Computation Offloading at Field Level: Motivation and Break-Even Point Calculation

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Abstract—Smart manufacturing has the objective of creating highly flexible and resource optimized industrial plants. Furthermore, the improvement of product quality is another important target. These requirements implicate more complex control algorithms. Processing these algorithms may exceed the capabilities of resource constrained devices, such as programmable logic controllers (PLCs). In this case, the necessity for computation offloading is given. Due to the fact that industrial plants are currently designed for a life-cycle-time of more than ten years, in a realistic smart manufacturing scenario, these devices have to be considered. Therefore, we investigate the impact of complex algorithms on conventional PLCs by simulating them with a load generator.

In addition, we propose a realistic factory scenario including benchmarks for both wireline and wireless communication systems. Thus, their round-trip time (RTT) is measured with and without additional load on the network. With the help of these investigations, break-even points for the application of computation offloading of two typical PLCs of Siemens S7 series can be calculated.

Index Terms—Computation offloading, PLC, smart manufacturing, Industry 4.0, industrial communication, wireless communications, cloud computing

I. INTRODUCTION

Today’s industrial production lines are controlled by PLCs. These systems are sophisticated for certain control tasks, but do not provide flexibility and only low computational power. In addition, with the vision of Industry 4.0, many novel use cases have emerged that bring up challenges and requirements that are different from the state of the art [1]. Besides mobility requirements imposed by the increasing number of mobile devices, machine learning (ML) and artificial intelligence (AI) will also have an important role in novel industrial facilities. Complex algorithms need to be solved to apply these methods. Here, the computing power of legacy field devices, such as PLCs, is not sufficient.

Following the return on investment and profitability, industrial plants are usually designed for a life-cycle-time of ten years or more [2]. Since changes to the plant hardware involve high costs and long holding times, it is not common to upgrade the entire plant to novel technologies and equipment during this time. Therefore, a way to integrate novel technologies as well as a migration path is a must for the so-called brownfield scenarios. To overcome the bottleneck of limited computing power, complex and time-consuming computations can be moved to an edge device. Thus, the limitations of conventional PLCs are presented in this paper.

In addition to the complexity of the algorithm to be offloaded, there are other parameters, such as network delay, that must be taken into account when calculating the break-even points. Using a previous work [3] and the research in this paper, each fraction of the break-even point calculation is identified. Accordingly, the following contributions can be found in this paper:

- Motivation for using computation offloading at PLCs to facilitate Industry 4.0 objectives.
- Proposal of a factory scenario, and identification of the RTT of different communication systems.
- Derivation of break-even points for two different PLCs, based on different communication technologies and open communication interfaces and protocols.

Therefore, the paper is structured as follows: Sec. II gives an overview about related work on this topic, while limitations of PLCs and benefits that can be achieved by applying computation offloading are presented in Sec. III. Moreover, Sec. IV lists relevant communication interfaces that are suitable for computation offloading. In addition, the factory scenario, which serves as basis for our break-even point calculations, as well as RTTs of different communication systems are proposed in Sec. V. Furthermore, Sec. VI evaluates the break-even points that are also derived in this section. Finally, a conclusion is given (Sec. VII).

II. RELATED WORK

For the realization of smart manufacturing, cloud computing is seen as one of the key technologies [4]. In particular, many mobile devices appear that require high-performance wireless communications that differ from today’s applications. Therefore, an architecture that can meet these requirements was introduced [5]. Since most mobile devices have limited resources in terms of computation and energy, [6] proposes a computation offloading approach to improve the energy consumption.
of mobile devices. This approach can be used to extend the operating time for battery-powered systems. However, resource-constrained devices, such as PLCs, are also found in the field level of industrial systems. Since these devices do not have any mobility, they are connected to all systems wireline. Therefore, battery life is not the focus when considering resource offloading. Here, especially the offloading of complex algorithms can bring advantages in terms of a lower processing time. Furthermore, offloading algorithms do not necessarily have to bring quantitative advantages, but can also enable advanced functions. For this reason, \cite{7} proposed several functions that enable seamless reconfiguration and redeployment of virtualized process controllers, while maintaining the required availability in the industrial environment, which is quite different from other domains. Moreover, \cite{8} demonstrates the feasibility of the proposed concept. Even if there are various reasons for applying computation offloading at PLCs, we focus on the performance, by identifying break-even points for the processing time. Here, the authors in \cite{3} have already assessed open interfaces and protocols of PLCs.

### III. Motivation for Computation Offloading

The first part of this section describes the state of the art process control and the limitations given by the utilization of conventional PLCs, while Section \[\text{III-B}\] explains the benefits, given by the application of computation offloading.

#### A. State of the Art Process Control

Today’s industrial plants are controlled by PLCs \cite{9}. A PLC is a special microprocessor-based control unit that is known for a deterministic and real-time (RT) program execution and communication. Thus, these controllers are highly sophisticated for continuous control tasks. Therefore, Fig. \[\text{1}\] shows the sequence for both program processing and data exchange. Each cycle starts with the reading of the input values, which are transmitted in the so-called “process image of the inputs”. This means that the values are fixed for the rest of the iteration of the control program. This step is important for a deterministic behavior, because changes from the sensor values during the calculations do not influence the control program for the recent cycle. In the next step, the program logic defines the correspondent output values and writes them into the “process image of the outputs”, which is than transmitted to the output modules. Afterwards, the next iteration starts.

For addressing RT aspects, the cycle time of the aforementioned process is a suitable Key Performance Indicators (KPIs), where the cycle time of a PLC depends on the number of inputs, number of outputs, and complexity of the executed algorithms. Consequently, raising the complexity of algorithms, e.g. for an improved closed-loop control, increases the cycle time of both, the PLC and the closed-loop application. As the complexity of algorithms in Industry 4.0 applications increases, such as for image recognition and ML, the computational power of PLCs is not sufficient. To simulate such a scenario, we built a load generator that calculates digits of the mathematical constant $\pi$ using Leibniz formula, which is shown in Eq. \[\text{1}\]

$$\pi = 4 \cdot \sum_{k=0}^{n} (-1)^k \frac{1}{2k+1}$$  \(1\)

Here, it is important to mention that $n$ does not represent the digits of $\pi$, but the partial sums of the Leibniz series. Therefore, Tab. \[\text{1}\] gives shows the required values for $n$, in order to obtain the first six digits.

Furthermore, the corresponding number of floating point operations (FLOPs) \[\text{2}\] is listed, calculated with formula Eq. \[\text{2}\] that determines the FLOPs of the Leibniz series dependant on the upper bound of the sum $n$.

$$\text{FLOP} = \left\lfloor n \cdot (n + 3) \right\rfloor + 1 = n^2 + 3n + 1$$  \(2\)

To investigate the influence of $n$ to the performance of the PLC, the load generator increases $n$ in each cycle. Fig. \[\text{2}\] illustrates the dependency between $n$ and the difference cycle time $\Delta t_{\text{cycle}}(n)$ for two representative PLCs that are listed in Tab. \[\text{1}\].

The plot shows that the dependency between these parameters are linear functions, until the point where the PLC goes into stop state. Thus, we have the following correspondence, where $\Delta t_{\text{cycle}}(n)$ refers to the increased cycle time, $n$ to the number of calculated partial sums, and $c$ is the constant time that is needed for each iteration of Eq. \[\text{1}\]

$$\Delta t_{\text{cycle}}(n) = c \cdot n \Rightarrow c = \frac{\Delta t_{\text{cycle}}(n)}{n}$$  \(3\)

\[\text{1}\]We do not differentiate between addition, subtraction, multiplication, and division.

#### Table I

| $\pi$ | $n$ | FLOP |
|-------|-----|------|
| 3     | 2   | $\approx 10^4$ |
| 3.1   | 32  | $\approx 10^5$ |
| 3.14  | 1,000 | $\approx 10^6$ |
| 3.141 | 10,000 | $\approx 10^7$ |
| 3.141 | 100,000 | $\approx 10^8$ |
| 3.14159 | 1,000,000 | $\approx 10^9$ |

Figure 1. State and sequence illustration of a cyclic PLC program.
| Equipment | Specification | Constant Name | Constant Value [ms] |
|-----------|--------------|---------------|---------------------|
| PLC S7-1512 | SIMATIC S7 CPU 1512SP F-1 PN for ET 200SP, Fw. V2.8 | c₁ | 3.65 · 10⁻² |
| PLC S7-314 | SIMATIC S7 CPU 314C-2 PN/DP, Fw. V3.3 | c₂ | 2.02 · 10⁻² |
| mini PC | Intel Core i7-8809G, 2x16 GB DDR4, Intel i210-AT Gibgabit NIC, Ubuntu 18.04 LTS 64-bit, Linux 4.19.103-rt42 | c₃ | 3.49 · 10⁻³ |

Therefore, Fig. 2 depicts the limits of conventional PLCs. In this case, the maximum value for the partial sums are \( n_{\text{max}} = 1.64 \cdot 10^5 \) for S7-1512 and \( n_{\text{max}} = 2.96 \cdot 10^5 \) for S7-314 PLC. This corresponds to the first five digits of \( \pi \) for S7-1512, and six digits for S7-314, respectively. If \( n_{\text{max}} \) is increased further, the PLC goes into a special stop state. This means, that the plant is going to be stopped. Therefore, this condition has to be avoided by adding more PLC central processing units (CPUs) or transferring the task to an edge node in cases there is a high load on the CPU of the PLC.

### B. Benefits by Computation Offloading

Besides the computation performance of the selected PLCs, Fig. 2 also shows the execution time of Eq. 1 for the same values of \( n \) of a commercial off-the-shelf (COTS) mini PC that is also listed in Tab. II. We decided to use a mini PC for the comparison because it is comparable to the used PLCs in terms of space consumption and pricing. Fig. 3 indicates that the cycle time of the mini PC is \( \approx 1 \cdot 10^{-3} \) lower compared to both PLC. This means that the computation performance of the small-sized PC has already the same computational performance as 1,000 PLCs. Thus, computation offloading can achieve a reduction in the cycle time of algorithms with a certain complexity. The criterion that must be satisfied so that there is a benefit is expressed in Eq. 4, where \( t_{\text{ro}} \) stands for the overall time consumed by resource offloading and \( \Delta t_{\text{cycle}} \) for the corresponding increase of the cycle time of the PLC.

\[
t_{\text{ro}}(n) < \Delta t_{\text{cycle}}(n) \quad (4)
\]

Therefore, the time consumed by offloading calculations can be divided up further, as shown in Fig. 3 and mathematically expressed in Eq. 5.

\[
t_{\text{ro}}(n) = t_{\text{update}} + t_{\text{network1}} + 2 \cdot t_{\text{nio}} + t_{\text{co}} + t_{\text{proc}}(n) + t_{\text{network2}} \quad (5)
\]

It can be seen that a high latency of the communication network has a negative impact on a closed-loop application that requires input data packets with a low latency. In addition, the update time plays a major role as it indicates the frequency with which data packets can be sent. It is defined as the "[...] time interval between any two consecutive messages delivered to the application." [10]. This value is characteristic for the investigated PLC, but is not network dependent. Moreover, \( t_{\text{ro}} \) depends on the delay of the network used for offloading the data. This is expressed by the delay of the forward path \( t_{\text{network1}} \) and the backward path \( t_{\text{network2}} \). In order to simplify Eq. 3, a variable \( t_{\text{network}} \) that is representing the total network delay, is used. As in a realistic scenario the algorithm is not processed on bare-

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**Figure 2.** Dependency between the number of calculations and the cycle time of two typical S7 PLCs compared to a mini PC.

**Figure 3.** Sequence Diagram for the application of computation offloading.
### Table III

**Comparison of the most common and open interfaces of two representative PLCs** [3].

| Interface Configuration | Protocol       | 1 Data Value       | 10 Data Values     | 100 Data Values     |
|-------------------------|----------------|--------------------|--------------------|--------------------|
|                         |                | S7-314             | S7-1512            | S7-314             | S7-1512            |
| Open User Communication | UDP            | 1.00               | 3.61               | 1.00               | 3.60               |
|                         | TCP            | 1.01               | 3.77               | 1.04               | 3.78               |
|                         | ISO on TCP     | 2.00               | 6.83               | 3.60               | 7.36               |
|                         | UATCP          | -                  | 9.11               | -                  | 30.35              |
|                         | UADP           | -                  | 1.02               | -                  | 1.26               |
|                         |                |                    |                    |                    |                    |

1 Due to a bug in the recent PLC’s firmware, where only 20 data values can be send, this value was estimated.
2 For the S7-314 series this value is doubled, because two requests have to be sent.

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...metal, there is also an overhead due to the use of virtualization technology for both the network interface \( t_{nio} \) and computation \( t_{co} \). The overall overhead caused by virtualization use can be calculated with the help of Eq. 6.

\[
t_{\text{overhead}} = 2 \cdot t_{nio} + t_{co}
\]  
(6)

Finally, the time required to process the algorithm is one of the summands of \( t_{nio} \). Taking into account the simplifications for network delay and virtualization overhead, Eq. 7 is a simplified version of Eq. 5.

\[
t_{\text{io}}(n) = t_{\text{proc}}(n) + t_{\text{network}} + t_{\text{update}} + t_{\text{overhead}}
\]  
(7)

### IV. Open Communication Interfaces of PLCs

In order to realize the offloading of algorithms, the communication interfaces and protocols of the devices under consideration must also be taken into account. As already mentioned, the update time is a suitable metric. Since Industry 4.0 requires data exchange between information technology (IT) and operational technology (OT) (IT-OT convergence), only open interfaces that use standard Ethernet and Internet Protocol (IP) layer are considered. Due to the fact, that most relevant communication interfaces of two representative PLCs were already identified and assessed in [3], we shortly list the findings that are relevant for this work. Hence, Tab. III lists the investigated communication interfaces as well as the values for the update time for three different message sizes. Since these interfaces and the measurements are described in [3] in detail, we only summarize the results.

#### A. Open User Communication (OUC)

The so-called OUC allows to send and receive user defined data packets that can use several IP-based protocols. Here, User Datagram Protocol (UDP) (RFC 768) and Transmission Control Protocol (TCP) (RFC 793) were identified as most suitable. Due to the fact, that the user data is directly packed into the data packet, no additional protocol header has to be generated. This makes this interface very efficient, resulting especially in a high performance of the S7-314 PLC. Compared to this PLC, the minimal update time of this interface using S7-1512 PLC is much higher. However, it can be seen, that the value does not increase a lot for larger data sets that are send using this interface for both PLCs.

#### B. LIBNODAVE

LIBNODAVE is a free and open source library for using the ISO-on-TCP protocol (RFC 1006) that is also known as “S7 Protocol” and uses port 102 for communication [11]. Furthermore, the edge device has to request the data from the PLCs by sending so-called Job messages, that are responded by an Ack_Data message. Here, it should be noted, that the protocol data unit (PDU) size of the S7-314 PLC is limited to 240 bytes. Therefore, only \( \approx 50 \) data values can be read within one request. Hence, for sending 100 data values, two requests have to be send. Thus, the update time for 100 data values is doubled for this PLC. Furthermore, it can be seen, that LIBNODAVE is less efficient compared to OUC for S7-314 PLC. This may be a result of the additional protocol overhead, given by the S7 Protocol. However, for S7-1512 PLC, the value is lower with respect to both, S7-314 PLC and OUC interface. This makes it a suitable interface for applying computation offloading for S7-1512 PLC.

#### C. Open Platform Communications Unified Architecture (OPC UA)

In order to facilitate the convergence between IT and OT, OPC UA [12] was introduced. It aims at a secure, simple and platform-independent exchange of information between industrial applications [13]. Since these specifications are not supported by S7-300 series, no readings are available for this PLC type. However, the usage of gateways that are connected close to the PLC are a possible solution, if OPC UA is required as communication interface between PLC and edge device [14].

1) **OPC UA Server Client:** The OPC UA server client pattern supports the binary TCP-based communication protocol (UATCP), which uses port 4840, and is well suited for embedded devices, such as PLCs. If data should be send from the PLC to the edge node using OPC UA server client, two different roles can be assumed. If the PLC is the client, it can send data to the edge node using so-called WriteService. In contrast, if the PLC is the server, the edge node must query the data values using ReadService. The latter can be compared to the LIBNODAVE interface. It can be seen, that using OPC UA...
Table IV

| Estimated constant | Constant | Value   |
|--------------------|----------|---------|
| line length        | 1        | 1,000 m |
| number of hops     | z        | 10      |
| network delay      | t_{network} | 80 µs  |
| virtualization overhead computation | t_{co} | 1 µs |
| virtualization overhead networking | t_{nio} | 1.5 µs |
| virtualization overhead | t_{overhead} | 4 µs |

client server model, the minimum update times of S7-1512 PLC using either WriteService or ReadService are higher compared to both other interfaces. This is a result of the big protocol overhead that brings up a lot of meta information [3]. Therefore, this interface can be important for a lots of use cases, but is not recommended if only the performance is relevant.

2) OPC UA Publish/Subscribe (PubSub): In addition to the server client model, the PubSub pattern was introduced in part 14 of the OPC UA specifications [15]. It allows devices to subscribe for messages that are published by other devices. Here, mappings to different well-known broker-based protocols, such as message queuing telemetry transport (MQTT) and advanced message queuing protocol (AMQP), as well as a custom UDP-based distribution that is called UADP are defined. Latter, that is based on the IP standard for multicasting, is recently the only one supported by the PLC and is used for the investigations. Even if the value for the update time of 100 data values had to be estimated, it is visible that the update time increases with higher data sets. However, for 1 and 10 data values it is the most efficient interface of S7-1512 PLC making it a good candidate for offloading data to an edge device.

V. FACTORY SCENARIO

In this section a factory scenario is proposed, on the basis of which the break-even points are derived in the following section (Sec. VI). Since the calculated break-even points are only valid for this specific scenario, it should be as realistic as possible. Thus, the factory scenario, which serves as basis for our investigations, is shown in Fig. 4. Since in a realistic factory scenario are other devices in the factory network besides the PLC and the edge node itself, we integrate three load generators that produce network traffic. Furthermore, we assume the following parameters for the factory network, which are also listed in Tab. IV.

Since the latency of a wired network depends mainly on the length of the line and the hops from the source to the receiver, but not necessarily on the complexity of the offloaded algorithm, it can be assumed to be constant for a given network. The authors in [16] identified the overhead of container virtualization technology compared to bare-metal. They assume <1 µs for the computation overhead and ≈ 1.5 µs for the network interface overhead with proper setup and configuration. The total overhead given by virtualization is thus assumed to be 4 µs.

Furthermore, for offloading data from a PLC to an edge node, which is mainly required for brownfield scenarios, we assume the following possible scenarios:

1) A local area network (LAN) is available and the PLC is integrated wireline.
2) No LAN is available and the PLC is integrated wireless.
   - Wi-Fi is used for the integration.
   - 4G/5G is used for the integration.

Since we assume all of the three possibilities as realistic, the RTT of these communication systems should be identified and added to the network delay of the factory network. Therefore, we made 10,000 samples per measurement for a update time of 1 ms for each of the communication systems with and without additional load on the network. For the wireline setup we used a standard 8-port Ethernet switch, for the Wi-Fi connection a COTS IEEE 802.11ac Wi-Fi router, and for the 4G communication system a commercial 4G system that serves as non-public network (NPN). The readings of the RTTs for the specific
communication system are shown in Fig. 5 and Tab. V.

![Figure 5. Readings of the RTTs for the following three communication systems with and without additional load: (i) Ethernet, (ii) Wi-Fi, (iii) 4G.](image)

| Round-trip time [ms] | Ethernet | Wi-Fi | 4G | 5G |
|---------------------|----------|-------|----|----|
|                     | w/o      | w/    | w/ | w/ |
|                     | load     | load  |    |    |
| **Median**          | 0.49     | 0.50  | 1.37| 104.60|
| **Max**             | 0.83     | 0.84  | 19.29| 4320.88|
|                     | 35.58    | 86.95 | -  | -  |

*This value was adopted from the specification of the 3GPP.*

VI. Evaluation

After all the constants of Eq. 7 have been determined, the break-even points of the examined interfaces and scenario can be determined. For calculating the break-even points, the condition in Eq. 8 has to hold.

\[
t_{\text{to}(n_{\text{be}})} = \Delta t_{\text{cycle}}(n_{\text{be}})
\]

(8)

Then, Eq. 3 can be inserted in Eq. 7 and resolved after \(n_{\text{be}}\), which leads to Eq. 9.

\[
n_{\text{be}} \cdot c_{\text{plc}} = n_{\text{be}} \cdot c_{\text{edge}} + t_{\text{network}} + t_{\text{update}} + t_{\text{be}}
\]

\[
\Rightarrow n_{\text{be}} = \frac{t_{\text{network}} + t_{\text{update}} + t_{\text{overhead}}}{c_{\text{plc}} - c_{\text{edge}}}
\]

(9)

The results, which can be found in Tab. III indicate the complexity of an algorithm that is required to have a quantitative benefit for computation offloading, taking the specific network into account. Additionally, a heatmap was produced out of the data and is shown in Fig. 6.

![Figure 6. Heatmap for the calculated break-even points of Tab. VI](image)

It can be seen, that using Ethernet as communication system, three traffic generators do not have a big impact on the RTT, compared to an idle network. This means, that the RTTs for the wireline setup are very low compared to the other communication systems, as expected. Looking at the Wi-Fi communication system, it can be seen, that the median value for the scenario without additional load on the network is also in the range of less than 1.4 ms. However, there are many outliers that are up to 15 times higher than the median value. If the values are compared to the load scenario, the values of the Wi-Fi systems are much worse. This is different in the 4G system. Here, the median values for the RTTs are basically higher compared to both other systems, but the determinism is much higher than in the Wi-Fi system and the 100% load does not have a big impact on the median value of the RTT. Moreover, it can be seen that the maximum value of the RTT for the 4G system is lower than the median value for the Wi-Fi system under load. Furthermore, since 5G communication systems are promising latencies of <1 ms for up- and downlink, we assumed a value of 2 ms as RTT for a possible 5G deployment.

It is visible, that the application of computation offloading for S7-314 and S7-1512 PLCs is very efficient using OUC. Thus, only the calculation of two digits of \(\pi\) using Leibniz series on the edge device is beneficial, compared to processing it on the PLC. Furthermore, using LIBNODAVE is only slightly lower in performance compared to using OUC for S7-314 PLC and much more efficient for S7-1512 PLC. Regarding OPC UA, it can be seen, that server client model might beneficial in several aspects, which are explained in [4], but PubSub is superior regarding performance.

Regarding the Wi-Fi connection, it is obvious, that for only more complex algorithms an advantage in terms of a lower overall processing time can be reached. Here, also the highest value is located, which requires an algorithm complexity of calculating approximately 4 digits of \(\pi\) using Leibniz formula. This is related to \(\approx 10^8\) FLOPs. Besides this fact, it is visible,
that the break-even points of the S7-1512 PLC for OUC are now smaller compared to the S7-314 PLC. This effect is caused by the higher RTTs of the communication system and the smaller computational power of the S7-1512 PLC and is also visible for the 4G system.

Looking deeper into the values for the break-even points of the 4G system, the points where it is beneficial to offload an algorithm is approximately doubled for the S7-314 PLC, compared to S7-1512 for both OUC and LIBNODAVE interface.

Last but not least, the effect of the smaller computational power of S7-1512 PLC and the better performance regarding update time of S7-314 PLC are approximately compensated for OUC using 5G as communication system.

### VII. Conclusion

In this paper, we proposed the motivation for the application of computation offloading at the field level of industrial plants using two representative PLCs as examples. Therefore, we elaborated on both their functionality and their limitations in terms of computational resources, interoperability, and flexibility compared to the computational resources of a potential edge node and the possibilities offered by virtualization technology. In addition, we listed relevant communication interfaces to access data of the PLCs and proposed a realistic factory scenario. Here, we assumed three different communication systems for the integration of a PLC in an IT environment. Moreover, we made measurements for these communication systems and the specific factory scenario and calculated the corresponding break-even points.

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