domOS: an "Operating System" for Smart Buildings

Junior Dongo[a], *Dominique* Gabioud[b], *Amir* Laadhar[a], *Martin* Meyer[b], *Brian* Nielsen[a], *Frédéric* Revaz[b], *Christian* Thomsen[a]

[a] Department of Computer Science, Aalborg University, Aalborg, Denmark. {juniord, amirl, bnielsen, chr}@cs.aau.dk

[b] Institute of Sustainable Energy, School of Engineering, University of Applied Sciences Western Switzerland Valais, Sion, Switzerland. {dominique.gabioud, martin.meyer, frederic.revaz}@hevs.ch

Abstract. Smart energy services deployed in buildings have the potential to increase their energy efficiency and to turn them into active nodes of energy grids, with limited costs and in the short term. Today, smart services are deployed by manufacturers of energy appliances as independent silo solutions. The lack of a common approach prevents the deployment of unified multi-appliance, multi-service solutions.

This paper presents the domOS ecosystem specification, a guideline for a unified organisation of energy services where multiple applications can access multiple on-line appliances and devices, if permitted. The specification leverages legacy IoT technologies and can be implemented with a limited effort on any existing IoT platform. A compliant IoT platform acts as an "operating system" for the building, effectively decoupling the application plane and the building infrastructure plane.

The domOS ecosystem specification builds upon the Web of Things (WoT) architecture defined by W3C. Compliant buildings feature a digital nameplate called Building Description (BD). The BD is a document readable by machines and humans that contains relevant metadata (e.g., construction type, size, energy system…) and provides handles to monitor and control local energy processes. The domOS ecosystem specification leads to a unified and standardised approach of energy services in buildings.

Keywords. smart building, IoT, ontologies, WoT, interoperability.

DOI: https://doi.org/10.34641/clima.2022.437

1. Introduction

Over the last two decades, digitalisation has penetrated almost all activity domains. The digitalisation in buildings can be assessed as late compared to other sectors. Buildings, and more specifically energy appliances in buildings, have a life duration of several decades. Hence, many date from the pre-digital era. Admittedly, recently installed appliances – from coffee machines to heat pumps – feature a digital interface and can be monitored and controlled remotely. However, each appliance features its own solution, which is generally proprietary and closed. Hence, the user experience is not optimal (users must cope with several apps, each one with its access control and presentation logic), and the deployment of multi-appliance solutions is complicated – if possible at all.

To overcome these limitations, the domOS project [1] designs and prototypes a mediating platform ("Platform") enabling:

- the integration of all connectible in-building appliances and devices ("Things"), and
- the deployment of applications for monitoring, visualisation, optimisation, or control ("Applications") to access any in-building infrastructure, if permitted by the owner.

In a computer, the operating system provides the hosted applications with an abstraction layer for the peripheral devices. The Platform offers a similar function for buildings.

The rest of this paper is organised as follows: In Section 2, the background context for energy and IoT is presented. Section 3 summarises the functional and non-functional requirements for the domOS ecosystem. Section 4 presents an overview of the WoT architecture, a main component of the domOS ecosystem. The ecosystem specification is detailed in Section 5. Section 6 illustrates the ecosystem with an example. Section 7 concludes the paper with an outline of future work.

Copyright ©2022 by the authors. This conference paper is published under a CC-BY-4.0 license.

2. Background

2.1 Energy and buildings

To limit global warming, countries have set ambitious objectives for the reduction of greenhouse gas emissions. Reaching these goals requires a radical transformation of the energy sector. Buildings, which are responsible for 40% of the total energy consumption, can make their contribution to the energy transition in two complementary ways: firstly, the energy infrastructure of the building can be upgraded (better isolated envelope, renewable energy prodution, CO2-free heat and cold generation…), and secondly smart services can optimize the operation of the existing energy infrastructure. The second approach requires less investment and can be deployed in the short term.

Research projects have shown that smart services can bring significant contributions to achieve more efficiency and more flexibility. A few examples are listed below:

- Closed-loop control of the heat system can lead to 8%-18% average energy savings [2].
- Providing feedback to consumers on their own energy consumption leads to reduction of the final energy consumption in the range from 5% to 10% [3].
- The available flexibility of space heating, domestic hot water preparation and electrical vehicle charging can be used to turn buildings into active nodes of the grids they are connected to [4] [5].

As of today, a wide cluster of smart services are available [6]. The two most common implementation patterns are:

- frameworks operated by appliance manufacturers, with a scope limited to the concerned appliances, and
- single-service frameworks (e.g., demand-response [7]).

It is not uncommon to find buildings equipped with multiple parallel and independent frameworks. However, the energy issue in buildings is essentially one, as illustrated by the following example: an Energy Management System (EMS) must orchestrate the heat pump, the electrical vehicle charging station, based on local production by the photovoltaic inverter and on the grid status.

The vision is to equip buildings with a mediating Platform, on which all Things are connected. Then a cluster of services ("Services") could arise from the interplay of Applications and Things, as illustrated in Fig. 1.

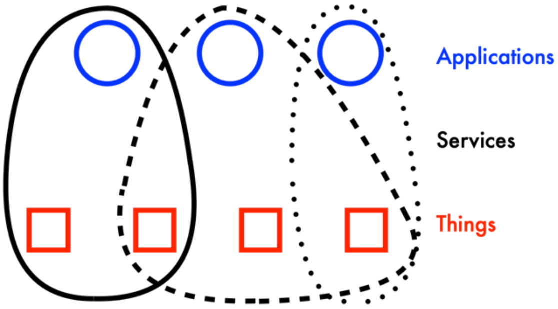

Fig. 1 - Things, Applications, and services

2.2 IoT and semantics

Today's IoT technologies allow to connect Things with investment and operation costs tending towards zero. New Things feature a communication interface, but each of them has its own IoT solution (Fig. 2 (a)). A unified solution (Fig. 2 (b)) is necessary to address the energy requirements.

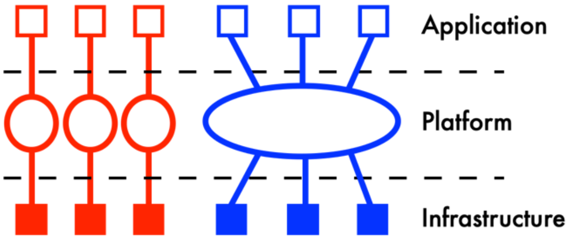

Fig. 2 - IoT in buildings: (a) current silo organisation, and (b) target unified organisation

Platforms take over auxiliary functions like provisioning, security management, privacy management, and supervision and can also work as proxies for Things. Platform functions can be implemented in a dedicated component hosted in the cloud or at the edge in a building gateway.

From a networking perspective, Things feature three layers:

- **Protocols ("*Language*")**: The platform and the Things must share a common set of protocols, including security mechanisms.
- **Interaction model ("*Verbs*")**: The set of operations that can be remotely triggered on a Thing forms its interaction model.
- **Semantic annotations ("*Nouns*")**: Semantics refers to the assignment of meaning (e.g., "instantaneous electrical power") to addressable entities within a Thing (e.g., "MQTT topic "@update/a3b61480/el_power").

It should be noted that the above description does not deal with semantics in general, but rather with semantics within Things.

In a unified organisation, Things must share:

- a set of protocols with their Platforms, and
- an interaction model and semantic annotations with Applications interacting with them.

One of the main challenges in the IoT landscape is achieving semantic interoperability between Things and Applications. To this end, standardised vocabularies have been defined by associations of manufacturers [8], by professional associations [9], by academics [10], and by legacy standardisation bodies [11]. They can take different forms: assignment of meanings to register numbers or message topics, or UML class diagrams

3. Requirements

We want to elaborate a specification called "domOS ecosystem specification" allowing the interplay of multiple Things and multiple Applications, according to a unified organisation as illustrated on Fig. 2.

3.1 Functional requirements

We assume the following situation:

- Things of different types (e.g., "heat pump") are deployed in buildings. There can be many Thing models (e.g., from different manufacturers) for a given Thing type.
- A cluster of generic (i.e., not building-specific) Applications is available.

The objective is to automate the deployment of Services on buildings featuring the required infrastructure.

Realising the objective requires that:

1. Applications can access building metadata, to learn relevant information regarding the building and to check whether the in-building topology is appropriate.
2. Applications can find addresses to access monitoring and control points in Things. An address includes all relevant parameters required to access an element within a Thing.
3. Applications can interact with Things, in a model-independent way, by making use of the interaction model and of addresses.

3.2 Non-functional requirements

It should be possible to integrate Things in their current state. Neither firmware upgrades nor adaptation gateways should be required.

The domOS ecosystem specification should leverage legacy IoT tools and processes. The technological threshold to implement the specification must be kept low, so that implementation requests a limited effort.

4. Introduction to the WoT Architecture

The W3C's Web of Things (WoT) architecture [12] is a key component of the domOS ecosystem specification. It is briefly introduced in this section.

4.1Model

In WoT, Consumers are software components interacting with Things (Fig. 3). To cope with the heterogeneity, each Thing must feature a formal description document called a Thing Description (TD) [13].

Fig. 3 - WoT Model [12].

4.2 The WoT interaction model

WoT introduces a simple interaction abstraction based on properties, events, and actions. This interaction model is generic enough to be applicable to all Things.

If permitted, Applications working as Consumers can (see Fig. 4):

- read or write properties, possibly also observe them and receive updates,
- subscribe to events and get notified of occurrences, and
- request the execution of actions.

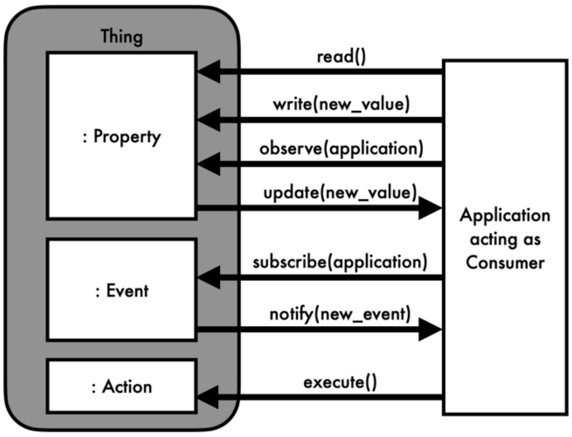

Fig. 4 - The WoT interaction model.

A unitary operation on a property, an event or an action is named an "interaction affordance".

4.3 Protocol bindings

In a real Thing, an interaction affordance is performed through the exchange of messages compliant with Things specific protocols.

A TD contains so-called protocol bindings describing how abstract interaction affordances are mapped to concrete protocol-level messages.

4.4 The WoT scripting API

Through the WoT scripting API, a Consumer can handle interaction affordances (i.e., operations on properties, events, and actions) independently of protocol bindings.

The structure of a WoT compliant system is presented on Fig. 5:

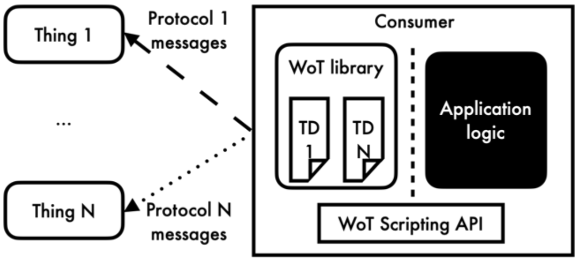

Fig. 5 - Structure of a WoT compliant system.

The WoT scripting API is implemented by WoT libraries [14].

The WoT architecture has been implemented in the Arrowhead IoT framework, which is used in two domOS demonstration sites [15].

5. The domOS Ecosystem Specification

The domOS ecosystem specification is made up of the four key components introduced in this section: the Thing Descriptions (TDs), the Building Description (BD), the domOS Common Ontology (dCO) and the Platform.

5.1 Thing Descriptions (TDs)

Energy appliances like photovoltaic inverters, electrical vehicle charging stations, heat pumps, meters and other monitoring devices are considered as Things.

TDs are elaborated by customising Thing-type specific documents that could be made available by manufacturers or by a user community.

5.2 Building Descriptions (BDs)

The Building Description (BD) is a machine and human-readable document containing a description of the building as an energy system. It contains for instance the following metadata (Fig. 6):

- energy flows within the building and between the building and the grids it is connected to,
- processes to consume, generate or transform energy including description of the corresponding appliances and monitoring devices, and
- links to interaction affordances in Things, to enable real-time monitoring and control.

The domOS ecosystem specification contains schemas for BDs. The semantics in BDs is provided by the dCO.

The BD is stored in a semantic knowledge base. By querying the BD, an Application can:

- determine if the building energy infrastructure is appropriate for its operation,
- understand the building's energy organisation, and
- associate meaning to interaction affordances in Things.

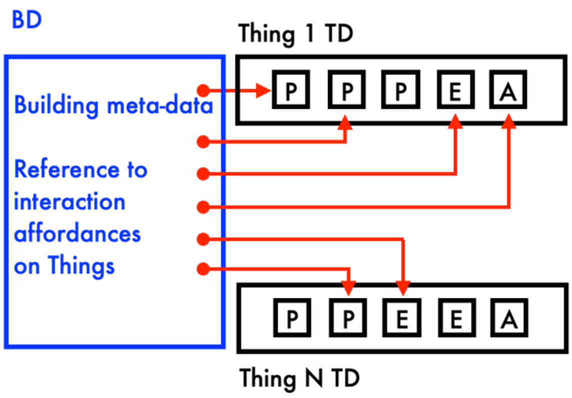

Fig. 6 - Building Description (BD) structure.

5.3 The domOS Common Ontology (dCO)

The domOS Common Ontology (dCO) is an information model for the domOS project [1] that allows a common understanding of the building as an energy system by humans and machines. dCO is available online [16] and is considered as the unique source of truth. The dCO has been designed by analysing the needs of the five demonstration sites of the domOS project, which cover a broad spectrum of uses cases. The dCO reuses existing ontologies whenever possible.

The following use cases of the dCO have been identified:

- **Semantic annotations of TDs**: TDs should be annotated using the entities of the dCO to correctly express the meaning of the Things' metadata. According to the WoT Thing Description recommendation [13], TDs can be annotated using the "@type" field (e.g., "@type": "dco:temperatureProperty"). Measurements can also be annotated with their unit using the dCO (e.g., "unit": "dco:Celsius").

- **Elaboration of BDs**: BDs are dCO compliant RDF documents.

- **Semantic validation of TDs and BDs.**

- **Semantic search of TDs and BDs**: Using semantic search queries, Applications can learn relevant features of buildings and of their Things without any prior knowledge.

- **Compliance check for Applications.** This process allows an application to formally verify before deployment that the building infrastructure is appropriate for its operation.

5.4 The Platform

Mediating Platforms are legacy IoT frameworks upgraded according to the domOS ecosystem specification.

Using appropriate interfaces, Platforms let facility operators register their buildings and upload their BDs, manage the life cycle (install, replace, decommission) of local Things, and subscribe to validated Services.

Platform administrators can register buildings and Applications.

Platforms are also in charge of privacy and safety rules enforcement: building facility operators should formally permit Applications to access Things monitoring and control points.

Applications can query the BD to check that the needed set of Things are installed. However, to support strong privacy rules, Platforms are designed to reveal only the parts of the BD required for the operation of Applications.

Platforms should monitor the health status of the Things and Applications, and trigger alerts when failures are detected, to ensure a reliably working distributed system.

Depending on the design, Platforms can work as proxies between Things and Applications, or only provide a directory service to Applications, which then communicate directly with Things.

The domOS ecosystem specification leaves a high degree of freedom to Platform developers: implementations on home gateways, in clouds, or a mix thereof are possible.

6. Example

Let us consider the sample single-family house "dco:b-001" illustrated on Fig. 7. Devices represented in orange are WoT Things and dispose therefore of TDs. Three Services will be deployed: a web-based energy dashboard for occupants, an electricity flexibility management service for space and domestic hot water heating, and a performance assessment service for heating.

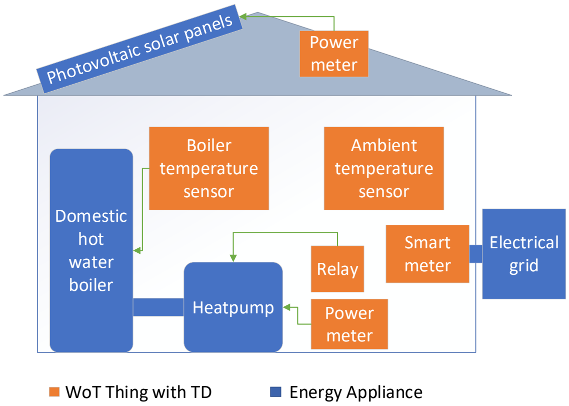

Fig. 7 – Topology of the sample building "dco:b-001".

Some of the RDF triples of the BD for the building "dco:b-001" are represented graphically in Fig. 8. One can recognise the metadata describing the building energy infrastructure as well as references to WoT properties.

A BD refers to a particular interaction affordance in two steps:

1. An instance of the classes dco:Property, dco:Event, dco:Action or of subclasses thereof is inserted in the BD (e.g., "dco:Temperature01").

2. This instance is linked to an interaction affordance of a Thing by two RDF properties: the property "dco:hasTD" refers to the URL of the Thing's TD ("https://domos.oiken.ch/b-001/pm1"), whereas the property "dco:hasInteractionName" refers to the name of a property, action or event in the TD ("Temperature01").

TDs can be instantiated in RDF and stored in a semantic knowledge base along with the BD. Therefore, semantic search queries are possible as the TDs and the BD are semantically integrated.

Using semantic queries, an Application can determine that the building envelope is heated by the heat pump. An Application can also find how to read the real-time values for the ambient temperature and for the heat pump active power, and how to control the heat pump operation by a relay property associated to the heat pump (not represented on Fig. 8).

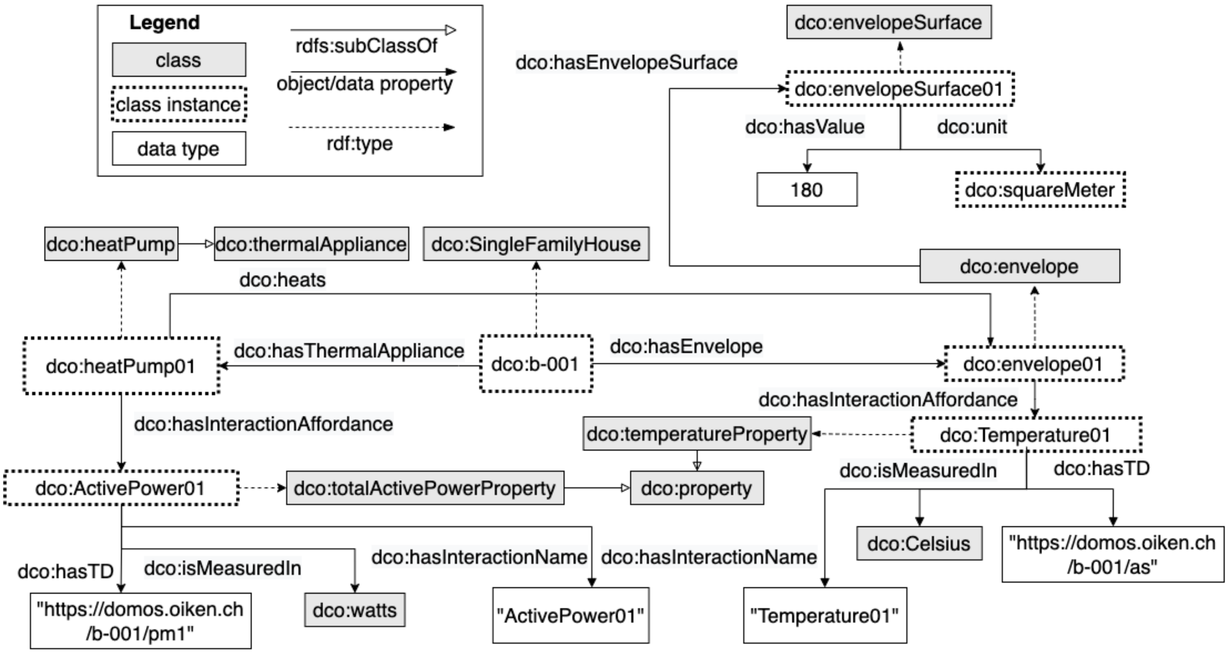

Fig. 8 - Building Description (BD) for the building "dco:b-001" (excerpt).

An excerpt of the TD for the ambient temperature sensor is presented on Fig. 9. It states that the "Temperature01" property can be read with a HTTP GET operation at the URL https://domos.oiken.ch/temperature/datapoint and that the response body contains the current temperature in Celsius as a character string.

```
{ "id": "21cf7981-59fb-4a0d-85e9-3f101c1aa633",
  "@context": [
    "https://www.w3.org/2019/wot/td/v1",
    {"dco": "https://w3id.org/dco/"}],
  "title": "Ambient sensor",
  "base": "https://domos.oiken.ch",
  "@type": "dco:ambientSensor",
  "properties": {
    "Temperature01": {
      "@type": "dco:temperatureProperty",
      "type": "number",
      "unit": "dco:Celsius",
      "forms": [{"href": "/temperature/datapoint
      "op":"readProperty"}]},
  "actions": {},
  "events": {}
}
```

Fig. 9 - Thing Description (TD) for the ambient temperature sensor (excerpt).

7. Conclusion

Thanks to the proposed domOS ecosystem specification, existing IoT frameworks can be upgraded to become Platforms supporting the integration of energy appliances and devices in buildings. A cluster of generic Applications can be deployed on buildings without a priori knowledge of the building configuration. This approach allows the industrialisation of the deployment of energy services without putting constraints on the field infrastructure inside buildings.

However, many challenges must be addressed to enable a large-scale deployment of compliant Platforms: WoT must become an established standard; the dCO must provide at the same time flexibility to deal with various building topologies and conciseness to ease Application development; privacy, cyber-security and liability issues require sound answers; Platform operator is a new role for which viable business models must be elaborated.

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

8. Acknowledgements

The domOS project leading to this research has received funding from the European Union's Horizon 2020 research and innovation program under grant no. 894240.

9. Bibliography

[1] domOS project team, "domOS project web site," [Online]. Available: https://www.domos-project.eu/.

[2] D. Grivon, P. Riederer, Y. Stauffer and A. Hutter, "Smart Control Strategy For The Reduction Of Energy," in *Building Simulation*, 2019.

[3] P. Zangheri, T. Serrenho and P. Bertoldi, “Energy Savings from Feedback Systems: A Meta-Studies’ Review,” *Energies,* vol. 12, no. 19, p. 3788, 2019.

[4] C. Hanmin, A. Hutter, E. Olivero, P. Roduit and P. Ferrez, “Load shifting for tertiary control power provision,” in *2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG)*, Riga, 2015.

[5] A. Karpenko, T. Kinnunen, K. Främling and B. Dave, “Open IoT ecosystem for smart EV charging,” in *2018 Global Internet of Things Summit (GIoTS)*, Bilbao, 2018.

[6] A. Verma, S. Prakash, V. Srivastava, A. Kumar and S. C. Mukhopadhyay, “Sensing, Controlling, and IoT Infrastructure in Smart Building: A Review,” *IEEE Sensors Journal,* vol. 19, no. 20, pp. 9036-9046, 2019.

[7] Sidqi, Y.; Ferrez, P.; Gabioud, D.; Roduit, P., “GOFLEX: Towards a New Integrated Solution for a Cost-Effective Use of Demand Response in Distribution Grids,” in *CIRED 2020 Berlin Workshop*, Berlin, 2020.

[8] SunSpec Alliance, “The SunSpec Alliance,” [Online]. Available: https://sunspec.org/.

[9] SmartGrid ready Assocation, “The SmartGrid ready Assocation,” [Online]. Available: https://www.smartgridready.ch/.

[10] daisy (Center for Data-intensive Systems), “Flex-Offers: Unified generalized modelling and management of flexibility in electricity demand and supply,” University of Aalborg, [Online]. Available: https://www.daisy.aau.dk/projects/flexoffers/.

[11] SAREF, “Smart Applications REFerence Ontology, and extensions,” ETSI, [Online]. Available: https://saref.etsi.org/.

[12] W3C WoT – Architecture Task Force, “Web of Things (WoT) Architecture 1.1 - W3C First Public Working Draft 24 November 2020,” World Wide Web Consortium (W3C), [Online]. Available: https://www.w3.org/TR/wot-architecture/.

[13] W3C WoT – Thing Description Task Force, “Web of Things (WoT) Thing Description 1.1 - W3C Working Draft 7 June 2021,” [Online]. Available: https://www.w3.org/TR/wot-thing-description11/.

[14] Eclipse Foundation, “Thingweb: A Web of Things Implementation,” [Online]. Available: http://www.thingweb.io/.

[15] J. Dongo, M. Albano, A. Skou and B. Nielsen, “Web of Things Interoperability for the Arrowhead Framework,” in *IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society*, 2021.

[16] A. Laadhar and C. Thomsen, “domOS Common Ontology,” University of Aalborg, [Online]. Available: https://www.dco.domos-project.eu/.