FLEX4FACT

Industrial flexibility platform
for sustainable factories

WP 1 - DEFINITION OF INDUSTRIAL USE CASES, FLEX4FACT REFERENCE SYSTEM ARCHITECTURE AND TEA/LCA SCOPE

D1.2 FLEX4FACT SYSTEM REFERENCE ARCHITECTURE, STANDARD AND PROTOCOLS, CYBER SECURITY

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DISSEMINATION LEVEL

PU – public, fully open	X
SEN – sensitive, limited under the conditions of the Grant Agreement	

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LIST OF ABBREVATIONS

ACRONYM	DESCRIPTION
AS-IS	The status at the start of the project
DSM	Demand-Side Management
KPI	Key performance indicator
LCA	Life cycle assessment
SLR	Systematic literature review
SMEs	Small and Medium-sized enterprises
TO-BE	The desired status at the end of the project
WP	Work package

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SUMMARY

Flex4Fact aims to create an end-to-end ecosystem that enhances the flexibility of manufacturing processes and energy flows from North to South Europe. To achieve this, the project will employ digital process twinning and machine learning techniques to augment manufacturing flexibility and tackle complex operational scenarios.

This undertaking of Task 1.2 began in M7 and is scheduled to conclude in M15, coinciding with the submission of the D1.2 FLEX4FACT System Reference Architecture, Standard and Protocols report. The report's focus is on developing a reference architecture for FLEX4FACT at the system level, which will present design principles, main system components, and their interrelationships in a simplified manner. Additionally, it will outline high-level requirements to guide subsystem development (including standards, protocols, and cybersecurity), address key functions, and document interfaces.

Section 2 of the report will detail the methodology for constructing the reference architecture and framework, including a survey to identify design principles for the project's development. Section 3 will briefly present the literature results and introduce the reference architecture framework. Section 4 presents the design principles based on the survey results.

This reference architecture and framework will be applied in use cases, with additional details reported in D1.4.

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1 INTRODUCTION

As an overarching goal of the EU Green Deal [1], Europe aims at climate neutrality by 2050. The manufacturing industries, and especially the process industries, have difficulties in using renewable energy sources and transitioning towards sustainable production. Complex, rigid manufacturing processes need to be aligned with distributed, swinging renewable energy flows.

In energy demand response, customers dynamically change their electricity consumption behaviour in response to time-of-use electricity price signals or real-time dispatching instructions to reduce critical-peak demand [2]. However, this approach can be challenging for industries like steel production to heat up and maintain production at a high temperature. At present, the research on demand response mainly focuses on the traditional demand response in power systems, while the research in the analytical technique and evaluation method is not comprehensive enough and is not from an industrial perspective [2].

Digital twin (DT) can provide ideas for solving the above problem by forming a one-to-one mapping between the physical and virtual layers and then optimizing manufacturing and service processes [3]. The increasing application of the Internet of Things (IoT) used in the manufacturing sector generated a massive amount of data [4] useful for product lifecycle monitoring and maintenance, which are crucial tasks in manufacturing. The aim is to detect production exceptions and ensure normal task execution [5]. These technologies can enhance energy and production flexibility, but the actual implementation in the industries still faces problems and barriers like data integration [6] and lack the industrial knowledge**. Therefore, there is a need for a holistic reference architecture framework that can improve the decision-making process in the short and long term, thereby enabling the goals of energy flexibility.**

The project Flex4fact aims to develop an end-to-end ecosystem that increases flexibility in manufacturing processes and energy flows. Further, it will provide a Flex4Fact platform to enable greater flexibility in the energy system by offering innovative services, removing entry barriers for vendors in the value chain, and ensuring data communication with existing IT legacy systems. The Flex4fact consortium will develop digital technologies and implement them in five industrial contexts, from North to South Europe.

1.1 DESCRIPTION OF WORK PACKAGE WP1: DEFINITION OF INDUSTRIAL USE CASES, FLEX4FACT REFERENCE SYSTEM ARCHITECTURE AND TEA/LCA SCOPE

Work package (WP) 1 has several objectives with a focus on defining the initial status of the industrial use cases of the FLEX4FACT project and describing the solutions for each use case. WP1 will be the basis for the technical WPs 2-5 and the integration and evaluation in WP6. It will map the physical AS-IS situation (processes, challenges, objectives, KPIs, etc.) and digital AS-IS situation (reference architecture of the overall system, Cybersecurity, interfaces, standards, protocols, etc.) in the 5 industrial use cases. After the initial mapping, the WP activities will support the development and description of the TO-BE solutions for each use case and finalize the TO-BE reference architecture based on the integration results. The WP will support the definition and scope of the techno-economic and LCA assessments for the industrial use cases.

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1.2 DESCRIPTION OF DELIVERABLE D1.2: FLEX4FACT SYSTEM REFERENCE ARCHITECTURE, STANDARD AND PROTOCOLS

The objective of this task is to create a reference architecture for the FLEX4FACT system. This architecture will define the design principles, main system components, and their interrelationships, and will establish high-level requirements that will guide subsystem development, including standards, protocols, and cybersecurity. Additionally, it will address key functions and document interfaces.

The structure of deliverable 1.2 is as follows: first, it explains the methodology used to map the current state of literature, workshops to develop and refine the framework, and the steps for conducting the survey for design principles. Chapter 3 details the reference architecture, while the next chapter presents the design principles based on the survey results. Finally, chapter 5 concludes the D1.2 report. The intended audience for this report includes industrial companies, technical providers, and researchers who require a reference architecture to enable manufacturing and energy flexibilities for industrial demand response. Moreover, it will help them understand the crucial design principles for facilitating developments in such a project. The report D1.2 is expected to be completed by month 15 of the Flex4Fact project.

1.3 RELATIONSHIP OF D1.2 WITH OTHER TASKS AND D1.4

The completion of T1.2 and D1.2 will have a significant impact on other tasks since it will provide a reference architecture and functional structure for the F4F project and its developments. This will influence all the tasks, and it will also offer design guidelines for technical developments. Task 1.4, titled "FLEX4FACT Final System Reference Architecture and consolidated use cases solutions," will leverage the experience gained from the validation phase of the industrial settings and perform finalization of the architecture. The focus will be on demonstrating its robustness in terms of scalability, adaptability, and replicability. Furthermore, it will provide an up-to-date description of the final implementation for the industrial settings, along with a summary of the results obtained. The due date for D1.4, the "FLEX4FACT Final System Reference Architecture and deployment solutions," is in month M39.i

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2 METHODOLOGY

To define and develop the reference architecture and design principles, we employed several methods. Additional information about these methods is provided in the subsection. Specifically, we implemented a **Three-step approach** to develop and refine the reference architecture at the FLEX4FACT system level, which involved conducting a literature review (2.1), a digital survey (2.2) and a series of digital workshops (2.3). To define the design principles, we conducted a survey (2.2) and digital workshops (2.3) within the F4F consortium.

2.1 STEP 1: SYSTEMATIC LITERATURE REVIEW

The goal of a systematic literature review is to facilitate theory development, align existing research, and discover areas where additional research is needed [7]. We conducted a systematic literature review using both Scopus and Web of Science databases to provide wide coverage of published literature. The reporting of this review was guided by PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-analysis extension for Scoping Reviews) [8]. To identify relevant literature, the search was performed on “Title, abstract and keywords” with terms listed in Table 1. In our search, we focus on peer-reviewed articles, conference proceedings and reviews to provide a wider overview of the digitalization of demand response within the manufacturing sector. Only publications in English were considered. The systematic literature review process flow is summarized in Figure 1 and the results are presented in Section 4.

Table 1: Keywords used in the SLR

MANUFACTURING	ENERGY	DIGITALIZATION
Production	Aggregator	Digital twin
Manufacturing	Demand response	Cloud computing
Industry	Smart Grid	Digitalization

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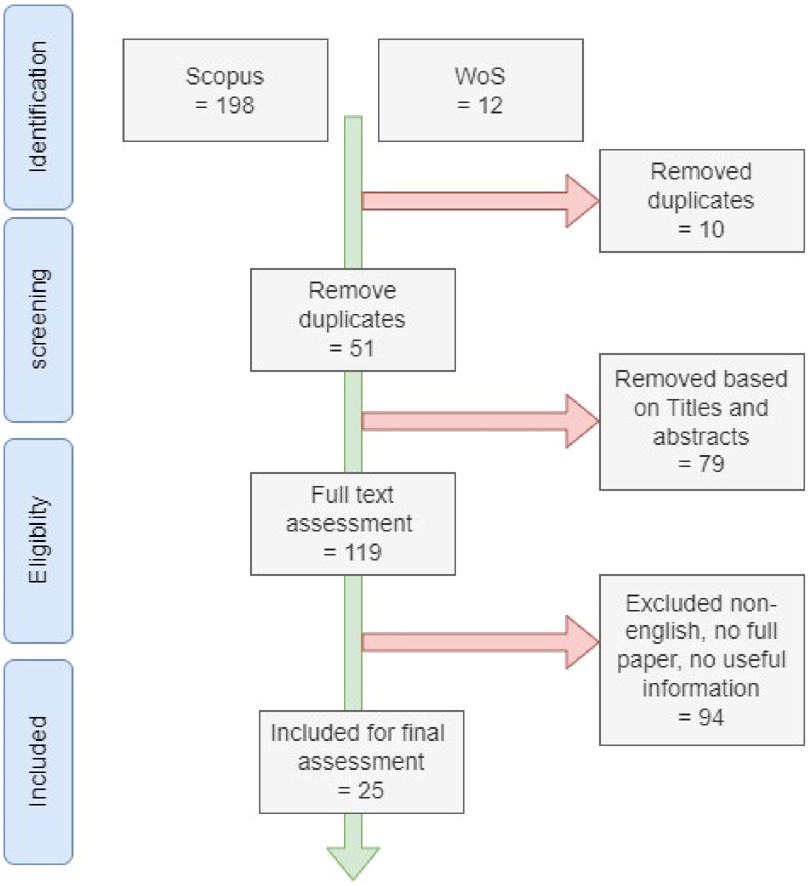

Figure 1: Systematic literature review process flow.

2.2 STEP 2: SURVEY

This section explains the survey design, administration, analysis, and validity. The present empirical study adopted a questionnaire-based survey approach to identify the favoured attributes, requirements, and types for open technologies, standard protocols, standard interfaces, data storage, modular architecture, no-vendor lock-in, service revenue stream, and cybersecurity. Our survey was conducted online using Google Forms to collect the data. The questionnaire contained 21 closed questions in total, and the average duration to complete was 50:22 minutes. For the closed questions, we used an ordinal scale where participants were asked to rate the attributes or requirements and nominal scales where participants were asked to choose from several possible answers, e.g., choose between different standard protocols.

To ensure the validity and reliability of the questionnaire, it was screened among several critics on web-based questionnaires and sent to experts for pilot testing. One of the most common criticisms of questionnaires is related to various biases. Addressing relevant biases in questionnaires is an important task to collect the most accurate data from respondents. Therefore, investigators must recognize and be able to prevent, or at least minimize, bias during the design of questionnaires. Choi and Pak [9] identified 48 types of common bias in questionnaires. These recommendations were considered during the design and administration of the survey presented in this report.

A pilot questionnaire was distributed to an expert panel of two members of F4F. The pilot survey helped articulate the questionnaire more precisely and helped to develop a comprehensive construct

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relevant to the field of study. Once the revised and enhanced online questionnaire was deemed suitable for distribution, a link was sent to 19 experts from F4F who are working in IT, engineering, etc. The respondents' answers were collected in a timeframe of 1 month. After the survey deadline had passed, the data was exported and analysed to visualize the results and identify insights.

The survey results and insights are presented in section 4.

2.3 STEP 3: WORKSHOP

To enhance the systematic literature review and address its limitations, several workshops were conducted. These workshops included participants from both academia and industry, with diverse roles such as researchers, consultants, IT experts, production leaders, and engineers. During the initial workshop, the results of the literature review were presented and discussed among the experts. Based on these discussions, the main layers and connections of the manufacturing and energy flexible framework for industrial demand response were determined. The participants were then divided into smaller focus groups to delve deeper into the main functions, activities, and decisions required at each layer. Table 2 summarizes the date, time purpose and number of attendees.

Table 2: Workshop details- the date, time purpose and number of attendees.

NO	DATE & TIME	NO. OF ATTENDEES	PURPOSE
1st	25th Nov 2022 1000- 1130	16	Literature review and framework
2nd	3rd Mar 2023 1000- 1100	18	Technical Aspects and survey results explanation
3rd	25th Apr 2023 0900-0930	5	Focus on the components on the Digital Twin layer
4th	25th Apr 2023 1000-1030	4	Focus on the components on the Energy layer
5th	26th Apr 2023 0930-1000	6	Focus on the components on the Production layer
6th	27th Apr 2023 1000-1030	8	Focus on the components on the Cluster layer

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3 REFERENCE ARCHITECTURE

3.1 LITERATURE REVIEW

We collected 25 academic papers from systematic literature review. They are then analysed and sorted into 4 different categories (i.e. the authors, key enabling technology, management area and the methods) as shown in the Table below.

Table 3: 25 papers sorted into 4 different categories.

AUTHOR	KEY ENABLING TECHNOLOGY	MANAGEMENT AREA	METHODS
[9]	WiMAX communication technology is the most preferred,	Communications	ZigBee, Multi-criteria decision making
[10]	Highlighted operational data generated during the building life cycle are essential for realizing the energy-efficient operation	Data processing and information sharing	Data-driven deep learning, physical model-driven
[11]	Traditional equipment efficiency correction models only consider the historical load factors and variations in the environmental factors	Energy load prediction and visualization	Digital Twin models, visualization models, polynomial regression, back propagation neural network
[12]	Framework using blockchain as an addition of a security layer	Cybersecurity	Copula model
[13]	Reinforced Learning algorithms select the optimum battery planning measures based on forecasts of wind power and photovoltaic availability.	Data visualization, forecasting	Multi-criteria decisions via an individual user
[14]	deep learning layout that uses generative adversarial networks (GAN) to forecast the hourly power generation	Forecasting	Reinforced learning
[15]	machine learning algorithms for forecasting, storage optimisation, energy management systems, power stability and quality, security, and energy transactions.	Optimising energy scheduling	Machine learning
[16]	Integrated digital twin and big data provides key technologies for data acquisition (such as sensor, Bluetooth, and WIFI for data communication) in energy-intensive production environments	Data processing and integration, prediction	Data mining algorithm, Big data analyses
[17]	The importance of the transformation from a	Decentralized	Decentralized decision

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	traditional centralized energy system to a decentralized one using IoT, smart grid, blockchain, fog computing	energy system	making
[18]	AI has been applied are network provision, forecasting (weather and energy demand), routing, maintenance and security, and network quality management.	Forecasting	ANN, fuzzy logic, SVMS and genetic algorithms
[19]	Energy systems are no longer passive and uni-directional but active and bi-directional with end-users taking active roles in the operation and management of the energy system	Energy demand based on user behaviour	Distributed Energy optimization method
[20]	Developed a novel approach to identify critical branches to strengthen and shield the smart-grid power system threats	Cybersecurity	Markov Decision Process Model
[21]	Developed uncertainty modelling approaches for optimization problems under uncertainty for circumventing the impact of ambiguous parameters	Operation and technical uncertainties in the energy grid	Deterministic model
[22]	The architecture can be used to reproduce any functional plant with minimal cost and is scalable	Communication	Cybersecurity testing, research, and education
[23]	Proposed a unified Hypervision scheme based on structured decision-making concepts, providing operators with proactive, collaborative, and effective decision support	Data management, security	Human-centred design approaches
[24]	Proposed an energy behaviour simulation in equipment digital twin model.	Data management, security	Data-driven hybrid Petri-net, Gaussian kernel extreme learning machine
[25]	Highlighted digital technologies can make modern power systems more effective, reliable, secure, and cost-effective	Energy demand management	Markov model and clustering algorithms, SVM-based technique
[26]	Concluded AI-initiated learning processes by using digital twins as training environments can enhance buildings' adaptability	Energy demand management	Building-integrated AI, Reinforcement learning
[27]	The proposed DT-based method can reduce the operating cost of IES by 63.5%, compared to the existing forecast-based scheduling methods.	Scheduling, forecasting	Deep neural network, multi-vector energy system
[28]	Investigated how blockchain and IoT together can improve existing smart grid ecosystem toward facilitation of better monitoring services.	Energy management and load control	Energy load control

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[29]	Presented new empirical evidence to validate data-driven twin technologies as novel ways of implementing consumer-oriented demand-side management	Energy demand management	DNN, Ordinary Differential equation, linear autoregression, Linear regression, Naïve model, Predictive analytics model
[30]	Highlighted that government should invest in the development of AI	Energy demand management	Various AI Models
[31]	Proposed the use of the Open Automated Demand Response standard protocol in combination with a Decentralized Permissioned Market Place based on Blockchain	Contracting and Services	Simulation modelling
[32]	Formulated a lumped model for forecasting the rate at which electricity is consumed with inadequate real-time energy data	Forecasting	Lumped model for forecasting
[33]	Propose an IoT-based privacy protection strategy via edge computing, data prediction strategy	Cybersecurity and prediction	Numerical simulations, edge computing system

From the collected papers, smart grid systems with communication technology have been highlighted as a key enabler for industrial demand response which can provide stable, efficient, scalable, and cleaner electrical energy systems [9], [17], [28], [33], [34]. Abdulsalam et al., [9] concluded that iMax is the most suitable for advancing metering in smart grids, followed by Zigbee; while Power Line Communication is the least suitable. Smart grids can generate different types of data, from energy generation to consumption, and can move from silo systems to integrated networks for data analysis to improve operational efficiency [10]. Moreover, the DT depends on communication technologies to efficiently manage devices in the system [41].

With the adoption of different data communication tools, cybersecurity of the energy system must be considered to prevent any malicious activities such as hacking. Lei et al., [20] proposed a chain of defence concept using reinforcement learning framework to empower the system operator to incorporate existing cyber protections and strategy in a more dynamic, adaptive, and flexible way to enhance cyber-resilience. Chen et al., [33] proposed a privacy protection strategy via edge computing, data prediction strategy, and pre-processing to overcome the drawbacks of the current cloud computing system. Blockchain can also be adopted in the energy system as an additional security layer. The data-storage structure of blockchain enables energy tracing and prevents data tampering [12], [35]. This is because any form of data tampering can alter the data analysis for forecasting.

Forecasting and predicting are the main decision areas in the demand response to improve energy efficiency by flattening the daily energy demand level [36]. By constructing digital twins of an integrated energy system, the manufacturing industry can benefit from its capabilities to improve coordination among various energy converters, hence enhancing energy efficiency, cost savings and carbon emission reduction [27]. For example, Ye et al., [11] demonstrate that digital twin forecasts of the renewal energy and load of both wind and solar energy were closely matched to the actual values. [27] trained a deep neural network to make statistical cost-saving scheduling by historical forecasting errors and day-ahead forecasts, and the proposed methods can reduce operating costs by 65%.

Forecasting the demand for energy usage is critical for better energy management where the industry can better coordinate with the production schedule [15]. In our search, most of the collected work only focuses on the energy perspective. Tomat et al., [37] highlighted that user behaviour can have a critical impact on demand response effectiveness. Lee and Yim [38] concluded that having a clear understanding of on-demand behaviour can enable an efficient operation of energy supply. Similarly, for the manufacturing sector, better integration of production scheduling and planning management with energy management is important to enabling optimizing industrial demand response services. For example, steel production requires a high amount of energy, often fossil fuel to bring the heat up to and must continue even though the cost of energy has gone up during operation. A holistic integration is still missing [18].

3.2 F4F REFERENCE ARCHITECTURE

The published frameworks identified in the SLR mainly focus on the interaction between the smart grid and aggregator layers or have a strong energy demand management focus in industrial cases. Throughout the workshops with experts from the aggregator, energy, digitalization, and manufacturing sides, all agreed that the current frameworks in literature lack providing a comprehensive framework that allows for implementation in industrial companies and for layers to be connected and communicated from the physical to the aggregator layer. The SLR results (section 4) emphasize the importance of smart grid systems in enabling industrial demand response, which can help create a stable, efficient, scalable, and cleaner electrical energy system. As a result, this framework focuses specifically on the key activities relevant to aggregators and industrial manufacturing companies. Both the literature and the expert group have recognized the general DT framework as suitable for representing the entire communication line with critical activities for industrial demand response services.

Manufacturing companies can find interruptions or significant reductions in production difficult to manage. To provide demand response capabilities that are attractive, it is advantageous to have local renewable energy and storage systems. These systems can be highly effective in allowing production to continue while simultaneously providing demand services to reduce energy peaks in the grid. However, these systems must be properly managed to interact with production and the aggregator at the right time. Therefore, it is essential to establish an end-to-end data infrastructure. Data plays a critical role in identifying high-energy consumers in production and understanding energy reduction capabilities. Appropriate sensors and meters need to be selected and applied to identify high-energy consumers in manufacturing, and machine data needs to be extracted. In the digital layer, which includes the data infrastructure layer, it is important to define data collection, interfaces, data structure, and data storage to ensure consistency, interoperability, and system robustness. The data must be processed (e.g., data cleaning, fusion, etc.) to enable data-driven simulation and optimizations. In the DT layer, various DTs need to be established and interact to reflect both manufacturing and energy flow processes. Their detailed representation allows for simulating and optimizing complex manufacturing processes, with a focus on energy factors, to provide a baseline and different scenarios for energy consumption profiles. The results of simulation and optimization must be presented and visualized for decision-making, which occurs in the management layer.

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The management layer focuses on establishing a manufacturing and energy system for flexible and adaptive consumption profiles. Decision-making in this layer ranges from strategic to operational levels. Production needs to identify its manufacturing flexibility in times of production scheduling, while energy needs to integrate renewable energy and storage systems and drive effective demand-side management. The aggregator agent that provides demand response services connects many different manufacturing companies, usually through a platform. The aggregator agent performs forecasting of energy demands and supplies to identify potential energy gaps and provide flexibility to the grid. By communicating with manufacturing companies and exchanging possible consumption profiles, the aggregator can optimize the cluster and provide incentives back to the manufacturing companies to encourage them to provide energy flexibility to the grid.

To enable demand response services, consistent and seamless interaction between the physical, data infrastructure, DT, management, and aggregator layers is essential. Through the use of an SLR and workshops with experts, the crucial activities and communication structure required for industrial demand response services have been identified and integrated into a framework. This framework is visualized in Fig. 2.

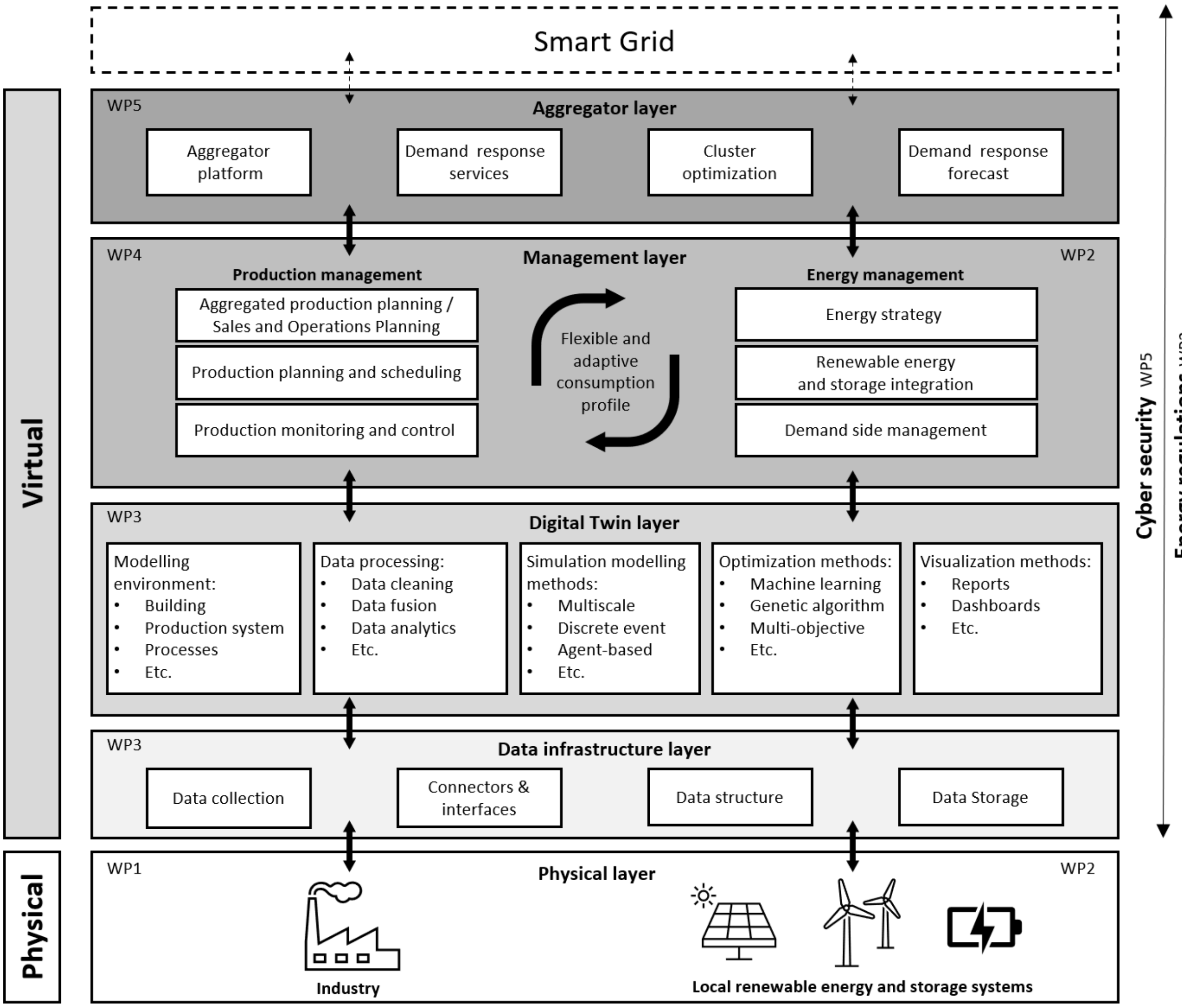

Figure 2: Framework for industrial demand response services

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Physical layer (WP1)

Industry area: In the process industry, the physical layer in a digital twin comprises the actual physical equipment and infrastructure involved in industrial processes, such as heating devices, extrusion devices, presses, electric motors and pumps, ovens, etc. It represents the tangible assets and their interconnections within the production system. The physical layer enables real-time data acquisition from sensors embedded in the equipment, providing accurate and timely information for the digital twin. It also supports the integration of control systems and actuators to simulate and manipulate the physical processes in the virtual environment. The accuracy of the physical layer is crucial for generating reliable insights, optimizing operations, and predicting potential failures in the process industry.

Local renewable energy storage systems: In order to facilitate the development of energy-flexible physical systems, it is essential to have suitable renewable energy generation and storage systems. Renewable energy generation encompasses the installation of photovoltaic (PV) panels, windmills, and other similar technologies. Meanwhile, storage systems for renewable energy involve industrial borehole solar thermal energy storage, batteries, and other relevant solutions. These systems are generally situated in proximity to the energy generation and consumption points, enabling enhanced efficiency and dependability in utilizing renewable energy.

Data infrastructure layer (WP3)

Data collection: Data collection in the digital twin layer refers to the process of gathering and acquiring relevant information from various sources within the physical system being replicated. It involves capturing data from sensors, instruments, devices, and other data-generating components in real-time or at regular intervals. The collected data may include measurements, readings, statuses, events, and other relevant parameters related to the physical assets and their environment. Various technologies and protocols are used for data collection in digital twins. The collected data is typically transmitted to the digital twin platform or cloud-based infrastructure for storage, processing, and further analysis.

Connectors & interfaces: Connectors and interfaces in the digital twin layer establish communication and interaction between components within the digital twin ecosystem. They enable the exchange of data, information, and commands across different layers and entities. Connectors act as bridges, facilitating integration and interoperability between systems, devices, or software components. They adapt data formats, protocols, and standards for seamless data flow. Interfaces define methods and protocols for communication, including APIs (Application Programming Interfaces), communication protocols (such as MQTT or RESTful APIs), standardized data models (such as OPC-UA or JSON), and other forms of structured communication. These mechanisms ensure effective communication and compatibility within the digital twin architecture.

Data structure: Data structure in the digital twin layer is designed to capture and model the relevant attributes, properties, and relationships of the physical assets and processes being replicated. It may include hierarchical structures, object-oriented models, or database schemas that organize data into meaningful entities and their associated attributes. Common data structures used in digital twins include time series data for capturing historical and streaming sensor data, object-oriented models for representing physical assets and their properties, and relational databases for storing structured data.

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Data storage: Data storage in the digital twin layer involves storing and managing data in the digital twin system. It utilizes databases, data lakes, or distributed file systems to handle structured and unstructured data. The storage architecture should be scalable, reliable, and support real-time data ingestion and retrieval. Data security, privacy, and compliance are important considerations. Replication and synchronization mechanisms ensure data redundancy and availability. The choice of storage technologies depends on factors like data volume and processing speed. Efficient storage enables data-driven analytics, visualization, simulation, and decision-making, improving understanding and optimization in the digital twin.

Digital Twin layer (WP3)

Modelling environment: The modelling environment in the digital twin layer for an energy system enables users to create a virtual representation of the system. It allows the configuration of components, such as HVAC, lighting, renewable energy sources, and production equipment. Users define physical characteristics, operational parameters, and energy consumption patterns. The modelling environment supports customized virtual replicas that are continuously monitored, analyzed, and optimized for enhanced energy efficiency and performance. Stakeholders gain insights, identify optimization opportunities, and make informed decisions to improve energy management in buildings, production facilities, or specific processes.

Data processing: Data processing in the digital twin layer involves manipulating and analyzing data to extract valuable insights. Tasks include data cleansing, aggregation, filtering, normalization, and transformation. Processed data validates and calibrates the digital twin model, enabling accurate representation of the real-world system. It supports simulations, scenario analysis, real-time analytics, and decision support. Data processing techniques are chosen based on objectives, requirements, and complexity, driving operational efficiency and performance improvements in the physical system.

Simulation modelling: Simulations with data-driven models enable analysis of system behaviour, testing operational strategies, and evaluating the impact of changes. They provide insights into system performance, optimization opportunities, and risks, supporting data-driven decision-making and proactive system management. The choice of modelling methods depends on the system, available data, and simulation objectives, with models calibrated and validated using real-world observations for accuracy and reliability. Data-driven simulation modelling methods, including multiscale, discrete event, and agent-based modelling, etc.

Optimization methods: Optimization methods in the digital twin layer enhance the system's ability to identify optimal solutions, uncover patterns, and make informed decisions. They enable the digital twin to continually adapt, improve, and optimize the performance of the physical system by utilizing data-driven analysis and iterative optimization processes. The selection of optimization methods in the digital twin layer depends on the goals, constraints, and characteristics of the system being optimized. Machine learning-based optimization methods learn patterns and optimal solutions from data, genetic algorithms mimic natural selection, and multi-objective optimization methods handle conflicting objectives. However, there are many more methods available, and their selection depends on the specific optimization problem and constraints. These methods can be used independently or in combination, depending on the complexity and requirements of the problem.

Visualization methods: Visualization methods in the digital twin layer transform data, models, and simulations into visual formats to enhance understanding and analysis. They present status data,

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analytical insights, and forecasts in formats that can be easily perceived by humans. These methods include 2D/3D graphics, dashboards, charts/graphs, heatmaps, animated simulations, and VR/AR. They offer intuitive views, concise information, and dynamic representations for monitoring, analysis, and decision-making. The choice of visualization methods depends on the type of data, objectives, and the intended audience. These methods convert complex information into meaningful visuals, enabling insights, decision support, and optimization of the physical system.

Management layer

This layer aims to integrate production and energy management to achieve a flexible and adaptable consumption profile for industries.

Production Management layer (WP4)

Aggregated production scheduling/ sales and operation planning: Aggregated production scheduling and sales and operations planning (S&OP) are essential for optimizing and coordinating manufacturing or production systems. Aggregated production scheduling involves creating an optimized plan for production activities to meet overall demand, considering resource allocation, minimizing costs, and maximizing throughput. The digital twin provides a virtual representation of the production system, enabling simulation, evaluation of scenarios, and optimization based on factors like capacity and customer demand. Sales and operations planning aligns sales forecasts with the production plan and business goals. It integrates the virtual representation with sales data and customer demand to optimize inventory levels, balance supply and demand, and enhance customer satisfaction. The digital twin facilitates real-time visibility, scenario evaluation, and informed decision-making. Ultimately, the digital twin optimizes production scheduling and improves coordination between sales and operations.

Production scheduling: Production scheduling includes planning, sequencing, and timing of production tasks within an industry or manufacturing facility, serving the purpose of meeting customer demand and enabling manufacturing flexibility. Manufacturing flexibility is particularly important in the context of a demand response system. It involves identifying additional manufacturing capacity to facilitate adaptability. To achieve manufacturing flexibility, data-driven methods and advanced algorithms are utilized. These approaches take into account multiple factors, such as energy consumption, demand patterns, production constraints, lead times, setup times, batch sizes, and task dependencies. By considering these variables, an optimal schedule can be devised, aligning with the desired energy consumption profile.

Production monitoring and control: These processes involve continuous monitoring of production activities, making necessary schedule adjustments, and implementing control measures to ensure efficient operations. Production monitoring needs tracking and observing various production stages to gather real-time data on productivity, quality, and performance. Production rescheduling involves modifying schedules to accommodate changes in demand, resource availability, and unexpected disruptions. It optimizes resource utilization and manages unforeseen events impacting production. Production control establishes rules, procedures, and standards to maintain order, optimize resource usage, implement corrective actions based on feedback, and coordinate activities across departments. Overall, these practices enable organizations to monitor, adapt, and execute production activities efficiently.

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Energy Management layer (WP2)

Energy Strategy: An energy strategy in an industrial setting is a comprehensive plan or approach developed by a company to effectively manage and optimize its energy usage. It includes the identification, evaluation, and implementation of various measures and practices aimed at improving energy efficiency and enabling energy flexibility. The energy strategy focuses on enhancing the overall energy performance of the company's operations while ensuring a reliable and cost-effective energy supply. By developing and implementing such a strategy, industrial companies can effectively tackle energy-related challenges, comply with regulations, and achieve sustainability targets. The strategy aims to maximize energy efficiency by identifying areas of energy waste and implementing measures to reduce it. This may include optimizing processes, upgrading equipment, improving insulation, and adopting energy-saving technologies. Additionally, long-term planning and evaluation are necessary to enable demand response and energy flexibility in the system. Furthermore, the energy strategy includes the integration of renewable energy and storage systems, as well as assessing energy procurement options to ensure a dependable and cost-efficient energy supply. This may involve negotiating favourable contracts, exploring opportunities in the energy market, and considering the implementation of energy storage solutions.

Renewable energy and storage integration: Renewable energy and storage integration in an industrial setting involve incorporating sources like solar or wind into a company's energy supply, along with implementing energy storage systems. This integration enables efficient management and balancing of energy supply and demand. The generated renewable energy is integrated into the company's infrastructure, either powering operations directly or feeding into the grid. Energy storage systems are crucial for enabling energy flexibility, storing excess renewable energy for times of high demand or low generation. Common storage technologies include batteries, pumped hydro storage, compressed air energy storage, and thermal energy storage. To achieve effective integration for energy flexibility, industrial companies must assess energy needs, evaluate renewable energy feasibility, determine storage system scale and capacity, and consider regulatory requirements, incentives, and infrastructure compatibility.

Demand side management: Demand-Side Management (DSM) in an industrial setting optimizes energy consumption through strategies and practices. It adjusts energy usage based on demand, grid requirements, and pricing signals, aiming to reduce peak demand, improve load profiles, and enhance energy efficiency. DSM includes load shifting, encouraging energy-intensive processes to off-peak periods to lower grid stress and potentially reduce costs. Demand response programs enable voluntary energy reduction during high-demand periods through production schedule adjustments, equipment shutdowns, or onsite generation/storage. Load management and optimization involve smart scheduling, load balancing, and advanced control systems for efficient energy utilization. It also emphasizes energy awareness and education to promote energy conservation practices among employees, fostering sustained energy savings and an energy-efficient culture.

Aggregator layer (WP5)

Aggregator platform: An aggregator platform in demand response refers to a system or software platform that facilitates the coordination and management of demand response programs. It acts as an intermediary between the grid operator or utility and the participating customers or end-users. The aggregator platform enables the aggregation of multiple distributed energy resources, such as industrial facilities, into a virtual power plant or a demand response portfolio. It allows these

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resources to collectively respond to grid conditions or signals. The aggregator platform communicates with participating customers, receiving signals from the grid operator indicating demand response actions. The platform distributes these signals to customers through notifications or integration with energy management systems. Customers then take actions to reduce energy consumption, such as adjusting schedules or reducing equipment usage. The aggregator platform collects data on energy reductions achieved and reports it to the grid operator, enabling compensation for participating customers.

Demand response services: Aggregators provide demand response services by coordinating and managing electricity usage for a group of customers in response to changes in the supply-demand balance of the grid. They act as intermediaries between grid operators and consumers, facilitating participation in demand response programs. Key services provided by aggregators include load monitoring and analysis, development of demand reduction strategies, real-time energy management, load shedding and shifting, automated control systems, and performance monitoring and reporting. Aggregators enable customers to effectively reduce their electricity consumption during peak periods and receive incentives or payments for their participation in demand response programs.

Cluster optimization: Cluster optimization in demand response involves grouping consumers or loads with similar characteristics or energy usage patterns to enhance their collective participation in demand response programs. Key steps include identifying and organizing consumers into clusters, analysing their load profiles for demand response opportunities, developing cluster-specific strategies, applying optimization algorithms to determine effective actions, facilitating communication and coordination with consumers, monitoring and evaluating the aggregated response, and refining the process based on feedback for future events. The aim is to optimize demand reduction within each cluster while minimizing negative impacts, leading to more efficient and effective demand response outcomes.

Demand response forecast: Demand response forecast involves analysing historical energy consumption data, weather patterns, market conditions, and other factors to predict future electricity demand and the potential for demand response participation. It utilises data analysis, weather analysis, market analysis, and understanding of demand response programs. Various modelling techniques are used for forecasting, with different time horizons. The forecasts come with uncertainty, and evaluation and refinement are carried out based on real-time data and post-event analysis. Accurate forecasts support the optimization of strategies, anticipation of demand fluctuations, and alignment of electricity usage with grid conditions and consumer needs for effective demand response implementation.

Smart Grid

A smart grid is an advanced electricity distribution system that utilizes modern technologies to improve the reliability, efficiency, and sustainability of the power grid. In the context of demand response, a smart grid enables real-time, two-way communication between grid operators and consumers, allowing for the exchange of information and the adjustment of electricity usage. It is equipped with advanced metering infrastructure, such as smart meters, which provide detailed energy usage data to monitor consumption patterns and identify demand response opportunities. Smart grids also support automated load control, enabling remote management of electricity usage through actions like load shedding and load shifting to optimize demand response and achieve desired reductions in demand.

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4 DESIGN PRINCIPLES

Design Principles serve as guidelines to steer the development of the F4F project. In this section, the survey results are presented along with a definition that serves as a guide for the developments. Additionally, key attributes that should be taken into account in the project are outlined.

4.1 OPEN TECHNOLOGIES

Open technologies in F4F

refer to technologies that are free and accessible to the public, typically with minimal or no restrictions on their use or modification. This can include software, hardware, or other products that are released with open-source licenses that permit the source code to be shared and modified by anyone. The goal of open technologies is to promote collaboration, innovation, and the development of new products and solutions. Open technologies also often allow for greater transparency and accountability, as the source code and design details are publicly available for review and improvement.

Fig 3 below shows that **accessibility**, **collaboration**, **interoperability** and **scalability** are the four most preferred open technologies attributes and are also recommended by the experts of the F4F partners.

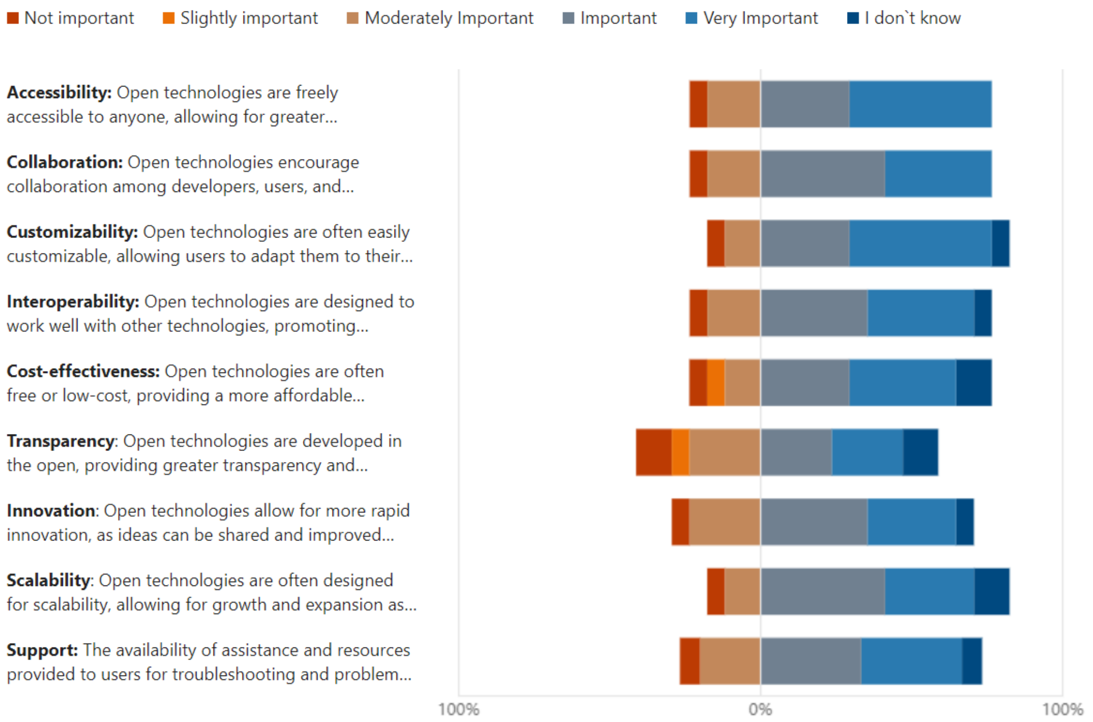

Figure 3: Preferred attributes for open technologies

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4.2 STANDARD PROTOCOLS

Standard protocols in F4F

are design principles in software engineering that promote interoperability, scalability, and modularity. Standard protocols refer to agreed-upon rules and formats for communication between different components or systems. By using standard protocols, different components can easily exchange data and information, even if they are developed by different organizations or manufacturers. This promotes interoperability and compatibility between different systems and reduces the risk of vendor lock-in.

Using standard protocols and interfaces can improve the reliability, maintainability, and overall quality of a system, as well as reduce the risk of technical debt and make it easier to integrate new technologies and components.

The figures below show that requirements and the preferred standard protocols of F4F. Fig 4 shows that **robustness**, **scalability**, **security** and **reliability** are the four most important requirements for standard protocols attributes in F4F. Fig 5 shows **HTPP(S)**, **DNS**, **TCP/IP**, **SSC/TLS** and **SSH** are the preferred standards protocols to consider and are also recommended by the experts of the F4F partners.

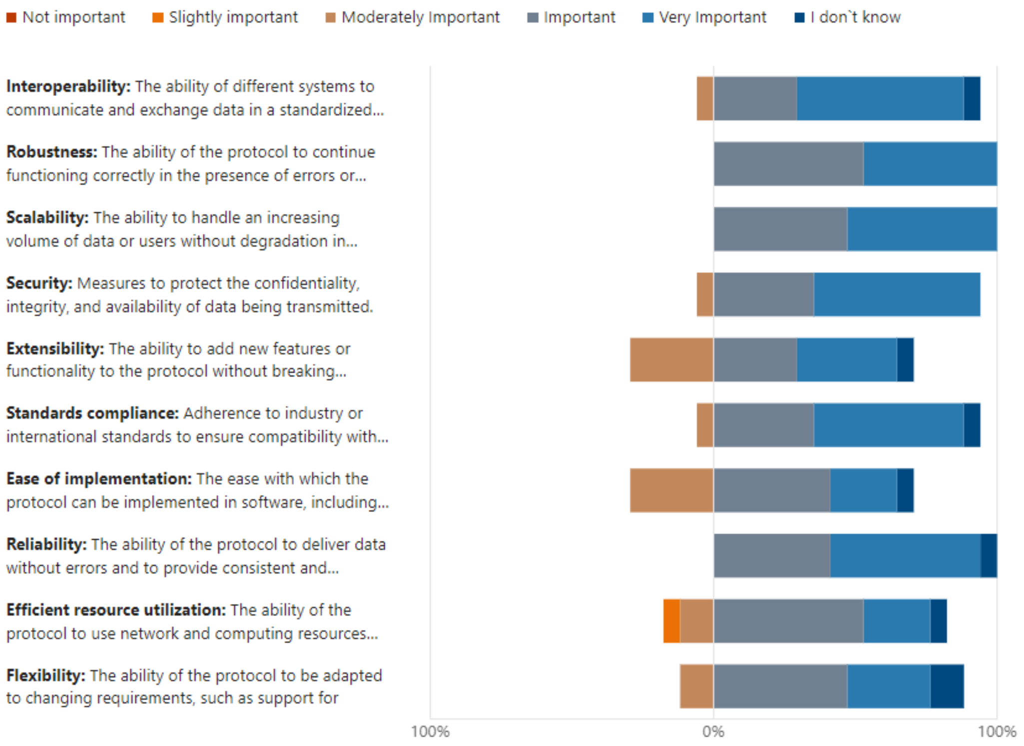

Figure 4: Requirements for standard protocol attributes in F4F

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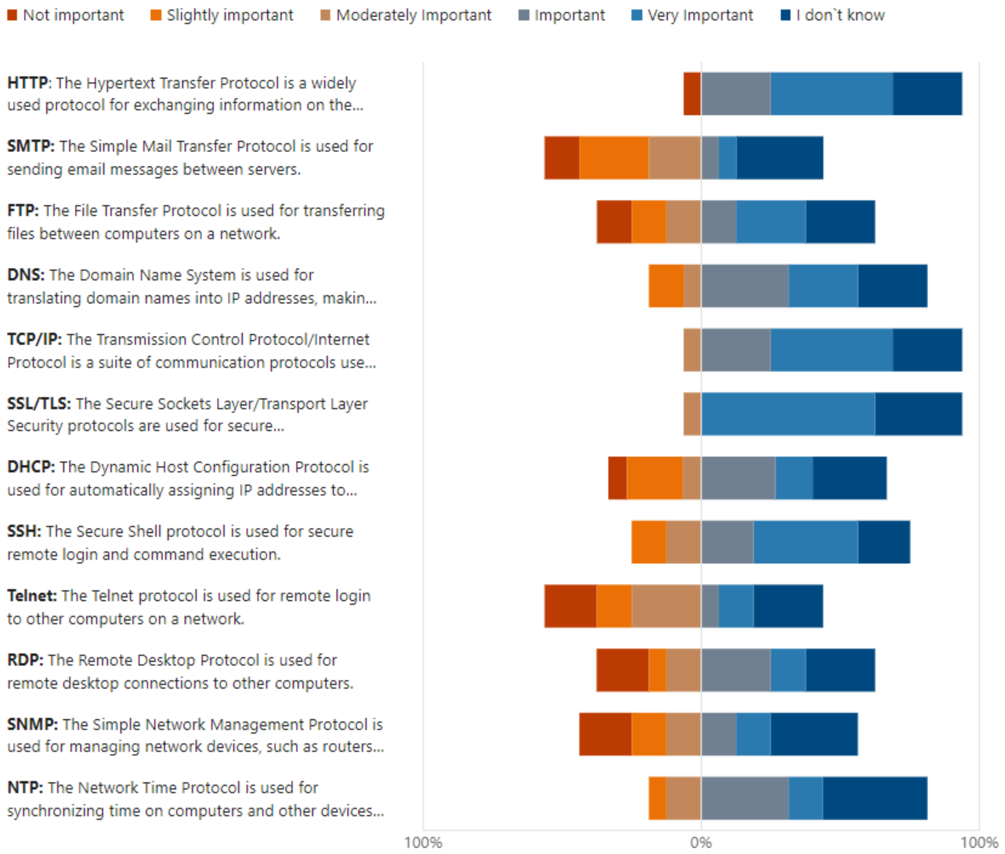

Figure 5: Preferred standard protocol in F4F

4.3 STANDARD INTERFACES

Standard interfaces in F4F

are design principles in software engineering that refers to the use of common, well-defined, and widely accepted interfaces between components, systems, or applications. A standard interface provides a consistent and well-understood means of communication and data exchange between different components.

Using standard protocols and interfaces can improve the reliability, maintainability, and overall quality of a system, as well as reduce the risk of technical debt and make it easier to integrate new technologies and components.

The figures below show that requirements and the preferred standard interfaces of F4F. Fig 6 shows that **extensibility**, **interoperability**, **robustness** and **security** are the four most important requirements for standard interface attributes in F4F. Fig 7 shows **REST**, **SOAP**, **AMQP** and **Websockets** are the preferred standards protocols to consider and are also recommended by the experts of the F4F partners.

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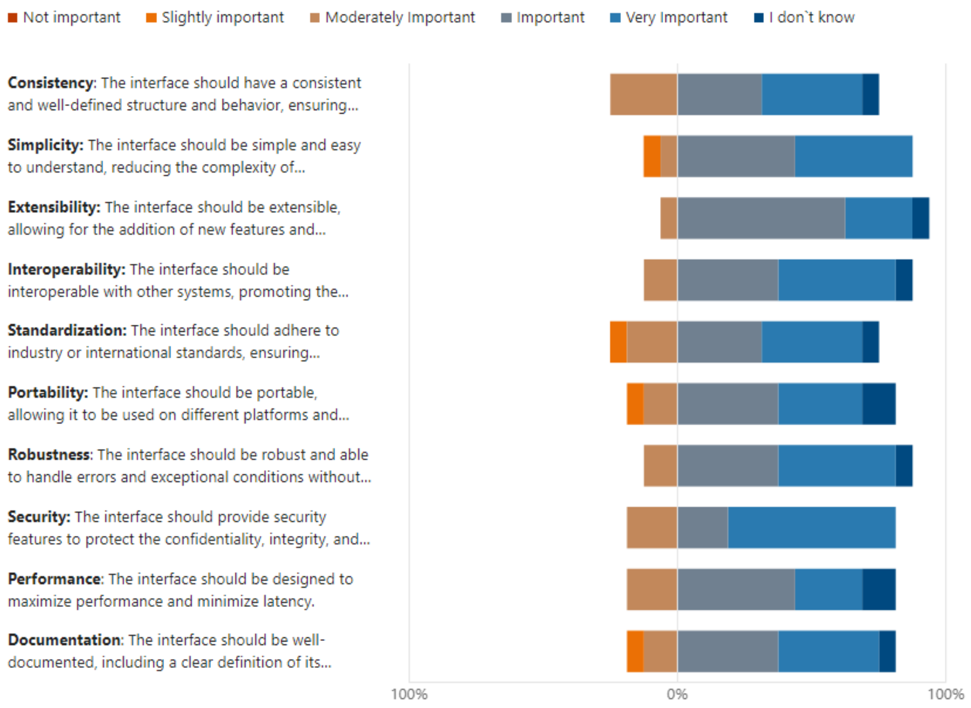

Figure 6: Requirements for standard interfaces in F4F

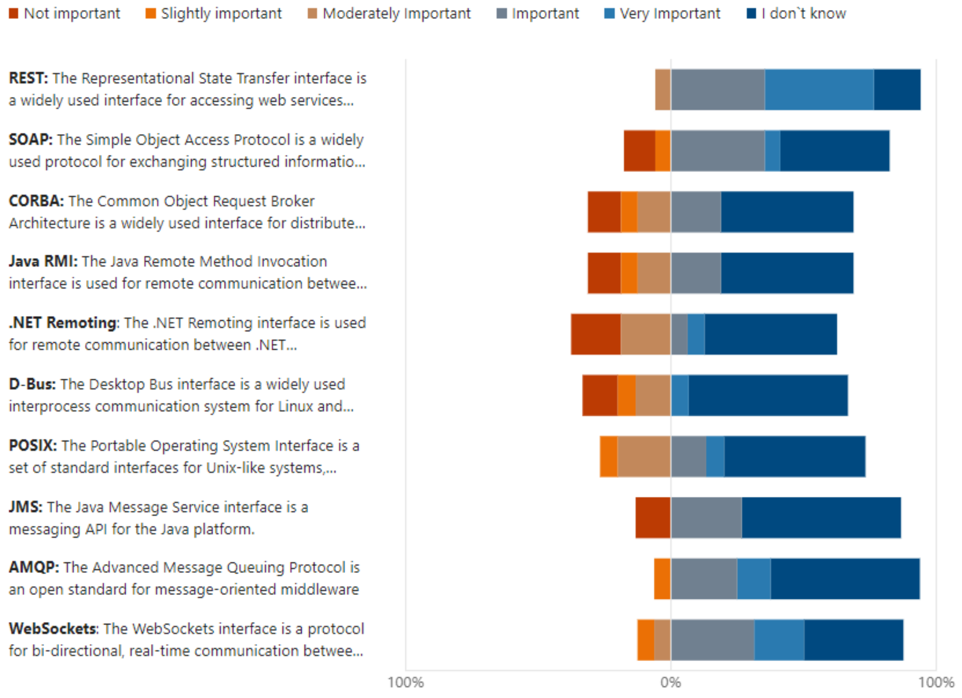

Figure 7: Preferred standard Interfaces in F4F

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4.4 DATA STORAGE

Data storage in F4F

Data storage as a design principle refers to the consideration of how data is stored and managed within a software system as an integral part of the software design process. This approach incorporates considerations of data storage and management into the development process from the earliest stages. The aim of data storage as a design principle is to ensure that the software can effectively store and retrieve data in a way that is secure, efficient, and scalable.

The figures below show that requirements and the preferred standard interfaces of F4F. Fig 8 shows that **scalability**, **interoperability** and **manageability** are the three most important requirements for data storage in F4F. Fig 9 shows **SQL database**, **JSON**, **NoSQL database** and **CSV** are the preferred data storage structures/formats to consider and are also recommended by the experts of the F4F partners.

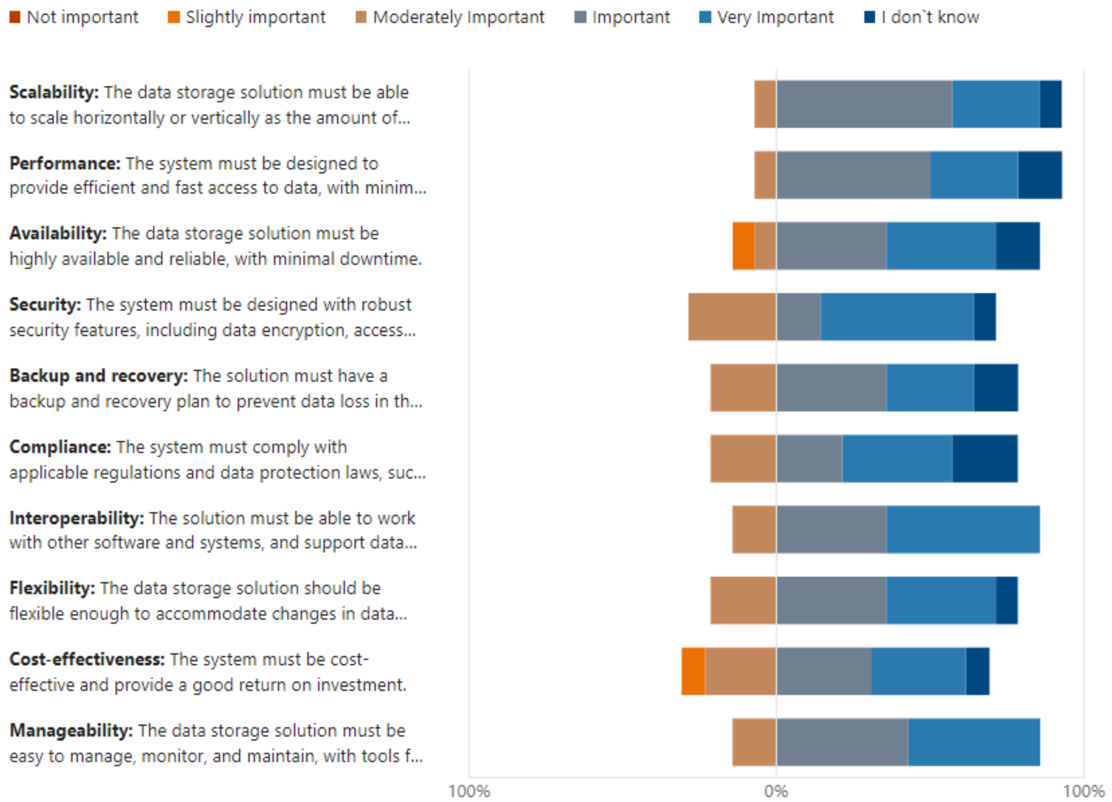

Figure 8: Requirements for data storage in F4F

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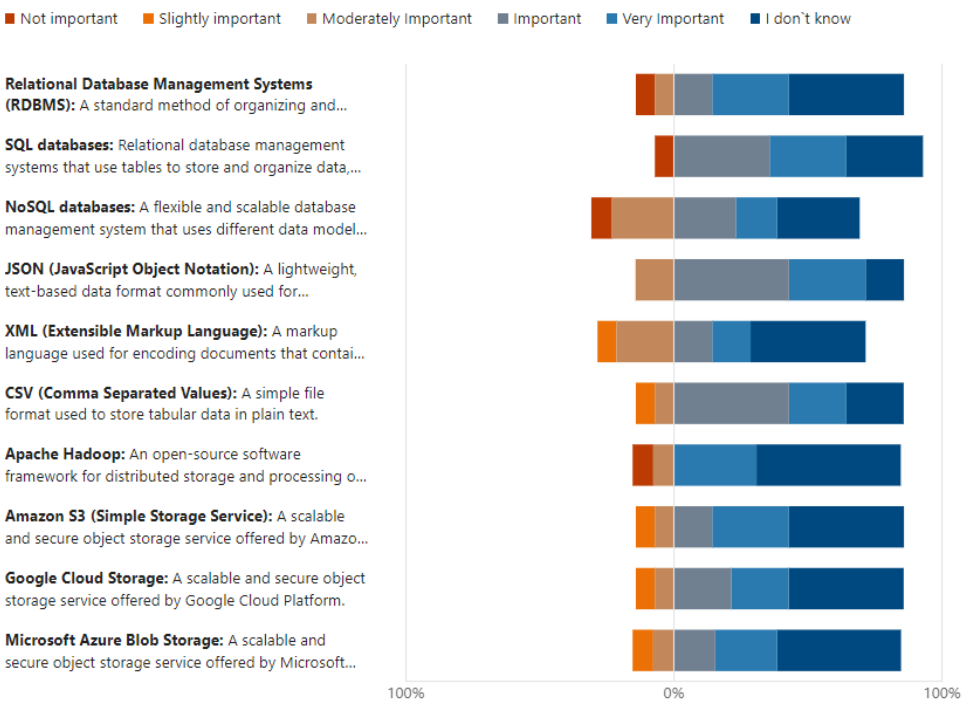

Figure 9: Preferred data storage in F4F

4.5 MODULAR ARCHITECTURE

Modular architecture in F4F

is a design principle that divides a complex system into smaller, independent, and interchangeable parts or modules. Each module has a specific function and can be designed, developed, tested, and maintained separately, making the overall system more flexible, scalable, and easier to manage.

In software engineering, modular architecture is a way to structure software systems into separate, reusable, and interchangeable components. This approach allows for faster development, improved maintainability, and easier integration of new features and technologies. Additionally, it enables the system to be modularly extended or replaced without affecting other parts of the system, reducing risk and facilitating innovation.

Modular architecture can be applied to various types of systems, including hardware, software, and more, and it is a key factor in achieving a scalable and sustainable design for complex systems. By breaking down a system into smaller, manageable parts, the modular architecture makes it possible to manage complexity, increase efficiency, and improve overall system performance.

Fig 10 shows that **abstraction**, **scalability, testability,** and **interchangeability** are the four most preferred modular architecture attributes and are also recommended by the experts of the F4F partners.

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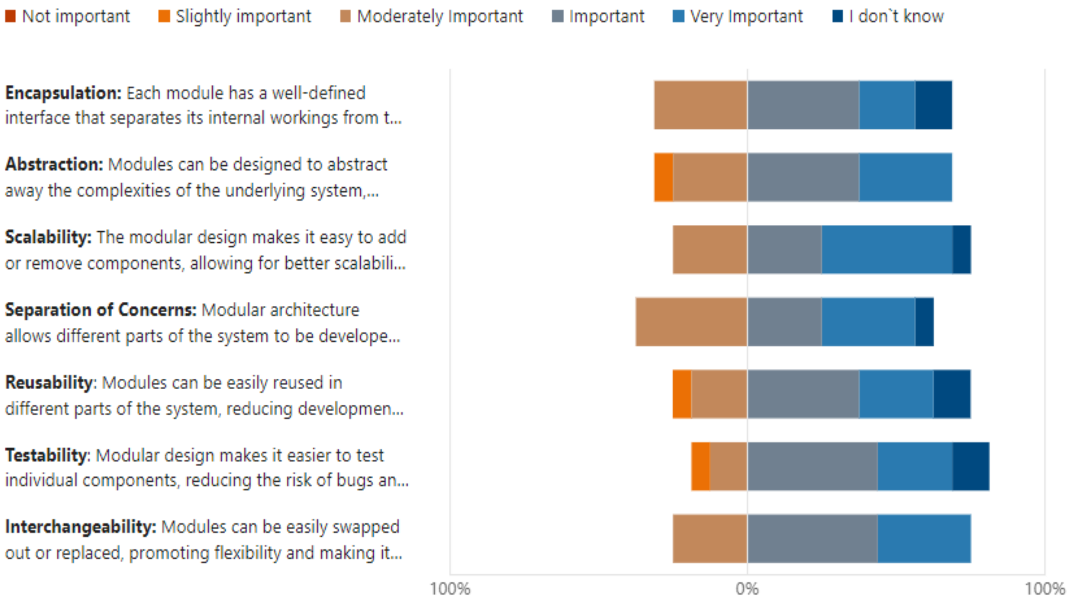

Figure 10: Preferred attributes for modular architecture in F4F

4.6 NO-VENDOR LOCK-IN

No-vendor lock-in in F4F

is a design principle that refers to the idea of avoiding dependencies on specific vendor products, technologies or platforms. The aim is to make it easier to switch to a different vendor or technology without incurring significant costs or disruptions. This can be achieved through the use of open standards, interoperable interfaces, and modular designs that allow different components to be swapped out easily. The goal of no-vendor lock-in is to increase flexibility and reduce the risk of being tied to a single vendor for a critical component of a system. This design principle is particularly relevant for enterprise software, where long-term costs and vendor stability can be significant factors in the decision-making process.

Fig 11 shows the **open standards**, **interoperable documented API,** and **standardization of data formats** are the four most preferred no-vendor lock-in attributes and are also recommended by the experts of the F4F partners.

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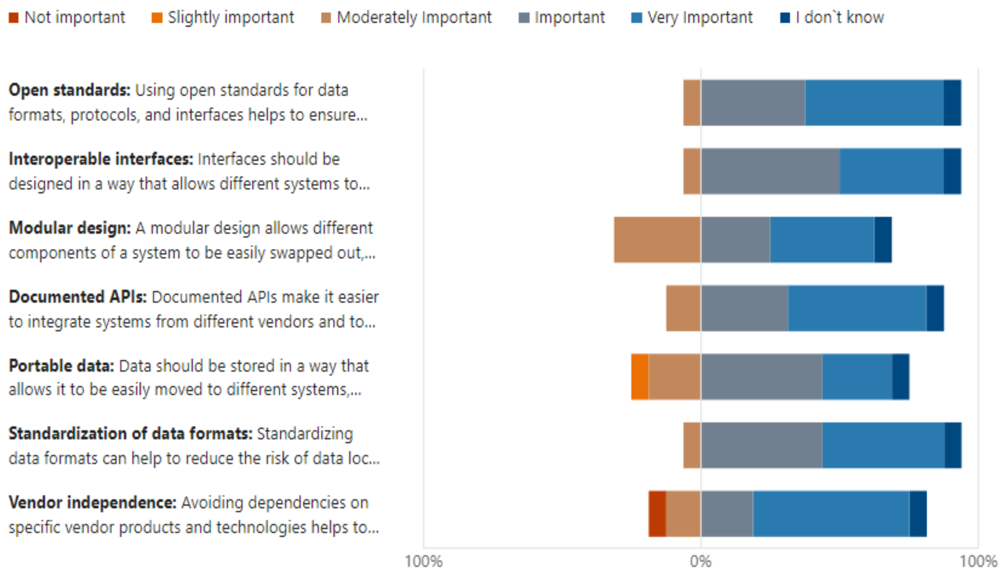

Figure 11: Preferred attributes for no-vendor lock-in in F4F

4.7 SERVICE REVENUE STREAM

Service revenue stream in F4F

refers to the idea of generating revenue from a product or service through recurring or subscription-based payments, rather than through a one-time sale. Service revenue streams are commonly used in software and technology-based businesses, where customers can subscribe to a service for ongoing access to a product or service. This approach provides a steady and predictable stream of revenue for the company and can help to ensure the long-term viability of the product or service. By providing ongoing value to the customer through regular updates, bug fixes, and new features, the company can encourage customers to continue using the service and renew their subscriptions. Service revenue streams can also provide valuable insights into customer behaviour and preferences, which can help the company to continuously improve its offerings and to better meet the needs of its customers.

Fig 12 shows that **continuous improvement**, **customer retention, scalability, flexibility,** and **customer satisfaction** are the five most preferred attributes for revenue value stream and are also recommended by the experts of the F4F partners.

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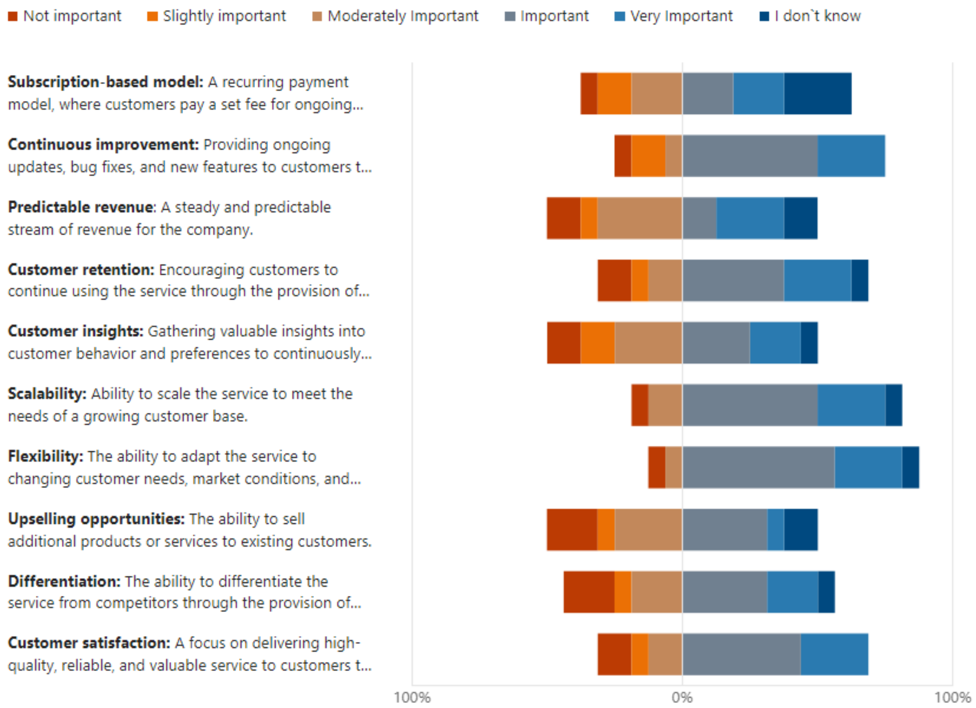

Figure 12: Preferred attributes for revenue value stream in F4F

4.8 CYBERSECURITY

Cyber security in F4F

refers to the practice of protecting computer systems, networks, and sensitive data from unauthorized access, use, disclosure, disruption, modification, or destruction. This includes protecting against a range of threats such as hacking, malware, phishing, and other forms of cyber-attacks.

In software engineering, incorporating cybersecurity into the design process means considering security at every stage of software development, from requirements gathering to deployment and maintenance. This involves implementing secure coding practices, using secure tools and libraries, conducting security testing and audits, and following industry standards and best practices for information security.

The goal is to build software that is secure by design, meaning that security is integrated into the very fabric of the system, making it more resilient to attacks and reducing the likelihood of a security breach. By making cybersecurity a design principle, software engineers can ensure that the systems they build are protected against the ever-evolving threat landscape and that sensitive information is kept safe.

The figures below show that attributes, requirements and preferred standard cybersecurity for F4F. Fig 12 shows that **confidentiality**, **integrity** and **availability** are the three most important attributes for data storage in F4F. Fig 13 shows **Access control, secure coding practice**, and **encryption of sensitive data** are three important requirements for cybersecurity and Fig 14 shows **ISO/IEC**

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27001, **NIST cybersecurity framework** and **OWASP Top 10** are the three important cybersecurity standards to consider for and are also recommended by the experts of the F4F partners.

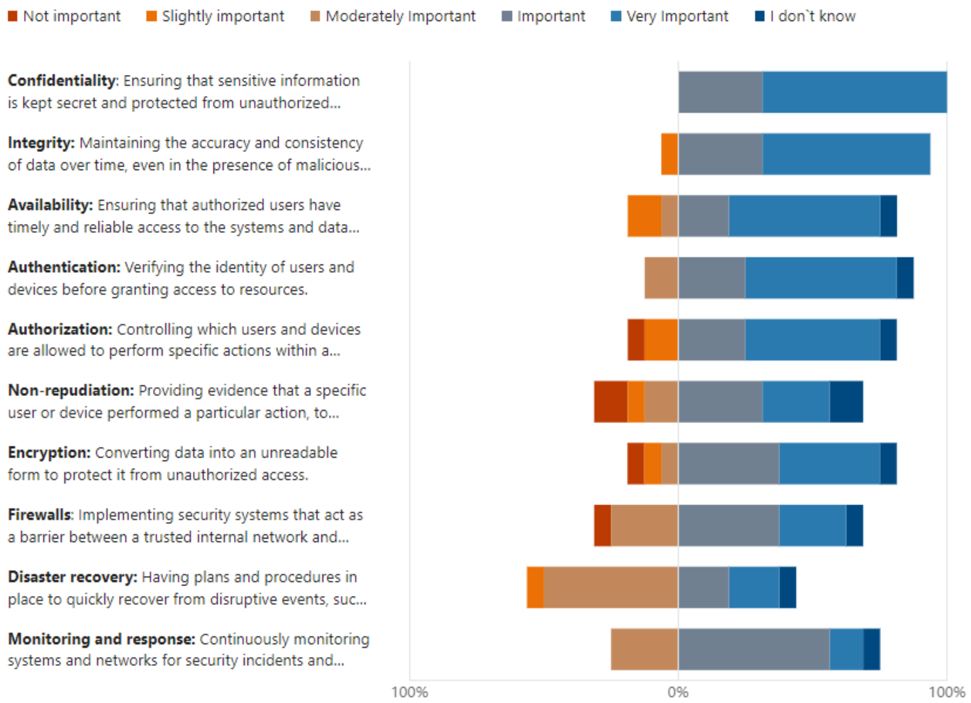

Figure 13: Preferred attributes for cybersecurity in F4F

Figure 14: Requirements for cybersecurity in F4F

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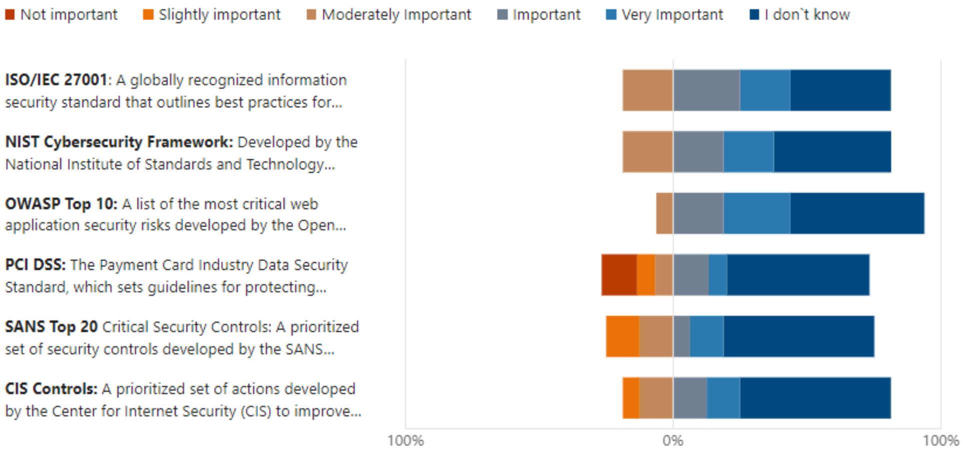

Figure 15: Preferred standard cybersecurity in F4F

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5 CONCLUSION AND RECOMMENDATIONS

This deliverable presents a reference architecture framework that provides guidance for industrial use cases in the F4F project and for industries aiming to enhance their manufacturing and energy flexibility for implementing industrial demand response services. The framework follows a three-step approach: systematic literature review, survey, and a series of workshops to develop and refine the reference architecture at the FLEX4FACT system level.

The key components of the reference architecture include the data layer, DT layer, management layer, and aggregator layer, which are vital for enabling demand response services and ensuring a consistent and seamless interaction between the physical and virtual elements. At the core of the framework for industrial demand response lies the identification, optimization, and adaptation of energy consumption profiles in manufacturing processes.

Utilising data-driven models that leverage real-time and historical production data allows for the identification of different energy consumption patterns at the product, machine, and process levels. This shift from aggregated energy consumption data allows for a reduction in complexity when dealing with the interplay between manufacturing processes and energy consumption.

The interplay between manufacturing and energy management, in conjunction with the aggregator agent, plays a crucial role in developing schedules that meet demand and orders, while concurrently improving energy consumption to lower energy prices and reduce CO2 emissions.

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