Software-Defined Networking for Industry 4.0

Theo Lins,
Mauricio Jose da Silva and
Ricardo Augusto Rabelo Oliveira

iMobilis Laboratory - DECOM
Federal University of Ouro Preto
Ouro Preto - MG - Brazil
Email: theosl,badricio,rrabelo@gmail.com

***Abstract*—The growing interest in Industry 4.0 increased the search for technologies that can help in its implementation. This technology has also evolved over the years enabling an increasing deployment of these industries. The Internet of Things (IoT), communication machine-to-machine (M2M) and Cypher Physical Systems (CPS) are essential for the implementation of Industry 4.0, while the Software Defined Networks (SDN), arrives as a new concept that can help in communicating devices that are part of the network that works with these industries. In our paper, we present an SDN architecture that implements the control plane together with the production control of an industry, where production decisions are passed directly to the SDN controller. In addition to the implementation of SDN communication, we also show the communication using a traditional network of computers. To validate the SDN architecture, we perform some simulation in scenarios of Industry 4.0, where success was obtained in the communications of industrial components.**

Keywords–Industry 4.0; SDN; IoT; M2M; CPS.

I. INTRODUCTION

With the emergence of new technologies over the past few years, several industry sectors have benefited from advances. The trend is that more and more technologies are created in to assist us in everyday tasks. But for this to happen, we must use them efficiently and effectively.

Among these technologies, we can highlight the Internet of Things, which are physical objects with some kind of technology such as Radio Frequency Identification (RFID) tags or sensors connected to the computer network, known as smart devices. These smart devices enable the integration of various processes such as communication devices themselves, production information, environmental information, equipment status and many other services.

New global requirements, such as environmental awareness also benefit from the use of these technologies, which have changed the way of production in industries with the use of green products and energy efficiency Based on these changes and developments, the main purpose of our paper is to propose a architecture of communication that can help in the technological evolution of industries, better known as Industry 4.0, making the communication more agile and efficient.

In Section II, we will present the technologies used in Industry 4.0. In Section III, we will present the SDN architecture for communication in Industry 4.0. In Section IV, we will perform the simulation with the proposed architecture, and finally in Section V, we present the conclusion and future work.

A. Problems and Goals

In the Industry 4.0, there may be hundreds of smart devices, devices that require network connections to cooperate with each other, and to perform increasingly complex tasks without manual assistance.

In addition to the proposal for an architecture that can connect the various components of Industry 4.0, from sensors to customers, there are also specific goals that would approach the requirements necessary for the operation of Industry 4.0.

Some requirements for the implantation of Industry 4.0 highlight some cited by Shrouf et al. [1]:

- Mass customization: Production processes have to meet varying requirements of production orders. It allows individuals to be included in the design, and enables last minute changes.
- Flexibility: Intelligent production processes and self configuration have to consider different aspects; such as time, quality, price and the ecological aspects.
- Factory visibility and optimized decision-making: Making the right decisions at anytime is a key to succeed in the market. IoT provides end-to-end transparency almost in real time (e.g., production status), allowing for optimization across factory sites in the area of production, and then improvement in factory efficiency.
- Connected Supply Chain: IoT will help manufacturers gain a better understanding of the supply chain information that can be delivered in real time. By connecting the machines and equipment to suppliers, all parties can understand interdependencies, the flow of materials, and manufacturing cycle times.
- Energy management: Energy efficiency improvement requires awareness of energy consumption behavior at production line and machine level. Smart meters can provide real time data, and take decisions based on their capabilities and in collaboration with external services.
- Creating values from big data collected: New improvements and value can be provided by the analysis of large quantities of data connected by IoT devices (i.e. big data).
- Remote monitoring: IoT technology will enable involvement by a third party (e.g., suppliers) in monitoring, operating and the maintenance of factories with

 ISBN: 978-1-61208-473-2

new services.
- Proactive maintenance: Monitoring production system and collecting performance data in real time will have a positive impact to improve proactive maintenance.

B. Contributions of Work

To achieve our main goal, we implemented an architecture of computer networks for Industry 4.0 using the paradigm of SDN to connect the components of Industry 4.0. With the new architecture we can mention some of the contributions:

- External communication for devices through Gateway SDN.
- Connection and management of data a cloud.
- Dynamic management of smart devices.
- Feed of data and automatically decision-making.
- Optimization and fault tolerance in production lines.
- Connection of customers and suppliers directly with Industry 4.0.
- We create scenarios for Industry 4.0 and run tests with simulators.

II. Industry 4.0 and its Technologies

The next step in the industrial development will be related to smart devices and the interaction of the products that are a part of the manufacturing process. Also called the New Industrial Revolution, Industry 4.0 or Intelligent Industry aims to transform the product which is usually a passive object into an active object, it is essential for decision-making and optimization of its manufacturing.

Among the main features of smart devices is the ability to self-monitor, detect faults, alter flows, perform calculations, and the main function is to communicate with other components.

Some recent research already addresses the Industry 4.0, Varghese et al. [2], discuss some of the challenges of wireless communication that must be met before it can be utilized in Industry 4.0. They describe how the 5G can help with the implementation, considering the communication m2m focused on latency, longevity, and reliability of communication. In our work in addition to addressing wireless communication and M2M communication, treat interoperability between communications technologies and validated through simulation, the implementation of an Industry 4.0. M2M communication, the study [3] Paelke show that the Intelligent Industry can also help users in manual tasks performed in the industry. An initial experience with an augmented reality system helps workers in an environment with constant changes in production decisions. The system helps workers in unfamiliar tasks through spatially registered task information in the users field of vision.

Gorecky et al. [4] also highlight the participation of users in Industry 4.0, with the flexibility proposed in this new concept, users will be faced with a wide variety of works ranging from the specification and monitoring, to also check production strategies. The aid technology will allow users to perform the management more accurately as well as control the production.

But there are still many essential concepts behind the Industry 4.0, such as Cyber Physical Systems, the Internet of Things and Machine-to-machine communication.

A. Cyber-Physical Systems

CPS are automated systems that enable connection of the operations of the physical reality with computing and communication infrastructures. Unlike traditional embedded systems, which are designed as standalone devices, the focus in CPS is on networking several devices. CPS goes with the trend of having information and services everywhere at hand, and its inevitable in the highly networked world of today [5].

The infrastructure of Industry 4.0 is composed of CPS, which makes the study of these systems necessary for correct implementation. Jazdi [5]present a prototype that demonstrates the essential aspects of Industry 4.0. In our work as well as evidenced in an architecture for network communication, we conducted several tests to validate the operation of the network.

B. Internet of Things

With the growth and popularization of the Internet emerged the IoT, this evolution is the future of communication and even computation. But for it to develop further, it depends on new technologies and service models that are being created and/or improved. For the IoT is a network of devices that make the integration between the physical and computational systems all through an infrastructure that collects and exchanges information.

To better understand the information circulating in IoT networks, Perera et al. [6] made a study of the context aware of this information. The work is an analysis of the context of the life cycle, and evaluates a subset of related projects. Based on these evaluations, they compare, highlight the lessons learned, and discuss the applicability to the Internet of Things.

In addition, the IoT is also one of the main factors involved in the implementation of Industry 4.0, if not the biggest supporter so that the next step is taken. This is due to its connectivity and interaction with many devices such as the Industry 4.0.

In [1], it is shown the relationship between IoT and Industry 4.0, which is created an architecture for Industry 4.0 based on IoT. They define the main characteristics of Industry 4.0 focused on sustainability. And propose an approach to power management in Intelligent Industries based on the paradigm IoT.

C. Machine-to-Machine

M2M technologies are used for communication between devices. Kim et al. [7] did a study on the M2M communication. They discuss the need for M2M platforms, comparing and analyzing the existing approaches and M2M solutions platforms, Thereby Identifying the requirements and functionality of the optimal service platform for M2M. Finally based on this information, the authors propose an architecture for M2M services platform (M2SP) and its features, then present the M2M ecosystem with this platform. Different application scenarios are presented to Illustrate the interaction between the components of the proposed platform.

So in the Industry 4.0 M2M, the communication between production components is allowed, enabling the exchange of information between them, facilitating decision making and speeding up the entire production process.

D. Software-Defined Networking

In recent years, the traditional networks have been limited compared to other technologies, as it relates to the management, performance, and scalability. Contrary to this limitation, a new paradigm in networks has shown to be the solution, SDNs propose networks which have more flexible and dynamic computers.

The idea of SDN is to separate the control plane from the data plane while the data plan stays in the forwarding devices, the control plane stays in a central controller with a software responsible for the behavior of the network. The protocol OpenFlow is the most used for communication of SDN components and the main focus of recent related research because it allows the creation of SDN networks with common forwarding devices.

Despite many studies related to SDN and OpenFlow, so far there are few studies using SDN applied to IoT, some work as [8], presenthow the structure should be made, but does not simulate and generate statistic results. Already in [9] they designed an approach defined by software to an IoT environment in a scenario involving a heterogeneous wireless network. The prototype then uses a scenario with electric vehicles, locations for electric loading, and a smart grid infrastructure. But the IoT network vehicle has different requirements from a network of Industry 4.0, as a much greater mobility.

SDN can also address many challenges of Industry 4.0, since the adaptability which is one of the main characteristics of SDN to the energy efficiency that can be improved with communication between devices. Because the Industry 4.0 has a knack for effective communication as well as its flexibility and self-management, its exactly what the SDN has to offer. What makes SDN one with a potential tool for technology deployment Industry 4.0.

A well-known SDN limitation is centralized control. In Industry 4.0 network this limitation tends to be lower, due to the low data flow during production. But the network controller is a point of failure, meaning that if it stops working, the whole network stops. But this problem has been solved by using some techniques [10] of distributed network control.

In this paper, the SDN network is responsible for every connection made by smart devices and products. In order to have more efficient connections, favoring communication between devices, products, customers, suppliers, and administrators.

III. SDN Architecture for Industry 4.0

The traditional computer networks are not prepared to adapt to constant changes that occur in the network flow and a lot of devices and information travels on it. These are the characteristics of most IoT networks. Based on these characteristics some authors have proposed SDN architectures for IoT [11][12][13], but to date none about Industry 4.0.

In Figure 1 it is shown an SDN architecture with applications and equipment used in Industry 4.0.

The application layer has applications that communicate with the SDN controller, and we implemented an Application Programming Interface (API) that communicates the SDN controller with the Production controller. The production controller is responsible for managing the production, as well as the one who makes all decisions related to production. When a decision is recieved, the production controller passes the information necessary to the SDN controller, in reverse the same thing is done when the SDN controller collects information related to the network, it transfers it to the production controller, all done through the API.

We also have the application layer of the cloud of data that

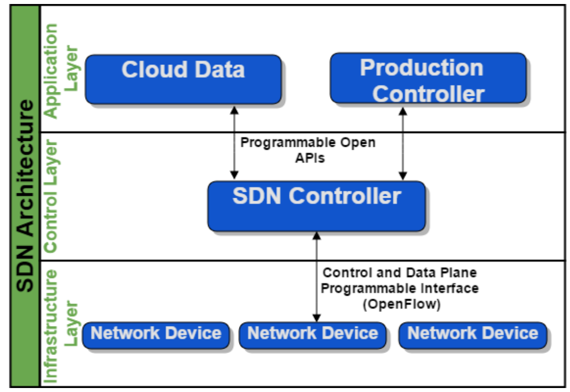

Figure 1. SDN architecture with the Production Controller.

is responsible for storing all the data collected. In the cloud, part of the production data can be accessed by customers and suppliers, who use this to follow the production process and to send data to the cloud, data that will be used by the production controller. While the production controller writes production data in the cloud, the Network Controller (SDN) enables automation of services, which is critical for cloud services. From the network details collected, all changes requested by cloud components are automatically reflected in the forwarding plane.

The control layer has the SDN Controller which is the central node of the industrys communications network, and responsible for all network management. The API that communicates with the application layer must be implemented in the same language of the controller. To communicate with the infrastructure layer a SDN protocol should be used, in our case, we use the OpenFlow.

In the infrastructure layer, all the SDN devices are managed by SDN controller, these devices have only the data plan that is sent by the controller, and any other decision is taken by the SDN controller, which has the control plane. While the switches receive and must perform packet forwarding, the gateway receives this and mounts their routes for communication. Status and information of sensors can be collected, as well as the necessary information to communicate with different networks and technologies, for example we can mention the cloud communications.

A. Packet Forwarding

The data path of an OpenFlow switch contains one or more flow tables. Each flow table in the switch contains a set of flow entries where each entry contains match fields, counters, and instructions. An entry is identified by its extensible match fields which comprise the switch ingress port and different packet header fields. For received packets on the data path, the switch tries to match the ingress port and packet headers with the match fields in the different flow entries.

If a flow entry field is wildcarded and has a value of ANY, it matches all possible values in the header. Only the highest priority flow entry that matches the packet must be selected. The counters associated with the selected flow entry must be updated and the included instruction set must be applied. If a matching entry is found, the instructions associated with the specific flow entry are executed. If no match is found in a flow table, the outcome depends on the switch configuration. The default in the OpenFlow switch specification version 1.2 is to

 ISBN: 978-1-61208-473-2

send packets to the controller over the OpenFlow channel via a packet-in message. Another option is to drop the packet. The packet-in message may either contain the entire packet or just a fraction of the packet header [14].

IV. Simulation and Validation

Industry 4.0 implies the use of concepts that tangent state of the art, such as CPS, M2M and IoT, to create a smart production process, which is self-manageable and dynamic. SDN apply under this scenario allows a flexible management resource. In order to evaluate the performance of the communication mechanisms of an SDN network a different simulation was implemented in OMNeT ++ simulator [15] with an extension to OpenFlow call ofomnet [14]. In addition to the performance analysis of the SDN, we also provide an analysis of the capacity of a production process on Industry 4.0 to self-manage and self stabilize.

A. Scenarios

Based on some studies [16][17], about Industry 4.0, we developed a production scenario that addresses some characteristics in these industries. The chosen scenario is a generic factory that has N line productions, with several interconnected devices. In Figure 2 a production line used at work in Industry 4.0. Therefore, all applications used in the scenarios were implemented in the Industry 4.0 standards.

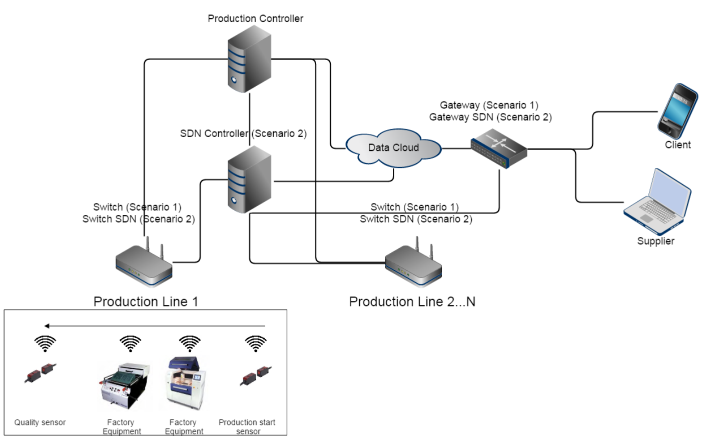

Figure 2. Scenario addressing Industry 4.0 on OMNeT ++.

To compare the possible deployments of Industry 4.0, we implemented two scenarios, the first scenario works with a traditional network of computers and is called Scenario 1. The second is Scenario 2 and works on an SDN network, in this case there is an additional network controller, and network switches are SDN, specifically OpenFlow.

Below is a description of each component of the scenario:

- Manufactured product: the product is an active object in production, where each product has an RFID tag, which will be used to identify the product, from the start of production until such time that it is ready to be sent to a client.
- Client: It is an agent, which can be a person or another industry, which should be able to place orders on demand and monitor the production process of your order. The manufacturing process is a response to a client request.
- Supplier: It is notified by Industry 4.0 when there is a need for more raw material for production.
- Production controller: Controls the entire process of production in Industry 4.0, in Scenario 2 some of its features are automated by the SDN. In addition to collecting information about each product throughout the production line, the production controller is able to make decisions such as:
  - When a production line is overloaded, the load is distributed with other production lines.
  - If the inventory level of raw material is low, more raw materials are required to go to the supplier
  - If the production line is idle, the line is used to produce another product.
- Data Cloud: The cloud stores all the information that is transmitted in Industry 4.0, and customers and suppliers also have access. The production control and data cloud could be implemented together, but for better organization and independence, we decided to implement them separately.
- SDN Controller: Is implemented using the OpenFlow protocol, and used in the scenario 2. The SDN controller is responsible for managing the Indust.ry 4.0 network. In the scenario 2, the SDN controller exchanges information with the production controller to make decisions about packet forwarding, and networking devices status check.
- Switch/Gateway: In the scenario 1 we use common switching devices. In scenario 2 everything is implemented using the OpenFlow protocol. In this case, the Switch/Gateway is managed by SDN controller, that mounts the data plan.
- Production start sensor (RFID Product): RFID sensor that collects product tags to begin the manufacturing process.
- Quality sensor (RFIDSize and RFIDWeigth): RFID sensors that are responsible for quality control. If the product does not have the quality requirements it is discarded and the request for a new product is sent to the server.
- Factory Equipment: The equipment is used in the manufacture of the product, and are also connected to the production controller by an switch. Eg laser cutting machine, laser welding system, bending machine, thermoforming machine, etc.

B. Testing and Results

In order to evaluate the use of traditional computer networks and SDN in Industry 4.0, we implemented two production lines that are able to attend the demand of a client automatically. Products used generically to illustrate that this process can be applied to other kinds of industry.

The simulation begins with a client requesting 100 products in producing. Throughout the simulation, the client makes 10 requests for 100 products in each. These requests are made periodically, and it is important to validate the properties of the industry cope with the demand scale, distributed production between the various production lines reducing the possibility that they are idle.

The production process begins when the production controller receives a client request. At this time, the production controller checks for raw materials in sufficient inventory to meet the new demand for products, if there is no stock of raw materials, or if the stock not enough, the production controller makes a request to the supplier for more feedstock. As we are dealing with a factory, it is common for some raw material is lost during the production process, therefore, the production controller considers it a waste rate of 10% when making a request to the supplier.

As noted above, a stock or raw material may exist, but this stock is not enough to attend the clients demands. In this case, the production controller requests the production of many products as the stock allows, and the other products of demand are produced when the production controller is able to guarantee enough stock to produce them.

Still with the objective of maintaining the tests applicable to other industries, monitoring the product within the production process is made by three sensors which represent: a sensor for registering the start of manufacturing of a product, from this moment the product is monitored until it is ready to be delivered to the customer.

The two other sensors represent quality tests to which products must attend. For each product, it is generated a random number between 0 and 1 with uniform distribution. If the generated number is greater than 0.9, the product is considered defective and the production process has to deal with such a problem requiring the production of a substitute product, guaranteeing that the client demand is met.

During the simulations, to meet customer demand of 1000 products, the error function used by the sensors detected in average 224 defective products in scenario 1 and 226 in scenario 2, that is, during the entire production process in average were produced 1224 products in scenario 1 and 1226 in scenario 2. Despite that error rate though it may seem large for a production process for our experiments it represents greater opportunities for communication, the greater amount of data transmitted and even still, an opportunity for more learning.

The simulations used parameters related to the Ethernet protocol, which can be seen in Table I. To generate the results we conducted 3 simulations for each scenario, then we averaged the results.

TABLE I. PARAMETERS USED IN THE SIMULATION.

Parameter	*Value*
Delay in channel	1μ
Transmission rate	$100Mbps$
Request package size	$200B$
Response package size	$1MB$

As a result the communication showed the most common metrics used in computer networks such as end-to-end delay, sent packets, and received packet. Figures 3 showed the end-to-end delay of main simulation devices, with the information of maximum delay, minimum delay, average delay, and standard deviation.

Made more comparisons between scenarios can be seen in the Figure 4, is made counting the number of incoming and outgoing packets in Mbytes, respectively. The communication usually begins with a request from a client that attends and is then answered by the server. As we can see in Table I, the size of the request and response packets are 200B and 1MB, respectively. That server usually answers the requests and the

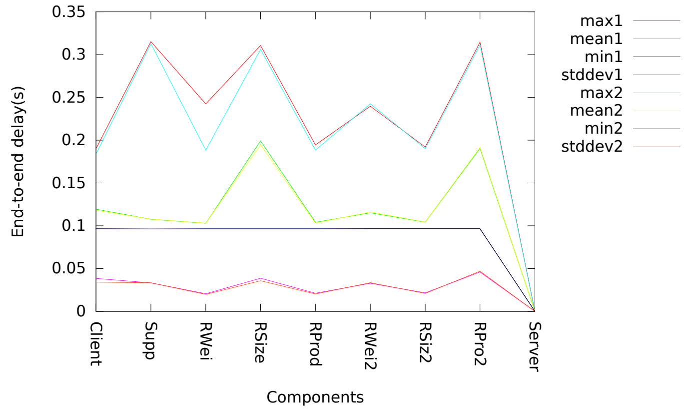

Figure 3. End-to-End delay - Scenario 1 and 2.

requests contain only 200B, which causes it to transmit fewer bytes than the other network nodes.

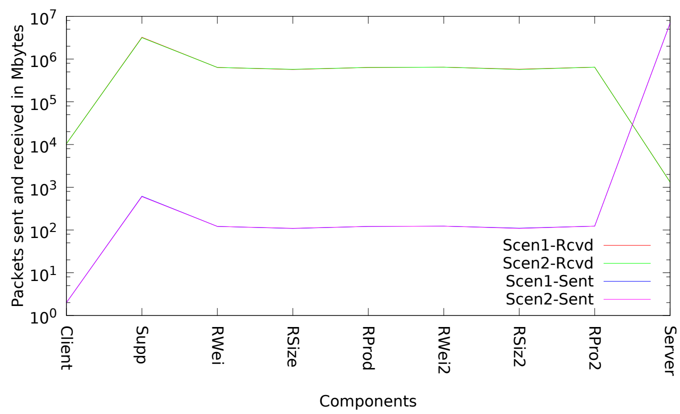

Figure 4. Number of packets sent and received in Mbytes.

To illustrate the benefits of using the SDN Industry 4.0, we made some simulations to show the efficiency of the use of SDN. In the simulation, a product takes on average 100s to finish, and a new product starts on the production line every 5s, thereby a production line has a maximum 20 products being produced.

In Figures 5 and 6, it is shown the simulation of 50 products in the same two scenarios with two Production Lines(PL1Cen1, PL2Cen1, PL1Cen2, PL2Cen2). In Figure 5, it is shown a number of products in process of production at an instant of time. The increasing number means new products being produced, and the declining number means products being finalized. During the simulation a failure occurs in a production equipment at 120s, between the interval of 60s and 180s.

In scenario 2, when a problem occurs in some equipment production, the moment in which the machine fails or stops the communicate, the Network Controller detects based on communication with the switch, and communicates the Production Controller. Then, the production controller changes the production line until the problem is resolved. In scenario 1, if the equipment fails, the production controller will not have a quick feedback, it will not know if the communication is slow or stopped. When the problem occurs in any network equipment, in scenario 2 it automatically can be solved by the network controller, which can change the route of communication, which can not be done in Scenario 1.

In Figure 6, it is shown the finished products where the scenario 1 finished all production in 355s, the scenario 2 finished the same amount of products in 305s. Other simulations were realized with some types of failures(Failure to equipment, switch overload, failure to sensors) and all had similar results.

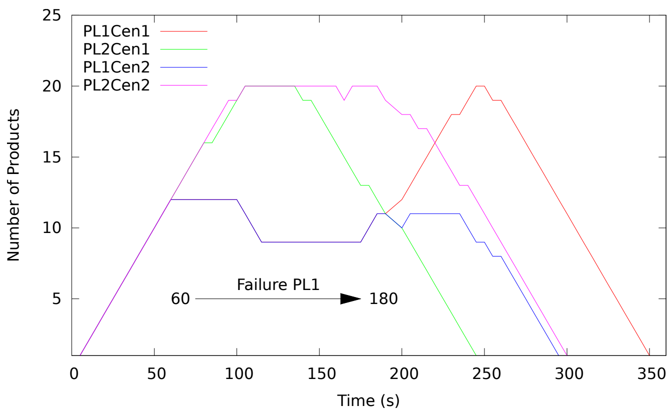

Figure 5. Production.

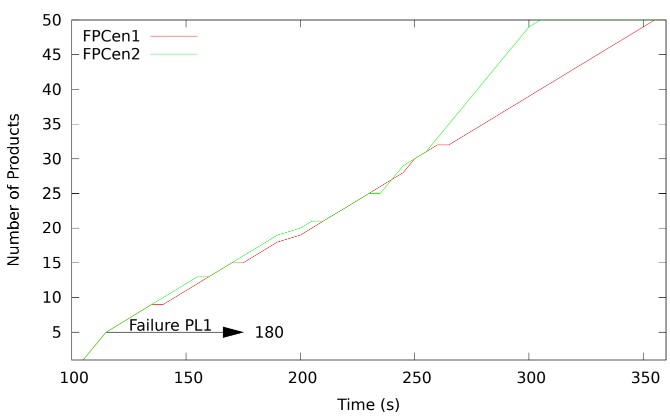

Figure 6. Finalized Products

From these results it is possible to observe that the bigger the number of production lines and equipment, the more evident will be the advantages of using the SDN.

V. Conclusion and Future Work

In the article, we propose an SDN architecture for network communication in Industry 4.0 based on SDN, which enables a flexible and effective management in the flow control of production and resources. The architecture uses the SDN Controller working together with the Production Controller, providing speed in decision making. Many APIs have been implemented and tested in a simulation in scenarios for Industry 4.0. The infrastructure has enabled customers and suppliers, consult and add information in real time on production.

The simulation results showed that it is possible to implement this new concept called Industry 4.0 and will soon be a reality for most industries. It was also shown that the features of technologies such as IoT, M2M, CPS and SDN are essential to the implementation of the Industry 4.0.

As future work we intend to simulate variations in the scenarios, implement new functions for SDN devices, and work on the security of network devices.

References

[1] F. Shrouf, J. Ordieres, and G. Miragliotta, "Smart factories in industry 4.0: A review of the concept and of energy management approached in production based on the internet of things paradigm," in Industrial Engineering and Engineering Management (IEEM), 2014 IEEE International Conference on. IEEE, 2014, pp. 697–701.

[2] A. Varghese and D. Tandur, "Wireless requirements and challenges in industry 4.0," in Contemporary Computing and Informatics (IC3I), 2014 International Conference on. IEEE, 2014, pp. 634–638.

[3] V. Paelke, "Augmented reality in the smart factory: Supporting workers in an industry 4.0. environment," in Emerging Technology and Factory Automation (ETFA), 2014 IEEE. IEEE, 2014, pp. 1–4.

[4] D. Gorecky, M. Schmitt, M. Loskyll, and D. Zuhlke, "Human-machine-interaction in the industry 4.0 era," in Industrial Informatics (INDIN), 2014 12th IEEE International Conference on. IEEE, 2014, pp. 289–294.

[5] N. Jazdi, "Cyber physical systems in the context of industry 4.0," in Automation, Quality and Testing, Robotics, 2014 IEEE International Conference on. IEEE, 2014, pp. 1–4.

[6] C. Perera, A. Zaslavsky, P. Christen, and D. Georgakopoulos, "Context aware computing for the internet of things: A survey," Communications Surveys & Tutorials, IEEE, vol. 16, no. 1, 2014, pp. 414–454.

[7] J. Kim, J. Lee, J. Kim, and J. Yun, "M2m service platforms: survey, issues, and enabling technologies," Communications Surveys & Tutorials, IEEE, vol. 16, no. 1, 2014, pp. 61–76.

[8] H. Huang, J. Zhu, and L. Zhang, "An sdn_based management framework for iot devices," in Irish Signals & Systems Conference 2014 and 2014 China-Ireland International Conference on Information and Communications Technologies (ISSC 2014/CIICT 2014). 25th IET. IET, 2013, pp. 175–179.

[9] Z. Qin, G. Denker, C. Giannelli, P. Bellavista, and N. Venkatasubramanian, "A software defined networking architecture for the internet-of-things," in Network Operations and Management Symposium (NOMS), 2014 IEEE. IEEE, 2014, pp. 1–9.

[10] A. Krishnamurthy, S. P. Chandrabose, and A. Gember-Jacobson, "Pratyaastha: An efficient elastic distributed sdn control plane," in Proceedings of the third workshop on Hot topics in software defined networking. ACM, 2014, pp. 133–138.

[11] N. Omnes, M. Bouillon, G. Fromentoux, and O. Grand, "A programmable and virtualized network & it infrastructure for the internet of things: How can nfv & sdn help for facing the upcoming challenges," in Intelligence in Next Generation Networks (ICIN), 2015 18th International Conference on. IEEE, 2015, pp. 64–69.

[12] L. Galluccio, S. Milardo, G. Morabito, and S. Palazzo, "Sdn-wise: Design, prototyping and experimentation of a stateful sdn solution for wireless sensor networks," in Computer Communications (INFOCOM), 2015 IEEE Conference on. IEEE, 2015, pp. 513–521.

[13] N. A. Jagadeesan and B. Krishnamachari, "Software-defined networking paradigms in wireless networks: a survey," ACM Computing Surveys (CSUR), vol. 47, no. 2, 2015, p. 27.

[14] D. Klein and M. Jarschel, "An openflow extension for the omnet++ inet framework," in Proceedings of the 6th International ICST Conference on Simulation Tools and Techniques. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2013, pp. 322–329.

[15] A. Varga et al., "The omnet++ discrete event simulation system," in Proceedings of the European simulation multiconference (ESM 2001), vol. 9, no. S 185. sn, 2001, p. 65.

[16] H. Kagermann, J. Helbig, A. Hellinger, and W. Wahlster, Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0: Securing the Future of German Manufacturing Industry; Final Report of the Industrie 4.0 Working Group. Forschungsunion, 2013.

[17] M. Hermann, T. Pentek, and B. Otto, "Design principles for industrie 4.0 scenarios: A literature review," 2015.