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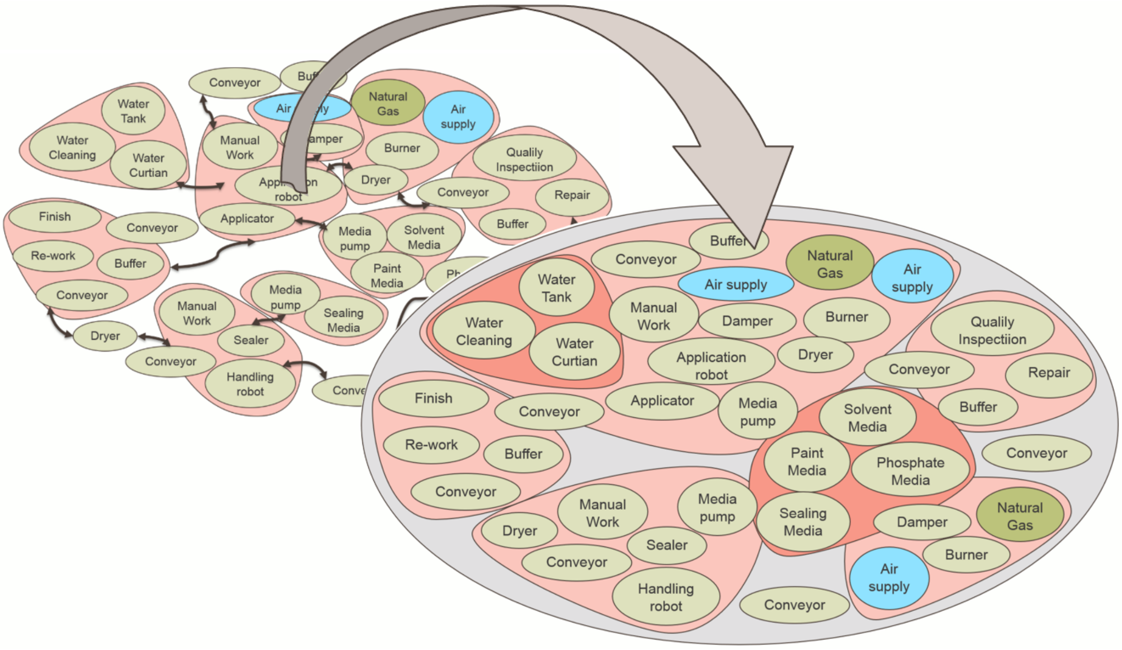

Concept for modeling and visualization of a complex paint process

A framework concept for Volvo Cars Paint Shop to visualize and structure data handling for a complex production system with innovative solution for accessibility, efficiency and management inspired by the Smart Factory concept and Industry 4.0.

Master's thesis in Systems, Control and Mechatronics

ANTON ALBO

Department of Electrical Engineering
Chalmers University of Technology
Gothenburg, Sweden 2018

MASTER'S THESIS 2018:48

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Cover: An illustration describing the transition from a fictional older paint shop divided into smaller set of resources, reconstructed with a new framework concept for a new plant, developed for this thesis.

Typeset in LaTeX
Gothenburg, Sweden 2018

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Abstract

For an industrial painting process with several collaborative control systems of various kinds, the level of complexity will make it difficult for a user, technician or management to follow the process and the event that may occur. Due to several different supplier of equipment during recurrent reconstruction and upgrades, the demand for a flexible, standardized and user-friendly visual interface is vital to connect and share information between all associated systems.

This thesis will provide a concept for extracting and visualize data in a standardized interface framework for abstraction of a complex production process. The concept is based on information from interviews with technicians and engineers at Volvo Cars to understand the current standard and situation but also potential improvements. The information is used to model and simulate a smaller paint process using Sequence Planner hierarchy as a tool to construct, modeling and running a sequence and extracting data to a virtual event pipeline, which then a human machine interface (HMI) is connected to for showing the constructed visual framework as a proof of concept. In addition, futuristic features are presented to show the potential of having all data available and accessible in terms of analysis, efficient preventive and predictive maintenance and energy reduction.

Keywords: modeling, simulation, control, visualization, smart factory, industry 4.0, formal methods, abstraction levels, framework

Acknowledgements

I would like to start by saying thanks to all the people a met during my work who showed their interest with a supportive and great attitude. I am also very grateful to my supervisor at Chalmers University of Technology, Petter Falkman, who believed in me from the start, inspired me and always have a way to shred some light over any obstacle I have encountered along this working progress.

Another big thank you to Kristofer Bengtsson, doctor at the division of automation at Chalmers University of Technology, who spent a great amount of time intoducing me to his work with Sequence Planner and helped me build the simulated model. I also want to include the PhD-student Martin Dahl who took time helping me debug and connect my running simulation in Sequence Planner as a client to the visual interface server.

Finally, a would like to thank my supervisor at Volvo Cars, Tony Prevander, and my technical supervisor, Patrik Johansson, for formulated and defined this case for me and giving me this opportunity to freely show my thoughts and competence in the field. Not to forget all the employees at Volvo Cars which I interviewed, who happily shared their opinion and input with great enthusiasm.

Anton Albo, Gothenburg, May 2018

Contents

List of Figures

1

Introduction

For an industrial painting process with several collaborative control systems of various kinds, the level of complexity will make it difficult for a user, technician or management to follow the process and the event that may occur. Due to several different supplier of equipment during recurrent reconstruction and upgrades, the demand for a flexible, standardized and user-friendly visual interface is vital to connect and share information between all associated systems.

1.1 Objective

Future manufacturing systems need to be more flexible, to embrace tougher and constantly changing market demands. The paint shop at Volvo Cars Torslanda is in need of an interface which can monitor several system to more easily get a good overview and update of the system. By applying new modern technology, inspired by the Smart Factory concept and Industry 4.0, it would be possible to reduce cost and optimize a paint process with respect to visualization and energy consumption. This project will define a concept for modeling and visualization of several dependant and independent control system working simultaneously in a complex paint process. The scientific challenges lies in data extraction and gathering of information from several control systems with a high level of complexity and to visualize a real-time process or simulation using this data with respect to user-friendliness, control and optimization.

1.2 Scope

This thesis will make a brief study regarding the associated system in the current paint process for Volvo Cars but mainly focusing on the painting area. A smaller and simplified paint process will be constructed and simulated, containing dynamic parameters and events with estimated values based on studies of a real system.
The simulation will consist of robots, media supply, transport system, water system and car body data and will show a proof of concept with a functional visual interface with all abstraction levels but not with all feature presented in the final concept framework.
The simulation will prove the complexity of several interfering control systems and will be used for data extraction in order to create and visualize a human machine interface (HMI) as a tool for production workers, technicians, managers and engineers. The final concept will include possible improvements for future implementation and

argument supporting the importance of the concept, but it will not result in a complete investment plan.

1.3 Contribution

The concept is designed and constructed based on input from technicians and engineers in the specific field of excellence, together with the years of experience as a maintenance technician, at the paint shop at Volvo Cars, that the author has. The modeling approach in Sequence Planner have been developed within the division of Automation at Chalmers University of Technology, where Dr. Kristofer Bengtsson and PhD-student Martin Dahl have supported and helped constructing the model used for simulation, which was specified and defined based on analysis and interviews from the current process.
The human machine interface has been created from beginning, including a simulated PLC with WinCC RT Advance as choice for visual interface. An OPC-server has been configured in order to get access to the generated data on the virtual event pipeline in Sequence Planner.

1.4 Thesis Outline

In chapter 1 – Introduction, the reason behind this report is described and the problem and the objective are defined. Chapter 2 provides the reader with background information related to the several different topics discussed in this thesis. Following chapter contains a pre-study of the existing paint plant with interviews and an analysis of the level of complexity in the different collaborative systems. Chapter 4 and 5 follows the setup of software needed to run a simulation with visual interface, and then how the simulated model is defined, build and what it generated. The final result of the whole concept is presented in chapter 6, with addition to the improvement and features this approach can accomplish theoretical. The last chapter summarize and evaluates the results and with suggestions for further improvement to the concept and realizability for future implementation.

2

Preliminaries

In the following chapter, a background for the painting process is described as well as the theory behind related works and different approaches for modeling a complex dynamic system.

2.1 Complexity of a painting process

A painting process is very common in the automotive industry and includes several collaborative systems to carry out the complex task of product quality and at the same time reduce process cycle time and material waste [1].
Industrial robots are widely used for autonomous spray paint application, but manual work could be necessary for specific tasks or rework. To meet the demands for high quality and efficiency, process modeling for robot trajectory movements together with simulation and paint thickness measurement is needed [2].
Crucial parameters for paint applications are the right working condition since the temperature and humidity of the air in the spray booth determines the properties of the paint [3]. Therefore, these parameters must be controlled by supporting systems as well. Some spray paint robots also have bearing air systems to control the flow of the paint and have high voltage solutions to increase the paint saturation on the surface.
Due to all interfering and collaborative systems with a mixed of discrete and dynamic constraints, it is easy to say that the level of complexity is higher in a paint process industry than in a manufacturing production industry or an assembly line.

2.1.1 Painting process in general

The paint process is not only a spray paint booth, a whole paint plant consists of several booths and different surface treatments where each white car body must go through in a specific order using a conveyor system for transportation [3]. To describe the flow from the car body's perspective, the process usually begins with an acid bath or electrolyte treatment for surface cleaning. This is followed by a rust protection layer through a phosphate treatment as a conversion coating with a subsequent oven.
After this pre-treatment, the body is undergoing a sealing process to prevent leakage and sound dampers to reduce vibration and noise. The body is then followed by the first spray booth with primer coating, followed by base coat and finally clear coat, each with a subsequent oven and cooling zone to dry the paint.

Throughout the whole process, several stations for quality inspection are included as well as rework and repair before leaving and transported away to the final assembly plant. Figure 2.1 illustrates the flow of a paint process plant.

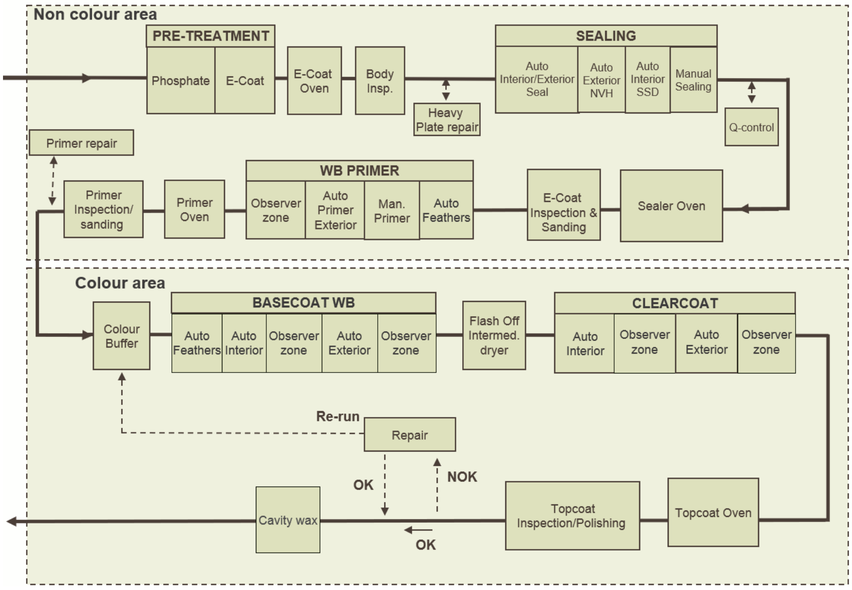


Figure 2.1: A simplified flowchart of the paint shop at Volvo Cars, Torslanda, where all white bodies follow through the process line.

2.1.2 Implementation and integration of collaborative system in a paint process

It is common for most manufacturing industries to invest in complete solution from supplier or contractors, or by partially upgrade or exchange the equipment as machines break or that they are no longer compatible with surrounding equipment and systems. A complex paint plant makes minor upgrades, but major implementations can be difficult as processes and surrounding systems are highly integrated with each other. A plant is therefore created to have a life span of 20-30 years, which also becomes a major investment for the company [4].

It is important for the company to be able to count on all expenses, and the importance of making detailed requirements specifications is crucial to have a good implementation standard further on even though minor changes or replacement of different systems will be done. Requirements for energy savings and flow efficiency can also lead to information from the entire process to be necessary for analysis and improvement work during the lifetime of a plant [5].

2.1.3 Visualization of event and progress in production system

Just as communication is important between people, communication between operators and machines is as important. Therefore, systems and production equipment

are developed with user-friendly visual interfaces with good and useful information, also known as the HMI (human machine interface) [6].
The visual interface is meant to highlight information that may be useful to a user, but also to be able to navigate and control the process. Different machines may have different types of interfaces depending on the supplier or which purpose the machine has. It may also target different types of users, such as operators, engineers or management.
For a better understanding and overview of the production, the interfaces can be used for multiple systems and production lines. Since interfaces may be included when purchasing a new machine, several versions and standard of execution can be discovered throughout the plant, which may over time cause compatibility issues with other systems. It could also lead to difficulties for users to easily understand all different versions due to the different standards [6].

2.2 Modeling and simulation of complex systems

In order to design and improve complex production systems, it may be advantageous to use theoretical models and simulation for testing and analysis of how the system behaves. It is important then to have reliable models that behave like the real system to to draw the right conclusions. There are several ways to do this on which will be touched more in this section.

2.2.1 Modeling of systems using formal methods

Since the growing complexity of the control problems in manufacturing industries as well as the demand for reduced development time, a formal approach in control systems is highly useful due to verification and validation procedures which the formal methods includes for static and dynamic properties in a complex system [7].
Formal methods are a mathematically based languages, techniques, and a tools for specifying and verifying systems and can be divided into two types; verification and synthesis, where verification usually is based on model-checking and where synthesis is based on the supervisory control theory (SCT) [8].
A model is described as an uncontrolled plant with different states as possible outcomes from certain events, constraints or inputs. For SCT, a plant has a specification for how the plant is supposed to behave, with the aim of constructing a supervisor to restrict and guarantee the right behavior of the modelled system [9].

2.2.2 Discrete event system and continuous dynamic system

When modeling a discrete sequence-based system, it may result in problems regarding synthesis and verification issues due to the size and complexity of a process [10].
To approach this, the Supervisory Control Theory (SCT) can be applied to construct controllable and non-blocking supervisors. The theory is used to solve synthesis and verification by graphically represent the process as discrete states with either petri net[11] or automata[12], both with transitions working as guards from an initial state to a desired marked state[8].

Petri nets is called a directed bipartite graph, represented by nodes (circles) as the state, connected by next node through arrows and transition, represented by bars. The initial state/node has a token, represented by a dot, and follows the directed arcs which places are pre- and/or postconditions for which transitions.
Automata is like the petri nets but does not use a token and bars for transitions, instead arrows of uncontrolled or controlled events. Figure 2.2 shows an example of how two small sequence-based systems is described as automata and combined with synthesis to form a larger state machine.

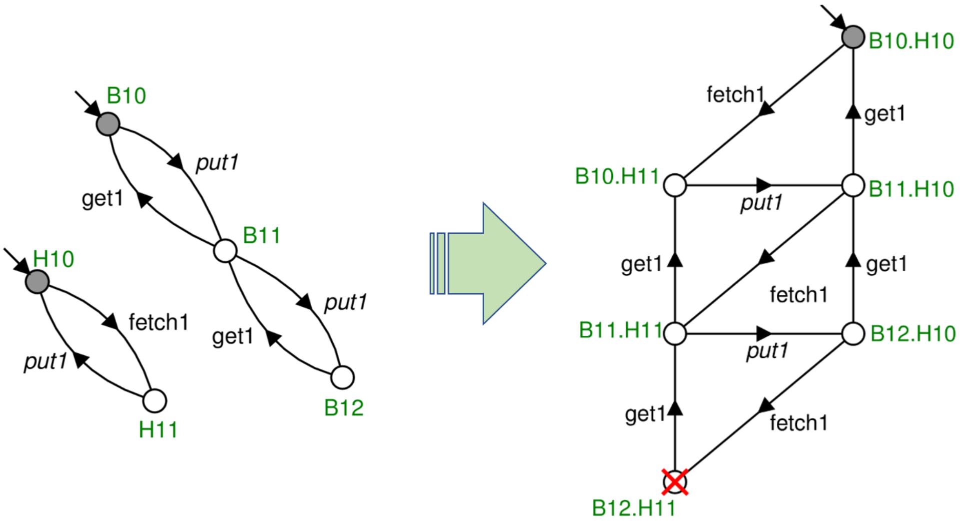


Figure 2.2: Example of two smaller automaton, describing a buffer and a handler system, that through synthesis creates a larger automaton with shared events.

It is very important to consider when modeling a real-world system, that the amount of possible discrete state can be too large to comprehend for simulation which would result in a so called state space explosion problem [10] and that is also why SCT can be of great use by using methods called modular synthesis and compositional synthesis to design a supervisor with properties such as guaranteed controllability and reduced number of possible states [8].

2.2.3 Virtual commissioning of a production system

Virtual commissioning (VC) is a concept concerning the visualization, programming and validation of a production system in a virtual environment, as a preparational step for the construction of new manufacturing plants or changes to an existing one [13, 14].
This method of modeling can be done in several ways, but often used in specialized simulation software with implementation of 3D-CAD drawings together a hardware-in-loop configuration, where the actual control logic and code can be tested for a production system [15]. The model is shown in 3D which gives an extra dimension of understanding on how a system operates. This method can save a lot of time and money since it reduces the actual commissioning time but modeling can be rather time consuming due to the level of details and visualization of a running system [16].

In [17], virtual commissioning was done with additional virtual reality equipment, for a user to freely walk around in a running simulation and both control a virtual visual interface as well as interfere and test the safety functions.

2.3 Related work and prior art

With modern technology and global growth in the automation industry, different applications for modeling and visualization of a complex production system has been made with different focus and in several different way which will be mentioned in this section.

2.3.1 Current standard of implementation and Industry 4.0

With the Industry 4.0 and Internet of things as the technical development after the industrial revolution, advanced digitalization within factories and the combination of Internet technologies and future-oriented technologies in the smart factory concept [18] has created a paradigm shift in industrial production [19]. Future production systems contain modular and efficient solutions, where every piece of equipment is connected and online for gaining knowledge of the process with all kinds of information and data accessible in a cyber-physical system architecture [20, 21].

With a big data environment, process data can be analyzed at any time and information about the production progress can be more intuitive. Instead of only statistical assumption used for preventive maintenance, algorithms using high-level knowledge for predictive maintenance can be applied for better error prediction or production efficiency as in [22].

2.3.2 The Tweeting Factory and LISA

In the paper “Modeling and optimization of hybrid systems for the tweeting factory “ [23], the concept of the tweeting factory is presented, where a predicate transition model for discrete event systems is generalized to include continuous dynamics. The concept is as it sounds, machines and low-level control systems which sends simple messages to a flexible online and event-based information architecture where it later can be used as high-level knowledge for further analyses and development.

The Line Information System Architecture (LISA) is presented in the paper “An event-driven manufacturing information system architecture for Industry 4.0” [24], where the idea is to utilize all data from an entire plant to obtain real-time information for decision-making. LISA is integrated for devices and services on both low and high-level control and enables usages of new smart services and analyzing tool. The body shop at Volvo Cars Torslanda has been evaluated and installed this architecture for real industrial data.

2.3.3 Sequence Planner - The Control Tower

Sequence Planner (SP), is a modeling and analysis tool of operation sequences, developed by employees at Chalmers University of Technology. The tool is developed in java, scala and functional programming and can be used as a high-level control system by listening to input from formal representations of the relation between product properties and process operations. The information which is obtained can then be translated into a formal graphical language for hierarchical operations and sequences of operations (SOPs), like the automata representation. This tool has been used for several application in the automation industry for control and optimization as in the paper “Sequence Planning for Integrated Product, Process and Automation Design” [8].

Sequence Planner is also used to control and determine in what order operations should execute. This is done by include high-level requirements, such as process parameters, constraints and safety concerns, to ensure that the supposed operation always execute before another and vice versa. The paper “Sequence planning using multiple and coordinated sequences of operations “ [25] is presenting the usage of SP and how the ordering of operation is beneficial for the industry.

3

Pre-study, analysis and collection of data from existing plant

In order to gain knowledge to make correct assumptions and good estimations, both interviews is carried out and scientific research are presented in this chapter with a summarized analysis.

3.1 Interviews with Volvo Cars employees

The focus of this report lies on the painting process and its associated systems. To obtain a good understanding of the interaction between the systems involved, technical information is required. Instead of collecting and reading technical documents and risking outdated information, interviews with technicians, engineers and managers at Volvo Cars are selected to get hands on information.

The following generalized questions were given to each selected employee by email in advance to have a well-prepared, relevant and good discussion:

- What are the preconditions for this specific system to start?
- What happen during the starting sequence?
- Which other systems are interfering during its run?
- What type of and how many resources does the system contain?
- What type of dynamic and data is processed and controlled?
- What are the inputs and outputs of the system?
- How user-friendly is the visual interface, if there exists one?
- What is the most frequently error occurrence?
- Which level of security is applied and integrated on the system and how does it effect the system when triggered?
- Are there any potential improvements?
- Would it be possible to reduce the energy consumption by possible future improvements?

The relevant information from all the different interviews are summarized in this sections.

3.1.1 Paint application and robot

A painting booth usually consists of between 4 to 10 painting robots depending on how the plant is designed, how the flow is constructed and in which stage of the process the booth is located. There are both robots for interior and exterior painting and the robots differ slightly depending on whether they are for primer, base coat or clear paint application.

All robots have their own unique set of trajectories but have the same functionality regarding the operating system and paint applicator. Pre-condition for starting is to be at home position with a cleaned applicator. The robot works as a slave to the PLC in most cases and can handle a lot of information regarding the paint process due to the paint applicator system attached to it. Since the robots have their own control system from the supplier, handling the complexity of the applicator, the focus will be to extract that information to the PLC for visualization and event logging.

A robot is depending on the safety circuit in the booth in order to operate, but it also needs to have air supply, high voltage from a cascade and paint/solvent pressure from the media supply system.

A CAD-drawing of a booth is shown in Appendix 1, Figure A.1.

3.1.2 Media supply system

The media supply to the base coat consists of 24 tanks of different colors, powered by hydraulic pumps to provide the correct color to the painting robots. The clear coat has 4 options mixed with hardener and the primer painting has 3 basic colors to choose from. Additionally, all robots have a solvent of some sort provided for cleaning the applicator.

This system is operating rather independent from the other systems, but is vital for the process and therefore very necessary to operate at all time. The system has its own visual interface for control and system diagnosis, but this information is not provided to any other system except for the pressure sensors which is send to the paint booth. This can cause problem when an error occur since only the workers at that specific place can react to it and manually inform the management or maintenance if needed.

This system is also a big energy consumer since the powerpack keeps all the hydraulic pumps ready to go at all time. With new developed paint with better properties, the need to be in circulation at all time to prevent dryness is not necessary.

3.1.3 Air supply system

The air supply system is the most dynamic and sensitive system due to a strict control of the humidity, temperature and falling speed of the air in the painting booth. All these parameters have a direct affect on the quality of the paint application.

The fall speed of the circulated air is correlated to the amount of paint that will attach and cover the car body, combined with an electrical field generated by the paint applicator at the robot which will point the paint towards the car due to a lower electrical potential. For the electrical field to perform under best condition, the humidity level must be around 62% with a tolerance of 2%. The efficiency for a modern applicator is up to 80% at best. If the humidity is to high, the air would be more electrically conductive and the high voltage from the applicator could then harm the body, leaving marks and result in bad quality. If the electrically conductive air would have less humidity, the high voltage would find the potential grounding for the robot more suitable to charge against instead of the body, resulting in less control over the paint covering the body.

The temperature in the booth is of importance due to the specification of the paint which has the best properties around 22°C. Lower temperature would cause the paint to be viscous, and higher temperature would cause the waterborne coating to vaporize or shift in color.

The air system is interfered by several systems, especially the water curtain system which usually has a lower water temperature and the intermediate and subsequent ovens that have a high process temperature. This must be regularly compensated for by the system. The water system also raises the air humidity level while the color system can implicate with solvent mist and other chemicals in the air, which must be filtered before it returns again.

It is difficult to measure and monitor what happens during the process, especially difficult to which of any system that caused an error. The system is also sensitive for incoming fresh air or by something as simple as the lighting in the booth. The communication between the air supply system and the booth is just the drift status and sensor values, which is visualized in a control interface for the operators, but the air system will not give all information and can for example not notice when the filters or damper are blocked, which can cause serious confusion for operators and technicians during the process.

A CAD-drawing of an air supply system and the area of filter and air distribution (plenum) are shown in Appendix 1, Figure A.4, respectively Figure A.3.

3.1.4 Water curtain and water cleaning system

The water curtains work as a collector for media waste in a booth and is places right under the running conveyor in the booth as a tilted floor. This system must be started for the air supply system to work and for the robots to get permission to paint since solvent media can be highly flammable if landing on dry surfaces.

The water is coming from big tanks in the basement and is distributed by several pumps to the booth. When the water returning, it must pass through additional tanks for cleaning, where waste can be separated from the water as well chemicals. It is a rather independent system with a process of its own and is like the media supply system not connected to a shared platform of information which makes it hard to follow the progress. Except for the fluid dynamics and measurement of chemicals, the system is not very dynamic since it is either on or off. It will on the other hand consume a lot of energy due to the big pumps, but depending on the operating mode in the booth, not the same amount of water is needed all the time.

A CAD-drawing of a basement with water curtain and associated water cleaning system is shown in Appendix 1, Figure A.2.

3.1.5 Oven and dryer system

The ovens are large systems and designed as closed tunnels where the car bodies pass through at a certain rate to dry the paint from previous station. All ovens are basically structured in the same way, but the difference is features and upgrades that may have come with newer models along the years.

The first section of an oven is a preheat system using IR followed by a warm air heating procedure, where natural gas fuels a burner to heat fresh air to a desired temperature, usually around 200-300 ° C. Several damper directs the air in the right amount into the oven for best quality before returning the air to the burner where the temperature is adjusted and controlled.

The start procedure for an oven is time consuming as a large amount of air is to be heated and this must always be done before the rest of the production is started. The start-up routine is done according to a manual approach, where start conditions are checked by technicians. Once the equipment is started, it runs continuously and constantly communicates with the previous system how the operating mode is, because it is very important that no bodies are stuck in the oven due to logistic error or malfunctions as this would damage the car body. The transport system must therefore keep track on how many bodies can enter the oven at a time to guarantee a buffer spot after leaving the oven.

The shut-down routine is also a slow process since hot air needs to escape out of the tunnel to decrease in temperature. To speed up this process, cold fresh air can be passed through the tunnel, called emergency shut-down, letting the hot air escape through the chimney on the roof, which also implies that cold air passes through the burner, which could result in tougher compression damage in the burner and in the air ducts. This has been a more common handling of the oven, as time can be limited for a stressed production plant.

3.1.6 Transport system and car body logistic

The transport system is the system which connects all the system related to the car bodies and keeps track of all buffers and all product data concerning each different car body. It consists of several horizontal and vertical conveyors and is using RFID-encoders (radio-frequency identification) to know where the bodies are located when passing by. For process planning, an additional software tool is used to control and operate how the bodies will move depending on priority and color grouping.

The safety circuits in the transport system is directly connected through every station, divided into different zones, which will prevent any movement if not satisfied. The control logic is basically only low-level components with no high-level knowledge and will therefore only do what is ordered by the process planning schedule.

3.1.7 Safety and legal restrictions

The most important of all things in every industrial manufacturing plant is to keep the workers out of harms way. Safety is therefore critical to prevent any accident from happening, but also for the safety of the equipment which can be damaged.

As already mentioned in previous interviews, some system is directly sharing safety circuits while other have their own or even non-existing. All systems are analyzed according to given safety standard protocol and legal restrictions and if a system would not risk harming an operator, it may not be of interest to invest in such solutions.

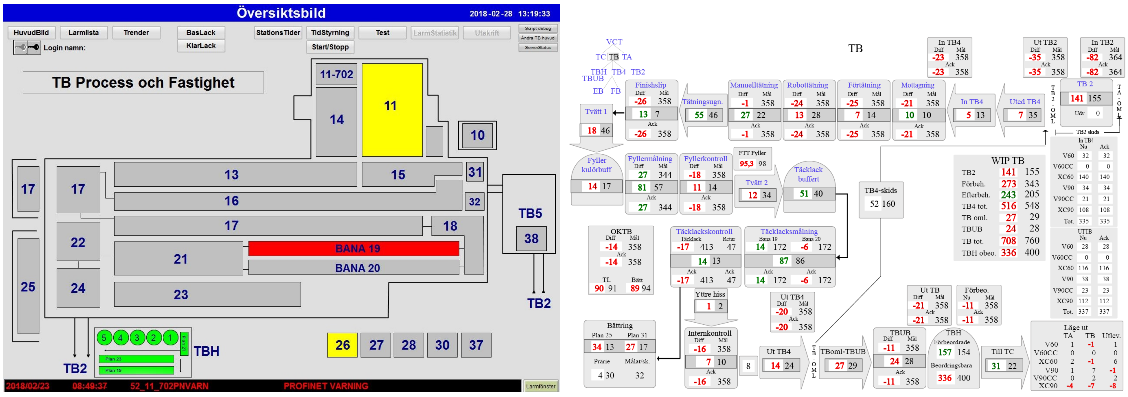
Due to safety classifications on different machines and equipment, it could mean that it is not allowed to be controlled by a third-party user. Accident will find its way, regardless on how much effort a company put into prevent it, but for a large, complex system with collaborative system on different location, it would be of great use if the information and status from surrounding system would be shown for every user and operator. For future application where high-level control may be of interest, it will be of highest importance to make sure nothing bad will happen in another system when the start button is triggered.

3.1.8 Current visual interface at the paint shop

As mentioned, there exists several different machine interfaces for the user due to different suppliers with their own standard and conception but also because of older and newer models. Each HMI have a certain operating system, using a certain industrial communication standard like Ethernet or profibus and then will describe different aspects of the process. To extract and listen to the older systems, some additional equipment may need to be integrated, therefore making it very hard to obtain all useful data with ease from all systems.

At the paint shop, a technical top view is used with the extracted data from most of the systems, where status and operating mode is shown with the extension of limited top control for the air supply and water supply system. The data is stored on a server with 2 additional backup servers.

Regarding the production overview for management, another top view is used which gathers data from the transport systems to show production rate, buffer status and predicted output from each station. Both of these top views is shown in Figure 3.1.



(a) Technical overview.

(b) Production overview.

Figure 3.1: First figure showing the top view over the current process from a technical perspective and the second figure showing the top view from a production management perspective.

Additional extra features can make use of the extracted data from both system to create clients application for devices like alarm notification for maintenance technicians or to managers cellphones.

3.2 Brief study on existing communication and safety of machinery standard

For all new implementation of machinery and equipment, Volvo Cars relies on their own standard called "Safety of machinery - General principles for design" (VCS 8010,39), which has been completely re-worked and based on the new standard ISO 12100:2010.
The general principles for designing new production lines must include a risk assessment and risk reduction plan with support from ISO 12100:2010 and is carried out to each supplier or contractor together with additional technical specifications.
The standard describes to which extend safety equipment should work and be used, like emergency stop, Safety Placards (SP) for machinery and Power Lockout routines.
Regarding standard for control and communication, ISA-95 (IEC 62264) has been used for LISA in the body shop at Volvo Cars and contains several elements how the visual interfaces are constructed.
The standard is separating control logic and information into four different levels where the first and second level monitors the sensor data from a process regarding continuous and discrete control with the time frame of hours, minutes and seconds.
The third level is for manufacturing and operation management with focus on work flow, procedure and top control, with the time frame of days, shift, hours and minutes.
The fourth level is for business planning and logistic for establishing a basic plant schedule of the production with regards to material usages, inventory, delivery and shipping time, with the time frame of month, weeks and days.
To extract information from new implementations using ISA-95, Volvo Cars uses a Virtual Device (VD), developed and runs as a standard JAVA application to deploy in any of the target platforms used at Volvo Cars: OpenVMS, Windows and Linux. VD also has built in support for management and monitoring by use of Java Management Extension (JMX).

3.3 Complexity and communication between collaborative system

To summarize the outcome and highlight the most important points from the preliminary study, complexity increases with the number of systems that exchange information in the same way as process control with several parameters puts high demands on surrounding equipment. Due to non-existing standards for implementation and old and outdated equipment, a lot of information is not available nor visualized since several systems are not communicating.

To illustrate this, Figure 3.2 shows a simplified flow chart of how the systems are communicating with the resources with the current technology in the paint shop.

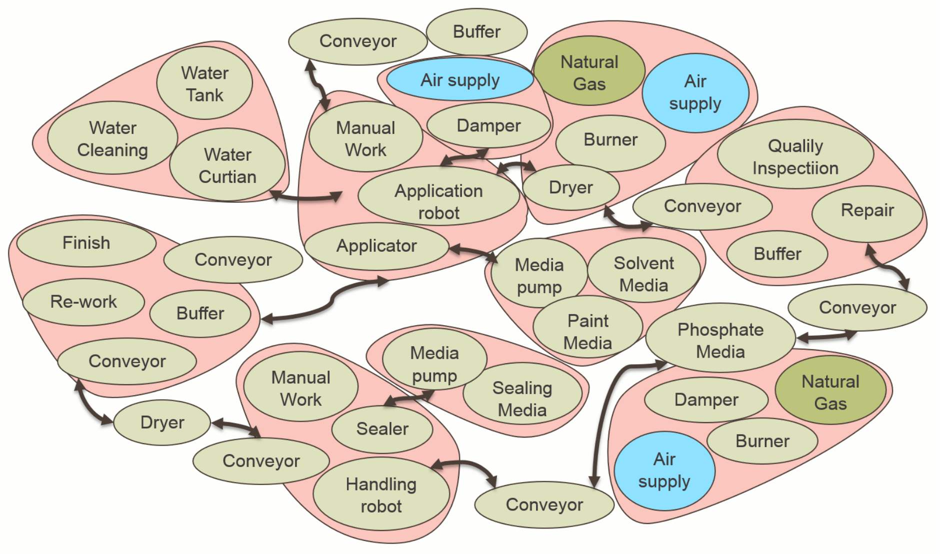


Figure 3.2: Illustration of a fictive painting plant with different kinds of resources grouped together creating a smaller area or station with collaborated systems partly communicating with the surrounding systems. The arrows represent how the system is joined together and partly how the car bodies is moving between each station.

4

Experimental setup for the simulated concept model

This chapter will describe the chosen components and software needed to model, build, run, visualize and evaluate a simulation of a paint process.

4.1 The Control Tower Hierarchy

Sequence Planner, is a tool for modeling and analysis of operation sequences but can also be used as a high-level control or a detailed scheduling system.

The unique traits of SP as a control system are:

- Mathematically guarantee of functional and safety requirements using formal methods
- Optimization of operation sequences
- Flexible control structures of operation sequences instead of hard coded sequences
- Autonomous and collaborative systems control
- Handling variability of products and operations

The control is divided into two main parts. One that handles the low-level control, called the Virtual Device (VD) and one that is handling the operations. When creating the control for a new system, one or many VDs are defined depending on the amount of resources followed by how many operations is needed and what type of products that are utilizing the system. The control systems used for the actual control, like PLCs, micro-controllers or robot controllers can be used in some cases if needed due to VDs support for external communication.

A VD can join multiple resources and their abilities into one logical entity that manages the communication with the hardware, or simulation in this thesis, with the rest of SP. The three layers of a VD together with the rest of SP's control hierarchy and features is shown in Figure 4.1.

For this thesis, SP will be act as a simulation, where the VDs driver segment will listen to created physical entities needed to describe the dynamic behavior of the paint shops different resources. SP is a suitable tool for this task since it has already been used at Volvo Cars before and because of the technical support which exist at Chalmers University of Technology.

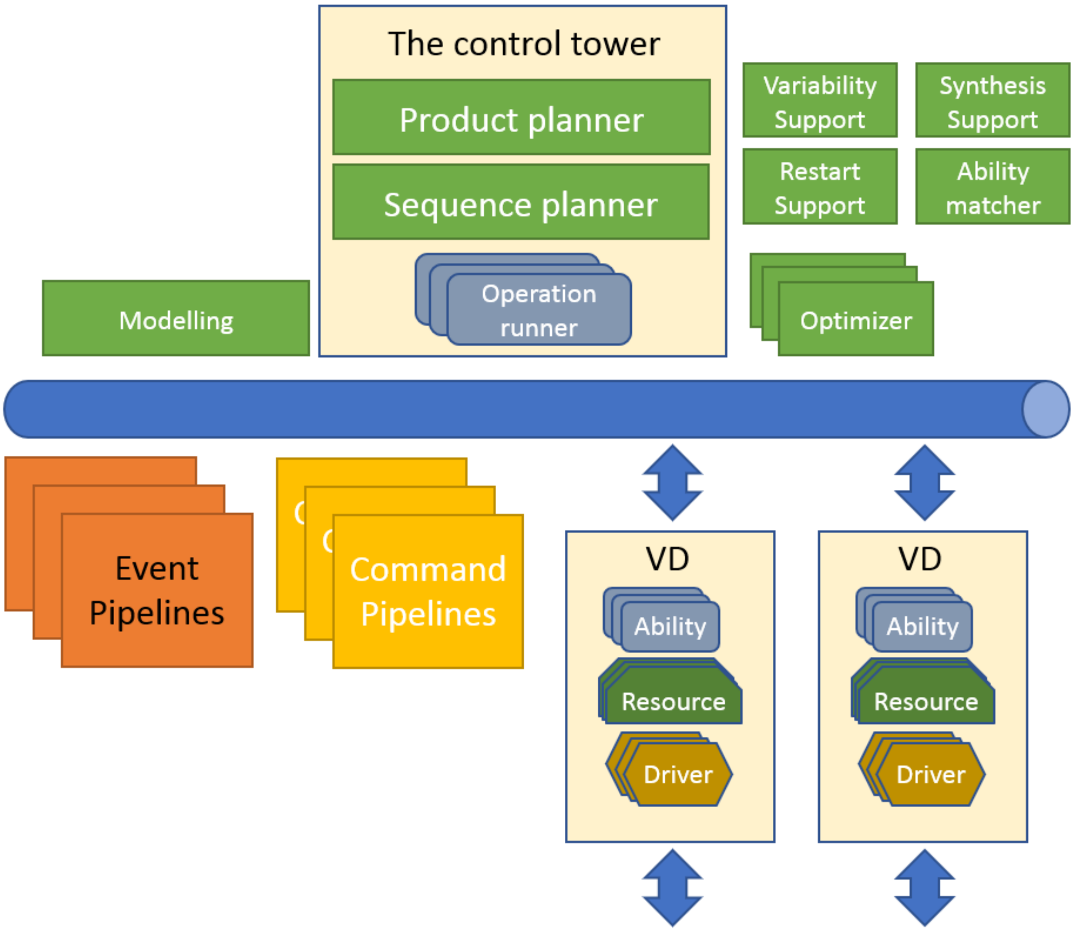


Figure 4.1: Illustration of how the control tower hierarchy is structured with all supportive functions and features communicating on a shared service bus.

4.2 Human machine interface using WinCC

The chosen platform for creating a visual interface is WinCC Runtime Advance, which is integrated in Siemens TIA-Portal V13 for PLC applications and is very common in manufacturing industries. A simulated PLC is implemented to the HMI project using S7-PLCSim V13 and will only handle the visual HMI-logic and will not interfere with any logic from the simulation. The PLC can, in addition, also be used to read and log information and events in the running simulation in SP through the HMI. The configuration is shown in Figure 4.2.

An interface can be designed in several different ways using different tools and software's, but the decision going with WinCC is partly due to it being widely used at Volvo Cars and many other industries, but also for the support of external communication which will be of good use when integrated with an external simulation.

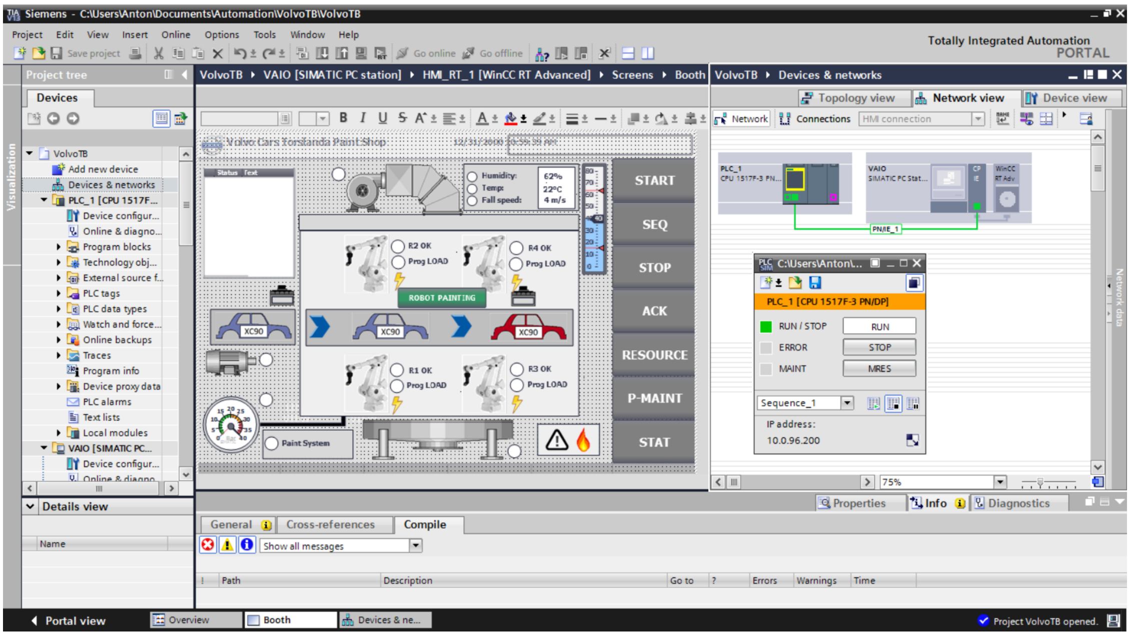


Figure 4.2: TIA-portal V13 with WinCC Runtime Advance and a simulated PLC using S7-PLCSim V13.

4.3 Virtual communication bus using OPC UA

To have a signal exchange between a visual interface and a running process, some standardized way of communication is of need. Well established techniques that are used within the field are OPC DA, or OPC UA, which with a standardized protocol transmit signals between the different clients over Ethernet.

By using WinCC Runtime Advance, a full configured OPC UA server can be provided which has support for standardized communication with other clients using the same protocol. Sequence Planner does also have support for OPC UA and is therefore also a suitable way to go.

4.4 Complete setup of the simulated model with human machine interface

SP will apply its hierarchy to construct a model of a paint plant with additional physics elements to be able to run a simulation. With the support of OPC UA as a communication solution, a developed human machine interface is designed and configured with a fully functional OPC UA server, to show and illustrate the extracted information and events occurring in the simulation as a proof of concept.

The complete setup for the simulation is illustrated in Figure 4.3.

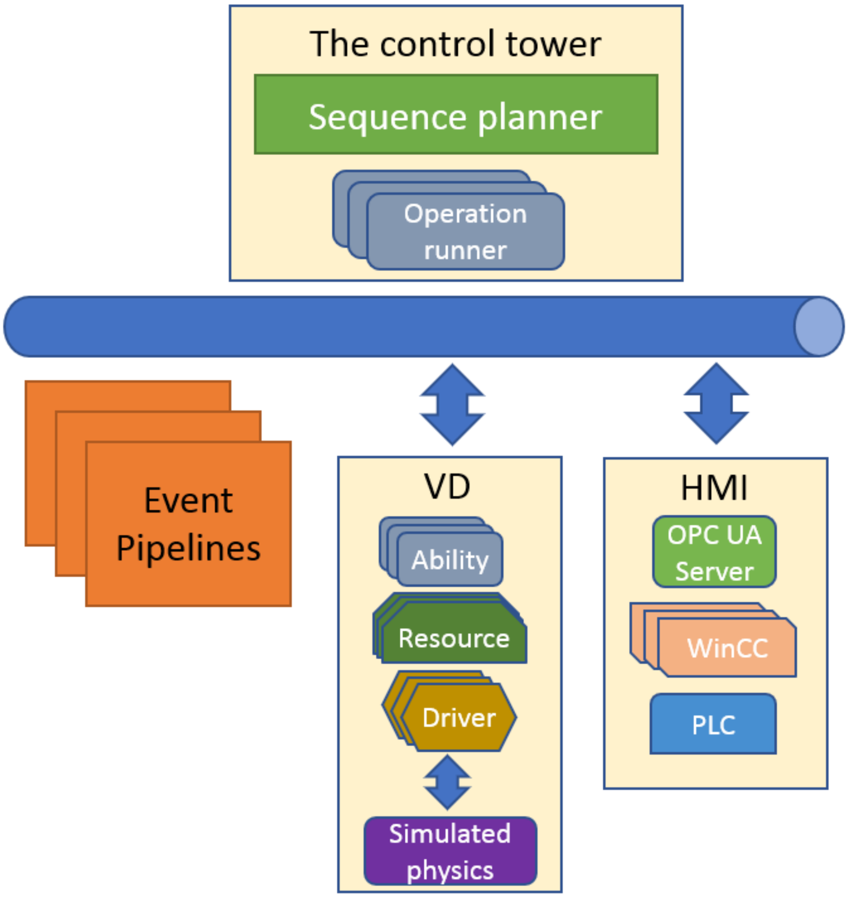


Figure 4.3: An illustration of how the experimental setup is using Sequence Planner without its extra features. Additional to the illustration is the developed HMI connected by OPC UA to the service bus together with a physics simulator embedded into the VD-structure.

5

Simulation of concept model and data extraction

This chapter will show how the concept model is constructed using the setup described in Chapter 4 and how the human machine interface is designed and how it make use of the data to visualize a running simulated process.

5.1 The simulated concept model

With the information of a running process given by the several interviews listed in Section 3.1, a simplified specification is created using Sequence Planner as a tool for modeling to evaluate and test it in a running simulation.

5.1.1 Defined resources and properties

The concept model will be reduced in size in comparison with a real process with more focus on the signal exchange and data extraction rather than the complexity of each different resources.
The modelled paint booth will contain:

- 1 conveyor for transport of car bodies
- 4 spray paint robots
- 4 paint media supply pumps
- 10 white car bodies in a buffer

All listed components have certain properties as sensors, length/size and physical placement, a simplified overview is illustrated in Figure 5.1. The car bodies are modelled as dynamic variables for keeping track of the process with additional information as body type and color code and are therefore not defined as resources like the other components.
A resource has drivers that listens to simulated dynamic variables, as pressure for the media pumps. A simulated time perception is provided for all resources that will operate under certain time frames since time does not normally exist in sequence based modeling and most therefore be constructed. This is also the case for SP which normally has drivers in direct contact with actual sensors from a physical system.
The different resources are defined with abilities as:

- Robot: program number, home position, start, stop
- Conveyor: start, stop, zones, presence sensor

- Pumps: pressure sensor, start, stop

The abilities may also include specific functionality as programs, modes and operations. The robot has several time dependent programs, while the conveyor has a set velocity and where the pumps has pressurize and depressurize modes.

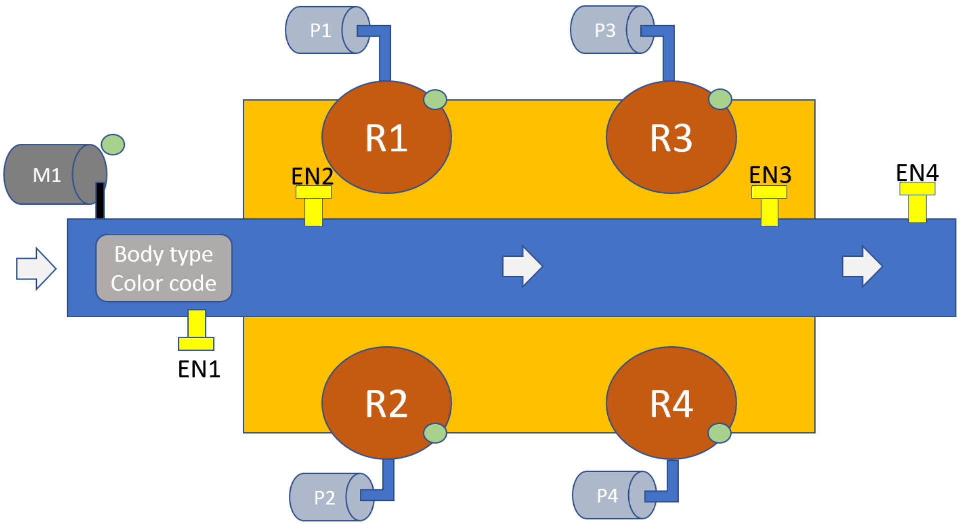


Figure 5.1: A simplified illustration of the main components in the constructed concept model.

5.1.2 Running sequences and plant definition

Sequence Planner wraps together the resources creates operations based on the abilities each resource has, to make a sequence flow chart for the process. The different operations constructed by SP are:

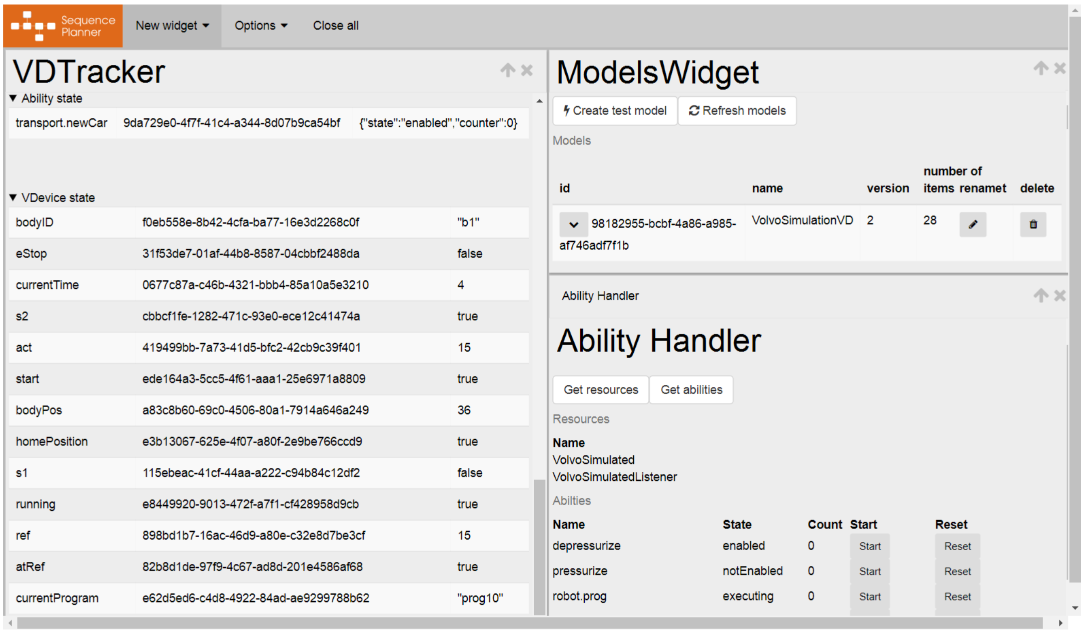
- call_newbody
- start_robotprog
- start_conveyor
- stop_conveyor
- start_pressurize
- start_depressurize

By pressing start in the visual interface for the booth, a sequence of events will start. First, the conveyor will start and if the first presence sensor in not active, a new car body will appear from the buffer. When the sensor gets a positive edge, the media supply pumps will activate and start building pressure for the spray robots. When the pressure sensor is at 15 bar and the car body has proceed in to the painting zone in the booth, the robots will run their given program for 10 seconds. When completed, the pumps will decrease the pressure back to 0 bar. After the body has left the booth and triggered the last presence sensor at the conveyor, the sequence repeats itself by calling for a new body. This is done for all 10 bodies before the buffer is empty and the conveyor stops.

5.2 Virtual Device and data extraction

The defined resources with their abilities and drivers are coded into scala-scripts, compiled in SBT, which is a build in scala compiler for Windows through the command prompt (cmd).

The "Ability" segment in VD allows SP to extract and monitor all information generated in the simulation. SP also contains support for control using a widget in the internet browser as seen in Figure 5.2. The widget imports the compiled scala-script as the result of SPs wrapping of the resources, now also including the defined operations which is seen under "ModelsWidget" in the figure. "VDTracker" lists all the defined signals and parameters for the process and the "Ability Handler" shows which operation is currently executing.



▼ Ability state

transport.newCar	9da729e0-4f7f-41c4-a344-8d07b9ca54bf	{"state":"enabled","counter":0}

▼ VDevice state

bodyID	f0eb558e-8b42-4cfa-ba77-16e3d2268c0f	"b1"
eStop	31f53de7-01af-44b8-8587-04cbbf2488da	false
currentTime	0677c87a-c46b-4321-bbb4-85a10a5e3210	4
s2	cbbcf1fe-1282-471c-93e0-ece12c41474a	true
act	419499bb-7a73-41d5-bfc2-42cb9c39f401	15
start	ede164a3-5cc5-4f61-aaa1-25e6971a8809	true
bodyPos	a83c8b60-69c0-4506-80a1-7914a646a249	36
homePosition	e3b13067-625e-4f07-a80f-2e9be766ccd9	true
s1	115ebeac-41cf-44aa-a222-c94b84c12df2	false
running	e8449920-9013-472f-a7f1-cf428958d9cb	true
ref	898bd1b7-16ac-46d9-a80e-c32e8d7be3cf	15
atRef	82b8d1de-97f9-4c67-ad8d-201e4586af68	true
currentProgram	e62d5ed6-c4d8-4922-84ad-ae9299788b62	"prog10"

Models

id	name	version	number of items	renamet	delete
98182955-bcbf-4a86-a985-af746adf7f1b	VolvoSimulationVD	2	28		

Resources

Name
VolvoSimulated
VolvoSimulatedListener

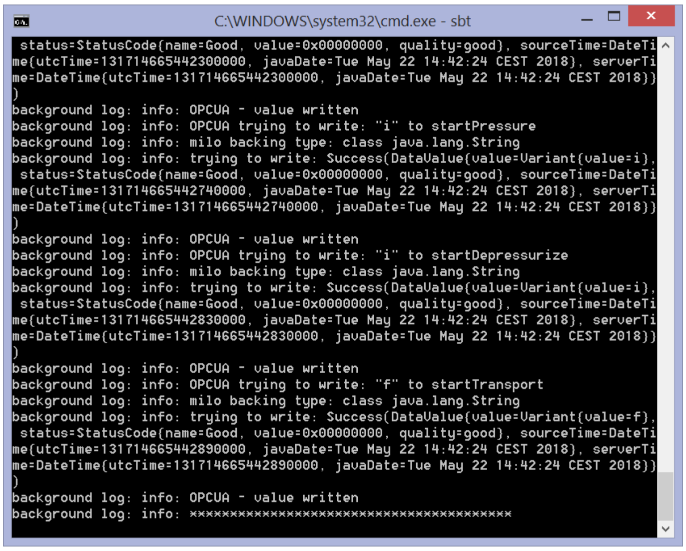
Abilties

Name	State	Count	Start	Reset
depressurize	enabled	0	Start	Reset
pressurize	notEnabled	0	Start	Reset
robot.prog	executing	0	Start	Reset

Figure 5.2: Sequence Planner operating widget running in real-time in the internet browser.

The command prompt will also present the progress and information generated to the event pipeline as raw data from the simulation as seen in Figure 5.3

The PLC will not interfere with the simulation but is used for logging and counting sequence data going through the HMI, just to prove how an event pipeline can be of use for other applications as well.



```
 status=StatusCode{name=Good, value=0x00000000, quality=good}, sourceTime=DateTi
me{utcTime=131714665442300000, javaDate=Tue May 22 14:42:24 CEST 2018}, serverTi
me=DateTime{utcTime=131714665442300000, javaDate=Tue May 22 14:42:24 CEST 2018}}
)
background log: info: OPCUA - value written
background log: info: OPCUA trying to write: "i" to startPressure
background log: info: milo backing type: class java.lang.String
background log: info: trying to write: Success(DataValue{value=Variant{value=i},
 status=StatusCode{name=Good, value=0x00000000, quality=good}, sourceTime=DateTi
me{utcTime=131714665442740000, javaDate=Tue May 22 14:42:24 CEST 2018}, serverTi
me=DateTime{utcTime=131714665442740000, javaDate=Tue May 22 14:42:24 CEST 2018}}
)
background log: info: OPCUA - value written
background log: info: OPCUA trying to write: "i" to startDepressurize
background log: info: milo backing type: class java.lang.String
background log: info: trying to write: Success(DataValue{value=Variant{value=i},
 status=StatusCode{name=Good, value=0x00000000, quality=good}, sourceTime=DateTi
me{utcTime=131714665442830000, javaDate=Tue May 22 14:42:24 CEST 2018}, serverTi
me=DateTime{utcTime=131714665442830000, javaDate=Tue May 22 14:42:24 CEST 2018}}
)
background log: info: OPCUA - value written
background log: info: OPCUA trying to write: "f" to startTransport
background log: info: milo backing type: class java.lang.String
background log: info: trying to write: Success(DataValue{value=Variant{value=f},
 status=StatusCode{name=Good, value=0x00000000, quality=good}, sourceTime=DateTi
me{utcTime=131714665442890000, javaDate=Tue May 22 14:42:24 CEST 2018}, serverTi
me=DateTime{utcTime=131714665442890000, javaDate=Tue May 22 14:42:24 CEST 2018}}
)
background log: info: OPCUA - value written
background log: info: ****************************************
```

Figure 5.3: Event pipeline from the running simulation in SBT, showing every updated event and background information.

5.3 Visualization of data in a running simulation

The information which being extracted in the running simulation can be reachable for other clients on the shared event pipeline, but to make it visual and easy to comprehend, some sort of framework is useful for a standardized implementation strategy.
A constructed framework is seen in Figure 5.4 which now allows full overview since all systems are connected to the same bus. The resources have been grouped with suitable collaborative systems in close contact, both geographically and process related, now forming cells like a painting booth for instance.

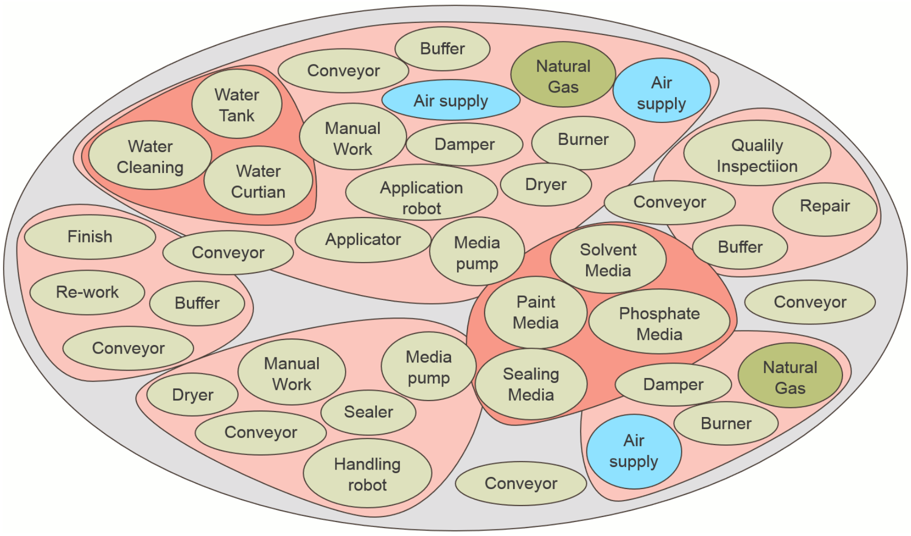


Figure 5.4: A new illustration of a simplified paint shop with the new constructed framework concept.

The framework concept further groups interacting cells to form a production line, where the production line lined together to represent the whole production prosses. These different types of groups are from now on referred to as abstraction levels.

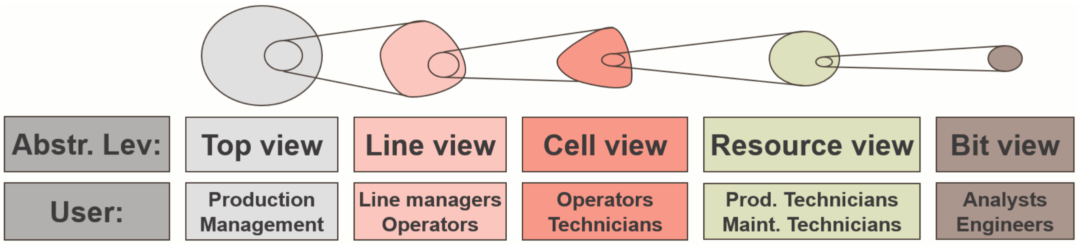


Figure 5.5: Illustration of the framework of the abstraction level from Top view to Bit view.

The abstraction levels, as described in Figure 5.5, representing different parts of the production plant from an users point of view. The users for the top view of the plant are the management which will have relevant information regarding the process and output. The line view addresses a smaller work group of operators with a line manager, which narrows the focus down on that specific area where they are responsible for with relevant information.

The cell view is one part of the production line and addresses to the operators working there for control and supervision of the specific tasks in that cell. In the cell view, the user can pick any resource to open the resource view to gain full access of the dynamic operating there, but is not included in this simulation but could be supported by an user interface from the supplier of the specific resource instead.

The bit view is not visible in a user interface and correlates direct to the raw data from all resources in the shared event pipeline and could be accessed by engineers and analysts.

This chapter will further describe how the different abstraction levels are created and designed for each user level with data from the running simulation. Additional features to certain levels will be presented in Chapter 6, since the simulation only has one cell operating and not a full scaled production plant.

5.3.1 Top view for a simulated model

The top view addresses to the management, or by anyone who needs certain information or overview for the whole process, like for example the maintenance or logistic department. This view will show current operating mode for all subsystems but since the simulation only has one cell implemented and operating, the top view will only show information and status from that booth.

Figure 5.6 shows how the top view is designed using the production flow chart as base with additional functionality and information, both as indicators and pop-up messages. The interface enables the user to point or click at the chart to go down to the line view for that specific area or navigate using the option buttons.

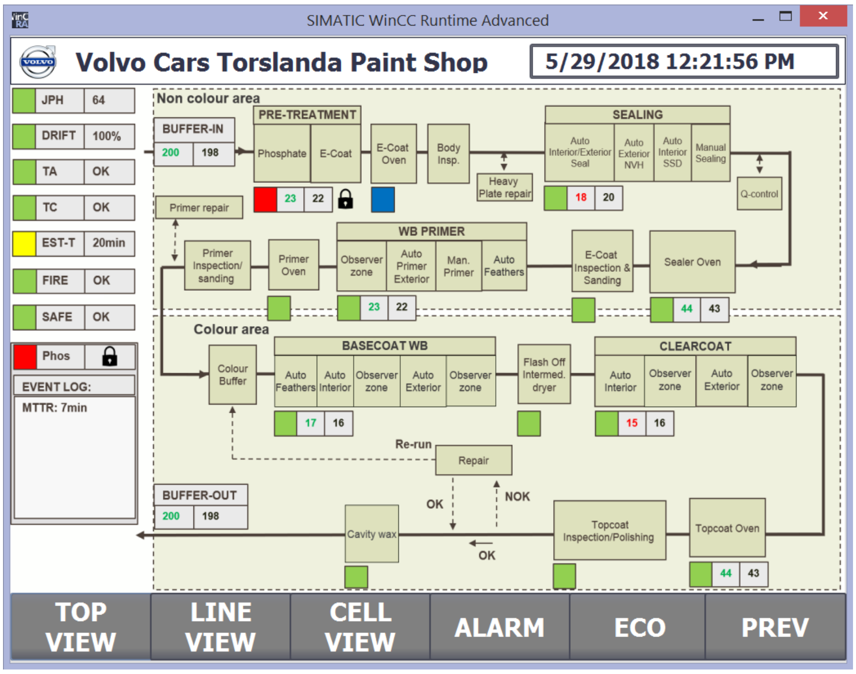


Figure 5.6: Top view interface of a simulated paint process, showing potential features for better understanding of the process for the whole plant.

5.3.2 Line view for a simulated model

The line view for the simulated concept model is shown in Figure 5.7.

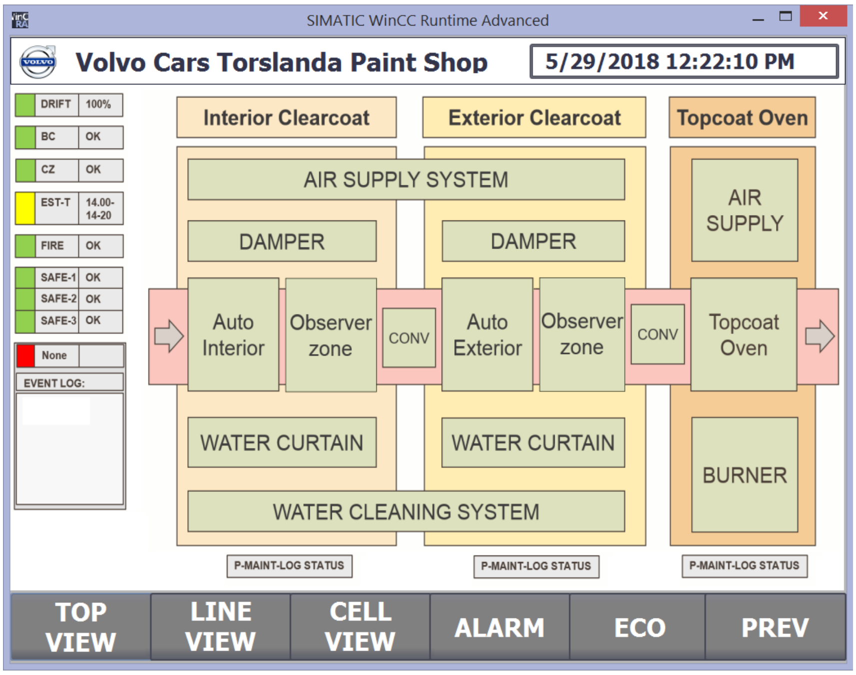
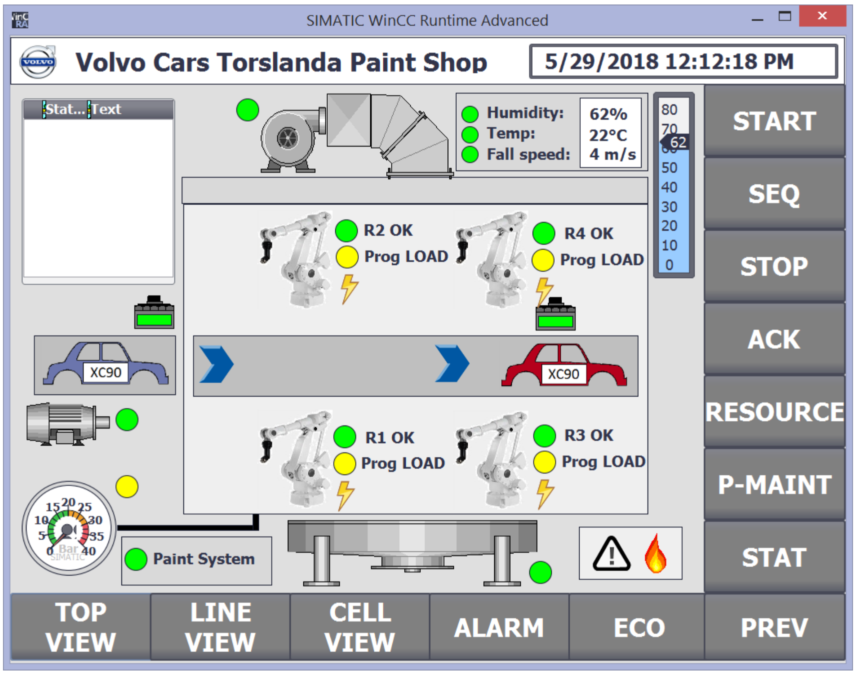


Figure 5.7: Line view interface of a simulated paint process, showing potential features addressed to line managers and operators by geographically close systems for a better understanding of surrounding processes and systems.

This view, particular for this simulation, is showing a production line in the paint area with two different paint booths with additional observer zones with a subsequent oven in one uninterrupted and closed line. Collaborative systems are also present and illustrated as how they are geographically located in relation to the transport system of car bodies. Similar to the top view, relevant information is shown to the left, but modified for this specific line since only information from the previous and next production lines are of interest and not the whole plant.
In this line view, three cells are presented which can be further invested in the cell view. Some of the resources may also be shared between different cells, like the air supply and water cleaning system.

5.3.3 Cell view for a simulated model

The cell view for the simulated concept model is for this case designed to fully represent and visualize the dynamic behaviour and the signal exchange between the different resources and is shown in Figure 5.8.
The sequence explained in Section 5.1.2, is presented by moving illustrations and indicators, together with useful information, both from the system itself but also from the collaborative systems. The cell view have an integrated control panel for operating the simulation by pressing start, stop or acknowledge an error. The view gives support for additional features, like a sequence diagram/chart, an alarm handling view and the current energy consumption.



SIMATIC WinCC Runtime Advanced

Volvo Cars Torslanda Paint Shop

5/29/2018 12:12:18 PM

Humidity: 62%
Temp: 22°C
Fall speed: 4 m/s

Figure 5.8: Cell view interface of a simulated paint process, showing the running simulation in real time with visual effects for better understanding.

Figure 5.9 shows the sequence diagram for the running cell to the right in real-time with more details of each operations transitions and guards (pre- and post conditions). The left diagram shows the diagram for the initialization step.

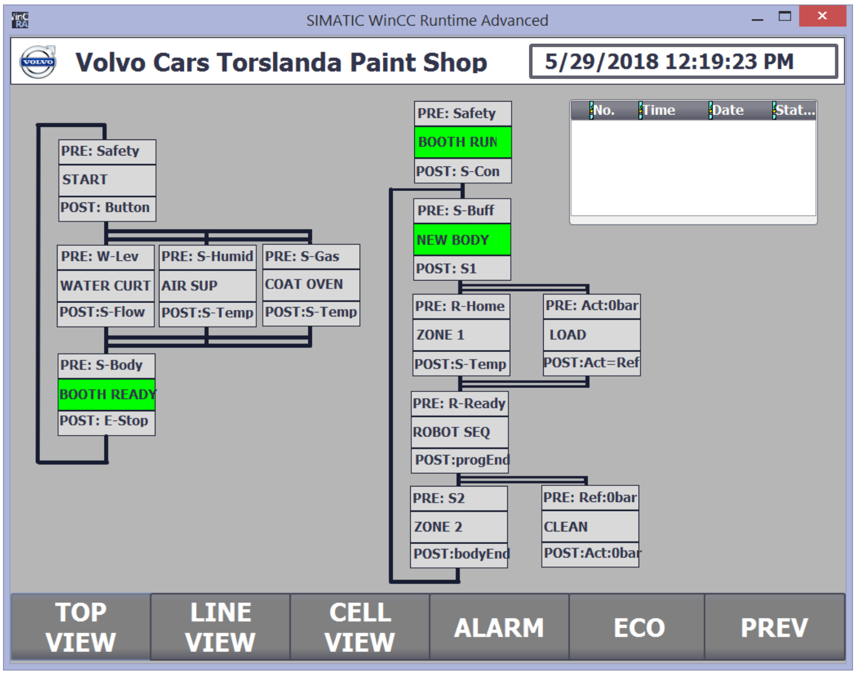
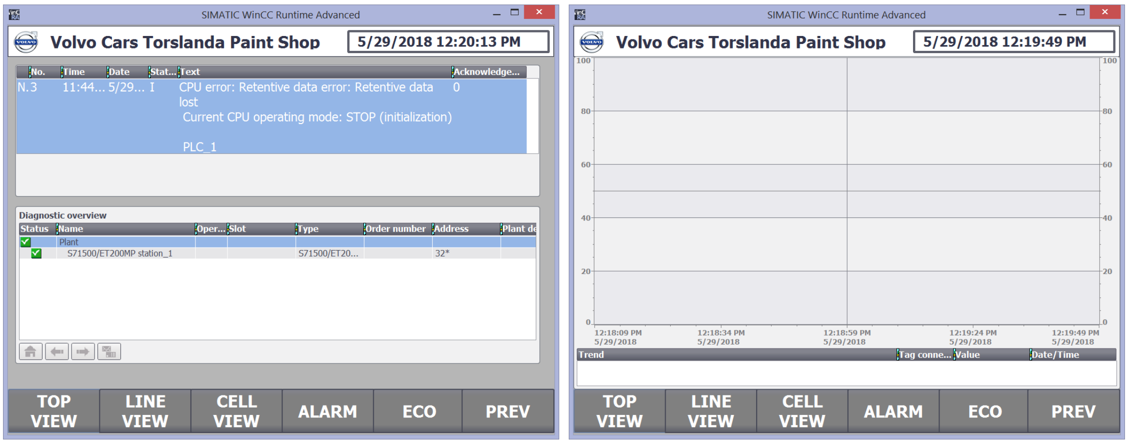


Figure 5.9: A sequence chart connected to the running simulation for easy understanding what is currently being executed.

Figure 5.10 shows the alarm and messages handling view with information sent to the pop-up window in each abstraction level, where also the current energy consumption chart is present.



No.	Time	Date	Stat...	Text	Acknowledge...
N.3	11:44...	5/29...	I	CPU error: Retentive data error: Retentive data lost Current CPU operating mode: STOP (initialization) PLC_1	0

Diagnostic overview

Status	Name	Oper...	Slot	Type	Order number	Address	Plant de
✓	Plant						
✓	S71500/ET200MP station_1			S71500/ET20...		32*	

(a) Alarm view **(b)** Eco view

Figure 5.10: Two more features for the visual interface, showing an alarm handling view and a a energy consumption and diagnosis chart

6
Results

This chapter will present the result of the whole concept idea, including the simulation as a proof of concept, but also with additional improvement and features for a real world future implementation.

6.1 Simulated model of a painting process

The results from the simulation of the concept model in Chapter 5 proves how a visual framework can be applied with the use of extracted data from a process. The benefits of using SP as a tool for handling the logic is the extra features its enables, like control, optimization and support for external connection with other clients using the same protocol for communication. There is currently no support for simulation of dynamic physics entities, but it has proven to be possible for implementation.

Templates for visual interface has been created in WinCC as a standard for each abstraction levels, which will allow additional system (simulation or physical equipment) to be implemented later in the framework hierarchy.

The virtual PLC used for the WinCC-project can also listen and monitor the shared event pipeline, which proves how an external client can build own logic to further analyze and support the process with supporting functions.

6.2 Level of abstraction from a user perspective

This section will present how each level of abstraction in the developed framework can be used if all data would be extracted and which additional features and benefits it can have.

6.2.1 Top view for a framework concept

Instead of having several different interfaces and systems monitoring certain aspects of the process, one complete top view is constructed to include and summarize the important information.

As seen in Figure 6.1, the two old top views from the paint shop is being merged into one, with both technical and process related parameters.

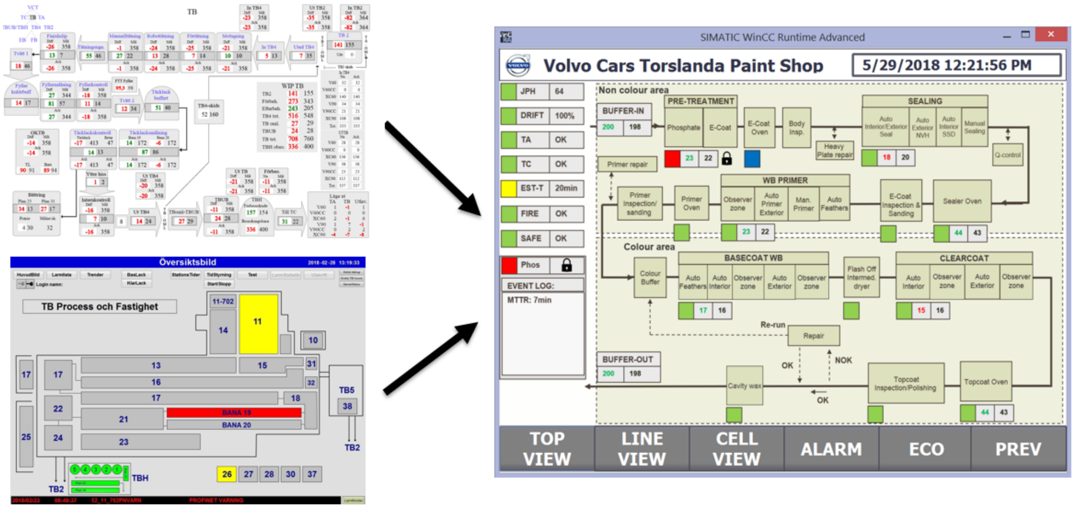


Figure 6.1: An illustration showing how two existing top views merge into one complete top view.

In addition to the top view presented in Figure 5.6, more features can be implemented as:
Maintenance status and progress for current breakdowns - Each machine send information regarding malfunctions and time estimation to start based on previous errors.
Error predictions - Based on statistic and high-level knowledge from a system, mean time to failure (MTTF) or equivalent methods can be shown.
Pop-up notifications from client services - A message window for all kind of information or external application to notify workers in an efficient way.
Energy consumption report - With extra knowledge of each machine and equipment, a report of the resulting energy consumption can be shown to gain knowledge and to take action to improve.
Target parameters and economic forecasts - Process parameters such as production rate, incoming and outgoing buffers together with a economic forecast can be shown.

6.2.2 Line view for a framework concept

For line managers or smaller teams of workers, the line view could support and organize work on daily or weekly basis. In addition to the line view presented in Figure 5.7, more features can be implemented as:
Status from collaborative system - If another process or interfering system have information that could be of use have an impact on the running line, for example, buffer status or blockage somewhere in the production chain, a notification can appear in the interface.
Operating mode and production rate - Information about which mode is currently active the subsystem and how the production rate is effected can be presented.
Prediction on downtime - As for the error prediction in the top view, this feature can estimate how long a breakdown can be which can be of use for smaller unplanned operate maintenance in the line.

Maintenance Report - Latest update from the maintenance report can be presented to share knowledge about errors and how to prevent them.
Weekend Planning - Planned work orders for the weekend can be presented in advance to better utilize the stop time during weekends.
Security and evacuation - In case of emergency, the line view can guide the workers in evacuation and support them with useful information where to call or get help.
Central control management - As long as supported by the limits of the Machinery Directive and safety protocol, some areas could be controlled and started from the line view from a distant location.
Starting procedure and estimated time to start - This can help the workers how to start the system and what need to be done manually, with the addition of a predicted time before started.

6.2.3 Cell view for a framework concept

As in Figure 5.8 but with more features, much depending of what type of cell it is:
Full overview of all interfering systems - Notification from different supportive function can be shown.
Resource status - Next-to-fail-prediction - The interface can keep track on each resource in regard to performance and runtime, notifying the user when a maintenance job needs to be done.
Integrated error management through CMMS (Computerized Maintenance Management System) - The interface sends information to the CMMS for automatic handling of work orders, see more in Section 6.4.2.
Top 5 most common errors and recommended actions - To prevent recurrent malfunctions and support the operator with recommended solutions.

6.2.4 Resource view for a framework concept

This view can implement and support the use from a suppliers interface for any resource. But in addition to that, some extra features can be of great use:
Runtime report - Generates a report with data to follow up the condition of a resource.
Analysis and estimations) - Lets the user create and follow any behaviour in a certain task or operation.
Resources linked to the spare parts management system - If a resource need to be changed, or is about to fail, a notification to the spare parts management system could alarm if a spare part needs to be ordered.

6.3 Level of abstraction from a technological perspective

The bit view in this framework concept is not a visual interface as the rest of the abstraction levels. It will instead represent all extracted data collected from every resource to be both reachable and accessible on the event bus, which is illustrated in Figure 6.2.

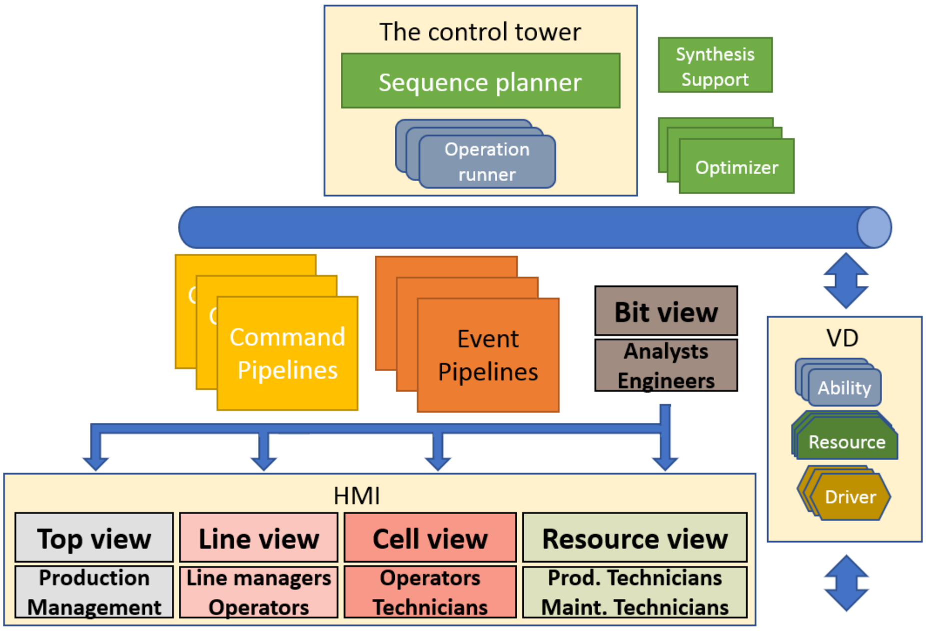


Figure 6.2: Final concept for real world implementation using Sequence Planner and the framework concept to extract and visualize data in several abstraction levels.

The final concept together with Sequence Planner can be used for real world application where the VD factory now listen to physical equipment and generating actual data to the event pipeline and accessible in the bit view to be distributed through the framework to the visual interfaces.

6.4 Functionality and improvements

Based by the information from interviews and analysis described in Section 3.1 together with the supported tools in SP and with the results from simulation, new functionality and improvements can be done for future investments in the paint shop at Volvo Cars.

6.4.1 Energy reducing improvements

When a central control unit in line with the Smart Factory concept is used, an energy effective mode for reducing energy by smart control is made possible. Both media, water and air supply systems can with different solutions reduce the usages or minimize the waste.

The media supply system can instead of using hydraulic pumps for all colors to be run at all time, electric direct started pumps can instead be installed on each tank to run only when the specific color is needed.

By controlling the supply of air in manual painting booths or other parent systems which are not always in use, a developed energy mode could prevent air to be distributed there which would save energy.
It is not optimal to reduce the supply of natural gas to the burners while the process is started but by limit the supply of air, less air would be needed to be heated, which can be distributed to areas which does not need high temperatures at the moment. To avoid the use of emergency cooling in the ovens, the connection to the burner must be restricted or lead away in other air-ducts since only the tunnel needs cooling. This must be specified for the suppliers when constructing new ovens and air-ducts.

6.4.2 Maintenance management system

A Computerized Maintenance Management System (CMMS) which is used today in several industries, is mostly manually carried out by administrators. With a whole process plant, connected to a shared bus with all time stamps data from every cell, the system itself can create and update a work order for every error or breakdown that may occur. Figure 6.3 is showing a typical error occurrence and what is happening in the system during this time.

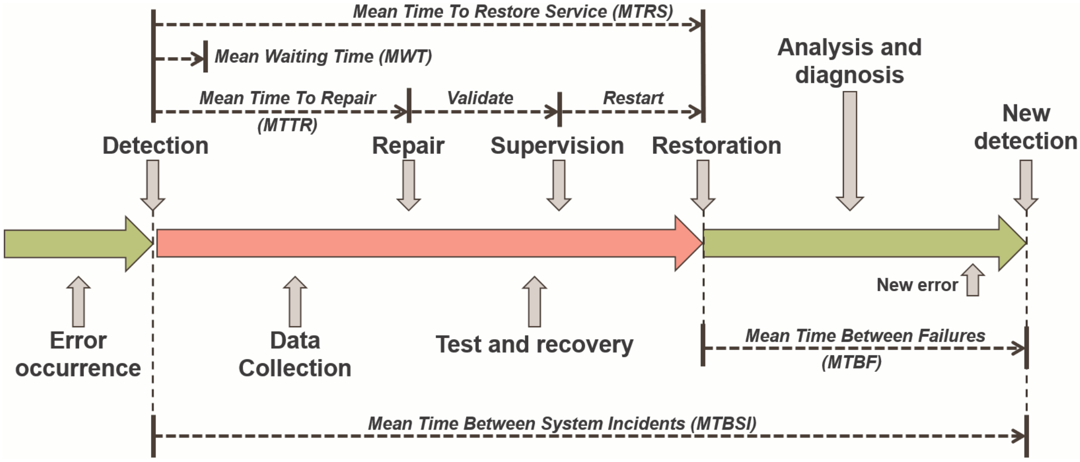


Figure 6.3: A time line for one unspecific cell or resource in a plant, where each relevant time stamp is logged and later used for the CMMS software to create and update a work order for maintenance

A CMMS client integrated in the cell view interface can make it possible for a maintenance technician to log and support the CMMS with progress status and notify when taking over the cell from the operator and when returning it when the job is done and the cell can be restarted again.
Real-time management data helps to improve the process in several ways, especially time efficiency. The information and progress can be presented to each abstraction level in the plant HMI, letting management and every employee knows what is currently going on in the production chain for them to take necessary actions.

7

Conclusion

This chapter will conclude the authors own opinion, summarize and evaluates the results in Chapter 6 together with suggestions for further improvement to the concept and how it can be realizable for future implementation.

7.1 General discussion

Sequence Planner as a tool for extracting data and create central control logic for subsystems and low-level components has already been proven to work as well as gathering data from running processes have been of interest for a long period of time. By using this technology and then implement a framework to visualize and make complex systems easier to understand and follow, the results would be beneficial for management and workers in several aspects.

The VD Factory's ”Driver” segment can make use of already standardized connectivity options to meet the suppliers' own interface in order to integrate it in the "Resource View". Furthermore, the gathered data that can be analyzed and optimized with respect to both control and production efficiency. Visualization for different systems and resources can be applied to the VD Factory's ”Ability handler” that can classify and tag data in correlation to the level of abstraction where it is of interest to a user.

The concept makes most use when applied on larger system due to the size and complexity but works as well on smaller ones. Worth to consider is, for a smaller industry to invest and buy a complete process from a different supplier, the supplier may have their own solution to this already which can be sufficient for a smaller plant.

7.2 Ethical and sustainability aspects

The investors, in this case Volvo, need to decide when buying a new production line or bigger process how they will merge the framework concept with the supplier's user interface. A supplier can have their own full-scale solution for both visual interface and central control unit which can create an implication or conflict since the supplier must readjust to another standard from what they are used to work with. The supplier will most likely want to sell and work with their own solution since it is easier to guarantee the best integration and performance, but also since their own solution may result in further need of technical support and maintenance, which is beneficial for the supplier and can generate profit for several years ahead.

Regarding the sustainability aspects, this concept will have a positive impact on the environment since the system can use build in tools for optimization to reduce energy consumption and at the same time visualize current consumption in real time for management to take direct action. This is also economically beneficial for the company since it will make the process more efficient.
Workers, managers and technicians will now have a better understanding of the process. Hopefully, resulting in a decrease of both stress and frustration and at the same time eliminate a lot of human handling errors.
This could can imply that some positions in a future factory would be unnecessary since new implemented features can replace a lot of the manual and administrative work. Analysis and development of the new visual framework concept will on the other hand open up new positions.

7.3 Future work and implementation

The concept developed in this report has only been validated and tested using a smaller and simplified simulation of a paint process, a natural step forward would therefore be to test and implement it on a more robust simulation or a full-scaled virtual commissioning. Further development would be a smaller physical system or booth, where data extraction can be verified and analyze with actual data from a running process.
In order to expand the concept towards a full-size process or plant, the need for a solid technical requirement specification is vital in order to have a common understanding with the suppliers for which feature is required by the different equipment and resources. This is to ensure that a compatible communication standard is used and to specify how data is stored and extracted.
With the new data, extracted from either a simulation or a real process, new algorithms can be designed and tested for specific purposes. A computerized maintenance management system could be integrated with the extracted data, since it is already widely used today in the industry.

7.4 Summary and final statement

This concept would be beneficial for Volvo Cars in order to meet the global growth and demands for energy efficiency and increasing production rate. The concept should be applied to new implementations of plants to gain best performance from new and modern technology. To make this possible, it is of highest importance that the technical specification to the suppliers is well defined to meet all requirements.
By making all data accessible, several different clients can be used and implemented to improve both the process by creating additional features or analyze the current process in different aspects and purpose. This flexible system can extend the lifespan of a plant and make future improvements easier to integrate.
Since a paint shop is built to be productive for 20-30 years, it can no longer have yesterday's technology since it will most likely be outperformed during its lifespan otherwise.

Bibliography

[1] H. Chen, T. Fuhlbrigge, and X. Li, “Automated industrial robot path planning for spray painting process: a review,” in *Automation Science and Engineering, 2008. CASE 2008. IEEE International Conference on.* IEEE, 2008, pp. 522–527.

[2] S.-H. Suh, I.-K. Woo, and S.-K. Noh, “Development of an automatic trajectory planning system (atps) for spray painting robots,” in *Robotics and Automation, 1991. Proceedings., 1991 IEEE International Conference on.* IEEE, 1991, pp. 1948–1955.

[3] N. R. Roobol, *Industrial painting: principles and practices.* Hanser-Gardner Publications, 1997.

[4] HARMONPA. (2017) How much will a new paint shop cost-a complete guide. [Online]. Available: https://www.pittsburghsprayequip.com/2017/05/19/much-will-new-paint-shop-cost-complete-guide/

[5] C. A. Geffen and S. Rothenberg, “Suppliers and environmental innovation: the automotive paint process,” *International Journal of Operations & Production Management*, vol. 20, no. 2, pp. 166–186, 2000.

[6] D. Gorecky, M. Schmitt, M. Loskyll, and D. Zühlke, “Human-machine-interaction in the industry 4.0 era,” in *Industrial Informatics (INDIN), 2014 12th IEEE International Conference on.* Ieee, 2014, pp. 289–294.

[7] G. Frey and L. Litz, “Formal methods in plc programming,” in *Systems, Man, and Cybernetics, 2000 IEEE International Conference on*, vol. 4. IEEE, 2000, pp. 2431–2436.

[8] B. Lennartson, K. Bengtsson, C. Yuan, K. Andersson, M. Fabian, P. Falkman, and K. Akesson, “Sequence planning for integrated product, process and automation design,” *Ieee transactions on automation science and engineering*, vol. 7, no. 4, pp. 791–802, 2010.

[9] M. Dahl, K. Bengtsson, P. Bergagård, M. Fabian, and P. Falkman, “Integrated virtual preparation and commissioning: supporting formal methods during automation systems development,” *IFAC-PapersOnLine*, vol. 49, no. 12, pp. 1939–1944, 2016.

[10] V. Khomenko, “State space explosion problem,” in *Eighteenth UK Asynchronous Forum*, 2006, p. 10.

[11] H. Hu and Z. Li, “Modeling and scheduling for manufacturing grid workflows using timed petri nets,” *The International Journal of Advanced Manufacturing Technology*, vol. 42, no. 5-6, pp. 553–568, 2009.

[12] M. Skoldstam, K. Akesson, and M. Fabian, “Modeling of discrete event systems using finite automata with variables,” in *Decision and Control, 2007 46th IEEE Conference on.* IEEE, 2007, pp. 3387–3392.

[13] P. Hoffmann, R. Schumann, T. M. Maksoud, and G. C. Premier, “Virtual commissioning of manufacturing systems a review and new approaches for simplification.” in *ECMS*, 2010, pp. 175–181.

[14] C. G. Lee and S. C. Park, “Survey on the virtual commissioning of manufacturing systems,” *J. Comput. Des. Eng.*, vol. 1, no. 3, pp. 213–222, 2014.

[15] S. Süß, S. Magnus, M. Thron, H. Zipper, U. Odefey, V. Fäßler, A. Strahilov, A. Kłodowski, T. Bär, and C. Diedrich, “Test methodology for virtual commissioning based on behaviour simulation of production systems,” in *Emerging Technologies and Factory Automation (ETFA), 2016 IEEE 21st International Conference on.* IEEE, 2016, pp. 1–9.

[16] N. Shahim and C. Møller, “Economic justification of virtual commissioning in automation industry,” in *Winter Simulation Conference (WSC), 2016.* IEEE, 2016, pp. 2430–2441.

[17] M. Dahl, A. Albo, J. Eriksson, J. Pettersson, and P. Falkman, “Virtual reality commissioning in production systems preparation,” in *Emerging Technologies and Factory Automation (ETFA), 2017 22nd IEEE International Conference on.* IEEE, 2017, pp. 1–7.

[18] D. Lucke, C. Constantinescu, and E. Westkämper, “Smart factory-a step towards the next generation of manufacturing,” in *Manufacturing systems and technologies for the new frontier.* Springer, 2008, pp. 115–118.

[19] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, and M. Hoffmann, “Industry 4.0,” *Business & Information Systems Engineering*, vol. 6, no. 4, pp. 239–242, 2014.

[20] J. Lee, H.-A. Kao, and S. Yang, “Service innovation and smart analytics for industry 4.0 and big data environment,” *Procedia Cirp*, vol. 16, pp. 3–8, 2014.

[21] J. Lee, B. Bagheri, and H.-A. Kao, “A cyber-physical systems architecture for industry 4.0-based manufacturing systems,” *Manufacturing Letters*, vol. 3, pp. 18–23, 2015.

[22] Frenus, “Customers´ voice: Predictive maintenance in manufacturing, western europe,” 2017. [Online]. Available: https://www.frenus.com/product/customers-voice-predictive-maintenance-manufacturing-report/

[23] B. Lennartson, K. Bengtsson, O. Wigström, and S. Riazi, “Modeling and optimization of hybrid systems for the tweeting factory,” *IEEE Transactions on Automation Science and Engineering*, vol. 13, no. 1, pp. 191–205, 2016.

[24] A. Theorin, K. Bengtsson, J. Provost, M. Lieder, C. Johnsson, T. Lundholm, and B. Lennartson, “An event-driven manufacturing information system architecture for industry 4.0,” *International Journal of Production Research*, vol. 55, no. 5, pp. 1297–1311, 2017. [Online]. Available: https://doi.org/10.1080/00207543.2016.1201604

[25] K. Bengtsson, P. Bergagard, C. Thorstensson, B. Lennartson, K. Akesson, C. Yuan, S. Miremadi, and P. Falkman, “Sequence planning using multiple and coordinated sequences of operations,” *IEEE Transactions on Automation Science and Engineering*, vol. 9, no. 2, pp. 308–319, 2012.

A

Appendix 1

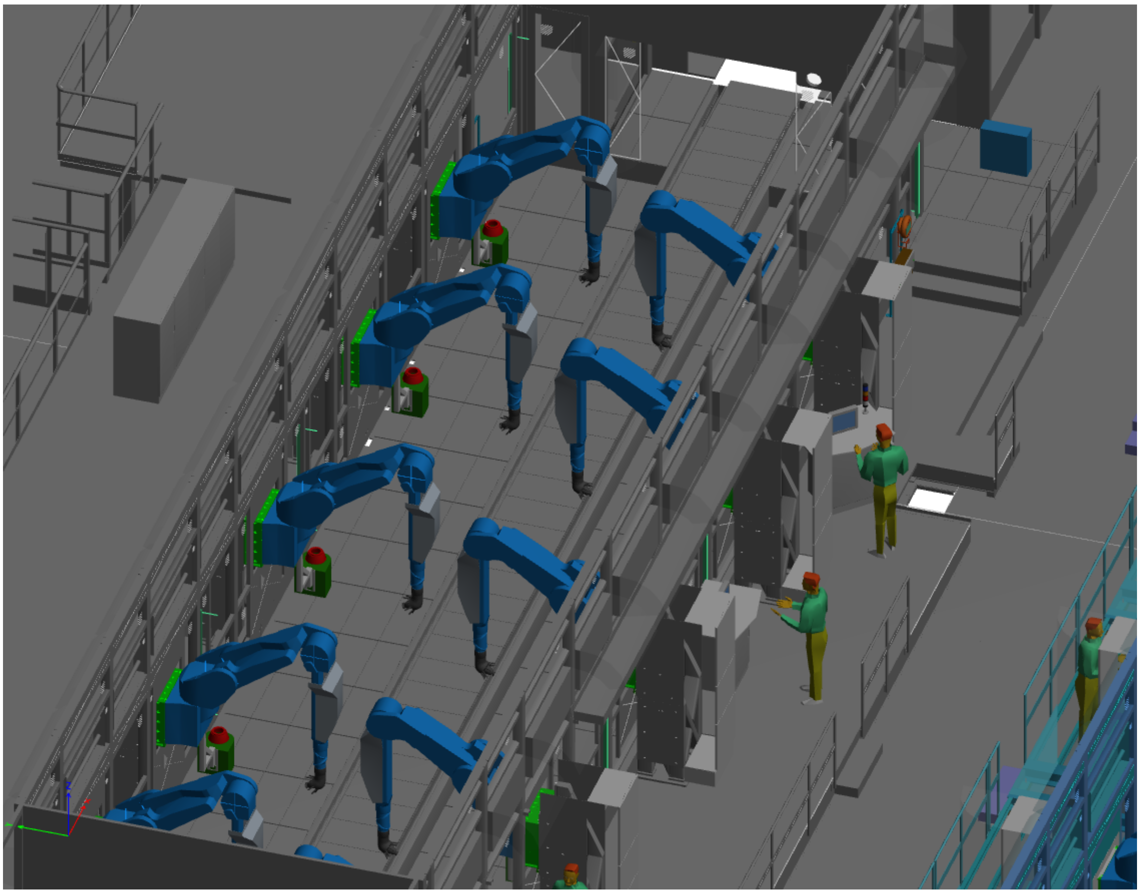


Figure A.1: Second level: Painting booth with application robots and a conveyor system for transporting car bodies. The booth is sealed from the operator.

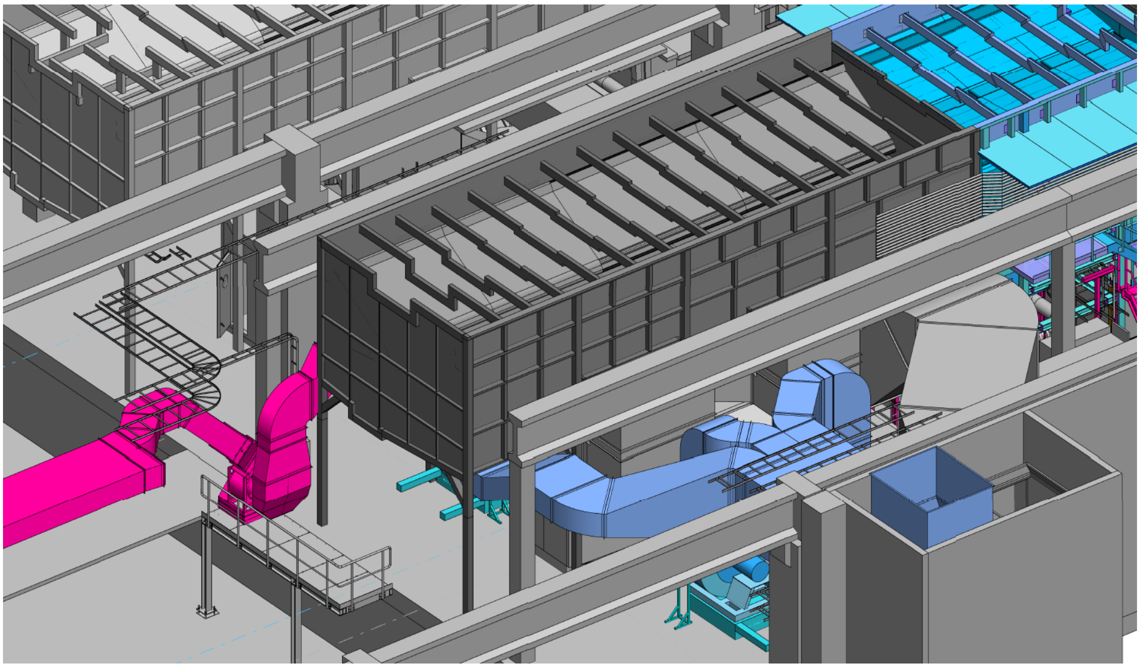


Figure A.2: First level: Basement placed right under the painting booth with water curtains and interlinked water cleaning system. The exhaust air from the booth is returning to the fourth upper level.

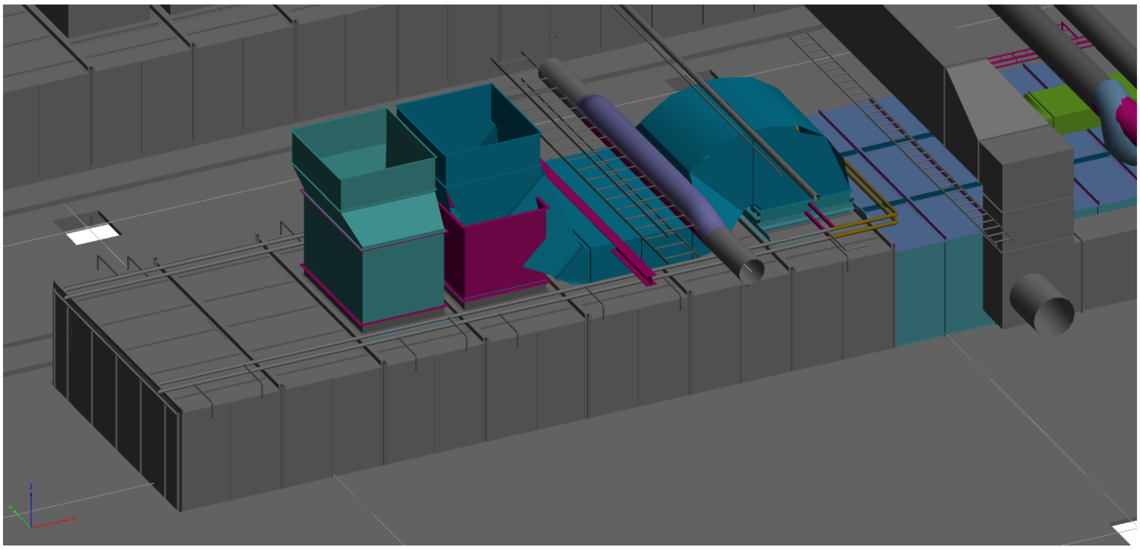


Figure A.3: Third level: Plenary area with dampers which distribute the humidified and tempered supply air from the upper fourth level down to the painting booth below.

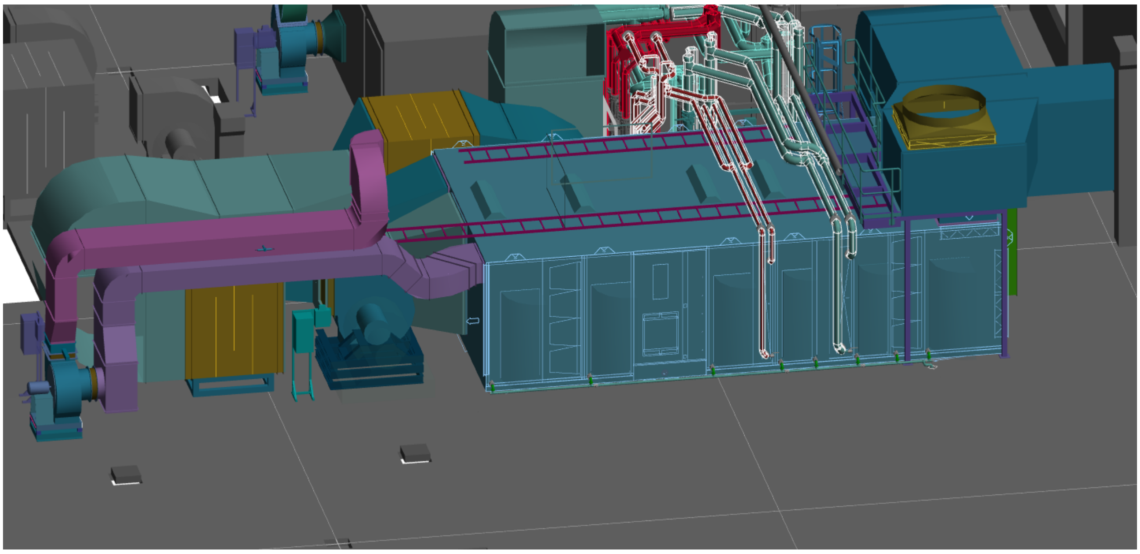


Figure A.4: Fourth level: Supply air system with mixed incoming fresh air and returned exhaust air going through a humidifier and cooler/heat regulator to obtain desired condition for the paint process.