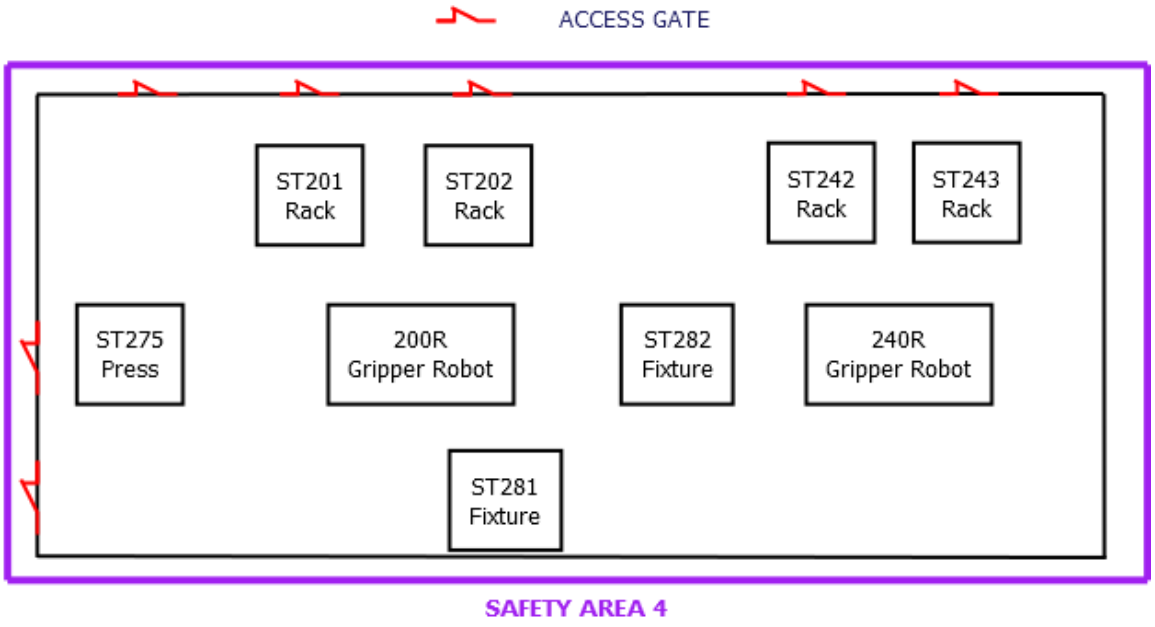

Figure 3.12. PLC2 safety area layout.

A large single safety area is controlled by PLC2. As explained in section 2.3.1, gates pertaining to the rack stations will only affect the respective gripper robot instead of the whole safety area.

Table 3.5. Safety Area 4 GRAFCET Variables

Variable	PLC Contact	Description
SA4OK	_SA04_2_SAFETY_AREA_OK	Safety Area 4 is OK
E-Stop	_SA00_1_Estops_OK	Emergency Stop
AG1	_2A511_GATE_OK	Access Gate 1
AG2	_2A513_GATE_OK	Access Gate 2
AG3	_2A517_GATE_OK	Access Gate 3

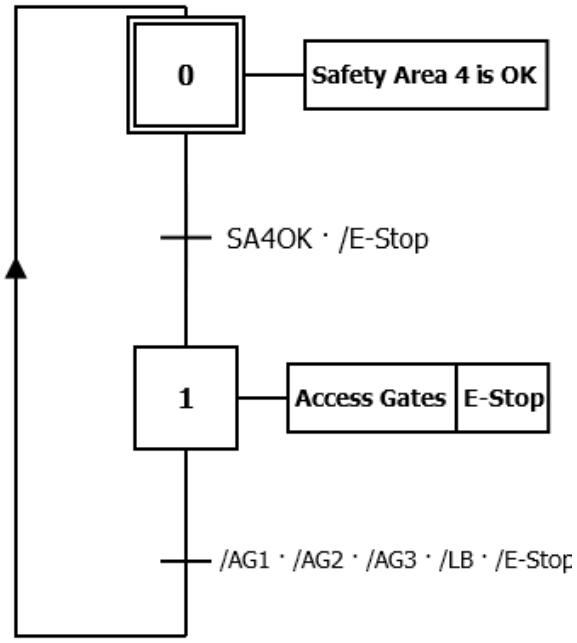

Figure 3.13. Safety Area 4 GRAFCET

3.5.3. PLC3

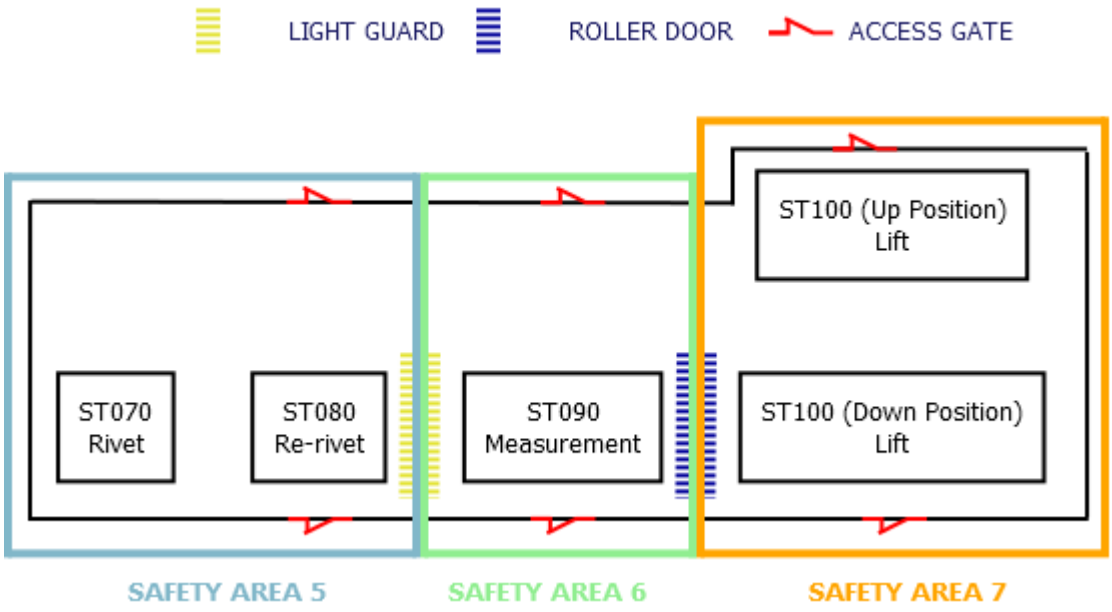

Figure 3.14. PLC3 safety area layout.

PLC3 has three safety areas. Safety areas 4 and 5 are separated by a roller door shown in figure 3.14. A light guard monitors the crossing between safety area 7 and the conveyor 10 safety area, it is not shown in the layout since it is controlled by the conveyor 10 PLC.

Table 3.6. Safety Area 5 GRAFCET Variables

Variable	PLC Contact	Description
SA5OK	_SA05_2_SAFETY_AREA_OK	Safety Area 5 is OK
E-Stop	_SA00_1_Estops_OK	Emergency Stop
LB	SA05_SA06_FenceLine_OK	Light Barrier
AG1	_3A511_GATE_OK	Access Gate 1
AG2	_3A512_GATE_OK	Access Gate 2

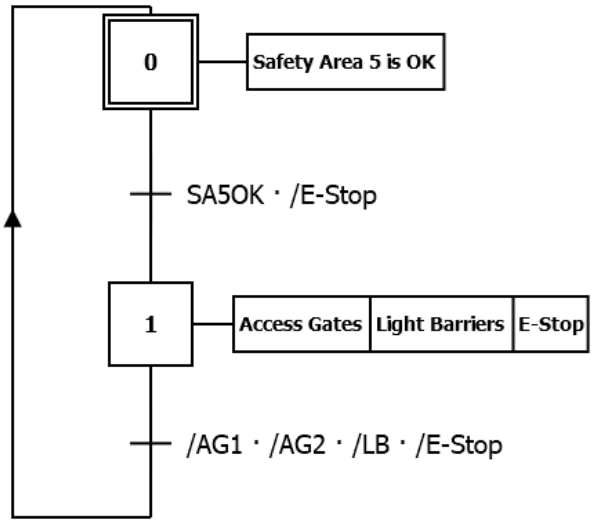

Figure 3.15. Safety Area 5 GRAFCET

Table 3.7. Safety Area 6 GRAFCET Variables

Variable	PLC Contact	Description
SA6OK	_SA06_2_SAFETY_AREA_OK	Safety Area 6 is OK
E-Stop	_SA00_1_Estops_OK	Emergency Stop
LB	SA06_SA05_FenceLine_OK	Light Barrier
AG3	_3A513_GATE_OK	Access Gate 1
AG4	_3A514_GATE_OK	Access Gate 2

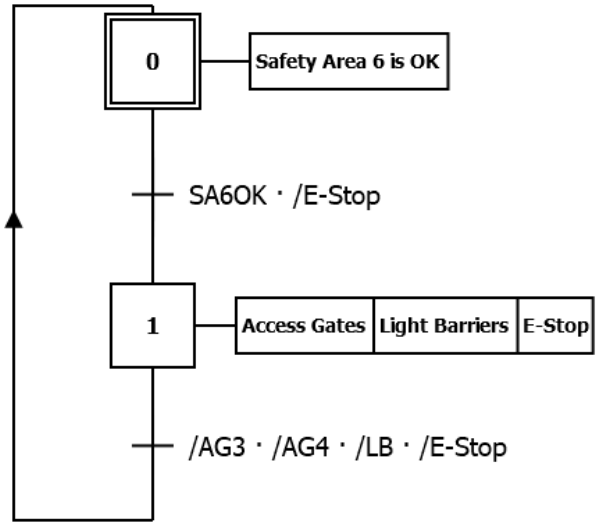

Figure 3.16. Safety Area 6 GRAFCET

Table 3.8. Safety Area 7 GRAFCET Variables

Variable	PLC Contact	Description
SA7OK	_SA07_2_SAFETY_AREA_OK	Safety Area 7 is OK
E-Stop	_SA00_1_Estops_OK	Emergency Stop
LB	SA06_SA05_FenceLine_OK	Light Barrier
AG5	_3A516_GATE_OK	Access Gate 5
AG6	_3A517_GATE_OK	Access Gate 6

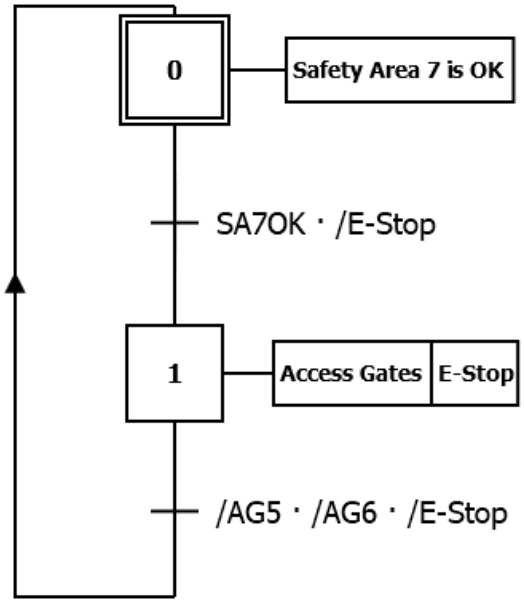

Figure 3.17. Safety Area 7 GRAFCET

4. Communications

Communication is made via ethernet/IP, encapsulating messages within standard TCP/IP protocol. The ethernet switch used in the line is an Allen Bradley Stratix 5700, in the 1783-BMS10CGL variant. It has a total of 10 ports, eight fast ethernet and two gigabit ethernet ports. All cabling is done in accordance to the T568B color code.

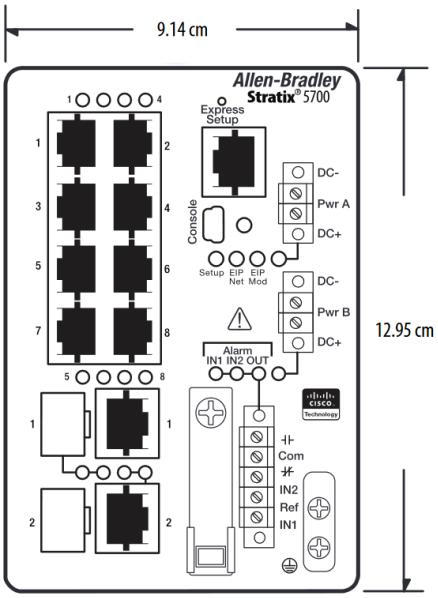

Figure 4.1. Stratix 5700 1783-BMS10CGL. Source: [8]

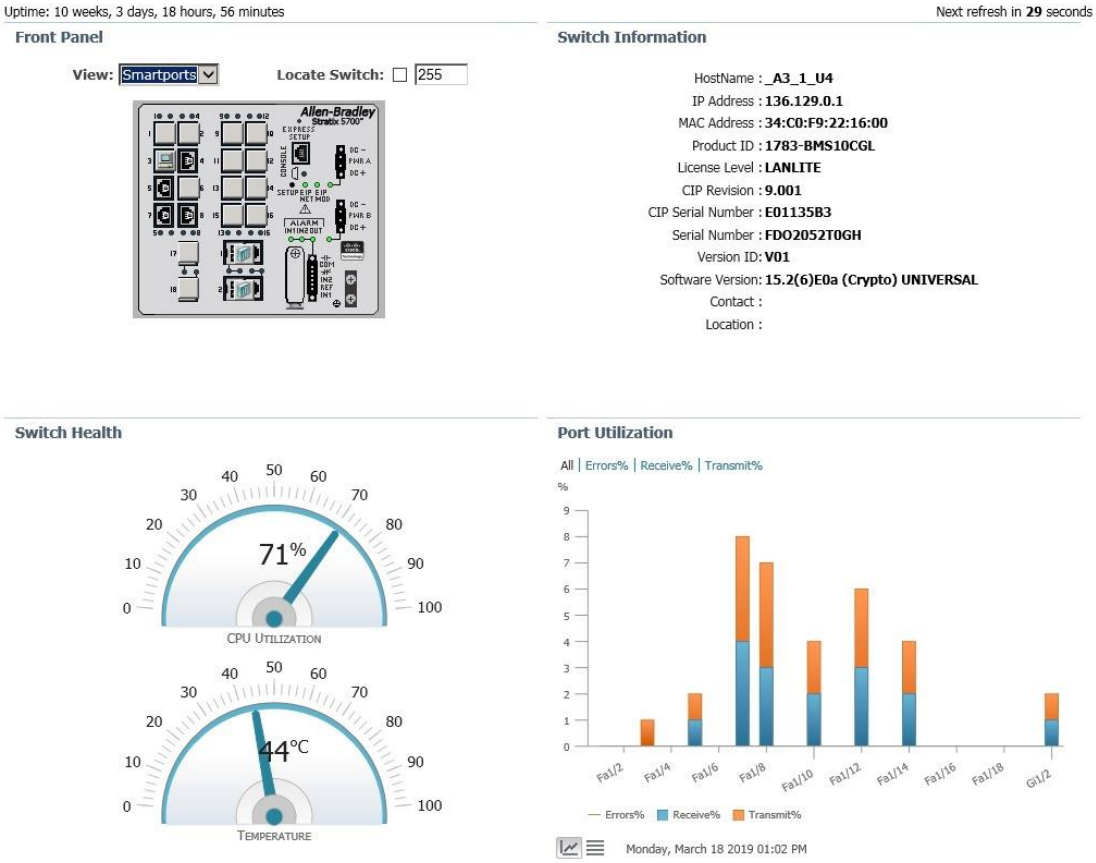

Figure 4.2. Stratix 5700 1783-BMS10CGL status on webserver.

In figure 4.2 the Stratix configuration, port utilization and port status can be seen in real time. The port utilization chart shows the available band width and net capacity for each channel is monitored. This way, the feasibility of a possible network upgrade or scan time improvement.

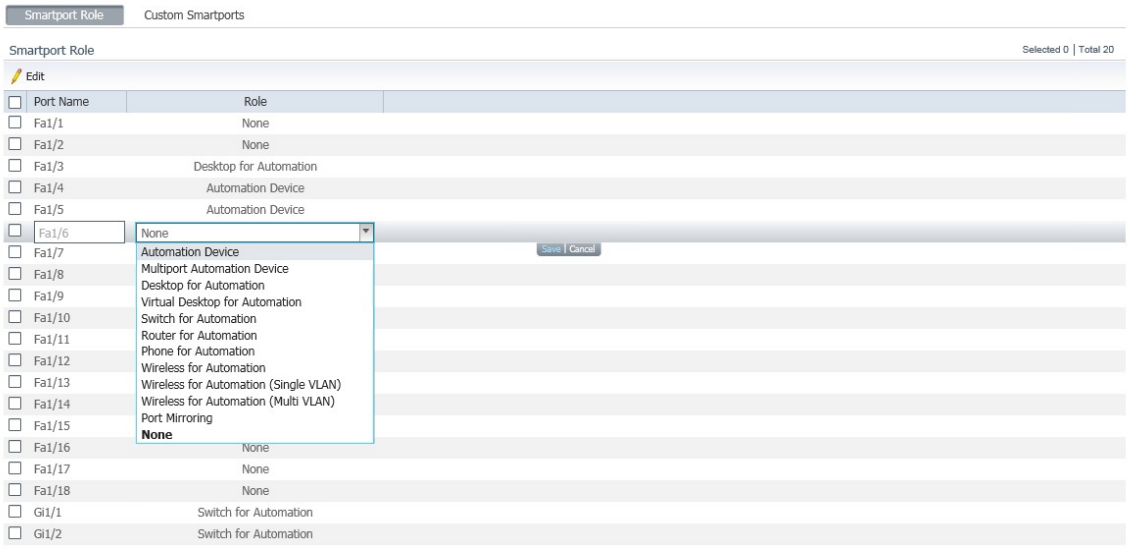

Figure 4.3. Stratix 5700 1783-BMS10CGL Smartport Role tab in webserver.

In the smartport role tab, the stratix ports can be configured individually to suit any given needs. Depending on the device type, the communication type will differ, ranging for example from 'automation device' for a PLC, or a 'switch for automation' to further expand the network.

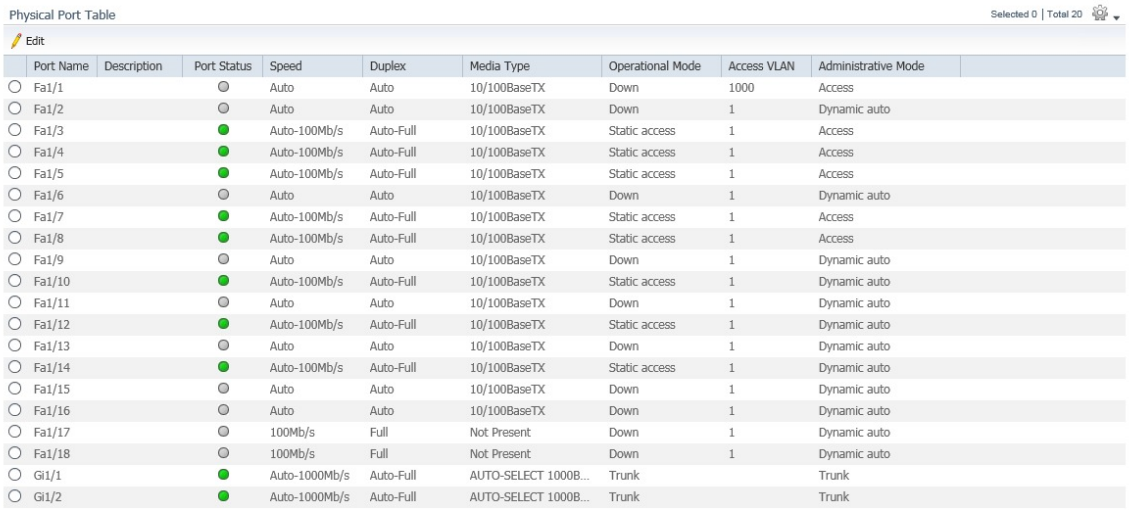

Figure 4.4. Stratix 5700 1783-BMS10CGL Physical Port Table in webserver.

The physical port table allows for continuous monitoring of the Stratix ports. This is a handy tool for quickly identifying network issues.

4.1. RSLinx Software

At the line PC, the communication software version used is Rockwell Automation's RSLinx Classic Gateway. Said software is responsible for communication configuration between device programming applications such as the PLC and HMI applications, in this case the Factory Talk software (more details on the HMI software in section 5.1), or with other data acquisition applications.

Networks and devices can be seen through the RSWho main window. From here all active network connections can be monitored and the DDE (Dynamic Data Exchange) topic can be configured.

RSLinx is an OPC (Open Platform Communications) compliant software and employs said communication standard to allow client applications access to plant floor data. The inter-application communication protocol standard used is DDE, allowing supported Windows programs to exchange data without specifying the type of data being exchanged.

4.2. PLC1

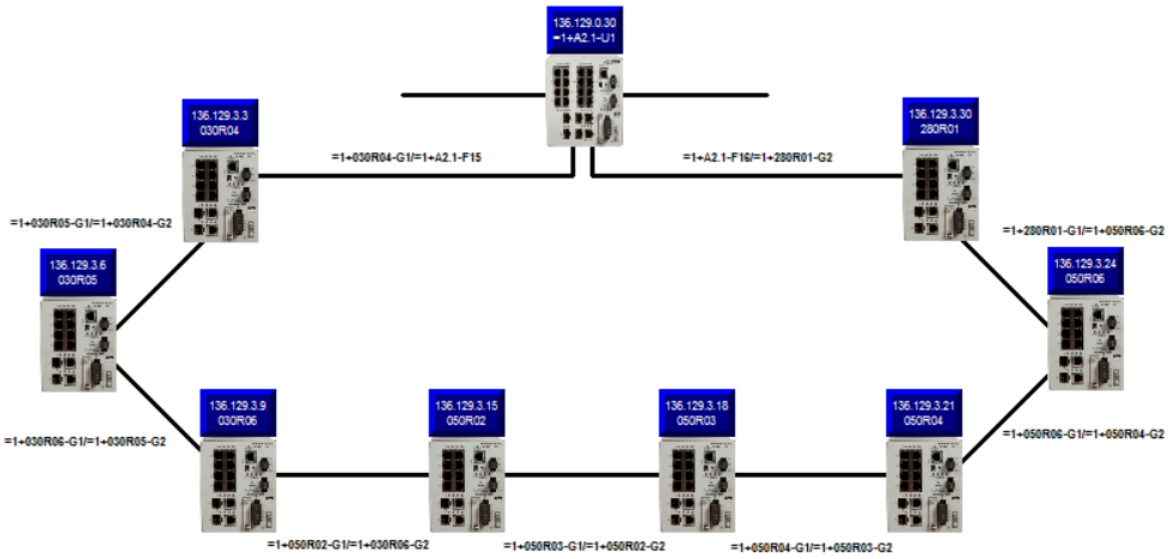

Figure 4.5. PLC1 Stratix communication. Source: [9]

The topology used is DLR (Device Level Ring) with the PLC acting as the supervisor node (connected in stratix =1+A2.1-U1), managing the network's traffic and monitoring the ring's integrity. DLR acts in the same way as an ordinary ring network except that due to the supervisor node faults can be easily identified and the whole network won't fail because of a single device error, which is the ring topology's main weakness. Instead, the network will switch to a linear topology functioning, avoiding the faulty device and allowing time to perform a repair without a network collapse.

The stratix =1+A2.1-U1 is connected with its equivalents in PLC2 and PLC3 (=2+A2.1-U1 and =3+A2.1-U1 respectively) in an open loop topology forming the roof line sub network.

4.3. PLC2

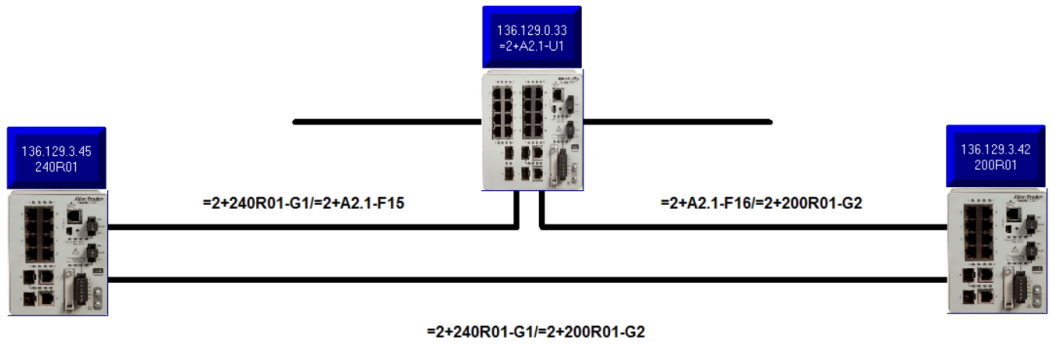

Figure 4.6. PLC2 Stratix communication. Source: [9]

The same DLR topology as explained in section 4.2 is employed, with the PLC (connected in stratix =2+A2.1-U1) acting as the supervisor node.

4.4. PLC3

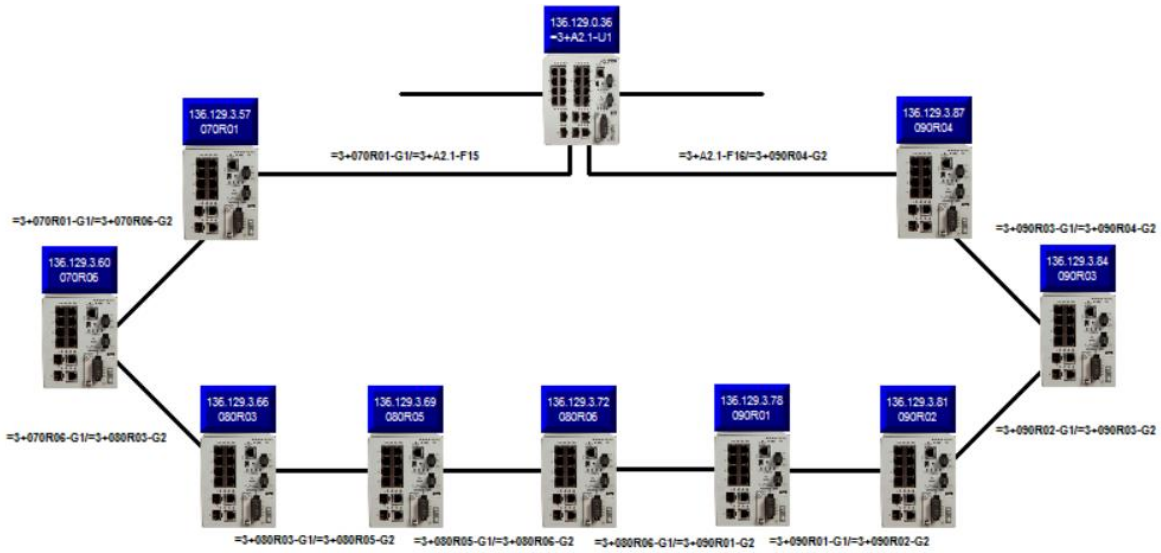

Figure 4.7. PLC3 Stratix communication. Source: [9]

The topology is the same as in PLC 1 and 2, being device level ring. DLR topology is described in section 4.2. The PLC (connected in =3+A2.1-U1) is the supervisor node.

5. Human Machine Interface (HMI)

5.1. FactoryTalk Software

HMI management is accomplished via the FactoryTalk View Machine Edition software package. Included in the package, is the FactoryTalk View Studio software, specifically version 9.0 is used in the line. It allows for the design and testing of HMI screens.

5.2. Developed HMI Application

An HMI application to monitor the status of the line has been developed. The application allows to know the state of the line at a glance by showing multiple situations: whether a vehicle is occupying a station, the state of the safety areas, access gate openings, roller door status, or request a vehicle for the proposed takeout station, details on said proposed station in section 6.1.

5.2.1. PLC Code

In order to test the correct functioning of the HMI application, a PLC program has been developed to simulate the vehicle bodies' movement and safety behavior of the line. The program is communicated with the HMI application via RSLogix Emulate 5000 Chassis Monitor, which allows the program to go online.

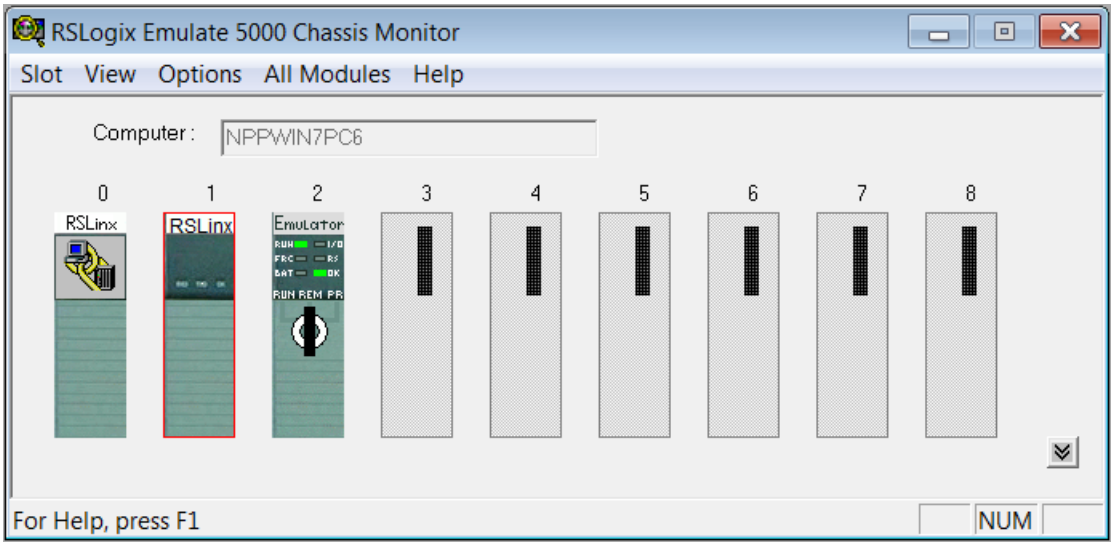

Figure 5.1. Emulogix virtual controller online.

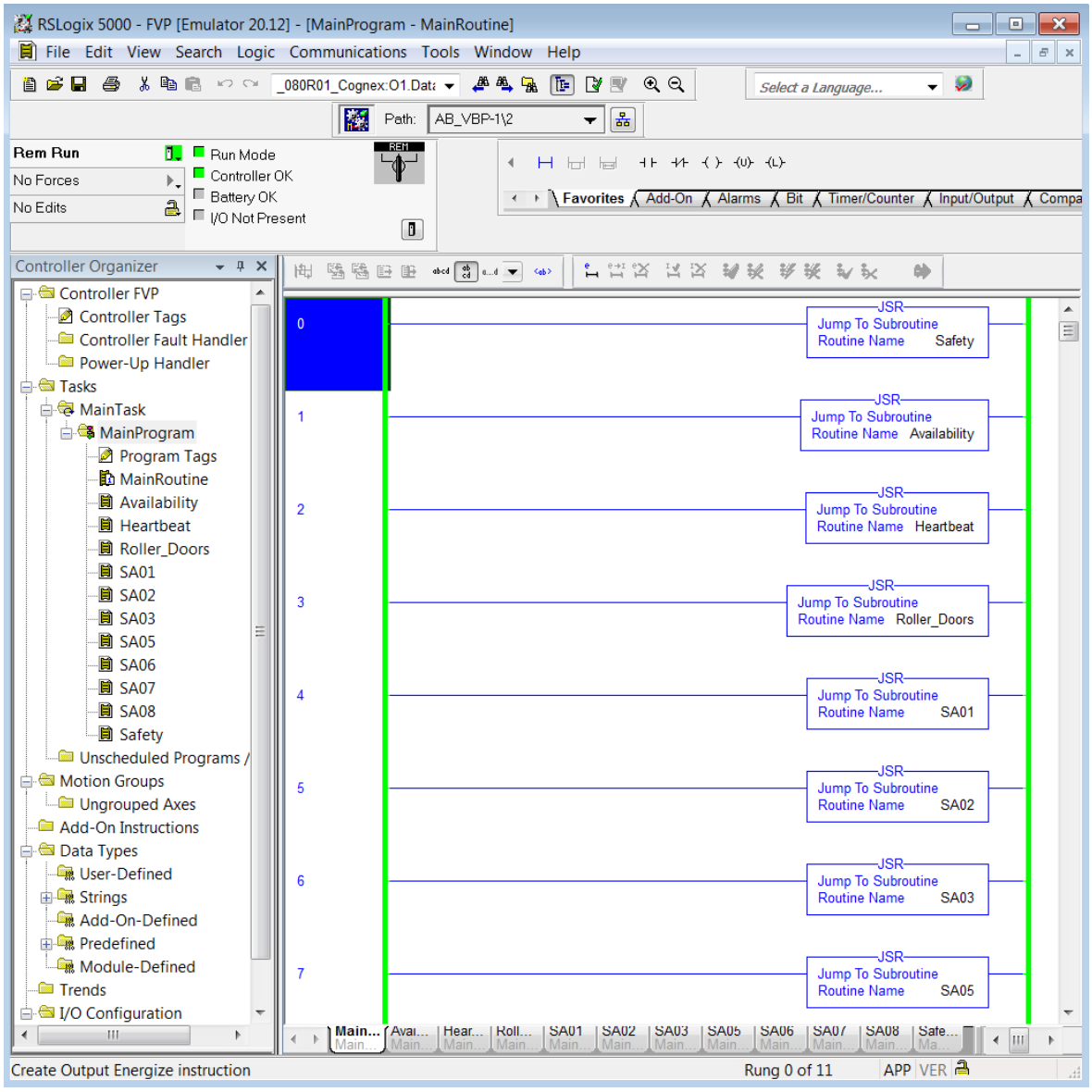

Figure 5.2. PLC program in run mode through virtual controller.

The program consists of 12 routines. The MainRoutine is used to call the rest of the routines. The Heartbeat routine creates a periodic signal which allows the HMI user to know if there is an interruption in communication should the signal stop. The safety area routines, 01 through 08 (named SA0X), simulate the movement of vehicle bodies in their respective safety areas. Availability provides conditions to avoid collisions between vehicles. The Roller_doors routine controls the movement of the roller doors which roll up or down depending if the triggered safety area is equipped with one. The Safety routine simulates the safety program controlling the functioning of light barriers and access gate openings therefore controlling the triggering of safety areas. It also handles the emergency stop function. The whole code for the program can be found in the annex.

5.2.2. HMI Display

The application consists of two displays that illustrate the path of the car body along the line through stations 010 to 100 (or 110 should a takeout request be made). At the top left corner of the display, two intermittent green squares represent the heartbeat signal. Underneath them is the “Continuous Mode” and “Add Body” buttons, which allow for a continuous flow of bodies, or a single body to enter the line respectively.

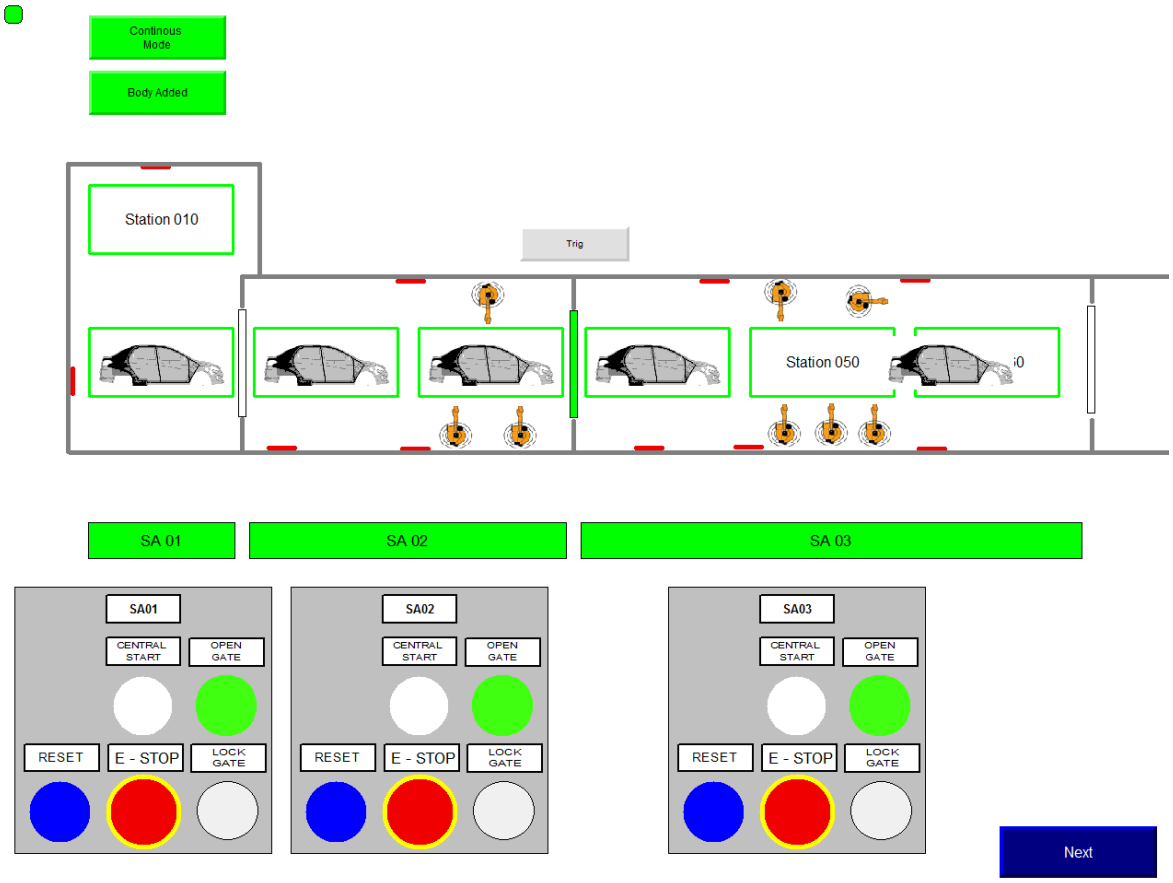

Figure 5.3. Display 1 under normal conditions.

At the bottom of the display, buttons simulating the control box located at each gate are placed. In this case, a control box per safety area has been assigned. The buttons simulate the behavior of the real control boxes under a variety of situations. On top of these boxes, indicators let the user know the state of the safety areas.

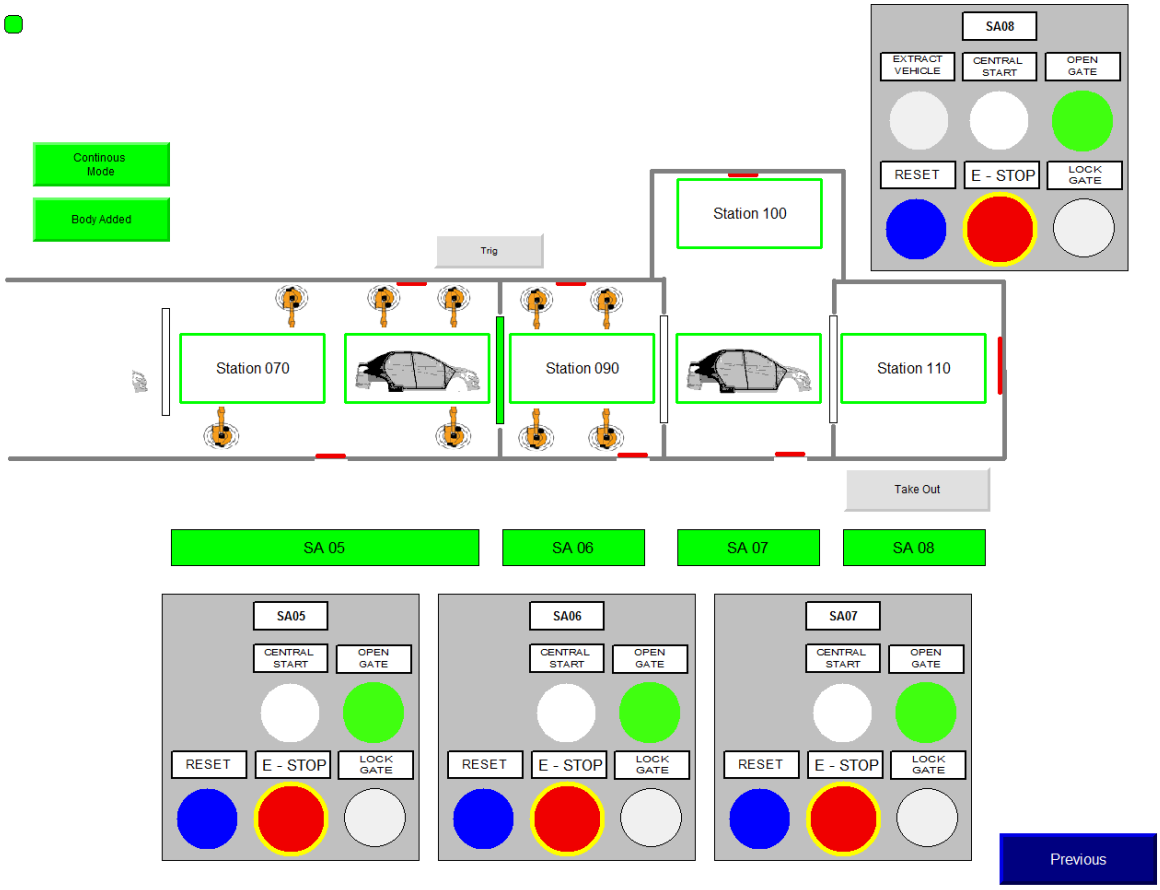

Figure 5.4. Display 2 under normal conditions.

In the case of safety area 8, an extra button for the control box has been added to allow for the extraction of vehicles through station 110. In addition to the safety area status indicators, for display 2 there is also an indicator for said extraction mode.

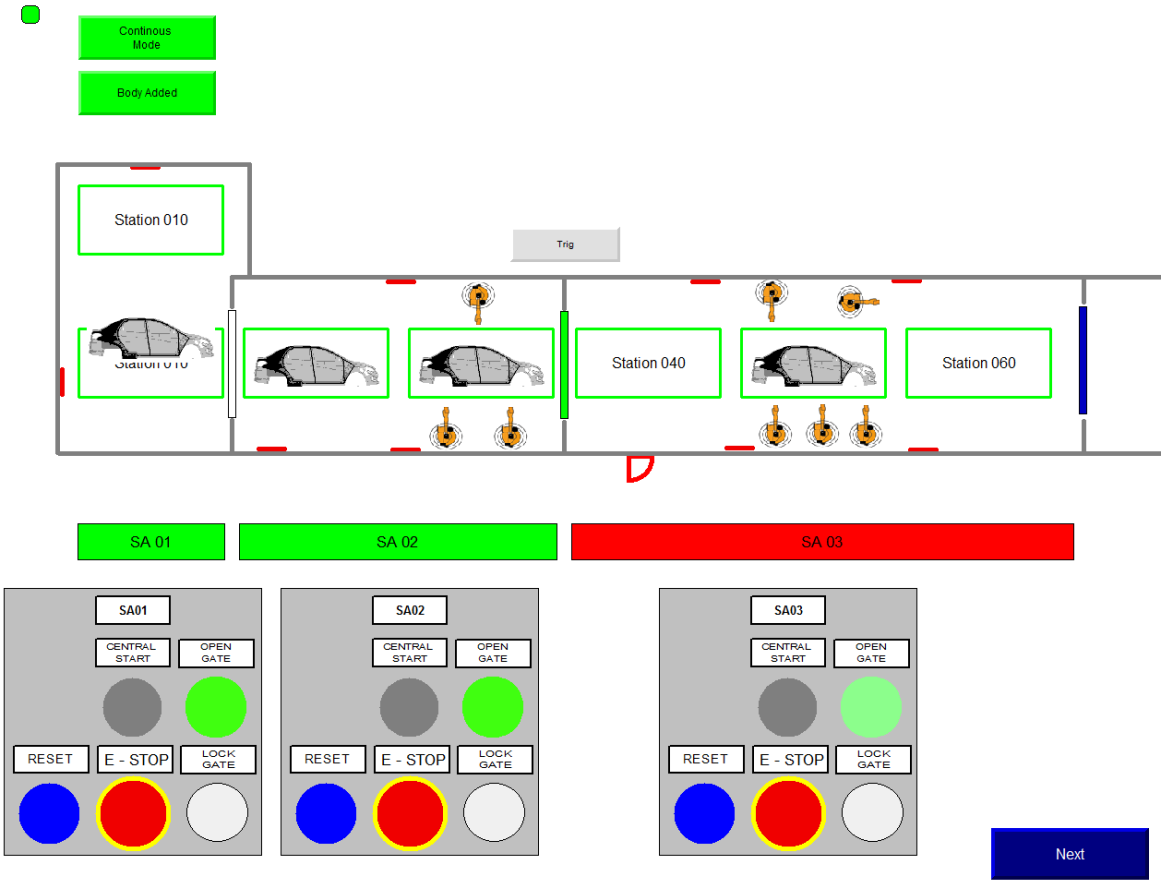

Figure 5.5. Display 1 with an access gate opening.

In the case of a door opening, the display shows the specific access gate being opened. In figure 5.5, an access gate request is made in safety area 3. The safety area goes down once vehicles present in the safety area reach a station, and afterwards allowing the gate to be opened, mimicking the real line's behavior. No more vehicles are allowed to enter the safety area and the roller door goes down, the movement being displayed in blue. Until the door is closed and the central start signal is reestablished, the line will not restart.

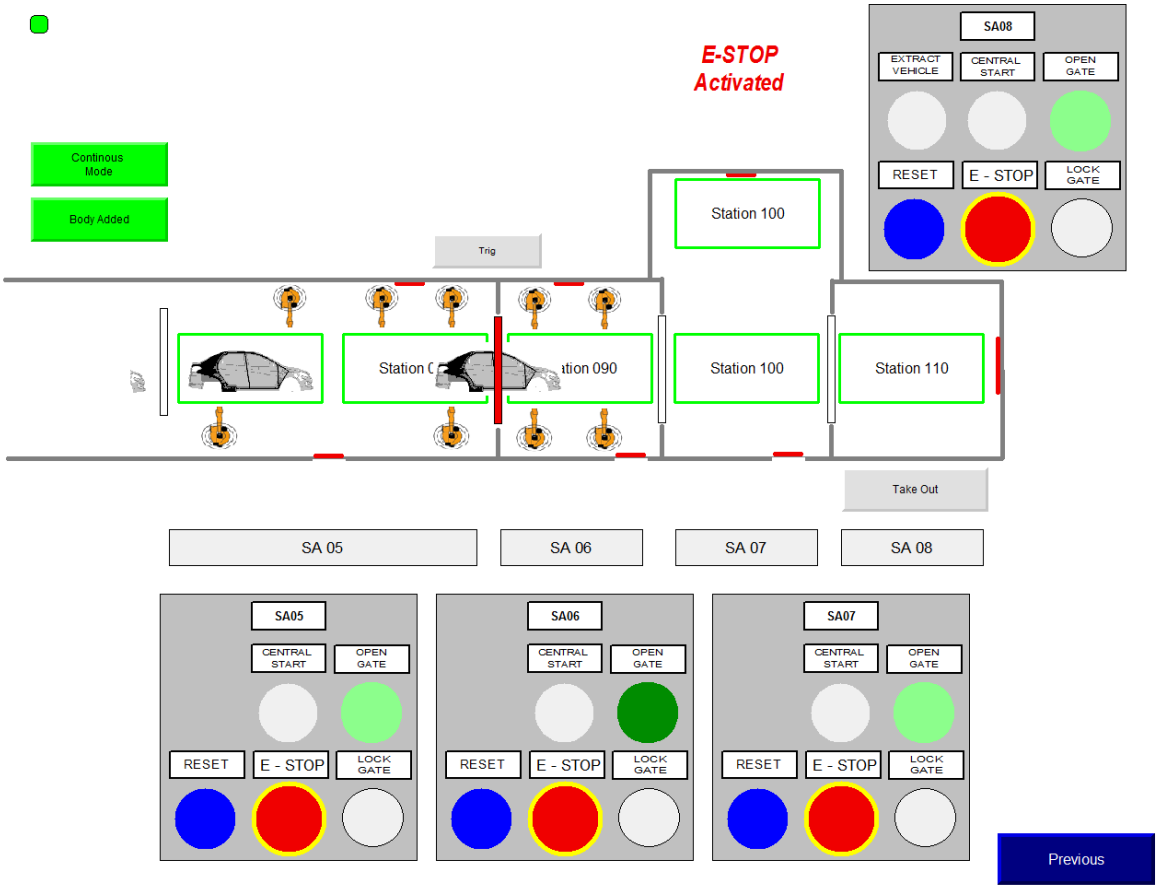

Figure 5.6. Display 2 with an E-stop activated.

In the event of an emergency stop, all vehicles will immediately stop and an E-stop Activated message will appear. In figure 5.6, a vehicle has stopped midway a light barrier, triggering it and therefore flashing in red. Until the stop is acknowledged by pressing the reset button, the line will not restart.

6. Improvements

6.1. ST110 Take Out Station

The takeout station allows vehicles or pallets to be both inserted and extracted from the line. Daily, car bodies are examined and taken off the factory's line for quality and measuring inspections in the workshop. Also, occasionally cars are damaged or do not meet the minimum measurement criteria established in station 90 automatic Perceptron system. In such scenarios, cars are taken out of the line for repairing or recycling purposes. The proposed takeout 110 station allows for these tasks to be carried out automatically without interrupting the assembly flow. Once vehicles have passed the inspection, been repaired, or simply empty pallets want to be inserted into the system, the take out station will insert them back to the system without losing the line's automatic mode. A rolling door and a large access gate are added, leaving the layout as shown in figure 6.1. In addition, when inserting vehicles, their variant is identified both by RFID and a barcode scanner, similar to the ones equipped in station 50, details on these in sections 2.2.1 for the RFID and 2.2.5 for the barcode scanner.

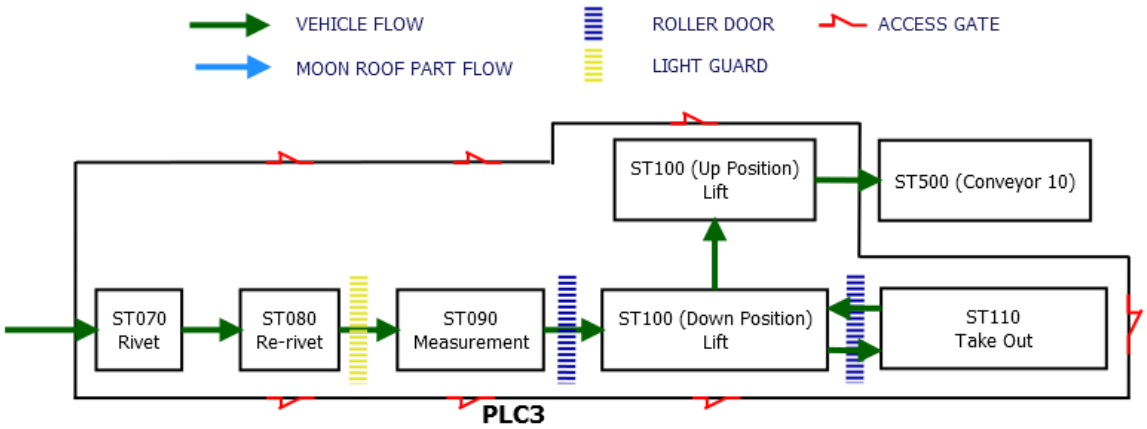

Figure 6.1. PLC3 Area Flowchart with Takeout Station.

Station 110 consists of two automatic work modes which can be selected manually by the operator via HMI when extracting or inserting a vehicle is desired, 'extract' or 'insert' mode respectively. When extracting and inserting vehicles, the station's access door must be opened. In order to achieve this task without losing the automatic mode, the safety program has been modified so that in the correct steps (vehicle waiting to be removed, or station awaiting car to be inserted) the door opening is not treated as an interlock, since in this case, the opening of the door is not an error. Of course, the opening of the door still triggers the safety area, turning off the motors and closing the air supply, allowing for a safe access to the station. The safety area distribution is illustrated on figure 6.2.

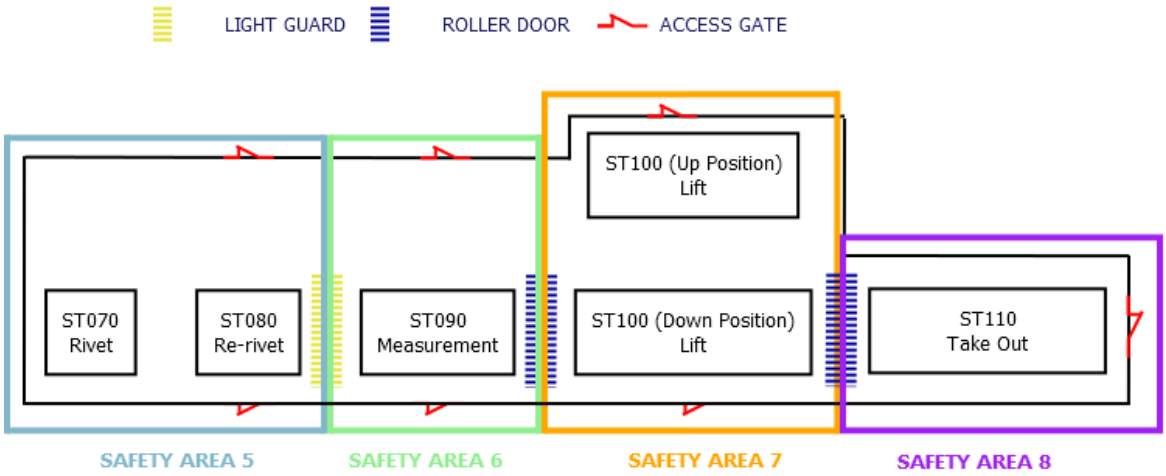

Figure 6.2. PLC3 Safety Area Layout with Takeout Station.

Table 6.1. ST110 Takeout Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[7].EOC	End of Cycle
BCROK	zzSeq[7].BCR1.BC.ReadOK	Barcode Read OK
BCRNK	zzSeq[7].BCR1.BC.ReadNOK	Barcode Read Not OK
BTTOK	_3_A2_43_512BT	Braking Transistor Temperature OK
EM	zzseq[7].Flag.24	Extract Mode
IM	zzseq[7].Flag.22	Insert Mode
MECP	_3_A2_43_2526CON_1	Motor Enable Contactor +
MECN	_3_A2_43_2526CON_2	Motor Enable Contactor -
MECF	_3_A2_43_2526CON_F	Motor Enable Contactor Feedback
SA6OK	_SA06_2_Safety_Area_OK	Safety Area 6 is OK
SA7OK	_SA07_2_Safety_Area_OK	Safety Area 7 is OK
SA8OK	_SA08_2_Safety_Area_OK	Safety Area 8 is OK
Rel2	zzSeq[7].Release.2	Station 100 to Station 90 Enter Forward Acknowledge Release
VIP	zzSeq[7].InPos[50].1	Vehicle In Position
HESOK	zzSeq[7].InPos[50].7	Hall Effect Sensor is OK
SeqOK	zzSeq[7].TypeOK	Sequence Type is OK
TFR	Type.InStation[7].13	Type Fixed Roof
TMR	Type.InStation[7].12	Type Moon Roof
Dry	Type.InStation[7].28	Type Dry Part
TMM	zzSeq[7].Flag.28	Type Miss Match
GC	_100S361B	RollerGate Closed
GO	_100S361A	RollerGate Open
Seq0	zzSeq[7].SeqTypeZero	Sequence Type is 0
T0	zzSeq[7].StnTypeZero	Station Type is 0
Rel1	zzSeq[7].Release.1	Station 10 to Station 20 Exit Forward Request Release

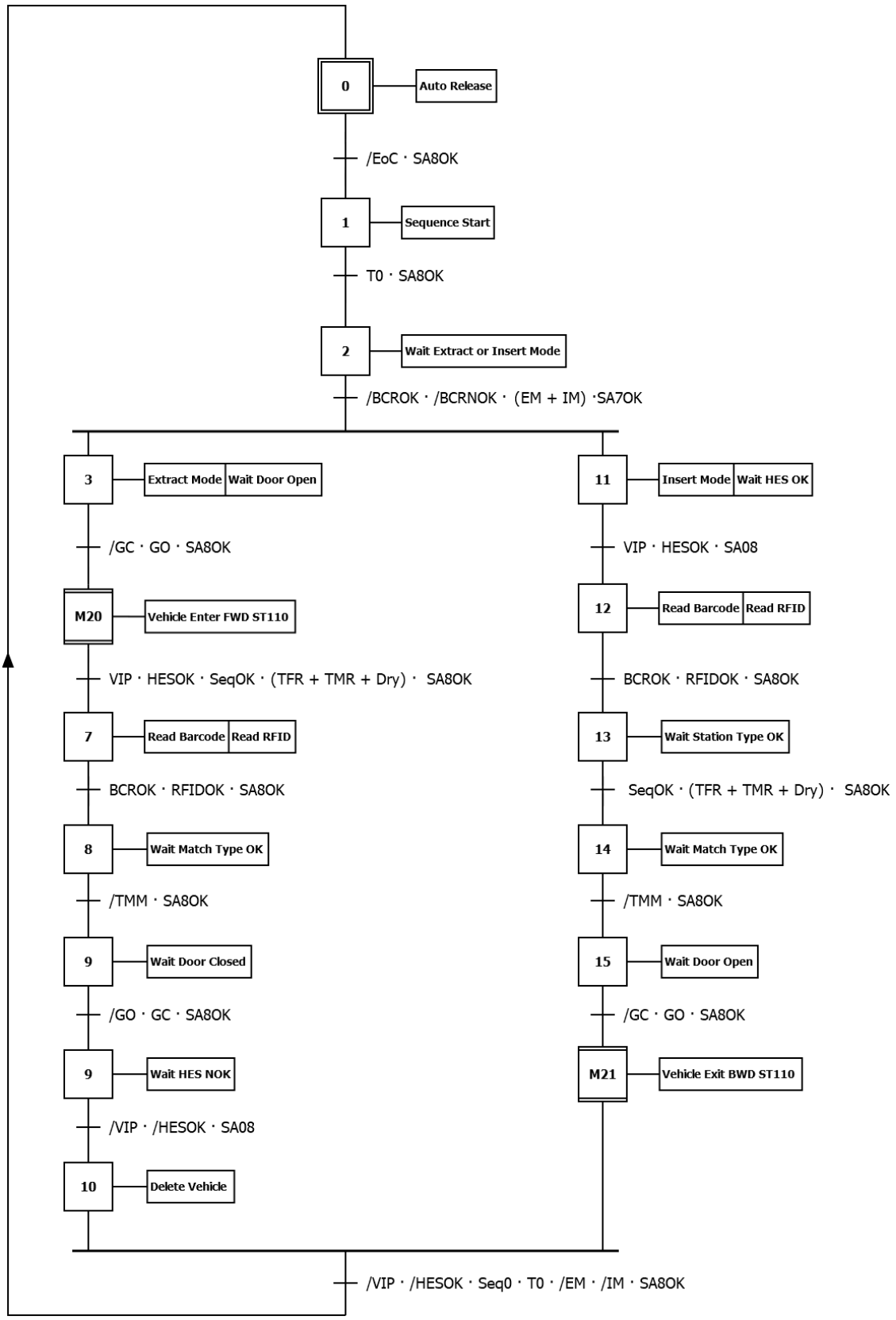

Figure 6.3. ST110 Lifter Sequence GRAFCET

The necessary modifications in the station 100 lifter sequence for station 110 to work properly are expressed in the following GRAFCET. Unless extract or insert mode is selected on station 110, station 100 will always work in normal mode.

Table 6.2. ST100 Lifter with takeout Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[6].EOC	End of Cycle
EM	zzseq[6].Flag.24	Extract Mode
IM	zzseq[6].Flag.22	Insert Mode
NM	zzseq[6].Flag.26	Normal Mode
BTTOK	_3_A2_42_512BT	Braking Transistor Temperature OK
MECP	_3_A2_42_2526CON_1	Motor Enable Contactor +
MECN	_3_A2_42_2526CON_2	Motor Enable Contactor -
MECF	_3_A2_42_2526CON_F	Motor Enable Contactor Feedback
SA6OK	_SA06_2_Safety_Area_OK	Safety Area 6 is OK
SA7OK	_SA07_2_Safety_Area_OK	Safety Area 7 is OK
SA8OK	_SA08_2_Safety_Area_OK	Safety Area 8 is OK
Rel2	zzSeq[6].Release.2	Station 100 to Station 90 Enter Forward Acknowledge Release
VIP	zzSeq[6].InPos[50].1	Vehicle In Position
HESOK	zzSeq[6].InPos[50].7	Hall Effect Sensor is OK
SeqOK	zzSeq[6].TypeOK	Sequence Type is OK
TFR	Type.InStation[6].13	Type Fixed Roof
TMR	Type.InStation[6].12	Type Moon Roof
Dry	Type.InStation[6].28	Type Dry Part
TMM	zzSeq[6].Flag.28	Type Miss Match
PSRest	_100S641B	Pallet Stop in Rest Position
PSWork	_100S641A_OK	Pallet Stop in Work Position
PLRest	_100S621B	Pallet Lock in Rest Position
PLWork	_100S621A	Pallet Lock in Work Position
NoVehST100ST90	zzSeq[6].Release.21	No Vehicle Between Stations 100 and 90
NoVehST500ST100	zzSeq[8].Release.21	No Vehicle Between Stations 500 (Conveyor 10) and Station 100
LRest	_100S191B	Latch in Rest Position
LWork	_100S191A	Latch in Work Position
DriveInDownPos	zzLifter[1].In_Pos2	Lifter Motor Drive in Down Position
GC	_100S361B	RollerGate Closed
GO	_100S361A	RollerGate Open
Seq0	zzSeq[6].SeqTypeZero	Sequence Type is 0
T0	zzSeq[6].StnTypeZero	Station Type is 0
Rel1	zzSeq[6].Release.1	Station 10 to Station 20 Exit Forward Request Release
DriveInUpPos	zzLifter[1].In_Pos1	Lifter Motor Drive in Up Position

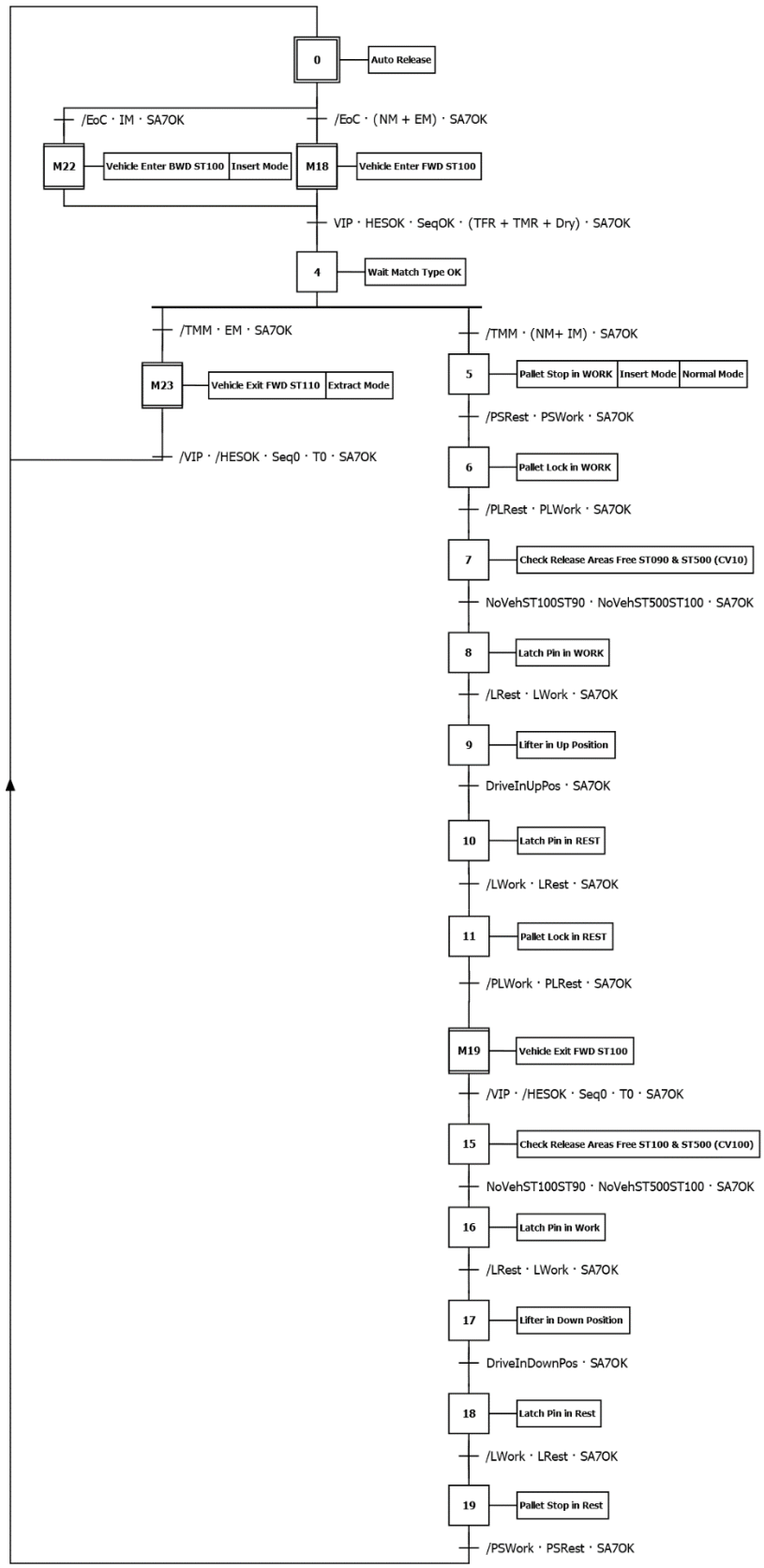

Figure 6.4. ST100 Lifter with takeout Sequence GRAFCET

6.2. Press Scrap Removal

In order to automate the removal of scrap from the station 275 press, sensors to the scrap container's drawers and a scrap catching system has been added. Two sets of sensors have been added, the first set will trigger a warning message once ¾ of the drawers scrap capacity has been reached. The second set will trigger a full drawers message. Operators should then press the confirmation button, which will allow the drawers to be released so that they can be emptied manually. While the drawers are removed, or when they are full, a scrap catcher system will deploy, which will catch the scrap and prevent it from falling into the full drawers or to the floor. The system will continue to catch the scrap until the drawers are placed back in, or for a duration of maximum 10 cycles, at which point no more cycles will occur. Once the emptied drawers are placed back, the scrap catcher will deploy, allowing the accumulated scrap to fall and the sequence to recommence.

Table 6.3. Press Scrap Removal Sequence GRAFCET Variables

Variable	PLC Contact	Description
EoC	zzSeq[24].EOC	End of Cycle
SA4OK	_SA04_2_Safety_Area_OK	Safety Area 4 is OK
S501	_275S501	Trolley 1 Fill Level Warning 1
S502	_275S502	Trolley 1 Fill Level Warning 2
S511	_275S511	Trolley 2 Fill Level Warning 1
S512	_275S512	Trolley 2 Fill Level Warning 2
S503	_275S503	Check 1 Trolley 1 Full
S504	_275S504	Check 2 Trolley 1 Full
S513	_275S513	Check 1 Trolley 2 Full
S514	_275S514	Check 2 Trolley 2 Full
OC	_2_275A621_S8	Operator Confirmation Button
S611A	_275S611A	Outside Lock Clamp Work
S611B	_275S611B	Outside Lock Clamp Rest
S240	_275S240	Drawer in Position Outside
S241	_275S241	Drawer in Position Inside
S242	_275S242	Trolley 1 Present
S243	_275S243	Trolley 2 Present
S601A	_275S601A	Inner Lock Clamp Work
S601B	_275S601A	Inner Lock Clamp Rest
SC E	zzSeq[24].InPos[219].1	Scrap Catcher Expanded
SC R	zzSeq[24].InPos[219].2	Scrap Catcher Retracted

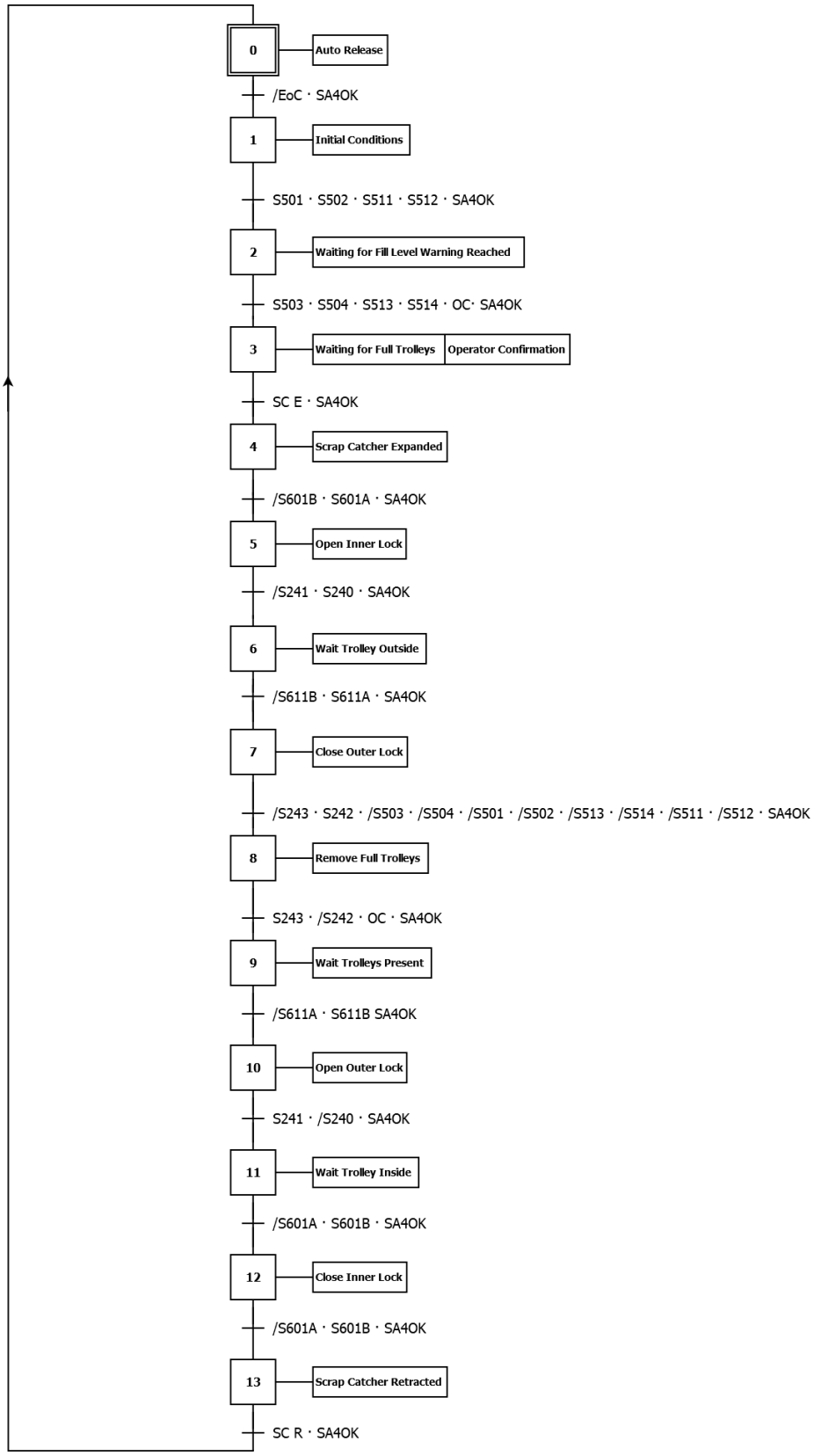

Figure 6.5. Press Scrap Removal Sequence GRAFCET

7. Environmental Impact Analysis

Along the car body roof assembly process, waste is generated when moon roof models are made. As explained in section 2.1, moon roof parts are cut by in the line by the press station. The cut waste falls down into the press' waste container. Because the waste consists of thin aluminum sheets, it is entirely recyclable. The aluminum is taken away for melting, so that it can be re-used for in this case to create more car body parts. However, there is no difference between primary and secondary recycled aluminum, and they can both be used to create final products. A simplified life cycle of aluminum is shown in the picture below.

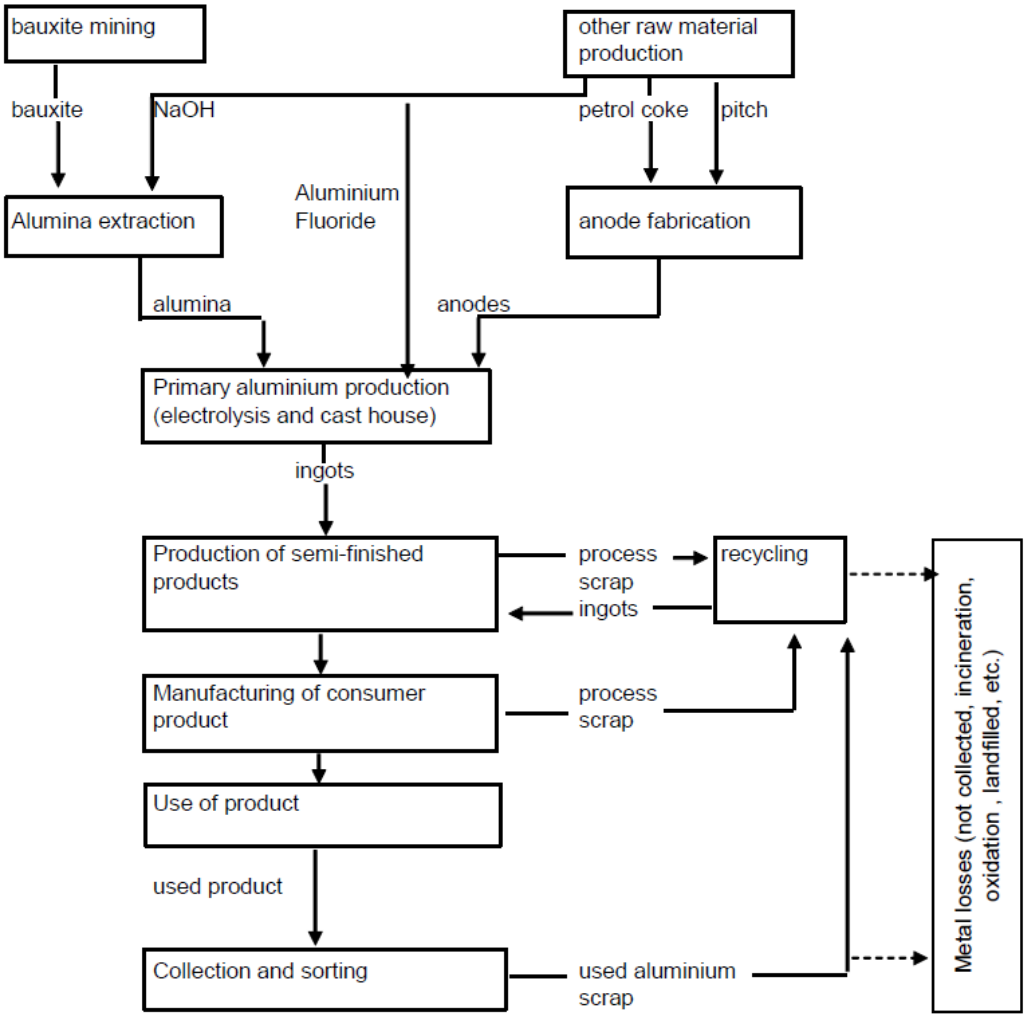

Figure 7.1. Simplified life cycle material flow chart of an aluminum product. Source: European Aluminium Association. Source: [10]

Aluminum recycling is far cheaper than refining new aluminum from raw ores, and only uses 5% of the energy required to get the metal from bauxite ore. This way, energy savings profits the environment but also represents an economic advantage, making aluminum recycling a very popular and sustainable practice.

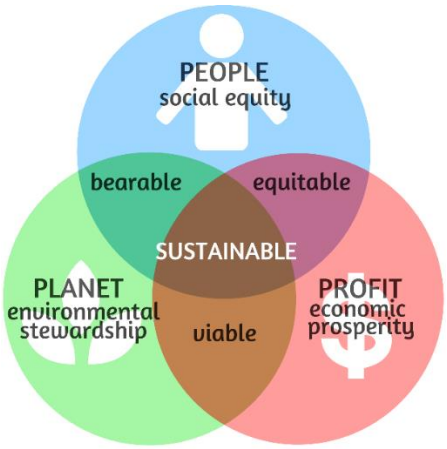

Figure 7.2. The triple bottom line of sustainability. Source: [11]

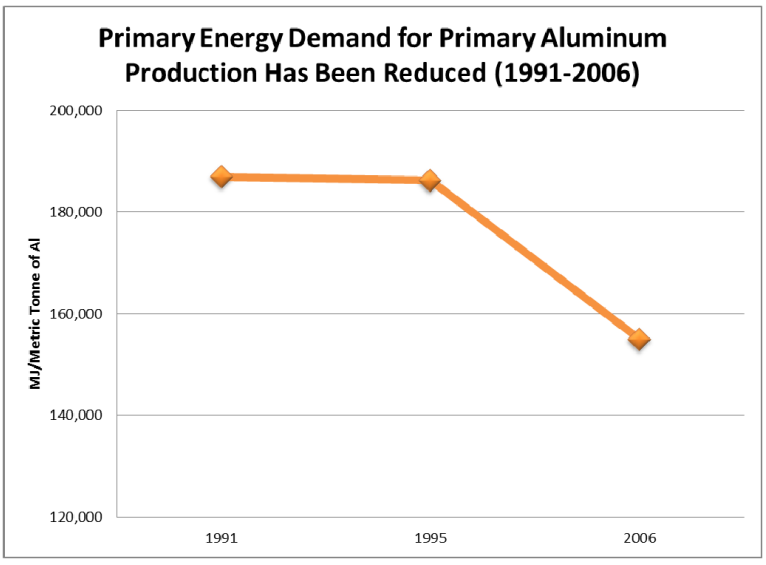

Figure 7.3. Primary energy demand for primary aluminum production. Figures obtained from the North American market. Source:[12]

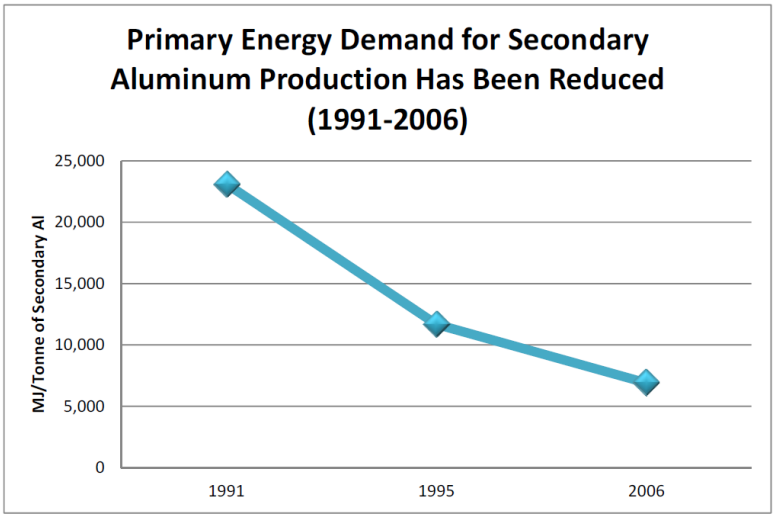

Figure 7.4. Primary energy demand for secondary aluminum production. Figures obtained from the North American market. Source: [12]

As seen on figures 7.3 and 7.4, in addition to energy savings over time due to increasingly efficient technologies, the savings between secondary and primary aluminum production is enormous. In 2006, primary energy demand for secondary aluminum production was 147.500 *MJ* per ton of aluminum less than its primary aluminum equivalent.

Greenhouse gas emissions savings are dependent on the type of energy used. Since this process is carried out outside of the car assembly plant and by an external company, it is out of the scope of this project the type of energy employed to recycle the roof assembly line aluminum scrap parts.

Conclusions

Although the HMI application developed is useful for both the assembly line maintenance personnel and the line's PLC programmer or controls engineer, it is more geared towards the use of the latter, as it deviates from the client's standard. The programmer or engineer can quickly identify safety issues, operating from any point in the line connecting the laptop to a suitable ethernet port, acting as a global monitoring unit. An increase in production performance is achieved as recovery from errors can be done faster. It is precisely because of these remote controlling capabilities that the application is more suited to the PLC programmer or controls engineer who has an advanced knowledge of the installation. A regular HMI application oriented towards the maintenance personnel is mounted on a fixed HMI station and can only have a scope limited to what can be physically seen from it.

The takeout station improves performance by removing vehicles not desired for normal production directly after the measuring station, therefore saving them from occupying space in the line destined for normal production vehicles.

The automated press scrap removal station allows for emptying the scrap drawer without stopping production, and also keeps the drawer from overflowing if maintenance where to have an oversight. If this where to happen, recovering from this error would take a long time and would halt the production or even worse, cause damage to the press.

Overall, these improvements successfully help to achieve the assembly line's core goal, which is to produce as many cars in as little time as possible.

Economic Analysis

PLC1 Area Budget

Table 0.1. PLC1 Stock list.

Manufacturer	Reference	Description	Unitary Price [€]	Units	Total [€]
RITTAL	TS 8285.500	Cabinet 1200x1800x500mm, 2 doors	578,15	2	1156,30
RITTAL	TS 8600.255	Cable marshalling base ts 1200x500mm	117,02	2	234,03
RITTAL	TS 8800.190	180deg HINGES	22,83	16	365,36
RITTAL	TS 8611.290	Comfort handle padlockable	27,33	2	54,66
RITTAL	TS 8611.100	Lock insert 7mm square	1,65	2	3,31
RITTAL	TS 8185.235	Side walls 1800x500mm	87,85	2	175,70
RITTAL	TS 8600.510	Side wall for cabinet plinth, 500mm	22,33	2	44,66
RITTAL	PS 4116.000	Drawing pocket for 600mm door	16,03	1	16,03
RITTAL	TS 4695.000	Support rail, depth 500mm	6,40	2	12,79
RITTAL	PS 4638.600	Laptop desk for 600mm door	84,28	1	84,28
RITTAL	TS 8800.430	Cabinet joining angle	7,60	4	30,41
RITTAL	TS 8800.490	Cabinet joining pieces exterior	13,01	6	78,05
RITTAL	TS 8800.410	Cabinet joining pieces vertical	6,32	6	37,93
RITTAL	TS 4590.700	Mounting plate infill	35,75	1	35,75
RITTAL	SZ 2477.000	24 pole blanking plate	1,57	22	34,55
SICK	6025906	Connector/cable (female connector-open)	15,70	2	31,40
WAGO	2006-1671/1000-0848	Earth test/Disconnect terminal 24Vac/Vdc	18,24	3	54,72

WAGO	2006-1691	End cover	0,21	3	0,64
WEIDMÜLLER	8860060000	Surge suppressor	257,31	1	257,31
MURRELEKTRONIK	9000-41034-0100600	MICO 4.6 4 channel circuit breaker	100,88	12	1210,61
MURRELEKTRONIK	9000-41034-0000002	MICO bridging set	4,97	7	34,77
SIEMENS	5SY4 310-6	10A 3PH 'B' mini-circuit breaker	12,40	2	24,79
SIEMENS	5ST3 013	Auxiliary contact	7,43	2	14,86
WAGO	787-854	EPSITRON 40A, 24Vdc power supply	379,34	2	758,68
WAGO	787-852	EPSITRON 20A, 24Vdc power supply	366,55	1	366,55
SCHNEIDER ELECTRIC	CA3-KN40BD	Control relay, 4no	21,90	2	43,80
SCHNEIDER ELECTRIC	LA4-KE1B	Varistor 12-24v	4,18	20	83,64
SCHNEIDER ELECTRIC	LA1-KN40	Auxiliary contact block, 4no	6,13	3	18,40
SCHNEIDER ELECTRIC	CA3-KN31BD	Control relay, 3no+1nc	20,03	10	200,33
SCHNEIDER ELECTRIC	LC1-D12BL	Contactor 12A 24Vdc	26,21	4	104,83
ROCKWELL AUTOMATION	1734-AENTR	Point I/O dual port ethernet adapter	114,88	4	459,50
PANDUIT	ISFX5502ATL-LED	Industrial ethernet cable 2x2xAWG24/7 (500m) Teal	881,64	44	38792,36
ROCKWELL AUTOMATION	1734-IB4	Point I/O input module	19,83	28	555,37
ROCKWELL AUTOMATION	1734-TBS	Point I/O connector	15,70	75	1177,69
ROCKWELL AUTOMATION	1734-IB8S	Pointguard input module	289,26	13	3760,33
ROCKWELL AUTOMATION	1734-EP24DC	Point I/O expansion power unit	41,31	9	371,83
ROCKWELL AUTOMATION	1734-OB4	Point I/O output module	23,64	25	590,91
ROCKWELL AUTOMATION	1734-FPD	Point I/O field power distributor	41,31	1	41,31
ROCKWELL AUTOMATION	1734-OB8S	Pointguard output module	70,25	7	491,74
SCHNEIDER ELECTRIC	GV2-ME08	Motor circuit breaker 2.5-4A	26,24	2	52,48
SCHNEIDER ELECTRIC	GV1-G09	Connector block	4,89	3	14,68

SCHNEIDER ELECTRIC	GV2-G345	3 way bridging comb, spacing 45mm	6,98	1	6,98
SCHNEIDER ELECTRIC	GV2-ME07	Motor circuit breaker 1.6-2.5A	26,24	1	26,24
SCHNEIDER ELECTRIC	GV2-ME21	Motor circuit breaker 17-23A	31,40	1	31,40
SCHNEIDER ELECTRIC	GV-AE11	Auxiliary contact NO+NC	8,63	2	17,26
SCHNEIDER ELECTRIC	GV2-ME14	Motor circuit breaker 6-10A	63,96	1	63,96
SCHNEIDER ELECTRIC	GV2-G245	2 way bridging comb, spacing 45mm	6,27	1	6,27
ROCKWELL AUTOMATION	1783-BMS20CGL	STRATIX 5700 ethernet switch 16+2+2 ports	1915,55	2	3831,11
ROCKWELL AUTOMATION	1784-SD1	SD memory card (1 GB)	76,16	2	152,31
PANDUIT	ISX6004AYL-LED	Industrial ethernet cable 4x2xAWG24/7 (500m) Yellow	946,58	9	8519,21
WAGO	2002-1201	2.5qmm terminal	0,37	588	218,68
WAGO	2010-1201	10qmm terminal	0,90	20	18,02
WAGO	2016-1201	16qmm terminal	1,06	9	9,52
WAGO	2006-1201	6qmm terminal	0,72	18	12,94
HARTING	0930 024 0301	24 pole chassie housing	26,60	32	851,31
HARTING	1930 024 1521	24 pole hood M25, low contruction	12,26	32	392,46
HARTING	0933 024 2616	Han 24ES, 24 pole male insert	29,57	32	946,25
HARTING	0933 024 4729	24 Pole wedge connector, female left	75,25	20	1504,96
HARTING	0933 000 9908	Coding pins	0,43	148	63,60
HARTING	0933 000 9909	Coding bushing	0,83	148	123,54
HARTING	0933 024 4739	24 Pole wedge connector, female right	75,25	12	902,98
LÜTZE	ST 3/F 680 572	Socket outlet, 230Vac	3,72	2	7,44
HARTING	1920 003 1250	Han3A surface housing	9,31	8	74,51
HARTING	1920 003 1440	Han3A hood	5,79	12	69,42
HARTING	0936 008 3001	Han 8D, 8 pole male insert	6,50	2	13,01

HARTING	0936 008 3101	Han 8D, 8 pole female insert	5,22	2	10,45
HARTING	0915 000 6201	1.5qmm crimp contact, female	0,81	16	12,96
HARTING	0915 000 6104	0.14-0.37qmm crimp contact, male	0,85	16	13,62
HARTING	1930 006 1540	6 pole hood, M20	11,03	12	132,40
HARTING	0933 006 2648	Han 6ES, 6 pole male insert	13,61	14	190,56
HARTING	0933 006 2748	Han 6ES, 6 pole female insert	14,75	14	206,53
HARTING	1962 806 1290	6 pole surface housing, 2xM20, EMC	24,91	3	74,73
HARTING	1962 806 1540	6 pole hood, M20, EMC	12,59	3	37,76
HARTING	0920 004 2611	Han 4A, 4 pole + pe male insert	7,26	8	58,12
HARTING	0920 004 2711	Han 4A, 4 pole + pe female insert	7,88	8	63,07
RITTAL	SV 3451.500	Earth connector 2,5-16qmm, for 5mm bar	6,31	70	441,40
RITTAL	SV 3450.500	Earth connector 1-4qmm, for 5mm bar	6,28	103	646,94
RITTAL	SV 9340.030	Busbar holder 1 pole	7,57	6	45,42
RITTAL	SV 3584.000	Busbar 30x5mm, 2400mm long	194,32	1	194,32
RITTAL	PK 9515.000	PK junction box 180x110x111mm	21,86	13	284,17
RITTAL	PK 9564.000	Mounting rail TS35/7,5	3,31	13	43,08
SCHNEIDER ELECTRIC	ZB5-SZ3	Blanking plug	1,54	25	38,43
SCHNEIDER ELECTRIC	ZB4-BVB4	Pilot lamp base with led, red	4,78	10	47,77
SCHNEIDER ELECTRIC	ZB4-BV043	Pilot lamp head, red	2,23	10	22,31
MURRPLASTIK	KS 15/27 8636 1010	White legend 15x27mm	0,16	71	11,15
MURRPLASTIK	BTK 22,5 8644 1016	Holder for 15x27mm legends	0,50	71	35,79
MURRPLASTIK	TA 15/27 8644 1410	Transparent cover 15x27mm	0,16	71	11,15
SCHNEIDER ELECTRIC	ZB4-BS844	Emergency stop PB, 40mm, red	9,62	10	96,20

SCHNEIDER ELECTRIC	ZB4-BZ104	Contact block, 2NC	5,94	10	59,42
SCHNEIDER ELECTRIC	ZBY-9330	Yellow emergency stop ring	1,01	10	10,08
SCHNEIDER ELECTRIC	ZB4-BA6	Pushbutton head, blue	2,38	10	23,80
SCHNEIDER ELECTRIC	ZB4-BZ101	Contact block, 1NC	4,05	20	80,99
SCHNEIDER ELECTRIC	ZB4-BW0B11	Illum. PB. base with led, white, 1NO	7,88	20	157,69
SCHNEIDER ELECTRIC	ZB4-BW313	Illum. PB. head, white	3,59	20	71,74
SCHNEIDER ELECTRIC	ZB4-BW0B31	Illum. PB. base with led, green, 1NO	2,76	10	27,60
SCHNEIDER ELECTRIC	ZB4-BW333	Illum. PB. head, green	3,59	10	35,87
RITTAL	AE 1050.500	AE junction box 500x500x210mm	62,84	3	188,53
RITTAL	SZ 2460.000	Lock insert 7mm square	1,78	3	5,33
WEIDMÜLLER	SH1PA KPL 0299860000	Bus-bar holder	0,46	6	2,78
WEIDMÜLLER	SSCH 10X3 CU 0348900000	10x3mm copper bus-bar, 1m long	11,97	3	35,90
WEIDMÜLLER	ZB4K GE/GN 0475360000	Earth clamps 4mm² GNYE	1,10	60	65,95
HARTING	2103 311 2400	M12 chassie socket, 4 pole, 0.5m tails	21,17	8	169,39
PHOENIX CONTACT	ELR W3-24DC/500AC-2I 22 97 03 1	Solid-state reversing starter	157,43	2	314,86
WAGO	2002-1211/1000-410	Terminal with diode	1,78	4	7,11
HARTING	0930 006 0301	6 pole chassie housing	10,42	4	41,69
HARTING	0920 003 0301	Han3A chassie housing	7,01	4	28,03
SEW EURODRIVE	BW033-012-01	Brake resistor	173,55	1	173,55
HARTING	2103 311 1402	M12 chassie plug, 4 pole, 0.5m tails	12,83	9	115,51
HARTING	1900 000 5060	M20-M16 REDUCER	2,70	9	24,32
SICK	DOL-1208-G05MAH1 6032449	OLM100 connection cable 5m	64,27	1	64,27
HARTING	0914 006 0303	Han-modular holding frame for 2 modules hood	16,67	1	16,67

HARTING	0914 006 0313	Han-modular holding frame for 2 modules housing	16,68	1	16,68
HARTING	0914 008 3001	Han-modular 8 pole male insert	5,29	1	5,29
HARTING	0914 008 3101	Han-modular 8 pole female insert	6,30	1	6,30
HARTING	0933 000 6117	0.14-0.37qmm gold crimp contact, male	3,45	8	27,64
HARTING	0933 000 6217	0.14-0.37qmm gold crimp contact, female	5,89	8	47,14
HARTING	0933 000 6122	0.5qmm gold crimp contact, male	2,93	2	5,87
HARTING	0933 000 6222	0.5qmm gold crimp contact, female	3,23	2	6,46
HARTING	2103 281 1405	M12 D-code ethernet connector, male straight	24,62	4	98,48
HARTING	2103 281 2405	M12 D-code ethernet connector, female	27,79	4	111,17
SICK	2055859	Power and I/O cable	82,88	3	248,63
SICK	CDM420-0007	Focus bar code scanner connection module	295,57	1	295,57
SICK	RFU 620-10100	RFID transponder	1445,21	2	2890,41
SICK	CLV690	Barcode reader	3596,30	1	3596,30
SICK	C4C-SA18030A10000	DeTec4 light barrier	1261,93	2	2523,87
				TOTAL [€]	84.059,94

PLC2 Area Budget

Table 0.2. PLC2 Stock list.

Manufacturer	Reference	Description	Unitary Price [€]	Units	Total [€]
RITTAL	TS 8285.500	Cabinet 1200x1800x500mm, 2 doors	578,15	2	1156,30
RITTAL	TS 8600.255	Cable marshalling base ts 1200x500mm	117,02	2	234,03
RITTAL	TS 8800.190	180deg HINGES	22,83	16	365,36
RITTAL	TS 8611.290	Comfort handle padlockable	27,33	2	54,66
RITTAL	TS 8611.100	Lock insert 7mm square	1,65	2	3,31
RITTAL	TS 8185.235	Side walls 1800x500mm	87,85	2	175,70
RITTAL	TS 8600.510	Side wall for cabinet plinth, 500mm	22,33	2	44,66
RITTAL	PS 4116.000	Drawing pocket for 600mm door	16,03	1	16,03
RITTAL	TS 4695.000	Support rail, depth 500mm	6,40	2	12,79
RITTAL	PS 4638.600	Laptop desk for 600mm door	84,28	1	84,28
RITTAL	TS 8800.430	Cabinet joining angle	7,60	4	30,41
RITTAL	TS 8800.490	Cabinet joining pieces exterior	13,01	6	78,05
RITTAL	TS 8800.410	Cabinet joining pieces vertical	6,32	6	37,93
RITTAL	TS 4590.700	Mounting plate infill	35,75	1	35,75
RITTAL	SZ 2477.000	24 pole blanking plate	1,57	45	70,66
SICK	6025906	Connector/cable (female connector-open)	15,70	4	62,81
WAGO	2006-1671/1000-0848	Earth test/Disconnect terminal 24Vac/Vdc	18,24	3	54,72
WAGO	2006-1691	End cover	0,21	3	0,64
WEIDMÜLLER	8860060000	Surge suppressor	257,31	1	257,31
MURRELEKTRONIK	9000-41034-0100600	MICO 4.6 4 channel circuit breaker	100,88	12	1210,61
MURRELEKTRONIK	9000-41034-0000002	MICO bridging set	4,97	7	34,77

SIEMENS	5SY4 310-6	10A 3PH 'B' mini-circuit breaker	12,40	2	24,79
SIEMENS	5ST3 013	Auxiliary contact	7,43	2	14,86
WAGO	787-854	EPSITRON 40A, 24Vdc power supply	379,34	2	758,68
WAGO	787-852	EPSITRON 20A, 24Vdc power supply	366,55	1	366,55
SCHNEIDER ELECTRIC	CA3-KN40BD	Control relay, 4no	21,90	1	21,90
SCHNEIDER ELECTRIC	LA4-KE1B	Varistor 12-24v	4,18	19	79,45
SCHNEIDER ELECTRIC	LA1-KN40	Auxiliary contact block, 4no	6,13	1	6,13
SCHNEIDER ELECTRIC	CA3-KN31BD	Control relay, 3no+1nc	20,03	2	40,07
SCHNEIDER ELECTRIC	CA3-KN22BD	Control relay, 2NO+2NC	20,65	16	330,45
SCHNEIDER ELECTRIC	LA1-KN22	Auxiliary contact block, 2NO+2NC	6,05	4	24,20
ROCKWELL AUTOMATION	1734-AENTR	Point I/O dual port ethernet adapter	114,88	2	229,75
PANDUIT	ISFX5502ATL-LED	Industrial ethernet cable 2x2xAWG24/7 (500m) Teal	881,64	35	30857,56
ROCKWELL AUTOMATION	1734-IB4	Point I/O input module	19,83	15	297,52
ROCKWELL AUTOMATION	1734-TBS	Point I/O connector	15,70	41	643,80
ROCKWELL AUTOMATION	1734-IB8S	Pointguard input module	289,26	8	2314,05
ROCKWELL AUTOMATION	1734-EP24DC	Point I/O expansion power unit	41,31	8	330,51
ROCKWELL AUTOMATION	1734-OB4	Point I/O output module	23,64	13	307,27
ROCKWELL AUTOMATION	1734-FPD	Point I/O field power distributor	41,31	2	82,63
ROCKWELL AUTOMATION	1734-OB8S	Pointguard output module	70,25	6	421,49
SCHNEIDER ELECTRIC	GV2-ME08	Motor circuit breaker 2.5-4A	26,24	2	52,48
SCHNEIDER ELECTRIC	GV1-G09	Connector block	4,89	3	14,68
SCHNEIDER ELECTRIC	GV2-G345	3 way bridging comb, spacing 45mm	6,98	1	6,98
SCHNEIDER ELECTRIC	GV2-ME07	Motor circuit breaker 1.6-2.5A	26,24	1	26,24

ROCKWELL AUTOMATION	1783-BMS20CGL	STRATIX 5700 ethernet switch 16+2+2 ports	1915,55	2	3831,11
ROCKWELL AUTOMATION	1784-SD1	SD memory card (1 GB)	76,16	2	152,31
PANDUIT	ISX6004AYL-LED	Industrial ethernet cable 4x2xAWG24/7 (500m) Yellow	946,58	3	2839,74
WAGO	2002-1201	2.5qmm terminal	0,37	540	200,83
WAGO	2010-1201	10qmm terminal	0,90	20	18,02
HARTING	0930 024 0301	24 pole chassie housing	26,60	7	186,22
HARTING	1930 024 1521	24 pole hood M25, low contruction	12,26	13	159,44
HARTING	0933 024 2616	Han 24ES, 24 pole male insert	29,57	13	384,41
HARTING	0933 024 4729	24 Pole wedge connector, female left	75,25	11	827,73
HARTING	0933 000 9908	Coding pins	0,43	52	22,35
HARTING	0933 000 9909	Coding bushing	0,83	52	43,40
HARTING	0933 024 4739	24 Pole wedge connector, female right	75,25	13	978,22
LÜTZE	ST 3/F 680 572	Socket outlet, 230Vac	3,72	2	7,44
HARTING	1920 003 1250	Han3A surface housing	9,31	6	55,88
HARTING	1920 003 1440	Han3A hood	5,79	6	34,71
HARTING	0936 008 3001	Han 8D, 8 pole male insert	6,50	6	39,02
HARTING	0936 008 3101	Han 8D, 8 pole female insert	5,22	6	31,34
HARTING	0915 000 6201	1.5qmm crimp contact, female	0,81	48	38,88
HARTING	0915 000 6104	0.14-0.37qmm crimp contact, male	0,85	48	40,86
HARTING	1962 806 1540	6 pole hood, M20, EMC	12,59	3	37,76
RITTAL	SV 3451.500	Earth connector 2,5-16qmm, for 5mm bar	6,31	58	365,74
RITTAL	SV 3450.500	Earth connector 1-4qmm, for 5mm bar	6,28	84	527,60

RITTAL	SV 9340.030	Busbar holder 1 pole	7,57	6	45,42
RITTAL	SV 3584.000	Busbar 30x5mm, 2400mm long	194,32	1	194,32
RITTAL	PK 9515.000	PK junction box 180x110x111mm	21,86	7	153,02
RITTAL	PK 9564.000	Mounting rail TS35/7,5	3,31	7	23,20
SCHNEIDER ELECTRIC	ZB5-SZ3	Blanking plug	1,54	7	10,76
SCHNEIDER ELECTRIC	ZB4-BVB4	Pilot lamp base with led, red	4,78	7	33,44
SCHNEIDER ELECTRIC	ZB4-BV043	Pilot lamp head, red	2,23	7	15,62
MURRPLASTIK	KS 15/27 8636 1010	White legend 15x27mm	0,16	47	7,38
MURRPLASTIK	BTK 22,5 8644 1016	Holder for 15x27mm legends	0,50	47	23,69
MURRPLASTIK	TA 15/27 8644 1410	Transparent cover 15x27mm	0,16	47	7,38
SCHNEIDER ELECTRIC	ZB4-BS844	Emergency stop PB, 40mm, red	9,62	7	67,34
SCHNEIDER ELECTRIC	ZB4-BZ104	Contact block, 2NC	5,94	7	41,60
SCHNEIDER ELECTRIC	ZBY-9330	Yellow emergency stop ring	1,01	7	7,06
SCHNEIDER ELECTRIC	ZB4-BA6	Pushbutton head, blue	2,38	7	16,66
SCHNEIDER ELECTRIC	ZB4-BZ101	Contact block, 1NC	4,05	14	56,69
SCHNEIDER ELECTRIC	ZB4-BW0B11	Illum. PB. base with led, white, 1NO	7,88	14	110,38
SCHNEIDER ELECTRIC	ZB4-BW313	Illum. PB. head, white	3,59	14	50,21
SCHNEIDER ELECTRIC	ZB4-BW0B31	Illum. PB. base with led, green, 1NO	2,76	7	19,32
SCHNEIDER ELECTRIC	ZB4-BW333	Illum. PB. head, green	3,59	7	25,11
				TOTAL [€]	53.004,45

PLC3 Area Budget

Table 0.3. PLC3 Stock list.

Manufacturer	Reference	Description	Unitary Price [€]	Units	Total [€]
RITTAL	TS 8285.500	Cabinet 1200x1800x500mm, 2 doors	624,61	2	1249,21
RITTAL	TS 8600.255	Cable marshalling base ts 1200x500mm	126,42	2	252,84
RITTAL	TS 8800.190	180deg HINGES	24,67	16	394,71
RITTAL	TS 8611.290	Comfort handle padlockable	29,53	2	59,05
RITTAL	TS 8611.100	Lock insert 7mm square	1,79	2	3,57
RITTAL	TS 8185.235	Side walls 1800x500mm	94,91	2	189,82
RITTAL	TS 8600.510	Side wall for cabinet plinth, 500mm	24,13	2	48,25
RITTAL	PS 4116.000	Drawing pocket for 600mm door	17,32	1	17,32
RITTAL	TS 4695.000	Support rail, depth 500mm	6,91	2	13,82
RITTAL	PS 4638.600	Laptop desk for 600mm door	91,05	1	91,05
RITTAL	TS 8800.430	Cabinet joining angle	8,21	4	32,86
RITTAL	TS 8800.490	Cabinet joining pieces exterior	14,05	6	84,32
RITTAL	TS 8800.410	Cabinet joining pieces vertical	6,83	6	40,98
RITTAL	TS 4590.700	Mounting plate infill	38,63	1	38,63
RITTAL	SZ 2477.000	24 pole blanking plate	1,70	22	37,32
SICK	6025906	Connector/cable (female connector-open)	16,96	2	33,93
WAGO	2006-1671/1000-0848	Earth test/Disconnect terminal 24Vac/Vdc	19,71	3	59,12
WAGO	2006-1691	End cover	0,23	3	0,70
WEIDMÜLLER	8860060000	Surge suppressor	277,99	1	277,99
MURRELEKTRONIK	9000-41034-0100600	MICO 4.6 4 channel circuit breaker	108,99	12	1307,89

MURRELEKTRONIK	9000-41034-0000002	MICO bridging set	5,37	7	37,56
SIEMENS	5SY4 310-6	10A 3PH 'B' mini-circuit breaker	13,39	2	26,79
SIEMENS	5ST3 013	Auxiliary contact	8,03	2	16,05
WAGO	787-854	EPSITRON 40A, 24Vdc power supply	409,82	2	819,64
WAGO	787-852	EPSITRON 20A, 24Vdc power supply	396,00	1	396,00
SCHNEIDER ELECTRIC	CA3-KN40BD	Control relay, 4NO	23,66	2	47,32
SCHNEIDER ELECTRIC	LA4-KE1B	Varistor 12-24v	4,52	26	117,46
SCHNEIDER ELECTRIC	LA1-KN40	Auxiliary contact block, 4no	6,63	3	19,88
SCHNEIDER ELECTRIC	CA3-KN31BD	Control relay, 3NO+1NC	21,64	14	303,00
SCHNEIDER ELECTRIC	CA3-KN22BD	Control relay, 2NO+2NC	22,31	10	223,13
SCHNEIDER ELECTRIC	LC1-D12BL	Contactor 12A 24Vdc	28,31	4	113,25
ROCKWELL AUTOMATION	1734-AENTR	Point I/O dual port ethernet adapter	124,11	5	620,54
PANDUIT	ISFX5502ATL-LED	Industrial ethernet cable 2x2xAWG24/7 (500m) Teal	952,49	44	41909,61
ROCKWELL AUTOMATION	1734-IB4	Point I/O input module	21,43	22	471,43
ROCKWELL AUTOMATION	1734-TBS	Point I/O connector	16,96	61	1034,82
ROCKWELL AUTOMATION	1734-IB8S	Pointguard input module	312,50	12	3750,00
ROCKWELL AUTOMATION	1734-EP24DC	Point I/O expansion power unit	44,63	9	401,71
ROCKWELL AUTOMATION	1734-OB4	Point I/O output module	25,54	18	459,64
ROCKWELL AUTOMATION	1734-FPD	Point I/O field power distributor	44,63	2	89,27
ROCKWELL AUTOMATION	1734-OB8S	Pointguard output module	75,89	10	758,93
SCHNEIDER ELECTRIC	GV2-ME08	Motor circuit breaker 2.5-4A	28,35	2	56,70
SCHNEIDER ELECTRIC	GV1-G09	Connector block	5,29	3	15,86
SCHNEIDER ELECTRIC	GV2-G345	3 way bridging comb, spacing 45mm	7,54	1	7,54

SCHNEIDER ELECTRIC	GV2-ME07	Motor circuit breaker 1.6-2.5A	28,35	1	28,35
SCHNEIDER ELECTRIC	GV2-ME21	Motor circuit breaker 17-23A	33,93	1	33,93
SCHNEIDER ELECTRIC	GV-AE11	Auxiliary contact NO+NC	9,32	2	18,64
SCHNEIDER ELECTRIC	GV2-ME14	Motor circuit breaker 6-10A	69,10	1	69,10
SCHNEIDER ELECTRIC	GV2-G245	2 way bridging comb, spacing 45mm	6,78	1	6,78
ROCKWELL AUTOMATION	1783-BMS20CGL	STRATIX 5700 ethernet switch 16+2+2 ports	2069,48	2	4138,96
ROCKWELL AUTOMATION	1784-SD1	SD memory card (1 GB)	82,28	2	164,55
PANDUIT	ISX6004AYL-LED	Industrial ethernet cable 4x2xAWG24/7 (500m) Yellow	1022,64	11	11249,07
WAGO	2002-1201	2.5qmm terminal	0,40	551	221,38
WAGO	2010-1201	10qmm terminal	0,97	20	19,46
WAGO	2016-1201	16qmm terminal	1,14	9	10,29
WAGO	2006-1201	6qmm terminal	0,78	18	13,98
HARTING	0930 024 0301	24 pole chassie housing	28,74	26	747,27
HARTING	1930 024 1521	24 pole hood M25, low contruction	13,25	26	344,50
HARTING	0933 024 2616	Han 24ES, 24 pole male insert	31,95	26	830,61
HARTING	0933 024 4729	24 Pole wedge connector, female left	81,29	14	1138,13
HARTING	0933 000 9908	Coding pins	0,46	148	68,71
HARTING	0933 000 9909	Coding bushing	0,90	148	133,46
HARTING	0933 024 4739	24 Pole wedge connector, female right	81,29	15	1219,42
LÜTZE	ST 3/F 680 572	Socket outlet, 230Vac	4,02	2	8,04
HARTING	1920 003 1250	Han3A surface housing	10,06	8	80,50
HARTING	1920 003 1440	Han3A hood	6,25	12	75,00
HARTING	0936 008 3001	Han 8D, 8 pole male insert	7,03	2	14,05
HARTING	0936 008 3101	Han 8D, 8 pole female insert	5,64	2	11,29
HARTING	0915 000 6201	1.5qmm crimp contact, female	0,88	16	14,00

HARTING	0915 000 6104	0.14-0.37qmm crimp contact, male	0,92	16	14,71
HARTING	1930 006 1540	6 pole hood, M20	11,92	12	143,04
HARTING	0933 006 2648	Han 6ES, 6 pole male insert	14,71	14	205,88
HARTING	0933 006 2748	Han 6ES, 6 pole female insert	15,94	14	223,13
HARTING	1962 806 1290	6 pole surface housing, 2xM20, EMC	26,91	3	80,73
HARTING	1962 806 1540	6 pole hood, M20, EMC	13,60	3	40,79
HARTING	0920 004 2611	Han 4A, 4 pole + pe male insert	7,85	8	62,79
HARTING	0920 004 2711	Han 4A, 4 pole + pe female insert	8,52	8	68,14
RITTAL	SV 3451.500	Earth connector 2,5-16qmm, for 5mm bar	6,81	70	476,88
RITTAL	SV 3450.500	Earth connector 1-4qmm, for 5mm bar	6,79	103	698,93
RITTAL	SV 9340.030	Busbar holder 1 pole	8,18	6	49,07
RITTAL	SV 3584.000	Busbar 30x5mm, 2400mm long	209,94	1	209,94
RITTAL	PK 9515.000	PK junction box 180x110x111mm	23,62	7	165,31
RITTAL	PK 9564.000	Mounting rail TS35/7,5	3,58	7	25,06
SCHNEIDER ELECTRIC	ZB5-SZ3	Blanking plug	1,66	9	14,95
SCHNEIDER ELECTRIC	ZB4-BVB4	Pilot lamp base with led, red	5,16	8	41,29
SCHNEIDER ELECTRIC	ZB4-BV043	Pilot lamp head, red	2,41	8	19,29
MURRPLASTIK	KS 15/27 8636 1010	White legend 15x27mm	0,17	52	8,82
MURRPLASTIK	BTK 22,5 8644 1016	Holder for 15x27mm legends	0,54	52	28,32
MURRPLASTIK	TA 15/27 8644 1410	Transparent cover 15x27mm	0,17	52	8,82
SCHNEIDER ELECTRIC	ZB4-BS844	Emergency stop PB, 40mm, red	10,39	8	83,14
SCHNEIDER ELECTRIC	ZB4-BZ104	Contact block, 2NC	6,42	8	51,36
SCHNEIDER ELECTRIC	ZBY-9330	Yellow emergency stop ring	1,09	8	8,71

SCHNEIDER ELECTRIC	ZB4-BA6	Pushbutton head, blue	2,57	8	20,57
SCHNEIDER ELECTRIC	ZB4-BZ101	Contact block, 1NC	4,38	16	70,00
SCHNEIDER ELECTRIC	ZB4-BW0B11	Illum. PB. base with led, white, 1NO	8,52	16	136,29
SCHNEIDER ELECTRIC	ZB4-BW313	Illum. PB. head, white	3,88	16	62,00
SCHNEIDER ELECTRIC	ZB4-BW0B31	Illum. PB. base with led, green, 1NO	2,98	8	23,86
SCHNEIDER ELECTRIC	ZB4-BW333	Illum. PB. head, green	3,88	8	31,00
RITTAL	AE 1050.500	AE junction box 500x500x210mm	67,89	3	203,68
RITTAL	SZ 2460.000	Lock insert 7mm square	1,92	3	5,76
WEIDMÜLLER	SH1PA KPL 0299860000	Bus-bar holder	0,50	4	2,00
WEIDMÜLLER	SSCH 10X3 CU 0348900000	10x3mm copper bus-bar, 1m long	12,93	4	51,71
WEIDMÜLLER	ZB4K GE/GN 0475360000	Earth clamps 4mm² GNYE	1,19	80	95,00
HARTING	2103 311 2400	M12 chassie socket, 4 pole, 0.5m tails	22,88	8	183,00
PHOENIX CONTACT	ELR W3-24DC/500AC-2I 22 97 03 1	Solid-state reversing starter	170,08	2	340,16
WAGO	2002-1211/1000-410	Terminal with diode	1,92	4	7,68
HARTING	0930 006 0301	6 pole chassie housing	11,26	4	45,04
HARTING	0920 003 0301	Han3A chassie housing	7,57	4	30,29
SEW EURODRIVE	BW033-012-01	Brake resistor	187,50	1	187,50
HARTING	2103 311 1402	M12 chassie plug, 4 pole, 0.5m tails	13,87	9	124,79
HARTING	1900 000 5060	M20-M16 REDUCER	2,92	9	26,28
SICK	DOL-1208-G05MAH1 6032449	OLM100 connection cable 5m	69,44	1	69,44
HARTING	0914 006 0303	Han-modular holding frame for 2 modules hood	18,01	1	18,01
HARTING	0914 006 0313	Han-modular holding frame for 2 modules housing	18,02	1	18,02
HARTING	0914 008 3001	Han-modular 8 pole male insert	5,71	1	5,71

HARTING	0914 008 3101	Han-modular 8 pole female insert	6,80	1	6,80
HARTING	0933 000 6117	0.14-0.37qmm gold crimp contact, male	3,73	8	29,86
HARTING	0933 000 6217	0.14-0.37qmm gold crimp contact, female	6,37	8	50,93
HARTING	0933 000 6122	0.5qmm gold crimp contact, male	3,17	2	6,34
HARTING	0933 000 6222	0.5qmm gold crimp contact, female	3,49	2	6,98
HARTING	2103 281 1405	M12 D-code ethernet connector, male straight	26,60	4	106,39
HARTING	2103 281 2405	M12 D-code ethernet connector, female	30,03	4	120,11
SICK	2055859	Power and I/O cable	89,54	3	268,61
SICK	CDM420-0007	Focus bar code scanner connection module	319,32	1	319,32
SCHNEIDER ELECTRIC	XVB-Z02	Beacon fixing base with mounting tube 80mm	9,85	1	9,85
SCHNEIDER ELECTRIC	XVB-C21	Base and cover for signal beacon	22,23	1	22,23
SCHNEIDER ELECTRIC	XVB-C37	Beacon lamp element, colourless	18,75	1	18,75
SCHNEIDER ELECTRIC	DL1-BDB1	LED lamp insert, ba15d, white	19,13	1	19,13
SICK	RFU 620-10100	RFID transponder	1561,34	2	3122,68
SICK	CLV690	Barcode reader	3885,29	1	3885,29
SICK	C4C-SA18030A10000	DeTec4 light barrier	1363,34	2	2726,68
				TOTAL [€]	91.795,79

Personnel Budget

Table 0.4. Personnel Costs

Description	Price per hour [€]	Hours	Total [€]
Programming	22,50	260	5850
Design	25	290	7250
Eplan - Blueprints and memories	15	50	750
		Total	13.850

Other Costs and Unforeseen Expenses

Many of the materials needed such as roller doors, the press, robots, the linear synchronous motor and its railings, are made tailored and specific to the client's needs, which makes it difficult to know the exact costs of these items. An estimation of these expenses is made in the following table.

Table 0.5. Other Costs and Unforeseen Expenses

Description	Unitary Price [€]	Units	Total [€]
Roller Door	18.000	4	72.000
Press	50.000	1	50.000
Robots	45.000	19	855.000
Liner synchronous motors and railing (per station)	100.000	11	1.100.000
		Unforeseen Expenses	50.000
		Total	2.127.000

Project Budget

Table 0.6. Summary and Totals

Description	Total [€]
PLC1 Area stock list	84.059,94
PLC2 Area stock list	53.004,45
PLC3 Area stock list	91.795,79
Personnel costs	13.850
Other Costs and Unforeseen Expenses	2.127.000
Pre-Total	2.369.710,18
Industrial Profit 10%	236.971,02
Base	2.606.681,20
VAT	21%
Total	3.154.084,25

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