# Feasibility Study on Virtual Process Controllers as Basis for Future Industrial Automation Systems

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Abstract—Industry 4.0 offers many possibilities for creating highly efficient and flexible manufacturing. To create such advantages, highly automated and thus digitized processes and systems are required. Here, most technologies known from the office floor are basically suitable for these tasks, but cannot meet the high demands of industrial use cases. Therefore, they cannot replace industrial technologies and devices that have performed well over decades "out of the box". For this reason, many technologies known from the office floor are being investigated and adapted for industrial environments. An important task is the virtualization of process controls, as more and more devices use computation offloading, e.g. due to limited resources. In this paper we extend the work on our novel architecture that enables numerous use cases and meets industrial requirements by virtualizing process controllers. In addition, a testbed based on a factory scenario is proposed to evaluate the most important features of the presented architecture.

*Index Terms*—Industry 4.0, Smart Manufacturing, Industrial Internet of Things, Virtualized Process Controller, Reconfiguration, Redeployment, Resilience

#### I. INTRODUCTION

The industrial Internet of Things (IIoT), which consists of industrial cyber-physical systems (ICPSs), can be understood as the basis for the realization of a smart manufacturing. In order to realize this, new kinds of use cases arise, which bring along challenges for both communication systems and automation systems. Those can be mobility requirements, the application of computationally intensive algorithms, such as for the use of machine learning (ML) or artificial intelligence (AI), as well as a highly flexible reconfiguration of manufacturing systems or entire factories. Here, in the sense of the German Industry 4.0 vision [1], reconfiguration or even redeployment of industrial automation systems in very short time intervals, e.g. before each workpiece, are also conceivable. Current industrial systems, on the other hand, cannot offer these capabilities, since they are usually based on dedicated hardware controllers, such as programmable logic controllers (PLCs) [2].

To tackle these challenges, virtualization is a suitable approach. The virtualization of industrial automation systems enables the application of concepts already known in the field of information technology (IT). Since most of these concepts cannot support the rigorous requirements of industrial applications "out of the box", adoptions are essential in order to be applicable in the operational technology (OT) domain. Thus, based on a specific architecture, we investigate whether Virtual Process Controllers (VPCs) are a feasible approach to serve emerging use cases.

Accordingly, the following contributions can be found in this paper:

- Specification of an abstract architecture based on VPCs, serving as basis for novel Industry 4.0 use cases.
- Identification of most important features that are given by VPCs, and their evaluation and validation based on a testbed.

Therefore, the paper is structured as follows: opportunities and challenges for a smart manufacturing are presented in Sec. II, while Sec. III gives a short overview about related work on this topic. In addition, the most important functional requirements are presented ((Sec. IV)as well as the abstract architecture that is capable of closing this gap (Sec. V). In order to validate our concept, a testbed that maps the abstract architecture to real hardware will be introduced and an evaluation for most important features will be given (Sec. VI).

### II. SMART MANUFACTURING IN INDUSTRY 4.0

A massive flexible and adaptive production is one of the main objectives in Industry 4.0. In order to allow the corresponding benefits, a multitude of novel use cases emerged, where the number of mobile applications such as mobile robotics (platooning, cooperative goods transport, etc.) is increasing. Therefore, Fig. 1 depicts an industrial automation network that serves as the basis for the investigations in this paper. The network consists of three factory buildings and one factory cloud, which is located at the factory's data center and are connected via a router. Since industrial plants have a lifetime of several decades, existing facilities must be taken into account. Therefore, each production hall contains a legacy segment. This segment mainly contains dedicated hardware controllers such as PLCs as well as sensors and actuators that communicate via heterogeneous

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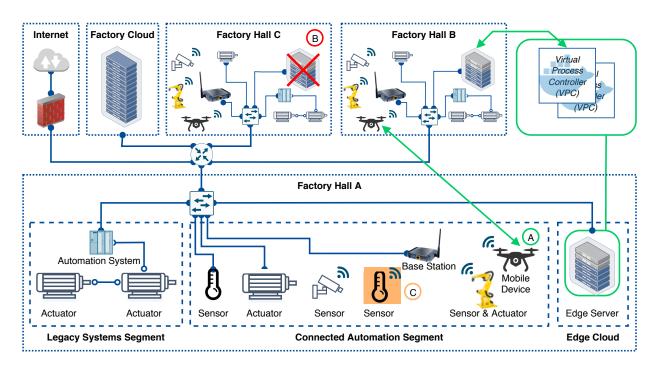


Figure 1. Factory Scenario with highlighted use cases (refined from [3]).

communication protocols like fieldbus or Industrial Ethernet (IE) protocols. These protocols are designed to meet the communication requirements of industrial applications, grouped in the real-time (RT) and use case classes that can be found in Tab. I. Typical requirements for the description of industrial applications are the cycle time and the synchronicity demanded by the devices. The synchronicity is expressed by the jitter, which represents the variation of the cycle time.

 Table I

 Use case classes and selected requirements [4]–[7]

Use case class	Requirements		RT
	Cycle time	Jitter	class
(I) Remote control, moni-	10-100 ms	≤ 1 s	1
toring			
(II) Mobile robotics, pro-	1-10 ms	$\leq 1 \text{ ms}$	2
cess control			
(III) Closed loop motion	< 1 ms	$\leq 1 \ \mu s$	3
control			

Typical use cases that can be found in the first use case class are monitoring use cases. Here, supervisory control and data acquisition (SCADA) and Human-Machine Interfaces (HMIs) can be found. New use cases that extend this class are additive sensing, predictive maintenance, and those that are part of the augmented reality (AR) domain. These applications, which belong to the lowest RT class 1, require cycle times of 10-100 ms and a jitter of less than 1 s. Use cases that are part of the second use case class belong to the process control domain, where cycle times of 1-10 ms and jitter of less than 1 ms are required. This class also includes mobile devices, such as drones for industrial inspection purposes as well as automated guided vehicles (AGVs) used to transport goods. Since some use cases, such as printing machines or machine tools, which are part of use case class III, have extremely high demands on cycle time and jitter, current wireless communications cannot cover them. Therefore the use cases belonging to this class are based on wireline systems, such as IE. The main argument for introducing wireless use cases in this class are the significant cost savings that can be achieved by replacing cables through wireless communications [4], [6], [8].

In order to realize emerging use cases, there is a connected automation segment in each of the production halls, containing novel technologies. Here open standards and communication protocols such as Open Platform Communications Unified Architecture (OPC UA) [9] and time-sensitive networking (TSN) [10] enter the scene, where especially their combination can be promising [11]. In the case of mobile use cases, high demands arise on wireless communications that cannot be met by state of the art solutions. Thus, concepts for the combination of TSN and 5th generation wireless communication system (5G) [7], [12], as well as TSN and wireless local area network (WLAN) [8], [13] are investigated. Furthermore, it must be taken into account that mobile devices often only have limited resources available, regarding computation power and energy consumption. To overcome this issue, computation offloading is a suitable approach [14]. In this case a service, such as a VPC, performs the processing instead of the resource-limited device. Thus, both computationally intensive algorithms, such as ML, AI or advanced control algorithms, and a longer battery life of the mobile devices can be achieved [15]. If a mobile device, such as a mobile robot, transmits the calculation of its motion trajectory to a VPC, the latter must also be mobile. In this use case, which is marked with "A" and shown in Fig. 1, the corresponding VPC is moved to the corresponding edge server that is located closer

to the robot, in order to fulfill the requirements. In addition, the migration should be performed live, i.e. at every noticeable interruption. Another case to consider (use case "B") is that devices like PLCs, have a maximum failure of less than one minute per year [5], which cannot be met by devices of the IT. Therefore, the failure of a device or its connectivity must be considered when using VPCs. As mentioned above, adding sensors during the lifetime of the system to improve product quality or to enable predictive maintenance is another possible scenario (use case "C"). Here, a seamless program update of the VPC is required.

#### III. RELATED WORK

Virtualization technology can be considered a key factor on the path to Industry 4.0 due to a number of advantages, such as immense computing power and automated management, provisioning and scaling of applications. However, the previously known virtualization technologies at hardware and operating system (OS)-level are not able to meet the high demands of the industry landscape. Therefore, several activities exist on this topic.

In order to achieve the required properties, [16] evaluated a virtualized PLC based on the virtual machines (VMs) that runs on Windows. With this setup a number of applications can already be realized. However, they were limited to applications that do not place high demands on cycle time an jitter. These so-called soft RT applications are not explicitly addressed in this paper and were therefore not mentioned in the previous section. Furthermore, several studies [3], [17], [18] compare hardware virtualization with OS level virtualization. Here [17] concluded that the performance of Docker containers is slightly worse than native OS, but better compared to using VMs. In addition, [18] investigated how the determinism of applications running inside and outside a container is related to a given RT priority and measured the virtual network interface handling latency of containers for the standard network drivers, thereby determining the virtualization overhead on the network interface. Since it can be advantageous for industrial applications to use a network driver other than the standard network driver, [3] included all of them in their investigations and compared them based on configuration effort, accessibility, scalability, security level, and performance. Due to better performance, [19], [20] suggest architectures for flexible industrial control systems, but limit them to container-based and IEC 61499-based controllers. Therefore [21] developed an abstract architecture using the 4+1 model [22]. The architecture presented in this paper follows the approach described in [21]. Furthermore [19] identified several features that must be supported by virtualized industrial automation systems that have been adopted by [20] and [21]. The most relevant features are described in the following section.

## **IV. FUNCTIONAL REQUIREMENTS**

In this section the most important functional requirements derived from Sec. II are listed that serve as basis for the architecture presented in Sec. V. 1) Reconfiguration: As already mentioned, Industry 4.0 includes a highly flexible reconfiguration of plant modules, entire factories or process controllers. Accordingly, reconfiguration of a VPC may also be necessary if an additional sensor is connected to the network. Therefore, it must be possible that both the controller firmware and the user-defined control program may need to be updated during normal operation. This means that the reconfiguration process must be performed without system downtime.

2) *Redeployment:* The redeployment process is a special case of reconfiguration. In this case the VPC has to be redeployed on another hardware node during normal operation without modifying the user-defined control program. This function is required on one hand by mobile devices which can change their location during operation (e.g. change of factory hall). On the other hand, it also covers the case that a system component requires an update or maintenance and is temporarily unavailable for this reason.

3) Resilience and Self-Healing: Very characteristic for industrial applications are the high demands on availability, which are very different from applications on the office floor. Industrial applications, belonging to the use case group of closed loop motion control, allow only a maximum failure of one minute per year [5]. Since this availability cannot be guaranteed by the equipment of the office floor as a rule, redundancy measures should be taken, whereby the failure of a redundant controller should not affect the process.

Since the required redundancy is no longer given after the failure of a system component, an automatic and seamless start of a further redundant instance on a separate hardware node should be triggered.

## V. COMPLETE FUNCTIONAL VPC ARCHITECTURE

Based on the functional requirements from the previous section, four different scenarios were derived (start up, normal operation, reconfiguration and replacement) and an architecture was designed using the 4+1 model [21]. This architecture is extended in this section and subsequently evaluated. The complete functional architecture is shown in Fig. 2.

The core component of the architecture is the VPC. It can be compared to a virtualized PLC and is the framework that collects the input values from ICPSs, executes one or more Virtual Process Control Functions (VPFs), and handles the transfer of the output values to the ICPSs. In general, an ICPS is an embedded system that connects industrial physical objects and processes with information processing units. Since not every ICPS has inputs and outputs, subtypes are also defined, where a sensor represents an ICPS that has only process inputs, while an actuator has only process outputs, and an I/O device has both process inputs and outputs. Moreover, gateways are foreseen for upgrading existing systems, which connect legacy components to the VPCs. In addition, Industry 4.0 covers the entire life cycle of assets. Therefore, an ICPS can also be the product itself. The assignment of several VPFs to one VPC can be especially useful if several VPFs depend on the same sensor value as input for process control, closed loop control, or similar. The scaling or adjustment of input vectors and the provision of

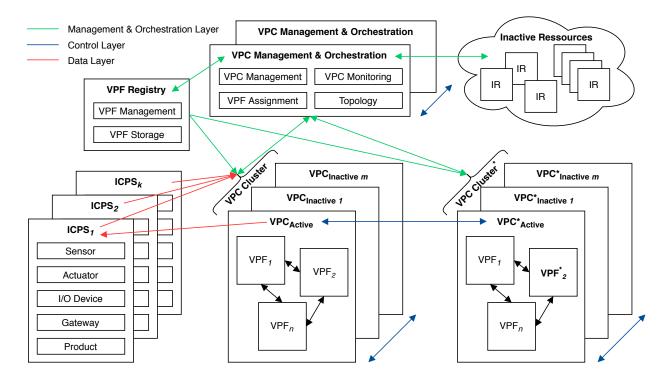


Figure 2. Complete functional VPC architecture including communication layers.

sensor values in databases (e.g. OPC UA information models) can then be performed once per VPC instead of for each VPF. This avoids data redundancy, inconsistency, and ensures data integrity. The VPFs represent the functions performed by the VPC. Consequently, they are the logic of the specific application and can be executed by the VPC cyclically or acyclically. In general, the complexity of a VPF can vary greatly depending on the application and use case. For example, it is possible that the task of a VPF is to set a single data value, while another VPF is responsible for controlling an entire machine. In order to be able to use redeployment or reconfiguration concepts efficiently, the finest possible granularity is preferred.

In addition to the VPC that actively controls the process and is called  $VPC_{Active}$ , a set of m  $VPC_{Inactive}$  backups are used to achieve the required redundancy and availability. Together these are referred to as VPC Cluster. The idea behind this is that all VPCs of a cluster receive the input values of all ICPSs and are state and time synchronized, but only the active controller passes the control data back.

If a reconfiguration or redeployment process is triggered, appropriate Inactive Resources (IRs) are selected to deploy new VPCs. IRs are specified as available and ready to use processing resources. The next step is to create a new VPC Cluster<sup>\*</sup> containing the reconfigured  $VPC^*$  and the new feature  $VPF^*$ . After a successful time and state synchronization a handover is initiated. Afterwards the old VPC Cluster is released. While the handover, time and state synchronization and replacement can be performed by the VPCs between each other, the decision which IR is best suited for the use of a particular VPC is coordinated by the VPC Management & Orchestration (VPC M&O). This allows the VPC M&O to query the features and

capabilities of each IR to meet the required quality of service (QoS) of the specific application. It also assigns the VPFs to the VPCs. The last component shown in Fig. 2 is the VPF registry. Here every VPF is stored and maintained.

As different message types with changing priorities and requirements are used, three message layers are added. First the Data Layer, where input /output (I/O) data is exchanged with the ICPSs. This data depends on the industrial device and can be any industrial protocol supported by the network. Therefore, in addition to communication on the IP layer, layer 3 (L3) communication, i.e. the exchange of Ethernet frames that belong to layer 2 (L2) communication, is also considered. The priority of these messages results from the requirements of the application. Second, the Control Layer covers control messages of the VPCs. Since VPCs may not fail, these messages have the highest priority, although some messages can have lower latency constraints than the data layer. Depending on the underlying network either L2 or L3 communication can be found here. Even if a time-limited failure of the VPC M&O would not affect the correct operation of the VPCs, it can also be advantageous to replicate it to have higher redundancy, eliminating a single point of failure. Therefore, control messages of the VPC M&Os to its backup are also part of the Control Layer. Finally, a delay of messages located at the Management & Orchestration Layer has the least impact on the system performance. However, since these messages are event-based rather than periodic, loss should be avoided. Therefore Transmission Control Protocol (TCP) is used in this layer.

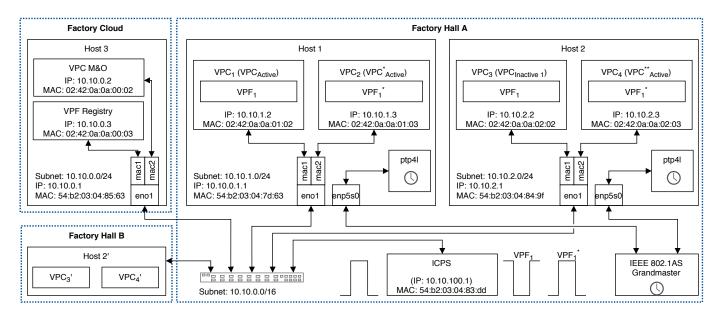


Figure 3. Testbed configuration based on the factory scenario that has been proposed in this paper.

### VI. TESTBED & EVALUATION

This section examines the feasibility of the proposed architecture for industrial use cases. Therefore, the logical architecture, which has been presented in the previous section, is mapped to real hardware. Moreover, three test cases are defined, and the testbed is used to evaluate all features that were identified as essential.

#### A. Testbed

The testbed that is depicted in Fig. 3 combines the factory scenario that has been presented in Sec. II and the physical view of the 4+1 model of the proposed architecture. There are two factory halls where edge resources are available and a factory cloud, which is located in the data center of the organisation, connected by an 8-port network switch.

Factory *Hall A* provides two servers (*Host* 1 and *Host* 2) that are part of the edge cloud. We decided to use mini personal computers (PCs) as hosts (see Tab. II), as they are comparable to typical industrial PCs (e.g. S7-300 [23] and its successor S7-1500 [24]) in terms of space consumption and pricing. Additionally, there are two VPCs running inside a Docker

Table II	
HARDWARE CONFIGURATIONS	S

Equipment	QTY	Specification	
Mini PC	4	Intel Core i7-8809G, 2x16	
		GB DDR4, Intel i210-AT	
		& i219-LM Gibgabit NICs,	
		Ubuntu 18.04 LTS 64-bit,	
		Linux 4.19.103-rt42	
Network Switch	1	8-Port Gigabit Ethernet	
		Switch	
TSN Evaluation Kit	1	RAPID-TSNEK-V0001,	
		IEEE 802.1AS-REV	

container on both hosts, each one assigned a VPF. Since it is currently assumed that TSN will be the future standard for deterministic data transmission in industrial environments, both hosts in factory *Hall A* are connected to a shared IEEE 802.1AS grandmaster and run the ptp4l service, which is part of Linux PTP [25]. Linux PTP is a free and open source gPTP implementation that complies with the IEEE 802.1AS standard. By using this implementation, a high synchronization accuracy between both hosts can be guaranteed, as shown in Fig. 4. Here,

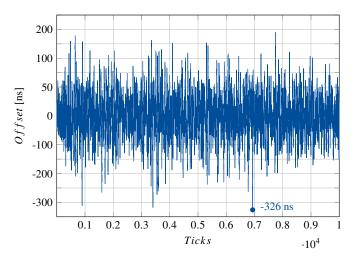


Figure 4. Synchronization accuracy between TSN Evaluation Kit and an Intel NUC mini PC for a sync interval of 31.25ms (2<sup>-5</sup>s).

for 10,000 samples the highest measured offset between one host and the grandmaster was 326 ns. This means that in the worst case the clock synchronization is less than  $2 \times 326$  ns. In most cases, however, a time synchronization of less than 500 µs can be assumed.

In addition, factory *Hall B* operates *Host 2'*, operating  $VPC'_3$  and  $VPC'_4$  to cover the redeployment process caused, for example, by an AGV moving from *Hall A* to *Hall B*.Next,

the VPC M&O and the VPF Reistry are also running inside containers on *Host* 3 that simulates the factory cloud. For the virtualization we follow the strategy proposed in [21]. There it was concluded that the macvlan network driver in combination with Docker Swarm as orchestration tool is well suited for the majority of industrial applications. In order to use Docker's automatic IP assignment and to avoid address conflicts, each host has its own /24 subnet. With this configuration each host is able to run 253 containers.

Moreover, an ICPS is located on the factory floor, which transmits sensor values to the VPC and receives actuator values in response. In this case, a periodically alternating binary signal has been selected as the sensor value, and there are two VPFs, of which  $VPF_1$  inverts the input signal and  $VPF_1^*$  does not change the input signal.

#### B. Test cases

1) Normal operation: This test describes the state in which the system runs without errors and no events, such as reconfiguration or redeployment, occurred. The VPC waits for the incoming process data of the ICPS, performs the VPF sends the control data back.

2) *Replacement:* This test describes how to ensure interruption-free operation of the entire system in case of a failure of one of the VPCs, either the active one. Since a failure of the active one is the most critical, this state is simulated by the inactive VPC not receiving a response to the synchronization message and thus taking over the task of the active VPC.

*3) Reconfiguration:* Here, a specific update of a VPF is initiated. After the two VPCs have synchronized, the handover is performed.

## C. Evaluation

This section aims to evaluate most important features of the proposed architecture. Therefore, the three tests that were introduced, are performed. Since we assume TSN as future communication system, and it is based on L2 communication, each of the tests is done for both Ethernet frames (L2) and UDP packets (L3), all of them sent with an transfer interval of 1 ms. For a better interpretation of the results, box plots containing 10,000 samples per data series have been created (see Fig. 5). By default, 50% of the values are located inside the boxes and the outliers are those values that exceed  $\pm 1.5 \times IQR$ . Assuming that every second value is close to the median value and the next value is significantly higher, this could lead to the worst case scenario where no values are placed between the boxes and the outliers and therefore only 50% of the samples lie within the box plots. Since this or similar cases are not sufficient for the rigorous demands of industrial applications, we also highlighted the borders for 99.99%.

It can be seen that the median for each measurement is between 300  $\mu$ s and 400  $\mu$ s. Furthermore, both the 99.99% and the maximum values are below 900  $\mu$ s. This means that each of the proposed use case and RT classes can be met in terms of cycle time. The only requirement that cannot be met so far is the jitter of RT class 3, which must be less than 1  $\mu$ s. This is due to the fact that the tests were performed acyclically and Looking at the replacement process more closely, it becomes clear that the displayed readings do not contain the missed packets until the second inactive instance notices the failure of the active VPC and starts transmitting. However, if the timeout of inactive VPC is chosen small enough, the failure of the active VPC can be detected in such a way that only one message of the ICPS is not answered by a VPC or is delivered delayed from the redundant VPC. This means that assuming that not two of the outliers occur consecutively, but only one outlier up to 600 µs is assumed, which corresponds to more than 99.9% of all samples, and that the subsequent value is around the median, even the failure of the active VPC does not violate the cycle time requirements of RT class 3.

Next, a detailed view of the reconfiguration process for three reconfigurations of a VPC is shown (see Fig. 6). The handovers are indicated by the dashed vertical lines. Here several time series are displayed, the first representing the input data of the VPC, the second its output data received by the ICPS, the third the ID of the active VPC and the fourth the measured values for the corresponding cycle time. It can be seen that the input signal is inverted at the beginning until the reconfiguration is triggered. Afterwards, the signal is not inverted anymore, until the next reconfiguration takes place. Here, several conclusions can be drawn. First, the reconfiguration process works correctly. Secondly, no increase of the cycle time can be detected during the handover. Last but not least it can be observed, that the jitter is too high for addressing RT class 3 until now. This problem will be addressed in future work, since didicated TSN or IE hardware would be required.

## VII. CONCLUSION

In this paper we have derived functional and quantitative requirements from a smart factory scenario and corresponding use cases, which have to be fulfilled for future industrial automation systems. Based on this, we proposed an architecture based on VPCs that is capable of meeting these challenges. Additionally, we proposed a testbed based on the smart factory scenario and evaluated the core features of the presented architecture. Based on the results, a feasibility for the application of VPCs for industrial use cases of each use case class can be proven.

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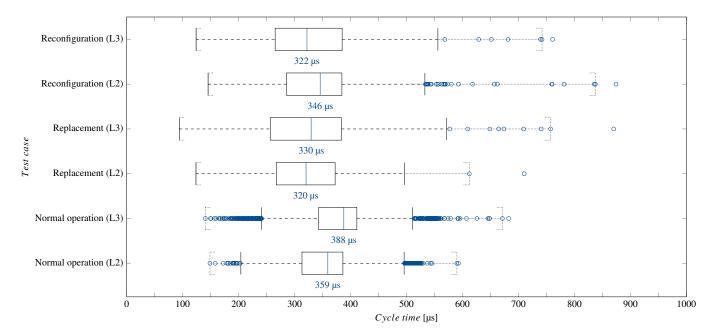


Figure 5. Readings of the cycle time for the three conducted test cases for L2 and L3 communication.

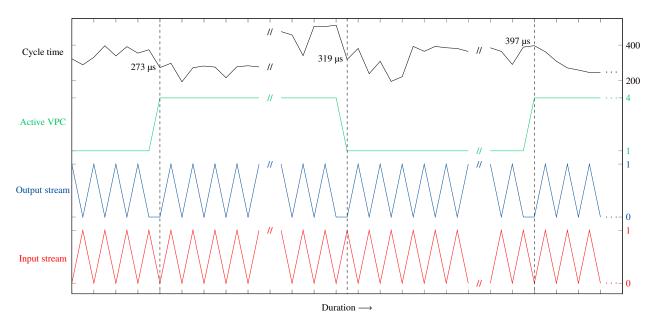


Figure 6. Illustration of the reconfiguration process.

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