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Industry 4.0 implementation for multinationals: a case study

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Abstract

Purpose – Multinational business deliver value via multiple sites with similar operational capacities. The age of the Fourth Industrial Revolution (4IR) delivers significant opportunities for the deployment of digital tools for business optimization. Therefore, this study aims to study the Industry 4.0 implementation for multinationals.

Design/methodology/approach – The key objective of this research is multi-site systems integration using a reproducible, modular and standardized "Cyber Physical System (CPS) as-a-Service".

Findings – A best practice reference architecture is adopted to guide the design and delivery of a pioneering CPS multi-site deployment. The CPS deployed is a cloud-based platform adopted to enable all manufacturing areas within a multinational energy and petrochemical company. A methodology is developed to quantify the system environmental and sustainability benefits focusing on reduced carbon dioxide (CO_2) emissions and energy consumption. These results demonstrate the benefits of standardization, replication and digital enablement for multinational businesses.

Originality/value – The research illustrates the ability to design a single system, reproducible for multiple sites. This research also illustrates the beneficial impact of system reuse due to reduced environmental impact from lower CO_2 emissions and energy consumption. The paper assists organizations in deploying complex systems while addressing multinational systems implementation constraints and standardization.

Keywords Petrochemical, Systems of systems, Cyber physical systems, Digital manufacturing

Paper type Research paper

1. Introduction

Globalization and the Fourth Industrial Revolution (4IR) drive businesses toward integrated multinational operations, optimizing processes through digital tools. This shift, from decentralized to hybrid centralized systems, enables global alignment while preserving local standards (Patalas-Maliszewska & Losyk, 2020; Wu & Shang, 2020; García, Irisarri, Pérez, Estévez, & Marcos, 2018; Lee *et al.*). Multinational operations, exemplified by Saudi Aramco, leverage diverse yet similar systems globally, such as crude oil distillation, fostering competitiveness through production optimization and customization. Amidst a global presence, Saudi Aramco prioritizes sustainability technologies to reduce carbon emissions, complementing its upstream capabilities and global downstream network (Weyer, Schmitt, Ohmer, & Gorecky, 2015). Implementing a single centralized system poses technical and non-technical challenges, necessitating comprehensive evaluation of benefits, environmental impacts and change management. Building on prior theoretical frameworks (Telukdarie, Buhulaiga, Bag, Gupta, & Luo, 2018), this study extends into a detailed case study at Saudi Aramco, focusing on their Cyber Physical System (CPS) as-a-Service, showcasing a pioneering approach in the energy and chemicals sector.

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2. Literature

2.1 Basis of sustainable business systems

Standardizing production processes requires collaboration among stakeholders to meet product specifications. This introduces additional requirements like integration, architecture and security, aiming to optimize specific production lines (Weyer *et al.*, 2015). The use of isolated applications hinders performance benchmarking and data consistency across enterprises, challenging standardization efforts (Alshammari & Sarathy, 2017). This research proposes a systematic approach to help manufacturers achieve sustainable business systems, irrespective of automation levels.

Manufacturers face challenges such as interoperability issues, functional overlap and increased total cost of ownership due to varying automation levels. The research recommends creating a reproducible and standardized multinational CPS for data integration, cost reduction and collaboration (De Carolis, Macchi, Negri, & Terzi, 2017; Neill & Jiang, 2017).).

Operating within a hybrid hierarchical model, manufacturers divide into manufacturing core business line of business (LoBs) and manufacturing supporting LoBs, with decentralization causing overlaps, redundancy, data inconsistencies and rigid processes. The proposal advocates for an integrated CPS to provide a unified user experience, addressing internal and external uncertainties and aligning with global regulations and practices.

Most manufacturers have a common vision that is set by the board of directors and communicated to each LoB to design internal goals and tasks to achieve this overall company objective. LoBs work with an overlap caused by the decentralization, adopted systems and technologies (e.g. sensors, actuators, networks, infrastructure and decision support tools). The decentralization causes (De Carolis *et al.*, 2017):

(1) Redundancy and rework

(2) Use of different sources of the truth (data sources) for the same data type (e.g. taking production rates from the data historian system or from enterprise resources planning)

(3) Different and rigid business processes

(4) Lack of management of change (MoC) processes

(5) Significant time wasted in allocating data and trying to make use of it instead analyzing data.

This overlap mandates the creation of an integrated CPS that assists in providing a unique system with a unified user-experience. CPS fosters collaboration and provides a single version of truth to be adopted by all manufacturer's personnel. CPS takes into consideration the differences caused by the multinational operations that include the country-specific regulations and local best practices. For example, environmental regulation such as the greenhouse gas (GHG) emissions limit can be different for a refinery in the state of California versus a refinery in west Texas and that discrepancy is accounted for in the CPS of both refineries and the global CPS. Therefore, CPS ensures that there is an alignment between the different parties within the manufacturers' ecosystem by addressing internal and external uncertainties (Lee, Ardakani, Yang, & Bagheri, 2015). Internal uncertainties include physical asset performance degradation and business process bottlenecking caused by human or automation systems. External uncertainties include changes in market or customer requirements, unavailability of raw material and unreliable supplier or manufacturing partners. In addition, manufacturers and suppliers have different agreements and related terms and conditions that vary due to quality and standard requirements (Lee, Kao, & Yang, 2014).

The 4IR facilitates CPS deployment, transforming the manufacturing industry by integrating physical assets and the cyber world into digital twins. CPS offers the 5C (see Figure 1) architecture, connecting physical systems, converting data, creating a cyber hub, utilizing big data and configuring role-based dashboards. Integrating 3C technologies, it supports the concept of the smart factory (Weyer *et al.*, 2015):

(1) Connect with the physical systems (physical space)

(2) Fetch and convert data into contextualized and useable format

(3) Provide cyber and information system hub that integrates all the information from all connected data sources and create a cyber space

(4) Make use of the big data by deploying Advanced Analytics and Cognitive Computing

(5) Configure role-based dashboards.

CPS aids multinational manufacturers in digitizing and digitally transforming operations, fostering global collaboration. The research aims to propose a methodology for implementing digital transformation and quantifying sustainable digital business system benefits through CPS-as-a-Service for multinational businesses (Lee *et al.*, 2015).

2.2 Designing for CPS

The literature emphasizes challenges in designing CPS and how CPS-as-a-Service addresses these challenges. Manufacturers pursue diverse initiatives, influenced by executive support and funding, aiming to optimize business processes and enhance plant effectiveness globally. This is achieved by exploring new and innovative ways to maximize economic recovery and benefit margins by driving the value of the bottom of the barrel, while addressing safety and environmental concerns. It is also achieved by increasing the extent of integration of the applications within the CPS space (Telukdarie *et al.*, 2018). However, these objectives and initiatives face operational challenges that hinder the implementation. The following section summarizes these challenges and provides an overview of how this research proposes resolving these challenges:

(1) Enterprise architecture and collaboration: Siloes and departmentalized organizations hinder collaboration. Standards organizations propose modeling capabilities and supporting atomic services to enhance enterprise integration (De Carolis *et al.*, 2017; Jaeger, Matyas, & Sihn, 2014).

(2) Lack of system integration and fragmented systems: Integration challenges arise due to a large volume of data, aging legacy systems and custom-built applications. Methodologies, such as modeling capabilities and atomics services, are proposed to enhance collaboration (Qi & Tao, 2019; Lee *et al.*, 2014).

(3) Initiatives expenditure justification: Justifying expenditure for new initiatives requires baseline data. CPS-as-a-Service provides a systematic methodology, forecasting cost benefits against baseline operations conditions (Jaeger *et al.*, 2014).

Source(s): Weyer *et al.* (2015)

Figure 1.
CPS 5Cs

(4) Holistic end-to-end supply chain business process: Disciplines work in silos, hindering collaboration. CPS-as-a-Service provides end-to-end business process management to facilitate collaboration (Neill & Jiang, 2017; Jaeger *et al.*, 2014).

(5) Operational excellence and continuous improvement culture: Creating an operational excellence culture requires a comprehensive view. CPS-as-a-Service fosters continuous improvement culture by declaring the vision, sharing common views and building plans (Moghaddam *et al.*, 2017; Jaeger *et al.*, 2014).

(6) Talent management: Urgent onboarding of the next generation workers is needed as the baby-boomer generation retires. Different tools and models, like Description Logic (DL) and Web Ontology Language (OWL), are used to model organizational knowledge (Buhulaiga, Telukdarie, & Ramsangar, 2019; Moghaddam *et al.*, 2017).

(7) Cloud-based services: Manufacturing organizations are transitioning to cloud models, facing challenges like IT security requirements. Quality of Services (QoS) is crucial, requiring effective service and network security management (Wang *et al.*, 2010).

The following section proposes new methods, adopted by the research team, to address the gaps identified in the literature.

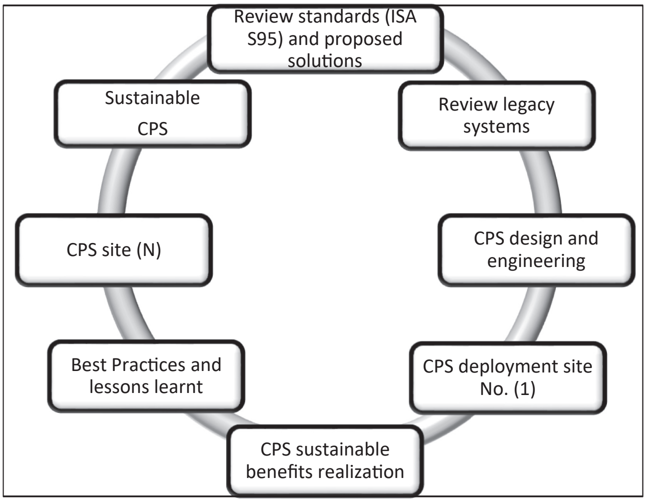
3. Research methods

This research employs a mixed-method approach to assess the value of CPS-as-a-Service as a sustainable business system for multinational manufacturers, emphasizing sustainability and reduced environmental impact. CPS-as-a-Service offers a standardized view of operational and enterprise data tailored to the user's role within the company.

The initial step in CPS delivery is design or architecture, following a roadmap derived from ISA-95 standards (Lee *et al.*, 2014). The reusable CPS, based on a reference architecture, is developed, and deployed at the first manufacturing site, designed to be a scalable and modular platform, serving as the reference site for CPS-as-a-Service. This approach ensures efficient CPS implementation with a focus on reusability, standardization and risk reduction (Weyer *et al.*, 2015).

To quantify the benefits of modular CPS, various tools are adopted, differentiating standalone and modular cloud-based software deployment infrastructure. These tools measure deployment advantages, including flexibility, scalability, standardized training, improved software utilization, reduced support costs and minimized total cost of ownership (TCO) (Li, Lin, Jin, & Chen, 2008). The organization utilizes these benefits to justify current and future CPS deployments, drawing lessons from the initial CPS deployment at the Jazan Refinery Complex Mega Project (JRCMP) in Saudi Arabia. The continuous improvement cycle of CPS deployment is illustrated in Figure 2.

In alignment with the 5Cs discussed in the literature, CPS-as-a-Service introduces a 6th "C" – a cloud-based system of systems, covering configurability, agility, performance, interfaces and operational-economic impacts crucial for manufacturers (Pattanayak & Roy, 2015). It establishes a standard enterprise architecture, offering a unified view of operational and enterprise data based on user roles within the company. CPS-as-a-Service employs a unified plant hierarchical reference model (UPHRM) to facilitate collaboration, providing a comprehensive view of the company's common objective with defined roles and responsibilities (Pattanayak & Roy, 2015). The CPS generates advisories to operators, guiding energy routing and asset utilization based on availability and cost optimization (Weyer *et al.*, 2015). Results sections detail the main logical components of manufacturing operations management (MOM) and decision support systems (DSSs), outlining basic CPS-as-



Source(s): Li *et al.* (2008)

Figure 2. Cyber physical systesm continuous improvement cycle

a-Service functionalities. The delivery of the architecture precedes discussions on the benefits derived from such an implementation.

3.1 CPS methodology of quantifying benefits

The second step focuses on benefits analysis post the implementation of Industry 4.0 at Saudi Aramco, proposing a novel methodology to quantify sustainability benefits of providing CPS-as-a-Service. The methodology evaluates impacts in man-hours, project cost, support, energy consumption and environmental effects like carbon dioxide (CO_2) emissions. It calculates resources used, computers/servers, manpower utilization percentage and average commuting mileage. The methodology showcases the economy of scale and increasing benefits with more implementations. Benefits are quantified as CPS sustainable environmental (CO_2 emission reduction) and economic benefits. The research considers only the impact of transport operations, excluding transport lifecycle or upstream fuel impacts. The environmental management systems is a key CPS module and is used to manage the manufacturing facility (refinery and gas plant) air quality and emissions including NO_x, SO_x, CO_x and other GHGs, this module's benefit calculations are quantified outside of this research case study. Table 1 quantifies the considerations in quantifying benefits.

The ability to calculate the impacts is delivered through various operational and non-operational equations, leading into a full model. The CPS calculation methodology adopted is shown below; the following variables are considered:

- x: Specific system under consideration such as production planning, material balance and others described in the CPS architecture.
- y: Project phase; Saudi Aramco uses 6 project phases; idea generation, feasibility, design, build, deploy and maintain.
- n: Number for project phases, number of systems
- N: Total number of the CPS projects

Variable	Description
System complexity	During the initial CPS system (version 0) development, a scoring methodology is created to score the system complexity based on criteria ranked from 1 low to 5 high. This ranking is adopted to differentiate the effort and differentiate the intensity of work required for each CPS system during each phase and subsequent deployments
System reuse benefit	This is the system reuse benefit as determined for re-using platforms, integration services and calculation templates
Manpower cost and hours	Applicable to the system design, system build, system deployment and test and performance testing phases
Project duration	The required project schedule
Server cost	Valid for the consultants and servers and dependent on the web, application, database and integration servers required based on technology licensor recommendations
License cost	License costs require to use the commercial of the shelf software and the license model may be based on number of sites, assets or users
Support cost	This includes licensor and manpower support costs
Transportation cost and CO_2 impact	Manpower mobilization and business travel result in increased road and air transport costs and an increased carbon emission
Energy consumption	This includes the typical energy cost and consumption for the build and computers that are being utilized

Source(s): Authors' own work

Table 1.
CPS calculation variables

S_x: System complexity, a cross-functional asset performance and safety management system may be complex compared to a single implementation of a single function system such as a historian.

$P_{x,\,y}$ System specific effort (x) per project phase (y); the effort is reduced for CPS 2 and CPS 3 (system reuse benefit)

U_y Resource utilization per project phase

$D_n = 1_{,x,y}$ Project duration for each phase and systems for CPS 1

$CPSD_{x,y}$ CPS project duration per system per phase

$CPSD_N$ CPS total project duration

$$\boldsymbol{CPSD_{x,y} = S_x * P_{x,y} * U_y * D_{n=1,x,y}} \quad (1)$$

Equation (1) represents the CPS effort per system per phase. While equation (2) represents the summation across all phases and systems.

$$\boldsymbol{CPSD_N = \sum_{x,y=1}^{n} CPSD_{x,y}} \quad (2)$$

The cumulative CAPEX costs are defined in Equation (3).

$$\boldsymbol{CPS(CAPEX)_N = \sum_{x,y=1}^{n} CPSD_{x,y} * M_{x,y} + L_x + I_x} \quad (3)$$

$CPS\ (CAPEX)_N$: Total once of cost of CPS including resources, licenses and infrastructure.

$M_{x,y}$ Resource cost for the specific system and phase of the project

L_x License cost for each system

I_x Infrastructure cost for each system

The cumulative OPEX costs are defined in Equation (3) .

$$CPS(OPEX)_N = \sum_{x,y=1}^{n} M_{x,y} + L_x + I_x \tag{4}$$

I_x Infrastructure operating cost for system x

CPS (OPEX) Cost for ownership for CPS including support manpower.

The total energy consumed is defined by Equation (5).

$$CPS(E)_N = \sum_{x,y=1}^{n} E_{x,y} + V_y \tag{5}$$

$E_{x,y}$ Energy consumption per system per project phase

V_y Other energy factors can be office space.

CPS $(E)_N$; CPS Project Energy usage

The total CO_2 produced is defined by Equation (5).

$$CPS(CO_2)_N = \sum_{x,y=1}^{n} P_{x,y} + C_{x,y} \tag{6}$$

$C_{(x,y)}$ Car CO_2 emissions per project phase per system

$P_{(x,y)}$ Plane CO_2 emissions per project phase per system

CPS (CO_2) CPS CO_2 dioxide emission

For the purpose of clarification of the calculation, the implementation is for a total of 14 systems, 2 support systems and across 6 phases. The 14 systems are as follows: planning, scheduling, mass balance, connected worker, predictive maintenance, asset performance and strategy, digital twin/T&IS, process safety, environmental management system, laboratory information management system, operations risk management, digital twin, global visualization, historian, with support systems: integration including ERP and automation and mobility.

4. Results: CPS architecture development and model application

4.1 Architecture

The services-oriented architecture (SOA) concept is adopted to enable constructing existing services and applications. It allows reusing hosted applications and platforms to easily decompose monolithic applications into reusable services and micro services to drive a modular service landscape. Businesses can then focus on innovating and building integrated solutions and services using existing applications to re-engineer business processes and enable quantum changes without having a risk of failure, as the applications and services were already field proven and tested in past implementations (Gifford, 2011).

4.2 Fundamental business functions built into architecture

It is essential to quantify and understand the diverse business functions built into the singular architecture.

The production planning and scheduling system supports planners to align the production targets with the sales plan considering any operational constraints. The production scheduling system supports the schedulers and operations to convert the daily targets into feasible operations instructions. The mass and energy balance systems tracks material being produced to ensure that efficiency is maintained, and yield is maximized while losses are minimized. The system helps personnel to track losses, maximize energy consumption and reduce inventory. The near real time advisory is now also available to help provide data quality analysis functions and detect sensor accuracy by collating data from instrument diagnostics and comparing those with the soft sensor calculated variables.

The predictive maintenance (PM) system is able to track the effective execution of predictive, preventative, reactive maintenance strategies. PM strategies are using multisensor asset-based fault-monitoring systems that advise operations of failure modes before they occur. The preventative and reactive maintenance strategies are part of the tradition maintenance planning systems and task list formulation. Asset performance management systems are adopted by reliability and maintenance engineers to track the performance of the asset compared to the manufacturer recommendations or based on the asset criticality determined from failure and risk studies. The system is a repository of best practices and lessons that can scaled across similar assets in different operating areas. The turnaround and inspection scheduling (T&IS) supports T&I engineers to scope, schedule and execute T&I plans. Recent advancements include connected worker and workforce tracking to maximize the crew utilization and safety.

The Process Safety Management (PSM) system is adopted as a repository to ensure that major safety equipment and safety protection systems are healthy and in place to prevent major catastrophes. The operational risk management (ORM) system is a day-to-day operations system confirming safe work site conditions during work permit issue as requested by maintenance and contractor crew. The environmental management system (EMS) is adopted by the facility to manage air, water and solid waste including hazardous waste. Typical environmental KPIs managed are GHG emissions, marine discharge. The system also supports safety and compliance to ensure audit the chemical inventory and material safety data during audits.

The laboratory information management system (LIMS) manages the sample result generation including sample collection and tracking to inform operations of the critical quality parameters. The sample results data quality is maintained using statistical quality control (SQC) to ensue sample results validity. Operations logs and shift handover support the management of the unit operations ensuring that scheduled production is communicated, and operations track and prevent abnormal situations maintaining visibility for supports from engineering and maintenance. The process historian is a system that collects real time data from the fields, including time series flow, temperature and pressure data. The historian often has standard functionality such as data conditioning and error filtering. The protocol adopted to manage the data is referred to as Object Linking and Embedding (OLE) for process control (OPC).

Master data management (MDM) and enterprise integration (EI) middleware supports centralized real time and message service bus that is able to interface data between many different and often legacy source and destination systems. The integration middleware uses the manufacturing master data to assist with the data translation and mapping as well as unit of measure alignment between the source and destination systems connecting various Information Technology (IT) and Operations Technology (OT) systems. The OT systems that may also include hardware have processing capability at the source device.

The main technology components of the architecture are sensing, instruction and controls that are connected to industrial control network using wired and wireless communications. Data are historized in the process historian while other sources are from relational systems or legacy systems. Smart sensors (edge), robotics, drones, humans, remote stations, blend and movement systems also generate data, and these are managed on the integrated industrial network and process network. The manufacturing operations management (MOM) and DSSs support the organization with processes conducted on a shift, daily and monthly basis and provide decision support for production, health and safety, environment and regulatory functions. In addition, the ERP supports the tactical and strategic business functions such as financial, human resources and sales and operations planning. The functionality of applications provided by traditional ERP and MOM technology providers are converging especially for the maintenance and reliability management, supply chain, material management and logistics systems.

The CPS-as-a-Service architecture includes the requirement of being service oriented architectures and decompose the functionality to services as described in the Industrial Internet Reference Architecture (IIRA) and the Reference Architecture Model Industry 4.0 (RAMI4.0) (Moghaddam *et al.*, 2017). The architecture includes data quality analysis as data points after filtering the data spikes, noise and out of range data.

The plant reference modeling is adopted in the CPS architecture to ensure the Manufacturing Master Data Management (MMDM) is enabled by contextualizing data from assets, resources, materials and other attributes like temperature, pressure, flow and other measure process variables into a hierarchal model. This reference model derived from ISA-88 plant is the reference hierarchy adopted to align various applications in plant, area, unit, asset and resource locations, as shown in Figure 3.

Figure 4 below illustrates the CPS-as-a-Service enterprise architecture described above resulting from this research as the reusable architecture to be reproduced across multinational business operating facilities. The modular and standardized cyber physical system (CPS) includes the main logical MOM and DSSs described above in addition to the mature applications, ERP, as well as process and industrial network. All these subsystems are connected as cloud based cyber physical systems forming a mesh of assets, people, processes and technology that support operating facilities in achieving their operations excellence objectives.

The multisite CPS-as-a-Service provides centralized functionalities that are provided as a service while maintaining the (plant-specific) functionalities, decentralized. The following are examples of the centralized CPS services (Pattanayak & Roy, 2015; Lee *et al.*, 2015).

(1) Integration services including the orchestration, enrichment and exchange of data.

(2) Policies & procedure including the business roles of identifying the data governance and authority as well as the priority of data handling.

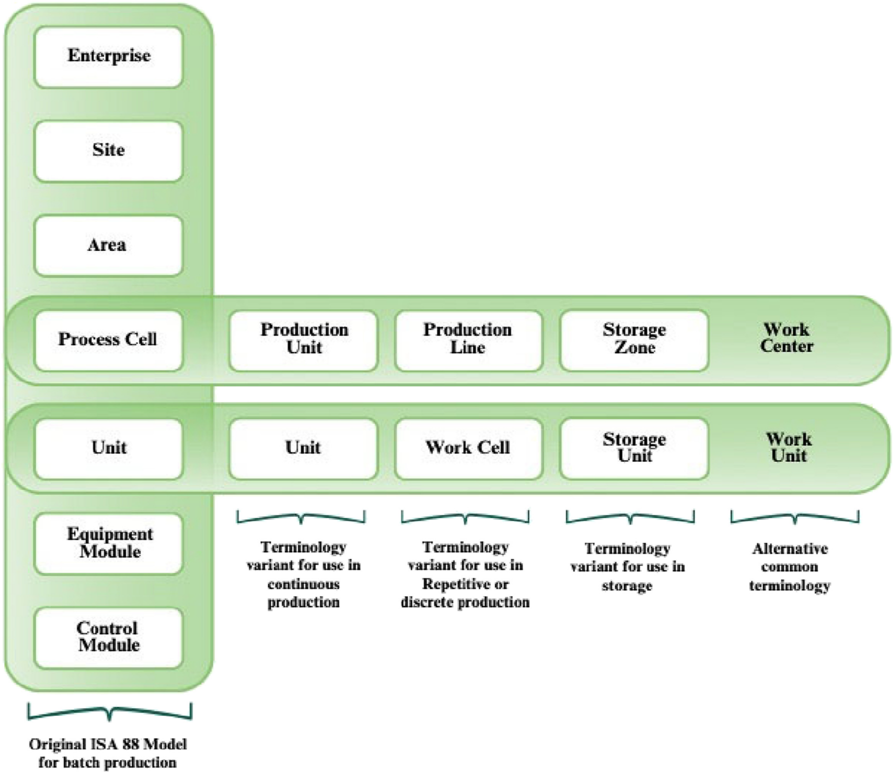
(3) Management of change including the impact of change of a data source for the connected users, processes and systems

(4) Business intelligence tools allowing for advanced analytics and self-service reports.

(5) Visualization including the different means of accessing the data such as web applications, digital twin, AR/VR and mobility.

(6) Security service adopted to manage the authentication, authorization and auditing of the system.

The CPS-as-a-Service system of systems expands beyond the multinational operating facilities to include the global ecosystem including suppliers and customers. In addition, it



Source(s): Gifford, (2011)

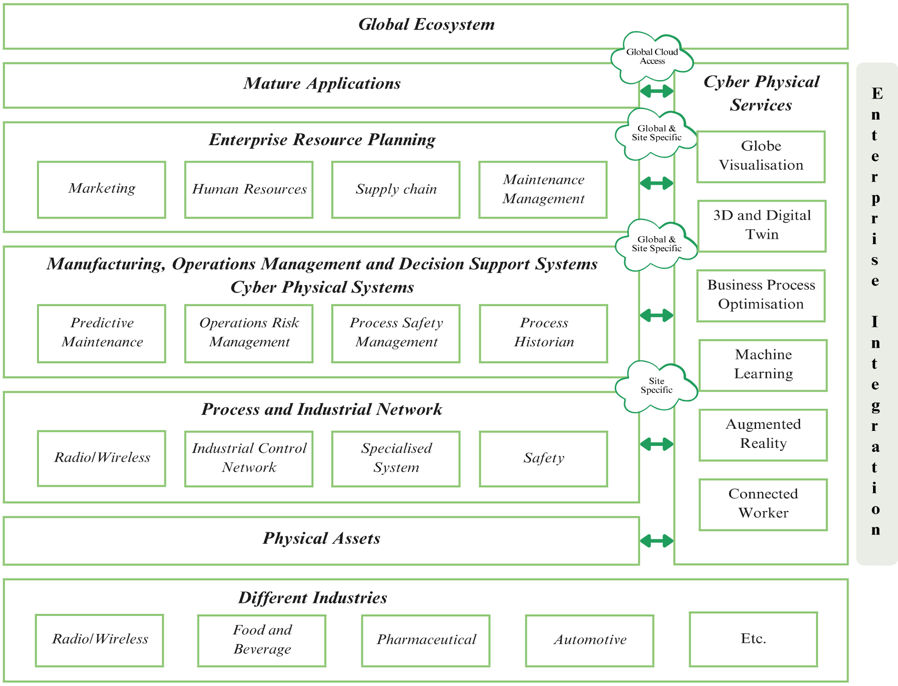
Figure 3.
Plant reference model

includes the remote access of original equipment manufacturers (OEM) fleet management cloud services and process licensor models to allow for remote diagnostics, PM and benchmarking.

4.3 CPS benefits defined

Manufacturers are spending significant amounts of money and effort during the CPS implementations. This gives managers the urge to argue that the manufacturing execution systems (MESs) are not needed and that the information available is good enough. These arguments are supported by the fact that these implementations are site-specific where MES/MOM projects overpromise and under deliver due to low utilization. It is also noticed that these systems require dedicated teams to keep them up and running, as the implementations are "high maintenance" and requires specific skill sets (Weyer *et al.*, 2015; Wang *et al.*, 2010).

The initial high initial investment, high maintenance and low utilization is compensated with a digital business system or CPS-as-a-Service that is built once and adopted across multisite and multinational manufacturers. In other words, taking the example mentioned earlier in the paper where an oil & gas major firm owns a refinery in the state of California and a refinery in west Texas. The traditional practices mandates building standalone CPS projects with a scope that requires the establishment of repeated infrastructure and applications for each project resulting in repeated investment for every new implementation



Source(s): Authors' own work

Figure 4.
Conceptual design of the CPS-as-a-Service enterprise architecture

see Table 2 below (García *et al.*, 2018; Bagajewicz & Chmielewski, 2010) illustrating the areas of investment for each investment.

(1) System of systems with Unified Enterprise Architecture

Manufacturers are focusing on the core business by strategically deploying standardized modular and reproducible CPS-as-a-Service thereby reducing the burden of stand-alone projects. Therefore, manufactures are able to use CPS to quickly to respond to dynamic and

	CPS project 1	CPS project 2
Hardware	√	√
Software license	√	√
Establishing the integration adapters with ERP	√	√
Establishing the integration adapters with legacy systems	√	√
Establishing the integration adapters and configuring the role-based dashboard	√	√
Establishing and configuring the integration middleware system for intra-CPS systems	√	√
Building major assets templates	√	√
Establish a network and data center to host the servers	√	√
Establish a support organization	√	√

Source(s): Authors' own work

Table 2.
CPS project scope

volatile markets. The efforts toward establishing CPS-as-a-Service and the major scope optimization for two manufacturers are summarized in Table 3 below.

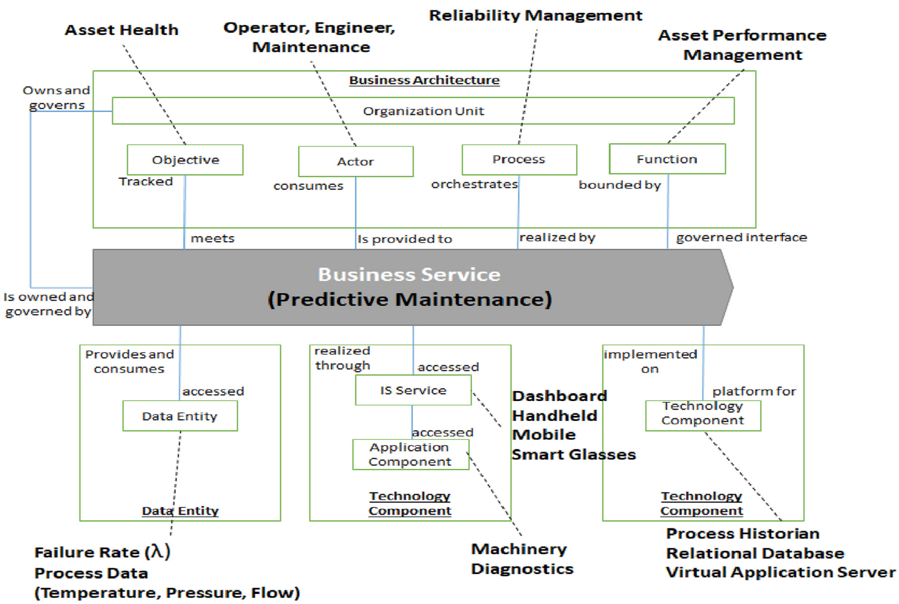
Using standardized SOA and cloud-based CPS-as-a-Service reduces the effort required to establish a new project by automating several steps required during the project phase (Patalas-Maliszewska & Losyk, 2020; Granlund & Jackson, 2013). Therefore, reusing the front end developed specifications requirements and possible solution ensures that the first project deployment is focused on evaluating and selecting most appropriate solution whereas the next can focus on identifying areas of improvements (Giret & Botti, 2006). The pre-engineered solutions help end users to document business requirements by providing best practices and lessons learned from previous projects and these templates and models including business processes, pain areas and automation gaps that allow the development of integrated solutions using a reference architecture, reference design and established methodology. The CPS-as-a-Service and system of systems concept allows for designing templates designed once and available as reusable for all. In case there is a need for a change or identified area of improvement, the change is achieved once at the template and applied for all similar functions (Hosseini & Helo, 2013). The manufacturer will also curtail the duplicate engineering efforts needed for establishing the integration between CPS applications and legacy existing applications. The consolidated efforts will result in a 50% effort reduction due to a consolidated effort on a single manufacturing middleware also known as a manufacturing service bus (Bagajewicz & Chmielewski, 2010).

Manufacturers focus on value realization including cost benefit and related investment calculations therefore developing net present value, return on investment and benefit calculations. Industry standards for benchmarking (e.g. SOLOMON) can be adopted to baseline and track the operational excellence KPIs. The change management program is adopted to focus on ownership, responsibility and scaling and developing reusable training programs, to increase the level of awareness of CPS end users. This approach ensures that knowledge is easily transferred, thereby eliminating the dependency on individuals by maintaining the knowledge within the CPS system. In addition to the significant reduction in project cost, system reuse ensures consistency in practices, business processes, training, and support. This allows for establishing a single team to scale up, scale out, support and maintain the CPS infrastructure. Figure 5 illustrates how a service such as PM is described in terms of objectives, roles/actors, process function, data, application services and technology platforms.

Item	CPS project 1	CPS project 2
Hardware	Infrastructure-as-a Service	
Software license	Software-as-a-Service and Platform-as-a-Service	
Establishing the integration adapters with ERP	Integration-as-a-Service	
Establishing the integration adapters with legacy systems	Integration-as-a-Service	
Establishing the integration adapters and configuring the role-based dashboard	CPS 1	
Establishing and configuring the integration middleware system for intra-CPS systems	CPS 1	
Building major assets templates	CPS 1	
Establish a network and data center to host the servers	Infrastructure-as-a-Service	
Establish a support organization	Leverage shared IT/OT system support teams	

Source(s): Authors' own work

Table 3.
CPS Optimization



Source(s): TOGAF, (2011)

Figure 5.
CPS service description

(2) Digital business systems – individual systems benefits

The value envisaged by deploying the different CPS systems differs across business operations, depending on the requirements and priorities. The following provides examples of the benefits of each system:

Mass balance and data reconciliation: undetected instrumentation bias cause errors and inaccurate data that leads to misinformed decisions. The redundancy and soft sensing function could detect and highlight the level of bias and shifting allowing the operator to detect the error earlier to initiate calibration maintenance notification or apply formula to correct the measurement after identifying the bias. This increases the accuracy of the data, helps in achieving mass balance and avoids giveaways. It is expected that system implementation will result in improvement of financial performance with an estimated NPV increase of (~$300,000 per unit) (Bagajewicz & Chmielewski, 2010).

PM and fault identification: faults and failure within process plant contribute significantly to the profitability and performance indicators weather the fault is related to assets or process unit. The faults could be performance deterioration (e.g. heat transfer coefficient) or underperforming from normal design-based conditions. The system helps in detecting faults using qualitative methods (e.g. faults trees, rule-based, failure propagation, knowledge based, etc.) or using machine learning to predict failure as well before they occur (e.g. neural networks, multivariate statistical method, deep learning, etc.). The sooner the problem is detected, the more beneficial it is for the operating facilities. It is expected that the implementation of fault detection would result in a net value of ~$25,000/asset (Bagajewicz & Chmielewski, 2010). Asset performance management (APM): operating facilities focus on maintenance activities and follow different types of strategies (e.g. run-to-fail, preventive (time-based), etc.). The APM focuses on the reliability and integrity which are proactive in nature and helps in preventing the problem from happening before they occur. It is expected that the implementation of APM would result in a significant improvement of each predicted and prevented failure (e.g. ~$1000/asset/day for each sever error (i.e. corrosion, wear, fatigue, overload, or misalignment). It is also expected to avoid up to ~$1,687,131 that resulted from spare parts optimization (Bagajewicz & Chmielewski, 2010).

(3) Quantifying benefits: Sustainable digital business system

The first implementation includes the establishment of the infrastructure as well as the integration between the MOM/MES and ERP. Thus, the resource utilization is high as the team of experts needed for integration and implementations spend a significant amount of time to prepare the infrastructure for future expansion. The typical considerations for the increase complexity are the technology maturity or novelty of the technology being introduced into the organization. This also includes the change in management requirements and data complexity, including cross-functional overlap that maybe required and number of interfacing systems. Table 4 describes variables and assumptions that are adopted as input into the model to calculate the CPS implementation cost are as follows:

Table 5 details the resource utilization and initial manpower required for the MOM and integration with the ERP and automation systems. The model multiplies the man-hours by

Table 4.
CPS baseline variables

Variable	Description
System complexity	In the base case, historian is 2, and a reliability system is ranked as 5
System reuse benefit	This is the system reuse benefit as determined for re-using platforms, integration services and calculation templates. The system reuse for a production planning system is <60% whereas the reuse for a KPI or dashboards is >60%
Manpower cost and hours	The average consultant cost is assumed as 100 dollar per hour (USD/h) with eight hours per working day, 21 days per month. The linear planning engineer or the system administrator have varying rates based on years of experience and unique skill
Project duration	The first CPS implementation had project duration was more than 2 years as the project was conducted at a Grassroots refinery. The remaining CPS implementation duration and cost was reduced due system reuse
Server cost	The servers hosted in the data center require a hosting and support fee and the cost for a CPS depends on the system technical architecture including web, application, database, and integration server required. The server cost is assumed as 1000 dollar per month (USD/month) for 120 servers
Licence cost	Commercial of the shelf software require license costs for permission to use the software configured based on number of sites, assets, or users
Support cost	This includes licensor maintenance fees and manpower support costs
Transportation cost and CO_2 impact	Travel is assumed as a round trip work commute of 40 km, additional project weekly travel of 200 km and 75 of staff are require having a weekly flight home commute of 1600 km. The emission for flights is assumed as 200g CO_2 per person/km and for vehicles 150 g CO_2 per person/km
Energy consumption	The average computer energy consumption is assumed as 100 W/h, energy consumption is estimated for 120 computers, and servers are adopted

Source(s): Authors' own work

Table 5.
Resource utilization CPS first implementation

Project phase	Idea (%)	Feasibility (%)	Design (%)	Build (%)	Deploy (%)	Maintain (%)
Primary Resources	30	80	80	100	100	30
Secondary Resources	10	60	80	100	100	20

Source(s): Authors' own work

the percentage of utilization and considers the resource variation for each subsequent CPS deployment. CPS reuse benefit is highest in the build phase compared to the idea, feasibility and maintain phases. This is referred to as the resource utilization described in the calculation methodology.

The benefits analysis of the centralized design is detailed with multiple sustainability quantifiable. It must first be noted that the systems, representing each functional area, are independent but integrated from a data perspective. Figure 6 below illustrates the 14 systems together with the key enabler (mobility) and the collective or integration system is quantified in terms of the six stages of implementation.

From Figure 6 it is very apparent that the "build" phase requires the most significant time investment, across all 14 systems followed by the design phase and then the deploy phase. The most intense build times are for the PM, asset performance, global visualization and integration systems. Planning, scheduling and mass balance are the systems with the least effort. The CPS implementation is not only around the time to implement but also around business value, including costs, environmental and people impacts.

Figure 7 below illustrates the benefits of CPS reuse compared to the standalone implementation, this case illustrates the example where 3 manufacturing sites are being enabled by reusing the initial CPS engineering and build effort are reduced in subsequent implementations. The largest benefit of reusing the CPS is seen for the less complex systems such as the laboratory information management system, environmental management system and mass and energy balance systems. The more complex site-specific integration and integrated visualization as well as the digital twins have less pre-engineering and reuse benefits. The mobility system reuse is 53% and is seen as the highest reuse benefits due to the reduction in design and build effort.

Figure 8 visualizes data from the same case study example where 3 manufacturing sites are enabled and illustrates the project phase specific benefits of the standalone vs shared CPS

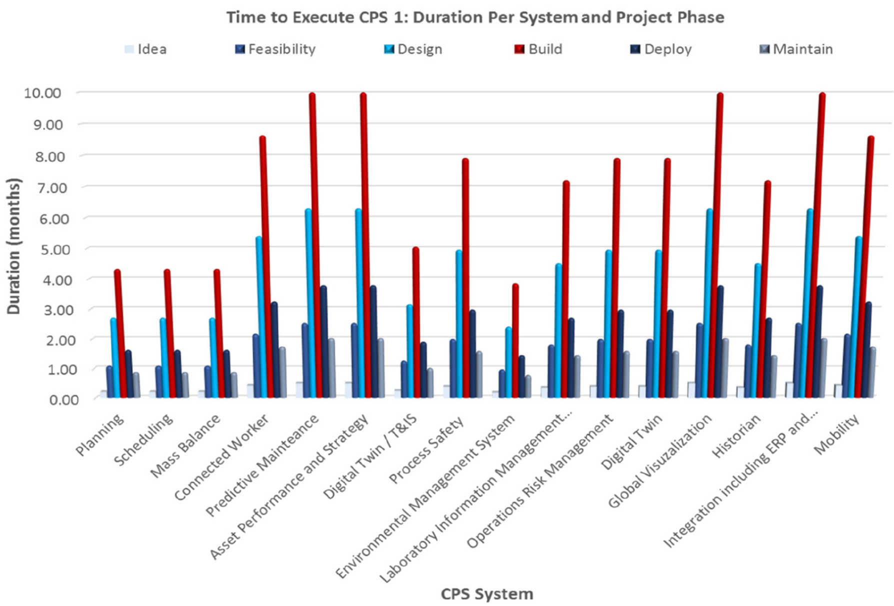


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Figure 6. CPS 1 systems duration per project phase

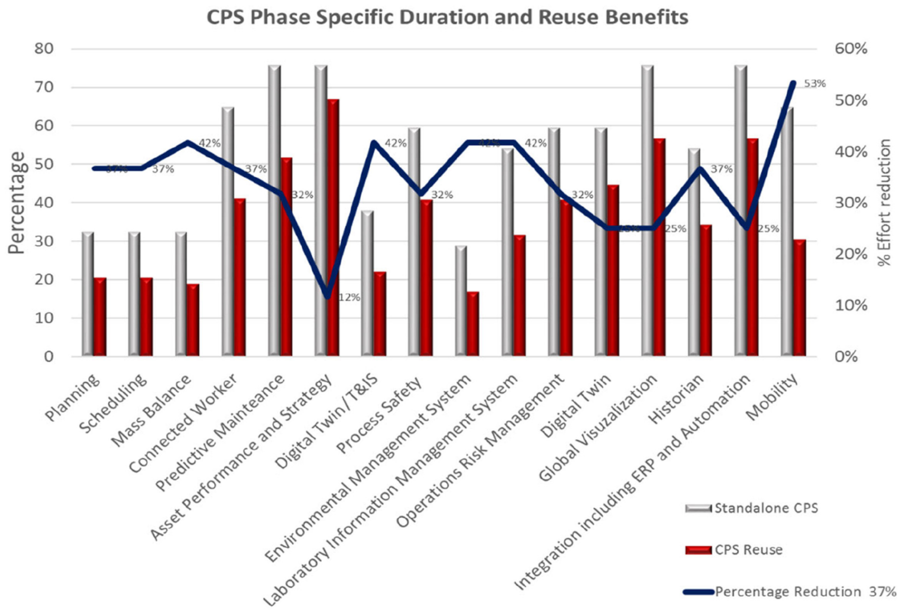


Figure 7.
Standalone CPS vs CPS reuse

Source(s): Authors' own work

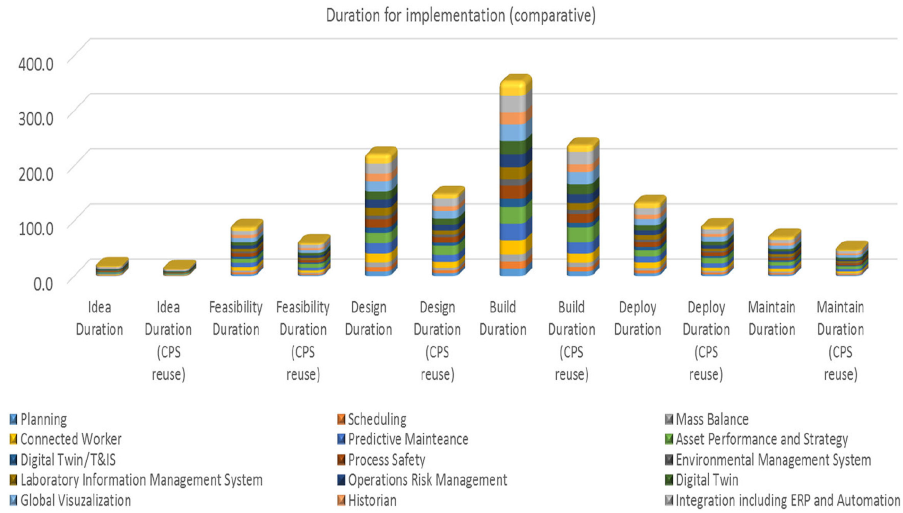


Figure 8.
CPS implementation: phases and time to develop

Source(s): Authors' own work

implementation. The stacked chart illustrates the duration of implementing standalones CPS systems and the duration for CPS reuse per system and project phase. Chart is multi-dimensional, including the time for each of the 14 functional areas. The largest implementation time is for the reliability systems as well integration and visualization systems.

The second CPS-as-a-Service implementations benefit from the previous implementations as a result of the reduction in the project execution engineering hours as the software installation, plant reference model, templates, forms, integration and configuration, can be re-adopted for new sites. The CPS deployments also benefits from cost, schedule and quality as the lessons learned from previous implementation are embedded in each recurring implementation. In addition, the best practices and innovation starts to gain momentum resulting in organizational benefits of increased IT and engineering skill and capacity (Trevisan & Bordignon, 2020; Petnga & Austin, 2016; Ji, Yu, Fan, & Fu, 2016).

(4) OPEX standalone vs CPS-as-a-Service

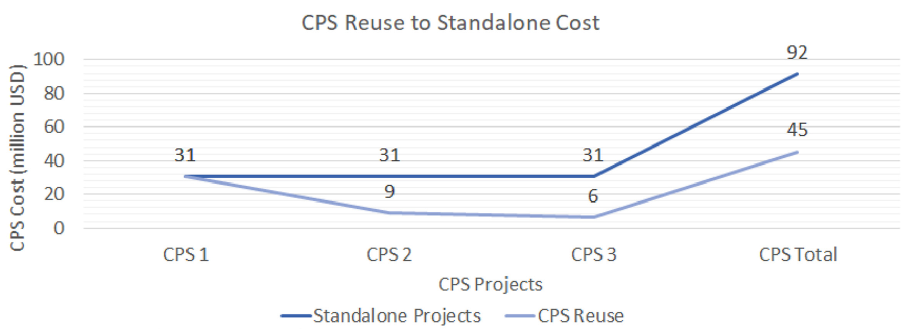
The methodology compares executing three (Wu & Shang, 2020) standalone CPS projects as opposed to one CPS-as-a-Service with 2 expansions (total of 3 CPS implementations). Figure 9 provides a comparison of the CAPEX of standalone CPS implementation as compared to CPS-as-a-Service reproducible one with a reduction of more the 50% of the total CAPEX, in favor of the CPS-as-a-Service.

The OPEX forecast shown from the calculations has a decreasing trend with an increase in reuse for CPS projects and solution deployments resulting in increasing total cost of ownership (TCO) benefits with each repeated CPS deployment.

The benefits forecast is the result of reduced support costs due to manpower, licenses, and maintenance as well as server hosting costs (TOGAF, 2011; Bagajewicz & Chmielewski, 2010). The overall benefit is a reduction of more than 50% of the OPEX costs as described in Figure 9 below. This reduction assumes and experience-based reduction of 30% in license, infrastructure hosting and manpower costs due to centralization and common use for all CPS implementations. The design phase is among the key accelerators and financial savings drivers. The organization assumptions adopted included that the support is centrally located with minimal staff located at each site, ensuring that central or corporate information and operations technology are providing constant support to the site CPS.

(5) Power consumption and CO_2 reduction with reusability

The typical emission per person is 20 tons CO_2 per annum (AEF, 2020; UK Power, 2020). Based on the number of consultants participating in the project and mileage traveled, CPS 1 is assumed to have an emission equivalent to 755-person. This is multiplied by 3 in case of standalone CPS implementation. With CPS-as-a-Service, CPS 3 has 152-person equivalent emissions person annum. The system reuse reduces the environmental impact by at least 5 times, which is a major contribution to the effort of reducing CO_2 emissions.



Source(s): Authors' own work

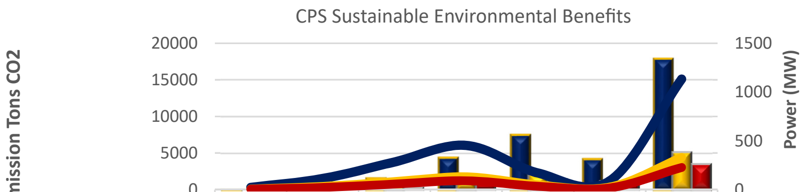
Figure 9.
CPS OPEX benefits

The average household power consumption is 1,000 kW per month. The first CPS is equivalent to 111 times equivalent annual household power consumption. If standalone implementation is pursued, then the total will be 333 times equivalent annual household power consumption. Due to the expansion of the existing infrastructure, CPS reuse (CPS-as-a-Services) resulted in benefits quantified as an impact reduction 111 times equivalent to the annual household power consumption to 22 times the average annual household consumption for the third CPS project (UK Power, 2020).

The power and emissions calculations provide interesting insights of the sustainability impact of a centralized model. The energy and CO_2 footprint of the subsequent implementations reduce significantly, see Figure 10 above.

(6) CPS benefit tracking net present value and simple payback

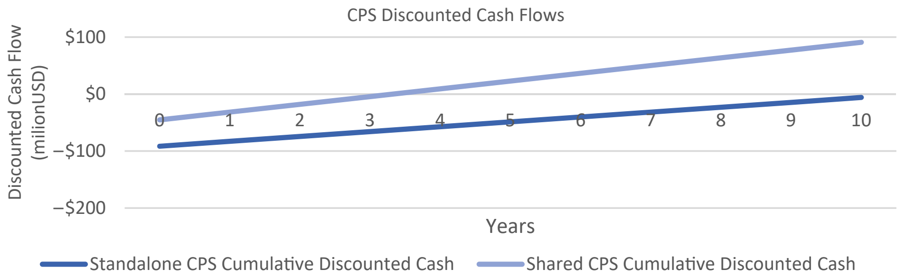
The figure below (Figure 11) illustrates the discounted cash flow for the standalone compared to the shared CPS implementation; this has been calculated based cumulative CAPEX, OPEX and benefits for CPS 1, CPS 2 and CPS 3. The tax rate assumed is 50% and the discounted cashflow rate is 10%. The cash inflow or CPS benefits are based on forecasting methodology in section 4.1 and includes the cumulative benefits of reduced giveaways, hydrocarbon losses due to flaring, avoided failures due to asset performance management, PM and managed abnormal situations within the manufacturing facility.



	Idea	Feasibility	Design	Build	Deploy	Maintain	Total
CPS 1 Power	2	2	121	331	563	316	1336
CPS 2 Power	0.5	0.4	35	95	164	92	387
CPS 3 Power	0.3	0.2	24	65	113	63	266
CPS 1 Emmissions	302	1511	3776	6042	2266	1208	15105
CPS 2 Emmissions	88	441	1101	1762	661	352	4406
CPS 3 Emmissions	61	303	758	1213	455	243	3032

Source(s): Authors' own work

Figure 10.
CPS CO_2 and power consumption reduction benefits

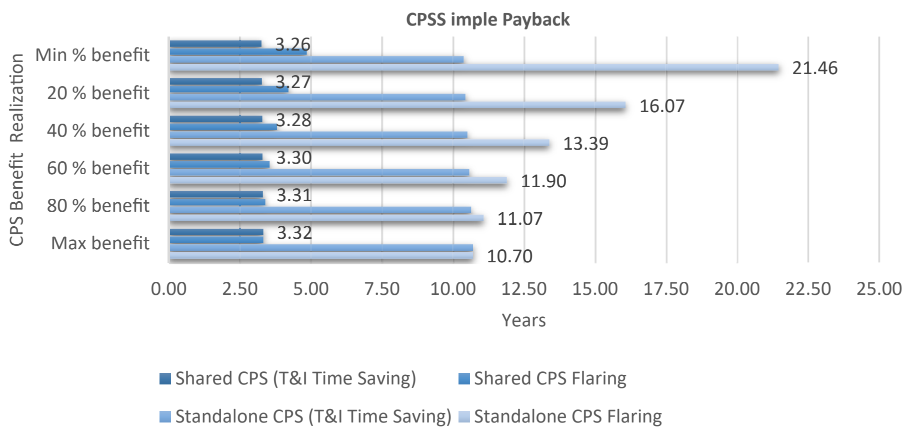


Source(s): Authors' own work

Figure 11.
CPS discount cash flow standalone compared to CPS-as-a-Service (Shared)

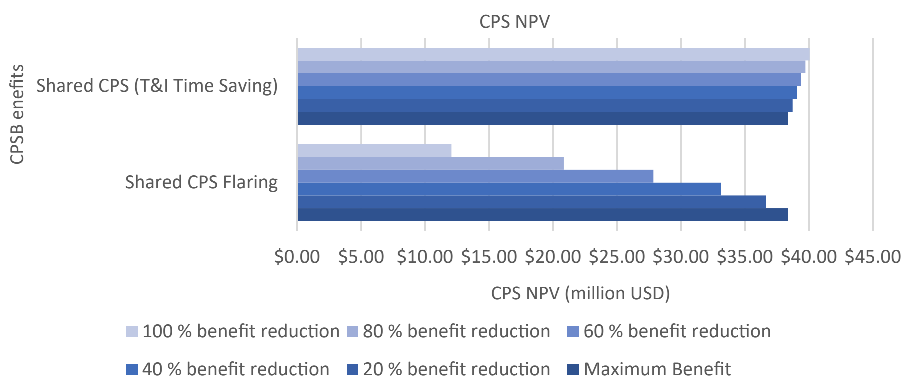
Figure 12 illustrates the manpower time efficiency improvements due to increasing the turnaround and inspection T&I engineer and maintenance planner productivity as result of the CPS T&I system and digital twin utilization to plan maintenance crew and maintenance resources. The T&I CPS benefit is compared with the benefit of preventing hydrocarbon losses due to the operations and engineering manpower effective use of a flare management system. This approach to effective method to quantify and track the CPS business case and benefits to ensure the forecast CPS net present value and the simple payback are achieved. The figure also compares the standalone, shared CPS implementation, and cost benefit scenarios as benefits range from maximum to minimum benefits realization. The figure below illustrates the results for the standalone CPS with maximum benefits realization result in a simple payback of 10.7 years, whereas a shared CPS with maximum benefits realization is forecast to achieve benefits in 3.26 years.

Figure 13 illustrates CPS-as-a-Service maximum benefits realization and sensitivity are related to profitability and product and in this case hydrocarbon loss prevention. The T&I benefits is focused on human efficiency and is related to time-savings therefore



Source(s): Authors' own work

Figure 12. CPS simple payback standalone and shared based on benefits realization



Source(s): Authors' own work

Figure 13. CPS-as-a-Service (shared CPS) benefits realization

manufacturers. This contract is shown to illustrate that manufacturing typically focuses efforts on the direct solution benefits rather than the time saving related or human efficiency benefits. Manufacturers should consider profitability and efficiency in the benefit tracking. The CPS also enables the unquantifiable as well as risk mitigation as well as health and safety benefits ensuring that operations, maintenance and engineering staff received valuable contextualized information to take informed decisions to prevent safety and environmental events, process upsets and process inefficiencies.

5. Discussion

The key objective of this study is to provide sustainability insights of centralized systems (shopfloor to top floor) for a multinational enterprise. The research team provides insights into the centralized design of systems followed by a sustainability justification. The results clearly indicate value beyond the centralization and standardization of systems. The time to deliver is accelerated; this is based on an upfront design and centralization of functionality. Further to these the subsequent design phases are almost eliminated. The resultant reuse of functionality, centrally and on subsequent sites results in significant financial impacts, both for OPEX and CAPEX. The energy and CO_2 impact is also quantified and proven to show tools to justify the centralization. The business benefits from the standardized functionality and the reduced services cost. A key value added is the integration benefits to staff, where multi-site visibility is now a possibility and best practices are now available.

6. Conclusion

The research highlights the value of multinational multiple site CPS-as-a-Service to reap the benefits of the significant opportunities of digital tools for business optimization. The fundamental justification for implementation and delivery of sustainable business systems is demonstrated as environmental (CO_2), energy and economic impacts. The quantification is based on specific sustainability calculations that illustrate the value of standardization and redeployment of pre-engineered solutions across other sites. The results highlight the value of reproducibility and field proven technology helping to create in house expertise and knowledge that help sustain the technology. The research provided details related to reduction in giveaways, predictive failures in addition to provide actual emissions, energy consumption reduction from the system reuse. These benefits clearly illustrate the value of standardization, replication and cloud-based digital enablement for multinational businesses. The research documents one of the cutting-edge sustainability technologies that Saudi Aramco is leading and how it helps in creating a base for knowledge and skills transfer and retention. The sustainable digital business system helps in reducing the CAPEX/OPEX of CPS projects by more than 50% and the system reuse results in reduced resource usage including travel and manpower resulting in reduced emissions and energy consumption significantly.

7. Limitations and future research

This research is focused on the CPS as system of systems, proposes reference architecture and provides a methodology to measure and justify multisite CPS deployments. The scaling and extension of the reference solution to other manufacturing facilities was described using a case study. The research has also described the direct benefits of the CPS in addition to standardizing business processes using shared resources and processes. The research limitations to be considered in future research include the extension of the current CPS model and a model to quantify and track environmental, safety, health and profitability benefits resultant of the CPS as direct benefits and realization tracking.

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