

*A clean-in-place (CIP) station has been investigated in this study. The task addressed relates to the lack of flexible methods for controlling formulations for a CIP station.*

*In most industrial systems, the cleaning algorithms are rigidly embedded in the control program, which complicates modification of technological procedures without intervention in the program code. This paper reports the development of a formalized approach to controlling the formulation for a CIP station based on the IEC 61512 standard principles, which ensures the separation of technological procedure descriptions from the implementation of equipment control functions.*

*The study includes an analysis of requirements within the IEC 61512 standard for formulation description, as well as the construction of a formalized model of procedures. An approach has been proposed to represent cleaning formulations as a structured list of technological operations with process parameters, which makes it possible to formalize the sequence of cleaning stages. It has been shown that such a technique of formulation description could be directly implemented in programmable logic controllers (PLCs) and systems of supervisory control and data acquisition (SCADA) without using additional specialized tools.*

*The results are attributed to the application of principles of equipment and procedure decomposition in accordance with the IEC 61512 standard, which makes it possible to separate process control from equipment control. A distinctive feature of the proposed approach is the possibility of modifying CIP cleaning recipes without changing the PLC program code, which reduces the time required for system reconfiguration.*

*The results could be practically implemented in the design and modernization of automated control systems for CIP stations in the food, pharmaceutical, and biotechnology industries, as well as in the development of SCADA interfaces for controlling formulation-related processes*

*Keywords: CIP station, IEC 61512, object-oriented control, decomposition, process cell, process unit*

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# IMPROVING THE APPROACH TO FLEXIBLY CONTROL FORMULATIONS FOR A CLEAN-IN-PLACE STATION

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## 1. Introduction

Current food and pharmaceutical productions are predominantly periodic technological processes. Their characteristic feature is the fabrication of a different range of products on the same technological equipment. This approach allows for increased production flexibility but, at the same time, significantly complicates the requirements for control systems since each type of product requires its specific technological process parameters.

An integral part of food and pharmaceutical enterprises are clean in place (CIP) stations, which provide cleaning of technological equipment. CIP stations directly affect the quality and safety of products, as well as compliance with regulatory requirements for production hygiene. By their nature, CIP washing processes are also periodic and formulation-based since they consist of a sequence of specific stages and require setting parameters that depend on the type of product and technological equipment.

Taking into account the variety of technological equipment, control systems for CIP stations must provide the ability to quickly change formulations without the need to make changes to the software for programmable logic controllers (PLCs) and visualization systems. The use of rigidly specified cleaning formulations leads to a complication of

the control system, an increase in equipment downtime, and an increase in the risk of errors when making changes to the control system.

In this regard, an urgent scientific problem is to devise and investigate approaches to controlling the formulation subsystem at production plants, in particular CIP stations. One of the most common international standards in this field is IEC 61512 (ISA-88), which defines the principles of building equipment models, technological processes, and formulations for periodic process control systems. The application of this standard creates prerequisites for separating the logic of the technological process from the implementation of physical equipment control functions.

Thus, research aimed at designing a formulation control subsystem for CIP stations in accordance with the IEC 61512 (ISA-88) standard is relevant for modern food and pharmaceutical industries. It meets the needs of increasing flexibility, reproducibility, and efficiency of periodic technological process control.

## 2. Literature review and problem statement

The basic principles of control over periodic technological processes, methods for formalizing equipment models,

technological process, and formulations are given in the IEC 61512 (ISA-88) standard [1]. In [2], it is defined that the standard shows that the use of hierarchical models makes it possible to structure software and ensure the reuse of functional components. At the same time, the standard is of a generalized nature and does not consider the specificity of particular systems for technological objects, in particular CIP stations. The reason is the universality of the standard, focused on a wide class of periodic productions.

In [3], methodological aspects of the IEC 61512 implementation are considered. It is shown that the formulation approach allows for flexible control when changing the product range. However, the issues of implementing the CIP-process formulation control subsystem remain undisclosed. This is due to the fact that the authors focus on basic production while CIP-stations are traditionally considered as auxiliary subsystems.

In work [4], issues of CIP station automation in the food industry are considered. It is shown that the use of sequential control algorithms makes it possible to ensure the stability of washing parameters and compliance with sanitary standards. At the same time, control algorithms are rigidly fixed in the cited work, which makes it impossible to change the washing algorithm without making changes to a PLC program. The main reason is the orientation of solutions to a specific equipment configuration.

In study [5], a methodology of CIP station decomposition according to the principles of IEC 61512 was devised, which includes the separation of the levels of the technological cell, technological units, equipment modules, and control modules. It is shown that such an approach provides a structured representation of the equipment and its functions, which enables the interaction of technological stages with the physical equipment of a CIP station. However, the work does not describe the formulation control at CIP stations. This is due to the fact that the authors focus on the decomposition of the physical model, rather than on the development of formulation control techniques.

In [6], a new object model for improving the use of formulations based on IEC 61512 is presented. The model's advantages for reusing formulations are shown but it does not solve the problem of dynamic changes in procedures during execution, which limits flexibility in practical tasks of product change. The authors also note the difficulties associated with the complexity of the structure of the equipment and formulation model, which makes it difficult to automatically switch between formulation variants without manual intervention.

In [7], the use of Unified Modeling Language (UML) and state-oriented models for process control is described. The authors show the advantages of using such models in terms of representing the process of setting up. At the same time, there is no description of interaction with the models described in the IEC 61512 standard, which complicates their simultaneous use. The reason is the design of their own tool for generating programs for PLCs and the use of proprietary approaches by the authors.

Study [8] proposed mechanisms for devising formulations and developed a set of templates and libraries for use in accordance with the IEC 61512 (ISA-88) standard. Despite the encouraging results, as described in the study, there are various pitfalls and critical points that companies may encounter when implementing the IEC 61512 standard. They consist in the lack of a formalized and standardized process for transforming a general formulation into a master formulation, as

a result of which this process was performed manually based on templates or similar products. In addition, establishing a connection between the technological parameters of the process and the parameters of specific equipment was difficult and ambiguous as these parameters could be measured in different units of measurement or generally be determined through indirect measurements.

The main idea of work [9] is to formalize the procedural model of production in accordance with the IEC 61512 standard, in order to reuse existing knowledge when designing digital twins. The authors built a conceptual model that formalizes the Sequential Function Chart (SFC) programs and the Asset Administration Shell (AAS) metamodel of the Industry 4.0 platform based on this conceptual model. A set of mapping rules is also proposed that make it possible to transform SFC programs into the corresponding AAS submodel. At the same time, the paper does not implement practical automation of the proposed approach but only declares its possibility. This is mainly objective in nature and is associated with the high complexity of formalizing real periodic processes, a significant variety of equipment and procedures, as well as the early stage of development of approaches to the application of AAS.

The issues of controlling periodic technological processes are widely covered in scientific literature and in a number of international standards, but many aspects remain insufficiently studied. All these sources demonstrate that the IEC 61512 standard is the basis for building a control system for periodic processes. However, most studies do not pay sufficient attention to the implementation of the formulation control subsystem, which limits the flexibility of control systems and makes it difficult to change the parameters of the technological process without modifying the PLC software. Approaches to describing procedural models, in particular using UML, SFC, and Asset Administration Shell, are mainly theoretical in nature and have not been brought to the level of practical use.

The above allows us to argue that it is advisable to conduct a study aimed at devising a formalized approach to formulation control at CIP stations in accordance with the IEC 61512 standard.

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### 3. The aim and objectives of the study

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The aim of our research is to devise an approach to controlling the CIP station formulation subsystem based on the IEC 61512 (ISA-88) standard, which enables the separation of process control functions from hardware equipment control. This will make it possible to change and adapt formulations without the need to change the programmable logic controller programs, reduce the time for equipment reconfiguration, and reduce the risk of errors during the modernization of control systems.

To achieve this goal, the following tasks were set:

- to analyze the requirements of the IEC 61512 (ISA-88) standard for describing procedures and formulations in the context of periodic CIP processes;
- to determine the interdependence between the equipment model and the CIP station process model in accordance with the IEC 61512 standard;
- to determine ways to represent formulations that are independent of the specific equipment configuration;
- to substantiate the possibility of practical application of the proposed approach for flexible control over CIP stations.

#### 4. The study materials and methods

The object of our study is a CIP station. The principal hypothesis assumes that the use of approaches to controlling periodic processes in accordance with the principles of the IEC 61512 standard makes it possible to separate the description of the technological process from the equipment control algorithms. This makes it possible to provide a flexible change in washing algorithms without modifying the PLC program code.

The IEC 61512 standard is focused on controlling periodic technological processes; therefore, this study adopted a number of assumptions that allow us to consider the CIP station as an object that meets the principles of this standard. The cleaning process is considered as a periodic process that is performed according to a defined formulation, has a beginning and end of execution. The cleaning composition is interpreted as a technological formulation in the sense of the IEC 61512 standard.

The study also accepted a number of simplifications. In particular, detailed physicochemical characteristics of the cleaning technological process, such as changes in temperature regimes and concentrations of cleaning solutions during the transition between cleaning stages, are not taken into account. This is due to the fact that our attention is on the structural representation of the control process, and not on its dynamic modeling. In addition, external factors of the production environment are not taken into account since the proposed approach is focused on studying the internal structure and organization of the control system at a CIP station. Also, the cleaning procedures are described in the form of typical technological stages without detailing possible variations of formulations or process parameters, which makes it possible to focus on analyzing the structure of the control system, and not on optimizing technological modes.

The methodological basis of our study is the provisions of the IEC 61512 standard. To formalize the structure of technological procedures and their interaction with equipment, structural analysis methods, hierarchical decomposition principles, as well as elements of an object-oriented approach to building automation systems were used.

To design CIP formulations, methods of representing compositions in the form of a list, table, Gantt chart, Sequential Function Chart (SFC) notation, and Procedural Function Chart (PFC) notation were used. These methods of representing formulations are widely used in industry and production management systems.

The data obtained during the study were used to assess the performance of the proposed approach to formulation control and to confirm the possibility of its application in the design of automation systems for CIP stations.

#### 5. Results of research on formulation control of CIP stations

##### 5.1. Analyzing the requirements from the IEC 61512 standard for describing procedures and formulations in the context of periodic CIP cleaning processes

According to the IEC 61512 standard, when designing and developing software for a control system, each automation object is considered as a separate entity. In turn, all automation objects at the ICS (industrial control system) level are divided separately into “process control” (how to make a product) and “equipment control” (what to make a product on) [10].

In periodic production, to which CIP stations belong, the range of products is constantly changing. Therefore, there is a need to devise or change the flow of technological processes: adding new formulations, changing their properties, removing old ones. In this case, the equipment can remain the same; its capability to perform technological actions also does not change. On the other hand, when installing new equipment (and control systems) in the system, it must be capable of using existing compositions.

Thus, the basic principle of building control systems according to the IEC 61512 standard is the initial division of control functions into two interrelated groups:

- control over the technological process, which directs the execution of technological actions in a given sequence;
- control over equipment, which enables the execution of a specific technological action (heating, mixing, etc.).

To connect “process control” and “equipment control”, elements of technological actions – procedures – are used. The production process involves the execution of a “technological program”, which consists of steps, each of which involves the execution of a certain procedure, for example cleaning with water, heating, cleaning with acid, etc. Process control is defined in a formulation per se, which also contains parameters (formula) and other information. In essence, the “technological program” in a formulation is also a procedure. That is, a formulation procedure consists of smaller procedures, and those, in turn, refer to specific instances in the equipment that can perform them. This is how the formulation is linked to the equipment. The smallest procedures are termed technological actions. Equipment (objects) at all control levels, except for control modules, can contain procedures.

##### 5.2. Determining the interdependence between the equipment model and the process model of a CIP station according to the IEC 61512 standard

The IEC 61512 standard considers control over batch production processes from two different points of view: the process and equipment. The representation of the process equipment is through the eyes of a mechanical, electrical, and instrumentation engineer; it ultimately becomes a physical model from the perspective of IEC 61512. The representation of the process is through the eyes of a technologist and describes the technology; ultimately, it is a process model. The ultimate goal of IEC 61512 is to make it possible to implement different processes on different available equipment.

In work [5], the decomposition of a CIP station was carried out, and a hierarchical model of the equipment was built in accordance with the IEC 61512 standard. The control modules of the technological equipment of the CIP station were highlighted; and their belonging to the objects of the hierarchy of higher levels was determined. Also, in [5], a model of the technological process of the CIP cleaning was built, which includes all levels of the technological process model in accordance with the IEC 61512 standard. These models reflect the general principles of building control systems in accordance with the IEC 61512 standard and can be used as a basic structure for further research. In particular, the dependence between the equipment model and the technological process model was determined. This dependence relates to the fact that each level of the equipment hierarchy is assigned to a level of the procedural model.

Procedures have a hierarchical structure. The hierarchy of procedures shows how smaller procedures implement the execution of higher-level procedures. The procedure that defines the technological process is the procedure of the technological

cell, that is, the entire CIP station. The smallest procedures that cannot include others are termed stages: technological actions belong to them. Thus, higher-level procedures include lower-level procedures, that is, coordinate their work. The principles of interaction in this hierarchy are somewhat similar to the equipment hierarchy. The technological cell procedure is performed within the equipment of the same name. Within the technological cell, one or more washes can be performed simultaneously. The execution of a specific wash requires technological nodes (CIP contours), in which technological stages are sequentially performed. Those, in turn, can consist of technological operations, and those – of technological actions. The presence of technological cell procedures and stages in the hierarchy is a mandatory condition, others – if necessary.

This makes it possible to implement the independence of the procedural model from a specific equipment configuration through the use of abstract references to equipment classes.

**5.3. Determining techniques for formulation representation independent of specific equipment configuration**

The functioning of the CIP station is characterized by the cleaning of technological equipment according to the formulation. When implementing the formulation production management system, it is assumed that the formulation will be specified as one of the convenient ways for defining the sequence of procedures.

The use of different techniques of formulation definition is described in [11], in which it is determined that when defining a method of formulation representation, the primary task is to agree on a set of requirements that it must meet. The representation method should:

- be simple to use (easy for a person to understand);
- be easy to construct (contain few syntactic elements);
- have an unambiguous representation of the order of execution (sequence, parallelism, alternative choice);
- be independent of the development environment.

The list method (Fig. 1) has the advantages of ease of visualization and apparent accuracy and unambiguity. It should be noted that historically it so happened that most formulations are described in text format or a list. Such formulations often look like a numbered list. However, a list is useful only in simple cases. If it is necessary to specify alternative or parallel branches, coordination of actions, this representation quickly becomes confusing and prone to misinterpretation.

Fig. 2 shows a composition in the form of a table; this format, unlike the previous one, makes it possible to specify parallel execution of procedures at each step. However, specifying procedure parameters (duration, temperature, etc.) can complicate the representation of the formulation, so they are often specified not in the composition itself but in an additional description.

Technological operation	Temperature, °C	Concentration, %	Duration, s
1 Flushing with returned water	20	0	300
2 Alkali washing	55	1	600
3 Flushing after alkali	20	0	300
4 Acid washing	55	0	600
5 Flushing after acid	20	0	300
6 Flushing with clean water	20	0	300

Fig. 1. An example of representing a CIP cleaning formulation using the list method

Technological operation	Cleaning stage					
	1	2	3	4	5	6
Flushing with returned water	+	–	–	–	–	–
Alkali washing	–	+	–	–	–	–
Flushing after alkali	–	–	+	–	–	–
Acid washing	–	–	–	+	–	–
Flushing after acid	–	–	–	–	+	–
Flushing with clean water	–	–	–	–	–	+
Dosage of concentrated alkali	–	+	–	–	–	–
Concentrated acid dosage	–	–	–	+	–	–

Fig. 2. Example of a CIP formulation represented using a table method

Gantt charts are useful for depicting the progression of activities over time (Fig. 3). They can also be used to depict activities at multiple levels of the hierarchy, such as the synchronization of a CIP station with a cleaned object. This form of representation is a good illustration of a formulation procedure in a process cell, which consists of one or more process node procedures that essentially operate independently of each other, coordinating with each other at certain points.

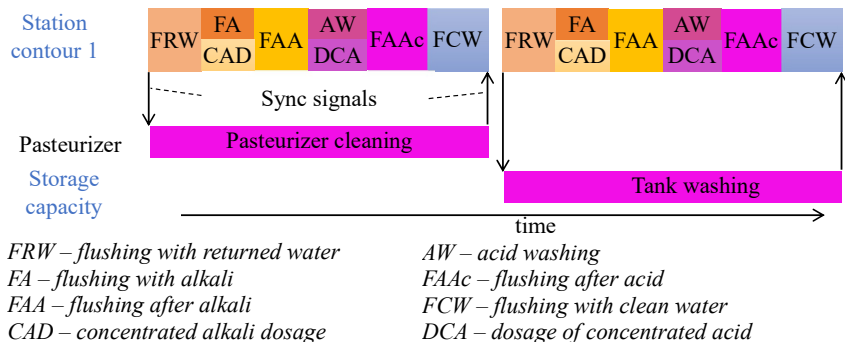


Fig. 3. Example of a CIP station formulation represented by a Gantt chart

However, when complex conditional logic is added, the Gantt chart becomes a very cumbersome tool for depicting the procedure. Although Gantt charts provide a powerful method for depicting machine procedures over time that the list method does not, they do not provide an adequate specification and representation of the conditional logic.

The third method is to use the SFC notation, which is defined in IEC 61131-3 [12]. SFC diagrams have gained wide acceptance in the process industry and provide a powerful means for describing conditional logic, which is lacking in the list methods and Gantt charts. An example of an operation procedure in the SFC format is shown in Fig. 4.

SFC provides a suitable tool for representing conditional logic, which is often required at the level of operation procedures. In contrast, using SFC at the level of formu-

lation procedures of a process cell results in diagrams that do not provide sufficient information. This is because there is no information about the material flow, synchronization between machine procedures, and the total time of the machine procedures in relation to each other. Another disadvantage of SFC is that SFC is more of a PLC programming language and is more suitable for implementing basic equipment control rather than procedural control.

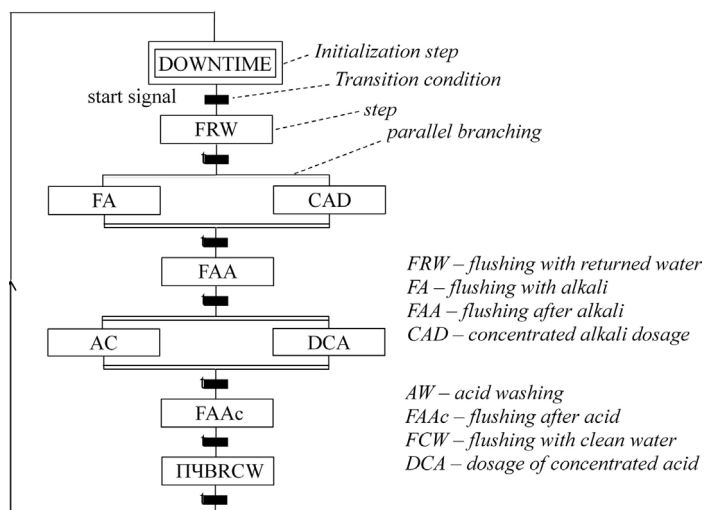


Fig. 4. Example of representing a CIP station formulation in Sequential Function Chart notation

The IEC 61512 standard describes a standard method for representing formulation procedural logic in the form of PFC notation [13]. PFC notation was developed using elements of three different formats: list, Gantt chart, and SFC language. At first glance, PFC notation (Fig. 5) may appear similar to SFC but there are subtle yet significant differences. These differences are necessary to meet the requirements of formulation-based procedural control, as opposed to the sequential execution of control actions (hardware control) for which SFC is used [8].

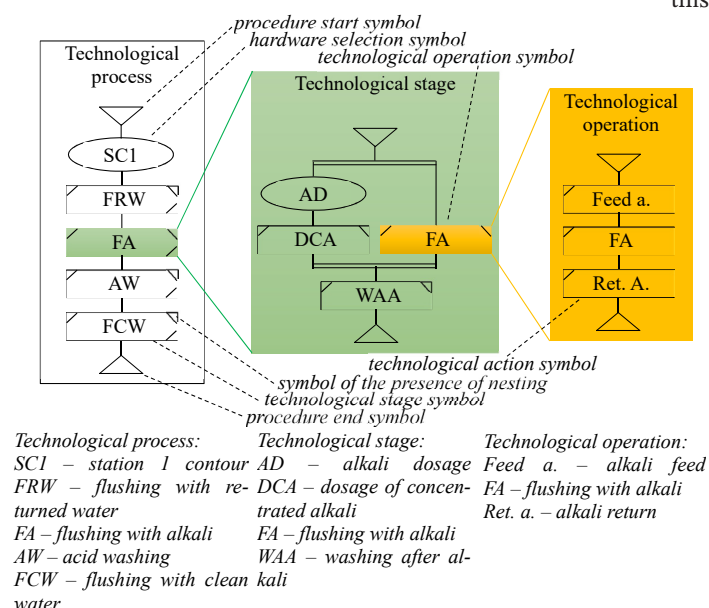


Fig. 5. Example of representing a CIP formulation in the Procedural Function Chart notation

At the hardware procedure and operation level, PFC allows for a hierarchical formulation structure where procedural elements can contain nested PFCs or directly reference hardware operations. This provides encapsulation of procedures and increases the readability of the diagram.

For the process cell level, PFC is used to coordinate parallel procedures of devices, synchronize their operation, and manage equipment resources. Despite its high visibility and functionality, when implemented, the use of PFC requires support for this language from the developer tool. Unfortunately, the number of such tools is very small, which significantly complicates the implementation. Therefore, for formulations without parallel execution of stages, the most practical way to represent the formulation in the form of a list is considered. For all others, the PFC language, with support for XML implementation.

The PFC notation is intended as a standard means of depicting procedural logic in formulations. It should be recognized that subsequently, along with PFC, alternative methods will also be used because, depending on the characteristics of the procedure (for example, size, complexity, and user needs), they may be more suitable. In practice, the use of PFC is associated with a number of difficulties, which is usually due to the requirements for the software in which this language is implemented. For CIP stations, where the formulation usually has simpler options than, for example, in the chemical or pharmaceutical industry, PFC could become an excessive and expensive tool.

#### 5. 4. Justifying the possibility of practical applicap tion of the proposed approach for flexible control over CIP stations

The practical implementation of the proposed approach to formulation control over CIP stations can be performed on the basis of modern programmable logic controllers and SCADA systems. The basis of such implementation is the separation of equipment control functions and process control in accordance with the principles of the IEC 61512 standard. In this case, the PLC software implements universal equipment control modules (pumps, valves, circulation circuits, reagent dispensers, etc.), while the logic of performing specific cleaning procedures is determined by the formulation stored in the form of structured data.

For CIP stations, where formulation procedures usually have a relatively simple sequential structure and consist of a limited number of technological stages, it is advisable to use the formulation representation method in the form of a list. This approach is intuitive for technologists and automation engineers, provides an unambiguous definition of the sequence of procedures, and does not require complex syntactic structures. In addition, the list is easily implemented in the PLC software as an array of structures or a table of parameters, which makes it possible to organize the execution of the formulation by sequentially processing its elements (Fig. 6).

Unlike the PFC notation, the use of such a representation does not require specialized tools or software environments that support the appropriate procedure description language. This significantly simplifies the practical implementation of formulation control in standard PLCs and SCADA systems and makes the proposed approach more accessible for implementation in automation systems for CIP stations.

In PLCs, the implementation of the proposed approach can be based on the use of a modular or object-oriented software structure. Each control module and technological procedure is implemented as a processing function of a certain class that performs specific technological actions (Fig. 7). Formulation procedures in this case are implemented as a sequence of calls to these modules with parameters specified by the formulation (temperature, concentration, stage duration). This approach makes it possible to change the cleaning algorithm by editing the formulation without the need to modify the PLC program code.

It is advisable to implement the functions of controlling the formulation subsystem at the SCADA system level. SCADA can store libraries of cleaning formulations for various types of technological equipment, as well as a designed interface to devise them, edit, and select before starting the cleaning process (Fig. 8).

CIP\_010425 > CPU 317-2 DP [CPU 317-2 DP] > PLC data types > PROC > Control\_Recipe

Control_Recipe			
	Name	Data type	Comment
1	ID	Int	Recipe ID
2	BATCHID	Dint	Washing ID
3	STRTIME	Dint	Start time 16#MMHH_MMSS
4	ENDTIME	Dint	Stop time 16#MMHH_MMSS
5	FORMULA	"FRM"	Formula (set of parameters)
6	RouteNumber	Int	Washing route number
7	PH1_FirstWash	"PH_PARA"	Parameters "Rinse with return water"
8	Step_Work_time	Int	Step execution time
9	FT_Out	Real	Set flow rate of cleaning solution supply
10	TIC_Out	Real	Set CIP supply temperature
11	CIC_Out	Real	Set CIP supply concentration
12	PIC_Out	Real	Set CIP outlet pressure
13	CIC_In	Real	Set CIP return temperature
14	TIC_In	Real	Set CIP return concentration
15	PH2_AlkCirc	"PH_PARA"	Parameters "Alkaline washing"
16	PH3_CleanAfterAlk	"PH_PARA"	Parameters "Rinse after alkali"
17	PH4_AcidCirc	"PH_PARA"	Parameters "Acid washing"
18	PH5_CleanAfterAcid	"PH_PARA"	Parameters "Rinse after acid"
19	PH6_CleanWash	"PH_PARA"	Parameters "Rinse with clean water"

Fig. 6. Example of representing a CIP formulation in a programmable logic controller

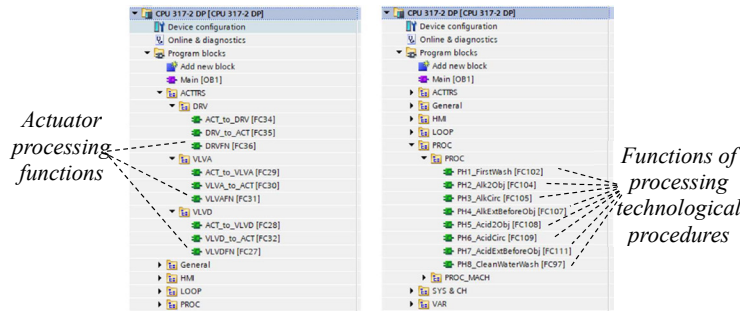


Fig. 7. Example of implementing formulation control in a programmable logic controller

### CIP1 recipe control

Recipe selection:  READ

Recipe number:  Recipe name:  SAVE

Route number:  Route name:

Cleaning object parameters:

Tank cleaning     Supply control by pressure     Circulation via buffer tank     Initial rinse with clean water

Line cleaning     Supply control by flow rate     Circulation via cleaning solution tank

Pipeline volume to object, L:     Disinfectant supply pump runtime, s:

Total volume of cleaning object, L:     Return flow absence time, s:

Recipe step parameters	Supply flow rate, m <sup>3</sup> /h	Supply pressure, bar	Supply temperature, °C	Return temperature, °C	Supply conductivity, mS/cm	Return conductivity, mS/cm	Step duration, s
1. Initial rinse	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 70,0	<input checked="" type="checkbox"/> 60,0	<input checked="" type="checkbox"/> 0,0	<input checked="" type="checkbox"/> 0,0	60
2. Alkaline washing	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 70,0	<input checked="" type="checkbox"/> 60,0	<input checked="" type="checkbox"/> 50,0	<input checked="" type="checkbox"/> 40,0	60
3. Rinse after alkali	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 70,0	<input checked="" type="checkbox"/> 60,0	<input checked="" type="checkbox"/> 0,0	<input checked="" type="checkbox"/> 0,0	60
4. Acid washing	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 70,0	<input checked="" type="checkbox"/> 60,0	<input checked="" type="checkbox"/> 50,0	<input checked="" type="checkbox"/> 40,0	60
5. Rinse after acid	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 70,0	<input checked="" type="checkbox"/> 60,0	<input checked="" type="checkbox"/> 0,0	<input checked="" type="checkbox"/> 0,0	60
6. Disinfection	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 70,0	<input checked="" type="checkbox"/> 60,0	<input checked="" type="checkbox"/> 0,0	<input checked="" type="checkbox"/> 0,0	60
7. Rinse after disinfection	<input type="checkbox"/> 10,0	<input type="checkbox"/> 10,0	<input type="checkbox"/> 70,0	<input type="checkbox"/> 60,0	<input type="checkbox"/> 0,0	<input type="checkbox"/> 0,0	60
8. Sterilization	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 70,0	<input checked="" type="checkbox"/> 60,0	<input checked="" type="checkbox"/> 0,0	<input checked="" type="checkbox"/> 0,0	60
9. Loop cooling	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 10,0	<input checked="" type="checkbox"/> 70,0	<input checked="" type="checkbox"/> 60,0	<input checked="" type="checkbox"/> 0,0	<input checked="" type="checkbox"/> 0,0	60

a

CIP1    IDLE    Route not ready

SAVE

Total washing duration:     Step duration:

STEP	Idle	Pre-rinse	Alkaline washing	Acid washing	Disinfection	Sterilization	End of washing
		00:01:00	00:02:15	00:02:35	00:00:00	00:00:00	

b

Fig. 8. Example of implementing a formulation control operator interface: a – formulation editing; b – formulation execution management

Before starting the wash, the selected formulation is transferred to PLC in the form of a structured set of parameters, after which the PLC carries out its sequential execution. This structure of the control system allows for flexible control, ease of operation, and the ability to adapt the system to new technological requirements without changing the control program.

## 6. Discussion of results based on investigating formulation control at a CIP station

Our research results can be attributed to the features in the proposed approach to implementing a formulation control subsystem for a CIP station. As a result of analyzing the requirements from the IEC 61512 standard, it was found that for the effective functioning of the control systems at a CIP station, it is advisable to apply the principle of functional separation of technological process control and equipment control. Unlike [2, 3], which considered a wide class of periodic productions, such a structural organization describes the relationship between the technological process model and the physical equipment model of a CIP station. This makes it possible to change the parameters and sequence of the technological process without changing the PLC program, which was not covered in [4]; that work was based on strictly specified sequences of cleaning execution. In PLC, the implementation of the proposed approach can be based on the use of a modular software structure. Each control module and technological procedure is implemented as a processing function of a certain class that performs specific technological actions (Fig. 7).

In [5], most attention is paid to the decomposition of equipment, but the issues of formulation control are not considered. In our study, this drawback is eliminated by establishing a connection between the equipment model and the technological process model, which makes it possible to implement formulation-based control.

In [6], an object model of formulations is proposed, but the problem of dynamic change of parameters and sequence of procedures is not solved. In contrast, our results make it possible to implement flexible control and change formulations, which is achieved by changing the parameters of procedures and using universal stages.

As a result of our analysis of approaches to the representation of formulations, it was found that each of the considered methods has advantages and limitations. Methods for the graphical description of procedures, in particular SFC (Fig. 4) and PFC (Fig. 5), provide extended possibilities for describing formulations. However, their use often requires specialized software and additional resources for the implementation of control algorithms. The method of description using Gantt charts (Fig. 3) well illustrates the procedure for formulating a technological cell, but becomes a very cumbersome tool, difficult to understand and implement.

In work [9], a model for representing procedures using SFC and AAS is proposed, but its practical implementation is absent. In contrast, in our work, the results are focused on direct implementation in PLC and SCADA systems, which enables their practical value. This becomes possible due to the choice of a simple technique for representing formulations that does not require specialized software.

CIP stations are characterized by a relatively simple structure of technological procedures. Under such condi-

tions, the use of complex graphic notations for representing formulations may be unnecessary since they significantly complicate the implementation and maintenance of the control system. Considering the formulated requirements for the method of representing formulations, namely ease of use, unambiguous interpretation, and independence from the development environment, it is advisable to use the method of representing the composition in the form of a list (Fig. 1) or in the form of a table (Fig. 2) for implementing a CIP station formulation management subsystem.

In [8], the lack of a formalized process of transition from a general formulation to a master formulation was identified. In our study, this task is solved by using a structured representation of the formulation. This approach makes it possible to represent the technological process as a sequence of procedures with specified parameters that can be stored as structures in the PLC software (Fig. 6) and edited via the SCADA system interface (Fig. 8). The transition from a general formulation to a master formulation occurs by transferring parameters from one structure stored in SCADA to a structure in the PLC, which is used when executing the CIP cleaning program.

Therefore, the technique of representing formulations in the form of a list provides sufficient control flexibility and makes it possible to configure the formulation management subsystem at a CIP station without the need for special software. Our results make it possible to use the formulation management subsystem in the PLC software and SCADA systems.

The advantages of the proposed solution include the following features. First, using a formulation in the form of a list makes it possible to manage the design and editing of formulations without additional software. Secondly, this technique of displaying formulations easily fits into the PLC and SCADA software environment. This makes it possible to store formulations as a set of parameters that can be changed from the SCADA interface and change the parameters of the technological process without changing the control system program. This is possible due to the fact that the logic of the technological equipment control and the logic of the technological process control are executed separately. The proposed approach is based directly on the principles of the IEC 61512 standard, which ensures uniformity and compatibility with industrial solutions, unlike the models reported in [7], which do not have a clear integration with this standard.

The results also help to partially solve the issue related to the fact that CIP control systems require constant changes in cleaning sequences and the addition of new cleaning objects. The proposed method makes it possible to devise different variants of cleaning formulations by changing composition parameters, as shown in Fig. 6. Thus, the issue of binding algorithms to a specific technological scheme is largely solved as the control system can perform different sequences of operations based on a variable set of parameters.

Thus, the proposed approach could be implemented using standard control system tools and does not require specialized software to control the formulation subsystem. This makes it convenient for practical implementation in the food and pharmaceutical industries where CIP systems have relatively simple formulations but require rapid adaptation to changing technological conditions.

At the same time, the research results have certain limitations that require consideration in the practical implementation of the proposed methodology. First of all, they are based

on the idea that steps in a formulation must be performed in order. This method works well for most CIP station options, but it may not work as well in systems where multiple processes need to be coordinated simultaneously. The study was conducted on standard control system architectures using PLCs and SCADA systems, so the results may require further modification for implementation in distributed or cloud-based control systems.

The shortcomings of our study include the lack of mechanisms in the proposed method for optimizing the cleaning process in terms of energy consumption, cleaning solution use, or cleaning duration. The proposed approach focuses on increasing control flexibility; therefore, optimization of technological parameters is not considered in this work. In some cases, this may complicate achieving optimal technological process parameters, even with a flexible control system.

Future development of this study may include expanding the functionality of the proposed approach. Combining the formulation management subsystem with process optimization tools and their integration with monitoring and analysis systems for production data to determine key performance indicators is a promising direction. It is also advisable to study the possibility of using more complex ways of representing formulations that can describe parallel or conditional branches of the technological process. This will make the method more flexible and universal and will allow it to be used in larger industrial settings.

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## 7. Conclusions

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1. The requirements from the IEC 61512 standard for the description of procedures and formulations for CIP station processes have been analyzed. It is shown that the key principle of the standard is the separation of technological procedure control from equipment control, which makes it possible to represent the technological process in the form of a composition procedure with a hierarchical structure of operations, stages, and technological actions. Unlike traditional algorithms with rigidly specified logic in PLC, this approach provides the ability to change the sequence of technological operations without modifying the program code of the control system, which increases the flexibility of CIP station operation.

2. The interdependence between the equipment model and the technological process model of the CIP station has been determined in accordance with the IEC 61512 standard, taking into account the formulation approach and the hierarchy of equipment. A feature of the established interdependence is the coordination of the hierarchy of technological procedures (process – stage – operation – action) with the hierarchy of equipment of the technological cell. This makes it possible to describe procedures at an abstract level and enables linking them with the corresponding equipment modules through the procedure mechanism, which explains its universality and reusability.

3. Techniques of representing formulations have been determined, independent of the specific equipment configuration. Our analysis revealed the possibility of using various

forms of composition description (list, table, Gantt charts, SFC-notation), among which, for CIP tasks, it is advisable to represent the formulation in the form of a structured list of technological operations with process parameters. A feature of such a representation is its simplicity, unambiguous interpretation, and independence from the programming environment, which explains the possibility of using the formulation description without employing specialized software tools.

4. The possibility of practical application of the proposed approach for flexible control at CIP stations has been substantiated. It is shown that the implementation of formulation control can be performed by means of programmable logic controllers and SCADA-systems by separating the functions of equipment control and control over technological procedures. A feature of the approach is the ability to change or design new formulations at the operator interface level without making changes to the PLC program, which shortens system reconfiguration time and reduces the likelihood of errors during operation.

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## Conflicts of interest

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The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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The study was conducted without financial support.

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## Data availability

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All data are available in the main text of the manuscript.

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## Use of artificial intelligence

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This work uses an artificial intelligence-based language model (ChatGPT, OpenAI GPT-5, version 2026) for grammatical, linguistic, and stylistic correction. The authors manually checked and edited the material and confirm that the artificial intelligence tools were only auxiliary and were not used for hypothesis generation and formulation, methodology, analysis of results or conclusions, and did not influence the research results.

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## Authors' contributions

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**Roman Mirkevych:** Conceptualization, Methodology, Software, Writing – original draft; **Volodymyr Polupan:** Software, Validation, Formal analysis, Writing – review & editing.

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