Technical Report

Researching Evolution in Industrial Plant Automation

Scenarios and Documentation of the Pick and Place Unit

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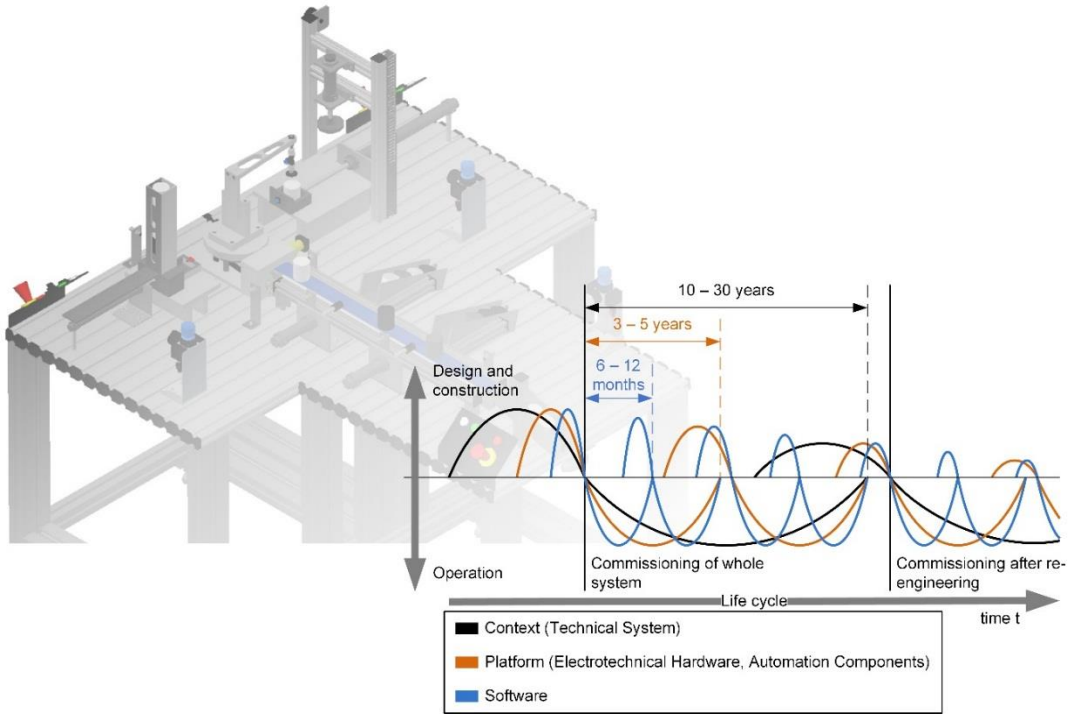

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1 Introduction

A case study "investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and context are not clearly evident" [1]. Case study research in the field of plant and machine engineering often results in cost and/or time-intensive demonstrators to evaluate an approach whose design fits well but solely to the respective approach. Generalization of research results and its applicability in industry is often difficult.

An open case study, i.e. a case study whose sophisticated documentation is available to the research community is beneficial in various ways: Firstly, the comparability of different research approaches is facilitated. Secondly, it eases to focus research because no application example for demonstration has to develop additionally and, therefore, cost and time can be used for research. Additionally, investigating aspects less frequently dealt with are enabled. Fourthly, exchanging research ideas and coordination between different research efforts is facilitated by a common case study. Fifthly, collaboration between research projects (also ones addressing complementary research aspects) is enabled.

Industrial plants are typically operated for some decades [2]. Thus, industrial enterprises are forced to evolve their facilities to address this challenge. But various reasons for evolution of industrial production systems exists [3], [4], e.g. changing requirements, fixing of failures, unanticipated situations on site, etc. An open case study for studying evolution of automation systems is provided by the Institute of Automation and Information Systems[1] by a bench-scale manufacturing system called Pick and Place Unit [3]–[5] (also referred to as PPU for short). As discussed in [4], the PPU is limited in size and complexity but provides a valuable trade-off between problem complexity and evaluation effort. In a first step, various Scenarios to study evolution have been defined and documented [3]. In the remainder of this technical report, a detailed description of the PPU's Scenarios is presented: at first, various different manifestations of the PPU called Scenarios are presented in section 2. Subsequently, one possible arrangement of Scenarios inspired by a real industrial application [3] is presented.

[1] http://www.ais.mw.tum.de, retrieved: 05/03/2015.

2 Scenarios of the Pick and Place Unit (PPU)

In this section, different manifestations of the Pick and Place Unit (PPU) within Scenarios are described separately. Each Scenario is described as a standalone section, i.e. independently from respective preceding or succeeding Scenarios. The components the PPU is composed of within a Scenario are described in detail. The respective documentation of the Scenarios is freely available from [6].

2.1 Scenario Sc0

Within ***Scenario Sc0***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 1) working as a work piece input storage, a ***ramp*** (no. 2) working as a work piece output storage and a ***crane*** (no. 3) for transporting work pieces by picking and placing them between these two working positions. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces in this Scenario. The models for this Scenario are freely available from [7]–[9].

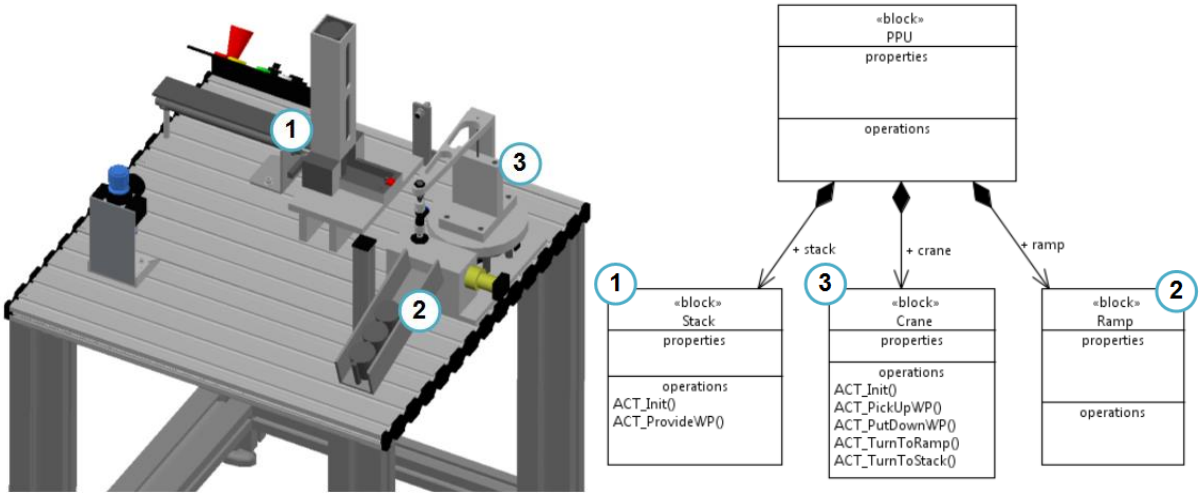

Fig. 1. Overview on the PPU in Scenario Sc0 (left: graphically [7]*, right: logically* [8]*)*

Whereas the ramp is a solely mechanical component, stack and crane are mechatronic components (cf. Table 1), i.e. they consist of sensors and actuators and require control for operation. These latter components are described in detail in the following. Subsequently, the initialization procedure and overall behavior of the PPU in Scenario Sc0 are presented.

Table 1. Component list of the PPU in Scenario Sc0 [9]

Position	Resource	Clamp	Description	Component	Type
1	100	X1	Stack		
2	200	X2	Crane		
3	300		Ramp		

2.1.1 PPU's structure in Scenario Sc0

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is described.

2.1.1.1 Stack's structure in Scenario Sc0

The ***stack*** serves as an input storage for the work pieces. It consists of a solely mechanical ***magazine*** (cf. no. 1 in Fig. 2) where the work pieces are stacked. For separating the lowermost work piece, the stack consists of a pneumatic ***cylinder*** (no. 2), which is equipped with two ***binary sensors*** indicating the positions of the cylinder, i.e. whether it is extended or retracted. The cylinder is a monostable cylinder and, hence, consists of a single ***valve*** for actuating. A digital ***micro switch*** (no. 3) intended to detect work pieces is installed at the so-called pickup position. The micro switch is activated if a work piece is pressed against it. However, due to the internal resistance of the micro switch, work pieces may be pressed back by the micro switch if not clamped properly by the cylinder. Therefore, it is essential to maintain the pressure against the micro switch in order to properly detect a work piece.

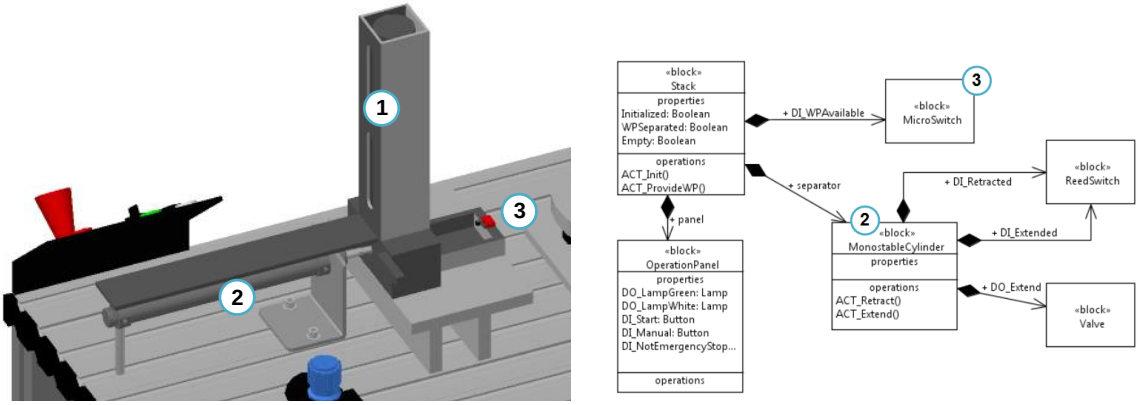

Fig. 2. Overview on the stack's architecture in Scenario Sc0 (left: graphically [7]*, right: logically* [8]*)*

A detailed overview on the stack's components as well as their respective terminal connections is shown in Table 2.

Table 2. Component list of the stack component in Scenario Sc0 [9]

Position	Resource	Clamp	Description	Component	Type
1	100	X1	Stack		
100	100A1	X1.1	Extend separator (Valve)	Stack	DO
100	100B9	X1.2	Separator is extended (Reed Switch)	Stack	DI
100	100B8	X1.3	Separator is retracted (Reed Switch)	Stack	DI
100	100S11	X1.4	WP is available (Micro Switch)	Stack	DI

2.1.1.2 Crane's structure in Scenario Sc0

The ***crane*** serves as the transportation unit for transporting the work pieces from the stack to the ramp. In Fig. 3, an overview on the crane's components is given. The crane consists of a pneumatic ***cylinder*** (no. 1) for lifting and lowering the work pieces. The cylinder consists of two binary position sensors (one at each end) to detect whether the cylinder is extended or retracted as well as one valve as actuator. On top of this cylinder, an arm with a ***vacuum gripper*** (no. 2) is installed. The vacuum gripper is controlled by two valves and contains a micro switch

which indicates whether a work piece is gripped. These components are mounted onto a ***turning table*** (no. 3) for rotational movement. At the bottom of the turning table, two ***tactile, digital sensors*** (no. 4) are installed. These micro switches are installed at the positions of the stack and at the ramp to indicate the crane's stopping positions. The rotational movement of the turning table is realized by a ***motor*** (no. 5).

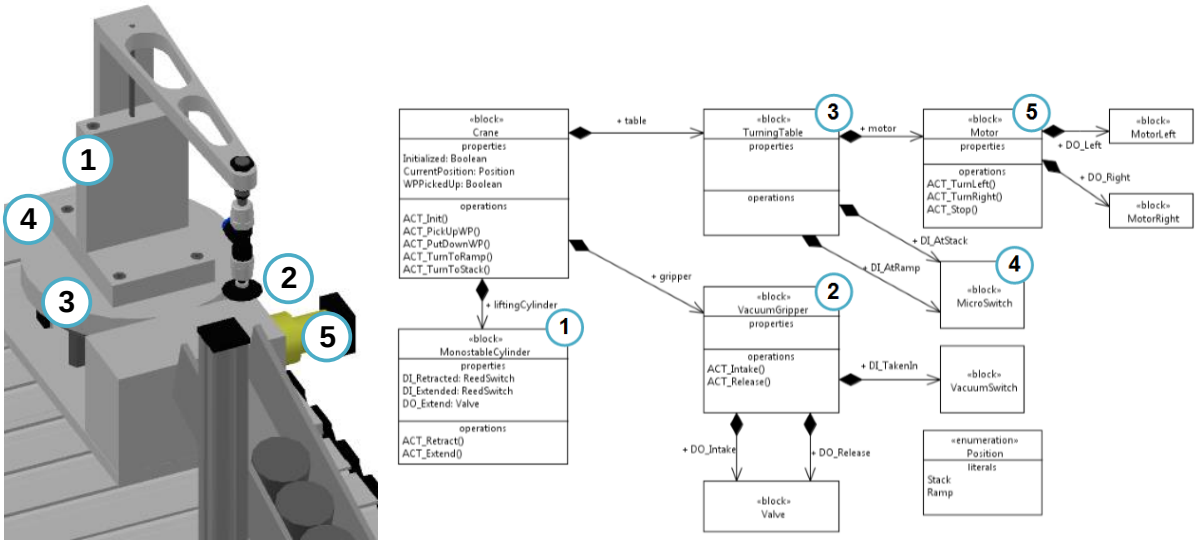

Fig. 3. Overview on the crane component's structure in Scenario Sc0 (left: graphically [7]*, right: logically* [8]*)*

A detailed overview on the crane's components as well as their respective terminal connections is shown in Table 3.

Table 3. Component list of the crane component in Scenario Sc0 [9]

Position	**Resource**	**Clamp**	**Description**	**Component**	**Type**
2	200	X2	Crane		
200	200A1	X2.1	Extend lifting cylinder (Valve)	Crane	DO
200	200B7	X2.2	Lifting cylinder extended (Reed Switch)	Crane	DI
200	200B6	X2.3	Lifting cylinder retracted (Reed Switch)	Crane	DI
200	200A2	X2.4	Intake work piece (Valve)	Crane	DO
200	200A3	X2.5	Release work piece (Valve)	Crane	DO
200	200B5	X2.6	WP taken in (Vacuum Switch)	Crane	DI
200	200S8	X2.7	Crane at stack (Micro Switch)	Crane	DI
200	200S9	X2.8	Crane at ramp (Micro Switch)	Crane	DI
200	200A5	X2.9	Turn left (Motor)	Crane	DO
200	200A6	X2.10	Turn right (Motor)	Crane	DO

2.1.1.3 Ramp's structure in Scenario Sc0

The ramp is a pure mechanical component for storing three work pieces. The movement of the work pieces is realized by a sloping angle of approximately 30 degrees.

2.1.2 PPU's behavior in Scenario Sc0

In the following subsections, the PPU's behavior, i.e. the initialization behavior, the automatic operation mode behavior and the emergency stop behavior of the PPU, is described.

2.1.2.1 Initialization behavior in Scenario Sc0

Within ***Scenario Sc0***, the PPU is started by pressing the start button of the operation panel. After the button has been pressed, the two mechatronic components, i.e. stack and crane, are initialized. The respective initialization procedure of the PPU is visualized in Fig. 4. Therein, the initialization procedures of the stack and the crane are called simultaneously after the start button of the operation panel has been pressed. The successful initialization is visualized using a green lamp. The stack's and crane's initialization procedures are described in the following.

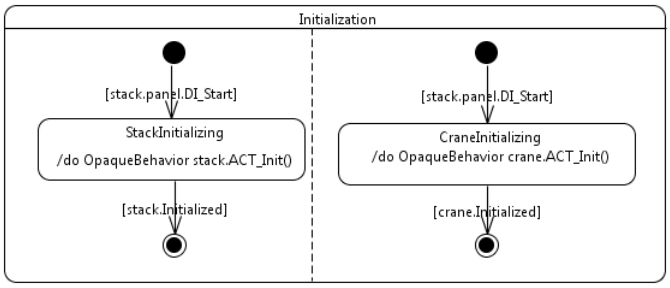

Fig. 4. Initialization procedure in Scenario Sc0 [8]

Within the stack's initialization procedure, at first, all local variables are initialized. Subsequently, the control software is waiting for an operator's interaction, i.e. to push the start button at the operator panel in order to start the automatic operation mode. After the button has been pressed, the stack's cylinder is extended shortly and subsequently retracted.

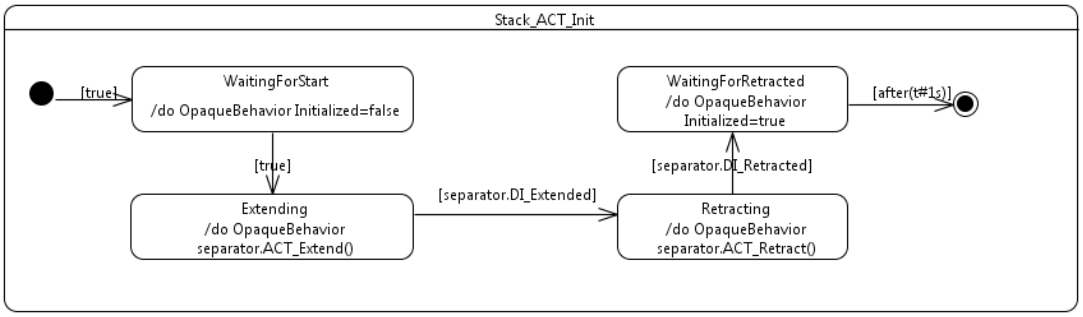

Fig. 5. Stack's initialization procedure in Scenario Sc0 [8]

Within the crane's initialization procedure, at first, all local variables are initialized. Subsequently, the control software is waiting for an operator's interaction, i.e. to push the start button at the operator panel in order to start the automatic operation mode. After the button has been pressed, the vacuum gripper is released shortly and the cylinder is extended.

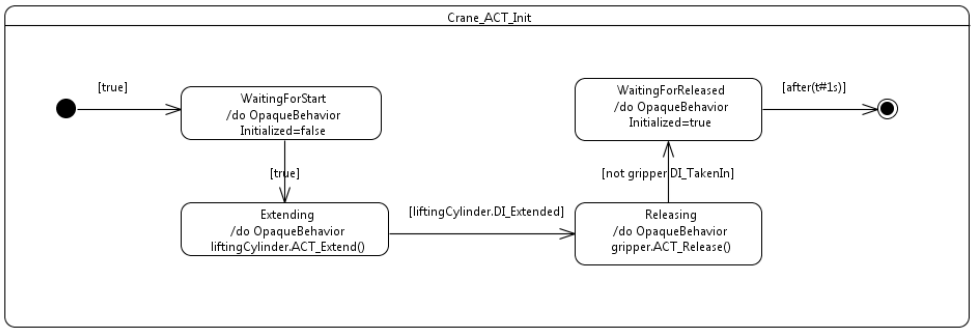

Fig. 6. Crane's initialization procedure in Scenario Sc0 [8]

2.1.2.2 Automatic operation mode behavior in Scenario Sc0

After successful initialization and after pushing the start button at the operation panel, the automatic operation mode of the PPU starts, cf. Fig. 7. Subsequently, the pneumatic cylinder of the stack acting as a separator pushes, by extruding, the bottom work piece from the stack to the pickup position. As soon as a work piece is detected by the micro switch, the crane picks up the piece with a vacuum, turns 90° anti-clockwise to the ramp and deposits the work piece over the ramp. Subsequently, the crane moves back to the pickup position at the stack and the work piece slides down the ramp, which can contain three work pieces at most. The crane's position (at the stack pickup position or the ramp) is detected by two (tactile) digital positioning sensors, which are attached to the bottom plate of the crane. However, there is no separate sensor to detect the absence of a work piece. Instead, the stack's micro switch is used to conclude the absence of a further object. If the sensor detects another work piece the process will restart at the stack.

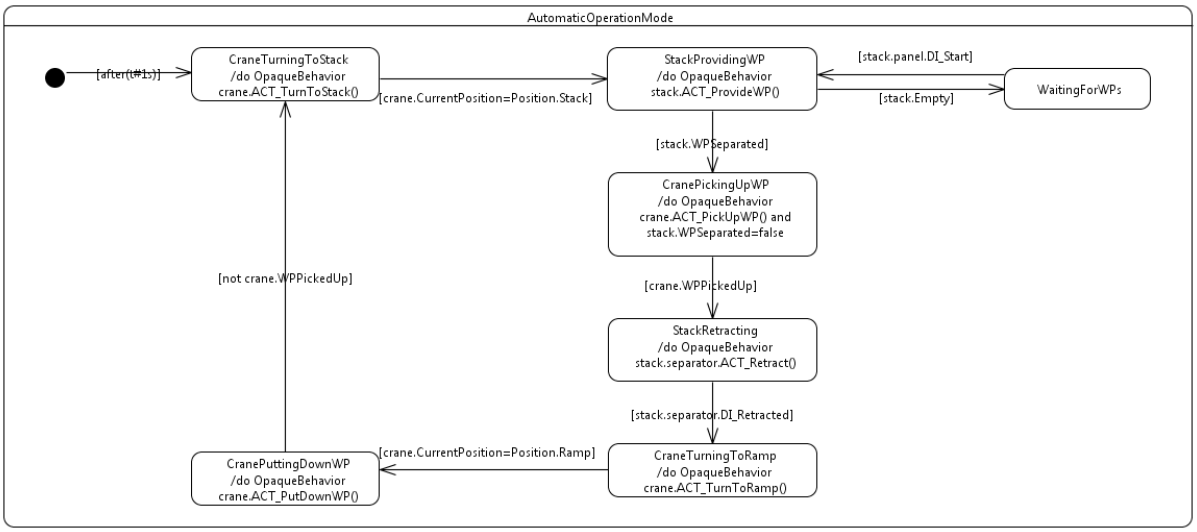

Fig. 7. Automatic operation mode behavior in Scenario Sc0 [8]

2.1.2.3 Emergency stop behavior in Scenario Sc0

In case of an emergency, via the operation panel, the operator may press an emergency button. Therefore, during the PPU's automatic operation behavior, the system can change into an emergency state (cf. Fig. 8). In case of an emergency, the crane's vacuum gripper must be turned off, the separator must retract and the crane's cylinder must be extended.

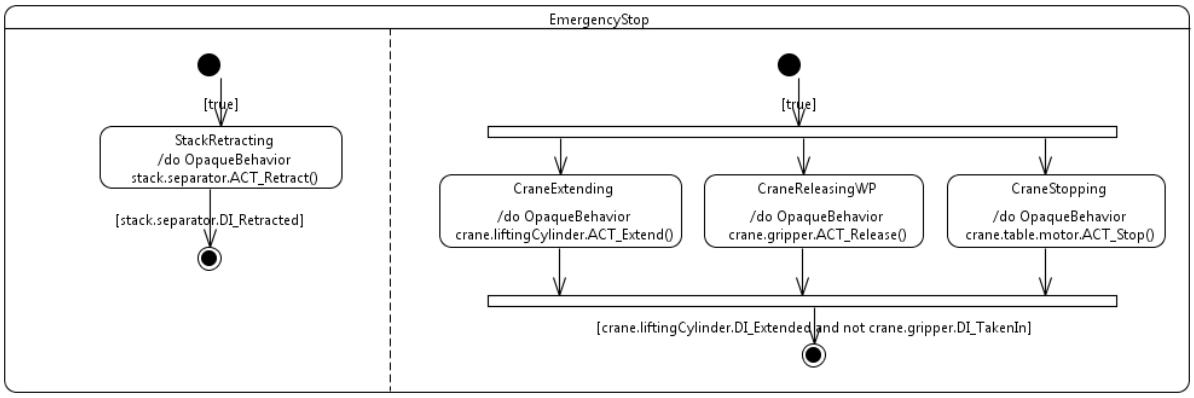

Fig. 8. Emergency stop behavior in Scenario Sc0 [8]

2.2 Scenario Sc1

Within the ***Scenario Sc1***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 9) serving as a work piece input storage, an ***Y-shaped ramp*** (no. 2) working as a work piece output storage and a ***crane*** (no. 3) for transporting work pieces by picking and placing them between these two working positions. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces in this Scenario. The models for this Scenario are freely available from [10]–[12].

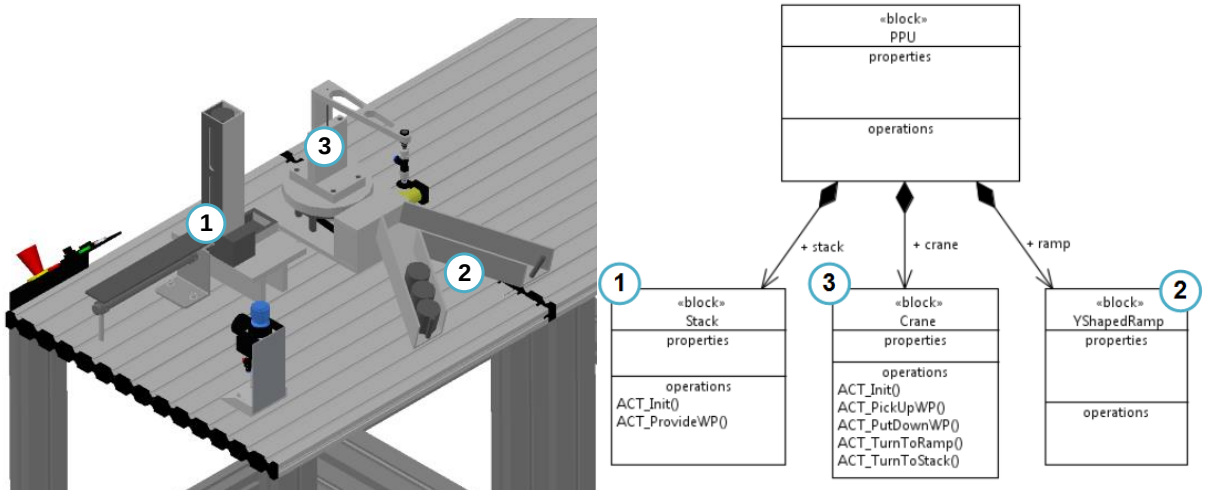

Fig. 9. Overview on the PPU in Scenario Sc1(left: graphically [10], right: logically [11])

Whereas the Y-shaped ramp is a solely mechanical component, stack and crane are mechatronic components (Table 4), i.e. they consist of sensors and actuators and require control for operation. These latter components are described in detail in the following. Subsequently, the initialization procedure and overall behavior of the PPU in Scenario Sc1 are presented.

Table 4. Component list of the PPU in Scenario Sc1 [12]

Position	Resource	Clamp	Description	Component	Type
1	100	X1	Stack		
2	200	X2	Crane		
3	300		Y-shaped ramp		

2.2.1 PPU's structure in Scenario Sc1

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is described.

2.2.1.1 Stack's structure in Scenario Sc1

The mechatronic component stack of the PPU in Scenario Sc1 is the same as in Scenario Sc0. Therefore, for a description of the stack's structure, see section 2.1.1.1.

2.2.1.2 Crane's structure in Scenario Sc1

The mechatronic component crane of the PPU in Scenario Sc1 is the same as in Scenario Sc0. Therefore, for a description of the crane's structure, see section 2.1.1.2.

2.2.1.3 Ramp's structure in Scenario Sc1

The Y-shaped ramp is a pure mechanical component for storing up to six work pieces. The movement of the work pieces is realized by a sloping angle of approximately 30 degrees.

2.2.2 PPU's behavior in Scenario Sc1

The PPU's behavior in Scenario Sc1 is the same as in Scenario Sc0. Therefore, for a description of the PPU's behavior, see section 2.1.1.3.

2.3 Scenario Sc2

Within the ***Scenario Sc2***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 1) working as a work piece input storage, a ***ramp*** (no. 2) working as a work piece output storage and a ***crane*** (no. 3) for transporting work pieces by picking and placing them between these two working positions. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces as well as metallic work pieces in this Scenario.

Whereas the ramp is a solely mechanical component, stack and crane are mechatronic components (cf. Table 1), i.e. they consist of sensors and actuators and require control for operation. These latter components are described in detail in the following. Subsequently, the initialization procedure and overall behavior of the PPU in Scenario Sc2 are presented. The models for this Scenario are freely available from [13]–[15].

2.3.1 PPU's structure in Scenario Sc2

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is described.

2.3.1.1 Stack's structure in Scenario Sc2

The ***stack*** serves as an input storage for the work pieces. It consists of a solely mechanical ***magazine*** (cf. no. 1 in Fig. 10) where the work pieces are stacked. For separating the lowermost work piece, the stack consists of a pneumatic ***cylinder*** (no. 2), which is equipped with two ***binary sensors*** indicating the positions of the cylinder, i.e. whether it is extended or retracted. The cylinder is a monostable cylinder and, hence, furthermore consists of a single ***valve*** for actuating. A digital ***micro switch*** (no. 3) intended to detect work pieces is installed at the so-

called pickup position. The micro switch is activated if a work piece is pressed against it. However, due to the internal resistance of the micro switch, work pieces may be pressed back by the micro switch if not clamped properly by the cylinder. Therefore, it is essential to maintain the pressure against the micro switch in order to properly detect a work piece. Moreover, at the pickup position, an ***inductive sensor*** (no. 4) is installed for detecting whether a work piece is a metallic one or not.

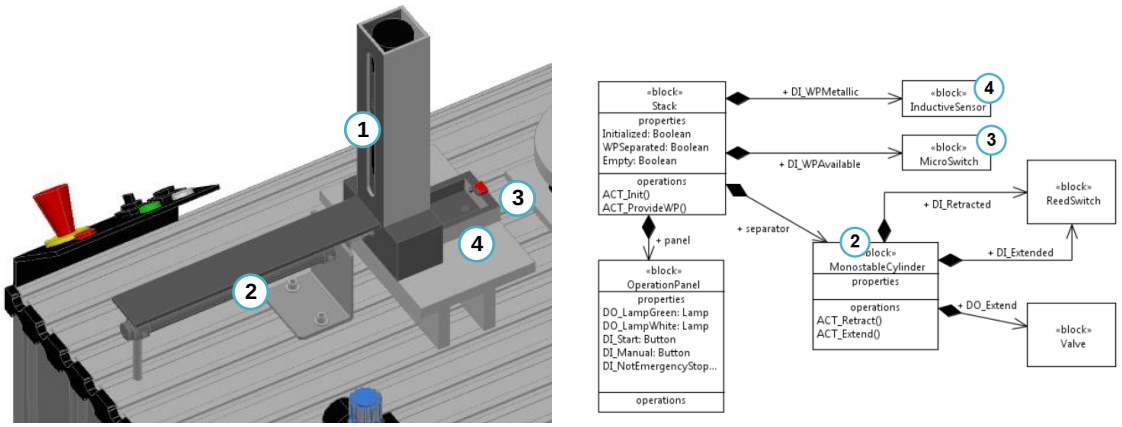

Fig. 10. Overview on the stack's architecture in Scenario Sc2 (left: graphically [13], right: logically [14])

A detailed overview on the stack's components as well as their respective terminal connections is shown in Table 5.

Table 5. Component list of the stack component in Scenario Sc2 [15]

Position	Resource	Clamp	Description	Component	Type
1	100	X1	Stack		
100	100A1	X1.1	Extend separator (Valve)	Stack	DO
100	100B9	X1.2	Separator is extended (Reed Switch)	Stack	DI
100	100B8	X1.3	Separator is retracted (Reed Switch)	Stack	DI
100	100S11	X1.4	WP is available (Micro Switch)	Stack	DI
100	100B10	X1.5	WP is metallic (Inductive Sensor)	Stack	DI

2.3.1.2 Crane's structure in Scenario Sc2

The mechatronic component crane of the PPU in Scenario Sc2 is the same as in Scenario Sc0. Therefore, for a description of the crane's structure, see section 2.1.1.2.

2.3.1.3 Ramp's structure in Scenario Sc2

The mechanical component ramp of the PPU in Scenario Sc2 is the same as in Scenario Sc0. Therefore, for a description of the ramp's structure, see section 2.1.1.3.

2.3.2 PPU's behavior in Scenario Sc2

The PPU's behavior in Scenario Sc2 is the same as in Scenario Sc0. Therefore, for a description of the PPU's behavior, see section 2.1.1.3.

2.4 Scenario Sc3

Within the ***Scenario Sc3***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 11) working as a work piece input storage, a ***ramp*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces and a ***crane*** (no. 4) for transporting work pieces by picking and placing them between these three working positions. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the ramp. In contrast, metallic work pieces are transported from the stack to the stamp, processed there and then transported to the ramp.

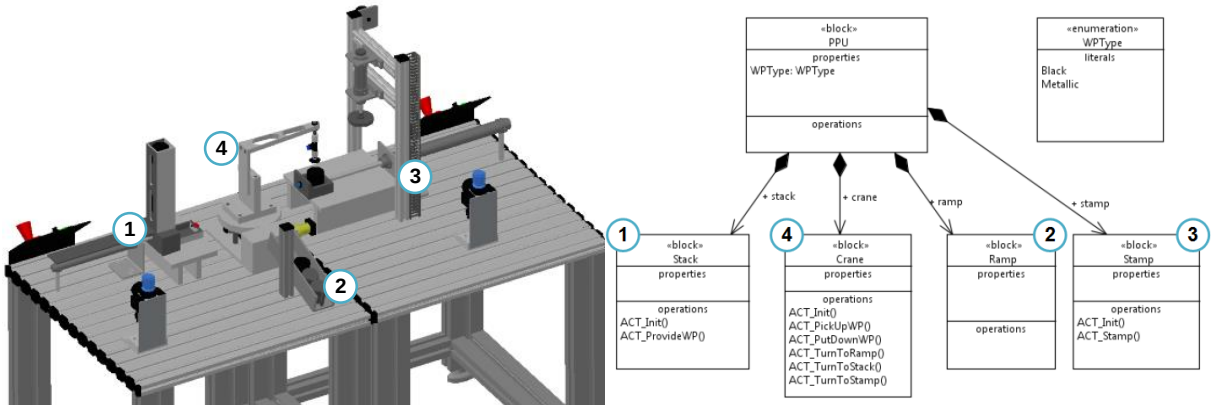

Fig. 11. Overview on the PPU in Scenario Sc3 (left: graphically [16], right: logically [17])

Whereas the ramp is a solely mechanical component, stack, stamp and crane are mechatronic components (cf. Table 6), i.e. they consist of sensors and actuators and require control for operation. These latter components are described in detail in the following. Subsequently, the initialization procedure and overall behavior of the PPU in Scenario Sc3 are presented. The models for this Scenario are freely available from [16]–[18].

Table 6. Component list of the PPU in Scenario Sc3 [18]

Position	Resource	Clamp	Description	Component	Type
1	100	X1	Stack		
2	200	X2	Crane		
3	300		Ramp		
4	400	X3	Stamp		

2.4.1 PPU's structure in Scenario Sc3

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is described.

2.4.1.1 Stack's structure in Scenario Sc3

The mechatronic component stack of the PPU in Scenario Sc3 is the same as in Scenario Sc2. Therefore, for a description of the stack's structure, see section 2.3.1.1.

2.4.1.2 Crane's structure in Scenario Sc3

The ***crane*** serves as the transportation unit for transporting the work pieces from the stack to the ramp as well as to the stamp. In Fig. 12, an overview on the crane's components is given. The crane consists of a pneumatic ***cylinder*** (no. 1) for lifting and lowering the work pieces. The cylinder consists of two binary position sensors (one at each end) to detect whether the cylinder is extended or retracted as well as one valve as actuator. On top of this cylinder, an arm with a ***vacuum gripper*** (no. 2) is installed. The vacuum gripper is controlled by two valves and contains a micro switch which indicates whether a work piece is gripped. These components are mounted onto a ***turning table*** (no. 3) for rotational movement. At the bottom of the turning table, three ***tactile, digital sensors*** (no. 4) are installed. These micro switches are installed at the positions of the stack, the stamp and at the ramp to indicate the crane's stopping positions. The rotational movement of the turning table is realized by a ***motor*** (no. 5).

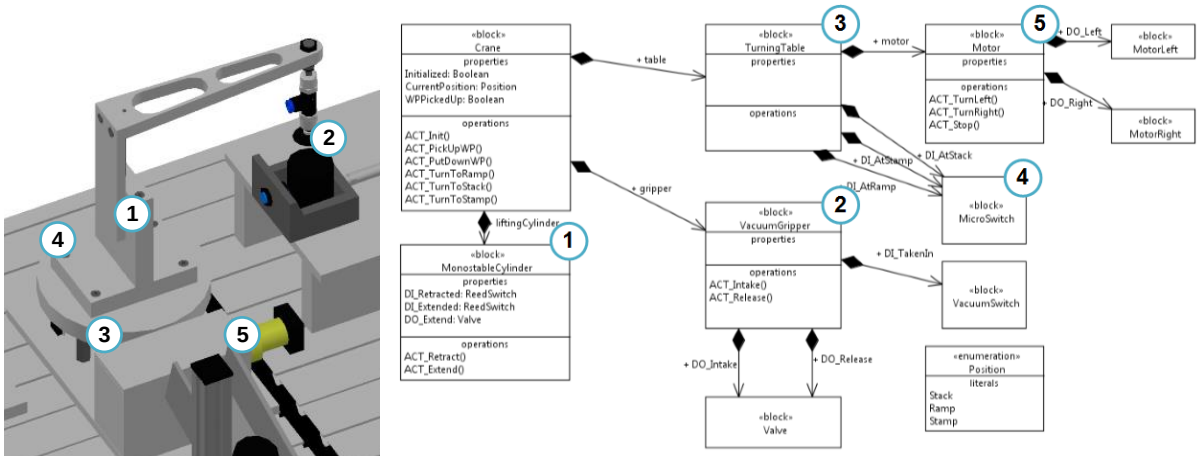

Fig. 12. Overview on the crane component's structure in Scenario Sc3 (left: graphically [16], right: logically [17])

A detailed overview on the crane's components as well as their respective terminal connections is shown in Table 7.

Table 7. Component list of the crane component in Scenario Sc3 [18]

Position	Resource	Clamp	Description	Component	Type
2	200	X2	Crane		
200	200A1	X2.1	Extend lifting cylinder (Valve)	Crane	DO
200	200B7	X2.2	Lifting cylinder extended (Reed Switch)	Crane	DI
200	200B6	X2.3	Lifting cylinder retracted (Reed Switch)	Crane	DI
200	200A2	X2.4	Intake work piece (Valve)	Crane	DO
200	200A3	X2.5	Release work piece (Valve)	Crane	DO
200	200B5	X2.6	WP taken in (Vacuum Switch)	Crane	DI
200	200S8	X2.7	Crane at stack (Micro Switch)	Crane	DI

200	200S9	X2.8	Crane at ramp (Micro Switch)	Crane	DI
200	200A5	X2.9	Turn left (Motor)	Crane	DO
200	200A6	X2.10	Turn right (Motor)	Crane	DO
200	200S10	X2.11	Crane at stamp (Micro Switch)	Crane	DI

2.4.1.3 Ramp's structure in Scenario Sc3

The mechanical component ramp of the PPU in Scenario Sc3 is the same as in Scenario Sc0. Therefore, for a description of the ramp's structure, see section 2.1.1.3.

2.4.1.4 Stamp's structure in Scenario Sc3

The ***stamp*** serves as the stamping component used to stamp work pieces. In Fig. 13, an overview on the stamp component is given. The stamp contains a pneumatic ***sliding cylinder*** (no. 1) used to extend or retract work pieces into or from the stamp module. The sliding cylinder consists of a ***valve*** intended to extend or retract the cylinder as well as two binary ***end position sensors*** for detecting whether the cylinder is extended or retracted. Moreover, ***a stamping cylinder*** (no. 2) is used to stamp the respective work piece. Therein, a ***valve*** is used to set a pressure needed for the stamping process. Respective ***end position sensors*** indicate whether the stamping cylinder is lowered or raised. A ***micro switch*** (no. 3) mounted to the stamp components detects whether a work piece has been placed by the crane or not.

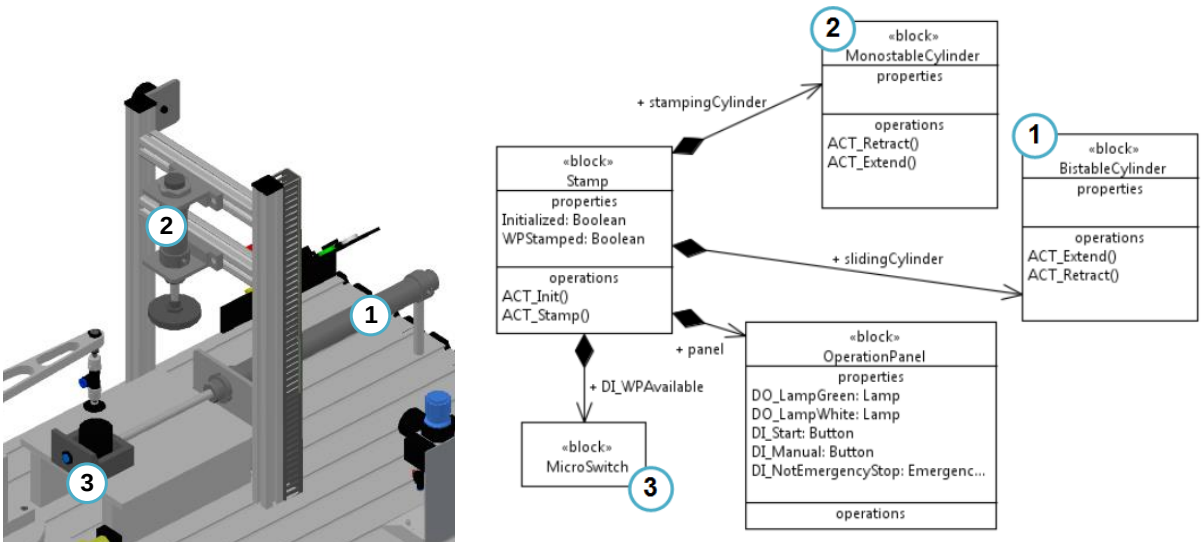

Fig. 13. Overview on the stamp component's structure in Scenario Sc3 (left: graphically [16], right: logically [17])

A detailed overview on the stamp's components as well as their respective terminal connections is shown in Table 8.

Table 8. Component list of the stamp component in Scenario Sc3 [18]

Position	Resource	Clamp	Description	Component	Type
3		X3	Stamp		
300	300B8	X3.1	Stamping cylinder raised (Reed Switch)	Stamp	DI
300	300B9	X3.2	Stamping cylinder lowered (Reed Switch)	Stamp	DI

300	300B7	X3.3	Sliding cylinder extended (Reed Switch)	Stamp	DI
300	300B6	X3.4	Sliding cylinder retracted (Reed Switch)	Stamp	DI
300	300S10	X3.5	WP is available (Micro Switch)	Stamp	DI
300	300A1	X3.6	Extend sliding cylinder (Valve)	Stamp	DO
300	300A2	X3.7	Retract sliding cylinder (Valve)	Stamp	DO
300	300A3	X3.8	Lower stamping cylinder (Valve)	Stamp	DO

2.4.2 PPU's behavior in Scenario Sc3

In the following subsections, the PPU's behavior, i.e. the initialization behavior, the automatic operation mode behavior and the emergency stop behavior of the PPU, is described.

2.4.2.1 Initialization behavior in Scenario Sc3

The PPU is started by pressing the start buttons at both operation panels. In Fig. 14, the main initialization state chart is given. For initializing the stamp, the start button of the operation panel located at this component has to be pressed. For initialization, the sliding as well as stamping cylinders are retracted and extended once (cp. Fig. 15). The initialization of the other components, i.e. crane and stack, is executed as described in section 2.1.2.1. A green lamp at each operation panel indicates a successful initialization.

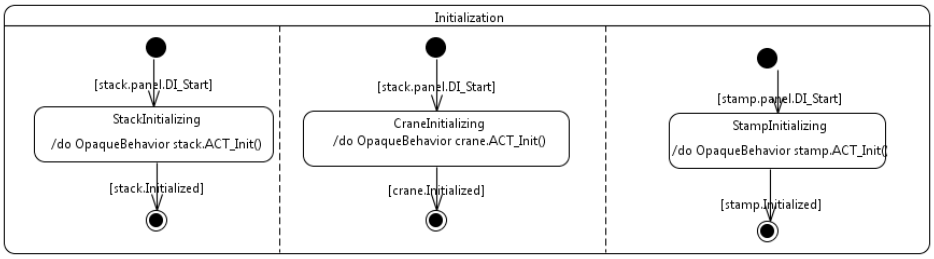

Fig. 14. Initialization procedure in Scenario Sc3 [17]

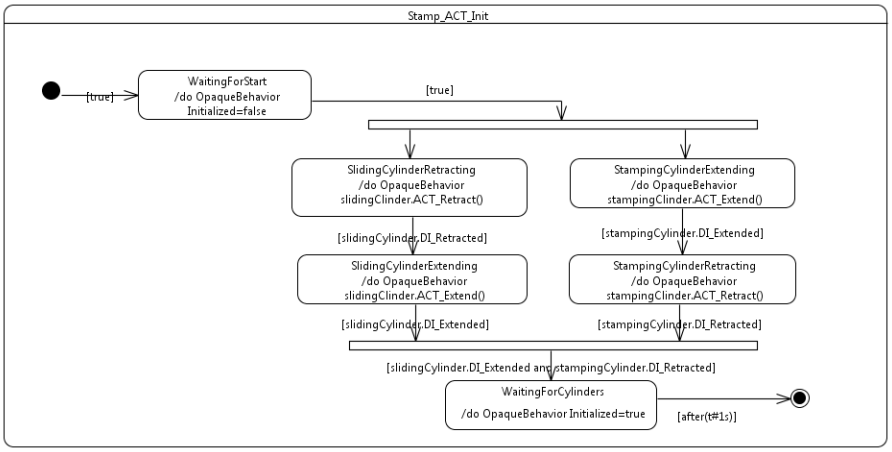

Fig. 15. Stamp's initialization procedure in Scenario Sc3 [17]

2.4.2.2 Automatic operation behavior in Scenario Sc3

Two kinds of work pieces are used in this Scenario and handled differently by the PPU: Black work pieces are directly transported to the ramp whereas metallic work pieces are firstly stamped and afterwards transported to the ramp.

After startup, one of the work pieces stored in the stack is separated and pushed to the pickup position for the crane (cf. Fig. 12). In order to ensure the correct position of the work piece, the separating cylinder of the stack remains extended. For a detailed description of the stack's functionality see section 2.1.2.2. As soon as a work piece is detected by the digital micro switch at the stack's pickup position, the crane starts turning clockwise and stops at the stack's position. The crane has to turn 90°-counterclockwise to transport black work pieces from the stack directly to the ramp. For metallic work pieces, the crane has to turn 180°-counterclockwise to place work pieces at the stamp. An inductive sensor, whose value is true for metallic work pieces, is used to check the specific kind of the extended work piece at the extension position of the stack. The crane then picks up the work piece by using the vacuum gripper, lifts, turns to the desired position, lowers, and deposits the work piece at the respective place. A detailed description about the pick and place functionality of the crane is described in section 2.1.2.2.

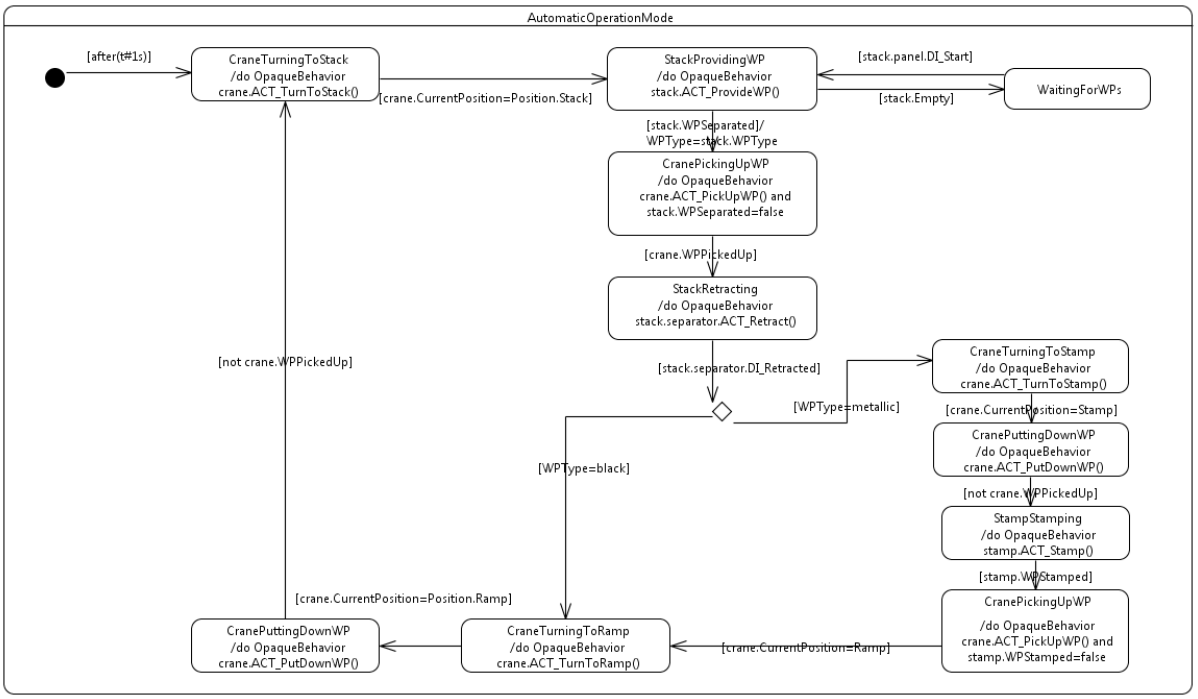

Fig. 16. Automatic operation mode behavior in Scenario Sc3 [17]

Whereas black work pieces are directly transported to the ramp, metallic work pieces run through an additional process at the stamp (cf. Fig. 16). Metallic work pieces are delivered by the crane at the sliding cylinder of the stamp. The sliding cylinder retracts and extends the work pieces to and from beneath the stamp. As soon as the retraction is detected the stamp is lowered for a certain time and with a fixed pressure, raised by setting the 'lower command' to false, and followed by the extension of the slider. As the extension is detected, the crane, waiting at the stamp, picks up the metallic work piece. Subsequently, the crane moves back 90°-clockwise to the ramp and deposits the work piece there.

If no further work piece is detected at the pickup position and the sliding cylinder at the stamp is empty, the plant stops operating. However, there is no separate sensor at the stack to detect the absence of a work piece. Instead, the not sending of the 'work piece detected'-signal while the cylinder is extended, is used to conclude the absence of a further object at the pickup position and also that no further work pieces are left in the stack. If the sensor detects another work piece the process will restart at the stack.

2.4.2.3 Emergency stop behavior in Scenario Sc3

There are two emergency buttons (negative logic), one at the stack and one at the stamp. In a case of emergency – if at least one emergency button is pushed – the PPU is set to a safe state. In this safe state, the pneumatic cylinder of the stack is retracted, the crane stops rotating and shuts off the vacuum (a gripped work piece falls down), the stamp raises and the magazine slider is extended (cf. Fig. 17).

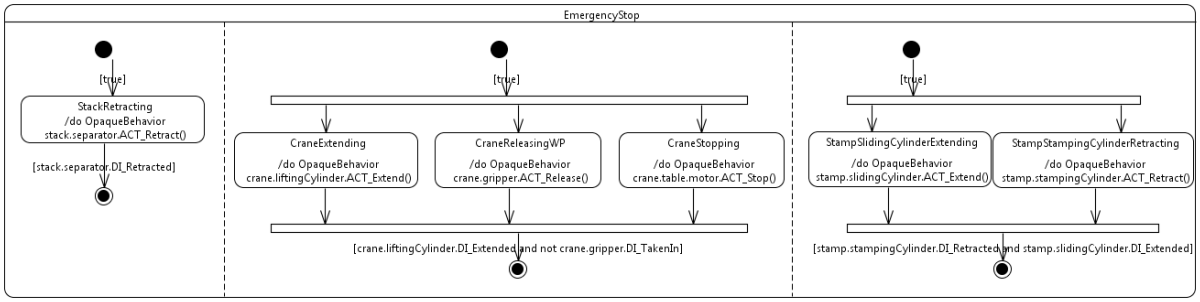

Fig. 17. Emergency stop behavior in Scenario Sc3 [17]

2.5 Scenario Sc4a

Within the ***Scenario Sc4a***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 11) working as a work piece input storage, a ***ramp*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces and a ***crane*** (no. 4) for transporting work pieces by picking and placing them between these three working positions. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the ramp. In contrast, metallic work pieces are transported from the stack to the stamp, processed there and then transported to the ramp.

Whereas the ramp is a solely mechanical component, stack, stamp and crane are mechatronic components (cf. Table 6), i.e. they consist of sensors and actuators and require control for operation. These latter components are described in detail in the following. Subsequently, the initialization procedure and overall behavior of the PPU in Scenario Sc4a are presented. The models for this Scenario are freely available from [19]–[21].

2.5.1 PPU's structure in Scenario Sc4a

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is described.

2.5.1.1 Stack's structure in Scenario Sc4a

The mechatronic component stack of the PPU in Scenario Sc4a is the same as in Scenario Sc2. Therefore, for a description of the stack's structure, see section 2.3.1.1.

2.5.1.2 Crane's structure in Scenario Sc4a

The ***crane*** serves as the transportation unit for transporting the work pieces from the stack to the ramp as well as to the stamp. In Fig. 18, an overview on the crane's components is given. The crane consists of a pneumatic ***cylinder*** (no. 1) for lifting and lowering the work pieces. The cylinder consists of two binary position sensors (one at each end) to detect whether the cylinder is extended or retracted as well as one valve as actuator. On top of this cylinder, an arm with a ***vacuum gripper*** (no. 2) is installed. The vacuum gripper is controlled by two valves and contains a micro switch which indicates whether a work piece is gripped. These components are mounted onto a ***turning table*** (no. 3) for rotational movement. At the bottom of the turning table, three ***inductive sensors*** (no. 4) are installed. These inductive sensors are installed at the

positions of the stack, the stamp and at the ramp to indicate the crane's stopping positions. The rotational movement of the turning table is realized by a ***motor*** (no. 5).

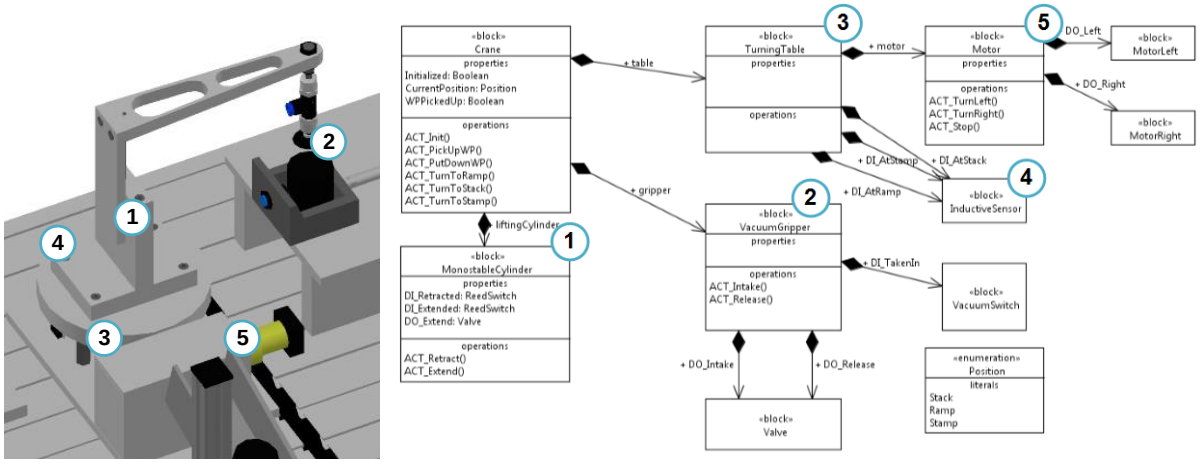

Fig. 18. Overview on the crane component's structure in Scenario Sc4a (left: graphically [19], right: logically [20])

A detailed overview on the crane's components as well as their respective terminal connections is shown in Table 9.

Table 9. Component list of the crane component in Scenario Sc4a [21]

Position	Resource	Clamp	Description	Component	Type
2	200	X2	Crane		
200	200A1	X2.1	Extend lifting cylinder (Valve)	Crane	DO
200	200B7	X2.2	Lifting cylinder extended (Reed Switch)	Crane	DI
200	200B6	X2.3	Lifting cylinder retracted (Reed Switch)	Crane	DI
200	200A2	X2.4	Intake work piece (Valve)	Crane	DO
200	200A3	X2.5	Release work piece (Valve)	Crane	DO
200	200B5	X2.6	WP taken in (Vacuum Switch)	Crane	DI
200	200S8	X2.7	Crane at stack (Inductive Sensor)	Crane	DI
200	200S9	X2.8	Crane at ramp (Inductive Sensor)	Crane	DI
200	200A5	X2.9	Turn left (Motor)	Crane	DO
200	200A6	X2.10	Turn right (Motor)	Crane	DO
200	200S10	X2.11	Crane at stamp (Inductive Sensor)	Crane	DI

2.5.1.3 Ramp's structure in Scenario Sc4a

The mechanical component ramp of the PPU in Scenario Sc4a is the same as in Scenario Sc0. Therefore, for a description of the ramp's structure, see section 2.1.1.3.

2.5.1.4 Stamp's structure in Scenario Sc4a

The mechatronic component stamp of the PPU in Scenario Sc4a is the same as in Scenario Sc3. Therefore, for a description of the stamp's structure, see section 2.4.1.4.

2.5.2 PPU's behavior in Scenario Sc4a

The PPU's behavior in Scenario Sc4a is the same as in Scenario Sc3. Therefore, for a description of the PPU's behavior, see section 2.4.2.

2.6 Scenario Sc4b

Within the ***Scenario Sc4b***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 11) working as a work piece input storage, a ***ramp*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces and a ***crane*** (no. 4) for transporting work pieces by picking and placing them between these three working positions. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the ramp. In contrast, metallic work pieces are transported from the stack to the stamp, processed there and then transported to the ramp.

Whereas the ramp is a solely mechanical component, stack, stamp and crane are mechatronic components (cf. Table 6), i.e. they consist of sensors and actuators and require control for operation. These latter components are described in detail in the following. Subsequently, the initialization procedure and overall behavior of the PPU in Scenario Sc4b are presented. The models for this Scenario are freely available from [22]–[24].

2.6.1 PPU's structure in Scenario Sc4b

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is de-scribed.

2.6.1.1 Stack's structure in Scenario Sc4b

The mechatronic component stack of the PPU in Scenario Sc4b is the same as in Scenario Sc2. Therefore, for a description of the stack's structure, see section 2.3.1.1.

2.6.1.2 Crane's structure in Scenario Sc4b

The ***crane*** serves as the transportation unit for transporting the work pieces from the stack to the ramp as well as to the stamp. In Fig. 19, an overview on the crane's components is given. The crane consists of a pneumatic ***cylinder*** (no. 1) for lifting and lowering the work pieces. The cylinder consists of two binary position sensors (one at each end) to detect whether the cylinder is extended or retracted as well as one valve as actuator. On top of this cylinder, an arm with a ***vacuum gripper*** (no. 2) is installed. The vacuum gripper is controlled by two valves and contains a micro switch which indicates whether a work piece is gripped. These components are mounted onto a ***turning table*** (no. 3) for rotational movement. At the bottom of the turning table, three ***inductive sensors*** (no. 4a) and three ***tactile, digital sensors*** (no. 4b) are installed. The micro switches are installed at the positions of the stack, the stamp and at the ramp to indicate the crane's stopping positions as depicted in section 2.4.1.2. The inductive sensors are

spatially shifted and hence provide redundant sensors for the respective micro switches. The rotational movement of the turning table is realized by a ***motor*** (no. 5).

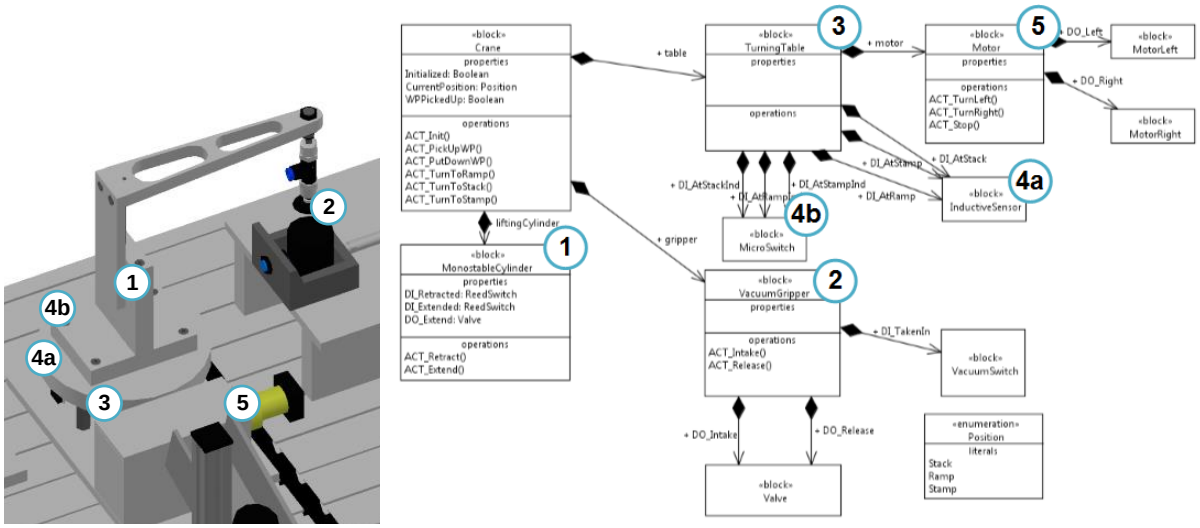

Fig. 19. Overview on the crane component's structure in Scenario Sc4b (left: graphically [22], right: logically [23])

A detailed overview on the crane's components as well as their respective terminal connections is shown in Table 10.

Table 10. Component list of the crane component in Scenario Sc4b [24]

Position	Resource	Clamp	Description	Component	Type
2	200	X2	Crane		
200	200A1	X2.1	Extend lifting cylinder (Valve)	Crane	DO
200	200B7	X2.2	Lifting cylinder extended (Reed Switch)	Crane	DI
200	200B6	X2.3	Lifting cylinder retracted (Reed Switch)	Crane	DI
200	200A2	X2.4	Intake work piece (Valve)	Crane	DO
200	200A3	X2.5	Release work piece (Valve)	Crane	DO
200	200B5	X2.6	WP taken in (Vacuum Switch)	Crane	DI
200	200S8	X2.7	Crane at stack (Micro Switch)	Crane	DI
200	200S9	X2.8	Crane at ramp (Micro Switch)	Crane	DI
200	200A5	X2.9	Turn left (Motor)	Crane	DO
200	200A6	X2.10	Turn right (Motor)	Crane	DO
200	200S10	X2.11	Crane at stamp (Micro Switch)	Crane	DI
200	200S11	X2.12	Crane at stack (Inductive Sensor)	Crane	DI
200	200S12	X2.13	Crane at ramp (Inductive Sensor)	Crane	DI
200	200S13	X2.14	Crane at stamp (Inductive Sensor)	Crane	DI

2.6.1.3 Ramp's structure in Scenario Sc4b

The mechanical component ramp of the PPU in Scenario Sc4b is the same as in Scenario Sc0. Therefore, for a description of the ramp's structure, see section 2.1.1.3.

2.6.1.4 Stamp's structure in Scenario Sc4b

The mechatronic component stamp of the PPU in Scenario Sc4b is the same as in Scenario Sc3. Therefore, for a description of the stamp's structure, see section 2.4.1.4.

2.6.2 PPU's behavior in Scenario Sc4b

The PPU's behavior in Scenario Sc4b is the same as in Scenario Sc3. Therefore, for a description of the PPU's behavior, see section 2.4.2.

2.7 Scenario Sc5

Within the ***Scenario Sc5***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 11) working as a work piece input storage, a ***ramp*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces and a ***crane*** (no. 4) for transporting work pieces by picking and placing them between these three working positions. Moreover, the crane may use the stamp component for buffering purposes. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the ramp. In contrast, metallic work pieces are transported from the stack to the stamp, processed there and then transported to the ramp. The models for this Scenario are freely available from [25]–[27].

2.7.1 PPU's structure in Scenario Sc5

The PPU's structure in Scenario Sc5 is the same as in Scenario Sc3. Therefore, for a description of the PPU's structure, see section 2.4.1.

2.7.2 PPU's behavior in Scenario Sc5

In the following subsections, the PPU's behavior, i.e. the initialization behavior, the automatic operation mode behavior and the emergency stop behavior of the PPU, is described.

2.7.2.1 Initialization behavior in Scenario Sc5

The PPU's initialization behavior in Scenario Sc5 is the same as in Scenario Sc3. Therefore, for a description of the PPU's initialization behavior, see section 2.4.2.1.

2.7.2.2 Automatic operation mode behavior in Scenario Sc5

Two kinds of work pieces are used in this Scenario and handled differently by the PPU: Black work pieces are directly transported to the ramp whereas metallic work pieces are firstly stamped and afterwards transported to the ramp.

After startup, one of the work pieces stored in the stack is separated and pushed to the pickup position for the crane (cf. Fig. 12). In order to ensure the correct position of the work piece, the

separating cylinder of the stack remains extended. For a detailed description of the stack's functionality see section 2.1.2.2. As soon as a work piece is detected by the digital micro switch at the stack's pickup position, the crane starts turning clockwise and stops at the stack's position. The crane has to turn 90°-counterclockwise to transport black work pieces from the stack directly to the ramp. For metallic work pieces, the crane has to turn 180°-counterclockwise to place work pieces at the stamp. An inductive sensor, whose value is true for metallic work pieces, is used to check the specific kind of the extended work piece at the extension position of the stack. The crane then picks up the work piece by using the vacuum gripper, lifts, turns to the desired position, lowers, and deposits the work piece at the respective place. A detailed description about the pick and place functionality of the crane is described in section 2.1.2.2.

Whereas black work pieces are directly transported to the ramp, metallic work pieces run through an additional process at the stamp (cf. Fig. 16). Metallic work pieces are delivered by the crane at the sliding cylinder of the stamp. The sliding cylinder retracts and extends the work pieces to and from beneath the stamp. As soon as the retraction is detected the stamp is lowered for a certain time and with a fixed pressure, raised by setting the 'lower command' to false, and followed by the extension of the slider. Simultaneously, after the metallic work piece is placed in the sliding cylinder and the crane is raised again, it is checked if there is a black plastic work piece available at the stack (refer to Fig. 20). If a black work piece is available at the stack, the crane uses the stamping time and starts turning clockwise to pick up the black piece and place it at the ramp. After depositing the work piece at the ramp, it is checked if the stamping process is finished and if another black work piece is on hand at the stack. As long as the stamping process is in progress, all available black work pieces are transported to the slide. However, as soon as the stamping process is completed, the crane handles the stamped metallic work piece from the stamp and deposits it at the ramp prior to picking up another work piece at the stack's pickup position. If the next available work piece at the stack is a metallic piece, while the stamping is still in progress, the crane waits at the stamp until the stamping process is finished. Depending on the time needed for the stamping progress, a certain number of black work pieces can be handled until the stamping is finished and the stamped work piece is transported. In the model seen in Fig. 20 only a single black work piece can be handled before the stamping process is complete. After the crane either placed a black or a metallic work piece at the ramp, the crane moves back to the pickup position at the stack or to the stamp and the work piece slides down the ramp of the output storage. See also Fig. 21 for the work piece supply.

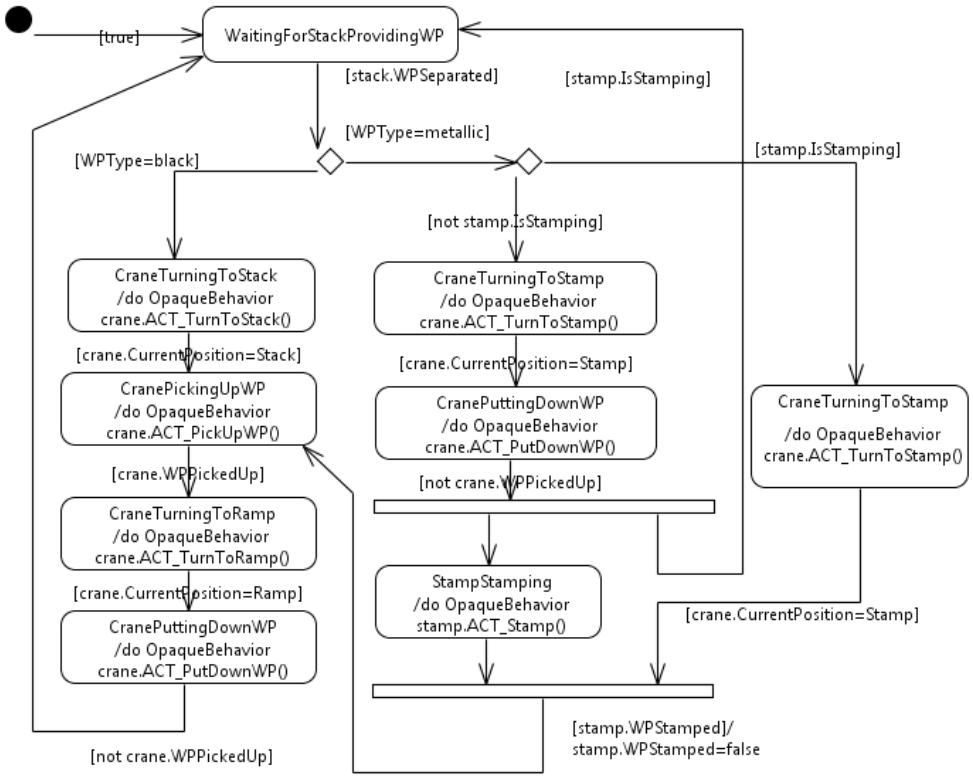

Fig. 20. Overview on crane behavior in Scenario Sc5 [26]

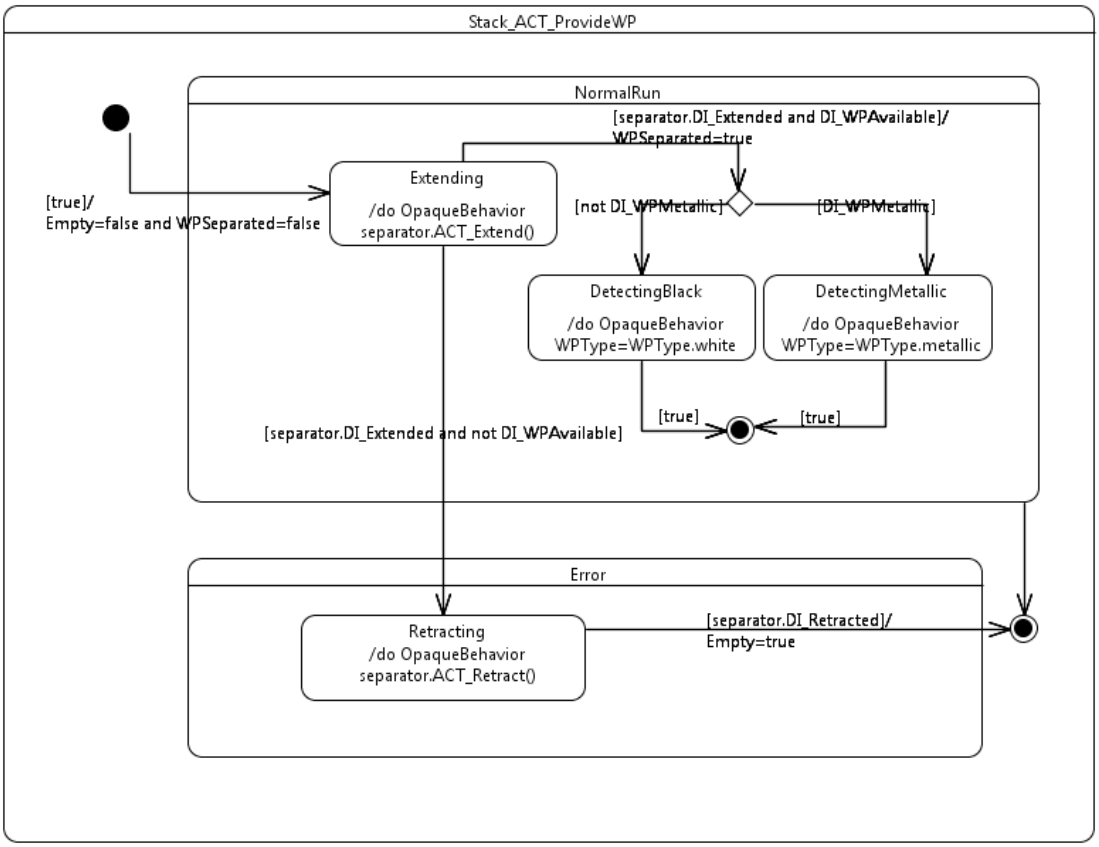

Fig. 21. Overview on work piece supply in Scenario Sc5 [26]

If no further work piece is detected at the pickup position and the sliding cylinder at the stamp is empty, the plant stops operating. However, there is no separate sensor at the stack to detect the absence of a work piece. Instead, the not sending of the ‘work piece detected’-signal while the cylinder is extended, is used to conclude the absence of a further object at the pickup position and also that no further work pieces are left in the stack. If the sensor detects another work piece the process will restart at the stack.

2.7.2.3 Emergency stop behavior in Scenario Sc5

The PPU’s emergency stop behavior in Scenario Sc5 is the same as in Scenario Sc3. Therefore, for a description of the PPU’s emergency stop behavior, see section 2.4.2.3.

2.8 Scenario Sc6

Within the ***Scenario Sc6***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 22) working as a work piece input storage, a ***ramp*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces, a ***mechanical buffer*** (no. 4) intended to buffer currently processed work pieces and a ***crane*** (no. 5) for transporting work pieces by picking and placing them between these three working positions. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the ramp. In contrast, metallic work pieces are transported from the stack to the stamp, processed there and then transported to the ramp.

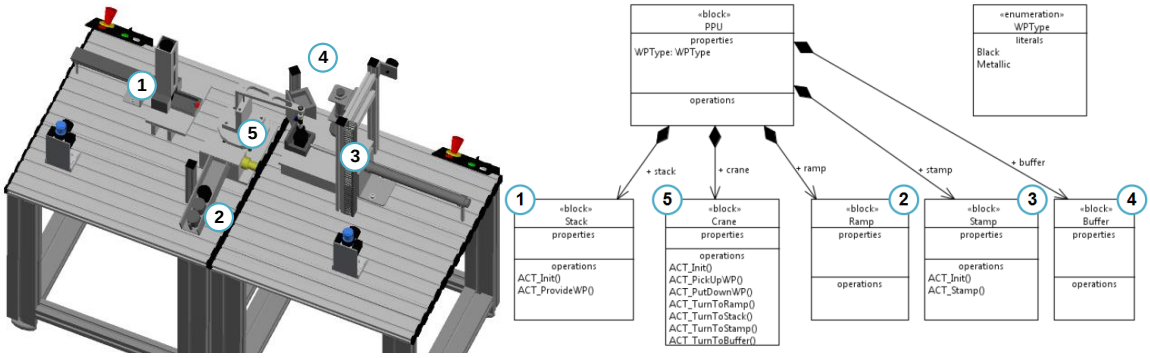

Fig. 22. Overview on the PPU in Scenario Sc6 (left: graphically [28]*, right: logically* [29]*)*

Whereas the ramp is a solely mechanical component, stack, stamp and crane are mechatronic components (cf. Table 11), i.e. they consist of sensors and actuators and require control for operation. These latter components are described in detail in the following. Subsequently, the initialization procedure and overall behavior of the PPU in Scenario Sc6 are presented. The models for this Scenario are freely available from [28]–[30].

Table 11. Component list of the PPU in Scenario Sc6 [30]

Position	Resource	Clamp	Description	Component	Type
1	100	X1	Stack		
2	200	X2	Crane		
3	300		Ramp		
4	400	X4	Stamp		
5	500		Mechanical Buffer		

2.8.1 PPU's structure in Scenario Sc6

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is described.

2.8.1.1 Stack's structure in Scenario Sc6

The mechatronic component stack of the PPU in Scenario Sc6 is the same as in Scenario Sc2. Therefore, for a description of the stack's structure, see section 2.3.1.1.

2.8.1.2 Crane's structure in Scenario Sc6

The ***crane*** serves as the transportation unit for transporting the work pieces from the stack to the ramp as well as to the stamp. In Fig. 12, an overview on the crane's components is given. The crane consists of a pneumatic ***cylinder*** (no. 1) for lifting and lowering the work pieces. The cylinder consists of two binary position sensors (one at each end) to detect whether the cylinder is extended or retracted as well as one valve as actuator. On top of this cylinder, an arm with a ***vacuum gripper*** (no. 2) is installed. The vacuum gripper is controlled by two valves and contains a micro switch which indicates whether a work piece is gripped. These components are mounted onto a ***turning table*** (no. 3) for rotational movement. At the bottom of the turning table, four ***tactile, digital sensors*** (no. 4) are installed. These micro switches are installed at the positions of the stack, the stamp, the ramp and at the buffer to indicate the crane's stopping positions. The rotational movement of the turning table is realized by a ***motor*** (no. 5).

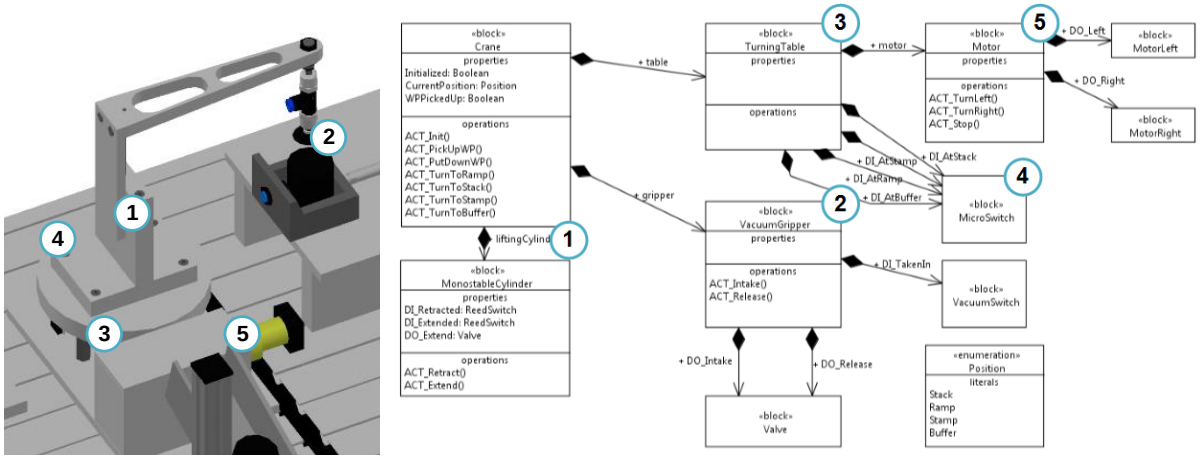

Fig. 23. Overview on the crane component's structure in Scenario Sc3 (left: graphically [28]*, right: logically* [29]*)*

A detailed overview on the crane's components as well as their respective terminal connections is shown in Table 12.

Table 12. Component list of the crane component in Scenario Sc6 [30]

Position	Resource	Clamp	Description	Component	Type
2	200	X2	Crane		
200	200A1	X2.1	Extend lifting cylinder (Valve)	Crane	DO
200	200B7	X2.2	Lifting cylinder extended (Reed Switch)	Crane	DI
200	200B6	X2.3	Lifting cylinder retracted (Reed Switch)	Crane	DI
200	200A2	X2.4	Intake work piece (Valve)	Crane	DO
200	200A3	X2.5	Release work piece (Valve)	Crane	DO
200	200B5	X2.6	WP taken in (Vacuum Switch)	Crane	DI
200	200S8	X2.7	Crane at stack (Micro Switch)	Crane	DI
200	200S9	X2.8	Crane at ramp (Micro Switch)	Crane	DI
200	200A5	X2.9	Turn left (Motor)	Crane	DO
200	200A6	X2.10	Turn right (Motor)	Crane	DO
200	200S10	X2.11	Crane at stamp (Micro Switch)	Crane	DI
200	200S11	X2.12	Crane at buffer (Micro Switch)	Crane	DI

2.8.1.3 Ramp's structure in Scenario Sc6

The mechanical component ramp of the PPU in Scenario Sc6 is the same as in Scenario Sc0. Therefore, for a description of the ramp's structure, see section 2.1.1.3.

2.8.1.4 Stamp's structure in Scenario Sc6

The mechatronic component stamp of the PPU in Scenario Sc6 is the same as in Scenario Sc3. Therefore, for a description of the stamp's structure, see section 2.4.1.4.

2.8.2 PPU's behavior in Scenario Sc6

In the following subsections, the PPU's behavior, i.e. the initialization behavior, the automatic operation mode behavior and the emergency stop behavior of the PPU, is described.

2.8.2.1 Initialization behavior in Scenario Sc6

The PPU's initialization behavior in Scenario Sc6 is the same as in Scenario Sc3. Therefore, for a description of the PPU's initialization behavior, see section 2.4.2.1.

2.8.2.2 Automatic operation mode behavior in Scenario Sc6

Two kinds of work pieces are used in this Scenario and handled differently by the PPU: Black work pieces are directly transported to the ramp whereas metallic work pieces are firstly stamped and afterwards transported to the ramp.

After startup, one of the work pieces stored in the stack is separated and pushed to the pickup position for the crane (cf. Fig. 12). In order to ensure the correct position of the work piece, the separating cylinder of the stack remains extended. For a detailed description of the stack's functionality see section 2.1.2.2. As soon as a work piece is detected by the digital micro switch at the stack's pickup position, the crane starts turning clockwise and stops at the stack's position.

The crane has to turn 90°-counterclockwise to transport black work pieces from the stack directly to the ramp. For metallic work pieces, the crane has to turn 180°-counterclockwise to place work pieces at the stamp. An inductive sensor, whose value is true for metallic work pieces, is used to check the specific kind of the extended work piece at the extension position of the stack. The crane then picks up the work piece by using the vacuum gripper, lifts, turns to the desired position, lowers, and deposits the work piece at the respective place. A detailed description about the pick and place functionality of the crane is described in section 2.1.2.2.

Whereas black work pieces are directly transported to the ramp, metallic work pieces run through an additional process at the stamp (cf. Fig. 16). Metallic work pieces are delivered by the crane at the sliding cylinder of the stamp. The sliding cylinder retracts and extends the work pieces to and from beneath the stamp. As soon as the retraction is detected the stamp is lowered for a certain time and with a fixed pressure, raised by setting the 'lower command' to false, and followed by the extension of the slider. Simultaneously, after the metallic work piece is placed in the sliding cylinder and the crane is raised again, it is checked if there is a black plastic work piece available at the stack (refer to Fig. 20). If a black work piece is available at the stack, the crane uses the stamping time and starts turning clockwise to pick up the black piece and place it at the ramp. After depositing the work piece at the ramp, it is checked if the stamping process is finished and if another black work piece is on hand at the stack. As long as the stamping process is in progress, all available black work pieces are transported to the slide. In case the next work piece is a metallic one, the crane starts turning clockwise to pick it up and place it at the mechanical buffer. Therefore, the crane turns 225°-counterclockwise and releases the metallic work piece at the buffer – without lowering itself because the buffer is high enough for direct placing – by deactivating the vacuum gripper (refer to Fig. 24). By occupying the mechanical buffer, the crane is able to handle another available black work piece while the stamping process is still in progress. However, only if the work piece following the second metallic work piece is a black one, the throughput of work pieces can be increased by using the additional storage. After depositing the metallic work piece at the buffer, the crane checks again whether the stamping process is finished – in that case, the crane moves back to the stamp, to transport the stamped work piece to the slide, followed by the clearing of the mechanical buffer by turning back counterclockwise to pick up the not yet stamped metallic work piece from the buffer and place it at the stamp. Then the checking starts again, as described above. In case the stamping is still not finished, the crane checks the specific kind of the available work piece at the stack again. Now only black plastic work pieces can be processed till the stamping process is finished because the mechanical buffer is blocked for a possible third metallic work piece – in that case the third metallic work piece has to wait till the buffer is cleared again.

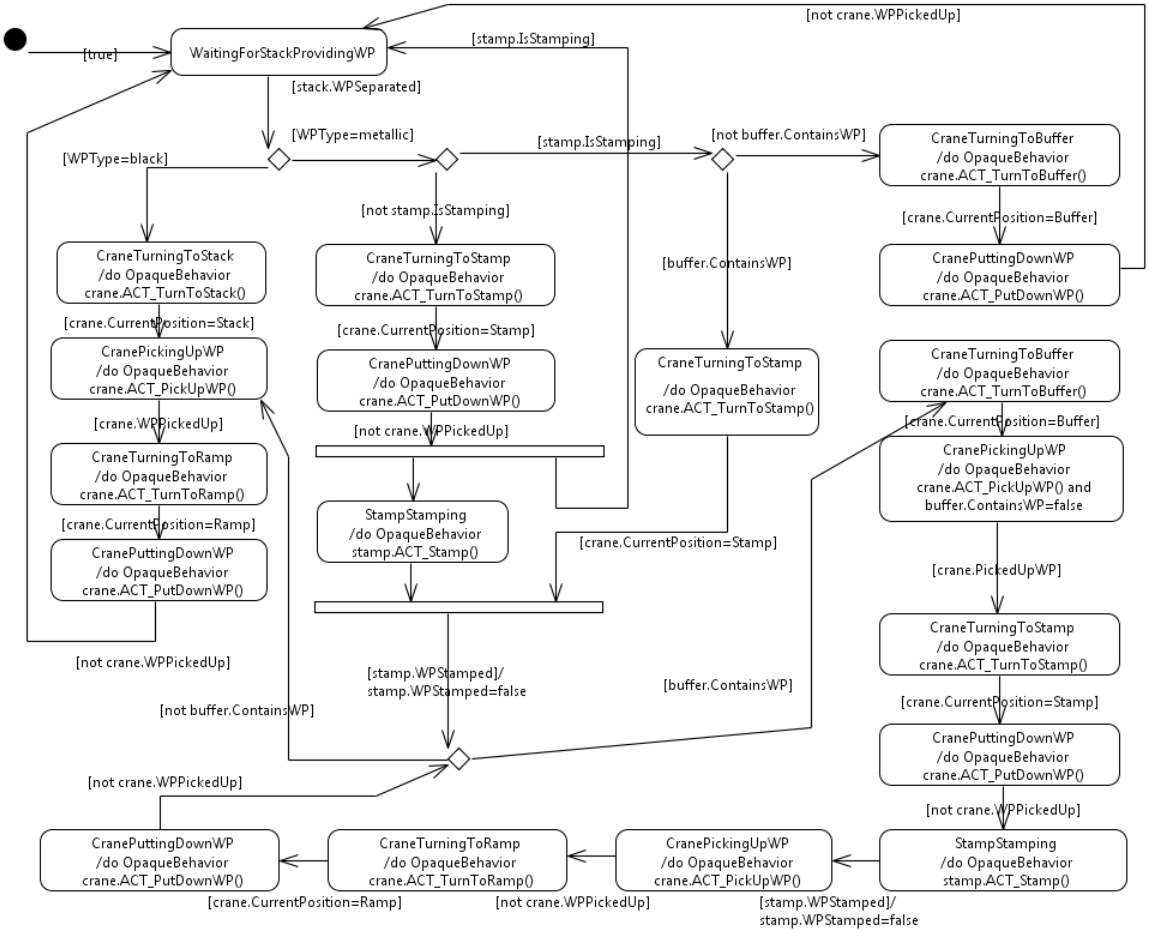

Fig. 24. Overview on crane behavior in Scenario Sc6 [29]

If no further work piece is detected at the pickup position or the mechanical buffer and the sliding cylinder at the stamp is empty, the plant stops operating. However, there is no separate sensor at the stack or the mechanical buffer to detect the absence of a work piece. Instead, the not sending of the 'work piece detected'-signal while the cylinder is extended, is used to conclude the absence of a further object at the pickup position and also that no further work pieces are left in the stack. To ensure that no work piece is left at the mechanical buffer, an internal status variable is used in the PLC code. If the sensor detects another work piece the process will restart at the stack.

2.8.2.3 Emergency stop behavior in Scenario Sc6

The PPU's emergency stop behavior in Scenario Sc6 is the same as in Scenario Sc3. Therefore, for a description of the PPU's emergency stop behavior, see section 2.4.2.3.

2.9 Scenario Sc7

Within the ***Scenario Sc7***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 11) working as a work piece input storage, a ***ramp*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces and a ***crane*** (no. 4) for transporting work pieces by picking and placing them between these three working positions. Moreover, the crane may use the stamp component for buffering purposes. For human interaction, an operation panel provides a start button as well

as an emergency stop. The PPU processes black plastic work pieces, white plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the ramp. In contrast, white plastic work pieces and metallic work pieces are transported from the stack to the stamp, processed there and then transported to the ramp. The models for this Scenario are freely available from [31]–[33].

2.9.1 PPU's structure in Scenario Sc7

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is described.

2.9.1.1 Stack's structure in Scenario Sc7

The ***stack*** serves as an input storage for the work pieces. It consists of a solely mechanical ***magazine*** (cf. no. 1 in Fig. 25) where the work pieces are stacked. For separating the lowermost work piece, the stack consists of a pneumatic ***cylinder*** (no. 2), which is equipped with two ***binary sensors*** indicating the positions of the cylinder, i.e. whether it is extended or retracted. The cylinder is a monostable cylinder and, hence, furthermore consists of a single ***valve*** for actuating. A digital ***micro switch*** (no. 3) intended to detect work pieces is installed at the so-called pickup position. The micro switch is activated if a work piece is pressed against it. However, due to the internal resistance of the micro switch, work pieces may be pressed back by the micro switch if not clamped properly by the cylinder. Therefore, it is essential to maintain the pressure against the micro switch in order to properly detect a work piece. Moreover, at the pickup position, an ***inductive sensor*** (no. 4) is installed for detecting whether a work piece is a metallic one or not. An ***optical sensor*** (no. 5) is intended to detect, whether a work piece has a light or a dark surface and is, hence, used for distinguishing between black and white plastic work pieces.

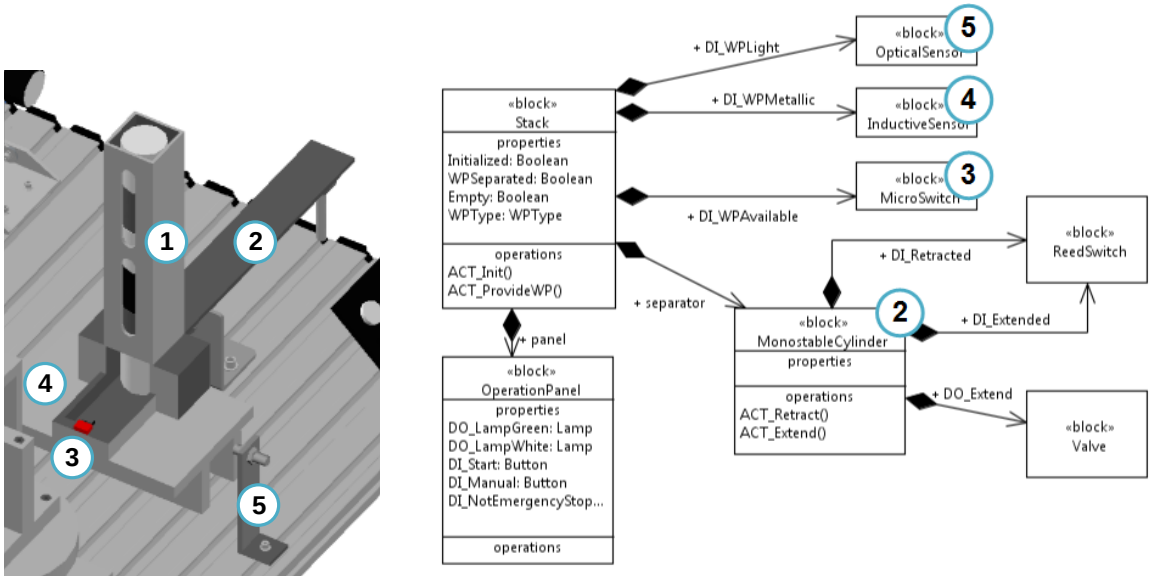

Fig. 25. Overview on the stack's architecture in Scenario Sc7 (left: graphically [31]*, right: logically* [32]*)*

A detailed overview on the stack's components as well as their respective terminal connections is shown in Table 13.

Table 13. Component list of the stack component in Scenario Sc7 [33]

Position	Resource	Clamp	Description	Component	Type
1	100	X1	Stack		
100	100A1	X1.1	Extend separator (Valve)	Stack	DO
100	100B9	X1.2	Separator is extended (Reed Switch)	Stack	DI
100	100B8	X1.3	Separator is retracted (Reed Switch)	Stack	DI
100	100S11	X1.4	WP is available (Micro Switch)	Stack	DI
100	100B10	X1.5	WP is metallic (Inductive Sensor)	Stack	DI
100	100B11	X1.6	WP is light (Optical Sensor)	Stack	DI

2.9.1.2 Crane's structure in Scenario Sc7

The mechatronic component crane of the PPU in Scenario Sc7 is the same as in Scenario Sc3. Therefore, for a description of the crane's structure, see section 2.4.1.2.

2.9.1.3 Ramp's structure in Scenario Sc7

The mechanical component ramp of the PPU in Scenario Sc7 is the same as in Scenario Sc0. Therefore, for a description of the ramp's structure, see section 2.1.1.3.

2.9.1.4 Stamp's structure in Scenario Sc7

The mechatronic component stamp of the PPU in Scenario Sc7 is the same as in Scenario Sc3. Therefore, for a description of the stamp's structure, see section 2.4.1.4.

2.9.2 PPU's behavior in Scenario Sc7

In the following subsections, the PPU's behavior, i.e. the initialization behavior, the automatic operation mode behavior and the emergency stop behavior of the PPU, is described.

2.9.2.1 Initialization behavior in Scenario Sc7

The PPU's initialization behavior in Scenario Sc7 is the same as in Scenario Sc3. Therefore, for a description of the PPU's initialization behavior, see section 2.4.2.1.

2.9.2.2 Automatic operation mode behavior in Scenario Sc7

Three kinds of work pieces are used in this Scenario and handled differently by the PPU: Black work pieces are directly transported to the ramp whereas metallic and white plastic work pieces are firstly stamped and afterwards transported to the ramp.

After startup, one of the work pieces stored in the stack is separated and pushed to the pickup position for the crane (cf. Fig. 12). In order to ensure the correct position of the work piece, the separating cylinder of the stack remains extended. For a detailed description of the stack's functionality see section 2.1.2.2. As soon as a work piece is detected by the digital micro switch at the stack's pickup position, the crane starts turning clockwise and stops at the stack's position.

The crane has to turn 90°-counterclockwise to transport black work pieces from the stack directly to the ramp. For metallic and white plastic work pieces, the crane has to turn 180°-counterclockwise to place work pieces at the stamp. An inductive sensor, whose value is true for metallic work pieces, is used to check the specific kind of the extended work piece at the extension position of the stack. An optical sensor, whose value is true for white work pieces, is used to check the specific color of the extended work piece at the pickup position. An overview on the detection of the work piece type is shown in Fig. 26. The crane then picks up the work piece by using the vacuum gripper, lifts, turns to the desired position, lowers, and deposits the work piece at the respective place. A detailed description about the pick and place functionality of the crane is described in section 2.1.2.2.

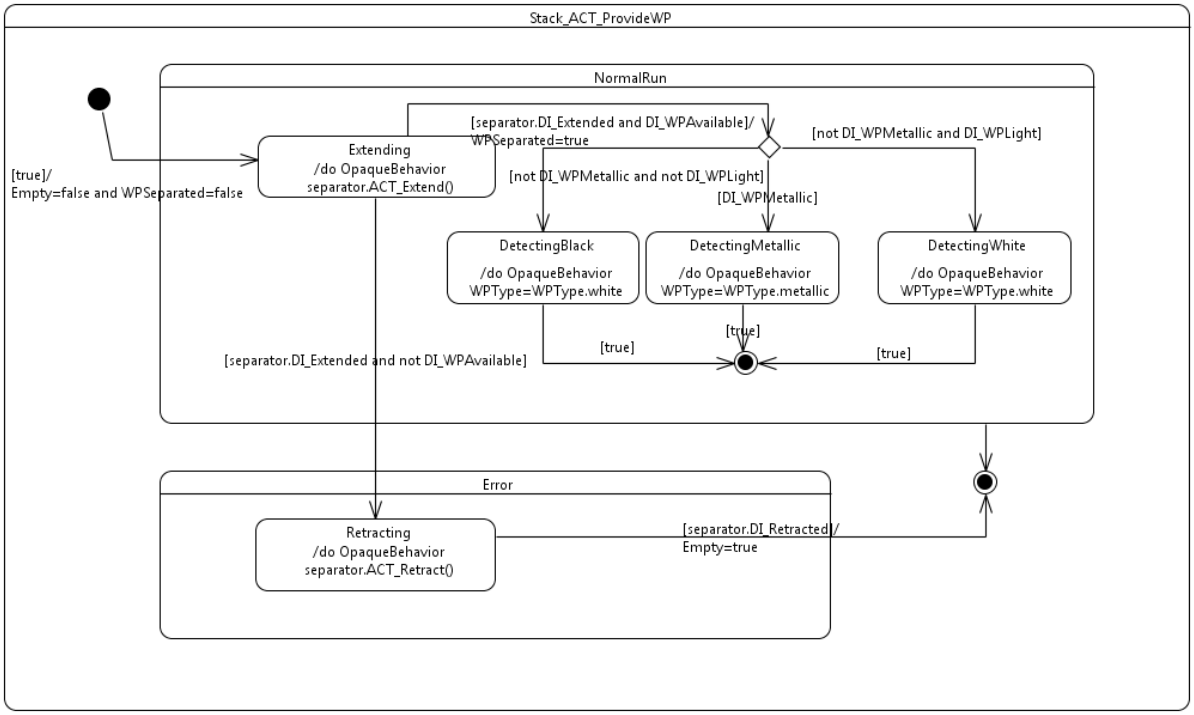

Fig. 26. Work piece detection in Scenario Sc7 [32]

Whereas black work pieces are directly transported to the ramp, metallic and white plastic work pieces run through an additional process at the stamp (cf. Fig. 27). Metallic and white plastic work pieces are delivered by the crane at the sliding cylinder of the stamp. The sliding cylinder retracts and extends the work pieces to and from beneath the stamp. As soon as the retraction is detected the stamp is lowered for a certain time and with a fixed pressure, raised by setting the 'lower command' to false, and followed by the extension of the slider. Simultaneously, after the metallic or white plastic work piece is placed in the sliding cylinder and the crane is raised again, it is checked if there is a black plastic work piece available at the stack (refer to Fig. 20). If a black work piece is available at the stack, the crane uses the stamping time and starts turning clockwise to pick up the black piece and place it at the ramp. After depositing the work piece at the ramp, it is checked if the stamping process is finished and if another black work piece is on hand at the stack. As long as the stamping process is in progress, all available black work pieces are transported to the slide. However, as soon as the stamping process is completed, the crane handles the stamped metallic or white plastic work piece from the stamp and deposits it at the ramp prior to picking up another work piece at the stack's pickup position. If the next available work piece at the stack is a metallic or white plastic piece, while the stamping is still

in progress, the crane waits at the stamp until the stamping process is finished. Depending on the time needed for the stamping progress, a certain number of black work pieces can be handled until the stamping is finished and the stamped work piece is transported. In the model seen in Fig. 20 only a single black work piece can be handled before the stamping process is complete. After the crane either placed a black, white or a metallic work piece at the ramp, the crane moves back to the pickup position at the stack or to the stamp and the work piece slides down the ramp of the output storage. See also Fig. 21 for the work piece supply.

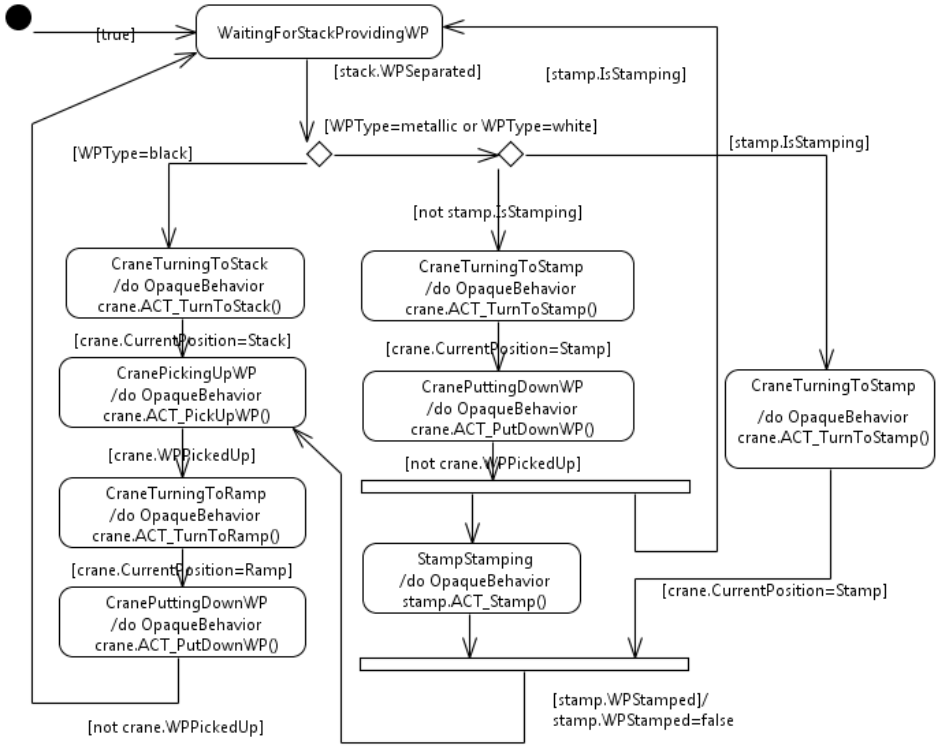

Fig. 27. Overview on crane behavior in Scenario Sc7 [32]

If no further work piece is detected at the pickup position and the sliding cylinder at the stamp is empty, the plant stops operating. However, there is no separate sensor at the stack to detect the absence of a work piece. Instead, the not sending of the 'work piece detected'-signal while the cylinder is extended, is used to conclude the absence of a further object at the pickup position and also that no further work pieces are left in the stack. If the sensor detects another work piece the process will restart at the stack.

2.9.2.3 Emergency stop behavior in Scenario Sc7

The PPU's emergency stop behavior in Scenario Sc7 is the same as in Scenario Sc3. Therefore, for a description of the PPU's emergency stop behavior, see section 2.4.2.3.

2.10 Scenario Sc8

Within the ***Scenario Sc8***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 11) working as a work piece input storage, a ***ramp*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces and a ***crane*** (no. 4) for transporting work pieces by picking and placing them between these three working positions. Moreover, the crane may use the stamp component for buffering purposes. For human interaction, an operation panel provides a start button as well

as an emergency stop. The PPU processes black plastic work pieces, white plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the ramp. In contrast, white plastic work pieces and metallic work pieces are transported from the stack to the stamp, processed there and then transported to the ramp. However, it is not sufficient to stamp the two materials – metallic and plastic work pieces – with the same pressure; hence, being able to carry out two different processes, one for each material, is necessary. Hence, white plastic and metallic work pieces are stamped using different pressure profiles. The models for this Scenario are freely available from [34]–[36].

2.10.1 PPU's structure in Scenario Sc8

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is described.

2.10.1.1 Stack's structure in Scenario Sc8

The mechatronic component stack of the PPU in Scenario Sc8 is the same as in Scenario Sc7. Therefore, for a description of the stack's structure, see section 2.9.1.1.

2.10.1.2 Crane's structure in Scenario Sc8

The mechatronic component crane of the PPU in Scenario Sc8 is the same as in Scenario Sc3. Therefore, for a description of the crane's structure, see section 2.4.1.2.

2.10.1.3 Ramp's structure in Scenario Sc8

The mechanical component ramp of the PPU in Scenario Sc8 is the same as in Scenario Sc0. Therefore, for a description of the ramp's structure, see section 2.1.1.3.

2.10.1.4 Stamp's structure in Scenario Sc8

The ***stamp*** serves as the stamping component used to stamp work pieces. In Fig. 28, an overview on the stamp component is given. The stamp contains a pneumatic ***sliding cylinder*** used to extend or retract work pieces into or from the stamp module. The sliding cylinder (no. 1) consists of a ***valve*** intended to extend or retract the cylinder as well as two binary ***end position sensors*** for detecting whether the cylinder is extended or retracted. Moreover, ***a stamping cylinder*** (no. 2) is used to stamp the respective work piece. Respective ***end position sensors*** indicate whether the stamping cylinder is lowered or raised. A ***micro switch*** (no. 3) mounted to the stamp components detects whether a work piece has been placed by the crane or not. An analogue ***pressure sensor*** (no. 4) is installed for measuring the current pressure imposed on the work piece. Moreover, a ***proportional valve*** (no. 5) is used to set a specific pressure needed for the stamping process.

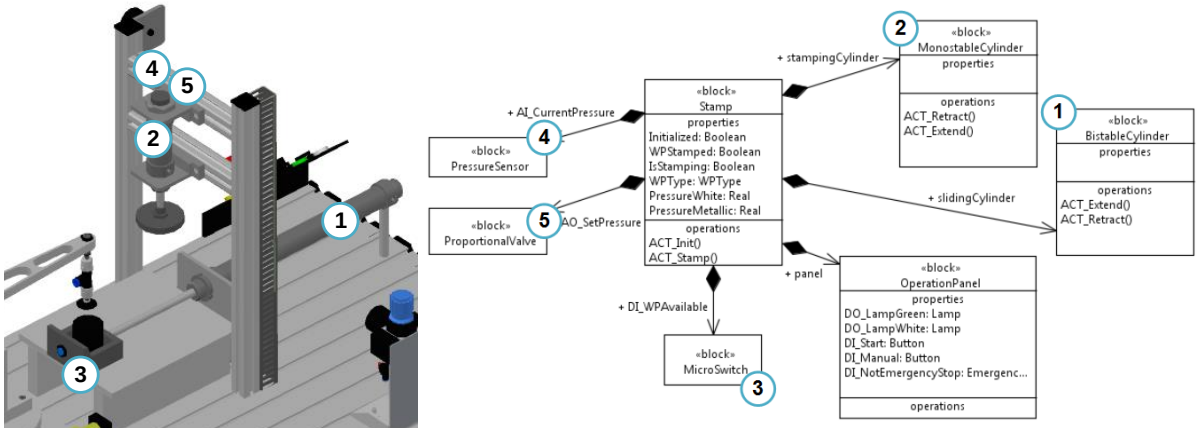

Fig. 28. Overview on the stamp component's structure in Scenario Sc8 (left: graphically [34]*, right: logically* [35]*)*

A detailed overview on the stamp's components as well as their respective terminal connections is shown in Table 14.

Table 14. Component list of the stamp component in Scenario Sc8 [36]

Position	Resource	Clamp	Description	Component	Type
3		X3	Stamp		
300	300B8	X3.1	Stamping cylinder raised (Reed Switch)	Stamp	DI
300	300B9	X3.2	Stamping cylinder lowered (Reed Switch)	Stamp	DI
300	300B7	X3.3	Sliding cylinder extended (Reed Switch)	Stamp	DI
300	300B6	X3.4	Sliding cylinder retracted (Reed Switch)	Stamp	DI
300	300S10	X3.5	WP is available (Micro Switch)	Stamp	DI
300	300A1	X3.6	Extend sliding cylinder (Valve)	Stamp	DO
300	300A2	X3.7	Retract sliding cylinder (Valve)	Stamp	DO
300	300A3	X3.8	Lower stamping cylinder with pressure (Proportional Valve)	Stamp	AO
300	300A4	X3.9	Stamping pressure (Pressure Sensor)	Stamp	AI

2.10.2 PPU's behavior in Scenario Sc8

In the following subsections, the PPU's behavior, i.e. the initialization behavior, the automatic operation mode behavior and the emergency stop behavior of the PPU, is described.

2.10.2.1 Initialization behavior in Scenario Sc8

The PPU is started by pressing the start buttons at both operation panels. In Fig. 14, the main initialization state chart is given. For initializing the stamp, the start button of the operation panel located at this component has to be pressed. For initialization, the sliding as well as stamping cylinders are retracted and extended once (cp. Fig. 29). Therein, the pressure of the proportional valve is set to a fixed value. The initialization of the other components, i.e. crane and

stack, is executed as described in section 2.1.2.1. A green lamp at each operation panel indicates a successful initialization.

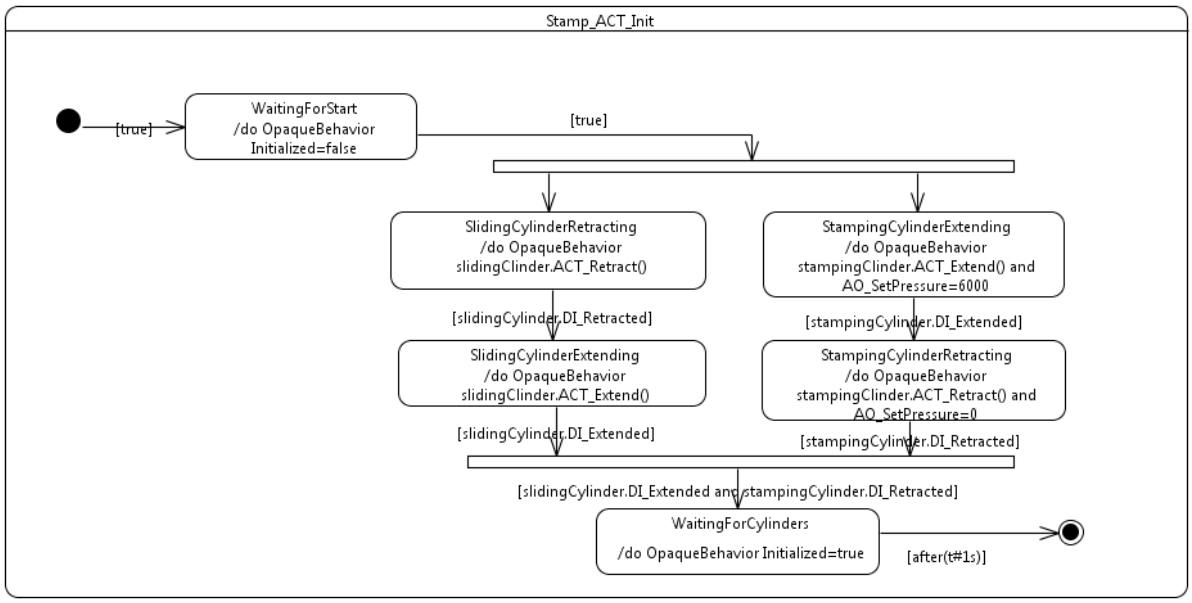

Fig. 29. Stamp's initialization procedure in Scenario Sc8 [35]

2.10.2.2 Automatic operation mode behavior in Scenario Sc8

Three kinds of work pieces are used in this Scenario and handled differently by the PPU: Black work pieces are directly transported to the ramp whereas metallic and white plastic work pieces are firstly stamped and afterwards transported to the ramp.

After startup, one of the work pieces stored in the stack is separated and pushed to the pickup position for the crane (cf. Fig. 12). In order to ensure the correct position of the work piece, the separating cylinder of the stack remains extended. For a detailed description of the stack's functionality see section 2.1.2.2. As soon as a work piece is detected by the digital micro switch at the stack's pickup position, the crane starts turning clockwise and stops at the stack's position. The crane has to turn 90°-counterclockwise to transport black work pieces from the stack directly to the ramp. For metallic and white plastic work pieces, the crane has to turn 180°-counterclockwise to place work pieces at the stamp. An inductive sensor, whose value is true for metallic work pieces, is used to check the specific kind of the extended work piece at the extension position of the stack. An optical sensor, whose value is true for white work pieces, is used to check the specific color of the extended work piece at the pickup position. An overview on the detection of the work piece type is shown in Fig. 26. The crane then picks up the work piece by using the vacuum gripper, lifts, turns to the desired position, lowers, and deposits the work piece at the respective place. A detailed description about the pick and place functionality of the crane is described in section 2.1.2.2.

Whereas black work pieces are directly transported to the ramp, metallic and white plastic work pieces run through an additional process at the stamp (cf. Fig. 27). Metallic and white plastic work pieces are delivered by the crane at the sliding cylinder of the stamp. The sliding cylinder retracts and extends the work pieces to and from beneath the stamp. As soon as the retraction is detected the stamp is lowered for a certain time and with a fixed pressure – depending on the type of work piece detected – raised by setting the 'lower command' to false, and followed by

the extension of the slider. As depicted in Fig. 30, as soon as the magazine slider is retracted, a choice for selecting the pressure profile is made. If the current work piece, which has been transported by the crane to the stamp, is metallic, the metallic pressure profile is executed. If the work piece is a white plastic one, the pressure profile for white plastic profiles is applied.

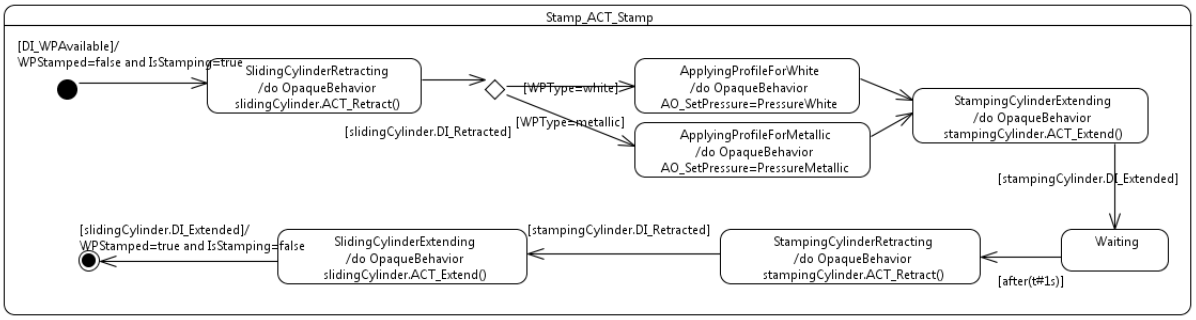

Fig. 30. Stamp's pressure profiled in Scenario Sc8 [35]

Simultaneously, after the metallic or white plastic work piece is placed in the sliding cylinder and the crane is raised again, it is checked if there is a black plastic work piece available at the stack (refer to Fig. 20). If a black work piece is available at the stack, the crane uses the stamping time and starts turning clockwise to pick up the black piece and place it at the ramp. After depositing the work piece at the ramp, it is checked if the stamping process is finished and if another black work piece is on hand at the stack. As long as the stamping process is in progress, all available black work pieces are transported to the slide. However, as soon as the stamping process is completed, the crane handles the stamped metallic or white plastic work piece from the stamp and deposits it at the ramp prior to picking up another work piece at the stack's pickup position. If the next available work piece at the stack is a metallic or white plastic piece, while the stamping is still in progress, the crane waits at the stamp until the stamping process is finished. Depending on the time needed for the stamping progress, a certain number of black work pieces can be handled until the stamping is finished and the stamped work piece is transported. In the model seen in Fig. 20 only a single black work piece can be handled before the stamping process is complete. After the crane either placed a black, white or a metallic work piece at the ramp, the crane moves back to the pickup position at the stack or to the stamp and the work piece slides down the ramp of the output storage. See also Fig. 21 for the work piece supply.

If no further work piece is detected at the pickup position and the sliding cylinder at the stamp is empty, the plant stops operating. However, there is no separate sensor at the stack to detect the absence of a work piece. Instead, the not sending of the 'work piece detected'-signal while the cylinder is extended, is used to conclude the absence of a further object at the pickup position and also that no further work pieces are left in the stack. If the sensor detects another work piece the process will restart at the stack.

2.10.2.3 Emergency stop behavior in Scenario Sc8

There are two emergency buttons (negative logic), one at the stack and one at the stamp. In a case of emergency – if at least one emergency button is pushed – the PPU is set to a safe state. In this safe state, the pneumatic cylinder of the stack is retracted, the crane stops rotating and shuts off the vacuum (a gripped work piece falls down), the stamp raises and the magazine slider is extended (cf. Fig. 17). Moreover, the pressure of the stamping cylinder is set to 0.

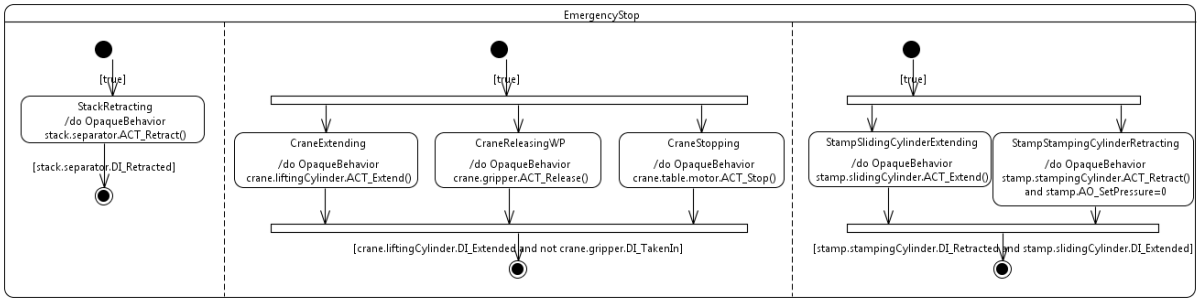

Fig. 31. Emergency stop behavior in Scenario Sc8 [35]

2.11 Scenario Sc9

Within the ***Scenario Sc9***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 32) working as a work piece input storage, a ***conveyor*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces and a ***crane*** (no. 4) for transporting work pieces by picking and placing them between these three working positions. Moreover, the crane may use the stamp component for buffering purposes. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces, white plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the conveyor. In contrast, white plastic work pieces and metallic work pieces are transported from the stack to the stamp, processed there and then transported to the conveyor. However, it is not sufficient to stamp the two materials – metallic and plastic work pieces – with the same pressure; hence, being able to carry out two different processes, one for each material, is necessary. Hence, white plastic and metallic work pieces are stamped using different pressure profiles.

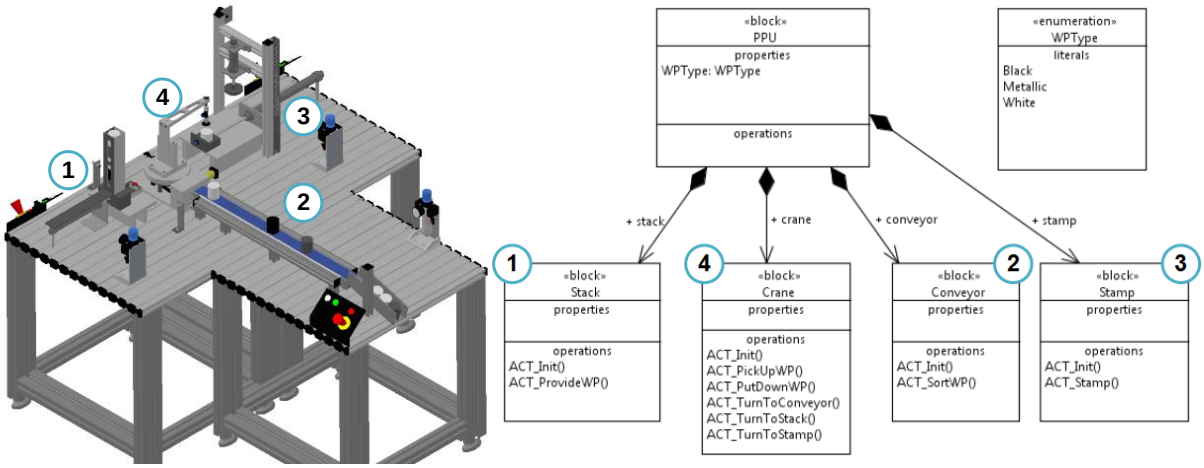

Fig. 32. Overview on the PPU in Scenario Sc9 (left: graphically [37]*, right: logically* [38]*)*

The four mechatronic components, i.e. stack, crane, conveyor and stamp (cf. Table 15), consist of sensors and actuators and require control for operation. These components are described in detail in the following. Subsequently, the initialization procedure and overall behavior of the PPU in Scenario Sc9 are presented. The models for this Scenario are freely available from [37]–[39].

Table 15. Component list of the PPU in Scenario Sc9 [39]

Position	Resource	Clamp	Description	Component	Type
1	100	X1	Stack		
2	200	X2	Crane		
3	300	X3	Stamp		
4	400	X4	Conveyor		

2.11.1 PPU's structure in Scenario Sc9

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is described.

2.11.1.1 Stack's structure in Scenario Sc9

The mechatronic component stack of the PPU in Scenario Sc9 is the same as in Scenario Sc7. Therefore, for a description of the stack's structure, see section 2.9.1.1.

2.11.1.2 Crane's structure in Scenario Sc9

The mechatronic component crane of the PPU in Scenario Sc9 is the same as in Scenario Sc3. Therefore, for a description of the crane's structure, see section 2.4.1.2.

2.11.1.3 Stamp's structure in Scenario Sc9

The mechatronic component stamp of the PPU in Scenario Sc9 is the same as in Scenario Sc8. Therefore, for a description of the stamp's structure, see section 2.10.1.4.

2.11.1.4 Conveyor's structure in Scenario Sc9

The ***conveyor*** serves as a transportation component in which work pieces are transported to a ramp. In Fig. 33, an overview on the conveyor component is given. The conveyor consist of a ***motor*** (no. 1) for realizing the translational movement of work pieces. A ***presence sensor*** (no. 2) mounted to the beginning of the conveyor detects whether a work piece was placed on the conveyor. Using a ***ramp*** mounted to the conveyor's end, work pieces can be stored.

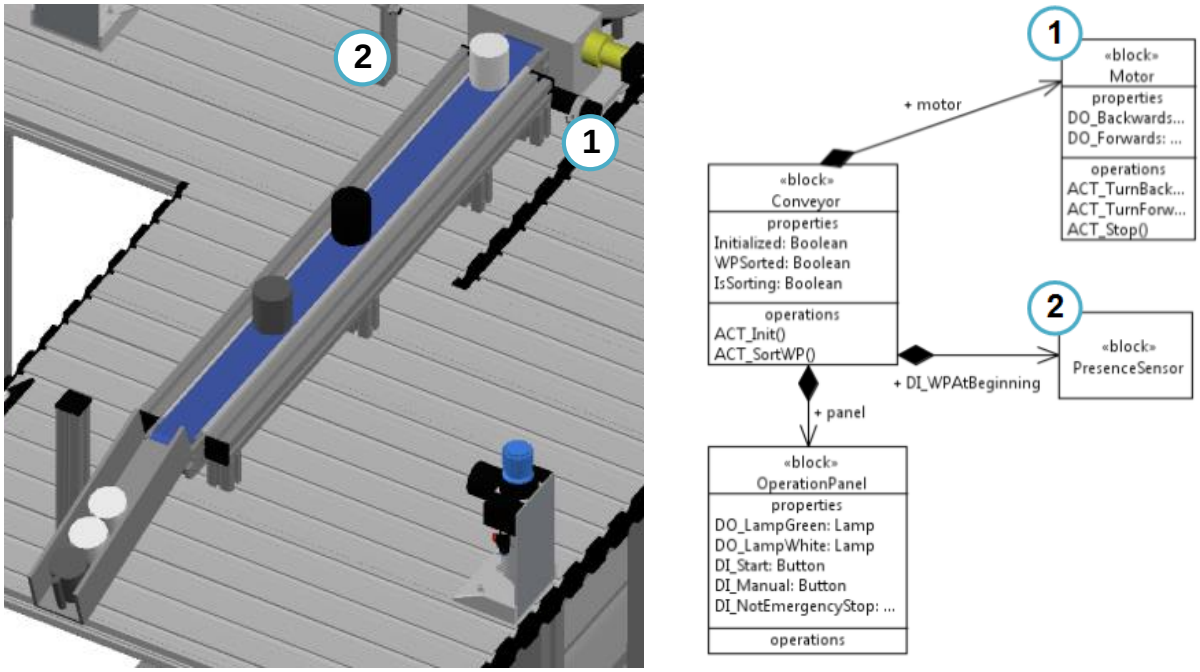

Fig. 33. Overview on the conveyor component's structure in Scenario Sc9 (left: graphically [37], *right: logically* [38]*)*

A detailed overview on the conveyor's components as well as their respective terminal connections is shown in Table 16.

Table 16. Component list of the conveyor component in Scenario Sc9 [39]

Position	Resource	Clamp	Description	Component	Type
4		X4	Conveyor		
400	400B1	X4.1	WP at conveyor's beginning (Presence Sensor)	Conveyor	DI
400	400A10	X4.2	Move conveyor backwards (Motor)	Conveyor	DO
400	400A11	X4.3	Move conveyor forwards (Motor)	Conveyor	DO

2.11.2 PPU's behavior in Scenario Sc9

In the following subsections, the PPU's behavior, i.e. the initialization behavior, the automatic operation mode behavior and the emergency stop behavior of the PPU, is described.

2.11.2.1 Initialization behavior in Scenario Sc9

The PPU is started by pressing the start buttons at all three operation panels. In Fig. 34, the main initialization state chart is given. For initializing the conveyor, the conveyor runs for a short period as shown in Fig. 35. The initialization of the other components, i.e. crane, stack and stamp, is executed as described in sections 2.1.2.1 and 2.10.2.1. A green lamp at each operation panel indicates a successful initialization.

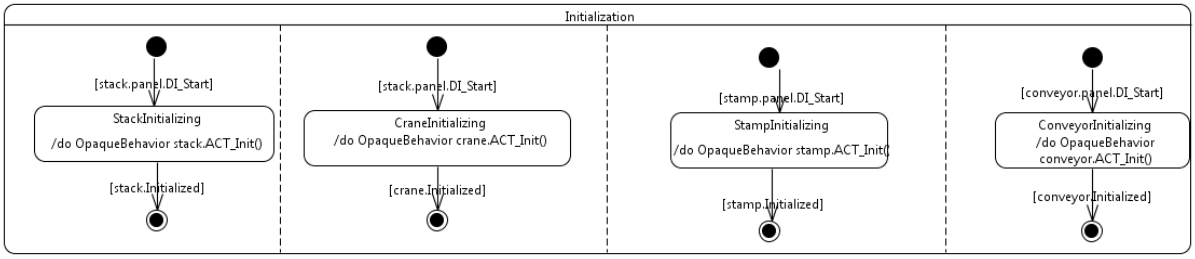

Fig. 34. Initialization procedure in Scenario Sc9 [38]

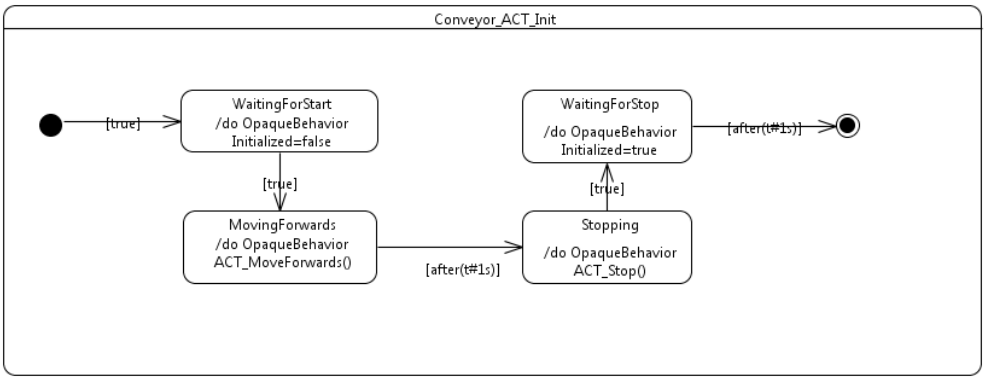

Fig. 35. Conveyor's initialization procedure in Scenario Sc9 [38]

2.11.2.2 Automatic operation mode behavior in Scenario Sc9

Three kinds of work pieces are used in this Scenario and handled differently by the PPU: Black work pieces are directly transported to the conveyor whereas metallic and white plastic work pieces are firstly stamped and afterwards transported to the conveyor.

After startup, one of the work pieces stored in the stack is separated and pushed to the pickup position for the crane (cf. Fig. 12). In order to ensure the correct position of the work piece, the separating cylinder of the stack remains extended. For a detailed description of the stack's functionality see section 2.1.2.2. As soon as a work piece is detected by the digital micro switch at the stack's pickup position, the crane starts turning clockwise and stops at the stack's position. The crane has to turn 90°-counterclockwise to transport black work pieces from the stack directly to the conveyor. For metallic and white plastic work pieces, the crane has to turn 180°-counterclockwise to place work pieces at the stamp. An inductive sensor, whose value is true for metallic work pieces, is used to check the specific kind of the extended work piece at the extension position of the stack. An optical sensor, whose value is true for white work pieces, is used to check the specific color of the extended work piece at the pickup position. An overview on the detection of the work piece type is shown in Fig. 26. The crane then picks up the work piece by using the vacuum gripper, lifts, turns to the desired position, lowers, and deposits the work piece at the respective place. A detailed description about the pick and place functionality of the crane is described in section 2.1.2.2.

Whereas black work pieces are directly transported to the conveyor, metallic and white plastic work pieces run through an additional process at the stamp (cf. Fig. 27). Metallic and white plastic work pieces are delivered by the crane at the sliding cylinder of the stamp. The sliding cylinder retracts and extends the work pieces to and from beneath the stamp. As soon as the

retraction is detected the stamp is lowered for a certain time and with a fixed pressure – depending on the type of work piece detected – raised by setting the 'lower command' to false, and followed by the extension of the slider. As depicted in Fig. 30, as soon as the magazine slider is retracted, a choice for selecting the pressure profile is made. If the current work piece, which has been transported by the crane to the stamp, is metallic, the metallic pressure profile is executed. If the work piece is a white plastic one, the pressure profile for white plastic profiles is applied.

Simultaneously, after the metallic or white plastic work piece is placed in the sliding cylinder and the crane is raised again, it is checked if there is a black plastic work piece available at the stack (refer to Fig. 20). If a black work piece is available at the stack, the crane uses the stamping time and starts turning clockwise to pick up the black piece and place it at the conveyor. After depositing the work piece at the conveyor, it is checked if the stamping process is finished and if another black work piece is on hand at the stack. As long as the stamping process is in progress, all available black work pieces are transported to the slide. However, as soon as the stamping process is completed, the crane handles the stamped metallic or white plastic work piece from the stamp and deposits it at the conveyor prior to picking up another work piece at the stack's pickup position. If the next available work piece at the stack is a metallic or white plastic piece, while the stamping is still in progress, the crane waits at the stamp until the stamping process is finished. Depending on the time needed for the stamping progress, a certain number of black work pieces can be handled until the stamping is finished and the stamped work piece is transported. In the model seen in Fig. 20 only a single black work piece can be handled before the stamping process is complete. After the crane either placed a black, white or a metallic work piece at the conveyor, the crane moves back to the pickup position at the stack or to the stamp. See also Fig. 21 for the work piece supply. Once the work piece is placed on the conveyor, it is detected by a sensor and the conveyor starts running for a certain time and transports the work piece to the ramp, where it slides down (cf. Fig. 36). Depending on the length and the speed of the conveyor, a timer is set to ensure the conveyor is running long enough for the work piece to reach the ramp.

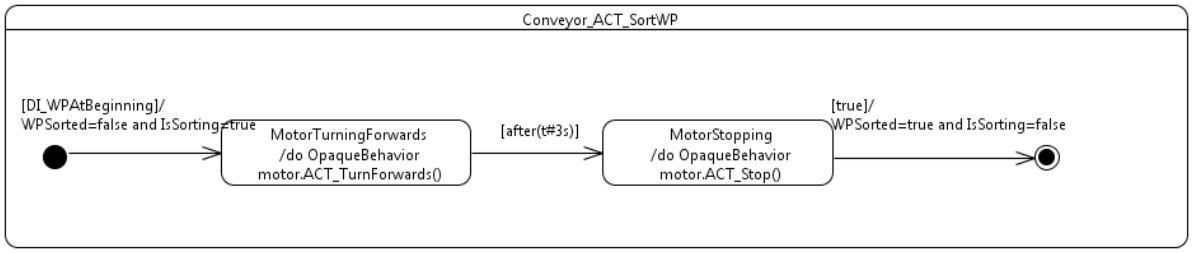

Fig. 36. Conveyor behavior in Scenario Sc9 [38]

If no further work piece is detected at the pickup position, the sliding cylinder at the stamp is empty and no work piece is present at the conveyor, the plant stops operating. However, there is no separate sensor at the stack to detect the absence of a work piece. Instead, the not sending of the 'work piece detected'-signal while the cylinder is extended, is used to conclude the absence of a further object at the pickup position and also that no further work pieces are left in the stack. If the sensor detects another work piece the process will restart at the stack.

2.11.2.3 Emergency stop behavior in Scenario Sc9

There are three emergency buttons (negative logic), one at the stack, one at the stamp and one at the conveyor. In a case of emergency – if at least one emergency button is pushed – the PPU is set to a safe state. In this safe state, the pneumatic cylinder of the stack is retracted, the crane stops rotating and shuts off the vacuum (a gripped work piece falls down), the stamp raises and the magazine slider is extended (cf. Fig. 17). Moreover, the pressure of the stamping cylinder is set to 0 and the conveyor is stopped (cf. Fig. 37).

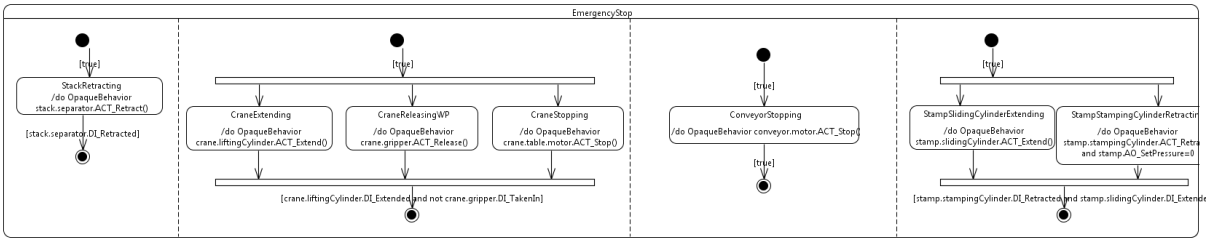

Fig. 37. Emergency stop behavior in Scenario Sc9 [38]

2.12 Scenario Sc10

Within the ***Scenario Sc10***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 38) working as a work piece input storage, a ***conveyor*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces and a ***crane*** (no. 4) for transporting work pieces by picking and placing them between these three working positions. Moreover, the crane may use the stamp component for buffering purposes. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces, white plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the conveyor. In contrast, white plastic work pieces and metallic work pieces are transported from the stack to the stamp, processed there and then transported to the conveyor. However, it is not sufficient to stamp the two materials – metallic and plastic work pieces – with the same pressure; hence, being able to carry out two different processes, one for each material, is necessary. Hence, white plastic and metallic work pieces are stamped using different pressure profiles. Within the conveyor, three ramps are used as output storages. Two of the ramps are filled using respective pushing cylinders. A third ramp mounted to the end of the conveyor is filled by translationally moving the work piece using the conveyor. The ramps shall be filled one by one – starting with the one at the end of the conveyor, then the mid-ramp and finally the ramp at the beginning of the conveyor.

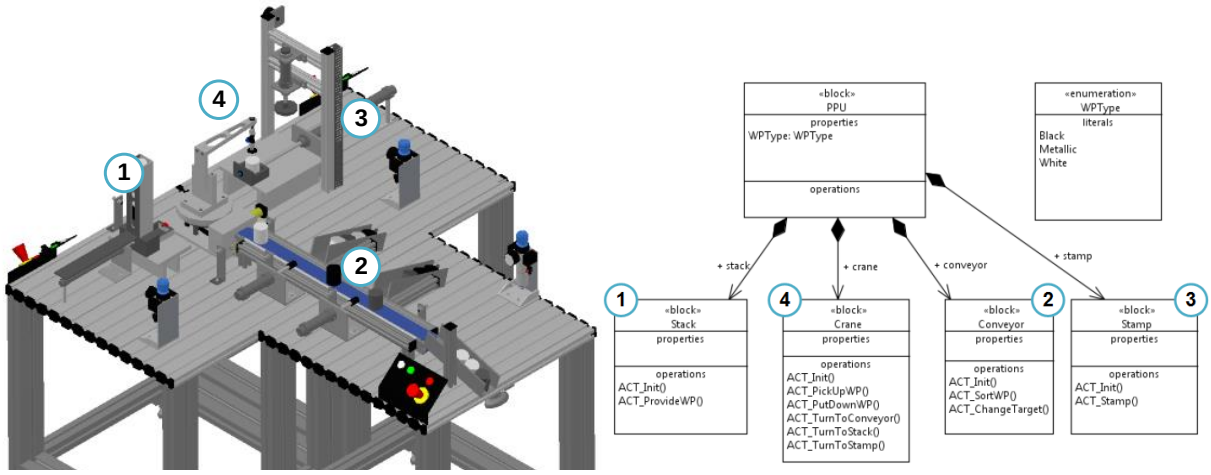

Fig. 38. Overview on the PPU in Scenario Sc10 (left: graphically [40], *right: logically* [41]*)*

The four mechatronic components, i.e. stack, crane, conveyor and stamp (cf. Table 15), consist of sensors and actuators and require control for operation. These components are described in detail in the following. Subsequently, the initialization procedure and overall behavior of the PPU in Scenario Sc10 are presented. The models for this Scenario are freely available from [40]–[42].

2.12.1 PPU's structure in Scenario Sc10

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is described.

2.12.1.1 Stack's structure in Scenario Sc10

The mechatronic component stack of the PPU in Scenario Sc10 is the same as in Scenario Sc7. Therefore, for a description of the stack's structure, see section 2.9.1.1.

2.12.1.2 Crane's structure in Scenario Sc10

The mechatronic component crane of the PPU in Scenario Sc10 is the same as in Scenario Sc3. Therefore, for a description of the crane's structure, see section 2.4.1.2.

2.12.1.3 Stamp's structure in Scenario Sc10

The mechatronic component stamp of the PPU in Scenario Sc10 is the same as in Scenario Sc8. Therefore, for a description of the stamp's structure, see section 2.10.1.4.

2.12.1.4 Conveyor's structure in Scenario Sc10

The ***conveyor*** serves as a transportation component in which work pieces are transported into three ramps. In Fig. 39, an overview on the conveyor component is given. The conveyor consist of a ***motor*** (no. 1) for realizing the translational movement of work pieces. A ***presence sensor*** (no. 2) mounted to the beginning of the conveyor detects whether a work piece was placed on the conveyor. ***Three ramps*** are mounted to the conveyor. For the ramps at the beginning as well as at the center of the conveyor, respective ***pushing cylinders*** (no. 3) are installed for pushing work pieces into the ramps. These pushing cylinders contain ***valves*** for extending or retracting

the cylinders as well as ***end position sensors*** for detecting whether the cylinder is extended or retracted. ***Optical sensors*** (no. 4) detect whether a work piece is at the ramp or not.

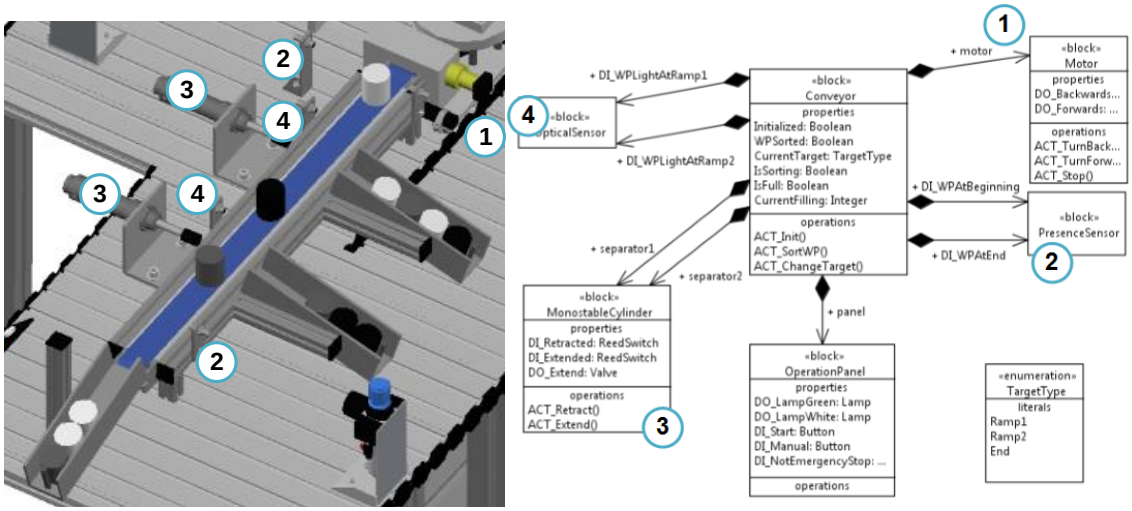

Fig. 39. Overview on the conveyor component's structure in Scenario Sc10 (left: graphically [40], *right: logically* [41]*)*

A detailed overview on the conveyor's components as well as their respective terminal connections is shown in Table 17.

Table 17. Component list of the conveyor component in Scenario Sc10 [42]

Position	Resource	Clamp	Description	Component	Type
4		X4	Conveyor		
400	400B1	X4.1	WP at conveyor's beginning (Presence Sensor)	Conveyor	DI
400	400A10	X4.2	Move conveyor backwards (Motor)	Conveyor	DO
400	400A11	X4.3	Move conveyor forwards (Motor)	Conveyor	DO
400	400B4	X4.4	Light WP at ramp 1 (Optical Sensor)	Conveyor	DI
400	400B6	X4.5	Light WP at ramp 2 (Optical Sensor)	Conveyor	DI
400	400B7	X4.6	WP at conveyor's end (Presence Sensor)	Conveyor	DI
400	400B8	X4.7	Separator at ramp 1 extended (Reed Switch)	Conveyor	DI
400	400B9	X4.8	Separator at ramp 1 retracted (Reed Switch)	Conveyor	DI
400	400B10	X4.9	Separator at ramp 2 extended (Reed Switch)	Conveyor	DI
400	400B11	X4.10	Separator at ramp 2 retracted (Reed Switch)	Conveyor	DI
400	400A12	X4.11	Extend separator at ramp 1 (Valve)	Conveyor	DO
400	400A13	X4.12	Extend separator at ramp 2 (Valve)	Conveyor	DO

2.12.2 PPU's behavior in Scenario Sc10

In the following subsections, the PPU's behavior, i.e. the initialization behavior, the automatic operation mode behavior and the emergency stop behavior of the PPU, is described.

2.12.2.1 Initialization behavior in Scenario Sc10

The PPU's initialization behavior in Scenario Sc10 is the same as in Scenario Sc9. Therefore, for a description of the PPU's initialization behavior, see section 2.11.2.1.

2.12.2.2 Automatic operation mode behavior in Scenario Sc10

Three kinds of work pieces are used in this Scenario and handled differently by the PPU: Black work pieces are directly transported to the conveyor whereas metallic and white plastic work pieces are firstly stamped and afterwards transported to the conveyor.

After startup, one of the work pieces stored in the stack is separated and pushed to the pickup position for the crane (cf. Fig. 12). In order to ensure the correct position of the work piece, the separating cylinder of the stack remains extended. For a detailed description of the stack's functionality see section 2.1.2.2. As soon as a work piece is detected by the digital micro switch at the stack's pickup position, the crane starts turning clockwise and stops at the stack's position. The crane has to turn 90°-counterclockwise to transport black work pieces from the stack directly to the conveyor. For metallic and white plastic work pieces, the crane has to turn 180°-counterclockwise to place work pieces at the stamp. An inductive sensor, whose value is true for metallic work pieces, is used to check the specific kind of the extended work piece at the extension position of the stack. An optical sensor, whose value is true for white work pieces, is used to check the specific color of the extended work piece at the pickup position. An overview on the detection of the work piece type is shown in Fig. 26. The crane then picks up the work piece by using the vacuum gripper, lifts, turns to the desired position, lowers, and deposits the work piece at the respective place. A detailed description about the pick and place functionality of the crane is described in section 2.1.2.2.

Whereas black work pieces are directly transported to the conveyor, metallic and white plastic work pieces run through an additional process at the stamp (cf. Fig. 27). Metallic and white plastic work pieces are delivered by the crane at the sliding cylinder of the stamp. The sliding cylinder retracts and extends the work pieces to and from beneath the stamp. As soon as the retraction is detected the stamp is lowered for a certain time and with a fixed pressure – depending on the type of work piece detected – raised by setting the 'lower command' to false, and followed by the extension of the slider. As depicted in Fig. 30, as soon as the magazine slider is retracted, a choice for selecting the pressure profile is made. If the current work piece, which has been transported by the crane to the stamp, is metallic, the metallic pressure profile is executed. If the work piece is a white plastic one, the pressure profile for white plastic profiles is applied.

Simultaneously, after the metallic or white plastic work piece is placed in the sliding cylinder and the crane is raised again, it is checked if there is a black plastic work piece available at the stack (refer to Fig. 20). If a black work piece is available at the stack, the crane uses the stamping time and starts turning clockwise to pick up the black piece and place it at the conveyor. After depositing the work piece at the conveyor, it is checked if the stamping process is finished and if another black work piece is on hand at the stack. As long as the stamping process is in progress, all available black work pieces are transported to the slide. However, as soon as the

stamping process is completed, the crane handles the stamped metallic or white plastic work piece from the stamp and deposits it at the conveyor prior to picking up another work piece at the stack's pickup position. If the next available work piece at the stack is a metallic or white plastic piece, while the stamping is still in progress, the crane waits at the stamp until the stamping process is finished. Depending on the time needed for the stamping progress, a certain number of black work pieces can be handled until the stamping is finished and the stamped work piece is transported. In the model seen in Fig. 20 only a single black work piece can be handled before the stamping process is complete. After the crane either placed a black, white or a metallic work piece at the conveyor, the crane moves back to the pickup position at the stack or to the stamp. See also Fig. 21 for the work piece supply. Once the work piece is placed on the conveyor, it is detected by a sensor. The ramp at the end of the conveyor is filled by simply transporting the work pieces all the way to the ramp where they slide down as soon as they reach the end. Filling up the two lateral ramps is done utilizing the two pneumatic cylinders set up next to the conveyor. Once the ramp at the end is completely filled with work pieces, the mid-ramp is used as an output storage. An optical sensor detects the work piece being transported by the running conveyor and controls the pneumatic cylinder, which pushes – by extending – the piece down the ramp. Like all the other pneumatic cylinders used in the plant, the two cylinders acting as pushers consist each of two binary position sensors (one at the front and one at the rear), which detect if the pneumatic cylinder is extended or retracted. Refer to Fig. 40 for the conveyor's behavior.

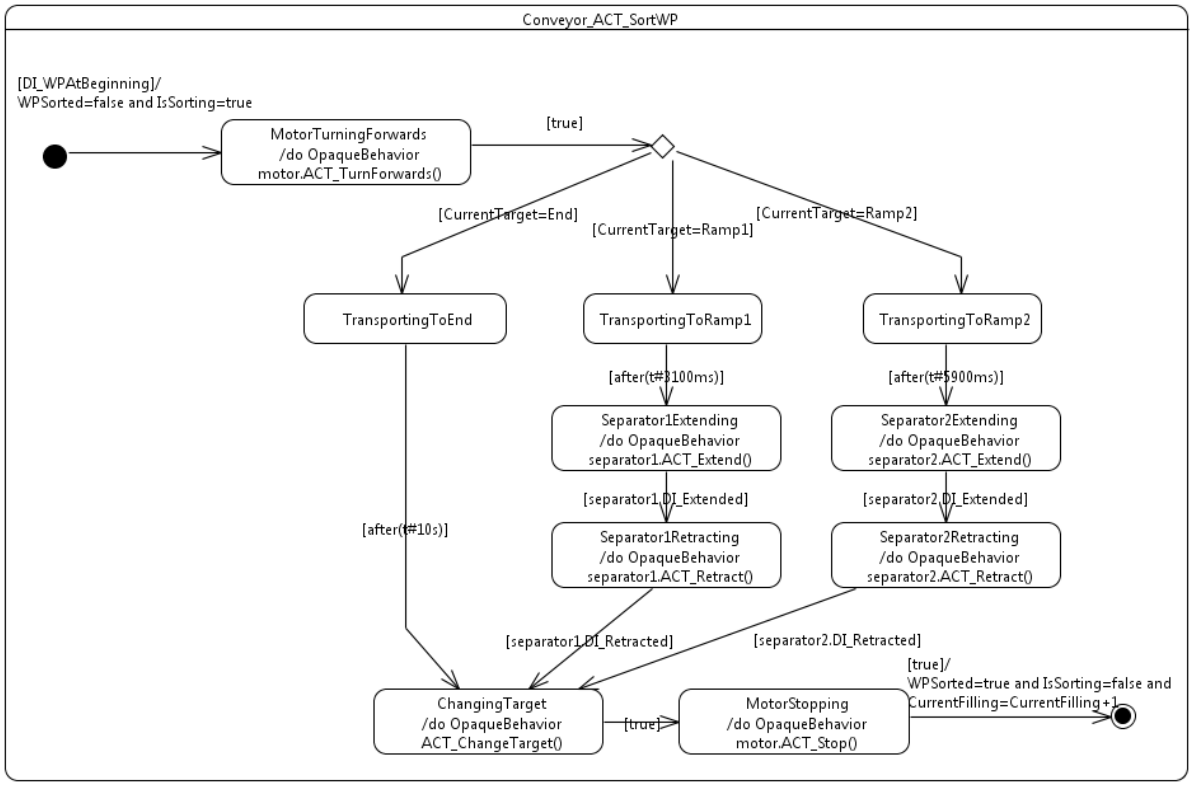

Fig. 40. Conveyor behavior in Scenario Sc10 [41]

If no further work piece is detected at the pickup position, the sliding cylinder at the stamp is empty and no work piece is present at the conveyor, the plant stops operating. However, there is no separate sensor at the stack to detect the absence of a work piece. Instead, the not sending

of the ‘work piece detected’-signal while the cylinder is extended, is used to conclude the absence of a further object at the pickup position and also that no further work pieces are left in the stack. If the sensor detects another work piece the process will restart at the stack.

2.12.2.3 Emergency stop behavior in Scenario Sc10

There are three emergency buttons (negative logic), one at the stack, one at the stamp and one at the conveyor. In a case of emergency – if at least one emergency button is pushed – the PPU is set to a safe state. In this safe state, the pneumatic cylinder of the stack is retracted, the crane stops rotating and shuts off the vacuum (a gripped work piece falls down), the stamp raises and the magazine slider is extended (cf. Fig. 17). Moreover, the pressure of the stamping cylinder is set to 0, the conveyor is stopped and the pushing cylinders at the conveyor are retracted (cf. Fig. 41).

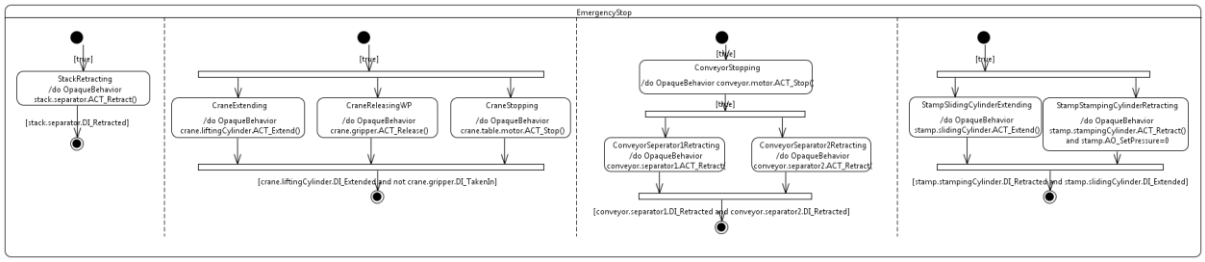

Fig. 41. Emergency stop behavior in Scenario Sc10 [41]

2.13 Scenario Sc11

Within the ***Scenario Sc11***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 38) working as a work piece input storage, a ***conveyor*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces and a ***crane*** (no. 4) for transporting work pieces by picking and placing them between these three working positions. Moreover, the crane may use the stamp component for buffering purposes. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces, white plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the conveyor. In contrast, white plastic work pieces and metallic work pieces are transported from the stack to the stamp, processed there and then transported to the conveyor. However, it is not sufficient to stamp the two materials – metallic and plastic work pieces – with the same pressure; hence, being able to carry out two different processes, one for each material, is necessary. Hence, white plastic and metallic work pieces are stamped using different pressure profiles. Within the conveyor, three ramps are used as output storages. Two of the ramps are filled using respective pushing cylinders. A third ramp mounted to the end of the conveyor is filled by translationally moving the work piece using the conveyor. Within the first ramp, white work pieces are stored. Within the second ramp, metal work pieces are stored and within the third ramp, black work pieces are stored. The models for this Scenario are freely available from [43]–[45].

2.13.1 PPU’s structure in Scenario Sc11

In the following subsections, the PPU’s structure, i.e. the composition of the PPU from its components, is described.

2.13.1.1 Stack's structure in Scenario Sc11

The mechatronic component stack of the PPU in Scenario Sc11 is the same as in Scenario Sc7. Therefore, for a description of the stack's structure, see section 2.9.1.1.

2.13.1.2 Crane's structure in Scenario Sc11

The mechatronic component crane of the PPU in Scenario Sc11 is the same as in Scenario Sc3. Therefore, for a description of the crane's structure, see section 2.4.1.2.

2.13.1.3 Stamp's structure in Scenario Sc11

The mechatronic component stamp of the PPU in Scenario Sc11 is the same as in Scenario Sc8. Therefore, for a description of the stamp's structure, see section 2.10.1.4.

2.13.1.4 Conveyor's structure in Scenario Sc11

The ***conveyor*** serves as a transportation component in which work pieces are transported into three ramps. In Fig. 39, an overview on the conveyor component is given. The conveyor consist of a ***motor*** (no. 1) for realizing the translational movement of work pieces. A ***presence sensor*** (no. 2) mounted to the beginning and the end of the conveyor detects whether a work piece was placed on the conveyor. ***Three ramps*** are mounted to the conveyor. For the ramps at the beginning as well as at the center of the conveyor, respective ***pushing cylinders*** (no. 3) are installed for pushing work pieces into the ramps. These pushing cylinders contain ***valves*** for extending or retracting the cylinders as well as ***end position sensors*** for detecting whether the cylinder is extended or retracted. ***Optical sensors*** (no. 4) detect whether a work piece is at the ramp or not. ***Inductive sensors*** (no. 5) detect whether a work piece is a metallic one or not.

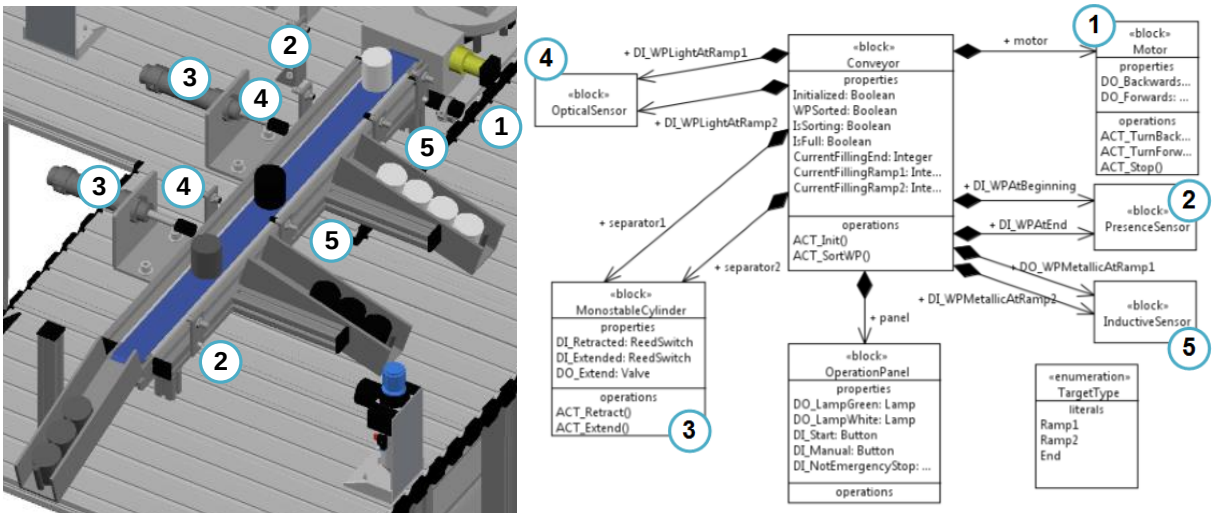

Fig. 42. Overview on the conveyor component's structure in Scenario Sc11 (left: graphically [43], *right: logically* [44]*)*

A detailed overview on the conveyor's components as well as their respective terminal connections is shown in Table 18.

Table 18. Component list of the conveyor component in Scenario Sc11 [45]

Position	Resource	Clamp	Description	Component	Type
4		X4	Conveyor		
400	400B1	X4.1	WP at conveyor's beginning (Presence Sensor)	Conveyor	DI
400	400A10	X4.2	Move conveyor backwards (Motor)	Conveyor	DO
400	400A11	X4.3	Move conveyor forwards (Motor)	Conveyor	DO
400	400B4	X4.4	Light WP at ramp 1 (Optical Sensor)	Conveyor	DI
400	400B6	X4.5	Light WP at ramp 2 (Optical Sensor)	Conveyor	DI
400	400B7	X4.6	WP at conveyor's end (Presence Sensor)	Conveyor	DI
400	400B8	X4.7	Separator at ramp 1 extended (Reed Switch)	Conveyor	DI
400	400B9	X4.8	Separator at ramp 1 retracted (Reed Switch)	Conveyor	DI
400	400B10	X4.9	Separator at ramp 2 extended (Reed Switch)	Conveyor	DI
400	400B11	X4.10	Separator at ramp 2 retracted (Reed Switch)	Conveyor	DI
400	400A12	X4.11	Extend separator at ramp 1 (Valve)	Conveyor	DO
400	400A13	X4.12	Extend separator at ramp 2 (Valve)	Conveyor	DO
400	400B3	X4.13	Metallic WP at ramp 1 (Inductive Sensor)	Conveyor	DI
400	400B5	X4.14	Metallic WP at ramp 2 (Inductive Sensor)	Conveyor	DI

2.13.2 PPU's behavior in Scenario Sc11

In the following subsections, the PPU's behavior, i.e. the initialization behavior, the automatic operation mode behavior and the emergency stop behavior of the PPU, is described.

2.13.2.1 Initialization behavior in Scenario Sc11

The PPU's initialization behavior in Scenario Sc11 is the same as in Scenario Sc9. Therefore, for a description of the PPU's initialization behavior, see section 2.11.2.1.

2.13.2.2 Automatic operation mode behavior in Scenario Sc11

Three kinds of work pieces are used in this Scenario and handled differently by the PPU: Black work pieces are directly transported to the conveyor whereas metallic and white plastic work pieces are firstly stamped and afterwards transported to the conveyor.

After startup, one of the work pieces stored in the stack is separated and pushed to the pickup position for the crane (cf. Fig. 12). In order to ensure the correct position of the work piece, the

separating cylinder of the stack remains extended. For a detailed description of the stack's functionality see section 2.1.2.2. As soon as a work piece is detected by the digital micro switch at the stack's pickup position, the crane starts turning clockwise and stops at the stack's position. The crane has to turn 90°-counterclockwise to transport black work pieces from the stack directly to the conveyor. For metallic and white plastic work pieces, the crane has to turn 180°-counterclockwise to place work pieces at the stamp. An inductive sensor, whose value is true for metallic work pieces, is used to check the specific kind of the extended work piece at the extension position of the stack. An optical sensor, whose value is true for white work pieces, is used to check the specific color of the extended work piece at the pickup position. An overview on the detection of the work piece type is shown in Fig. 26. The crane then picks up the work piece by using the vacuum gripper, lifts, turns to the desired position, lowers, and deposits the work piece at the respective place. A detailed description about the pick and place functionality of the crane is described in section 2.1.2.2.

Whereas black work pieces are directly transported to the conveyor, metallic and white plastic work pieces run through an additional process at the stamp (cf. Fig. 27). Metallic and white plastic work pieces are delivered by the crane at the sliding cylinder of the stamp. The sliding cylinder retracts and extends the work pieces to and from beneath the stamp. As soon as the retraction is detected the stamp is lowered for a certain time and with a fixed pressure – depending on the type of work piece detected – raised by setting the 'lower command' to false, and followed by the extension of the slider. As depicted in Fig. 30, as soon as the magazine slider is retracted, a choice for selecting the pressure profile is made. If the current work piece, which has been transported by the crane to the stamp, is metallic, the metallic pressure profile is executed. If the work piece is a white plastic one, the pressure profile for white plastic profiles is applied.

Simultaneously, after the metallic or white plastic work piece is placed in the sliding cylinder and the crane is raised again, it is checked if there is a black plastic work piece available at the stack (refer to Fig. 20). If a black work piece is available at the stack, the crane uses the stamping time and starts turning clockwise to pick up the black piece and place it at the conveyor. After depositing the work piece at the conveyor, it is checked if the stamping process is finished and if another black work piece is on hand at the stack. As long as the stamping process is in progress, all available black work pieces are transported to the slide. However, as soon as the stamping process is completed, the crane handles the stamped metallic or white plastic work piece from the stamp and deposits it at the conveyor prior to picking up another work piece at the stack's pickup position. If the next available work piece at the stack is a metallic or white plastic piece, while the stamping is still in progress, the crane waits at the stamp until the stamping process is finished. Depending on the time needed for the stamping progress, a certain number of black work pieces can be handled until the stamping is finished and the stamped work piece is transported. In the model seen in Fig. 20 only a single black work piece can be handled before the stamping process is complete. After the crane either placed a black, white or a metallic work piece at the conveyor, the crane moves back to the pickup position at the stack or to the stamp. See also Fig. 21 for the work piece supply. Once the work piece is placed on the conveyor, it is detected by a sensor. As soon as the work piece reaches the first pair of opposing optical (diffuse sensor – true for light reflecting pieces) and inductive (true for metallic) sensors, located shortly before the first ramp, the specific kind of the work piece is checked. If a white work piece is detected (optical true, inductive false) the pneumatic cylinder opposing the first ramp is extended a certain time after detecting the work piece (the time depends on the conveyor

belt speed which is set manually) and directly retracted after full extension. By extending the cylinder, the work piece on the conveyor is pushed down the first ramp, where the white pieces are stored. If a metallic work piece is detected (optical true, inductive true) the pusher opposing the first ramp remains in its retracted position and the work piece passes it. Next, the work piece passes the second pair of opposing optical and inductive sensors, which are located shortly before the second ramp and the type of the work piece is checked again. If a metallic work piece is detected (optical true, inductive true) the pusher opposing the second ramp will be extended a certain time after detection (as before depending on the conveyor belt speed) and directly retracted after full extension. Black work pieces pass both of the lateral ramps without extension of the pneumatic cylinders and are transported to the ramp at the very end of the conveyor. Refer to Fig. 43 for the conveyor's behavior.

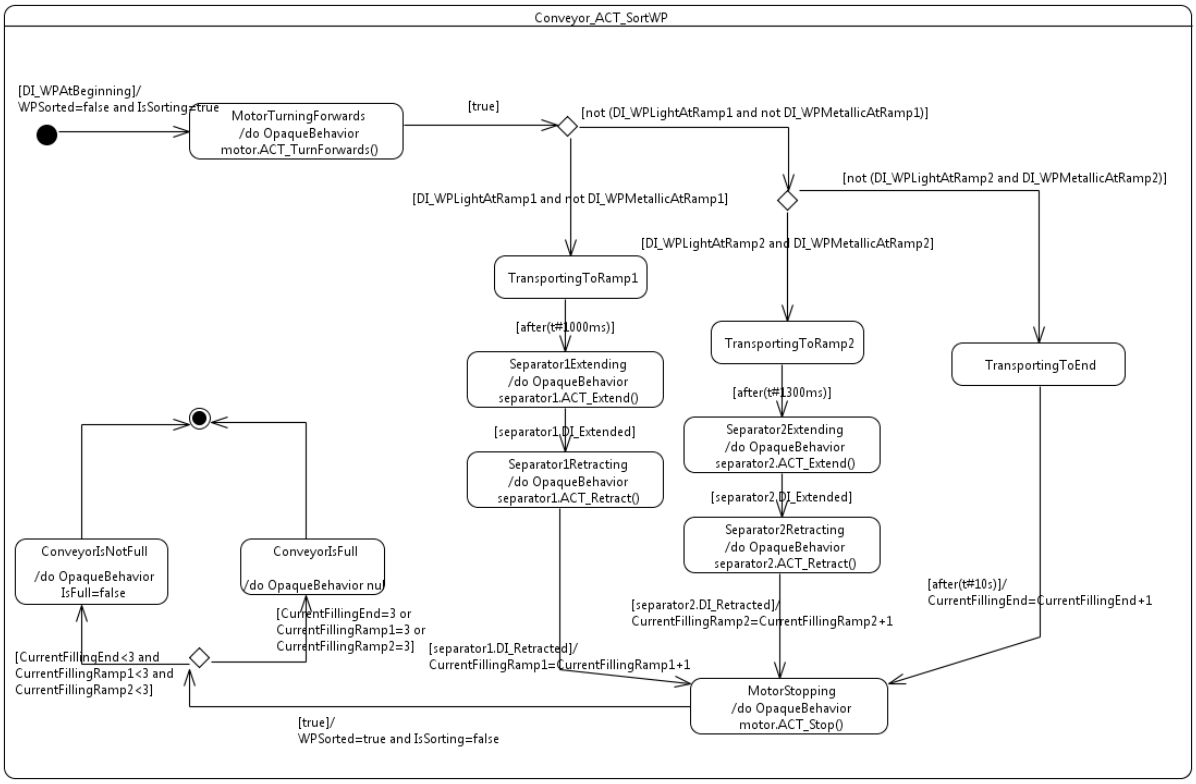

Fig. 43. Conveyor behavior in Scenario Sc11 [44]

If no further work piece is detected at the pickup position, the sliding cylinder at the stamp is empty and no work piece is present at the conveyor, the plant stops operating. However, there is no separate sensor at the stack to detect the absence of a work piece. Instead, the not sending of the 'work piece detected'-signal while the cylinder is extended, is used to conclude the absence of a further object at the pickup position and also that no further work pieces are left in the stack. If the sensor detects another work piece the process will restart at the stack.

2.13.2.3 Emergency stop behavior in Scenario Sc11

The PPU's emergency stop behavior in Scenario Sc11 is the same as in Scenario Sc10. Therefore, for a description of the PPU's emergency stop behavior, see section 2.12.2.3.

2.14 Scenario Sc12

Within the ***Scenario Sc12***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 38) working as a work piece input storage, a ***conveyor*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces and a ***crane*** (no. 4) for transporting work pieces by picking and placing them between these three working positions. Moreover, the crane may use the stamp component for buffering purposes. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces, white plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the conveyor. In contrast, white plastic work pieces and metallic work pieces are transported from the stack to the stamp, processed there and then transported to the conveyor. However, it is not sufficient to stamp the two materials – metallic and plastic work pieces – with the same pressure; hence, being able to carry out two different processes, one for each material, is necessary. Hence, white plastic and metallic work pieces are stamped using different pressure profiles. Within the conveyor, three ramps are used as output storages. Two of the ramps are filled using respective pushing cylinders. A third ramp mounted to the end of the conveyor is filled by translationally moving the work piece using the conveyor. Each of the ramps shall have the same sorting order of work pieces – mixed work pieces shall henceforth be stored within the ramps. The models for this Scenario are freely available from [46]–[48].

2.14.1 PPU's structure in Scenario Sc12

The PPU's structure in Scenario Sc12 is the same as in Scenario Sc11. Therefore, for a description of the PPU's structure, see section 2.13.1.

2.14.2 PPU's behavior in Scenario Sc12

In the following subsections, the PPU's behavior, i.e. the initialization behavior, the automatic operation mode behavior and the emergency stop behavior of the PPU, is described.

2.14.2.1 Initialization behavior in Scenario Sc12

The PPU's initialization behavior in Scenario Sc12 is the same as in Scenario Sc9. Therefore, for a description of the PPU's initialization behavior, see section 2.11.2.1.

2.14.2.2 Automatic operation mode behavior in Scenario Sc12

Three kinds of work pieces are used in this Scenario and handled differently by the PPU: Black work pieces are directly transported to the conveyor whereas metallic and white plastic work pieces are firstly stamped and afterwards transported to the conveyor.

After startup, one of the work pieces stored in the stack is separated and pushed to the pickup position for the crane (cf. Fig. 12). In order to ensure the correct position of the work piece, the separating cylinder of the stack remains extended. For a detailed description of the stack's functionality see section 2.1.2.2. As soon as a work piece is detected by the digital micro switch at the stack's pickup position, the crane starts turning clockwise and stops at the stack's position. The crane has to turn 90°-counterclockwise to transport black work pieces from the stack directly to the conveyor. For metallic and white plastic work pieces, the crane has to turn 180°-counterclockwise to place work pieces at the stamp. An inductive sensor, whose value is true for metallic work pieces, is used to check the specific kind of the extended work piece at the

extension position of the stack. An optical sensor, whose value is true for white work pieces, is used to check the specific color of the extended work piece at the pickup position. An overview on the detection of the work piece type is shown in Fig. 26. The crane then picks up the work piece by using the vacuum gripper, lifts, turns to the desired position, lowers, and deposits the work piece at the respective place. A detailed description about the pick and place functionality of the crane is described in section 2.1.2.2.

Whereas black work pieces are directly transported to the conveyor, metallic and white plastic work pieces run through an additional process at the stamp (cf. Fig. 27). Metallic and white plastic work pieces are delivered by the crane at the sliding cylinder of the stamp. The sliding cylinder retracts and extends the work pieces to and from beneath the stamp. As soon as the retraction is detected the stamp is lowered for a certain time and with a fixed pressure – depending on the type of work piece detected – raised by setting the 'lower command' to false, and followed by the extension of the slider. As depicted in Fig. 30, as soon as the magazine slider is retracted, a choice for selecting the pressure profile is made. If the current work piece, which has been transported by the crane to the stamp, is metallic, the metallic pressure profile is executed. If the work piece is a white plastic one, the pressure profile for white plastic profiles is applied.

Simultaneously, after the metallic or white plastic work piece is placed in the sliding cylinder and the crane is raised again, it is checked if there is a black plastic work piece available at the stack (refer to Fig. 20). If a black work piece is available at the stack, the crane uses the stamping time and starts turning clockwise to pick up the black piece and place it at the conveyor. After depositing the work piece at the conveyor, it is checked if the stamping process is finished and if another black work piece is on hand at the stack. As long as the stamping process is in progress, all available black work pieces are transported to the slide. However, as soon as the stamping process is completed, the crane handles the stamped metallic or white plastic work piece from the stamp and deposits it at the conveyor prior to picking up another work piece at the stack's pickup position. If the next available work piece at the stack is a metallic or white plastic piece, while the stamping is still in progress, the crane waits at the stamp until the stamping process is finished. Depending on the time needed for the stamping progress, a certain number of black work pieces can be handled until the stamping is finished and the stamped work piece is transported. In the model seen in Fig. 20 only a single black work piece can be handled before the stamping process is complete. After the crane either placed a black, white or a metallic work piece at the conveyor, the crane moves back to the pickup position at the stack or to the stamp. See also Fig. 21 for the work piece supply. Once the work piece is placed on the conveyor, it is detected by a sensor. As soon as the work piece reaches the first pair of opposing optical (diffuse sensor – true for light-reflecting) and inductive (true for metallic) sensors, located shortly before the first ramp, the specific kind of the work piece is checked. With the installed sensors, it is possible to detect which type of work piece is momentarily being transported by the conveyor. Once detected, the white work pieces (optical true, inductive false) and the metallic work pieces (optical true, inductive true) are handled like the black work pieces (as described above): After determining the specific kind, the work piece is transported to one of the ramps not yet containing that certain kind of work piece. Hereby, the lateral ramps are filled by utilizing the pneumatic cylinders as pushers, the one at the end simply by transporting the work piece to the end of the conveyor. Internal variables are used to record which type of work piece has been stored in which one of the ramps. Once a work piece type has been identified by the sensors and the piece is stored in a ramp, the count of the variable allocated to that specific

ramp and that specific type is raised by one. By using those variables, the ramps not yet containing the presently transported work piece type can be determined. Refer to Fig. 44 for the conveyor's behavior.

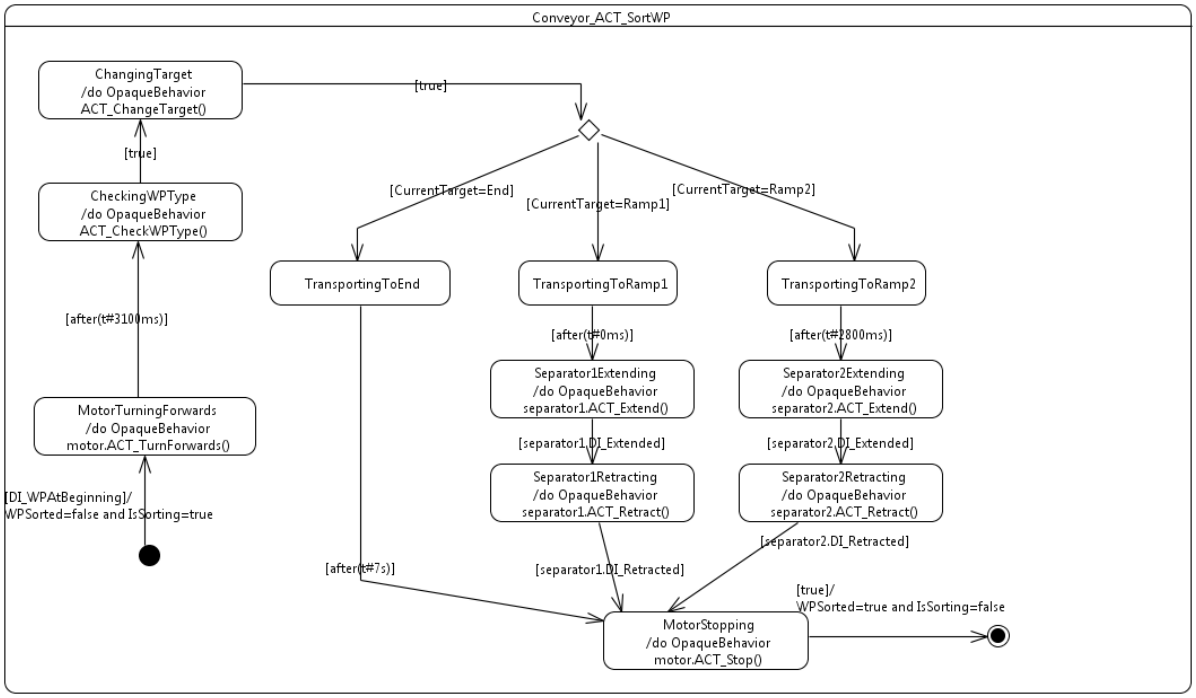

Fig. 44. Conveyor behavior in Scenario Sc12 (part 1) [47]

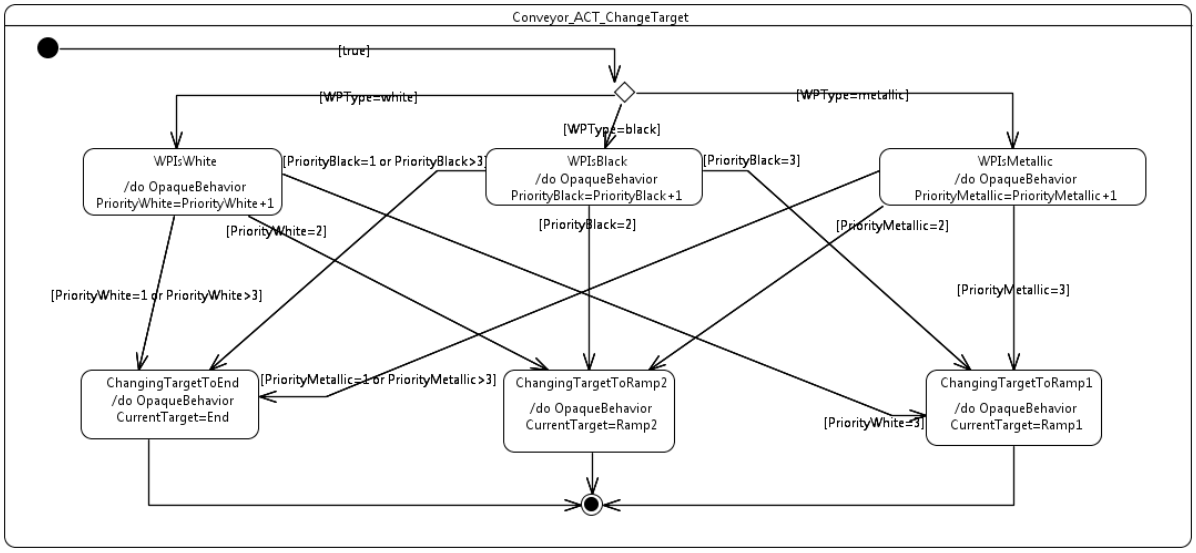

Fig. 45. Conveyor behavior in Scenario Sc12 (part 2) [47]

If no further work piece is detected at the pickup position, the sliding cylinder at the stamp is empty and no work piece is present at the conveyor, the plant stops operating. However, there is no separate sensor at the stack to detect the absence of a work piece. Instead, the not sending of the 'work piece detected'-signal while the cylinder is extended, is used to conclude the absence of a further object at the pickup position and also that no further work pieces are left in the stack. If the sensor detects another work piece the process will restart at the stack.

2.14.2.3 Emergency stop behavior in Scenario Sc12

The PPU's emergency stop behavior in Scenario Sc12 is the same as in Scenario Sc10. Therefore, for a description of the PPU's emergency stop behavior, see section 2.12.2.3.

2.15 Scenario Sc13

Within the ***Scenario Sc13***, the PPU consists of a ***stack*** (cf. no. 1 in Fig. 38) working as a work piece input storage, a ***conveyor*** (no. 2) working as a work piece output storage, a ***stamp*** (no. 3) for stamping work pieces and a ***crane*** (no. 4) for transporting work pieces by picking and placing them between these three working positions. Moreover, the crane may use the stamp component for buffering purposes. For human interaction, an operation panel provides a start button as well as an emergency stop. The PPU processes black plastic work pieces, white plastic work pieces as well as metallic work pieces in this Scenario. Black work pieces are separated at the stack and subsequently transported directly to the conveyor. In contrast, white plastic work pieces and metallic work pieces are transported from the stack to the stamp, processed there and then transported to the conveyor. However, it is not sufficient to stamp the two materials – metallic and plastic work pieces – with the same pressure; hence, being able to carry out two different processes, one for each material, is necessary. Hence, white plastic and metallic work pieces are stamped using different pressure profiles. Within the conveyor, three ramps are used as output storages. Two of the ramps are filled using respective pushing cylinders. A third ramp mounted to the end of the conveyor is filled by translationally moving the work piece using the conveyor. Each of the ramps shall have the same sorting order of work pieces – mixed work pieces shall henceforth be stored within the ramps. The models for this Scenario are freely available from [49]–[51].

2.15.1 PPU's structure in Scenario Sc13

In the following subsections, the PPU's structure, i.e. the composition of the PPU from its components, is described.

2.15.1.1 Stack's structure in Scenario Sc13

The mechatronic component stack of the PPU in Scenario Sc13 is the same as in Scenario Sc7 Therefore, for a description of the stack's structure, see section 2.9.1.1.

2.15.1.2 Crane's structure in Scenario Sc13

The ***crane*** serves as the transportation unit for transporting the work pieces from the stack to the ramp as well as to the stamp. In Fig. 12, an overview on the crane's components is given. The crane consists of a pneumatic ***cylinder*** (no. 1) for lifting and lowering the work pieces. The cylinder consists of two binary position sensors (one at each end) to detect whether the cylinder is extended or retracted as well as one valve as actuator. On top of this cylinder, an arm with a ***vacuum gripper*** (no. 2) is installed. The vacuum gripper is controlled by two valves and contains a micro switch which indicates whether a work piece is gripped. These components are mounted onto a ***turning table*** (no. 3) for rotational movement. At the bottom of the turning table, a ***potentiometer*** (no. 4) is installed. The potentiometer is used to detect the current position of the crane. The rotational movement of the turning table is realized by a ***motor*** (no. 5).

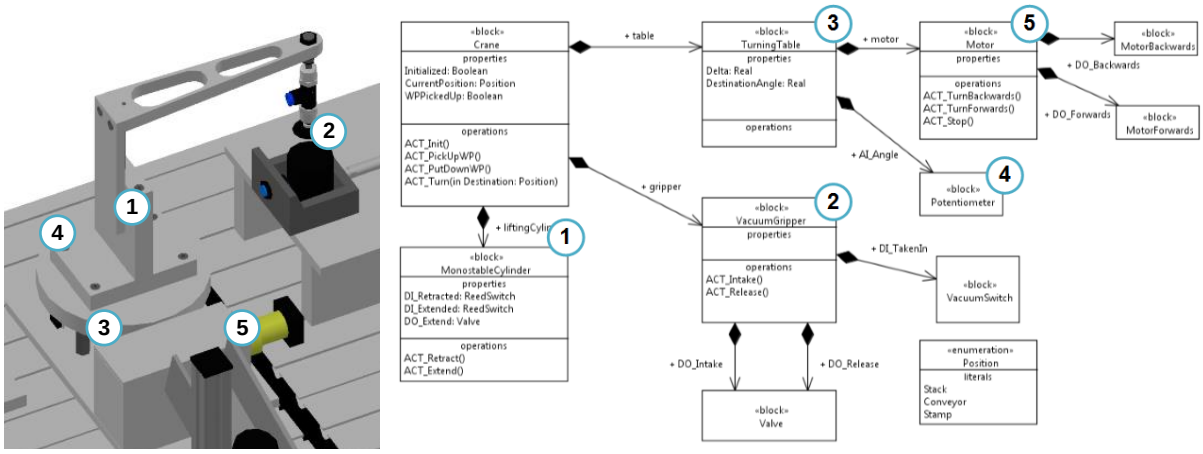

Fig. 46. Overview on the crane component's structure in Scenario Sc13 (left: graphically [49]*, right: logically* [50]*)*

A detailed overview on the crane's components as well as their respective terminal connections is shown Table 19.

Table 19. Component list of the crane component in Scenario Sc13 [51]

Posi-tion	Resource	Clamp	Description	Component	Type
2	200	X2	Crane		
200	200A1	X2.1	Extend lifting cylinder (Valve)	Crane	DO
200	200B7	X2.2	Lifting cylinder extended (Reed Switch)	Crane	DI
200	200B6	X2.3	Lifting cylinder retracted (Reed Switch)	Crane	DI
200	200A2	X2.4	Intake work piece (Valve)	Crane	DO
200	200A3	X2.5	Release work piece (Valve)	Crane	DO
200	200B5	X2.6	WP taken in (Vacuum Switch)	Crane	DI
200	200B6	X2.7	Potentiometer	Crane	AI

2.15.1.3 Stamp's structure in Scenario Sc13

The mechatronic component stamp of the PPU in Scenario Sc13 is the same as in Scenario Sc8. Therefore, for a description of the stamp's structure, see section 2.10.1.4.

2.15.1.4 Conveyor's structure in Scenario Sc13

The mechatronic component conveyor of the PPU in Scenario Sc13 is the same as in Scenario Sc11. Therefore, for a description of the conveyor's structure, see section 2.13.1.4.

2.15.2 PPU's behavior in Scenario Sc13

In the following subsections, the PPU's behavior, i.e. the initialization behavior, the automatic operation mode behavior and the emergency stop behavior of the PPU, is described.

2.15.2.1 Initialization behavior in Scenario Sc13

The PPU's initialization behavior in Scenario Sc13 is the same as in Scenario Sc9. Therefore, for a description of the PPU's initialization behavior, see section 2.11.2.1.

2.15.2.2 Automatic operation mode behavior in Scenario Sc13

Three kinds of work pieces are used in this Scenario and handled differently by the PPU: Black work pieces are directly transported to the conveyor whereas metallic and white plastic work pieces are firstly stamped and afterwards transported to the conveyor.

After startup, one of the work pieces stored in the stack is separated and pushed to the pickup position for the crane (cf. Fig. 12). In order to ensure the correct position of the work piece, the separating cylinder of the stack remains extended. For a detailed description of the stack's functionality see section 2.1.2.2. As soon as a work piece is detected by the digital micro switch at the stack's pickup position, the crane starts turning clockwise and stops at the stack's position. The crane has to turn 90°-counterclockwise to transport black work pieces from the stack directly to the conveyor. For metallic and white plastic work pieces, the crane has to turn 180°-counterclockwise to place work pieces at the stamp. A detailed overview on the crane behavior is given in Fig. 47. An inductive sensor, whose value is true for metallic work pieces, is used to check the specific kind of the extended work piece at the extension position of the stack. An optical sensor, whose value is true for white work pieces, is used to check the specific color of the extended work piece at the pickup position. An overview on the detection of the work piece type is shown in Fig. 26. The crane then picks up the work piece by using the vacuum gripper, lifts, turns to the desired position, lowers, and deposits the work piece at the respective place. A detailed description about the pick and place functionality of the crane is described in section 2.1.2.2.

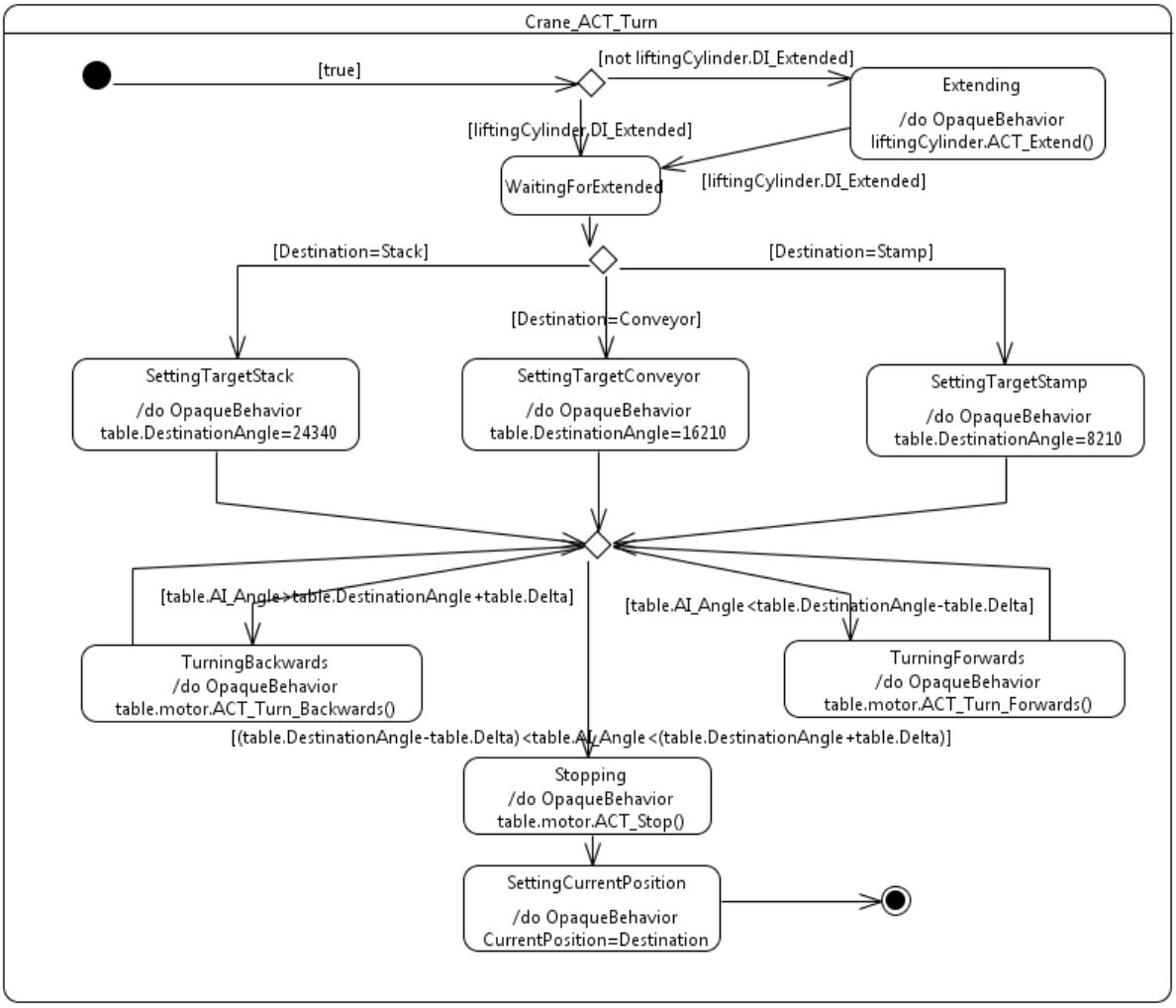

Fig. 47. Crane behavior in Scenario Sc13 [50]

Whereas black work pieces are directly transported to the conveyor, metallic and white plastic work pieces run through an additional process at the stamp (cf. Fig. 27). Metallic and white plastic work pieces are delivered by the crane at the sliding cylinder of the stamp. The sliding cylinder retracts and extends the work pieces to and from beneath the stamp. As soon as the retraction is detected the stamp is lowered for a certain time and with a fixed pressure – depending on the type of work piece detected – raised by setting the 'lower command' to false, and followed by the extension of the slider. As depicted in Fig. 30, as soon as the magazine slider is retracted, a choice for selecting the pressure profile is made. If the current work piece, which has been transported by the crane to the stamp, is metallic, the metallic pressure profile is executed. If the work piece is a white plastic one, the pressure profile for white plastic profiles is applied.

Simultaneously, after the metallic or white plastic work piece is placed in the sliding cylinder and the crane is raised again, it is checked if there is a black plastic work piece available at the stack (refer to Fig. 20). If a black work piece is available at the stack, the crane uses the stamping time and starts turning clockwise to pick up the black piece and place it at the conveyor. After depositing the work piece at the conveyor, it is checked if the stamping process is finished and if another black work piece is on hand at the stack. As long as the stamping process is in progress, all available black work pieces are transported to the slide. However, as soon as the stamping process is completed, the crane handles the stamped metallic or white plastic work

piece from the stamp and deposits it at the conveyor prior to picking up another work piece at the stack's pickup position. If the next available work piece at the stack is a metallic or white plastic piece, while the stamping is still in progress, the crane waits at the stamp until the stamping process is finished. Depending on the time needed for the stamping progress, a certain number of black work pieces can be handled until the stamping is finished and the stamped work piece is transported. In the model seen in Fig. 20 only a single black work piece can be handled before the stamping process is complete. After the crane either placed a black, white or a metallic work piece at the conveyor, the crane moves back to the pickup position at the stack or to the stamp. See also Fig. 21 for the work piece supply. Once the work piece is placed on the conveyor, it is detected by a sensor. As soon as the work piece reaches the first pair of opposing optical (diffuse sensor – true for light-reflecting) and inductive (true for metallic) sensors, located shortly before the first ramp, the specific kind of the work piece is checked. With the installed sensors, it is possible to detect which type of work piece is momentarily being transported by the conveyor. Once detected, the white work pieces (optical true, inductive false) and the metallic work pieces (optical true, inductive true) are handled like the black work pieces (as described above): After determining the specific kind, the work piece is transported to one of the ramps not yet containing that certain kind of work piece. Hereby, the lateral ramps are filled by utilizing the pneumatic cylinders as pushers, the one at the end simply by transporting the work piece to the end of the conveyor. Internal variables are used to record which type of work piece has been stored in which one of the ramps. Once a work piece type has been identified by the sensors and the piece is stored in a ramp, the count of the variable allocated to that specific ramp and that specific type is raised by one. By using those variables, the ramps not yet containing the presently transported work piece type can be determined. Refer to Fig. 44 for the conveyor's behavior.

If no further work piece is detected at the pickup position, the sliding cylinder at the stamp is empty and no work piece is present at the conveyor, the plant stops operating. However, there is no separate sensor at the stack to detect the absence of a work piece. Instead, the not sending of the 'work piece detected'-signal while the cylinder is extended, is used to conclude the absence of a further object at the pickup position and also that no further work pieces are left in the stack. If the sensor detects another work piece the process will restart at the stack.

2.15.2.3 Emergency stop behavior in Scenario Sc13

The PPU's emergency stop behavior in Scenario Sc13 is the same as in Scenario Sc10. Therefore, for a description of the PPU's emergency stop behavior, see section 2.12.2.3.

3 Evolution steps of the Pick and Place Unit (PPU)

Within the following, the ***drivers*** and ***enablers*** for the evolution steps of the PPU are introduced. In the following, we will refer to ***drivers*** as the initiation of a plant's evolution due to e.g. new technological developments, market dynamics etc. Moreover, the term ***enabler*** will be used to describe the specific evolution itself, i.e. how the respective change from one Scenario to another Scenario is implemented.

An overview on the evolution steps of the Pick and Place Unit is shown in Fig. 48. The graph illustrated in the figure consists of Scenarios of the PPU represented as nodes. The edges between these nodes represent the migration from one Scenario to another, i.e. the ***evolution steps***, which are forced by ***drivers*** and implemented by their respective ***enablers***.

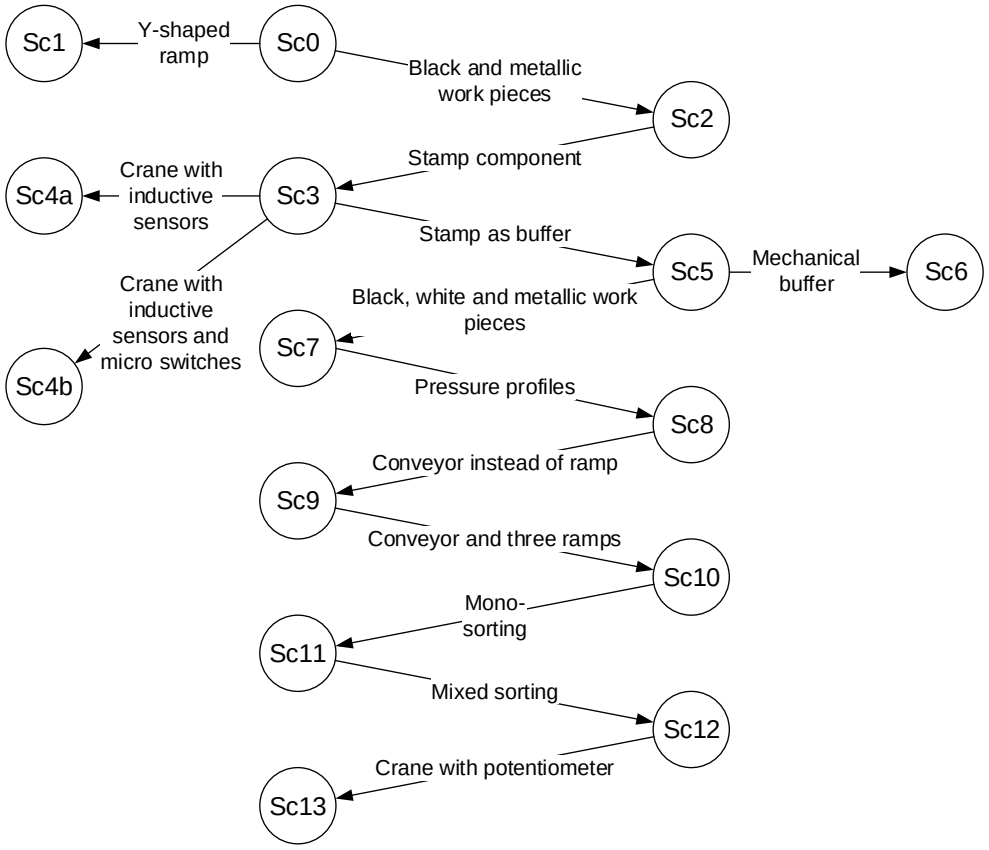

Fig. 48. Overview on evolution steps

An overview on the respective changes made from one evolution step to another are illustrated in Table 20. Therein, a cross denotes a change from one evolution step to another. Both changes in structure and behavior of the PPU are illustrated in the table. Moreover, it is distinguished in changes of the PPU's components' ***structures***, i.e. ***Stack***, ***Crane***, ***Stamp***, ***Ramp*** and ***Conveyor***, as well as their respective behavior, i.e. ***Initialization***, ***Automatic mode*** and ***Emergency*** behavior. As changes to automation systems can involve all disciplines of the engineering process, i.e. mechanical engineering, electrical/ electronics engineering and software engineering, these changes can also be classified as ***context*** changes (involving the mechanical parts of the system), ***platform*** changes (involving the electrical/ electronics part of the system) and ***software*** changes.

Table 20. Overview on Evolution Steps

No.	Structure					Behavior		
	Stack	**Crane**	**Stamp**	**Ramp**	**Con-veyor**	**Initiali-zation**	**Auto-matic**	**Emer-gency**
Sc0	X	X		X		X	X	X
Sc1				X				
Sc2	X							
Sc3		X	X			X	X	X
Sc4a		X						
Sc4b		X						
Sc5							X	
Sc6		X					X	
Sc7	X						X	
Sc8			X			X	X	X
Sc9					X	X	X	X
Sc10					X	X	X	X
Sc11					X		X	
Sc12							X	
Sc13		X					X	

3.1 Evolution Step Ev1: Increasing ramp capacity (Sc0 → Sc1)

Within Scenario Sc0, the PPU is able to handle a maximum amount of work pieces as the ramp utilized in Scenario Sc0 may only hold maximum three work pieces. However, in a first evolution step, it is identified that three work pieces to be handled are not enough. Hence, the capacity of the output ramp must be increased (***driver***). In order to address this need, the ramp used in Scenario Sc0 is replaced by a Y-shaped ramp in Scenario Sc1 (***enabler***).

Evolution step Ev1 hence involves a structural change of the ramp component. As the ramp component is purely mechanical, only the ***context*** of the PPU is changed.

3.2 Evolution step Ev2: Handle both metallic and black work pieces (Sc1 → Sc2)

Within Scenario Sc0, the PPU may only process metallic work pieces. Nevertheless, the customer raises the need to handle black plastic work pieces additionally and to identify the specific kind of work piece at the stack position. Therefore, different work pieces need to be processed (***driver***). Thus, in Scenario Sc2, an additional inductive sensor is added to the stack component in order to identify whether a metallic work piece was provided or not (***enabler***).

Evolution step Ev2 therefore involves a structural change of the stack component, as an inductive sensor is added. Therefore, only electrical components are changed – hence, only the ***platform*** is adapted.

3.3 Evolution step Ev3: Stamp metallic products (Sc2 → Sc3)

Within Scenario Sc2, the PPU can handle both metallic and black plastic work pieces. Moreover, the PPU is able to distinguish between metallic and black work pieces. However, due to changed customer requirements, an additional process within the PPU is necessary: metallic

work pieces need to be stamped before being transported to the ramp (***driver***). In order to enable the stamping of metallic products, an additional stamp component is added to the PPU in Scenario Sc3 (***enabler***).

As the stamp component includes components from all disciplines, the changes made in evolution step Ev3 involve ***context***, ***platform*** and ***software***: The context is changed as the mechanical components of the stamp are added. The platform is changed as respective actuators and sensors are mounted to the system. Moreover, the software changes as the crane behavior needs to be re-implemented. Hence, structural and behavioral changes are involved in evolution step Ev3.

3.4 Evolution step Ev4: Decreasing failure of micro switches (Sc3 → Sc4a)

Within Scenario Sc3, micro switches placed at the bottom of the crane's turning table are used in order to identify the respective position of the crane, i.e. whether the crane is at the stack's, the ramp's or the stamp's position. Nevertheless, during operation of the PPU, it is identified that due to pollution these mechanical contacts underlie failures: sensor signals may be missing and, consequently, the crane cannot stop at the required position. Therefore, the need to increase the PPU's availability by decreasing these failures arises (***drivers***). Hence, the micro switches are replaced in Scenario Sc4a by inductive sensors providing a magnetic measuring principle (***enabler***).

As within evolution step Ev4 only the micro switches are changed, changes in this evolution step are only related to the structure of the ***platform***.

3.5 Evolution step Ev5: Increasing reliability (Sc3 → Sc4b)

Within Scenario Sc3, micro switches placed at the bottom of the crane's turning table are used in order to identify the respective position of the crane, i.e. whether the crane is at the stack's, the ramp's or the stamp's position. Nevertheless, during operation of the PPU, it is identified that due to pollution the mechanical contacts underlie failures: sensor signals may be missing and, consequently, the crane cannot stop at the required position. Therefore, the need to increase the PPU's availability by decreasing these failures arises (***drivers***). Hence, additionally to the micro switches, inductive sensors are installed at the bottom of the crane's turning table in Scenario Sc4b. By that, reliability and availability of the PPU can be increased by redundant position sensors (***enabler***).

As within evolution step Ev5, only the micro switches are changed, changes in this evolution step are only related to the structure of the ***platform***.

3.6 Evolution step Ev6: Increasing throughput of the crane (Sc3 → Sc5)

In the PPU's current state in Scenario Sc3, only one work piece can be processed simultaneously. During the PPU's operation, a higher throughout of work pieces is needed (***driver***). In order to satisfy this imposed requirement, the engineer identifies that during the stamping process of metallic work pieces, the crane may pick available black plastic work pieces and transport them to the ramp. Hence, within Scenario Sc5, the crane's behavior is changed to fulfil the newly imposed needs (***enabler***).

This evolution step Ev6 only involves changes in the system's behavior, which is related to the ***software***.

3.7 Evolution step Ev7: Increasing throughput of the crane (Sc5 → Sc6)

Within Scenario Sc5, the crane picks available black plastic work pieces as long as the stamp is stamping a metallic work piece. Nevertheless, as soon as another metallic work piece is provided by the stack component, the crane needs to pause its current process until the stamping of the metallic work piece is finished. The customer however demands an even higher throughput of work pieces (***driver***). In order to fulfil these requirements, an additional mechanical buffer is added to the PPU (***enabler***). Hence, the crane behavior can be changed in Scenario Sc6: If a metallic work piece is currently stamped and the stack provides another work piece at the same time, the crane can pick and subsequently place the work piece on the mechanical buffer. By that, two metallic work pieces can be handled within the PPU at the same time.

In this evolution step Ev7, a mechanical component is added – hence, the structure of the PPU's ***context*** is changed. Moreover, the crane needs a fourth micro switch; hence, changes in the ***platform*** are triggered. Finally, the ***software*** needs to be adapted as the crane's behavior must be changed.

3.8 Evolution step Ev8: Handle metallic, white plastic and black plastic work pieces (Sc5 → Sc7)

In the PPU's current state in Scenario Sc5, the PPU is able to handle metallic and black plastic work pieces. The customer however decides that processing these two work piece types is not sufficient – additionally, white plastic work pieces should be handled (***driver***). In order to realize the handling of white work pieces, an optical sensor is added to the stack (***enabler***) in Scenario Sc7, thus providing the possibility to distinguish between metallic, black plastic and white plastic work pieces. Therein, white work pieces shall be processed similar to metallic work pieces: first, a stamping process is needed and second, the work pieces are to be stored in the ramp.

This evolution step Ev8 involves structural changes in the ***platform*** as an additional optical sensor is added to the stack component. Moreover, the ***software*** is involved: the crane behavior needs to be changed in order to process all three types of work pieces.

3.9 Evolution step Ev9: Different pressure profiles for stamping (Sc7 → Sc8)

Within Scenario Sc7, the PPU is able to handle metallic, black plastic and white plastic work pieces. Black plastic work pieces are stored in the ramp while metallic and white work pieces are stamped before being stored in the ramp. However, during operation of the PPU, it has been pointed out that white plastic work pieces are more fragile than metallic ones. Hence, the need of having two different pressure profiles at the stamp – one profile for white plastic work pieces and one for metallic work pieces – arises (***driver***). Therefore, a proportional valve and a pressure sensor are installed in Scenario Sc8. Hence, the valve's working point can be set differently by setting an analog set value (***enabler***).

As electrical/ electronic components are added to the stamp component in this evolution step Ev9, changes to the ***platform***'s structure are made. Moreover, the ***software*** is changed as the stamping behavior needs to be re-implemented.

3.10 Evolution step Ev10: Increasing distance between handling and storing (Sc8 → Sc9)

In Scenario Sc8, work piece are provided by the stack, and subsequently stamped and/or stored. Nevertheless, the customer may point out that the ramp is not positioned ideally as transporting work pieces from the ramp to subsequent processing units may be difficult. Hence, the requirement to increase the distance between the work piece handling (*crane*) and storing (*ramp*) arises (***driver***). In order to increase this distance, the ramp is replaced in Scenario Sc9 by a conveyor at whose end a ramp is installed (***enabler***).

In the evolution step Ev10, a new component is added to the PPU – hence, all dimensions ***context***, ***platform*** and ***software*** are involved: The respective mechanical components of the conveyor are added. Sensors and actuators are added to the system. The new behavior of the conveyor is implemented. Hence, both structural and behavioral changes are made.

3.11 Evolution step Ev11: Changing transport due to logistical reasons (Sc9 → Sc10)

In the PPU's state in Scenario Sc9, work pieces are placed on a conveyor and subsequently moved translationally to a ramp mounted to the end of the conveyor. Hence, work pieces can be transported from this ramp to respective subsequent processing units. Nevertheless, during operation of the PPU, it has been identified that such a single pick-up position is not sufficient. The need to provide multiple pick-up positions in order to transport work pieces to subsequent units arises (***driver***). Therefore, in Scenario Sc10, two additional ramps, separating cylinders as well as optical sensors used to detect work pieces at these ramps are installed at the conveyor (***enabler***). By that the work pieces, can be pushed into the ramps. In Scenario Sc10, these ramps are filled as described in the following: Firstly, the ramp installed at the end of the conveyor is filled. Secondly, the central ramp is filled and thirdly, the ramp installed at the beginning of the conveyor is filled.

In order to implement the driver in this evolution step Ev12, the conveyor component is changed: mechanical ramps (***context***), as well as respective sensors and actuators (***platform***) are added. Moreover, the conveyor's behavior is changed (***software***).

3.12 Evolution step Ev12: Changing transport due to logistical reasons (Sc10 → Sc11)

In Scenario Sc10, work pieces are pushed into ramps mounted to the conveyor in order to provide three different pick-up positions. By that, work pieces can be picked up and subsequently transported to further processing units. Due to logistical reasons, the need to provide one type of work piece in each ramp arises – white work pieces are stored in the first ramp, metallic work pieces in the second one and black work pieces in the third one (***driver***). In order to realize this mono-fraction sorting of work pieces in Scenario Sc11, inductive sensors are installed additionally to the ramps – hence, at each ramp, it can be distinguished whether metallic, white plastic or black plastic work pieces are present (***enabler***).

As electrical/ electronic components are added, ***platform*** changes are involved in evolution step Ev12. Moreover, as the sorting order is changed, the ***software*** is involved in this evolution step.

3.13 Evolution step Ev13: Changing transport due to logistical reasons (Sc11 → Sc12)

In Scenario Sc11, work pieces are sorted into the three ramps of the conveyor. However, due to logistical reasons, in reach ramp, all types of work pieces must be provided in the ramp – each ramp must hence contain a black plastic, a white plastic and a metallic work piece (***driver***). Hence, the conveyor's behavior is changed in Scenario Sc12 (***enabler***).

In the evolution step Ev13, the sorting order of work pieces is changed to fulfil the imposed drivers. Therefore, only changes to the system's behavior (***software***) can be anticipated.

3.14 Evolution step Ev14: Increasing exactness of crane's positioning (Sc12 → Sc13)

In Scenario Sc12, the crane is positioned using micro switches: If the crane is positioned at the stack, stamp or conveyor position, a mechanical contact activates the micro switch, hence, enabling to detect whether the crane is positioned at the intended position or not. Nevertheless, accuracy and exactness need to be improved due to customer requirements (***driver***). Therefore, these three micro switches are replaced by a single potentiometer (***enabler***). Using the potentiometer, an analog value (voltage) represents the current turning angle of the turning table.

Besides replacing the crane's micro switches by a potentiometer (***platform*** change), the respective ***software*** needs to be changed.

References

[1] R. K. Yin, *Case Study Research: Design and Methods*. 2009.

[2] Zentralverband Elektrotechnik- und Elektronikindustrie e.V. (ZVEI), *Life-Cycle-Management für Produkte und Systeme der Automation*. 2010.

[3] C. Legat, J. Folmer, and B. Vogel-Heuser, "Evolution in industrial plant automation: A case study," in *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, 2013, pp. 4386–4391.

[4] B. Vogel-Heuser, J. Folmer, and C. Legat, "Anforderungen an die Softwareevolution in der Automatisierung des Maschinen- und Anlagenbaus," – *Autom*, vol. 62, no. 3, pp. 163–174, Jan. 2014.

[5] Institute for Automation and Information Systems (AIS), "The Pick and Place Unit –Demonstrator for Evolution in Industrial Plant Automation," Online available: http://www.ppu-demonstrator.org. 2013.

[6] B. Vogel-Heuser, J. Folmer, C. Legat, and S. Feldmann, "Researching Evolution in Industrial Plant Automation: Scenarios and Documentation of the Pick and Place Unit," 2014.

[7] B. Vogel-Heuser, C. Legat, and J. Folmer, "CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc0," 2014.

[8] B. Vogel-Heuser, J. Folmer, and C. Legat, "SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc0," Online available: https://mediatum.ub.tum.de/node?id=1188664. 2014.

[9] B. Vogel-Heuser, C. Legat, and J. Folmer, "Component List of the Pick and Place Unit: Scenario Sc0," 2014.

[10] B. Vogel-Heuser, C. Legat, and J. Folmer, "CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc1," 2014.

[11] B. Vogel-Heuser, J. Folmer, and C. Legat, "SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc1," Online available: https://mediatum.ub.tum.de/node?id=1200553. 2014.

[12] B. Vogel-Heuser, C. Legat, and J. Folmer, "Component List of the Pick and Place Unit: Scenario Sc1," 2014.

[13] B. Vogel-Heuser, C. Legat, and J. Folmer, "CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc2," 2014.

[14] B. Vogel-Heuser, J. Folmer, and C. Legat, "SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc2," Online available: https://mediatum.ub.tum.de/node?id=1200555. 2014.

[15] B. Vogel-Heuser, C. Legat, and J. Folmer, "Component List of the Pick and Place Unit: Scenario Sc2," 2014.

[16] B. Vogel-Heuser, C. Legat, and J. Folmer, "CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc3," 2014.

[17] B. Vogel-Heuser, J. Folmer, and C. Legat, "SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc3," Online available: https://mediatum.ub.tum.de/node?id=1200556. 2014.

[18] B. Vogel-Heuser, C. Legat, and J. Folmer, "Component List of the Pick and Place Unit: Scenario Sc3," 2014.

[19] B. Vogel-Heuser, C. Legat, and J. Folmer, "CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc4a," 2014.

[20] B. Vogel-Heuser, J. Folmer, and C. Legat, "SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc4a," Online available: https://mediatum.ub.tum.de/node?id=1200557. 2014.

[21] B. Vogel-Heuser, C. Legat, and J. Folmer, "Component List of the Pick and Place Unit: Scenario Sc4a," 2014.

[22] B. Vogel-Heuser, C. Legat, and J. Folmer, "CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc4b," 2014.

[23] B. Vogel-Heuser, J. Folmer, and C. Legat, "SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc4b," Online available: https://mediatum.ub.tum.de/node?id=1200558. 2014.

[24] B. Vogel-Heuser, C. Legat, and J. Folmer, “Component List of the Pick and Place Unit: Scenario Sc4b,” 2014.

[25] B. Vogel-Heuser, C. Legat, and J. Folmer, “CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc5,” 2014.

[26] B. Vogel-Heuser, J. Folmer, and C. Legat, “SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc5,” Online available: https://mediatum.ub.tum.de/node?id=1200559. 2014.

[27] B. Vogel-Heuser, C. Legat, and J. Folmer, “Component List of the Pick and Place Unit: Scenario Sc5,” 2014.

[28] B. Vogel-Heuser, C. Legat, and J. Folmer, “CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc6,” 2014.

[29] B. Vogel-Heuser, J. Folmer, and C. Legat, “SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc6,” Online available: https://mediatum.ub.tum.de/node?id=1200560. 2014.

[30] B. Vogel-Heuser, C. Legat, and J. Folmer, “Component List of the Pick and Place Unit: Scenario Sc6,” 2014.

[31] B. Vogel-Heuser, C. Legat, and J. Folmer, “CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc7,” 2014.

[32] B. Vogel-Heuser, J. Folmer, and C. Legat, “SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc7,” Online available: https://mediatum.ub.tum.de/node?id=1200561. 2014.

[33] B. Vogel-Heuser, C. Legat, and J. Folmer, “Component List of the Pick and Place Unit: Scenario Sc7,” 2014.

[34] B. Vogel-Heuser, C. Legat, and J. Folmer, “CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc8,” 2014.

[35] B. Vogel-Heuser, J. Folmer, and C. Legat, “SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc8,” Online available: https://mediatum.ub.tum.de/node?id=1200562. 2014.

[36] B. Vogel-Heuser, C. Legat, and J. Folmer, “Component List of the Pick and Place Unit: Scenario Sc8,” 2014.

[37] B. Vogel-Heuser, C. Legat, and J. Folmer, “CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc9,” 2014.

[38] B. Vogel-Heuser, J. Folmer, and C. Legat, “SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc9,” Online available: https://mediatum.ub.tum.de/node?id=1200563. 2014.

[39] B. Vogel-Heuser, C. Legat, and J. Folmer, “Component List of the Pick and Place Unit: Scenario Sc9,” 2014.

[40] B. Vogel-Heuser, C. Legat, and J. Folmer, “CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc10,” 2014.

[41] B. Vogel-Heuser, J. Folmer, and C. Legat, “SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc10,” Online available: https://mediatum.ub.tum.de/node?id=1200564. 2014.

[42] B. Vogel-Heuser, C. Legat, and J. Folmer, “Component List of the Pick and Place Unit: Scenario Sc10,” 2014.

[43] B. Vogel-Heuser, C. Legat, and J. Folmer, “CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc11,” 2014.

[44] B. Vogel-Heuser, J. Folmer, and C. Legat, “SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc11,” Online available: https://mediatum.ub.tum.de/node?id=1200566. 2014.

[45] B. Vogel-Heuser, C. Legat, and J. Folmer, “Component List of the Pick and Place Unit: Scenario Sc11,” 2014.

[46] B. Vogel-Heuser, C. Legat, and J. Folmer, “CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc12,” 2014.

[47] B. Vogel-Heuser, J. Folmer, and C. Legat, “SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc12,” Online available: https://mediatum.ub.tum.de/node?id=1200567. 2014.

[48] B. Vogel-Heuser, C. Legat, and J. Folmer, “Component List of the Pick and Place Unit: Scenario Sc12,” 2014.

[49] B. Vogel-Heuser, C. Legat, and J. Folmer, “CAD Model of the Pick and Place Unit for AutoCAD: Scenario Sc13,” 2014.

[50] B. Vogel-Heuser, J. Folmer, and C. Legat, “SysML Model of the Pick and Place Unit for Papyrus UML: Scenario Sc13,” Online available: https://mediatum.ub.tum.de/node?id=1200569. 2014.

[51] B. Vogel-Heuser, C. Legat, and J. Folmer, “Component List of the Pick and Place Unit: Scenario Sc13,” 2014.