Fog-based Logistic Application Modeling in an Industry 4.0 Framework

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Abstract. The industrial growth introduced the Industry 4.0 revolution, which uses several IoT-based technologies to manage the huge amount of data generated by its connected systems. This revolution aims to exchange data between the different parts and improve the performance of the manufacturing process. Facing several limitations, this paradigm needs the Fog Computing to ameliorate the Cloud services and the distribution of real-time decision-making and the secure and interoperable data analysis. The internal logistics presents the need to transmit and treat the data in real-time to take more efficient decisions in a shorter delay. The Fog-based architecture is composed of terminal devices, Edge, Fog and Gateway devices. A model is presented to optimize the Fog integration (The cost of the links and nodes). Experimental results of an exact method optimization using Fico Xpress show a reduction of the Fog Computing integration cost in an internal logistic center.

1. Introduction

The increasing complexity of production systems and quantity of data is due to several factors such as sensor networks integration, software applications, variability of markets, etc. As a result, the emergence of a fourth revolution does not only strengthen the competitive position of developed countries, but also generates solutions to global and specific challenges such as energy, resource efficiency, complexity of systems and demographic changes management [1]. The Industry 4.0 emergence is becoming a necessity to satisfy the demand of process automation, integration of artificial intelligence, flexibility and high products customization.

The Industry 4.0 is based on several components like IoT (Internet of Things), the CPS (Cyber Physical Systems), Cloud Computing and Big Data [2]. These components lead the Industry 4.0 to another level of intelligence, automation and interoperability.

The Industry 4.0 requires computing data and making decision in real-time, however the Cloud Computing features are not adequate to transmit the information quickly [4]. Several new solutions able to increase the information pertinence and reduce time delay and computing consumption are developed to overcome the Cloud Computing lacks [5]. ©Cisco Systems has presented the “Fog Computing” paradigm as the most adequate solution for this issue. The Fog Computing is an Edge Computing solution, defined as the highly virtualized platform that extends the Cloud services and processes information directly at edge of the network [4], to accomplish processing, computing, storage, and routing services between traditional Cloud terminals and servers. The adoption of the Fog in the industry
Industry 4.0 is limited by numerous challenges (Cost, power consumption, interoperability, security, etc.) that needs to be overcome [6]. One of the most influencing challenges is the cost of the Fog solution. Several industrial applications can be ameliorated by adopting a Fog-Computing solution to reduce delay and cost. One of these application is the internal logistic. This paper presents the importance of integrating the Fog Computing in the internal logistic application especially in the Industry 4.0 framework and defines its architecture composed of different layers. It also presents a model that decides whether to deploy or not the different architecture nodes, which optimize the cost of integrating the Fog Computing solution.

The paper is structured as follows: The next section (Section 2) presents an overview of the internal logistic in the Industry 4.0 and the existing works. The Section 3 presents the Fog-based architecture and the cost optimization model of an internal logistic Fog-based application. This section gives also the results of the model optimization. The paper ends with a conclusion on the future directions of research for enhancing the model and using its optimal solution on a real use case that deploys the Fog in an internal logistic application.

2. Internal logistic in Industry 4.0

While the Cloud offers virtually high computational resources making data processing extremely efficient, the resulting data movement could have an impact on the application performance due to possibly significant latencies of the transmission. To improve this type of applications, proper information logistics become fundamental for delivering information at the right time, the right place, and with the right quality [7]. The Industry 4.0 afford smart services and smart products to final users. The logistics, as an important part of the industrial process, needs to adapt to the succession of revolutions and the changing industrial vision. The logistic process inside the workshop involves numerous types of connected systems such as AGVs (automated guided vehicles, which follow path lines to transport materials and products around the industrial workshop), machines, manual posts, etc. The ordinary manners and technologies that support industrial logistics are no more enough for the Industry 4.0 requirements, therefore integrating the Fog features is beneficial [8]. Considering the importance of such application to organize the transfer, the industry 4.0 requires that logistic services need to become more and more smart, efficient and real-time reacting to respond to the high artificial intelligence level. Adding the Fog Computing characteristics will help taking quickly the most adequate decision to ameliorate the logistic operations. Connecting the Fog with the Cloud will deliver more analysis that manage future logistic tasks.

To integrate the Fog Computing, many aspects need to be studied especially modeling the application architecture and optimizing the cost of such solution and considering the latency, distribution and capacity limitations. Some works interested in this research domain like [9], which presented the integration of the Cloud Manufacturing in the production logistic. Authors in [10] presented a Fog-based solution in the logistic centers.

3. Fog-based architecture modelling

Among numerous Industry 4.0 applications, we are interested in logistic application. This paper presents an example of deploying the Fog Computing architecture in an Industry 4.0 framework, which is illustrated in Figure 1. This architecture is composed of four layers communicating between each other’s to ensure a distributed real-time data transmission and computing.
3.1. Model and constraints

Our work is based on the model proposed by [10] used in logistic centers in an Industry 4.0 context. An additional constraint “Networking capacity” is added to restrict a maximal bandwidth that transmission cannot exceed. This model aims to reduce the cost of links between Edge, Fog and Gateway and the cost of installing each node of them. The model will be solved using the exact optimization approach to activate the minimal number of links.

Minimize the objective function $Z (1)$:

$$Z = c_f \sum_{i \in C \cup \Omega_G \cup \Omega_F} x_{ij} d_{ij} + c_G \sum_{e \in \Omega_G} G_e + c_F \sum_{m \in \Omega_F} F_m + c_E \sum_{n \in \Omega_E} E_n$$

With $c_f$ is the cost of one unit of optical fiber for high-speed network, $x_{ij}$ is the binary decision variable that decide if there is a link between nodes $i$ and $j$. $G_e$, $F_m$ and $E_n$ are the binary decision variable deciding if the node is active or not. $c_G$, $c_F$ and $c_E$ are the cost of installing Gateway, Fog and Edge nodes respectively. $d_{ij}$ is the distance between two nodes $i$ and $j$. $S$ is the AGVs set, $C$ is the Cloud servers set and $\Omega_G$ is a Gateway set, $\Omega_F$ is a Fog set and $\Omega_E$ is a Edge set.

Considering that the initial positions and the distances are fixed, activating nodes and establishing links will be according to several constraints. The first constraint is the activating requirements. Constraint (2), (3) and (4) is forcing that each AGV needs to be connected to one Edge and each edge must be activated if it is related to at least one AGV.

$$\sum_{n \in \Omega_E} x_{nk} = 1, \forall k \in S$$

$$E_n \leq \sum_{k \in S} x_{nk}, \forall n \in \Omega_E$$

$$x_{nk} \leq E_n, \forall n \in \Omega_E, \forall k \in S$$

The same constraints are defined for the Edge-Fog and Fog-Gateway links. These constraints guarantee that each higher node will be connected to one and only lower node and activated when it is related at least to one lower node. The link between Cloud and Gateway depends on the same constraint.

The second constraint type is the capacity demand. Each higher node cannot accept more than it maximal computing capacity (5) and (6) (respectively for the Edge $H^E_n$, Fog $H^F_m$ and Gateway $H^G_C$). And the capacity demand for an $\omega(E_n)$ is depending of the total of its connected lower nodes, but it can not exceed its maximum capacity $E_{max}$ (respectively for the $\omega F(F_m)$ and $F_{max}(7)$ and the $\omega G(G_e)$ and $G_{max}(9)$). The $r_{AGV}$ is the demand of each AGV. The same constraints (8) and (10) are established for Fog and Gateway links.

**Figure 1.** A Fog-based industrial architecture.
\[\omega(E_n) = \sum_{k \in S} r_{AGV} \cdot x_{nk} \quad \forall n \in \Omega_E\]  
\[\omega(E_n) \leq E_n \cdot H_n^E \quad \forall n \in \Omega_E\]  
\[\omega(F_m) = \sum_{n \in \Omega_E} E_{\text{max}} \cdot x_{mn} \quad \forall m \in \Omega_F\]  
\[\omega(F_m) \leq F_m \cdot H_m^F \quad \forall m \in \Omega_F\]  
\[\omega(G_c) = \sum_{m \in \Omega_F} F_{\text{max}} \cdot x_{cm} \quad \forall c \in \Omega_G\]  
\[\omega(G_c) \leq G_c \cdot H_c^G \quad \forall c \in \Omega_G\]

Constraint (11) defines delay of each transmission needs to respect the maximal latency (for Edge \(\gamma_n^E\), Fog \(\gamma_m^m\) and Gateway \(\gamma_m^c\) ) that could be reached between the two levels. 

\[L \cdot E_n \leq \gamma_n^E \left( \sum_{k \in S} x_{nk} \cdot \mu_{kn} \right) \forall n \in \Omega_E\]  

With \(L\): data length, \(\mu_{kn}\): the data rate from an AGV to an Edge node. The same procedure is followed for Edge-Fog and Fog-Gateway links. 

As the terminals are wireless connected and the AGVs are mobile, they need to be present in an Edge coverage zone to be attached. The constraint (12) defines the area where the robot can be connected to the edge node, with \(R_n\) is the Edge diameter. 

\[x_{nk} \cdot d_{nk} \leq \frac{R_n}{2} \quad \forall n \in \Omega_E, \forall k \in S\]  

The constraint (13) requires that each Edge node cannot connect devices more than its link capacity \(N_E\) (Respectively \(N_F\) for Fog and \(N_G\) for Gateway), which distributes the terminal device on the active nodes. 

\[\sum_{k \in S} x_{nt} \leq N_E \quad \forall n \in \Omega_E\]  

### 3.2. Optimization

The architecture is simplified and illustrated in Figure 2 to present the potential position of the Edge, Fog, Gateway and Cloud nodes. We supposed in the example that all the terminal nodes are AGVs, which are wirelessly connected with the Edge nodes. The AGVs insure the internal logistic in an Industry 4.0 workshop. The rest of the links are wired (using optical fiber). This scenario needs to be optimized to reduce the cost of this Fog-based architecture. The initial architecture is composed of 4 AGVs, 2 machines, 1 3D printer, 12 Edge, 7 Fog, 2 Gateway and 1 Cloud. The position of each node is fixed and the distance between each node is calculated depending on their link type (wireless/fiber). The model is solved using the exact method approach and the Linear Programming using simplex method. The model is optimized using the solver of Fico “Xpress IVE” to minimize the initial cost of the Fog-based solution. This solver is using Mosel language. The Figure 3 shows the results of the model optimization. As an input data, two distance matrix are prepared (a Manhattan distance for the wired links and a Euclidean distance for the wireless links) and all potential position of the different nodes and terminal devices according to their position on the plan. The Z (cost) is notably reduced from 3754.85 to 385.314.

### 4. Conclusion

The integration of the Fog Computing in the Industry 4.0 applications is the result of the increase use of the IoT that enables the communication between each other machines and humans in real time and the use of what is known as advanced digitalization. The internal logistic requires faster decision making and data transmission which is possible due to the Fog Computing capabilities. This paper presented the modeling and the optimization of a Fog-based solution for a logistic framework using AGVs and Fog servers, while considering several constraints (Links, latency, demand capacity and coverage). The results of the exact method solver shows an optimization in term of the Fog-based solution cost and reducing the number of active nodes. Future works are interested in ameliorating the current model and
optimize the results of a larger scale Industry 4.0 example. The optimized model results will be also adopted in a real use case (Using the Cesi’s prototype of a connected manufacturing system). This Fog servers will execute models to analyze data locally and provide more efficient information to the terminal devices and transmit data to the Cloud servers for more analysis and storage. Other challenges should be studied like the data security and the interoperability between the different existing operating systems.

![Diagram of Potential and Optimized Nodes Positions](image)

**Figure 2.** Potential nodes positions.  
**Figure 3.** Optimized nodes positions.

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6. References
[1] Kagermann, H., Helbig, J., Hellinger, A., & Wahlster, W. (2013). 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.
[2] Kang, H. S., Lee, J. Y., Choi, S., Kim, H., Park, J. H., Son, J. Y., & Do Noh, S. (2016). Smart manufacturing: Past research, present findings, and future directions. International Journal of Precision Engineering and Manufacturing-Green Technology, 3(1), 111-128.
[3] Khan, W. A., Wisniewski, L., Lang, D., & Jasperneite, J. (2017, June). Analysis of the requirements for offering industrie 4.0 applications as a cloud service. In 2017 IEEE 26th International Symposium on Industrial Electronics (ISIE) (pp. 1181-1188). IEEE.
[4] Chang, C., Srirama, S. N., & Buyya, R. (2017). Indie fog: An efficient fog-computing infrastructure for the internet of things. Computer, 50(9), 92-98.
[5] O’Donovan, P., Gallagher, C., Leahy, K., & O’Sullivan, D. T. (2019). A comparison of fog and cloud computing cyber-physical interfaces for Industry 4.0 real-time embedded machine learning engineering applications. Computers in Industry, 110, 12-35.
[6] Bouzarkouna, I., Sahmoun, M. H., Sghaier, N., Baudry, D., & Gout, C. (2018, August). Challenges facing the industrial implementation of Fog Computing. In 2018 IEEE 6th International Conference on Future Internet of Things and Cloud (FiCloud) (pp. 341-348). IEEE.
[7] Bill, L. (2016). ORGIndustry 4.0: Intelligent and flexible productionDigitization.
[8] Bar-Magen Numhauser, J., & Guitierrez de Mesa, J. A. (2013). XMPP distributed topology as a potential solution for fog computing. In MESH 2013 the sixth international conference on advances in mesh networks.
[9] Qu, T., Lei, S. P., Wang, Z. Z., Nie, D. X., Chen, X., & Huang, G. Q. (2016). IoT-based real-time production logistics synchronization system under smart cloud manufacturing. The International Journal of Advanced Manufacturing Technology, 84(1-4), 147-164.
[10] Lin, C. C., & Yang, J. W. (2018). Cost-efficient deployment of fog computing systems at logistics centers in industry 4.0. IEEE Transactions on Industrial Informatics, 14(10), 4603-4611.