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ASPEKTY NÁVRHU A IMPLEMENTACE AAS V PRŮMYSLOVÉ AUTOMATIZACI

TOWARDS DESIGN AND IMPLEMENTATION OF AAS IN THE INDUSTRIAL AUTOMATION

HABILITAČNÍ PRÁCE
HABILITATION THESIS

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ABSTRAKT

S příchodem konceptu Průmysl 4.0 se zrychlila digitalizace průmyslových výrobních podniků a vývoj technologií, které umožňovali transformaci výroby k tzv. chytré továrně. Jednou ze základních komponentů této moderní továrny je I4.0 komponenta skládající se z prostředku a jeho virtuální obálky (AAS). Právě virtuální obálka tvoří komplexní digitální dvojče prostředku a umožňuje interakci s okolím. Standard AAS se postupně tvoří, přičemž již existují části umožňující návrh a implementaci tzv. pasivní části AAS. Původní myšlenka se pomocí teorie transformuje na semi-formální popis, který už je možné implementovat v různých aplikací. S AAS a jeho nasazením se pojí další technologie, jako je např. OPC UA, REST API, TSN, které zajišťují komunikaci a samotnou implementaci. Tento dokument diskutuje různé aspekty, které souvisí s rolí, návrhem a implementací AAS v různých aplikacích.

KLÍČOVÁ SLOVA

AAS, Průmysl 4.0, OPC UA, TSN, IoT, REST API, testbed

ABSTRACT

With the rise of the Industry 4.0 concept, the digitization of industrial production enterprises and the development of technologies that enabled the transformation of production into a so-called smart factory accelerated. One of the core components of this modern factory is the I4.0 component consisting of a resource and its virtual envelope (AAS). The the virtual envelope forms the complex digital twin of the resource and enables interaction with the environment. The AAS standard is gradually being formed, while there are already parts enabling the design and implementation of the so-called passive part of AAS. Using the theory, the original idea is transformed into a semi-formal description, which can already be implemented in various applications. Other technologies such as OPC UA, REST API, TSN are connected with AAS and its deployment, which ensure communication and the implementation itself. This paper discusses various aspects that are related to the role, design and implementation of AAS in various applications.

KEYWORDS

AAS, Industry 4.0, OPC UA, TSN, IoT, REST API, testbed

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PROHLÁŠENÍ

Prohlašuji, že svou habilitační práci na téma „Aspekty návrhu a implementace AAS v průmyslové automatizaci“ jsem vypracoval samostatně a s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce.

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PŘEDMLUVA

Překládaná habilitační práce je ucelený soubor vybraných vědeckých publikací, na kterých jsem se podílel, týkajících se různých aspektů návrhu a implementace virtuální obálky (AAS) prostředků průmyslové automatizace. Cílem tohoto díla je shrnout mé aktivity na Ústavu automatizace a měřicí techniky FEKT VUT v Brně v letech 2017 až 2023. Dalšími přínosy předložené práce je popis současného stavu v dané oblasti z hlediska standardizace, částečné obsvětlení vývoje AAS v letech 2011 až 2023, rešerše výzkumné aktivity v dané oblasti a pojmenování aktuálních výzev.

Uvedené výsledky a publikace vznikly převážně na půdě Vysokého učení technického v Brně, a to v prostorách Fakulty elektrotechniky a komunikačních technologií. Velká část práce byla také uskutečněna díky spolupráci s firmami a jinými zahraničními pracovišti, jako je Compas, spol. s r.o. (Česká republika), Timap GmbH (Německo), Otto von Guericke University Magdeburg (Německo), Institut für Automation und Kommunikation (Německo) a Vysoká škola polytechnická Jihlava (Česká republika). Část výsledků také vychází ze studentských závěrečných prací VUT, které jsem vedl nebo mentoroval.

Poděkování patří všem spolupracovníkům Ústavu automatizace a měřicí techniky, kteří vytvářeli vhodné prostředí pro vědeckou a pedagogickou práci. Díky jejich radám a podnětům jsem měl možnost se také zapojit do výzkumných projektů, což mi umožnilo získat širší pohled na aktuální stav rozvíjející se oblasti Průmysl 4.0. Poděkování si také zaslouží kolegové z Ústav teoretické a experimentální elektrotechniky. Díky účasti na jednáních pracovní skupiny *OPC UA for AAS* pod záštitou konsorcia OPC Foundation se mi také podařilo získat pravý pohled na některé aspekty týkající se zkAAS.

Převážná část výsledků mohla vzniknout díky aktivní účasti v národních a mezinárodních vědecko-výzkumných projektech. Činnost na těchto projektech dala nejen základ publikacím, které jsou uvedeny v druhé části předložené práce, ale také mi umožnila získat zasvěcený pohled na aktuální stav v oblasti ohledně mnoha aspektů rozvíjející se technologie - virtuální obálky prostředků průmyslové automatizace. Mezi relevantní projekty řadím:

- DIH DIGIMAT - výzkum a rešerše v oblasti digitalizace podniku (2016)
- RACAS, TF04000074 - Digital Representation of Assets with Configurable AAS for CPP-Systems (2016 až 2018),
- SECREDAS, H2020-EU.2.1.1.7 - Product Security for Cross Domain Reliable Dependable Automated Systems (2018 až 2021)
- MPO TRIO FV40247 - Kooperativní robotické platformy pro automobilové a průmyslové aplikace (2019 až 2021)

OBSAH

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ÚVOD

Koncept Průmysl 4.0 je jedním z hlavních témat v oblasti průmyslové automatizace a řízení průmyslových procesů. Tento koncept je vnímán jako fenomén, reforma, revoluce, či jako síla pro zavádění moderních informačních technologií do průmyslové výroby. Setkáváme se s pojmy jako digitalizace, chytrá továrna, virtuální dvojče, kyber-fyzikální systém, časově kritické (TSN) komunikace a virtuální obálku prostředku (AAS), které měly zpočátku nejasnou definici a nepředstavitelnou implementaci, avšak v poslední době se tyto pojmy stávají skutečnější.

Vznik konceptu Průmyslu 4.0 z hlediska technologického nelze přesně určit, avšak z hlediska publikačního se začátek rozmachu iniciativy datuje na rok 2011. V tomto roce začali tři evropské země spolupracovat na národní úrovni na novém konceptu, což vyústilo v iniciativy: aliance Industrie du Futur ve Francii, Platform Industrie 4.0 v Německu a Piano Industria 4.0 v Itálii [40]. Tato společná iniciativa vedla k dalším inovativním myšlenkám a rozšíření do ostatních oblastí, jako je standardizace, průmyslové komunikace, informatika, funkční bezpečnost, kyber-bezpečnost, ekonomie, marketing, výroba elektrické energie a sociální oblast. Kromě Evropy tento koncept našel ohlas i v USA, Číně a Japonsku. [1]

V současné době se ve výrobních podnicích implementují technologie podporující digitalizaci většinou ve formě získávání dat z výroby a jejich přenos do cloudového prostředí s vidinou zpracování pomocí výkonné výpočetní techniky. Zpracování pomocí metod strojového učení přináší určitý vhled do výroby a umožňuje kvantifikovat potřebné změny výrobních procesů vedoucí k jeho zefektivnění či optimalizaci vůči zvolenému kritériu.

V případě požadavku na strojové zpracování dat i z řídicích procesů je avšak nutné pro interpretaci informací použít určitou úroveň formálních jazyků. Tato skutečnost platí nejen pro data, ale i strukturu a vlastnosti systémů, ze kterých jsou data zpracovávána. Potom bude možné strojově konfigurovat výrobní proces i z hlediska řízení přímo za jeho běhu na základě aktuálních dat a provádět multi-kriteriální rozhodnutí. Příkladem může být požadavek na ubrání materiálu a požadavek na vytvoření kruhového otvoru v materiálu vedoucí na jednu tutéž výrobní operaci - vrtání. [41]

Spekuluje se také, že decentralizované řízení pomocí AAS se bude uplatňovat i uvnitř podniku, čemuž je společně s bezpečností, integracemi a komunikací věnována velká část práce.

1 STAV SOUČASNÉHO POZNÁNÍ

Následující kapitola se komplexně věnuje technologii AAS a dalším relevantním technologiím uplatnitelných pro řízení průmyslových procesů a jeho částí. Tato kapitola obsahuje jak teoretické poznatky ustanovené standardy a autoritami v daném oboru, tak vědecké články přinášející další pohledy a inovace.

Mezi nejvýznamnější konsorcia v oblasti Průmysl 4.0 patří ZVEI, VDI/VDE, IDTA (Industrial Digital Twin Association) a NAMUR ve spolupráci s dalšími projekty, jako je např. GMA 7.20 a BaSys 4.2. Tyto skupiny jsou aktivní obzvláště z hlediska tvorby standardů, definic pojmů, určování směrů a formování myšlenek. ZVEI publikuje své postoje, myšlenky, výzvy a ustálené definice na Platform Industrie 4.0 formou tzv. *white-paper*. Tyto texty jsou brány veřejností a mnohými firmami jako udávaný směr a mnohdy staví na již existujících standardech.

Technologie a myšlenky zde uvedené jsou platné v oblasti průmyslové výroby. Tím se rozumí hlavně diskrétní průmyslová výroba (např. strojírenství). Jelikož se spojité průmyslové výrobě (procesní) používají podobné komponenty, technologie a architektury, jsou uvedené myšlenky aplikovatelné i na tento typ průmyslové výroby. O zavedení konceptu Průmysl 4.0 do spojité průmyslové výroby se stará organizace NAMUR ve spolupráci s ZVEI [31]. Díky úsilí, které se v komerční i akademické praxi ohledně Průmysl 4.0 zvedlo, se tento koncept či jeho části aplikují i do jiných oblastech jako je chytré zemědělství nebo energetika [26].

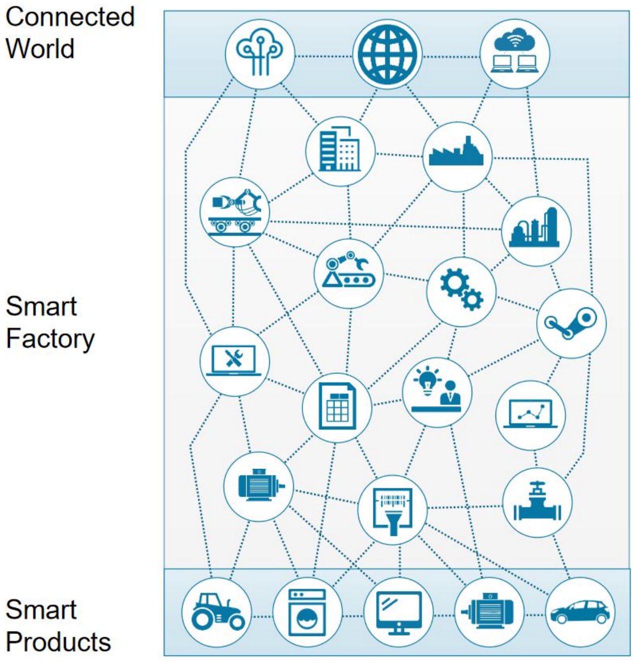
1.1 Průmysl 4.0

Termín Průmysl 4.0 byl oficiálně definován v DIN SPEC 16593-1, přičemž základní vize se objevily na veletrhu Hannover Fair v Německu v roce 2011. Jedná se o koncept zasahující hlavně do oblastí průmyslové výroby, ekonomiky a společnosti. Mezi hlavní cíle patří integrace moderních metod a technologií do průmyslové výroby podle jednotného konceptu, a to propojením fyzického a kybernetického světa pomocí tzv. kyberneticko-fyzických systémů. Přitom staví na šesti principech, jež jsou nositeli základních myšlenek:

- interoperabilita - propojení zařízení, technologií, lidí a jiných entit,
- virtualizace - modelování fyzické reality a vlastností (schopností) za účelem simulace a predikce,
- decentralizace - částečné přenesení rozhodování do jednotek se zvýšením autonomie entity na nižší úrovni,
- reálný čas - všechny procesy a komunikace musí probíhat v reálném čase pro dosažení výsledku do daného okamžiku,

- orientace na služby - způsob komunikace stylem nabídka/poptávka, což přináší schopnost dynamického řešení problémových situací,
- modularita - zapouzdření funkcionalit vedoucí k systémovému přístupu.

Směr Průmysl 4.0 vznikl aplikací konceptu internetu věcí (angl. *Internet of Things*) do průmyslového prostředí. Myšlenka vytvoření systému zařízení, které disponují společným komunikačním rozhraním, nabízejí služby a komunikují spolu na stejné úrovni, se line celým konceptem Průmysl 4.0. Tato geneze zapříčinila názor na změnu tradiční pyramidy systému řízení výrobního podniku na zploštěnou architekturu navzájem komunikujících prvků, které jsou napojeny na chytré produkty směrem dolů a do globálního prostoru směrem nahoru (viz obr. 1.1) tvořící tzv. chytrou továrnu (angl. *Smart Factory*).

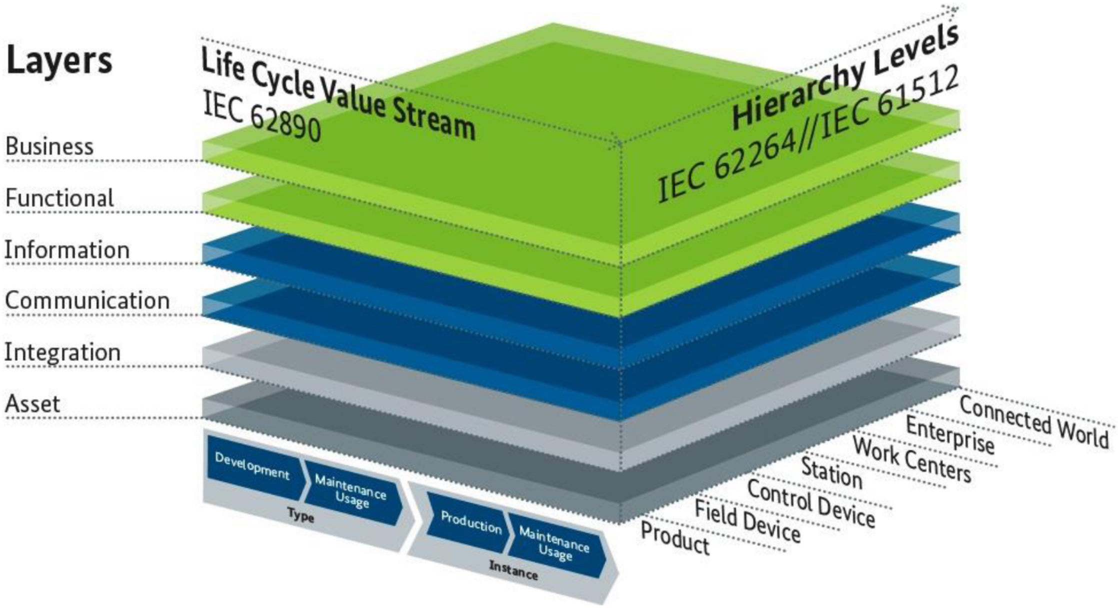


Obr. 1.1: Architektura pojetí chytré továrny [38]

Vizí Průmyslu 4.0 je provázaný systém skládající se z I4.0 komponentů (viz kap. 1.1.2), které spolu interagují pomocí I4.0 komunikace, která může být zajištěna technologiemi OPC UA (viz kap. 1.1.4), TSN (viz kap. 1.1.5), aj. Ústřední architekturou takovéhoto systému je uznávaný model RAMI 4.0 (viz kap. 1.1.1). Výrobní systém dle konceptu Průmysl 4.0 generuje obrovské množství heterogenních dat, přičemž snahou je sdílet anonymizované informace o produktu a statistikách procesu (např. data o vlastnostech výrobku nebo celková spotřeba energie), která mohou být využita i jinými subjekty. Tomuto aspektu se věnuji iniciativa Manufacturing-X (viz kap. 1.1.3), jenž vychází z iniciativy Průmysl 4.0.

1.1.1 RAMI model

Referenční architektura Průmyslu 4.0 (RAMI 4.0) je výsledkem požadavku na společnou standardizovanou strukturu technologií Internetu věcí v průmyslové oblasti. Jedná se o tří-dimenzionální model (vic obr. 1.2), jehož osy se sestávají z kategorií daných příslušnými standardy. Tento model zajišťuje kategorizaci technologií a společné názvosloví pro určování jejich mezí. RAMI kombinuje všechny prvky informačních komponentů do vrstev s životním cyklem prostředku. [38]

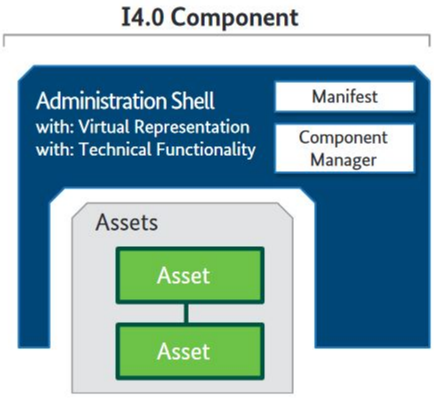


Obr. 1.2: RAMI model [38]

1.1.2 I4.0 komponenta

Standard IEC 62832 CD2 Part 1 definuje strukturu komponent v digitální továrně jako tzv. třída objektu, čímž částečně navazuje na filosofii datových modelů z oblasti objektově orientovaného programování (OOP). Tato třída se skládá z hlavičky (angl. *header*) a těla (angl. *body*). Část *header* slouží pro jednoznačnou identifikaci v rámci továrny. V části *body* lze definovat jednotlivé datové elementy, třídy objektů, aj. Datové elementy obsahují dle standardu IEC 61360 vlastnosti pro identifikaci (přezdívka, název, kód, definice, poznámka) a pro hodnotu (list, datový typ, formát, jednotka). Standard IEC 62832 umožňuje modelovat objekty v systému výroby, strukturální vztahy, vlastnosti a jiné technické aspekty. I4.0 komponenta se skládá z AAS (virtuální obálky objektu) a zastřešovaného objektu nebo objektů (viz obrázek 1.3). [37]

V případě propojení více I4.0 komponent se takovéto uskupení nazývá I4.0 systém (angl. *I4.0 infrastructure*). Tento systém je ohraničen rozhraními jednotlivých komponent. I4.0 systém může být zastřešen AAS rozhraním, které se stará o správu a navenek vystupuje jako jedna komponenta.



Obr. 1.3: Model I4.0 komponenty [37]

1.1.3 Manufacturing-X

V roce 2021 vznikla iniciativa Gaia-X pro sdílení dat za účelem tvorby datového prostoru vhodného pro vývoj a testování inovativních technologií. Gaia-X má být otevřená platforma z mnoha odvětví spojující svět komerční, akademický a i politický. Tento prostor má vést k vytvoření standardu pro transparentní, spravovatelnou, interakční technologii, která plánované sdílení dat umožní. Manufacturing-X je iniciativou vycházející z Gaia-X zaměřující se na oblast digitalizace dodavatelského řetězce a transformaci firem k udržitelným a resilientním podnikům. [13]

1.1.4 OPC UA

OPC UA je dle [33] platformově nezávislá architektura založená na konceptu služeb, která integruje komunikačního rozhraní OPC. Jedná se standardizovanou komunikaci (standard IEC 62541) obsahující informační model a další funkce, jako je:

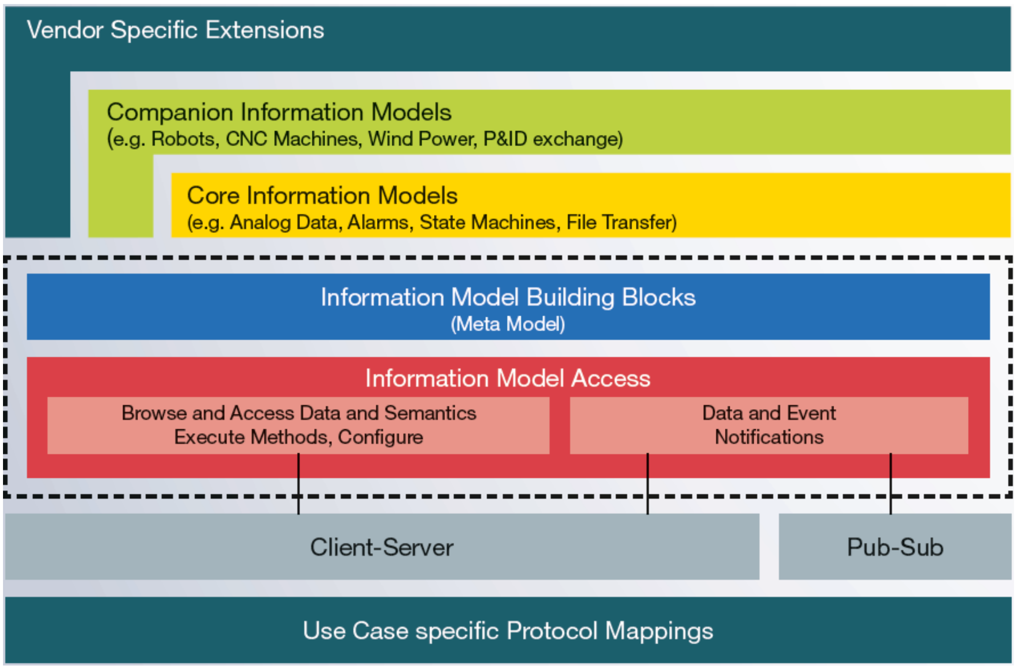
- prohledávání - hledání dostupných OPC serverů,
- adresní prostor - data jsou strukturalizována hierarchicky, přičemž každá informace je uložena ve svém prvku (angl. *node*),
- řízení přístupu - povolení čtení a zápis dat na základě povolení,
- subskripce - u zapsaných prvků probíhá komunikace pouze při změně dat,
- události - avízo o událostech dle nastavení,
- metody - klient může vykonat program na serveru.

Architektura technologie (viz obr. 1.4) je rozdělena na vrstvy kvůli zapouzdřenosti a větším možnostem rozšiřování, např. o nové bezpečnostní technologie nebo aplikační služby.

Vrstva komunikace může využívat různá komunikační rozhraní, nejčastěji se ale jedná o TCP. Komunikace probíhá stylem klient-server, přičemž dnes už standard podporuje i styl pub-sub, kdy se dané informace komunikují pouze při jejich změně.

Vrstva informačního modelu uchovává data ve formě uzlů (angl. *nodes*) obsahující název a hodnotu. Informační vrstva umožňuje číst / zapisovat data, vykonávat metody, vyvolávat události a vyhledávat ve struktuře uzlů. Uzly také poskytují informace o kvalitě informace (závisí na době posledního vyčtení a nastavení obnovení informace). Komunikace typu klient-server umožňuje díky SOA paradigmatu operace s uzly a metodami. Komunikace typu publisher-subscriber byla do standardu přidána později, přičemž definuje alternativní mechanismus (optimalizovaný pro komunikaci mezi více účastníky) pro vyčítání informací pouze při jejich změně a propagaci událostí. [33]

Rozšiřující vrstva dodává technologii OPC UA flexibilitu pro nasazení i v případech, kde nevyhovuje standardní informační model. Mohou být použity modely např. pro zpracování alarmů, časových řad, binární soubory, aj.



Obr. 1.4: Architektura technologie OPC UA [33]

V konceptu Průmysl 4.0 je technologie OPC UA považována v současné době za vhodný komunikační prostředek mezi strojem / PLC a výrobním systémem, příp. mezi částmi výrobního systému. Komunikaci lze také nasadit mezi procesní

/ PLC zařízení, přičemž časově kritická komunikace je zajištěna variantou *OPC UA over TSN*. Vztah technologie OPC UA a AAS a detaily jejich integrace jsou stále předmětem diskuze standardizačních skupin. Při porovnání metamodelů těchto technologií lze spatřit podobnosti ve struktuře uchovávání informací, tedy lze mapovat uzly v OPC UA na datové elementy v AAS a hierarchii modelů v AAS lze mapovat na hierarchii uzlů v OPC UA. Taktéž metody a události lze mapovat. Výsledkem je základní možnost použití OPC UA pro implementaci základní funkcionality AAS. Strukturu pasivní části AAS je tedy možné modelovat a provozovat na OPC serveru.

1.1.5 TSN komunikace

Jako standard pro časově kritickou komunikaci mezi I4.0 komponentami byla zvolena skupina IEEE 802.1 obsahující požadavky, které by měla splňovat TSN technologie. Původně byl tento standard určen pro audio / video komunikační přenosy, přičemž díky požadavkům na reálný čas se jeho aplikace rozšířila i do ostatních sfér, jako je automobilismus, letectví [16] a řízení průmyslové výroby [53]. V kontrastu s existujícími Ethernet technologiemi (ProfiNet, EtherCAT, aj.), TSN popisuje rozšíření poplatné novým nárokům. Tato rozšíření se hlavně týkají: [49]

- synchronizace času - všechna zařízení účastnící se časově kritické komunikace musí mít společný čas,
- řízení komunikace - všechna zařízení účastnící se komunikace podléhají stejným pravidlům pro směrování a zpracování komunikačních paketů,
- rezervace linek (odolnost vůči poruchám) - všechna zařízení účastnící se komunikace podléhají pravidlům pro rezervaci komunikačních drah (linek) a časových slotů za účelem zajištění odolnosti vůči poruchám.

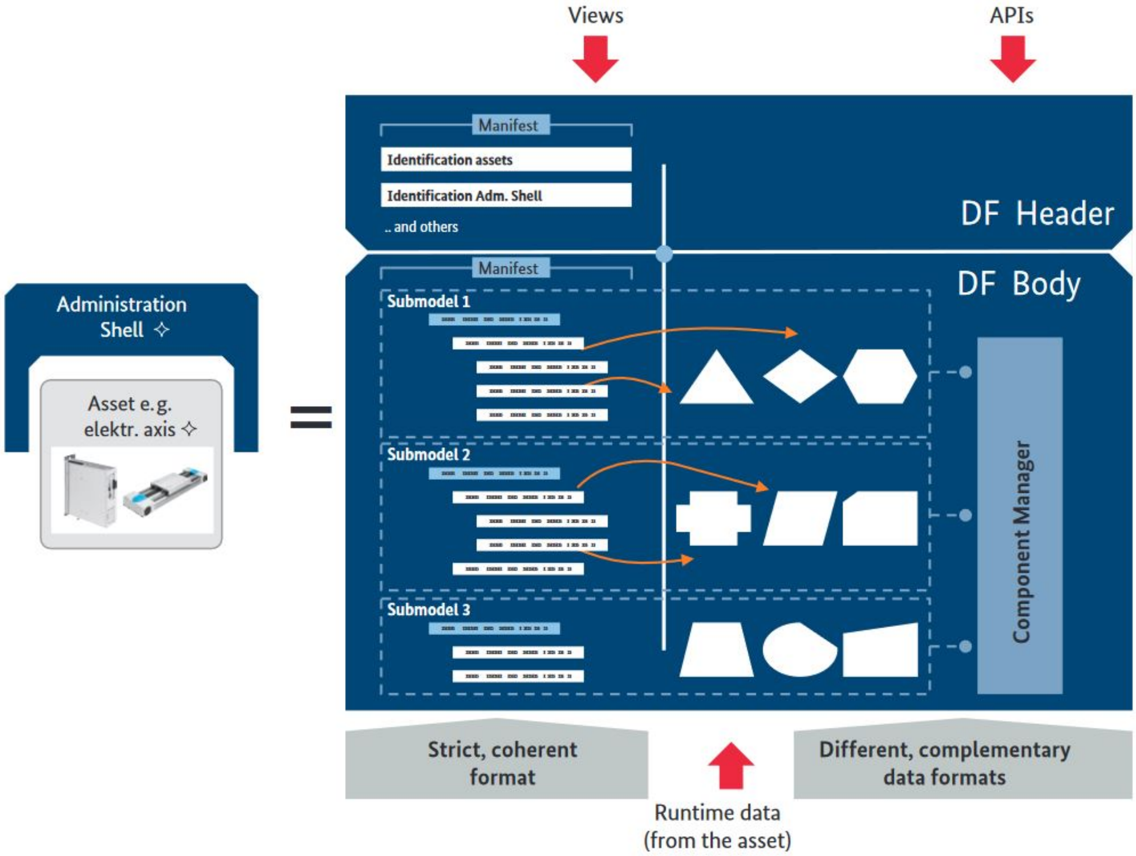
TSN standard tedy definuje požadavky na dodržení determinismu, resp. časové omezení operací. Pro správné dodržení časových podmínek je nutná synchronizace času, která může být implementována pomocí techniky PTP definované v IEC 61588. Ve standardu TSN je definována synchronizace času podle IEC 802.1 AS. Synchronizace je založena na existenci jediného zdroje přesného času, který se s minimální latencí přenáší pomocí speciálních přepínačů (angl. *switch*) až ke koncovým uzlům. Přenos přesného času probíhá pomocí původního protokolu PTP dle IEEE 1588:2021.

Komunikace dle TSN standardu se použije hlavně mezi zařízeními zajišťujícími rychlé děje (např. řízení pohybu) nebo bezpečnostní funkce (např. bezpečnostní PLC a monitory). Pokud by tato zařízení měla mezi sebou komunikovat prostřednictvím AAS musela by I4.0 komunikace mezi nimi splňovat TSN standard. Další aplikací TSN technologie je komunikace mezi AAS a prostředkem v rámci kyberfyzikálního systému pro zajištění maximální odezvy v rámci regulačních smyček.

Tradiční průmyslové komunikační technologie (ProfiNet, EtherCAT, Powerlink, aj.) se snaží reagovat na novinky zavedené TSN standardem. Aby ale byly tyto technologie zcela v souladu s novým standardem, musely by se transformovat od základu, což je nákladné a zároveň by bylo problematické zajistit zpětnou kompatibilitu s již existujícími instalacemi. V současné době probíhá vývoj a definice nových komunikačních technologií, které respektují TSN principy. Tento vývoj je veden dílčími skupinami, jako jsou IEEE 802.1CS, IEEE 802.1Qdd nebo DetNet [22].

1.2 AAS

Podle [47] je AAS „standardizovaná digitální reprezentace prostředku, resp. základní prostředek pro interakce mezi aplikacemi zajišťujícími řízení výrobního procesu. Dále umožňuje udržovat digitální modely z hlediska různých aspektů a popisovat technické funkcionality daného prostředku."



Obr. 1.5: Struktura AAS [37]

Jedná se tedy o informační strukturu (viz obr. 1.5), která strukturovaně udržuje veškerá data o svém prostředku (angl. *asset*) v elektronické podobě. Zároveň umí interagovat s okolními aplikacemi pomocí standardizovaných rozhraní. Také komunikuje se svým prostředkem pomocí určeného rozhraní, kterým prostředek disponuje. Obecně se skládá z hlavičky (angl. *head*) a těla (angl. *body*). Hlavička slouží převážně pro identifikaci a tělo slouží pro strukturované uchovávání datových modelů (angl. *submodel*).

AAS je spjato s prostředkem, se kterým komunikuje a který zastřešuje. S okolním světem komunikuje pomocí svého rozhraní. V případě komunikace pomocí I4.0 rozhraní je AAS s prostředkem označováno jako I4.0 komponenta. Tato komponenta se nachází v definovaném prostředí a komunikuje pomocí I4.0 jazyka (viz kap. 1.1.2). AAS je tedy virtuální reprezentací I4.0 komponenty [34].

V dřívějším pojetí se AAS dělilo na pasivní a aktivní. Resp. jako pasivní část byla považována část obsahující datové modely. Aktivní část by obsahovala komponenty pro:

- interakci s okolím - pomocí I4.0 komunikačního kanálu,
- orchestraci - dirigování činností v komponentě (např. postup výroby produktu dle daného předpisu),
- vyjednávání - komponenta zajišťující domluvení výrobní operace dle vyjednávacího algoritmu, aj.

V současné době se ale od tohoto pojetí upouští a používá se rozdělení dle interakčních typů (viz kap. 1.2.4).

1.2.1 Asset

Podle IEC TS 62443-1-1:2009 je prostředek (angl. *asset*) definován jako „fyzický nebo logický objekt vlastněný organizací nebo pod její správou, který má pro tuto organizaci jakoukoliv hodnotu". [47]

Jedná se tedy o hmatatelný nebo softwarový prostředek, který je v organizaci vytvářen, zpracováván, přijímán nebo odesílán. Organizace musí znát všechny podrobnosti o daném prostředku, aby mohla vytvořit a spravovat k takovémuto prostředku AAS. Pokud je prostředek organizací přijímán, tak už by k němu měl být AAS vytvořen odesílající organizací. Prostředek je pevně spjat se svým AAS po celou dobu svého životního cyklu.

1.2.2 Kritéria

Pro správný návrh a implementaci AAS byla stanovena kritéria, která musí být validována. V roce 2017 vznikla první ustálená verze těchto kritérií, přičemž každý rok prochází procesem obnovy dle aktuálního stavu dostupných technologií. Dále jsou nastíněna kritéria v horizontu pěti let (střednědobá) a deseti let (dlouhodobá). Tato kritéria jsou stanovována dle následujících aspektů: [42]

- sebehodnocení - každá organizace si sama může vyhodnotit, zda kritéria splňuje, přičemž není nutná certifikace,
- jednoduchost - kritéria jsou prezentována co nejjednodušeji, aby organizace nepotřebovala součinnost další organizace,
- vlastní identifikace - organizace může použít vlastní značení, které bude dostupné pro zákazníky raději než obecné značení,
- volná licence - organizace se může rozhodnout, zda bude zveřejňovat použití kritérií,
- volná dostupnost - použití kritérií je bez poplatků,
- implementační entity - pouze komise ZVEI-SG a pracovní skupina Platform Industrie 4.0 AG1 mohou stanovovat kritéria, aby byla nezávislá pro všechny organizace.

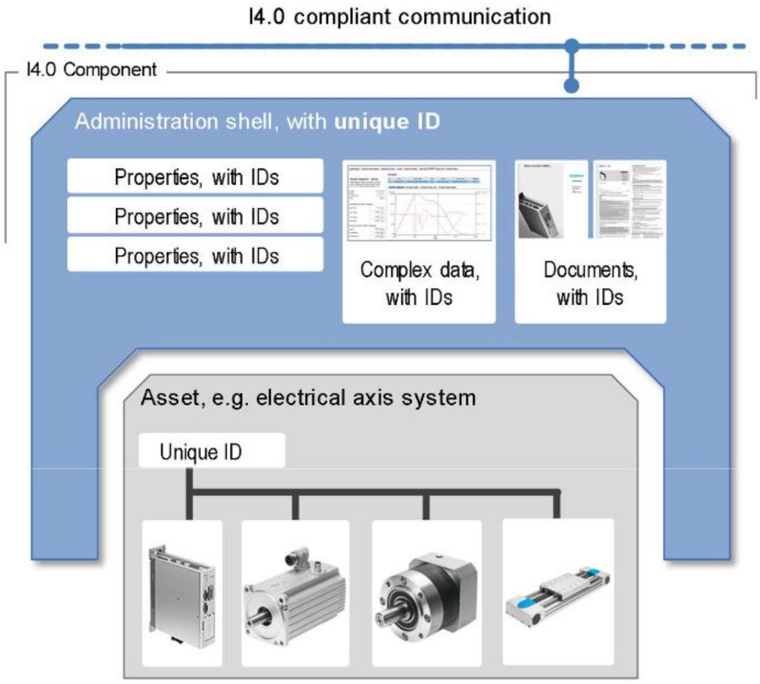
Naposledy byly požadavky v jednotlivých kritériích stanoveny a publikovány v roce 2020, přičemž tato kritéria (skupiny požadavků) jsou:

- identifikace - globálně platná identifikace AAS a také prostředku, přičemž prostředek a AAS musí být spárovatelné,
- I4.0 komunikace - způsob přenosu informací od organizace k zákazníkovi ve všech fázích životního cyklu,
- I4.0 sémantika - formát dat, která je možné získat prostřednictvím AAS, by měl být zvolen z otevřených dostupných standardů,
- virtuální popis - popis prostředku ze všech možných aspektů v digitální podobě zachycený standardní formou,
- I4.0 služby a stav - dostupnost popisu ovládání a monitorování stavu prostředku standardizovaným způsobem,
- standardní funkce - funkce společné pro všechna AAS bez ohledu na organizaci, na kterých je možné stavět další funkcionalitu,
- bezpečnost - minimální požadavky na kybernetickou bezpečnost.

1.2.3 Identifikátory

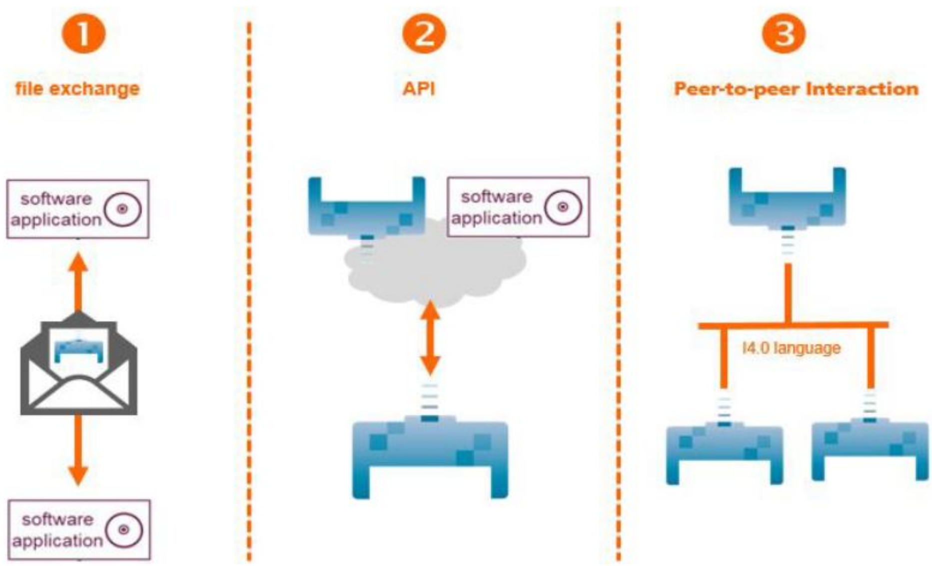
Identifikátory slouží pro jednoznačnou identifikaci entity v doméně průmyslové výroby. Tato identifikace musí být jednoznačná a platná obecně. Pro formální popis je identifikace vyžadována u těchto entit a situací (viz obrázek 1.6):

- AAS jako celku (např. http://www.zvei.de/SG2/aas/1/1/demo11232322),
- prostředek (angl. *asset*),
- entity uvnitř AAS,
- popis vlastností s odkazem na externí slovníky (eCl@ss nebo IEC CDD).



Obr. 1.6: Identifikátory entit v AAS [39]

Dle standardu jsou uznávány globální identifikátory IRDI a URI. Další způsoby jsou povoleny pro využití výrobcem a není zaručena globální platnost (např. GUID). IRDI je definováno v IEC 6523 a musí být určeno standardizační autoritou. URI nebo také URL je popsáno v RFC 3986 a může být vytvořeno spojením unikátní doménové adresy a unikátního řetězce definovaného výrobcem. [39]



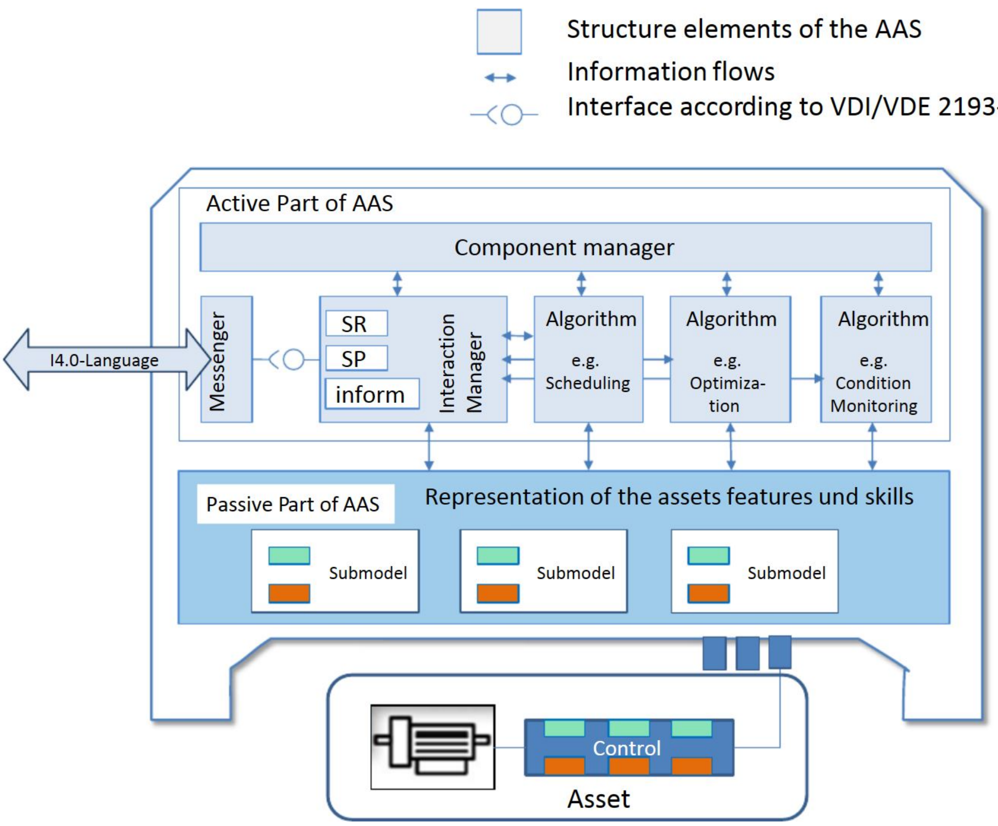
Obr. 1.7: Způsoby AAS implementací z hlediska interakce s okolím [44]

1.2.4 Interakční typy AAS

Existuje více způsobů, jak provozovat AAS, resp. výměnu informací dle koncepce AAS. Tyto způsoby určují obor použitelných technologických prostředků a umožňují určité druhy interakce s okolím (viz obrázek 1.7). Při vytvoření a nasazení AAS musí být zabezpečení připojení v souladu s procesem uvedeným IEC 62443-4-1. K tomu je potřeba plně využít technické zabezpečení technologie, která je použita ke komunikaci s okolním prostředím.

První způsob - pasivní AAS - využívá souborových technologií k přenosu informací, které jsou strukturovány dle AAS metamodelu. Informaci jsou strukturovány dle standardu AAS, poté jsou transformovány do souborového formátu a odeslány jakýmkoliv komunikačním kanálem příjemci. Pro bezproblémovou interpretaci je důležité správně namapovat metamodel AAS danou reprezentační technologií.

Druhý způsob - reaktivní AAS - již využívá samostatného modulu, který se sestává z daného AAS a komunikační technologie s rozhraním API zajišťující přenos komunikaci s okolím. Tento modul musí běžet v nějakém prostředí a musí být přístupný danému oboru účastníků.



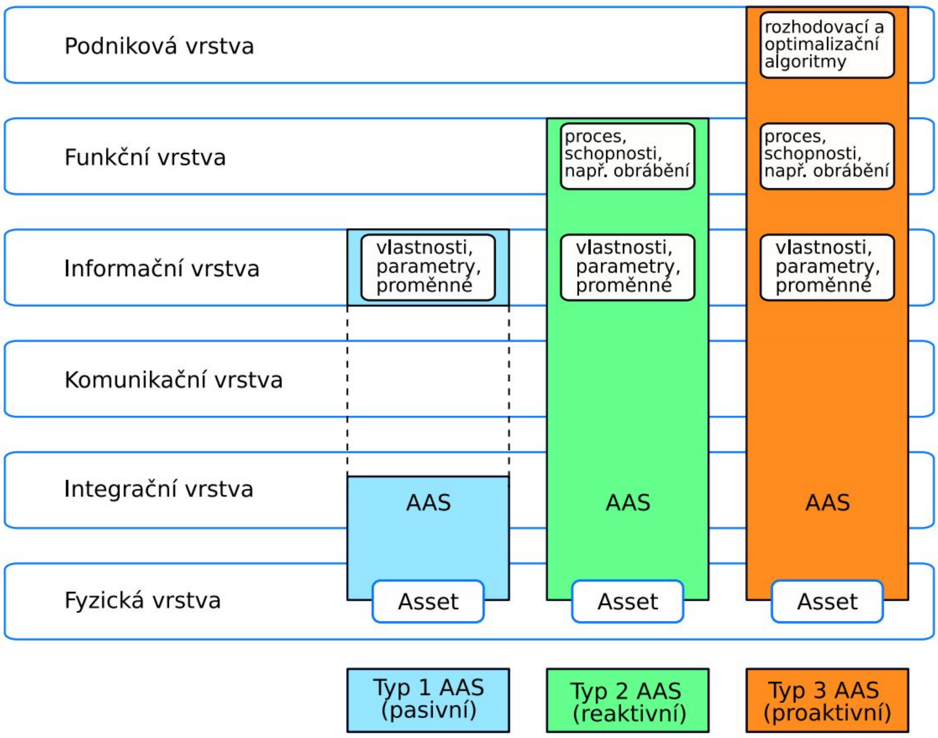
Obr. 1.8: Struktura proaktivního AAS [4]

Standard [43] definuje model této komunikace jako platformově nezávislý, který obsahuje funkce pro práci s daty, identifikaci, navigaci a dohledatelnost jednotlivých entit. Model rozhraní umožňuje operace v souladu s ROA přístupem, který je principiálně blízký k REST rozhraní. Tento přístup je postaven na třech hlavních pilířích:

- stateless - API rozhraní je bezestavové, tj. každá operace je nezávislá na jiné,
- resources - každý prostředek je jasně definovaný,tj. má unikátní jméno a vazby na jiné prostředky,
- methods - určitá skupina funkcí je použita na popis sémantiky všech operací; tyto metody jsou GET, GETALL, POST, PUT, DELETE, SET a INVOKE.

Třetí způsob - proaktivní AAS - se od druhého způsobu liší použitím I4.0 komunikačního adaptéru jako komunikačního rozhraní, který používá I4.0 jazyk a způsob přenosu zpráv. Standard v této oblasti ještě není kompletní, přičemž je třeba dokončit definici sémantiky a obsahu (slov). Aktivní část může také obsahovat další funkce, jako je např. plánování, optimalizace nebo vyhodnocení alarmů. Struktura je zachycena na obr. 1.8.

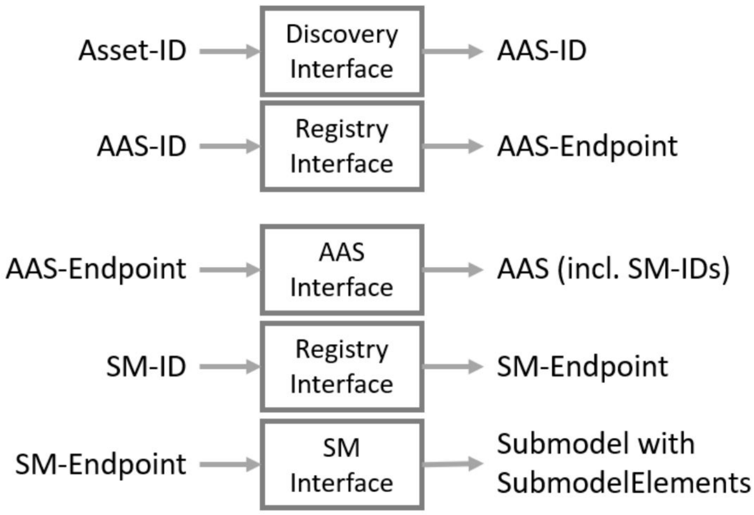
Rozlišení jednotlivých typů AAS lze také zasadit do kontextu vertikální osy RAMI 4.0 (viz obr. 1.9). Pasivní AAS pouze poskytuje data, reaktivní AAS navíc obsahuje funkcionalitu v podobě metod a proaktivní AAS obsahuje elementy s vlastní logiku.



Obr. 1.9: Srovnání interakčních typů AAS pomocí RAMI 4.0 [36]

1.2.5 Navigace v AAS

Dle standardu musí každé AAS disponovat nezbytně funkcemi pro navigaci ve své struktuře. To znamená, že na základě ID prostředku nebo AAS, které musí být veřejně přístupné (AAS-ID globálně a Asset-ID stačí lokálně). Podle těchto identifikátorů musí být možné získat komunikační přípojky (angl. *endpoint*), dále jednotlivé modely a datové elementy (viz obr. 1.10).



Obr. 1.10: Funkce pro prohledávání AAS pomocí identifikátorů (po získání Asset-ID nabo AAS-ID postupně od shora) [43]

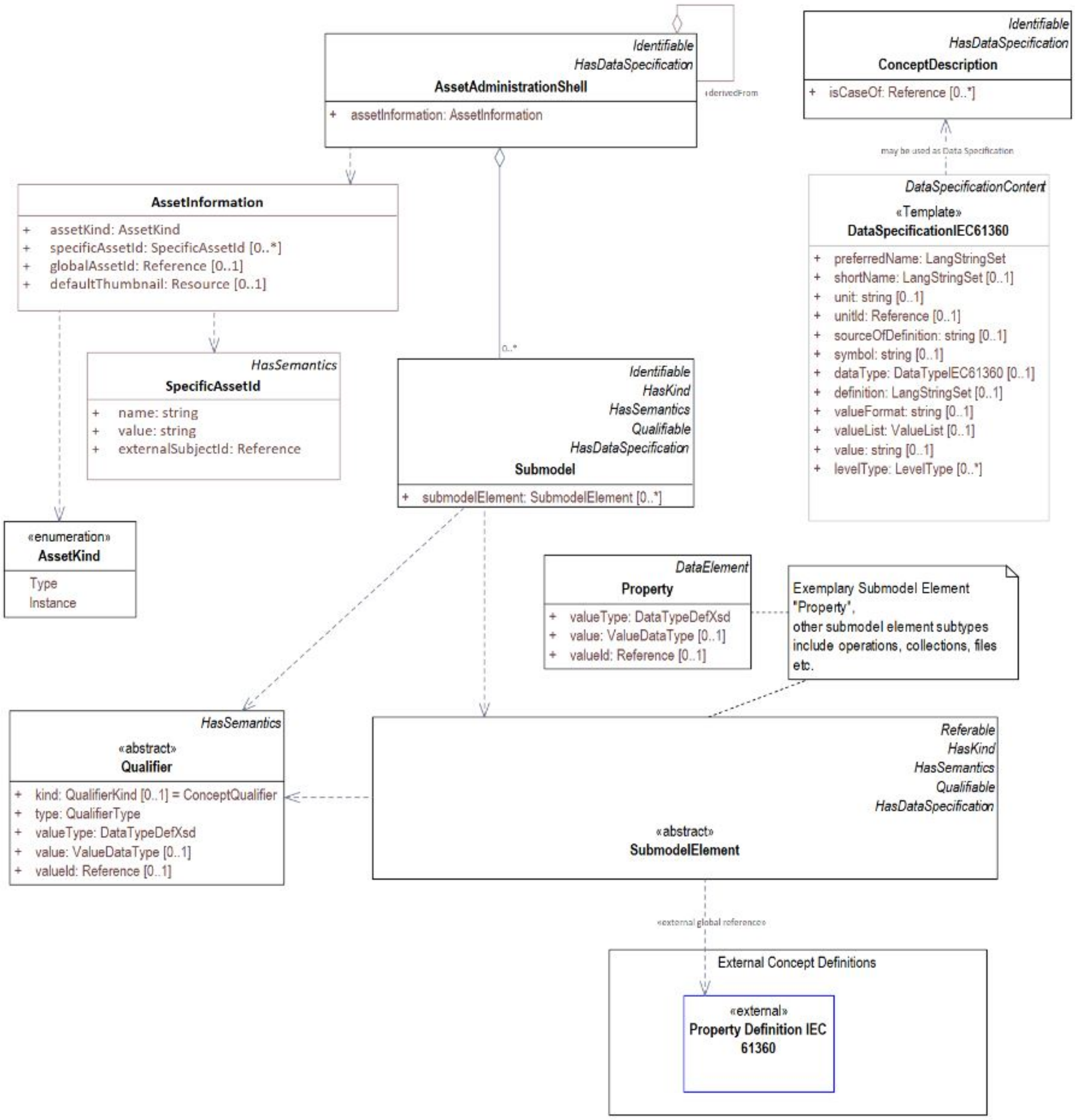
1.2.6 I4.0 jazyk

Oblast	Element	Popis	Použití
Datová oblast	InteractionElements	Data z elementů modelu	Volitelný
Rámec	Type	Typ zprávy	Povinný
Rámec	Sender	Odesílatel	Povinný
Rámec	Receiver	Příjemce	Nepovinný
Rámec	ConversationId	Identifikátor konverzace	Nepovinný
Rámec	MessageId	Identifikátor zprávy	Povinný
Rámec	ReplyTo	Reference odpovědi na zprávu	Nepovinný
Rámec	ReplyTill	Odpověď do času	Nepovinný

Tab. 1.1: Struktura zprávy dle VDI/VDE 2193-1 [4]

Výměna informací mezi I4.0 komponentami je založená na přenosu zpráv. Standard VDI/VDE 2193-1 definuje strukturu (viz tab. 1.1) a typ těchto zpráv spolu se slovníkem definující význam přenášených informací. Standard VDI/VDE 2193-2 popisuje sémantiku interakčního protokolu, přičemž je zahrnut i vyjednávací algoritmus. I4.0 jazyk je definován nezávisle na komunikační technologii, přičemž jako příklad implementace je jazyk kódován pomocí technologie JSON. V praktické realizaci je tedy elementu *messenger* předřazen element rozhraní (angl. *messenger interface*). [4]

1.3 AAS metamodel



Obr. 1.11: Přehledový metamodel AAS [47]

Struktura AAS je popsána pomocí diagramu tříd (angl. *class diagram*) v podobě metamodelu. Ve specifikaci uvedené v [47] jsou jednotlivé metamodely uvedeny samostatně popisující část celkového metamodelu AAS. V příloze uvedeného dokumentu je avšak uveden příklad implementace modelu v jazyce XML. Přehledový metamodel AAS je uveden na obrázku 1.11.

Ústřední entitou v modelu je AAS, která si nese atributy definující název, identifikaci a zabezpečení. Informace jsou dále strukturovány dle konceptu submodelů. Submodely popisují dílčí funkcionalitu a seskupují elementy, jako je proměnná (angl. *property*), operace (angl. *method*) a události (angl. *events*). Proměnné jsou dále navázány na externí slovník nebo na položky interního slovníku (angl. *data specification*).

Modely jednotlivých entit jsou provázané pomocí vazeb typu agregace (angl. *aggregation*) a závislost (angl. *dependency*). Entity dále mohou implementovat společné atributy, které přidávají další vlastnosti. Tyto společné atributy jsou seskupeny do entit, které mohou být zděděny:

- Identifiable - atributy definující identifikaci entity v globálním měřítku
- HasKind - atributy určující typ entity mezi instancí a šablonou
- Qualifiable - atributy určující ohodnocení proměnné, který se váže k hodnotě, sémantice nebo šabloně
- Referable - volitelné atributy definující identifikaci v rámci jmenného prostoru (např. pouze v submodelu nebo v rámci AAS)
- HasSemantics - povinné atributy definující referenci na globální slovníky
- HasDataSpecification - atributy rozšiřující popis datového elementu
- DataElement - atributy popisující entitu typu proměnná, operace a událost
- HasExtension - atributy popisující rozšíření elementu

Datové entity mohou uchovávat hodnotu (angl. *value*), která je dále dle atributů opatřena typicky vlastnostmi jako je jednotka, maximální hodnota, minimální hodnota a kategorie. Kategorie nabývá možností konstanta (neměnná hodnota po celou dobu), parametr (změna hodnoty probíhá zřídka) a proměnná (změna hodnoty může proběhnout kdykoliv).

1.3.1 Submodel

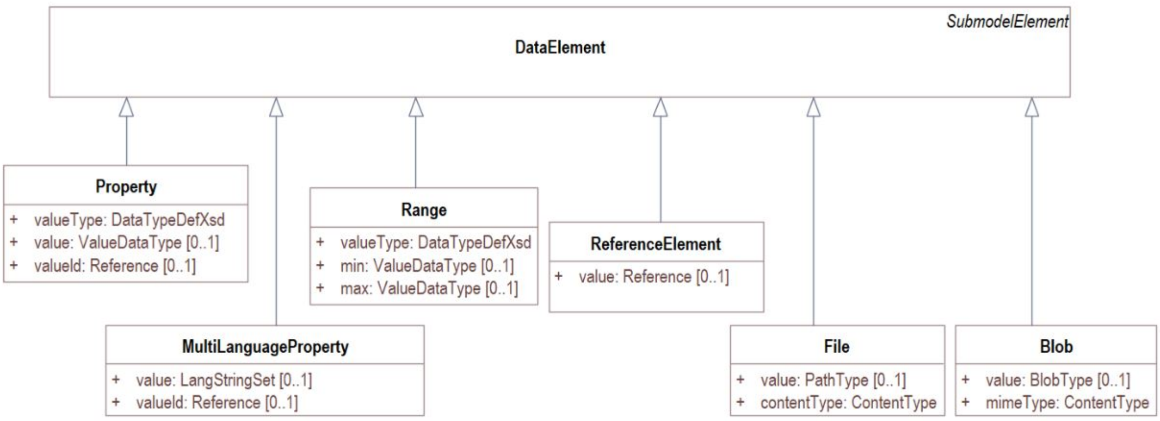
Submodel je základním prvkem pasivní části AAS. Tato entita může modelovat dílčí funkcionalitu nebo jen seskupovat další entity logicky patřící k sobě. Dle [39] musí každý submodel mít označení *semanticId*, ale v novém vydání [47] je už tento atribut pouze doporučený. Submodel hierarchicky obsahuje elementy [47]:

- DataElement - obsahuje elementy typu nesoucí data,
- Operation - je používána pro vyvolání předdefinované procedury,
- EventElement - slouží pro zpětnou asynchronní indikaci změn,

- Capability - slouží pro definici nabízených služeb,
- RelationshipElement - slouží pro provázání entit,
- SubmodelList - zahrnuje hierarchicky další submodely.

1.3.2 Datový element

Datový element (angl. *DataElement*) je nositelem informací. Informaci o prostředku mohou být jeho parametry, provozní veličiny, způsob zapojení, způsob provozu, technické listy, výkresová dokumentace, aj. Jedná se o heterogenní data různého formátu. Metamodel datové elementu proto zahrnuje většinu standardních formátů dat v informatice (viz 1.12). Každá entita tohoto metamodelu obsahuje atributy, které zpravidla popisují datovou informaci a její souvislosti i s referencemi na globální slovníky příp. jiné zdroje. Kromě standardních atributů je datové element kategorizován na datový bod typu proměnná, parametr, nebo konstanta. [47]



Obr. 1.12: Metamodel datového elementu [47]

1.3.3 Reference

Reference tvoří vazby mezi jednotlivými entitami nebo mezi entitou a prvkem mimo AAS, u kterého je zajištěn globální přístup. Jedná se o nástroj umožňující propojení entit s cílem vytvoření kontextu, resp. provázání jednotlivých informací do sítě. Reference se také používá k prostému navázání externích dat nebo interního datového souboru k příslušné entitě. Kromě popisných atributů obsahuje metamodel reference položku *key*, která jednoznačně linkuje entitu s cílovým prvkem. Tato položka může nabývat těchto typů [47]:

- FragmentKey - klíč na interní soubor či jeho část, nebo na jinou entitu modelu
- AasReferables - klíč na submodel nebo jiné entity modelu

- GloballyIdentifiables - klíč na jednoznačně dosažitelný, globální, externí prvek

Hodnotami pro reference na globální prvky jsou typicky identifikátory IRDI nebo URI, příp. jiné jednoznačně unikátní identifikátory platné celosvětově. Hodnota reference je datového typu *text*, aby bylo možné vložit libovolnou hodnotu. Klíče různého typu mohou být spárovány. Pro spárování dvou referencí je nutné, aby všechny hodnoty všech klíčů byly identické.

1.3.4 Datové typy

Datové typy dle standardu AAS se dělí na jednoduché (angl. *simple data types*) a primitivní (angl. *primitive data types*) [47].

Metamodel AAS používá jednoduché datové typy definované jazykem XSD a RDF:

- string (XSD) - standardní typ typu textový řetězec,
- boolean (XSD) - true/false,
- byte (XSD) - -128 až +127
- langString (RDF) - textový řetězec s označením jazyka.

Primitivní datové typy se používají pro uložení heterogenních dat a datové typy některých speciálních atributů:

- BlobType - pro uložení dat v *byte* formátu,
- Identifier - textová hodnota identifikátoru,
- LangStringSet - pole hodnot řetězců s anotací jazyka,
- ContentType - textová hodnota definující MIME typ souboru,
- PathType - cesta k lokálnímu souboru,
- QualifierType - textová hodnota rozšiřujícího atributu,
- ValueDataType - hodnota dat v XSD atomickém datovém typu (string, boolean, integer, float, dateTime, decimal, byte, ...),
- Enumeration - sada obsahující entity modelu daného typu.

1.3.5 Reprezentace informací

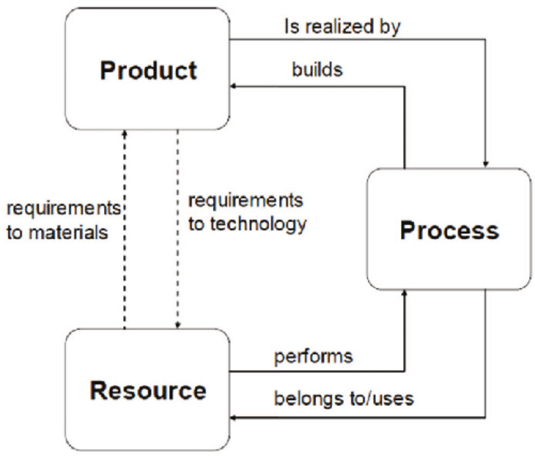
Dle standardu je vhodné všechny informace v pasivní části AAS linkovat na položky z globálních slovníků, aby těmto informacím rozuměl jakýkoliv účastník. Jednotlivé položky slovníku popisují význam dané informace a případně i další informace, jako je např. rozsah a veličina. V dřívějším standardu AAS bylo možné si vytvořit vlastní slovník, avšak od tohoto konceptu se upustilo z důvodu vytváření duplicitních položek, které jsou platné pouze lokálně. V současné době existují dva globální slovníky pokrývající velkou část informací z oboru strojírenství a elektrotechniky. Tyto slovníky se nazývají CDC (Common Data Dictionary) a eCl@ss. Položky ve slovnících jsou hierarchicky uspořádány (segment, hlavní skupina, skupina, podskupina) a lze je jednoznačně identifikovat - eCl@ss používá IRDI identifikátor [45]. Struktura globálních slovníků je definovaná standardem IEC 61360, který popisuje metamodel položek a slovníku jako takového.

1.4 Reprezentace výrobních schopností

Pro reprezentaci heterogenních schopností a výrobních požadavků se jako nejvhodnější nástroj jeví ontologie. Ontologie formálně popisují systém a vztahy mezi jeho prvky. Tvoří tedy sémantické sítě využívající slovníky pro reprezentaci dat. Využití při řízení průmyslového procesu nachází v těchto situacích a akcích:

- popis požadavků na výrobní operace produktu, popis možností výrobních operací zařízení a porovnání požadavků s možnostmi,
- struktura výrobní operace produktu na atomické operace a rozhodnutí o schopnosti vyrobení strojem na základě formální verifikace [41],
- reprezentace metadat a heterogenních expresivních dat o zařízení (viz struktura AAS).

Řízení výroby založené na schopnostech je jedním významných aspektů Průmyslu 4.0 a je definován tzv. PPR (Product-Process-Resource) modelem (viz obrázek 1.13). Prostředky v tomto modelu znají své schopnosti (schopnosti prostředku), které zapouzdřují dovednosti, aniž by věděli v jakém výrobním procesu budou použity. Proces specifikuje výrobní možnosti (schopnosti výroby) dle požadavků na výrobní proces. Tyto schopnosti v kombinaci s požadavky na výrobu produktu určují, zda je prostředek schopen splnit požadovanou operaci v daném výrobním procesu. [11]

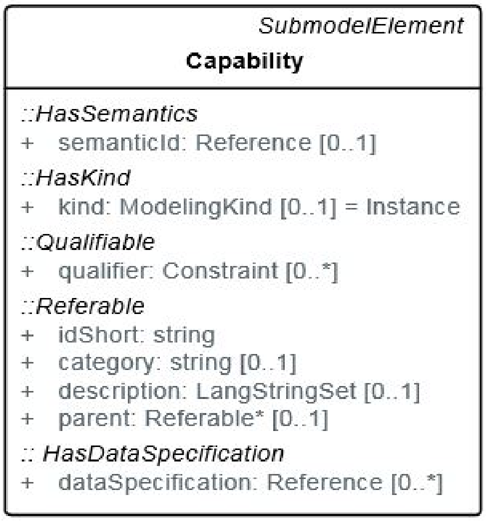


Obr. 1.13: Model produkt-proces-zdroje [11]

Reprezentace dovedností zařízení, resp. výrobních schopností může být implementována různými způsoby: [41]

- stavová proměnná - jednoduché řešení s omezenou mírou komplexity,
- trigger proměnná - starší způsob implementace volání operací,
- operace - standardní řešení bez podpory dlouho vykonávajících se funkcí,
- funkční blok - standardní řešení v PLC, které podporuje delší vykonávání pomocí stavového automatu, avšak má omezenou míru komplexity,
- sémantický protokol - zajišťuje vyšší stupeň komplexity a autonomie při vyjednávání požadované výrobní operace.

V AAS lze výrobní schopnosti modelovat pomocí vlastností v submodelu, což je považováno za standardní cestu. Novější výzkum a přístup ovšem navrhuje zapouzdřit výrobní schopnosti do vlastního submodelu s odkazem na submodel dané schopnosti, což bude umožňovat komplexnější správu a vyhodnocení vhodnosti (pomocí externího ontologického nástroje) výrobní operace k výrobnímu požadavku. Metamodel výrobní schopnosti pro AAS zachycuje obrázek 1.14.



Obr. 1.14: Model elementu výrobní schopnosti v AAS [41]

Existují různé nástroje původně vyvinuté jen pro informační doménu, jako je OWL nebo RDF. Jednou z nevyřešených výzev je formalizovat procesy, systémy a schopnosti z hlediska průmyslové výroby za účelem strojového přiřazování úkolů k jednotlivým strojům pomocí základě formální verifikace. Rozhodovací systém tedy musí být schopen rozhodnout schopnost splnit úkol zadaný obecněji nebo specifičtěji než je předpis jeho schopnosti, např. vytvořit ovál v desce bude pro stroj znamenat vyvrtat sérii děr vedle sebe s následným zahlazením stran nebo schopnost frézování.

1.4.1 RDF

RDF je ontologický jazyk pro tvorbu sémantického webu postavený nad technologií XML vyvinutí a udržovaný konsorciem W3C. Formálně se jedná o množinu trojic (hran grafu) ve tvaru S (subjekt) – P (predikát) – O (objekt), které tvoří orientovaný graf. RDF Schema rozšiřuje původní abstraktní model o další klíčová slova, která poskytují mechanismus pro rozlišení typů zdrojů, základní práci s třídami a vlastnostmi. Tento ontologický jazyk neumí zaznamenat skutečnost, že dvě různé entity reprezentují jednu entitu, a neumožňuje pracovat s počtem stejných vlastností třídy. Některé limitace řeší OWL. [55]

1.4.2 OWL

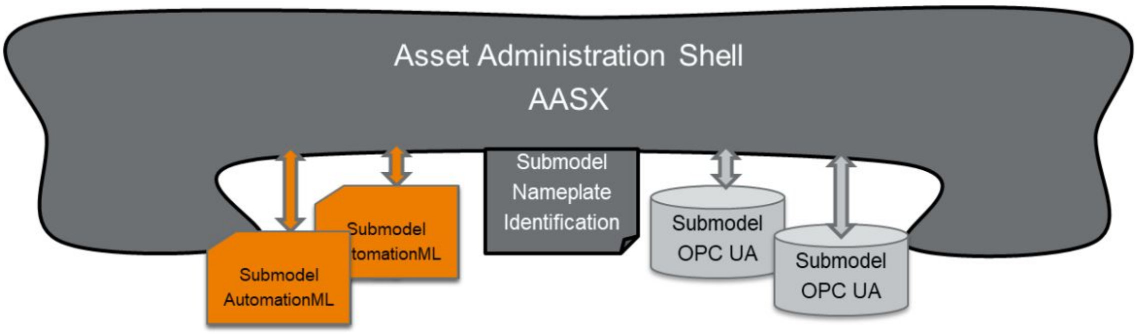
OWL je webový ontologický jazyk, jehož základními kameny jsou *axiom*, *entity* a *expression*. Vychází z RDF Schema, který doplňuje o třídy, vlastnosti a expresivní operátory. Odlišily se tři podjazyky OWL Lite, OWL DL a OWL Full. Standard OWL také definuje další strukturální prvky kromě RDF, jako je OWL/XML, Manchester syntax či Functional syntax, které mají za cíl popsat skutečnost jiným způsobem. Jako identifikační technologie slouží IRI, která umožňuje použití a integraci již existujících ontologií, slovníků nebo jiných zdrojů z webu Linked Open Data. V současné době je nejnovější OWL2 verze 2 od roku 2012. [56]

1.4.3 Automation ML

Pro popis dat ve fázi návrhu je možné použít mnoho popisných jazyků, které pokrývají nějakou doménu. Pro zastřešení všech těchto přístupů byla vyvinuta technologie AutomationML (standard IEC 62714). Jedná se o popisný jazyk na bázi XML pokrývající domény mechanickou (kinematika, topologie, geometrie), elektrickou, automatizační, aj. AutomationML je otevřený standard, který může být rozšiřován, a skládá se v základu z těchto technologií:

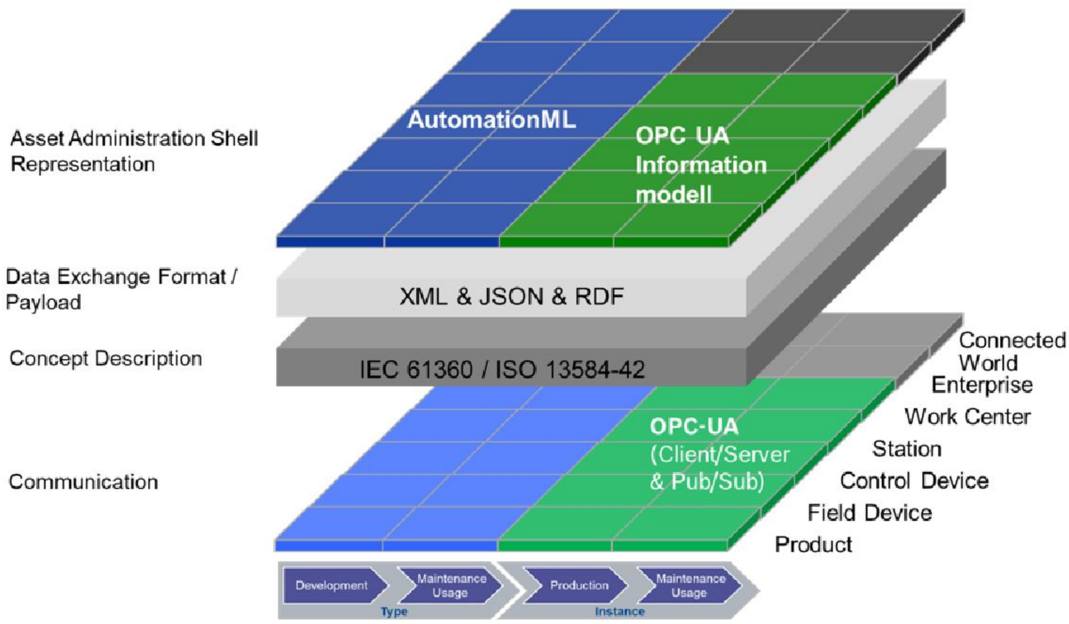
- CAEX (IEC 62424) - pro popis topologie hierarchicky,
- COLLADA - pro popis geometrie a kinematiky,
- PLCopen - pro popis automatizační logiky.

Organizace AutomationML deklarovala [2], že vztah AAS a AutomationML standardu je takový, že jazyk AutomationML bude sjednocujícím formátem pro výměnu dat hlavně ve fázi návrhu (angl. *type*) v rámci vývojového cyklu a pro přenesení dat do fáze výroby (angl. *instance*) se použije AAS jako nosná technologie, přičemž data se potom budou mapovat do OPC UA technologie pro zajištění interakce (viz obr. 1.15).



Obr. 1.15: Vztah AutomationML a AAS technologií [2]

Dříve také OPC Foundation uvedlo, že AutomationML se bude používat jako nástroj pro uložení informací v AAS, čímž se překlene rozdíl mezi fází návrhu a výroby [34]. Jedná se ale o prvotní pokus definování relace mezi těmito technologiemi. V [47] už je také uvedeno použití AutomationML ve fázi návrhu a OPC UA ve fázi výroby, přičemž obě tyto technologie budou použity v informační vrstvě RAMI modelu, resp. budou součástí reprezentace AAS (viz obr. 1.16).



Obr. 1.16: Použití AutomationML a OPC UA v informační vrstvě AAS [47]

Vztah technologie AutomationML a AAS a detaily jejich integrace jsou stále předmětem diskuze standardizačních skupin.

1.5 Technické zajištění

AAS je informační obálka tvořená daty uspořádanými v modelu a dalšími komponentami. Musí tedy běžet v nějakém běhovém prostředí. Běhové prostředí může být zajištěno různými prostředky disponujícími různým výpočetním výkonem, např. cloud prostředí, edge prostředí, desktop prostředí nebo embedded prostředí. Dle použitých prostředků plynou vlastnosti běhového prostředí, které můžeme kategorizovat [44]:

- cloudové řešení - ústředním prostředkem je cloudový systém v různé formě (SaaS, PaaS nebo IaaS), který koordinuje a monitoruje připojená zařízení
- edge řešení - ústředním prostředkem je edge zařízení, který může posílat předzpracovaná data do cloud, přičemž cloud vykonává výpočetně náročné podpůrné funkce
- stand-alone řešení - veškerou koordinaci a výpočetní kapacitu zajišťují zařízení bez cloudových služeb

Použití technologií je závislé na požadavcích kladený na míru interakce AAS, resp. použití dalšího software k prohlížení nebo ukládání informací. Dle interakčních typů uvedených v kap. 1.2.4 můžeme odhadovat vhodné technologie pro vytvoření, přenos a provoz AAS.

První způsob (pasivní AAS) využívá reprezentačních technologií pro mapování informací z AAS metamodelu. Mezi uplatnitelné technologie můžeme řadit např. AASX, XML, JSON nebo AutomationML. Pro komunikaci jedna strana vytvoří soubor s požadovanými informacemi a pošle ji komunikačním kanálem druhé straně. Druhá strana musí pomocí reverzního procesu správně informace dekomponovat.

Druhý způsob (reaktivní AAS) může využít technologie OPC UA server, REST server a MQTT jako datovou část, na kterou mapuje všechny submodely a funkce, přičemž technologie OPC UA se jeví jako nejvhodnější z hlediska souladu s AAS metamodelem. Technickými prostředky pro komunikaci mohou být OPC UA, REST API nebo MQTT. Zabezpečení připojení a komunikace poté leží na použité technologii. V případě přístupu pomocí technologie REST API, je požadována ochrana připojení alespoň použitím komunikační technologie HTTPS. V případě přístupu pomocí technologie MQTT, může být spojení technicky ochráněno prostřednictvím certifikátu na úrovni MQTT komunikace. Při použití OPC UA je zabezpečení komunikace zajištěno bezpečným spojením s klientem na úrovni TLS komunikace, která se vytvoří výměnou a ověřením certifikátů. [46]

Třetí způsob (proaktivní AAS) využívá I4.0 komunikačního adaptéru, který může být postaven na bázi HTTPS jako komunikačního rozhraní. Zabezpečení připojení a komunikace je tedy plně v režii nižších vrstev, resp. komunikačního protokolu. Standard AAS nastiňuje model zabezpečení na bázi certifikátů, kdy si účastníci komunikace (resp. server) ověří přijatý certifikát u certifikační autority, a až poté zpřístupní data.

Struktury AAS je možné exportovat do tzv. AASX-Package. Jedná se uskupení souborů pro popis struktury a souborů se zdroji (např. PDF, 3D modely, apod.). Samotnou strukturu AAS je možné zachytit pomocí technologií XML, JSON nebo RDF. Tato struktura může být poté načtena a spuštěna v běhovém prostředí. Export struktury umožňuje například software AAS Package Manager. Dalšími prostředky pro offline uložení AAS jsou technologie AML a UAnodeset v případě zajištění běhu čistě na technologii OPC UA. [46]

1.5.1 Model služeb

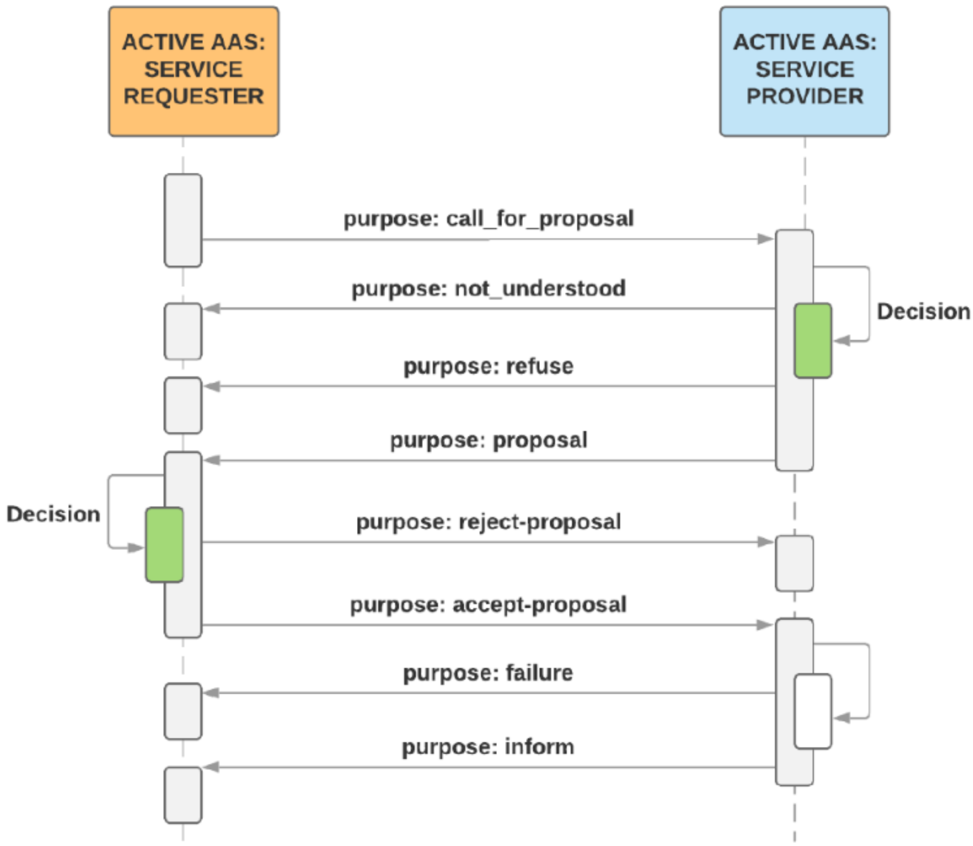
Model služeb dle konceptu I4.0 je odvozen z architektury interakce dle DIN SPEC 16593-1 a uplatňuje se jak na služby spojené s prostředkem (angl. *asset*), tak na služby infrastruktury. Způsob operační interakce se službou může být dvojího typu. Prvním interakční typ je založen na volání procedur (metod). Druhý interakční typ navíc integruje stavový automat, čímž zavádí podporu sekvenční logiky. Model služeb mapuje kaskádově obecné entity až na jejich implementaci a rozlišuje čtyři úrovně [44]:

- technologicky neutrální (angl. *technology neutral*) - koncepty nezávislé na implementaci (např. klient-server)
- technologická (angl. *technology specific*) - koncepty založená na použitých technologiích (např. OPC UA, MQTT, REST)
- implementační (angl. *implementation*) - koncepty založené na implementačním nástroji (např. C#, Java, Python)
- operační (angl. *runtime*) - koncepty založené na konkrétní operační technologii

Na technologicky neutrální úrovni popisuje služba (angl. *service*) obor podporovaných funkcionalit. Rozhraní (angl. *interface*) definuje připojení s mapováním na API a může být využito více službami. Operace definují entity, které mohou být volány a jsou implementovány na technologické úrovni pomocí API metod.

1.6 Orchestrace výroby

Standardní architekturou řízení průmyslového podniku je centralizované řešení, kdy jeden řídicí prostředek je nadřazený ostatním a poveluje výrobu. V procesním průmyslu se naopak uplatňuje spíše distribuovaná architektura, kdy řídicí funkce jsou distribuovány do řídicích prostředků v dané lokalitě, přičemž tyto prostředky si mezi sebou vyměňují procesní data. Koncept Průmysl 4.0 navrhuje řízení pomocí decentralizované architektury, kdy každý účastník výroby disponuje řídicími funkcemi a jednotlivými interakcemi se naplní vyšší cíl celého uskupení. V současnosti se avšak od takhle striktního pojetí ustupuje a navrhují se plánovací služby, které pomáhají plánovat výrobní operace, resp. vzniká hybridní architektura.

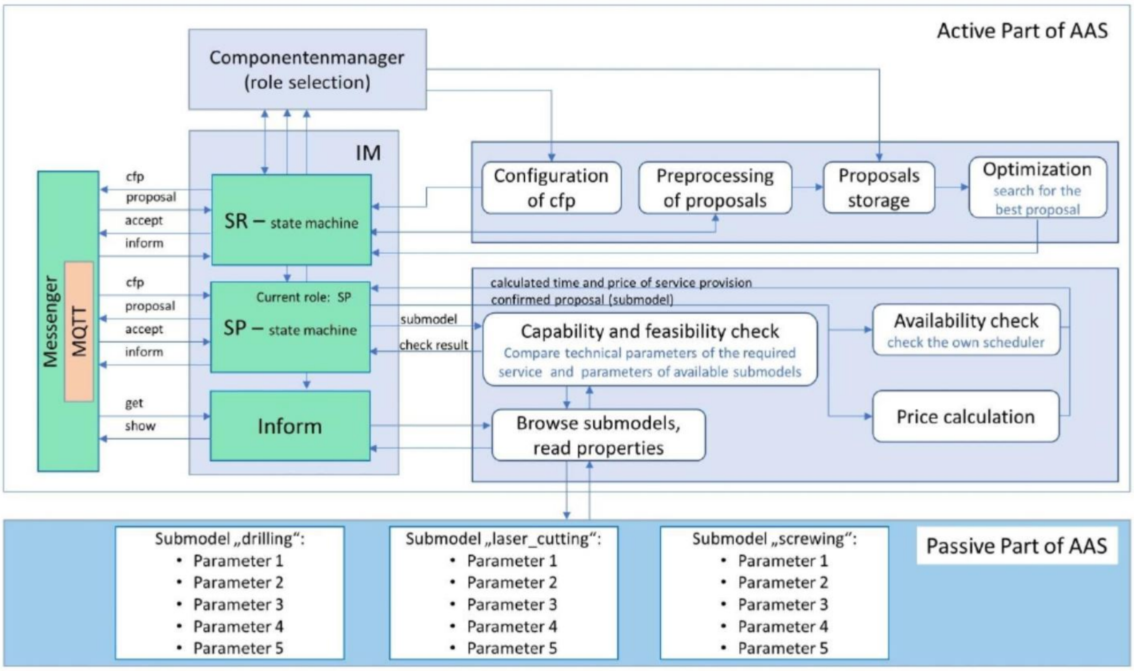


Obr. 1.17: Sekvenční diagram vyjednávacího algoritmu [4]

Základním způsobem řízení výroby v chytré továrně se bere tzv. *vyjednávací algoritmus* (zachycen na obr. 1.17) dle standardu VDI/VDE 2193, který se uplatňuje mezi prostředky v rámci výrobní jednotky. Každý prostředek poskytující výrobní operace se chová jako služba a produkt se chová jako poptávající účastník. Služba nabízí požadované výrobní operace s ohodnocením a poptávající se rozhodne, zda nabídku akceptuje nebo ne. V případě akceptace se služba provede a kontrakt skončí. Tento algoritmus má mnoho modifikací, které se snaží řešit jeho problémy vznikající z prioritních produktů a nestandardních situací. V modifikovaných algoritmech se uplatňují např. fronty nebo jiné způsoby umožňující dynamické přeplánování. [4]

Z hlediska teoretického popisu lze vyjednávací algoritmus modelovat pomocí formálních nástrojů, jako jsou systémy diskrétních událostí, Petriho sítě a přechodové systémy. Poté již lze vyšetřit, zda mohou nastat situace, kdy se např. produkt nevyrobí nebo čas jeho výroby bude neúměrně velký z důvodu ohodnocení výrobní operace. Tento výpočet lze také dále upravovat pro optimální plnění výroby (např. pomocí techniky genetických algoritmů).

Zařazení vyjednávacího algoritmu do struktury proaktivního AAS je možné vícero způsoby, přičemž se nabízí integrovat vyjednávání do komunikační entity. Další funkce, jako je výpočet ohodnocení, rozhodnutí mezi nabídkami a kontrola proveditelnosti se týkají procesu soupeření, a proto nejsou již nejsou součástí standardu. Vyjednávací algoritmus je pro obě role (služba a produkt) definován pomocí stavového automatu. Tento automat musí ale být v aktivní části provozován pomocí nějaké entity udávající cyklicky takt. Obr. 1.18 ukazuje příklad struktury reaktivního AAS obsahující vyjednávající algoritmus. [4]



Obr. 1.18: Příklad architektury AAS s vyjednávacím algoritmem [4]

1.7 Standardizace

Tvorbou standardů v oblastí průmyslové automatizace se zabývá skupina IEC TC 65 [21]. Podskupina SC 65E této skupiny se blíže zaměřuje na zařízení a integrace v pokročilých systémech. Pracovní skupiny této podskupiny se již blíže zaměřují na jednotlivé technologie, z nichž relevantní z hlediska AAS a Průmysl 4.0 jsou:

- WG1 - termíny a definice,
- WG8 - OPC,
- WG9 - AutomationML,
- WG16 - digitální továrna,

- JWG21 - chytrá továrna - referenční modely,
- WG23 - chytrá továrna - rámce a koncepty,
- WG24 - AAS.

V široké oblasti chytré továrny, ve které se nachází i AAS, již existují standardy pro jednotlivé technologie a aspekty. Tyto standardy se dělí na základní, které jsou výchozími dokumenty v této oblasti, a na rámcové, které jsou pouze navrhnuty k použití i v této oblasti a měly by se ještě revidovat. Specifickým standardem v této oblasti, který staví na standardech obou skupin, je IEC 63278, který definuje strukturu a pojmy související s AAS. Mezi základní standardy v oblasti chytré továrny patří:

- IEC PAS 63088 - RAMI 4.0 model,
- IEC TR 63319 - přístupy k modelování chytré továrny,
- IEC 63339 - sjednocený model chytré továrny,
- IEC 63283-3 - doporučení pro kybernetickou a funkční bezpečnost.

Mezí rámcové standardy pro oblast chytré továrny se řadí:

- IEC 62832 - digitální továrna,
- IEC 62264 - MOM (MES),
- IEC 62541 - OPC UA,
- IEC 61131 - PLC,
- IEC 61360 - slovník CDD,
- IEC 63365 - digitální štítek,
- IEC 62443 - kyberbezpečnost,
- IEC 61508 - funkční bezpečnost,
- IEC 62890 - správa životního cyklu, aj.

1.8 Ostatní aspekty

Se vzrůstající komplexitou a provázaností systémů vzrůstají rizika spojená s kybernetickou a funkční bezpečností. Požadavky na bezpečnost je v oblasti průmyslové automatizace popsána standardy, které vyžadují akce ze strany výrobce zařízení, integrátora, ale také podniku jakožto zaměstnavatele. Standard AAS musí být také připraven na použití moderních metod, jako jsou virtualizace a AI/ML, které se pojí s dalšími problémy stran integrace.

1.8.1 Kyberbezpečnost

Kybernetická bezpečnost se v průmyslové automatizaci řídí standardy z rodiny IEC 62443. V praxi jsou často využívány metody, které analyzují riziko nežádoucí manipulace s informacemi. Jedním z nejpoužívanějších modelů pro vyhodnocení je

STRIDE, který analyzuje systém z hlediska typů hrozeb, které znehodnocují žádoucí vlastnosti systému, jako je autentičnost, integrita, neodvolatelnost, věrohodnost, dostupnost a oprávnění.

Pro zajištění kyberbezpečnosti zatím ještě není pro AAS standard, který by tuto problematiku komplexně řešil. Obecně se postupuje podle obecného standardu IEC 62443, resp. podle souvisejících standardů jako jsou např. standardy rodiny IEC 27000 pro informační systémy. Proces hledání rizik a jejich minimalizace by měl být zakomponován do životního cyklu výroby stroje. [30]

V současné době je doporučeno využít při implementaci zabezpečení, které poskytuje použitá komunikační technologie, např. HTTPS. Technologie HTTPS ověří podle poskytnutého certifikátu server pomocí důvěryhodného zdroje a vytvoří zabezpečený šifrovaný komunikační kanál. [43]

Pro ověření certifikátu uživatele je možné také využít certifikátu, který se ověří u autentifikační autority za vzniku tokenu, který se posílá v rámci HTTPS požadavku v hlavičce zprávy. Certifikát klienta může být uložen v AAS a v současné době existuje doporučení (šablona) pro strukturu v informačním modelu. [43]

Informační model AAS disponuje systémem řízení přístupu k entitám pomocí atributů (angl. *Attribute Based Access Control*). Jedná se o označení entit atributy, které zamezují nebo povolují operace (např. zápis) s entitou (např. vlastností). Tento systém nabízí obecný přístup k autorizaci. Pro implementaci musí avšak být řízení přístupu správně namapováno na použitou komunikační technologii. [47]

1.8.2 Funkční bezpečnost

Funkční bezpečnost je součást celkové bezpečnosti zařízení a je souborem metod k zajištění chodu, který minimalizuje riziko újmy. Obecné požadavky jsou stanoveny v normě IEC 61508, přičemž pro průmyslovou automatizaci se více specializují normy IEC 61511 pro procesní výrobu a IEC 62061 pro strojní výrobu a další odvozené standardy.

Provoz AAS se omezuje na běh softwarové aplikace a komunikace, proto jsou požadavky na funkční bezpečnost, resp. spolehlivost kladeny z pohledu požadavků na software, příp. komunikační technologie. V případě použití AAS jako prvku v bezpečnostní funkci by se tedy uplatňovaly bezpečnostní požadavky i na samotné AAS, tedy vývoj dle V-modelu a validace dle příslušné kategorie.

Aplikacemi, kde by se funkční bezpečnost uplatňovala ve spojení s AAS, jsou bezpečnostní monitory, bezpečnostní PLC, ESD (Emergency Shutdown System), frekvenční měniče (funkce bezpečného zastavení, funkce omezení bezpečného momentu), aj.

1.8.3 AI/ML

Metody umělé inteligence a strojového učení se uplatňují v průmyslové výrobě stále častěji, čemuž dopomáhá strategický záměr konceptu Průmysl 4.0. V první fázi přechodu na koncept tzv. chytrých továren, tedy digitalizaci se uplatní techniky strojového učení pro zpracování výrobních dat např. v úlohách hledání anomálií, klasifikaci produktů, simulace regrese dějů ve výrobě (prediktivní údržba) nebo hledání optimálního nastavení procesu. V současné době není standardizace integrace AI/ML v AAS vydaná, takže tato oblast ještě skýtá mnoho výzev a výzkumný potenciál.

1.9 Přehled výzkumných témat v oblasti AAS

Výzkumná činnost je v oblasti Průmysl 4.0, resp. AAS poměrně aktivní. Soustředí se hlavně na definici problémů a návrhy jejich řešení s ohledem na aktuální situaci. Ačkoliv hlavní slovo v aplikační sféře mají vydané standardy, přináší výzkum nové pohledy a inovativní řešení, která umožňují efektivněji využít moderní metody jako je IoT, cloudový výpočetní výkon, AI/ML, aj.

Témata publikací v rámci oboru Průmysl 4.0, resp. AAS lze kategorizovat do několika hlavních skupin. Tato kategorizace je orientační a nemůže pokrýt kompletně všechny vědecké materiály. V této rešerši jsou tedy rozlišeny příspěvky týkající se:

1. definice struktury AAS, resp. jeho rozšíření,
2. popisu relevantních technologií (např. OPC UA, TSN, 5G) a jejich rolí,
3. ukázek inovativních aplikací s AAS,
4. implementace AAS a možnosti realizace,
5. návrhu propojení AAS s jinou oblastí a dalšími aspekty (např. AI/ML, energetická spotřeba a prediktivní údržba),
6. procesu získávání a zpracovávání informací pro AAS (např. pomocí technik zpracování textu),
7. sdílení dat a utajení citlivých informací,
8. řízení výrobního procesu a horizontální integrace (např. ve spojení s logistikou a skladovým hospodářstvím),
9. definice sémantiky a syntax pro popis prvků a jejich vztahů (např. ontologie) za účelem vytvoření formálního popisu,
10. vertikální integrace od komunikace s prostředkem až po vykonání lokálních obchodních rozhodnutí,
11. funkční a kybernetická bezpečnost kyberfyzikálních systémů.

V následujících podkapitolách budou k vybraným oblastem uvedeny popisy třech zastupujících referencí, které jsou relevantní vzhledem ke kontextu. Jednotlivé akademické příspěvky jsou aktuální, resp. byly uvedeny v posledních pěti letech.

1.9.1 Struktura AAS

Autoři v [18] navrhují použití atributů typu klíč-hodnota definovaného v DIN SPEC 92000 pro označení entit v informačním modelu AAS, které se týkají schopností a požadavků na výrobní operace. Atributy by definovaly typ entity na *požadavek*, *měření*, *nabídka* a *zajištění*. Následně by se na základě těchto atributů vyhodnocovalo párování nabídky a požadavku ve fázi před i po zahájení výroby produktu, čímž by se zjistila vyrobitelnost v daném nastavení výrobní linky.

V [15] je uveden návrh AAS pomocí metodologie modelem řízená architektura. Autoři navrhují v první fázi vytvořit specifický model případové studie, z ní poté vygenerovat AAS. Struktura AAS je tedy řízena modelem a nastavením nástroje pro generování, které může zahrnovat specifické požadavky platné na úrovni podniku. Aby vygenerované AAS splňovalo požadavky kladené standardem, musí obsahovat alespoň základní součásti.

Jeden z návrhů struktury aktivního AAS je prezentován v [14]. Autoři navrhují AAS složené z funkcionalit pro zajištění vyjednávacího algoritmu, ohodnocení výrobních operací, rozhodování mezi nabízenými operacemi a orchestrátoru pro plánování výrobních kroků. Informace pro jednotlivé funkcionality by byly uloženy v modelech v pasivní části AAS. Horizontální komunikace mezi AAS je v tomto případě zajištěna pomocí technologie MQTT, navzdory tomu, že koncepce AAS popisuje nezávislé komunikační rozhraní na bázi HTTP.

1.9.2 Relevantní technologie

Příspěvek [12] navrhuje mapování AAS v JSON formátu na technologii OPC UA, kde hierarchická struktura JSON určuje, zda se jedná o model, proměnnou nebo hodnotu. Ukázána je reprezentace pasivní části AAS a identifikace (hlavičky).

Literární rešerše [51] provedená pomocí automatizovaných nástrojů rozpoznání textu na velkém množství vědeckých článků ukazuje vlastnosti a technologie, které dominují ve spojitosti s konceptem Průmysl 4.0. Výsledky potvrdili, že AAS je nejvhodnější technologií pro komplexní virtuální reprezentaci prostředku, přičemž musí splňovat kritéria identifikace, komunikace, sémantiky, virtuálního popisu, služeb, funkcí a bezpečnosti. Z množství vědeckých článků také vyplynulo, že relevantní technologie ve spojitosti s AAS jsou OPC UA, HTTP, REST, MQTT, AutomationML a MAS. Z hlediska klíčových technologií jsou skloňovány od nejčetnějšího kyberfyzikální systémy, interoperabilita, digitální dvojče, OPC UA, informační model, internet věcí, flexibilita, komunikační technologie a další.

Jak uvádí [5], stále existuje mnoho výzev stran implementace konceptu Průmysl 4.0, které je potřeba vyzkoumat a vyřešit. Mnoho z těchto výzev plyne z transformace spojení IT a OT světa, jako je např. zabezpečení OT zařízení, používání nemoderních

OT prostředků a sjednocení IT a OT rozhraní. Autoři diskutují o technologie TSN jako o vhodném standardu pro zajištění komunikace reálného času, který využívá protokolu PTP pro synchronizaci času. Potvrzují také možnost vytvoření systému pomocí Eclipse BaSyx AAS, který umí synchronizovat čas jednotlivých prostředků na komunikační síti.

1.9.3 Ukázky inovativních aplikací

Příspěvek [35] popisuje použití AAS pro monitorování stavu motoru, přičemž implementace je provedena přímo do PLC, které umožňuje přenesení hodnot voláním svých funkčních bloků pro OPC komunikaci. Rozhraní také umožňuje nastavovat limity, podle kterých potom PLC zařízení vyhodnocuje alarmy a následné akce.

Jak navrhuje [7], AAS je také možné použít jako virtuální obálku pro PLC program definovaný normou IEC 61131-3. Jednotlivé položky softwarové struktury vybavení PLC mohou být modelovány pomocí datových elementů modelu AAS spolu s hardwarovou konfigurací obsahující seznamy vstupů a výstupů. V případě integrace PLC jádra je možné dokonce AAS používat jako virtuální PLC.

Autoři v [57] navrhují a ukazují použití AAS pro řízení robotického manipulátoru standardizovaným přístupem dle RAMI 4.0. V této aplikaci vznikl průmyslový kyberfyzikální systém, který zapouzdřuje pohybové regulační smyčky pomocí standardního rozhraní, umožňujícího konfiguraci, ovládání a monitorování stavu.

1.9.4 Implementace a možnosti realizace AAS

V [60] je demonstrováno nasazení AAS na výukový panel obsahující dopravníkové pásy, roboty, PLC, senzory a gateway zařízení s web aplikací, přičemž každá z těchto komponent má své AAS a komunikuje s ostatními pomocí vybraných komunikačních technologií.

Z hlediska implementace I4.0 komponenty popisuje [28] vrstvovou architekturu, která se sestává směrem nahoru z funkční, operační a servisní vrstvy. Jako příklad je uveden robot řízený robotickým kontrolérem, který je ovládaný pomocí PLC, které komunikuje s počítačem, např. v podobě jednodeskového počítače.

Náplní v [61] je prezentace současných možností vývoje AAS a jeho implementace umožňující vývoj digitálního řešení pro kyberfyzikální aplikace. Studie ukazuje architekturu založenou na propojení reálného a virtuálního světa pomocí technologie OPC UA, přičemž virtuální část je rozdělena na část edge a cloudovou. V edge části běží AAS shromažďující data, přičemž v cloudové části běží služby a webové aplikace. Příspěvek také popisuje proces generování AAS a mapování souboru AASX na OPC UA informační model.

1.9.5 Propojení s jinou oblastí a dalšími aspekty

Článek [50] přináší návrh použití AI technik pro spravování metadat prostředku společně s AAS, resp. navrhují AAS pro AI prostředek. Autoři ukazují možnosti prezentace informací pojící se s celým řetězcem nasazení obecné AI techniky od přípravy dat až po operační fázi, přičemž datové typy dělí na textové, dataset, model a metadata. Zvolili hierarchickou koncepci, kdy každá část AI metody, jako je model, algoritmus a dataset, je vlastní entitou, a tedy má své AAS. Tato koncepce umožňuje volbu kombinace datasetu a AI algoritmu ve fázi ladění.

Údržba jedním z hlavních aspektů průmyslové výroby. Prediktivní údržba se na základě historických dat z výroby snaží naplánovat údržbové akce, aby se snížily náklady na odstávky a snížila pravděpodobnost závažných poruch. Řetězec tvořící funkcionalitu prediktivní údržby se skládá z procesu získávání dat, jejich zpracování a procesu rozhodování, resp. estimace zbývajícího času provozu (angl. *Remaining Useful Lifetime*). Proces estimace RUL většinou zahrnuje techniky strojového učení, jako je klasifikace na základě hlavních příznaků, nebo umělé inteligence, jako je vytvoření sofistikovaného modelu. Autoři v článku [8] navrhují zabalit funkcionalitu zpracování dat a rozhodování pomocí AAS, čímž by se prediktivní údržba stala jednou z funkcí systému tzv. chytré továrny.

Interakce s člověkem je jeden z hlavních aspektů standardní koncepce průmyslové výroby. V tzv. chytré továrně se interakce s člověkem transformuje na integraci do procesu komplexnějšího rozhodování nebo činností (např. montáž nebo údržbu), které nelze zatím automatizovat. Člověk tedy musí získat dostatek relevantních informací (např. relevantní výrobní informace, seznam komponentů nebo návod), aby mohl udělat patřičné rozhodnutí nebo aby mohl vykonat správně danou akci. V [25] jsou uvedeny požadavky na model AAS pro interakci s člověkem provádějící údržbu. Model interakce s člověkem není zatím specificky standardizován, a proto k tomu lze přistupovat z pohledu AAS jako k obecnému aspektu.

1.9.6 Získávání a zpracování informací

Typická struktura AI/ML systému, který se nasazuje v průmyslové výrobě je uvedena v [52]. Autoři uvádějí variantu, kdy většina výpočtů je prováděna na *edge* úrovni, což umožňuje nasazení v systémech reálného času. *Cloud* úroveň slouží pro trénování modelů. Jednotlivé komponenty jsou propojeny pomocí síťových služeb a integrovány do MES/MOM. Autoři také diskutují vhodnost jednotného rozhraní jak ze strany výrobních prostředků, tak ze strany serverových AI/ML služeb, což je stále výzvou AAS.

Proces získávání informací by měl dle konceptu Průmysl 4.0 probíhat automaticky v rámci celého životního cyklu výrobku, takže jednotlivé informace už budou kontextově uloženy. Jedná se o dokumenty popisující produkt, ale také o provozní dokumenty vznikající v rámci výroby, jako jsou např. reporty a statistiky. Při přechodu na technologii AAS se ale musí ohromné množství stávajících dokumentů v digitální podobě zpracovat a informace uložit dle kontextu, přičemž se využijí ML nástroje pro zpracování textů a dalších formátů. V [58] je představen takovýto proces tvorby grafově orientovaného kontextu z výrobních dokumentů na základě vzdálenosti pozice slov v dokumentu.

Příspěvek [29] navrhuje metodologii pro zpracování dat pro AAS za využití formátu AutomationML. Tento proces zahrnuje jak zpracování dat do společného úložiště, tak prezentaci dat jinému účastníku pomocí AAS. Díky této metodologii je možné zpracovat heterogenní informace z již existujících software a technik uplatňujících se ve fázi návrhu výrobku.

1.9.7 Sdílení dat

Článek [32] spojuje technologie AAS, OPC UA a Eclipse Dataspace Connector (EDSC), přičemž navrhuje datový model pro zajištění interoperability mezi podniky. Navrhovaná architektura implementuje koncept SMaaS (Sustainable Manufacturing-as-a-Service), přičemž horizontální integrace je zajištěna výměnou dat EDSC mezi AAS jednotlivých podniků, resp. přes hranice podniků. Autoři ale uvádějí, že praktická realizace takovéto decentralizovaně řízené ekonomiky pomocí dat je obtížná. Další výzvou je synchronizace řízení výroby pomocí AAS a úplné sjednocení významu informací mezi AAS mezi podniky.

Myšlenkou přechodu ke konceptu „funkce jako služba” se zabývá i [54]. Autoři navrhují otevřenou architekturu systému Smart Factory Web jako řešení pro otevřené virtuální tržiště v oblasti průmyslové výroby. Pro nasazení takovéhoto systému je ale zapotřebí ještě vyřešit mnoho technických i výzkumných výzev, jako je volba nejlepší IT strategie, požadavky na systém, parametry systému, volba technologií a také volba obchodního modelu. Proces obchodu výrobní služby se sestává z řetězce poptávky, nabídky, rozhodnutí, výroby a předání výsledků, přičemž ve fázi specifikace poptávky a nabídky se uplatní s výhodou ontologie. Autoři popisují výhody použití AAS v tomto systému pro registraci entit nebo i pro interakci ve fázi poptávky a nabídky.

Technologie pro sdílení výrobních data skýtá v současné době mnoho technických i akademických výzev, jako je např. zabezpečení spojení nebo vylepšení vyjednávacího protokolu. Příspěvek [24] navrhuje architekturu založenou na konceptu Gaia-X a technologii AAS. Celková architektura je založena na konceptu vyjednávání služeb, resp. návrh je založen na datových službách, které jsou po kladném vyjednání zpřístupněny určitému příjemci od určitého poskytovatele. Autoři navrhují obalení jednotlivých entit pomocí AAS, přičemž definují šablony jednotlivých potřebných modelů.

1.9.8 Řízení výrobního procesu

Příspěvek [27] poukazuje na vhodnost standardu IEEE 2660.1 pro návrh komunikace mezi prostředkem a agentem v MAS pro řízení výroby, procesu a budov. Agent v rámci kyberfyzikálního systému je součástí informační části, tedy AAS. Autoři také potvrzují vhodnost MAS technologie pro řízení výroby, který umožňuje distribuci inteligence a lokální rozhodování na síť navzájem komunikujících agentů. Mezi problémy v této oblasti a možnostmi dalšího výzkumu patří modernizace FIPA standardů o koncept průmyslového kyberfyzikálního systému, rozšíření metriky komunikace, resp. standardu ISO/IEC 25010, aplikace reálného času umožňujícího deterministické řízení pomocí MAS a případně začlenění dalších metod, jako je AI/ML.

V [10] je popsán návrh řízení výroby pomocí AAS, který odděluje proces a prostředky. Na základě schopností a výrobních požadavků, které se vytvoří při zavedení produktu do výroby pomocí MES, je potom možné dynamicky provést párování. Jako komunikaci autoři použili společnou TCP sběrnici, přičemž data ze zařízení jsou přenášena prostřednictvím OPC UA.

V příspěvku [23] jsou modelovány potřebné části AAS pro zajištění vykonávání a dynamické plánování procesu výroby. Systém je založen na technologii holonického systému Janus SARL, který je zapouzdřen a který řeší vyjednávací proces. Holonický agent komunikuje s AAS prostřednictvím OPC UA a REST technologií. Autoři naznačují možnost implementace vyjednávacího algoritmu, který by využíval data ze společného datového prostoru zvaného Shared Production, umožňujícího párování i mimo meze samotného podniku, čímž by se zajistila horizontální integrace.

1.9.9 Sémantika a syntax

Shrnutí [3] ukazuje četnost vědeckých článků týkajících se sémantiky v posledních pěti letech. Jednou z klíčových úloh sémantiky je interoperabilita mezi stroji a komunikace znalostí na bázi uložených informací, což je prekurzorem systému reagujícího dynamicky na nastalé problémy. Z rešerše vyplynulo, že pro tvorbu informačního modelu AAS se nejvíce používají ontologie RDF a OWL. Z hlediska sémantiky komunikace je časté použití informační a komunikačních technologií OPC UA a Semantic Web of Things. Z průzkumu také vyplývá, že formální standardizace AAS není ještě úplná, resp. chybí sjednocující popis beroucí v potaz již vytvořené popisy dílčích aspektů výroby, jako je např. prediktivní údržba. Také je potřeba vyřešit nedostatečnost formálního popisu založeného na logice nepodporující zpracování numerických hodnot. Neméně důležitým problémem z hlediska sémantiky je popis a začlenění modelu člověka v procesu výroby pro přenos jednoduchého rozhodování na stroje a pro integraci člověka do procesu komplexnějšího rozhodování.

Příspěvek [9] rozebírá možnost interoperability mezi kyberfyzikálními systémy použitím standardu IEEE 1451 pro ontologie, resp. JSON-LD technologie pro vytvoření kontextu. Pomocí tohoto nástroje lze vytvořit ontologii, která je propojitelná s OWL a RDF, přičemž autoři uvedli příklad popisu komunikace s převodníkem.

Pro párování schopností výroby a poptávky výrobních operací se jeví jako nejlepší nástroj ontologie, jak je rozebráno v [19], přičemž je ale nutné zvolit vhodný jazyk a integraci. Autoři ukazují architekturu založenou na službě s ontologií, na kterou se připojují jednotlivé AAS. Jako jazyk pro interakci s ontologií zvolili autoři SPARQL, přičemž služba umožňuje komunikaci pomocí API. Jako výhled do budoucna je uvedena implementace kontroly vyrobitelnosti, kterou by tato služba mohla také podporovat.

1.9.10 Vertikální integrace

Článek [48] demonstruje vertikální integraci výpočetních služeb založené na FCP architektuře propojené s OT zařízeními pomocí TSN komunikace. Autoři také potvrzují vhodnost těchto technologií v rámci implementace kyberfyzikálního systému obsahujícího AAS. Rozvíjející se standard TSN avšak ještě stále skýtá další výzkumné výzvy a nedořešené problémy, např. v podobě konfigurace sítě za běhu a její řízení. Autoři tedy navrhují konfigurační prvek, který zároveň řídí komunikaci dle priority a *deadline* zpráv za účelem splnění včasnosti, jakožto nutné podmínky determinismu.

Při použití RFID technologie pro značení produktů ve výrobě vznikají problémy, které se týkají neaktivní komunikace produktu v rámci systému, což se může projevit např. tím, že se neuloží informace o chybách, jako je např. přerušení výroby s následným vyhozením apod. Pomocí vertikální integrace se tyto problémy mohou zmírnit, jak uvádí [6], vytvořením zařízení, které bude aktivně komunikovat se systémem a které bude v průběhu životního cyklu výrobku ukládat informace o výrobě do jeho interní pasivní paměti. Předpokladem je, že se ve všech etapách výrobek spojí se zařízením. Další výhodou je decentralizace informací a fakt, že lze paměť přímo na výrobku pokládat za jediný bod pravdivých informací.

Návrh architektury podporující vertikální integraci dle RAMI 4.0 ukazuje [62], přičemž vrstva procesní instrumentace (prostředků) je propojena s AAS typu D pomocí TSN, které jsou agregovány pomocí vrstvy AAS typu R. V nadřazené vrstvě řízení výroby se nacházejí služby, jako je detekce anomálií, řídicí modul, plánovací modul a monitorovací modul. Směrem nahoru se nacházejí informační služby interagující se zákazníkem. Tento přístup se zdá být kompromisem mezi *flat* architekturou a vrstevnatým modelem děleným podle funkcí jednotlivých softwarových modulů.

1.9.11 Funkční a kybernetická bezpečnost

V [59] je definován model hrozeb z hlediska kybernetické i funkční bezpečnosti obecného kyberfyzikálního a IoT systému. Autoři také nabízí techniky ke zmírnění těchto rizik ve fázi návrhu i provozu, jako je architektura založená na modelu, deviace provozních parametrů, zabezpečené protokoly a provozní diagnostika.

Článek [20] komplexně shrnuje aspekty kybernetické bezpečnosti kyberfyzikálních systémů. I když se přímo autoři nezaměřují na AAS, uvedené problémy a možnosti řešení se na ně vztahují. Jelikož se jedná o spojení virtuálního a fyzického světa, musí se vyhodnotit u těchto systémů všechny typy hrozeb, přičemž pro samotné AAS jsou rizikové hrozby ve virtuální doméně. Autoři kategorizují hrozby do dimenzí podle typu systému, úrovně implementace a bezpečnosti. Jelikož AAS interaguje s okolím pomocí komunikace, vyplývají rizika i z této části. Autoři obecně navrhují a postupují podle platných postupů pro vyhodnocování bezpečnosti, jako je např. metoda STRIDE.

Příspěvek [17] navrhuje referenční architekturu poskytující základ pro vývoj bezpečného AAS. Z pořádaného semináře vyplynulo, že požadavky a možnosti stran kybernetické a funkční bezpečnosti digitalizace, resp. AAS lze kategorizovat na bezpečný návrh (specifikace bezpečnosti už ve fázi návrhu), spolupráce mezi podniky (řízení toku informací za hranice podniku) a digitální dvojče (testování bezpečnosti na modelu). Autoři mapují proces funkční a kybernetické bezpečnosti do časových fází (návrh, vývoj, činnost) a účastníků (výrobce, integrátor, provozovatel). Navrhovaná referenční architektura obsahuje modely obsahující informace pro kybernetickou a funkční bezpečnost. V aktivní části jsou bezpečnostní funkce a metody (např. detektor útoku na bázi AI). V API části se uplatňují techniky spojené s HTTP komunikací, jako je autentizace pomocí certifikátů, autorizace na základě rolí, validace a vyhodnocení výkonu.

2 VÝSLEDKY PRÁCE

Následující kapitola obsahuje okomentované publikační výsledky relevantní k tématu tohoto dokumentu řazené chronologicky. Jednotlivé podkapitoly se zabývají jednotlivými publikacemi, přičemž je uveden stručný popis obsahu publikace a dále je diskutováno zasazení do kontextu AAS, resp. konceptu Průmysl 4.0. Řazení podkapitol odpovídá řazení textů publikací nacházejících se v příloze A tohoto dokumentu.

Tabulka 2.1 se snaží zařadit uvedené publikační činnosti do kategorií výzkumné oblasti se zaměřením na AAS. Tyto kategorie jsou informativní a vychází částečně z kap. 1.9, přičemž některé publikace jsou zařazeny do více kategorií. Řazení publikací v tabulce odpovídá řazení v následující části, resp. seznamu uvedenému v příloze A. Číslo publikace v prvním sloupci tabulky 2.1 odpovídá řazení publikací a číslu podkapitoly, která se dané publikaci věnuji blíže. Výpis zvolených kategorií:

- K1 - struktura AAS,
- K2 - diskuze relevantních technologií,
- K3 - inovativní aplikace,
- K4 - implementace a realizace,
- K5 - propojení s jinou oblastí (AI/ML, prediktivní údržba, energetika),
- K6 - získávání a zpracování informací,
- K7 - sdílení a ochrana dat,
- K8 - řízení výrobního procesu (horizontální integrace),
- K9 - sémantika a popis informací,
- K10 - vertikální integrace,
- K11 - funkční a kybernetická bezpečnost,
- K12 - modelování procesu řízení výroby,
- K13 - integrace člověka,
- K14 - demonstrátor AAS,
- K15 - digitální dvojče,
- K16 - AAS a MES.

Č.	K1	K2	K3	K4	K5	K8	K9	K10	K11	K12	K13	K14	K15	K16
1		x				x			x					
2			x	x				x			x			
3						x		x				x		
4		x						x						
5			x	x				x						
6		x												
7													x	
8				x		x	x			x		x		
9	x		x					x						x
10				x								x		x
11			x		x			x						
12						x		x				x		
13		x												

Tab. 2.1: Zařazení publikací do kategorií vědeckých článků týkajících se AAS

2.1 Zavedení Průmyslu 4.0 do diskrétní výroby: možnosti a úskalí

V publikaci [AZBMKB18] jsou prezentovány myšlenky konceptu Průmysl 4.0 s ohledem na tehdejší stav poznání. Dále jsou prezentovány aplikace a možnosti zavedení zmíněných technologií do průmyslové výroby, resp. diskrétní výroby. Mezi hlavní přínosy publikace patří popis a zasazení vyjednávacího algoritmu do sféry řízení výrobního procesu. Tento algoritmus se sestává ze stavového automatu pro účastníka typu služba a účastníka typu klient. Analýzou stavových automatů a jejich vzájemné interakce v aplikaci průmyslové výroby vyvstaly různé problémy a otázky, které je ještě potřeba vyřešit.

Publikace byla vytvořena v rámci mezinárodního projektu RACAS, který se věnoval integraci AAS do průmyslové výroby. Jedná se o mé první dílo v oblasti, přičemž v tehdejší době vyvstanula myšlenka použít AAS i jako prvek podílející se aktivně na řízení výroby i na úrovni strojů a produktů ve výrobní lince. Spolu s německými kolegy, kteří se aktivně podíleli na tvorbě standardu v rámci organizace VDI/VDE jsme hledali možnosti uplatnění AAS i na této úrovni řízení s následnou snahou o formalizaci algoritmů v podobě stavových automatů.

2.2 AAS pro operátora v rámci konceptu Průmysl 4.0

Publikace [MZABVBDSB18] popisuje systém chytrého oděvu, který snímá veličiny v okolí člověka a poskytuje je ve standardizovaném formátu AAS. V tomto systému byla implementace AAS provedena pomocí technologie OPC UA, na kterou byly namapovány potřebné části informačního modelu AAS. Role vytvořeného prvku byla pojata jako HMI, tedy bylo umožněno pouze čtení naměřených informací. Pomocí technologie node-red byly data zpracovávány do formátu, který je vhodný pro vizualizaci.

AAS tedy lze použít i v roli rozhraní pro operátora (HMI) v rámci řídicího systém výroby. Důležitější přínos ale spočívá v mapování informačního modelu AAS na informační model OPC UA. Tyto informační modely mají podobné základy, ale existuje mnoho dílčích problémů, které zabraňují k jejich sjednocení. V současné době se tyto problémy řeší v rámci evropské standardizační skupiny *OPC UA for AAS*. Sjednocením těchto informačních modelů by došlo ke standardizaci podpory technologie OPC UA pro implementaci reaktivního AAS.

2.3 Testbed Průmyslu 4.0: principy a návrh

Publikace [KBBA18] prezentuje návrh a principy testbedu implementujícího decentralizované řízení výrobního procesu kombinujícího dávkovou a diskrétní výrobu. Testbed je tvořen výrobními buňkami: sklad nádob, sklad surovin, generátor stlačeného plynu, míchač, manipulátor, aj. Každá výrobní buňka obsahuje PLC spolu s HMI a chová se autonomně. Buňky mohou být povelovány nadřazeným systémem. Zpočátku komunikace s jednotlivými buňkami probíhala pomocí protokolu S7, ale již od počátku bylo v plánu přejít na technologii OPC UA. Oživení testbedu proběhlo pomocí vytvořeného MES systému podle standardu MOM definovaný normou ISA-95, avšak účelem celého zařízení je implementovat do každé výrobní buňku AAS s funkcí řízení výroby. Každý nový produkt by si tedy pomocí svého AAS řídil výrobu sám dle svého vnitřního předpisu a vyjednával by si zajištění výrobních operací.

Tento testbed byl navržen a realizován na Ústavu automatizace a měřicí techniky Fakulty elektrotechniky a komunikačních technologií, VUT v Brně. Na tvorbě se podíleli jak zaměstnanci, tak studenti formou svých závěrečných prací. Vzniklo tak zařízení, do kterého je možné implementovat jakékoliv řízení na bázi PLC, přičemž jednotlivé výrobní buňky jsou oddělitelné od zbytku systému a rekonfigurovatelné na jiné místo na pracovní ploše. V případě přítomnosti více buněk stejného typu je tedy možné demonstrovat řízení na bázi AAS, kdy dojde k dynamickému přeplánování za vzniku simulované poruchy. Implementace AAS přímo do PLC ještě není standardizovaná, avšak existují nějaké přístupy a pokusy. Další možností je využít technologii OPC UA, ale ta je většinou v PLC zařízeních omezená a nedisponuje všemi funkcemi jako standardní verze.

2.4 Komunikační systémy pro Průmysl 4.0 a IIoT

Publikace [ZMBABV18] rozebírá možnosti použití TSN komunikací ve spojitosti s I4.0 komponentou. Zejména se zaměřuje na technologii OPC UA jako jednoho z vhodných kandidátů. Použití komunikační technologie ovlivňuje vlastnosti komunikace, zejména při procesu vyjednávání je žádoucí nízká latence mnoha odpovědí. Spíše než rychlost komunikace patří mezi požadované vlastnosti včasnost, determinismus, robustnost a implementovatelnost. TSN komunikační standard je vyvíjen na míru těchto požadavků, přičemž např. pro Ethernet se jedná o standard IEEE 802.1AS využívající protokol PTP. Je nutné avšak současné real-time komunikace tomuto standardu více přiblížit.

V době, kdy se uvažovalo o OPC UA jako o horkém kandidátovi na implementaci AAS, také vznikaly názory na použití TSN komunikačních technologií, zejména pro řízení výroby na nižší úrovni. Heterogenní architektury těchto komunikačních technologií ovšem neumožňují jejich bezproblémovou integraci. AAS by tedy bylo provozováno v nějakém běhovém prostředí, přičemž komunikace směrem nahoru a mezi účastníky by byla zajištěna technologií OPC UA. Na druhé straně směrem k zařízením výroby a k prostředkům by probíhala pomocí TSN komunikace. Také časově kritcké děje, např. kooperace PLC a CNC kontroléru (kooperaci mezi manipulátorem a výrobní buňkou) musí být real-time v případě řízení na lokální úrovni.

2.5 Nové přístupy integrace chytrého oděvu v souladu s Průmysl 4.0

Článek [MABZDDSBKB19] představuje topologie systému pro sběr dat ze senzorů chytrého oděvu - oděv opatřen senzory měřicími okolí člověka - kvalita ovzduší, teplota, orientace v prostoru, aj. Tyto senzory zašité do oděvu mohou komunikovat každý zvlášť s koncentrátorem dat ve stylu IoT. Dalším přínosem publikace ale je návrh AAS pro zapouzdření komunikace s těmito senzory s následnou prezentací dalším účastníkům komunikační síti.

AAS lze použít jako zastřešující obálku i pro data koncentrátor, který sbírá data lokálně ze senzorů. Výhoda je, že senzory lze i konfigurovat pomocí volání metod či nastavení vlastností v informačním modelu. V případě, že nejsou kladeny velké real-time nároky, lze pro komunikaci s prostředky využít i lokální bezdrátovou komunikační technologii, jako je ZigBee postavenou na standardu IEEE 802.15.4 nebo Bluetooth. AAS chytrého oděvu může vystupovat v prostředí autonomně, případně může být součástí AAS operátora.

2.6 TSN jako komunikační technologie budoucnosti v souladu s Průmysl 4.0

Publikace [ZMBAB19] pojednává o vhodnosti současného trendu skupiny IEEE 802.1, resp. nového vývoje vedoucího k souladu TSN s definicí komunikace v pojetí Průmyslu 4.0. Některé standardizované protokoly jsou již vhodné pro real-time komunikace, jako je Profinet IRT, EtherCAT nebo Powerlink, avšak každá z těchto technologií používá jinou metodu k zajištění včasnosti a determinismu v časové oblasti. Mezi hlavní komponenty standardu TSN se řadí časová synchronizace, řízení datového toku a výběr komunikačních cest.

Standard TSN je spojován s pozicí komunikačního standardu pro časové kritické systémy. Objevují se i názory, že by AAS mělo podporovat tento standard nejen jako komunikaci s prostředkem, resp. skupinou prostředků, ale i směrem nahoru, tedy mezi I4.0 komponentami. Jedná se například o situaci spojení CNC stroje se strojem řízeným pomocí PLC. Pokud by se AAS používalo i na řízení těchto vzájemně komunikujících strojů, musí komunikaci TSN podporovat. Tohle pojetí ovšem také implikuje požadavek na běh samotného AAS, který musí být deterministický a splňovat časové požadavky (včasnost).

2.7 Digitální dvojče a AAS v pojetí Průmysl 4.0

Publikace [MBZAB19] prezentuje koncept digitálního dvojčete a diskutuje požadavky na jeho implementaci. Jedinou současnou implementací digitálního dvojčete je AAS, které modeluje jednotlivé aspekty prostředku ve více doménách.

AAS pomocí modelových struktur dokáže zaznamenat jednotlivé aspekty prostředku. Díky standardu AAS je možné namodelovat téměř jakoukoliv funkci, aspekt či chování, přičemž je ale nutné spojit jednotlivé proměnné s významem pomocí dostupných slovníků. Omezení při modelování tedy spíše pramení z nedostupnosti prvku ve slovníku.

2.8 Automatický návrh a implementace AAS jako komponenty výroby dle Průmysl 4.0

Článek [ABMBSBWBKZDD21] se zabývá návrhem a implementací AAS z pohledu aktivního účastníka při řízení výroby. Z hlediska návrhu AAS pro konkrétní prostředek lze použít dostupného software pro vytvoření jednotlivých modelů, což je zdlouhavé a neefektivní obzvláště v případě použití podobných vzorů. Vyvinutá webová aplikace umožňuje správu a automatizaci tohoto procesu.

V rámci této práce byl dále vytvořen demonstrátor Combed, který simuluje výrobní linku obsahující více stejných zařízení. Tato linka je řízená pomocí AAS. Při řízení se hlavně uplatňuje proaktivní část AAS, resp. vyjednávací komponenta, která zajišťuje dynamické párování vyráběného produktu ke stroji pomocí vyjednávacího algoritmu. Simulace výrobní linky byla vytvořena v prostředí ABB Robot Studio a bylo vytvořeno spojení mezi virtuálním strojem a AAS, které běželo mimo toto prostředí. Virtuální scéna byla vytvořena tak, aby umožnila simulovat poruchy strojů.

Další částí byla simulace výrobní linky s více stroji stejného typu modelována pomocí matematického nástroje - systém diskrétních událostí. Pomocí tohoto nástroje lze definovat výrobní čas a poruchy pravděpodobnostním rozložením. Simulace definovaných scénářů ukazuje pravděpodobný čas provedení výroby definovaného počtu výrobků i za přítomnosti poruch strojů.

O výhodách a nevýhodách nasazení technologie AAS se v současné době vedou diskuze a jsou předmětem zkoumání. Automatizovaný nástroj pro návrh a implementaci přispívá k efektivnímu nasazení. Modelováním výroby a provedením simulací lze analyzovat vlastnosti dynamického distribuovaného řízení výroby i za přítomnosti poruch a srovnat výsledky s během tradičního plánování. Problémem také je vytvoření metriky, která by tyto situace vyhodnotila. Nabízí se použít rozšířený průmyslový indikátor OEE (definovaný standardem ISO 22400), jehož vyčíslení je ale v distribuovaném způsobu řízení výroby problematické, protože zdrojová data pro vyčíslení nejsou úplná na jednom místě.

2.9 Přezkoumání role MES v Průmysl 4.0

Publikace [KBAMZJV22] analyzuje roli MES v průmyslovém řídicím systému podle Průmysl 4.0. V novém konceptu už MES nemá centrální úlohu a roli orchestrátora výroby, ale jeho úloha se z hlediska řízení výroby redukovala hlavně na zavedení produktu do výroby, monitorování a vyhodnocení statistik. Řízení a plánování se distribuovalo na jednotlivé účastníky zastřešenými AAS komponentami. Jsou tedy uvedené metamodely umožňující implementaci vyjednávacích algoritmů do AAS pro účastníky typu produkt a služba. Tyto metamodely vycházejí z generického modelu MOM podle ISA-95.

V současné době existuje standard vyjednávacího mechanismu decentralizovaného řízení výroby pomocí AAS, avšak jedná se pouze o základní algoritmus, který selhává v určitých situacích, jako je prioritizace produktu a dynamické přeplánování výrobních front. Vytvoření standardu je zdlouhavý a komplexní proces, přičemž existuje mnoho návrhů a přístupů. Přenos částí ze standardu ISA-95 by mohl být vhodný k urychlení standardizačního procesu.

2.10 Názorný výrobní systém řízený pomocí AAS

Publikace [CA22] ukazuje simulaci výrobního systému, která je řízena pomocí MES prostřednictvím AAS. Jedná se o koncept, kdy výrobní proces jako celek je zapouzdřen pomocí AAS, které interaguje s MES systémem, resp. jeho AAS.

V případě, že tvorba jednotlivých AAS k účastníkům systému řízení výroby je příliš nevýhodné z hlediska zdrojů, je možné použít AAS pro zapouzdření celého výrobního procesu. AAS tedy neplní funkci distribuovaného plánování, ale pouze zapouzdřuje výrobní proces, a tím vytváří standardní rozhraní. Tato publikace vznikla z vedené bakalářské práce a byla prezentována na mezinárodní konferenci.

2.11 AAS - optimalizace spotřeby energie výrobního procesu

Publikace [BKSADHMB22] diskutuje možnost optimalizace výrobního procesu řízeného pomocí AAS distribuovaným způsobem. V procesu vyjednávání poptává produkt operaci po službách, které odpovídají svou nabídkou v podobě ceny. Právě výpočet nabízené ceny může zahrnout různé aspekty (např. výměna nástroje, rekonfigurace stroje, aj.), které zmenšují efektivitu procesu výroby. S optimalizací procesu výroby se může optimalizovat spotřebovaná energie.

Proces vyjednávání, které je zajištěno aktivní částí AAS, zahrnuje výpočet ceny, což představuje číslo, které ohodnocuje poptávanou výrobní operaci. Výpočet ohodnocení není v současné době standardizovaný a může zahrnovat různé aspekty. Pokud započítáme veškerou energii vynaloženou na poptávanou operaci v závislosti na stavu stroje, může distribuovaný řídicí proces plánovat optimálně vzhledem ke spotřebované energii. Do procesu ohodnocení vstupuje i mnoho dalších parametrů, jako je např. priorita, takže ve výsledku může být vliv energetické optimalizace potlačen.

2.12 Experimentální produkční linka schopná demonstrovat principy konceptu Průmysl 4.0

Publikace [MJVZBKA22] popisuje testovací výrobní linku CP-Factory vyrobenou společností Festo, která se sestává ze samostatných výrobních jednotek (strojů) a manipulátoru (mobilní robot), který umí převážet produkty mezi těmito výrobními jednotkami. V současné době komunikace probíhá pomocí technologií RFID (mezi výrobkem a strojem) a TCP mezi stroji, resp. mezi strojem a MES systémem. Výrobní linka má omezené možnosti co se týče komunikace - systémy v základní variantě umožňují pouze základní povely zajišťující chod linky. Každý stroj je řízen pomocí PLC, jehož software lze upravit.

V případě provedení úprav software pro PLC a obslužných software bude možné ke každému stroji přidružit AAS a testovat chování linky v případě implementace distribuovaného řízení. Další možnost implementace AAS spočívá v zastřešení celého výrobního systému a propojení s dalšími výrobními nebo dodavatelskými procesy v rámci horizontální integrace, čímž by se dodavatelský řetězec propojil a vznikl automatický proces.

2.13 Myšlenky konceptu Průmysl 4.0: Sedm let poté

Publikace [ZJVMBKAB22] srovnává původní myšlenky konceptu Průmysl 4.0 a současný stav vývoje v oblasti průmyslové automatizace. Diskutovány jsou architektury a metody pro technologie IIoT, TSN, OPC UA a hlavně AAS. V současné době brzdí nasazení procesů dle konceptu Průmysl 4.0 hlavně: malá úroveň digitalizace podniků, nedostatečná nebo neúplná standardizace technologií, slabá podpora AI/ML algoritmů a nedostatečné zabezpečení (kybernetická a funkční bezpečnost).

Po době turbolentního zkoumání a testování technologií vhodných pro tvorbu chytrých továren se ustálily některé názory na vhodné technologie, jako jsou OPC UA, TSN a zejména AAS, které se bere jako komplexní implementace digitálního dvojčete. Další důležitou technologií, která se dnes hojně využívá je 3D virtualizace stroje / linky, což umožňuje vyřešit mnoho chyb už ve fázi návrhu rámci životního cyklu stroje / produktu.

3 ZÁVĚR

AAS je jedou z ústředních technologií konceptu Průmysl 4.0, resp. chytré továrny a považuje se za implementaci digitálního dvojčete. Návrh a implementace AAS není v současné době ustálená oblast a skýtá mnoho nevyřešených otázek. Tato práce je podána formou souboru vybraných publikací relevantních k tématu, které mají za cíl obsvětlit některé problémy, přinést návrhy řešení a zaznamenat dílčí technická i výzkumná řešení.

3.1 Současné poznání

Koncept Průmysl 4.0 výrazně zasahuje do oblasti řízení výrobního procesu a automatizace. Díky tomuto trendu a tlaku vládních složek se ve výrobních podnicích více nasazují moderní technologie umožňující digitalizaci výroby a přechod ke konceptu tzv. chytré továrny. Technologie pro digitalizaci, virtualizaci a AI/ML jsou dnes již hojně využívány, což se ukázalo jako přínos pro optimalizaci výroby z hlediska efektivity, logistiky a spotřeby energie. Implementace celého konceptu avšak v současné době ještě není úplná hlavně z důvodu standardizace a limitů jednotlivých technologií. Mezi hlavní technologie, které se aktuálně vyvíjejí se snahou o masivní nasazení, patří AAS, což je virtuální obálka jakéhokoliv vlastněného prostředku výrobního podniku.

AAS se používá pro zapouzdření prostředku a tvorbě jeho rozhraní pro interakci s okolním prostředím. Pasivní část poskytuje informační model umožňující uchovávat a prezentovat informace ve strukturované podobě. Pomocí modelů je možné zaznamenat jednotlivé aspekty prostředku a prezentovat je ve formě informací. Za účelem standardizování formy těchto informací je nutné používat definované pojmy z globálních slovníků jako je eclass nebo CDC.

Pro nasazení AAS se již ustavilo použití jednotlivých technologií, jako je OPC UA pro implementaci pasivní části AAS a pro komunikaci mezi AAS a ostatními účastníky. Dále je to REST API pro interakci AAS a účastníků na stejné úrovni nebo real-time komunikační technologie podle standardu TSN pro interakci s prostředky a výrobními zařízeními. AAS se také považuje za jedinou komplexní implementaci digitálního dvojčete, které je základem kyber-fyzikálního systému. AAS spolu se svým prostředkem tvoří tzv. I4.0 komponentu, jakožto základní prvek tzv. chytré továrny.

Jedním z v praxi dosud nedostatečně doceněných a aplikovaných pilířů je decentralizace, která představuje potenciál pro revoluční změnu v oblasti řízení a plánování výroby. Je to právě decentralizace, která umožňuje dynamicky řešit nahodilé poruchy ve výrobě. Decentralizace také přenáší určitou část řízení výroby na lokální úroveň tvořenou účastníky, jako je výrobní linka. Ačkoliv jsou vyjednávací algoritmy původně určeny na interakci mezi výrobními linkami / podniky, uvažuje se i o implementaci přímo uvnitř výrobní linky, kde si vyjednávání výrobních operací poptává přímo samotný produkt nebo výrobní dávka.

3.2 Aktuální problémy

V důsledku transformace myšlenek konceptu Průmysl 4.0 do průmyslové praxe plynou různé obtíže a problémy, které se nejčastěji pojí s procesem tvorby definic, standardů a také s implementací jednotlivých technologií. Použité technologie musí splňovat řadu požadavků, které jdou mnohdy proti sobě. Tento problém pramení z faktu, že se jednotlivé technologie už dlouhou dobu v praxi používají a byly vyvinuty dříve, než vznikly požadavky a standardy na technologie zapadající do konceptu Průmysl 4.0. Otázkou je, zda tyto technologie za nových okolností používat, zda je modifikovat nebo zda definovat a vytvořit technologie nové. Příkladem mohou být real-time komunikace (Profinet IRT, EtherCAT, Powerlink) používané na úrovni bezprostředního řízení, který by měly splňovat standard TSN komunikací.

Mezi hlavní problémy brzdící nasazování AAS do praxe patří neúplná standardizace. Některé části AAS (pasivní část a interakce) již standardizovány jsou, ovšem např. aktivní část AAS, sémantika I4.0 komunikace a bezpečnost AAS ještě standardizovány nejsou. Firmy a systémoví integrátoři tak zatím mohou implementovat architekturu a jednotlivé technologie podle svého výkladu. Tvorba standardů je úlohou pracovních standardizačních skupin skládajících se z představitelů firem, výzkumných a jiných organizacích. Vytvoření dokumentu se standardem je ovšem dlouhý a komplexní proces, který musí zohlednit jak již existující standardy, tak realizaci nových myšlenek.

Mezi další technická úskalí nasazení AAS do praxe lze řadit slabou digitalizaci firem, které často nedisponují potřebným vybavením výpočetní techniky a potřebnou infrastrukturou. V současné době lze AAS provozovat v plné komplexitě pouze pomocí serverové infrastruktury, jako např. firma Festo. Pro implementaci AAS přímo do PLC stroje tedy často chybí výpočetní výkon resp. omezené technické vybavení, které musí implementovat výrobci těchto zařízení. Pro decentralizaci řízení výroby se často musí volit kompromisní řešení mezi mírou implementace a dostupným výkonem daných zařízení včetně komunikační sítě. Také implementace vyjednávacího algoritmu skýtá problémy v podobě nedefinované reakce na speciální situace a limity komunikačních prostředků, které musí zvládnout zvýšený provoz pramenící z distribuce aktivních účastníků.

Další problémy nasazování AAS pramení z neúplného vědeckého výzkumu. Jedná se např. o kalkulaci ceny za službu v procesu vyjednávání výrobních operací (na úrovni výrobních podniků se cena stanoví jako cena produktu), kdy je potřeba zohlednit energetickou optimalizaci, redukovat prostoje, dynamicky zohledňovat priority výroby produktů, redukovat opotřebení strojů, aj. Dynamické plánování decentralizovaného systému je z větší části probádaná oblast, avšak je zde prostor pro další výzkum a vývoj algoritmů, které budou deterministické, formální a nebudou obsahovat nebezpečné situace, jako je *deadlock* nebo *livelock*.

Důležitým aspektem provozu IT a OT prostředků je kybernetická bezpečnost. Výrobci komponent tedy musí reagovat na současné standardy, zejména u prostředků průmyslové automatizace. Na druhé straně je snaha o harmonizaci současných standardů s technologií AAS.

3.3 Přínosy v oblasti

Hlavní přínosy v oblasti návrhu a implementace AAS do průmyslové výroby jsou zaznamenány v přiložených publikacích. V těchto publikacích jsou diskutovány problémy implementace AAS a relevantních technologií do řídicího systému průmyslové výroby a návrh na jejich řešení. Jsou zde demonstrovány principy konceptu Průmysl 4.0 se zaměřením na digitalizaci, komunikaci a AAS. Mezi návrhy řešení vědeckých problému lze začlenit návrh architektury aktivní části AAS umožňující orchestraci výroby pomocí standardního přístupu definovaného v ISA-95. O konečné definici ovšem rozhodne až budoucí standard.

Jedním z hlavních zdrojů přínosů byla aktivní spolupráce na evropském projektu RACAS, který se zabýval implementací AAS do řízení výrobní linky a dalšími aspekty nasazení AAS, jako je tvorba informačního modelu a mapování na technologii OPC UA. Dalším zdrojem je podíl na vývoji a výrobě testbedu obsahující výrobní buňky, na kterém je možné demonstrovat decentralizované řízení. Současné řízení zatím obsahuje centrální vyjednávací algoritmus, který je nachystán na decentralizaci do jednotlivých výrobních buněk. Další reálné aplikace používají AAS v různých architekturách, a to jako informační obálku pro stroj / výrobek nebo jako obálku pro celou výrobní linku.

Mezi relevantní realizované technické výsledky patří webová aplikace (Wizard) pro návrh a vytvoření AAS s možností použití šablon. Tato aplikace je schopná vytvořit pasivní část AAS. Dalším výsledkem je virtuální demonstrátor (Combed) obsahující výrobní linku s redundantními stroji, které jsou napojeny pomocí vytvořeného rozhraní na AAS a je možné ji pomocí těchto AAS řídit. Namodelováním procesu řízení výrobní linky pomocí vyjednávacího algoritmu vznikl demonstrátor, který umožňuje simulovat chod výrobního procesu ve zkráceném čase, přičemž výrobní čas strojů a poruch je modelován pomocí pravděpodobnostního rozložení.

3.4 Zhodnocení

Závěrem lze říci, že tato práce přinesla zhodnocení současného stavu problematiky aplikace technologií dle konceptu Průmysl 4.0 se zaměřením na AAS. Také přinesla dílčí technická i výzkumná řešení na některé problémy, které v oblasti průmyslové automatizace zabraňují reálnému nasazení ve firmách. Navzdory tomu se podařilo navrhnout a implementovat dílčí aplikace a demonstrátory, které ukazují použití AAS z různých aspektů a také proces jeho nasazení. Ačkoliv proces standardizace brzdí širokému nasazení, je už dnes možné alespoň ukázat výhody technologie pramenící z jednotného popisu a přístupu, kterému bude každý rozumět, takže bude možné lépe integrovat a propojovat jednotlivá zařízení a výrobní linky.

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SEZNAM SYMBOLŮ, VELIČIN A ZKRATEK

I4.0 Průmysl 4.0 – Industry 4.0

AAS administrační obálka komponenty – Asset Administration Shell

TSN časové kritické komunikace – Time Sensitive Networks

RAMI referenční architektura Průmyslu 4.0 – Reference Architectural Model Industrie 4.0

OWL ontologický značkovací jazyk – Ontology Web Language

RDF systém popisu zdrojů – Resource Description Framework

URI jednotný identifikátor zdroje – Uniform Resource Identificator

URL jednotný lokátor zdroje – Uniform Resource Locator

IRDI mezinárodní identifikátor zdroje – Internationalized Resource Identifier

GUID globálně unikátní identifikátor – Globally Unique Identifier

XML obecný značkovací jazyk – Extensible Markup Language

XSD definice schéma XML – XML Schema Definition

JSON JavaScriptový objektový zápis – JavaScript Object Notation

AASX formát souboru balíčku AAS – package file format for AAS

PLC programovatelný logický automat – Programmable Logic Controller

PPR model výrobek-proces-prostředek – Product-Process-Resource

OPC UA univerzální komunikační prostředek na bázi OPC – OPC Unified Architecture

TLS zabezpečení na transportní vrstvě – Transport Layer Security

REST reprezentační prostředek na bázi HTTP – Representational State Transfer

API aplikační rozhraní aplikace – Application Programming Interface

MQTT komunikační protokol na bázi TCP – MQ Telemetry Transport

HTTPS internetový zabezpečený protokol – Hypertext Transfer Protocol Secure

IEC Mezinárodní elektrotechnická komise – International Electrotechnical Commission

AML jazyk AutomationML – AutomationML

CDD Globální slovník vlastností – Common Data Dictionary

SOA Architektura zaměřená na služby – Service-Oriented Architecture

ROA Přístup zaměřený na prostředky – Resource-Oriented Approach

HMI Rozhraní člověk-stroj – Human–Machine Interface

PTP Protokol přesného času – Precision Time Protocol

CNC Číslicově řízený stroj – Computer Numeric Control

OEE Indikátor efektivity výroby – Overall Equipment Effectiveness

IoT Internet věcí – Internet of Things

IIoT Internet věcí v průmyslu – Industrial Internet of Things

MES Systém řízení výroby – Manufacturing Execution System

MOM Standard pro systém řízení výroby – Manufacturing Operations Management

TCP Internetový spojovaný protokol – Transmission Control Protocol

RFID Identifikace pomocí rádia – Radio-Frequency Identification

AI Umělá inteligence – Artificial Intelligence

ML Strojové učení – Machine Learning

HTTP Internetový protokol – Hypertext Transfer Protocol

MAS Multiagentní systémy – Multi-agent System

FCP Architektura lokálních výpočetních jednotek – Fog Computing Platform

OT Operační technologie – Operational Technology

MDA metodika systémového návrhu softfare dle modelu – Model Driven Architecture

MTL metrická temporální logika – Metric Temporal Logic

UML modelovací jazyk – Unified Modeling Language

TRL úroveň připravenosti technologie – Technology Readiness Level

FMS strojová výroba – Flexible Manufacturing System

FSM konečný stavový automat – Finite State Machine

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Implementing Industry 4.0 in Discrete Manufacturing: Options and Drawbacks

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Abstract: The Industry 4.0 concept embodies a topic widely discussed during specialized meetings and tutorials. Originally, this approach was interpreted as an attempt to shift industrial processes towards establishing the fully digitized smart factory; at present, however, it already exerts an influence on many other fields and disciplines. In this article, the concept is described from the perspective of discrete manufacturing. The implementation possibilities are outlined, with options such as the Asset Administrative Shell or Consumer-Provider model introduced in greater detail. We also mention some drawbacks to implementing job shop scheduling as provided by the latter option; these disadvantages include, for instance, the deadlock situation. Some methods to solve the problem are demonstrated to facilitate well-balanced presentation. A job shop scheduling algorithm using the AAS is also addressed, and a new evaluation function is proposed.

Keywords: Manufacturing plant control, decentralized and distributed control, deadlock

1. INTRODUCTION

The challenges and needs in discrete manufacturing is very influenced by the concept of German Industry 4.0. As development and production goes further and higher, some strategies and ideas are possible and accessible. Although it has industry in name, this concept involves all parts of society because new technologies are researched and the job market is changing. Essentially, it brings new ideas and strategies together. The integral part of it is science and engineering therefore electrical, mechanical, and software engineering are crucial.

Recently, there are many articles about this concept, e.g. [Zezulka et al. (2016)] or [Marcon et al. (2017)]. Lets repeat only the integral areas of the concept I4.0 (see Fig. 1):

- IIoT and CPS - The concept of Industrial Internet of Things comes from using IoT technology in industrial area. The Cyber-Physical System integrates the hardware part with its computational capabilities referring to its configuration, identification, simulation, energy consumption, and other properties defining the system. The interconnection of CPSs is one of the key concepts of Industry 4.0.
- Additive manufacturing - It brings new paradigm of the product manufacturing. Although there are many problems, this area is very promising.
- Big data - The collecting of data, which amount is needed to be higher than before, is tricky. Especially, when the connection is not the best like wireless transferring that is demanded more and more. Here are often used methods for high data rate collection and then artificial intelligence can process these data or the data are saved into a database.
- Artificial intelligence - It comes where data are collected. Using the right algorithm is the crucial part of effective decision making. Also predictive maintenance is demanded as the production is perceived as the function of time.
- Robots - The increasing development and use of collaborative robots (cobots) ensures safe cooperation with humans. Robots perform routine operations. There are ways how to include human in manufacturing only to make though operational decisions.
- Virtual reality - Virtual reality might be used for simulation and modelling. The promising area is also the augmented reality where the reality and virtual reality is combined together.
- Business - Business is also impacted and some new business models has to be created. There is also a way to use Industry 4.0 concept and automatize procedures using standards.

This article comes out of the project that tries to implement some new features using concept Industry 4.0 to mid-range companies for discrete manufacturing. This type of company has usually several types of machines mostly based on CNC (Computer Numeric Control). They usually

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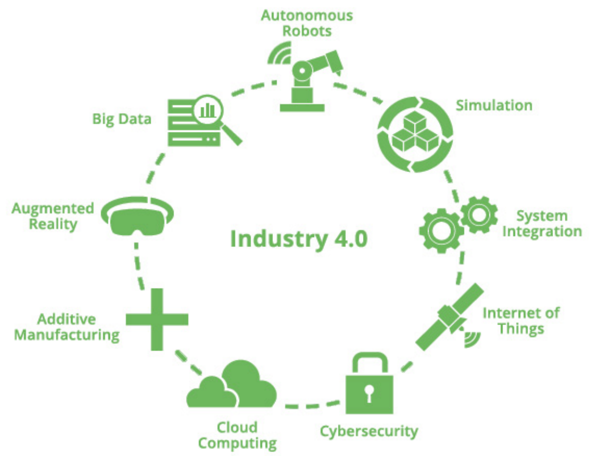

Fig. 1. The integral ares of I4.0 [LeapAustralia (2017)]

have ERP (Enterprise Resource Planning) and some of them have also MES (Manufacturing Execution System). The organization of the machines is line or standalone machines guaranteeing specific operations. The production is *batch* type with the finite count of products.

The improvement of this type of production lies in *digitization* of the production. This usually means to make a connection between ERP and machines using MES and data concentrators to collect manufacturing data about machines like idle/run/fault state and about products like count or traceability. This area is widely exploited and the problem lies only on finding a compromise between complexity and price. This area is therefore out of the scope of this article.

The second way how to transform the discrete manufacturing towards *smart factory* is being researched and some mechanisms, interactions, and standards are not known at present. The concept of Industry 4.0 interfere with all parts of the company, from the business through administration and management down to the machines on the shop floor. As this area is being defined at present, there could not be mentioned all innovative parts.

2. IMPLEMENTATION POSSIBILITIES

This chapter presents some defined innovation for the discrete manufacturing in terms of Industry 4.0. These innovations try to solve current manufacturing industry challenges like shortening of the product cycles, increasing product diversity systematically, cost reduction, quality improvement, resource efficiency, and customer service improvement.

2.1 OPC UA

OPC UA (Open Platform Communication Unified Architecture) is already settled approach to exchange data among plant components. It is based on service-oriented communication model (SOA) in accordance to the I4-concept. The server part contains informational models to provide an object-oriented way for data operation. The object can be in form of variable, method, and other. The server also supports push notifications called *subscriptions*. So the communication with a server can be event-based instead of polling-type. The specification of OPC UA (see Fig. 2) is multi-part and consists of security model, address space model, servies, information model, mappings, profiles, data access, alarms and conditions, programs, historical access, discovery, and aggregates.

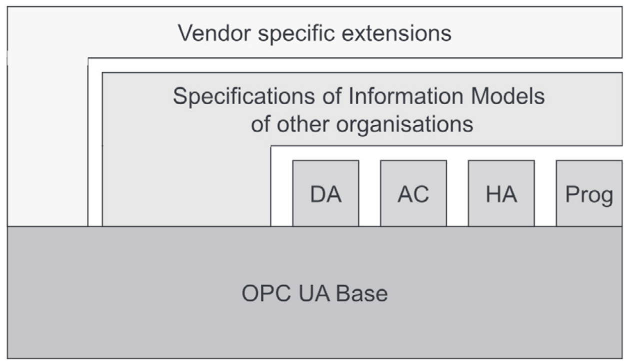

Fig. 2. OPC UA specification [Bangemann et al. (2016)]

The research in this area lies on optimization of TSN (Time-Sensitive Network) that are industrial communication network mostly based on IEEE 802.3 standard. This network has to be deterministic and as fast as possible. Moreover, the reliability needs to be standardized. The real-time ethernet protocol are also standardized but the need to be modified to support real-time OPC UA transactions for the *edge cloud* communication on shop floor.

2.2 Industrial CPS

CPS (Cyber-Physical System) is one of the key concept of I4 that is generally a group of hardware, software, and interactions of a functional part. Industrial CPS should cover industrial components like axis, machines, or even MES parts. The concept is based on standardised interactions among ICPS and their internal integrity. CPS is the integration of software, e.g. electronic in hardware, which is mostly an embedded device enhanced some communication features. As the I4-concept this system is in accordance to vertical integration of RAMI (Reference Architectural Model Industrie 4.0) model and is implemented as the *I4-component*.

The *I4-component* contains *asset* that may be device, machine, software module, or other software resource. The asset is represented virtually by AAS (Asset Administration Shell). AAS is based on OPC UA and provides structured data (submodels) in form of properties and methods. The data are grouped to containers. There are already some containers standardized (see Fig. 3).

The AAS submodel might also describe a *digital twin* of an asset. The digital twin concept demonstrates the interaction of the real asset with a digital simulation model. This model was a detailed virtual copy of all parts in the mockup of the industrial component, including material flow. The interaction of the manufacturing facilities and the simulation model may bring new insight into the dynamics of the production process.

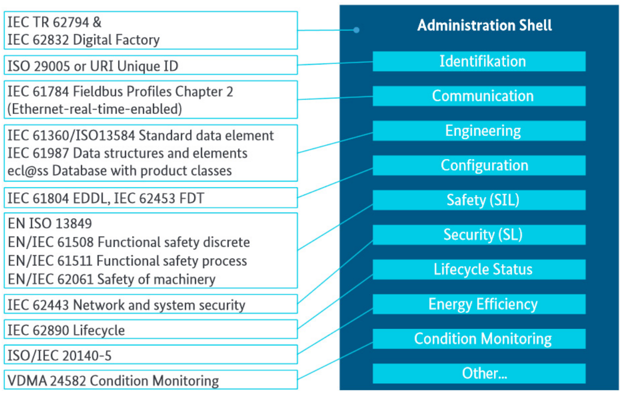

Fig. 3. Standardized content of the Administration Shell [Plattform Industrie 4.0 (2016)]

2.3 Product life-cycle

The *product life-cycle* is the way how to store systematically product information over all phases of the production. There are many possibilities how to trace all data. I4-concept suggests use of PLM (Product Life-cycle Management) that is the specialized software cooperating with ERP and MES. On the other hand, we think that the most promising is the concept of the *Administrative Shell* that creates submodels from data and provides access in the structured way. The product data is ideally collected from the product planning to the end of using with emphasis on its standardization. This collection might be then used to production optimization, product quality, and cost reduction using the machine learning algorithms (see Fig. 4) or to improve the reliability [Kazarik et al. (2015)].

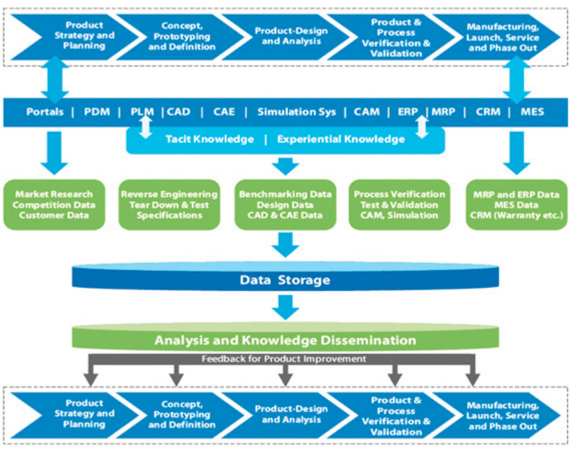

Fig. 4. Process Life-cycle Management and its usage [Asar and Millenium Engineering and Integration (2017)]

2.4 Big data

In the discrete manufacturing, big data research is used to collect more data in less time on less space using effective data interface drivers [Mikolajek et al. (2015)]. The current relational database systems are sufficient for storage of the manufacturing data. In case of increasing amount of data, there are some methods how to compress the data like making a report from historical data, use of detached databases, or compressing the historical data. As the product data are linked to the specific product, the object database model might be more suitable to keep the data organized. On the other hand, some operations could last longer.

2.5 Cloud computing

As the digitization of production is growing, the collected manufacturing data might be used to implement more sophisticated features. At present, there is used production plan monitoring, machine fault history, product tracing, or resource monitoring. The research focuses on predictive maintenance (plans part exchange according to some machine learning methods over collected data), product life-cycle (logs all relevant data to the specific product), production optimization, or making of optimal logistic decisions. These features uses artificial intelligence to get appropriate results helping to make tough business decisions.

2.6 Augmented Reality

Sensor level in the Industry 4.0 framework includes also powerful visual systems equipped with cameras. In traditional industry plant they are used to quality inspection and measuring, moreover these systems might be used also for monitoring and supervise. Suitable state-of-the-art example of such visual system can be the ADAS system described in [Horak and Kalova (2010)].

2.7 Standardisation

As the supplier base of assets is growing, the interfaces of components are heterogeneous due to supplier politics. The aspiration of system integrators and customers is to standardize interfaces and descriptions. This lead to the possibility of the supplier independence. Moreover, some task might be automated like device setting after its migration. There are some tendencies to settle a standard for properties description and the most promising is eCl@ss.

2.8 Business model

I4-concept has also an impact to the business of the company. The importance of KPIs (Key Performance Indicator) is growing with the production optimization. This is also more supported by the amount of collected production data and processing over it. Next improvement comes from interactions among systems like ERP and MES to achieve more precise product creation time estimation or more optimized resource planning.

The most innovative improvement comes from the horizontal integration of the RAMI model. All services might communicate with others regarding scheduling and optimization across the company or even across the companies. This brings more research in the security flaws mitigation and marketing procedures to build the complex resilient inter-connected system.

2.9 Shop floor scheduling

The classical approach of the central production scheduling by MES system is going to be upgraded to a hybrid scheduling. The global scheduling at the resources-product level will stay in the scheduler that is a part of MOM (Manufacturing Operations Management) at the level 3. But the difference is obvious on the heterogeneous production lines where one operation can be accomplished by more machines.

The innovation, which comes from the communication among CPSs, is to pass the decision making directly to the shop floor equipment at the level 2 (as described on Fig. 5). So the product itself can chose the service unit (machine) that will make the required operation. The model of the communication is based on consumer-provider model. The manufacturing machines provide parametrized operations and the product itself take an operation that match its parametrized requirements. The scheduling at this level is more flexible and should solve problems rising from the actual shop floor situation. On the other hand, some new scheduling problems can occur that are more deeply described later.

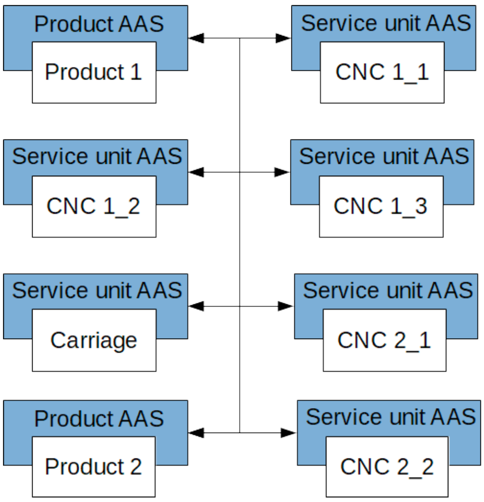

Fig. 5. Shop floor communication system

The role of MES scheduler is to start the production process of the specified product according to the ERP. Then the product itself ask to all service units for the possibility of an accomplishment of the required operation with specific parameters. In case of positive answer, the product ask to the transport service unit(s) for the possibility of transport to the specific position. After that, product sends to the service unit detailed manufacturing data of the operation (CNC program or parameters for PLC program). After the operation is performed, the service unit makes an acknowledge to the product and MES. The product picks up the next operation in its model and performs the negotiation again. This process is depicted as the sequence diagram on Fig. 6.

3. SHOP FLOOR SCHEDULING PROBLEMS

During the job shop scheduling process, there might occur some problems, especially if they are not handled at the beginning. Some of these problems are systematic (algorithm singularity, deadlock, livelock, design, implementation) and the others are faults based on random events (deadlock, communication timeout, communication errors). On top of that, the scheduling itself is np-hard resource constrained optimization problem. So there is an area to optimize the evaluation function of the agent-based scheduling algorithm.

The most of the mentioned problems are connected with the bidding phase of the interaction. This is due to its complexity coming from the fact that all participated actors have to communicate together in the real-time manner. Because of the mentioned complexity, some assumptions have to be stated:

- All actors have sufficient and reliable computation power to perform required operations.
- The communication net is designed well to have enough throughput.
- The communication net (OPC UA) is under the edge. So the security risk is minimized.
- In the system, there is a detector monitoring the communication net to search an actor that is busy for a long time.
- All operations demanded by the products are provided by the at least one active service unit.

We have defined three main problems regarding the job shop scheduling process:

- The bidding evaluation function,
- the bidding negotiation implementation,
- the possibility of deadlock.

3.1 The bidding evaluation function

The bidding evaluation function chooses the best offer from the service unit answers and determines followed transportation and manufacturing actions. So this is the point of making a decision. This determines the place of the operation. The time of the operation is determined by the concurrent race of the products to be manufactured which is influenced by the scheduler in MES because of FCFS (first come first serve) implicit dispatching policy. From the centralized point of view the scheduling algorithm might be optimized using the appropriate algorithm (see Sousa et al. (2017)).

Regarding the best offer evaluation, the most suitable method is to solve the unconstrained problem over the definite set of the feasible solutions using the penalty function (see eq. 1). The feasible solution has to accomplish all required operations under the given parameters by the product. The penalty function is computed from the input parameters that are the distance to the service unit, the total machine work time, the machine state (the time to be ready), and the predicted machine work time (the machine willingness to do some work as the result of the predictive maintenance algorithms). The approached penalty function is (see eq. 2) whereas the parameters needs to be standardized.

$$x^* = argmin_{x \in S} f(x) \tag{1}$$

where x^* is the optimal solution (offer), S is the finite set of the possible solutions (the offers that match the bid), and $f(x)$ is the penalty function.

$$f(x) = \sum w_i p_i \tag{2}$$

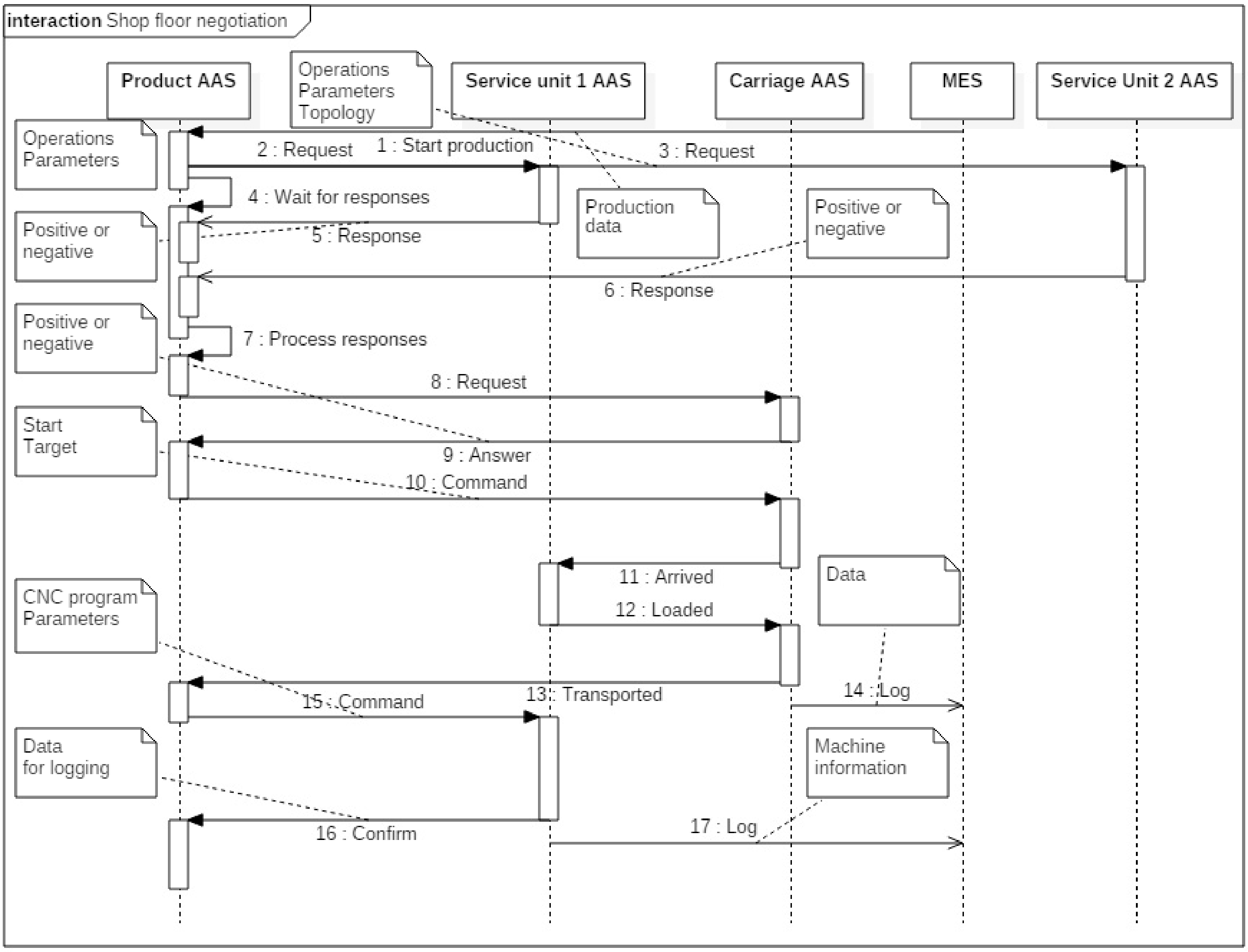

Fig. 6. Shop floor communication sequence diagram

where $f(x)$ is the penalty function, w_i are the coefficients of the parameters, p_i are the above mentioned standardized parameters. The parameter coefficients needs to be adjusted to the specific factory situation.

3.2 The bidding negotiation implementation

The communication link between product and service unit is intended to be OPC UA that is the core of the AAS. Therefore the communication type can be *client-server unicast* or *producer-subscriber multicast*. None of these does not support the requirement of the multicast bid sending followed by the multicast offer receiving.

Therefore, the communication state machine has to be slightly modified. Product, as the *multicast producer*, sends an offer and then waits in a separate thread for the responses. The count of the responses has to be the same as the count of the subscribers. If the timeout expires before all responses are received, the error state will be fired. After the bid evaluation process ends, product will send the final contract (the bid paired with the service unit) to all participants as *multicast producer*. In this state only one answer from the winner service unit is expected to continue the manufacturing process. The approached state automaton is depicted on Fig. 7.

3.3 The deadlock mitigation

The job shop scheduling algorithm is distributed so many actors are involved in making a decision. Every actor has its own plan that might collide with another actor plan. Therefore the deadlock can occur. Deadlock is defined as the situation that one actor owning A resource wants B resource while second actor owning B resource wants A resource.

There are some strategies how to avoid this situation:

- Formal model checking of the scheduling algorithm (e.g. by finding the Petri net P-invariants). This method is hard to solve with the grooving complexity of the system.
- Running random simulations followed by result verification (seeNie et al. (2017)). This method does not have to catch all states therefore some deadlock might remain uncovered.

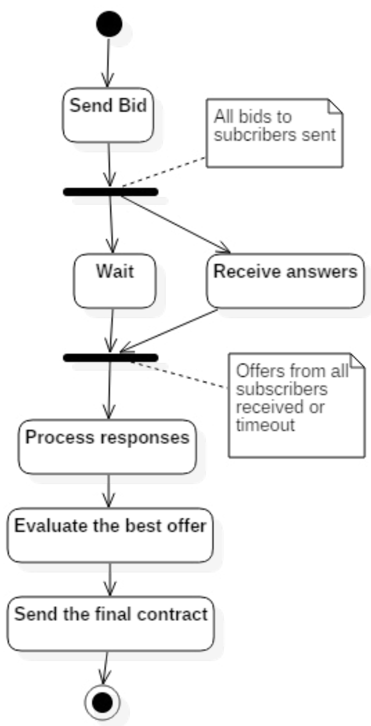

Fig. 7. The approached bidding state automaton

- Make some place (buffer) to put the product in. The product will then wait for the free service unit. The count of such places might be determined by the count of the service units or types of the supported operations.

4. CONCLUSION

The purpose of this article is to point out some problems that can occur during the Industry 4.0 concept implementation and draw out some possible solutions how to avoid it. Some promising implementations are presented and its weakness are discussed. The job shop scheduling is addressed deeper so the communication state diagram between involved actors and the bid evaluation function are approached. The classical consumer-producer communication model is not suitable for the bidding negotiation so the modification is approached. The offer evaluation function has to consider the actual state and make the right decision. The approached function takes into consideration the machine state, the planned transport length, and the steady work balance. The further steps in this area are approaching another variants, the implementation, test performing, and standards agreement.

ACKNOWLEDGEMENTS

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The Asset Administration Shell of Operator in the Platform of Industry 4.0

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***Abstract*—We discuss the Asset Administration Shell (AAS) concept of Industry 4.0 (I4.0), characterizing the current status of industrial automation and outlining the advantages of more deeply digitized manufacturing where the AAS is employed. In the proposed analysis, the basic subjects are apply complemented with possible submodels and standards of the Asset Administration Shell (identification, communication, engineering, configuration, safety, security, life cycle status, energy efficiency, condition monitoring, and examples of AAS-based applications). An exemplary interaction pattern directed towards the domain, or specific submodels in the AAS, is also introduced in the given context. Further, the authors propose a specific digital example of an operator using a smart jacket.**

Keywords—asset administration shell, industry 4.0, MQTT, OPC UA, RAMI 4.0

I. Introduction

In the European interpretation, the Internet of Things (IoT) is segmented into the CIoT (Commercial Internet of Things) and the IIoT (Industrial Internet of Things). The CIoT abbreviation is not used frequently, and the IoT represents the Internet of all things. In American technical terminology, however, the IoT covers the entire set of concepts subsumed under Industry 4.0 (I4.0) within the European approach.

The most significant recent achievement has been materialized through the European-made definition of the Asset Administration Shell (AAS) chapter of I4.0. The AAS is an item that stands out among all the Industry 4.0 notions: it creates an interface between the physical and the virtual production steps, embodying a virtual digital and active representation of an I4.0 component in the I4.0 system.

The Industry 4.0 component is a model for describing in more detail the properties of cyber-physical systems, namely, real objects in a production environment networked with virtual objects and processes. Hardware and software components in production environments, from production systems and machines to internal machine modules, become Industry 4.0-capable by satisfying such properties [1].

Any production component in the I4.0 environment has to have an administration shell. The structure of the AAS is then expected to satisfy the requirements of different production aspects and has to enable the functionality of I4.0 components from all basic perspectives, including the market, construction, power, function, positioning, security, communication ability, and understandability domains.

This article characterizes the basic structure and properties of the AAS, aiming to outline the benefits of the AAS together with the differences between the current state of things (things) and things with the AAS.

II. Models of Industry 4.0

The fundamental model of I4.0 exploits RAMI 4.0 (the Reference Architecture Model Industry 4.0, Fig. 1), a tool designed by the BITCOM, VDMA, and ZVEI corporations and associations. These subjects decided to develop a 3D model to represent all the diverse manually interconnected features of the technico-economic properties. The SGAM model (the Smart Grid Architecture Model), formed to foster communication in renewable energy sources' networks, appeared to embody an appropriate model for Industry 4.0 applications as well [2-3]. As a matter of fact, RAMI 4.0 is actually a small modification of the SGAM framework [4-6].

As both the SGAM and the RAMI 4.0 bodies are entered into by approximately fifteen industrial branches, RAMI 4.0 is structured to facilitate being viewed from different perspectives and aspects. The layers in the vertical axis thus represent the various viewpoints associated with the individual aspects (those of the relevant market, functions, information, communication, and integration abilities of the components) [7,8].

The authors acknowledge financial support from the Technology Agency of the Czech Republic (TF04000074 - Digital Representation of Assets as a Configurable AAS for OT and IT Production Systems) The research was also supported by the Ministry of Education, Youth and Sports under project No. CZ.02.2.69/0.0/0.0/16_027/0008371 - "International mobility of researchers at the Brno University of Technology".

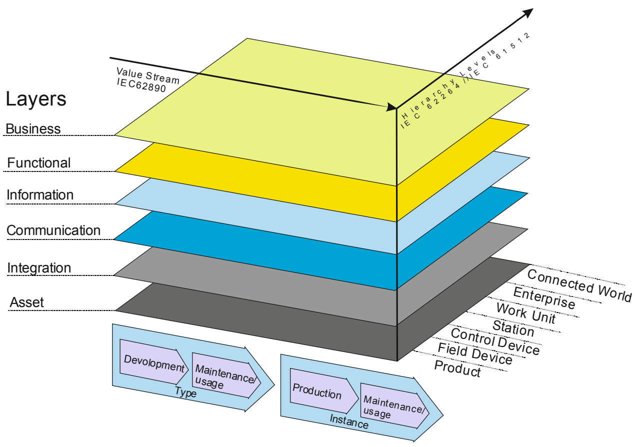

Fig. 1. The RAMI 4.0 model [5], inspirated by ZVEI, VDI/VDE [1].

In modern engineering, a very important criterion consists jointly in product life cycle and the related value stream. The feature is displayed on the left-hand horizontal axis in the above image. The set of items expressed comprises, for example, constant data acquisition throughout the entire life cycle. By extension, even with a completely digitized development cycle, the market chain still offers a large potential for improving the products, machines, and other layers of the I4.0 architecture. This viewpoint matches well the IEC 62890 draft standard.

The other corresponding model axis (the right-hand one at the horizontal level) indicates the positions of component functions in I4.0, defining and assigning the functionalities involved. The axis respects the IEC 6224 and 61512 standards; however, these are intended for the specification of components at positions applicable to one enterprise or manufacturing unit only. Thus, the highest level on the right-hand horizontal axis is the connected environment.

A second essential model for the purposes of I4.0, developed by BITCOM, VDMA, and ZVEI last year, is the I4.0 components model (Fig. 2).

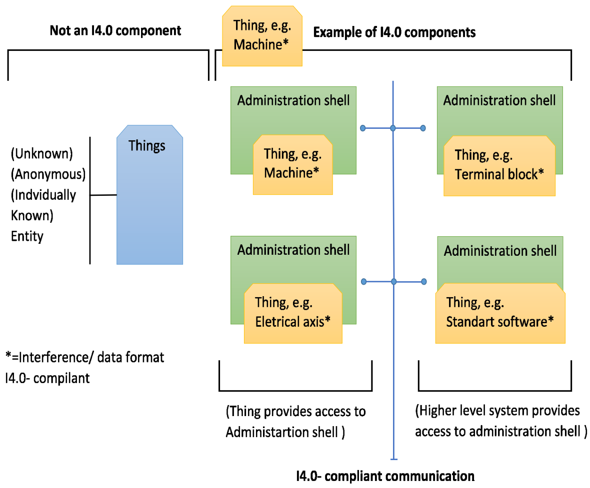

Fig. 2. The Asset Administration Shell [6], inspirated by VDI/VDE [9].

This framework is intended to help producers and system integrators to create HW and SW components for I4.0, and it embodies the first and only (as of July 2016) specific model based on RAMI 4.0. Significantly, the concept allows refined description of relevant cyber-physical features and enables us to characterize the communication between virtual and cyber-physical objects and processes [9], [10]. Within manufacturing of the future, the HW and SW components will be capable of executing the requested tasks by means of the implemented features specified in the I4.0 components model.

The most critical feature in the discussed context is the ability of the virtual objects and processes to communicate with their real counterparts during manufacturing; this model then specifies the conforming communication. The corresponding physical realization rests in that a component of the I4.0 system utilizes an electronic container (shell) of secured data during the entire life cycle; the data are available to all entities of the technical production chain. The model therefore arises from the standardized, secure, and safe real-time communication of all components in the production cycle. The electronic data container (shell) and the global Industry 4.0 component model are visualized in Fig. 3, which also displays a diagram of the AAS as a crucial I4.0 component (Fig. 3).

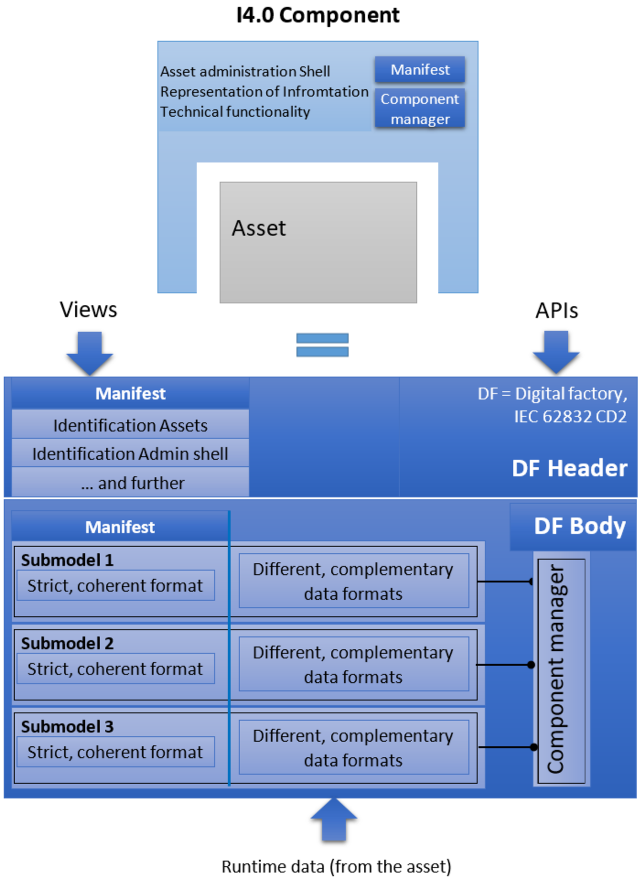

Fig. 3. The Asset Administration Shell, inspirated by [9].

III. Asset Administration Shell

The AAS creates an interface between the physical and virtual production steps; the framework is the virtual digital and active representation of an I4.0 component in the I4.0 system, more information you can find in literature [1] and [5].

As already pointed out above, any production component n the I4.0 environment needs an administration shell. The structure of the AAS is then expected to satisfy the requirements of different production aspects and has to enable the functionality of I4.0 components from all basic perspectives, including the market, construction, power, function, positioning, security, communication ability, and understandability domains.

The AAS is composed of a body and a header; the header contains identifying details regarding the asset administration shell and the represented asset, while the body comprises a certain number of submodels for an asset-specific characterization of the asset administration shell.

As is obvious from Fig. 3, the AAS accommodates a series of submodels. These represent different aspects of the asset concerned; thus, for example, they may contain a description relating to the safety or security but also could outline various process capabilities, such as drilling or installation. Possible submodels of the AAS are indicated in Fig. 4.

Generally, the aim is to standardize only one submodel for each aspect. Such a scenario will enable us to search for, e.g., a welding machine via seeking the AAS containing "welding" with relevant properties. A second submodel in the example, e.g., "energy efficiency", could ensure that the welding station will save electricity when idling.

Each submodel contains a structured quantity of properties which can refer to data and functions. A standardized format based on the IEC 61360 is required for the properties; the data and functions may be available in various complementary formats.

Administration Shell IEC TR 62794 & IEC 62832 Digital factory	
Submodels	**Standards**
Identification	ISO 29005 or URI unique ID
Communication	IEC 61784 Fieldbus profiles
Engineering	IEC 61360/ISO13584 Standard data elem.; IEC 61987 Data structures and elements; Ecl@ss database with product classes
Configuration	IEC 61804 EDDL; IEC 62453 FDT
Safety (SIL)	EN ISO 13849; EN/IEC 61508 Functional safety discrete; EN/IEC 61511 Functional safety process; EN/IEC 62061 Safety of machinery
Security	IEC 62443 Network and system security
Lifecycle status	IEC 62890 Lifecycle
Energy Efficiency	ISO/IEC 20140-5
Condition monitoring	VDMA 24582 Condition monitoring
Examples of AAS usage	Drilling, Milling, Deep drawing, Clamping, Welding, Painting, Mounting, Inspecting, Printing, Validating …

Fig. 4. Possible AAS submodels, inspirated by [11].

The properties of all the submodels therefore result in a constantly readable directory of the key information, or, by another definition, the manifest of the asset administration shell and thus also of the I4.0 components. To enable binding semantics, the asset administration shells, assets, submodels, and properties must be clearly identified. The permitted global identifiers are the ISO 29002 – 5 (e.g., eCl@ss and the IEC Common Data Dictionary) and URIs (Unique Resource Identifiers, e.g., for ontologies).

Figure 5 shows how an interaction pattern is directed towards the domain-specific submodels in the asset administration shell; the process is illustrated on a possible example from a discrete manufacturing procedure.

As regards the language for I4.0, Fig. 6 presents an approach to the item from the sub-working standardization group [5].

In a component of I4.0, such purposes are facilitated by the interaction manager, the tool responsible for the processing of the interaction patterns in the network. A domain-independent basic ontology then safeguards the connection with the domain-specific submodels in the AAS.

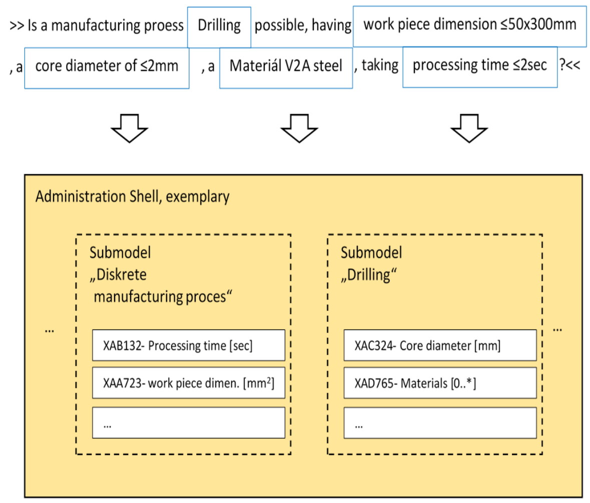

Fig. 5. An interaction pattern directed towards the domain-specific submodels in the AAS, inspirated by ZVEI [5].

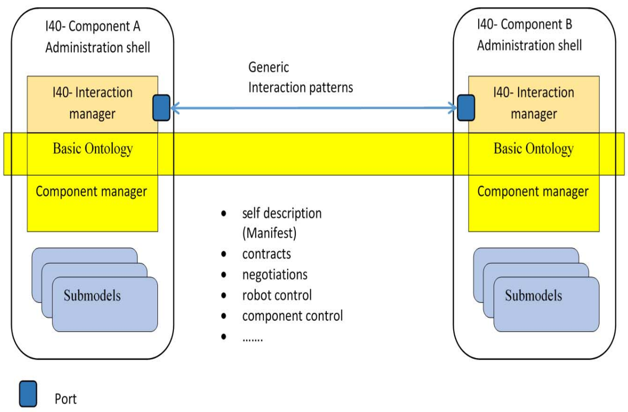

Fig. 6. An approach to the topic "Languages of I4.0" (Source: prof. Diedrich, Platform Industrie 4.0 Working Group 1, Ontology Sub-Working Group).

IV. Operator Asset Administration Shell

As mentioned earlier, every production element (e.g., a product, a machine, or control systems) has its own AAS in the context of I4.0. The question, however, is how to implement an operator AAS.

In this paper, we use the example of an operator AAS represented by a Human-Machine Interface (HMI); for demonstration purposes, we also attached a smart-jacket to this AAS. Figure 7 shows the block diagram of an operator AAS and the communication interface with other AASs in a manufacturing process.

The HMI includes information about the operator and also values from the smart jacket sensors. A major component of the AAS, then, is the NodeRED programming tool, which can run on, for example, a Raspberry PI. NodeRED comprises three significant elements: a) an OPC UA bridge to facilitate data conversion from string or MQTT messages into an OPC UA message ; b) an OPC UA client to communicate information to other AASs, such as an AAS or MES service and transport units, in the production area; and c) an OPC UA server to receive information for visualizing the Graphical User Interface (GUI).

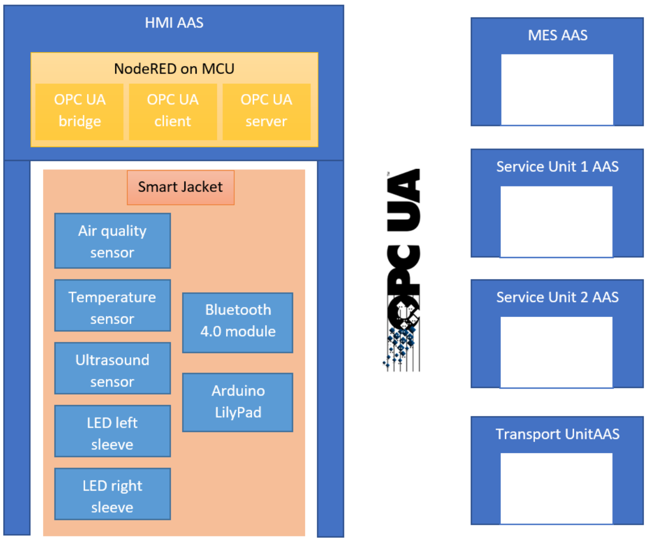

Fig. 7. A smart jacket operator represented via an HMI.

A. *Properties of the Smart Jacket*

Based on the scenario and intention to control and monitor important industrial parameters at a shop floor, the smart maintenance jacket is integrated with a use case. To preserve worker or operator safety on the industry shop floor, the item is configured with an Arduino LilyPad and sensors (Fig. 8), [12] and [13]. The primary functionality and components of the jacket are explained below.

The central part of the smart maintenance Jacket consists in an Arduino Lilypad with a SparkFun bluetooth module (BlueSMiRF). The Lilypad is suitable for smart wearable things (e-textile projects) because of its size and weight. The Lilypad model configured in the jacket utilizes an ATmega168 microcontroller, which has 14 analog and digital I/Os.

The BlueSMiRF is the latest Bluetooth 4 wireless serial cable replacement by SparkFun Electronics. The modems work as a serial (RX/TX) pipe: any serial stream from 2,400 to 115,200bps can be passed seamlessly from our Arduino.

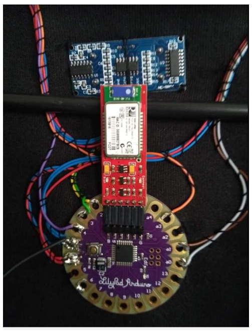

Fig. 8. An Arduino LilyPad with a bluetooth and an ultrasonic modules.

An MQ-135 air quality sensor (Fig. 9) detects NH3, NOx, alcohol, benzene, smoke, or CO2 and ensures air quality analysis. This sensor is then configured with the smart maintenance jacket, with the aim to prevent breathing at a polluted area or processing plant.

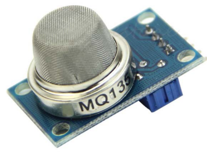

Fig. 9. An MQ-135 air quality sensor.

Figure 10 (left) shows an HC-SR-04 ultrasonic sensor. This small module is a cheap solution to measure distance up to 4-5 meters via ultrasound.

In order to avoid hazardous situations at the shop floor (heavy manufacturing plants), this ultrasonic sensor warns the bearer quickly with a buzzer located at the back side of the jacket neck.

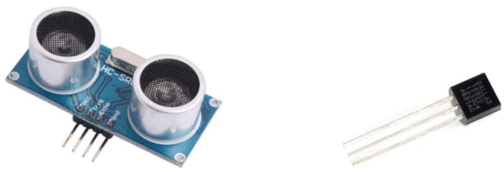

Fig. 10. Left: an HC-SR-04 ultrasonic sensor; right: a DS18B20 1-wire temperature sensor.

For the temperature measurement, we used a DS18B20 1-Wire digital temperature sensor by Maxim IC, Fig. 10 (right). The device reports degrees in Celsius between -55°C and 125°C at 9 to 12-bit precision, with a resolution of ±0.5°C. Each sensor has a unique 64-bit serial number etched into its body; this allows a large number of sensors to be used on one data bus.

The smart jacket contains an RGB LED strip (five diodes) on the left and right sleeves. If the MQ-135 sensor recognizes impaired air quality, the operator's right sleeve flashes yellow. If distance sensor detects a problem nearby, both sleeves blink red and the buzzer produces an intermittent tone. Similarly, if a fault in the manufacturing process is found, the left sleeve will flash red and the right one green. The operator then identifies the GUI where the malfunction occurred.

B. NodeRED on an MCU

Figure 11 displays a block diagram representing the algorithms implemented in the NodeRED programming environment.

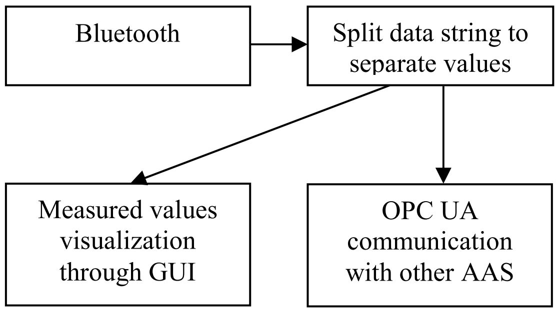

Fig. 11. A DS18B20 1-wire temperature sensor.

The serial data are received via a Bluetooth module. We obtain one string consisting of the temperature value, distance value, and air quality. The next step is to split the data into separate variables to be publishable via the GUI. Figure 12 presents the current and daily data of the measured values in charts. In addition to the actual visualization, the measured data can be sent to the OPC UA server [14]. To execute this operation, we use the node OPC UA IIoT Write.

The Write node facilitates sending the data to the OPC UA server: It handles single and multiple data requests. All *write* requests will produce an array of StatusCodes for writing in the server.

Fig. 12. The Graphical User Interface: the value measured by the smart jacket.

V. Conclusion

The article summarizes the basics of the Asset Administration Shell and its application in I4.0. In this context, the frameworks of the Industry 4.0 component model and the Asset Administration Shell are demonstrated as the key factors to allow the interconnection of individual production components. The related bidding and quotation processes, together with the communication between two assets, are exemplified in Fig. 4. The German approach to developing and implementing I4.0 principles into different case studies is employed throughout the presentation. In chapter IV, an AAS suitable for an operator wearing a smart jacket serviced via an HMI is characterized, together with the relevant implementation. The measured values in Fig. 12 are displayed through the GUI.

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An Industry 4.0 Testbed (Self-Acting Barman): Principles and Design

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Abstract: We describe the preconditions and procedural aspects characterizing the design of a testbed (an automatic barman) intended to practically demonstrate and verify the principles set forth within the conceptual system known as Industry 4.0. To complement the design properties, we analyze the specific impact of the project and discuss its position in terms of the novel systematic interpretation of the role assumed by industry and related fields or disciplines. Outlining the individual stages and features of the selected manufacturing procedure, the paper defines the envisaged application possibilities and comprehensive functionality of the automatic barman, namely, a device that suitably satisfies the demands of automated production as related to effective customer servicing. In the given context, the concrete hardware and software options for the actual testbed structuring sequence are presented in relation to the general theoretical framework.

Keywords: **Industry 4.0, Intelligent Manufacturing Systems, Industry Automation, Educational aids, Additive Manufacturing**

1. INTRODUCTION

At present, industrial manufacturing is gradually being transformed according to the principles of the Industry 4.0 trend, and the process has generated the need to introduce into university instruction multiple novel, predominantly interdisciplinary topics and problems. Based on long-term experience, it can be proposed that such topics are not easy to grasp for students focusing on automation, and this deficiency then appears to arise from two central issues. First, we can point in this respect to the fact that the students are required to cope with large quantities of mainly theoretical information which, however, clarifies only certain elementary principles, and the transition to a matter as comprehensive as manufacturing processes and related aspects embodies a great leap to an obscure zone. Second, it is vital to stress the already mentioned problem of interdisciplinarity, where a student of industrial automation, whose practical skills are almost exclusively oriented towards regulator design, the application and measurement of sensors and their characteristics, or programming basic control algorithms, is suddenly required to be both a mechanical engineer knowing the principles of design and an IT expert on systems and their interoperability. All of these prerequisites, moreover, usually surface in a manufacturing environment swarmed with regulations and requirements for data and functional safety.

It would probably be easy to close one's eyes before such reality, designating the theoretical training as sufficient and maintaining the *status quo*. Although we can claim that the students will eventually learn most of what they need through their professional careers, this is true only to some extent; the members of our team share the opinion that the students should be prepared for regular work thoroughly, gaining already during their studies not merely a brief practical insight to complement the theory but rather a comprehensive corpus of skills and experience beyond a basic sketch of manufacturing technologies and applicable IT tools.

Importantly, this outlook has paved the way to the actual idea of designing and materializing a testbed to facilitate the practical and theoretical understanding, demonstration, and verification of the principles of Industry 4.0. In addition to the classic topics stemming from the solution of the major problems that appear at the lower stages of the automation pyramid (such as control and handler algorithm programming; sensor data processing and actuator commanding; and solving various algorithm processing sequences or designing continuous regulators for feedback systems), new options are available, enabling us to perform the following actions/operations:

- Designing algorithms to control the real manufacturing of physical products. Such production can be, with respect to the testbed setup, interpreted as the discrete manufacturing of

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individual pieces. The testbed, however, will also allow us to demonstrate the principles of batch production according to the related standard, ISA-S88.

- Designing and operating a manufacturing execution system (MES) and an enterprise resource planning (ERP) management system, again above the real manufacturing of physical products. It should be noted here that, considering the character of finalized products and the cost of input materials, we can run also relatively long production sequences to yield, process, and evaluate relevant data.

- Demonstrating the principles that characterize Industry 4.0, including above all the modularity of manufacturing devices, customization of the manufacturing cycle, and horizontal integration.

- Communicating with a cloud platform, such that an edge controller will be employed to collect data supplied by connected devices on the operating hours, temperatures, and energy consumption. The controller will pre-process the data, subsequently sending them to the platform; from there, the information can be accessed by classic web browsers, both locally and worldwide. Apart from visualization, the data are applicable also for other analyses (machine learning, data mining) to enhance the effectivity and simplify the planning within an enterprise and/or the entire supply chain.

- Using augmented reality: the testbed will be complemented also with an augmented reality system, namely, a functionality where a mobile video camera and related applications monitor the present manufacturing conditions. The shot will then show interactive spots which, if clicked on, will provide information about a concrete device.

- Implementing a cyber-physical system (CPS), in which simulation tools will be exploited to create a *digital twin* of the entire testbed. The twin will enable us to verify and demonstrate the functionality of the testbed, facilitating its possible further development, and it will also open the above-outlined options to a substantially higher number of students interested.

2. INDUSTRY 4.0

The previous three industrial revolutions arose from the invention and advancement of steam-powered mechanical manufacturing devices, electrified mass production, and operational electronic systems and computers (Mařík 2016). By comparison, the present - or fourth - revolution, in addition to being focused on industrial production, also introduces fundamental changes to multiple fields beyond the traditional interpretation of the concept. Thus, the process virtually embodies a novel philosophy to transform various branches of industry, technical standardization, safety, education, legislation, science, research, the job market, the social system, and other related provinces.

The onset of novel technologies leads to procedural requirements such as the pressure for higher flexibility in industrial production, increased cybersafety, and effective interdisciplinarity. In this context, Industry 4.0 does not constitute merely an effort to digitize production but rather a comprehensive system of changes associated with different activities. Within industrial manufacturing, the concept transfers production from individual automatized units to fully integrated, automatized, and continuously optimized operating environments. The basic principles of Industry 4.0 applied to production are as follows:

- Interoperability, or the ability of the CPS, persons, and all other components of smart factories to communicate together using dedicated networks.

- Virtualization, or substituting physical prototypes with virtual production designs, means, and processes. The actual commissioning is then realized within a single integrated procedure involving both the manufacturer and the supplier.

- Decentralization, where the decision-making and control are performed autonomously and in a parallel manner within the individual subsystems, which communicate together via a common network (IoT).

- Real-time operation as a key precondition for communicating, decision-making, and control in real-world systems.

- Concentration on services, in which the naturally preferred actions are the offering and utilization of standard services (SOA architecture).

- Modularity and reconfigurability, where the systems exhibit maximum modularity and capability in autonomous reconfiguration based on the automatic recognition of present conditions.

- Horizontal integration, extending from systems that receive and confirm an order through the manufacturing section to dispatching the finished product and supporting its post-production life cycle. This stage includes the possibility of optimizing the manufacturing processes within the entire value chain.

- Vertical integration, from the lowest level of the automatic control of physical processes characterized by critical time demands through the manufacturing section management to allocating the company resources via ERP systems with time constants in the order of days or weeks.

2.1 Production life cycle

The term *production life cycle* denotes a continuous, comprehensive development process beginning with the initial design of a manufacturing device and running through the device’s structuring, operation, and modification towards the eventual end of its life. The individual stages require mutual cooperation between specialists from diverse fields and disciplines, and these experts have to show advanced understanding of the given interdisciplinary problem. The sections below discuss the differences between the traditional manufacturing design and an approach utilizing the options of Industry 4.0.

2.1.1 Manufacturing design 3.0

The production life cycle, whether within the manufacturing or the process (batch) domains, invariably starts from the initial idea of the product to be manufactured (Wagner et al. 2017).

- Step 0 (not illustrated in Fig. 1) has to define the manufacturing basics, such as these: In the former domain, a plank is transported to a drill to bore a hole, the result is checked, and the plank moves away; in the latter domain, a mixture is let in a tank, stirred, heated up, cooled down, and let out.

- Step 1 involves a process engineer to structure and document the manufacturing procedure for the pre-defined concept (step 0). To enable the intended functions (such an plank boring and shifting), basic parameters are set to be subsequently made more precise in an iterative manner. In the present step, the design remains abstract, meaning that no concrete hardware requirements are specified. At the next stages, however, the designed abstract objects (referred to as *roles*) and their individual links or relationships will be substituted with technical instruments. The output of the present step consists in documents typical of relevant fields (piping and instrumentation diagrams or flow charts).

- Step 2 consists in finding the manufacturer (most often through catalog choice) and identifying suitable types of all of the designed devices. The output of this stage is a list of sensors, actuators, controllers, other equipment, IT infrastructure, and SW elements (firmware, libraries, SCADA, MES, ERP).

- Step 3 comprises detailed planning, with the main focus on developing the source code for the controllers; planning the electrical connections and IT configuration; finalizing the manufacturing plans; ordering the product parts; and, if necessary, carrying out the simulations.

- Step 4 encompasses supplying, installing, and interconnecting the individual components. The source code is initiated in the controllers, and the designed process is subjected to gradual adjustment.

- Step 5 rests in the factory acceptance test, commissioning and delivery to the plant owner. *To rebuild or modify the plant, the cycle has to start from the first step again.*

The steps as described above are often subdivided into multiple tasks or merged together. During the launching and testing phases, the hardware and software are invariably modified (for example, using another device type requires changes in the electrical connections and controller software). The central problem then lies in that such variations, although not fundamental, often remain unquoted in the documentation, which thus ceases to reflect the real conditions and has to be corrected at a substantial cost of time and money.

Currently, integrated tool chains and the automated detection of plant configuration are available but not regularly employed within industry, mainly because a large number of users still prefer utilizing several different planning tools, which,

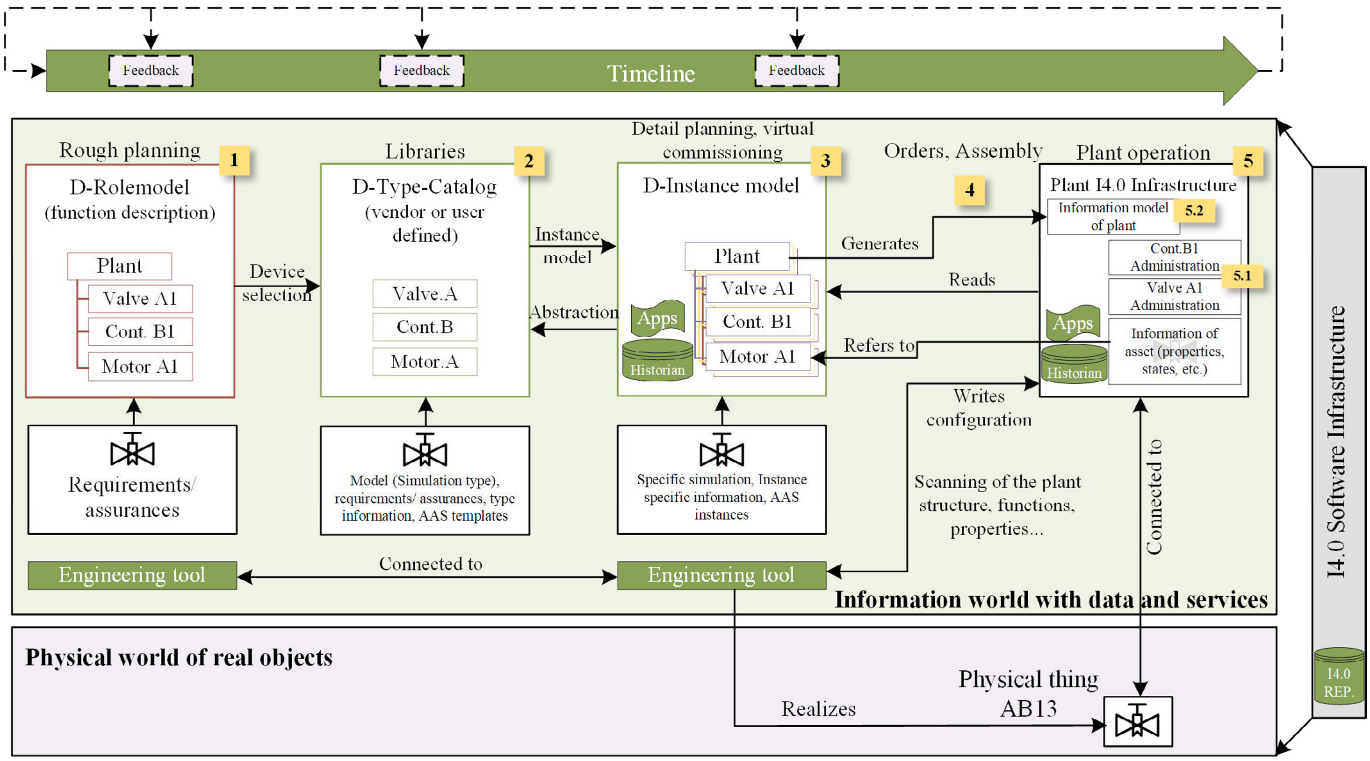

Fig. 1: Production planning 4.0 (Wagner et al. 2017)

importantly, often do not share one storage space. Moreover, various companies with diverse views and internal regulations participate in the process, thus further contributing to the frequent confusion, misunderstanding, and inconsistencies.

2.1.1 Manufacturing design 4.0

In Industry 3.0, the devices on an assembly line communicate together only vertically, without being aware of other similar units. Each aspect of production, each error or maintenance handling case needs to be known during the implementation of the control algorithms; the behavior of the entire system is then considered deterministic. Production changes (such as a new piece being introduced into the cycle or the replacement of a manufacturing tool) must be planned and announced in advance. The process is costly, time-intensive, and prone to errors.

Manufacturing design 4.0 introduces components facilitating communication over the Internet and capable of detecting the environment (namely, the components in the vicinity). After being connected, components within the 4.0 concept may register in the network, provide their metadata (including, for example, the functionality and capacity), and detect neighboring elements to supply them with the configuration data required for the completion of a given production process task. Although the individual components may originate from various suppliers, their interoperability is guaranteed if we use the standardized I4.0 communication interface (see the asset administration shell, chapter 3.4).

The adapted production life cycle using the subconcepts of Industry 4.0 can be organized into five steps, similarly to the above-outlined case. The stages are as follows:

- Step 0, in accordance with the previously described scenario, defines the manufacturing basics.

- Step 1, compared to that of Industry 3.0, involves creating a complete digital model of all planned devices. The knowledge and assumptions provided by the system engineers are explicitly modeled and stored in an object model, which is abstract and does not contain any concrete information on the hardware. Each of the objects represents a functionality (role) to be performed within the subsequent steps. Further, the precision of the model and the roles is subjected to improvement.

- Step 2 consists in selecting particular devices from the manufacturers' catalogs. Here, however, the catalogs are assumed to be available electronically and thus browseable via standardized interfaces. We also assume the availability of not only the design-related geometrical models (mechanical planning) but also the electrical diagrams, PLC functional blocks to facilitate the interaction, and lists of required PLC inputs/outputs.

- Step 3 involves the formation of the instance model (namely, the manufacturing information model, where a set of concrete devices is chosen for each role type). The selected type is thus instanced, and the created instance is assigned a unique identifier and parameters. Within the model, each instance represents a concrete physical device. Over an individual instance, functionality simulation can be run. The instance model is applicable for the development and testing of control algorithms (virtual prototype). Then, the entire formed model is, among industrial system development tools, stored in a common repository such that any of its parts were accessible to the testing and simulation instruments.

- Step 4 employs an object-oriented model to order the components and to set up, test, and run the manufacturing devices.

- Step 5 exploits the real manufacturing parameters and devices to automatically generate the production-based instance model in a retroactive manner, using information obtained from the standardized interfaces. Where a production change is required, the complete design, simulation, and commissioning of the modified concept can be performed via relevant software. The instance model is commonly denoted by the term *digital twin*, representing an "integrated multi-physics, multi-scale, probabilistic simulation of a system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its real twin" (Shafto et al. 2010).

The interconnection with a physical PLC (hardware-in-the-loop) is also known as virtual commissioning (Lee and Park 2014) and can be realized when the assembly model is fully described at the level of sensors and actuators. Without virtual commissioning, a manufacturing system will have to be stabilized solely by real commissioning with real plants and real controllers, which is very expensive and time consuming. The advantages of virtual commissioning were previously clearly demonstrated through relevant research (Koo et al. 2011).

In the context of the above discussion, it is possible to claim that the true innovation behind Industry 4.0 rests in the software (package or platform) to handle the information from the instance model.

3. BASICS OF THE TESTBED

3.1 Mechanical structure

The testbed is built upon a workspace of 2,000 x 1,000 mm. This area accommodates several autonomous process islands (cells) and related devices. Below this space is located another, equally large zone to contain support and control elements accompanied with IT technologies such that the entire unit would embody a complete manufacturing plant.

More concretely, the basis houses the following devices:

- A spirits dispenser process island to store the basic ingredients, including alcoholic beverages and flavored syrups to be dispensed in small quantities (2 to 5cl). Utilizing a recipe saved on an NFC chip, the cell is able to automatically deliver the ingredients into an inserted drinking glass. The cell is structured with a two-story pivoting frame carrying bottles with ingredients on its perimeter.

- A soft drinks dispenser process island to store and pour out larger quantities (1 to 3 dl) of liquid ingredients, such as juices. The cell comprises cooled stainless steel tanks, whose contents are delivered through electromagnetic valves and pulse flow meters. By extension, the drinking glass spot is equipped with a tensometric member to ensure that the liquid volume being poured out corresponds to the preset value.

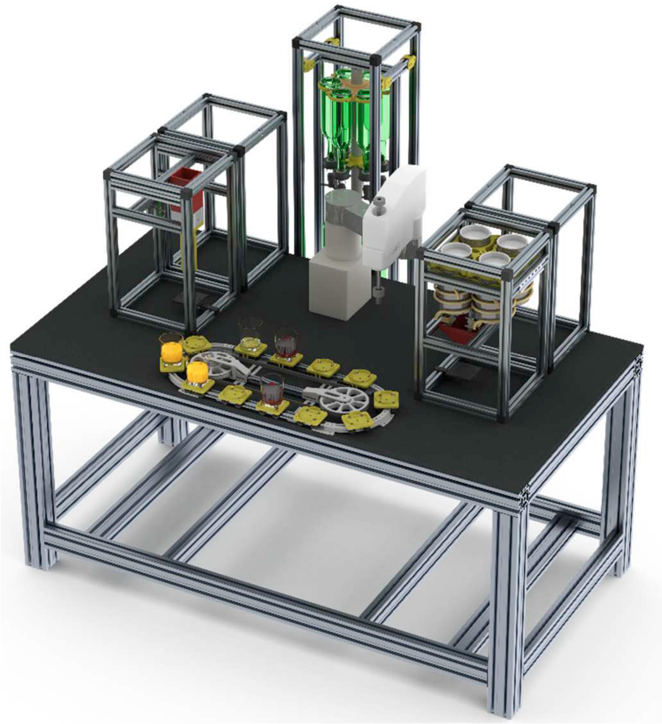

Fig. 2: The hitherto designed mechanical part of the testbed.

- An ice crusher process island to store ice cubes, delivering them crushed into a glass. The ice dispenser is conditioned by a Peltier cooler system. The actual dispensing procedure employs rotary crushing knives and a tensometric member to measure the ice crush volume.

- A shaker process island to blend the individual liquid ingredients. The procedure relies on a moving stainless steel tank sealed by an electromagnetic valve during operation.

- A glasses dispenser process island to store clean and used glasses, comprising a manipulator stacking the glasses in several columns. The device is located in the center of the cell and rotates about its vertical axis; thus, using its arm, the manipulator is capable of gripping a glass to transfer it from the stack to the exit point or vice versa.

- A conveyor belt to aggregate and distribute finished products.

- A SCARA robot manipulator to transfer a product between the individual manufacturing levels and to lay the piece on the conveyor belt.

All of the cells located in the workspace are built of aluminium frames having the ground plan of 330 x 330 mm and height of 500 mm. In each cell, a specific trajectory is pre-defined for the manipulator to follow when inserting or extracting a glass. Here, the main efforts are to unify the trajectories such that the individual cells were as much interchangeable as possible.

3.2 Functionality from the customers' perspective

This section characterizes in a simple manner a concrete product manufacturing procedure as perceived by a customer watching the production line in operation. In the individual cells, it is possible to materialize the sequential fabrication of a specific customized piece. A glass to hold the final product, after gradually passing through the cells, is to be transferred by means of a robot. Thus, at the first stage, the robot picks a clean glass from the stack. This glass is then placed in the spirits dispenser to pour in the required volume of the liquid. Subsequently, the glass is transferred to another cell to execute the next task in the chain according to the recipe. Within the process, in fact, the glass passes through all the necessary cells to be eventually positioned by the manipulator onto a conveyor belt tray and dispatched to the customer. The belt is also used for disposing of empty glasses, which are transported to the corresponding dispenser.

Fig. 3: The soft drinks dispenser process island.

3.3 Product life cycle

The production system materializing the manufacturing process, whose principles were outlined in chapter 3.2, differs only minimally from the naive mechanical models that facilitate common tuition in high-school or university laboratories; in this respect, the probably sole difference consists in the geometrical dimensions. However, the aspect where the testbed definitely digresses from the regular tools rests in the integration of multiple manufacturing and business-related processes and principles of Industry 4.0.

Within the discussed system, product manufacturing begins with a customer placing an order through the online web application. After being confirmed by the customer, the order is submitted to the ERP system, and following its verification at the plant (during test cycles, orders are put to production immediately), a new work order is created and transferred to the MES system. The manufacturing management system then accepts the work order to perform production planning (namely, to include the order in the manufacturing queue). The queuing position can be dynamically modified until the start of the physical manufacturing of the piece, using these criteria:

- Queue waiting time
- Production aggregation options to ensure that similar products are manufactured in rapid succession
- Production line options (considering possible error in an autonomous CPS or service quality reduction).

Each product being formed on the testbed is subjected to life cycle monitoring that extends from the origins of the structural design to the physical demise of the last fabricated piece. The monitoring procedure again exploits the Teamcenter platform. As the entire manufacturing cycle is interconnected in the direction of the MES and ERP systems, we observe each product between its introduction and decline.

In the case of our testbed, the actual fabrication starting point can be understood as the moment when the product recipe has been uploaded to the related transporter (an RFID chip glass). The decline then consists in taking an empty glass back from the customer and erasing the information from the chip. During the product manufacturing, the relevant data are being made available from the RFID chip (meaning that the manufacturing process is autonomous), and, simultaneously, transmitted to the database, which enables the parent system to be informed of any operation in all products.

As already mentioned, finished products are laid on a conveyor belt. A portion of this belt is beyond reach of the robot, thus remaining accessible to the customer. A complete product on the belt is clearly identified and described on a large display behind the approachable section of the conveyor; here, the actual functionality rests in that the identification data move along together with the glass, allowing the customer to effectively recognize their order and to collect the item. While the customer is reaching for the glass, the belt stops. The empty glass, if also placed on the conveyor, is subsequently moved by the robot to the corresponding dispenser.

The above-outlined process, where the final product forms progressively at the individual stages of the production line, is best represented by the characteristics of the manufacturing domain; the same definition applies to the distribution system, in which the finished products are transported via the conveyor to the user. Considering the nature of the final product (being a blend of various ingredients), we can nevertheless interpret the testbed equally well as falling within the process, or batch, domain. From such a perspective, a gradually forming product is denotable by the term *material lot*. The term *recipe* employed in batch production can then be understood as a list of operations in single-piece production.

3.4 Utilizing the principles of Industry 4.0

The central vision of Industry 4.0 lies in the transition from individual automated units to integrated automated setups (see 2.1.1). The individual autonomous cells (see 3.1) are interpretable as decentralized cyber-physical systems (CPS), with each of them constituting a building element of the whole testbed, or a smart factory. In future applications, the cells will be capable of mutual information exchange and responses to a variation in present conditions. The production within the cells will be realized on an autonomous basis, and most decision-making processes, including a portion of the production planning, will be transferred to the cells too. The islands will be interconnected via Ethernet, meaning that each of them will carry its own IP address. Such a configuration will enable us to manufacture highly customized products (the pieces will be processed in different cells, with diverse sequencing, and each of them will be subjected to a specific procedure within a specific cell).

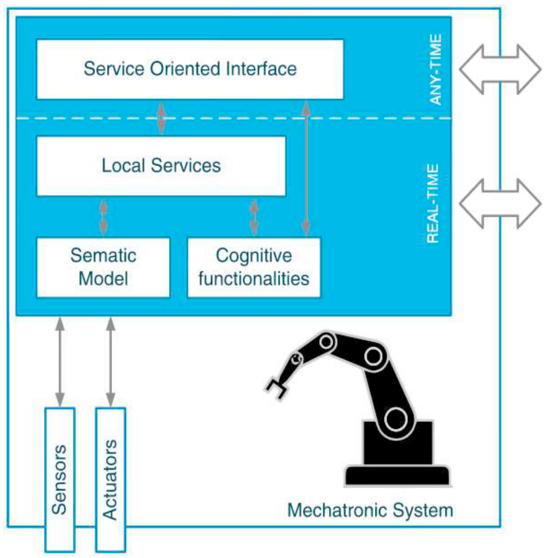

Fig. 4: The CPS comprising a cell controlled via PLC and the administration shell.

In Industry 4.0, the key factor rests in that the autonomous units in the manufacturing system embody not only the machines and their components but also the conveyor belts, robots, and products, subsuming the input material batches or individual segments. The described testbed assumes an autonomously behaving conveyor belt and SCARA manipulator, too. All of the autonomous cells are to communicate together in order to materialize the distributed product manufacturing.

As the envisaged horizontal and vertical integration requires us to apply standardized communication interfaces and to define the functionalities ensured by the individual subsystems, the cells will be integrated into the testbed via the principles of SOA (Service Oriented Architecture). We assume the use of the Publisher-Subscriber communication model. Here, the basic idea is that the individual CPSs will offer their services, such as blending or ice refilling, via standardized means (connection with an enterprise service bus); the CPS robot will then exploit the information about both the product being prepared for a concrete glass and the product's stage of completion to select the cell where the glass is to be filled.

In the given context, a single CPS will facilitate time-critical communication, such as that between the module controlling the conveyor belt and the robot controller, where it is vital to synchronize the components' motion at a high precision (in cases of customer interaction, the conveyor will stop immediately, and so will the robot, which was just placing a glass on the running tray conveyor).

The manufacturing data, together with various status-related information (including, for example, the processing temperatures and energy consumption rates), will be transferred to the Mindsphere cloud system (PaaS cloud) via an edge controller; the data will thus be accessible for not only browsing but also application in different digital solutions and services.

3.5 Hardware and software instrumentation

3.5.1 Administration shell

One of the pillars of Industry 4.0 consists in the standardization of protocols and interfaces. A standardized interface in each I4-component is the administration shell, which provides data from its submodels. The AS embodies a software interface for a hardware unit, an interface which possesses that unit's replica, being its *digital twin.*

Submodels then cluster the data from one subject area, such as identification, communication, configuration, safety, security, or energy efficiency. Some submodels are mandatory. Submodels may contain various data, but on the outside they have to provide interfaces of the variable-value or function-parameter types to enable the execution of desired operations.

The administration shell exploits the OPC UA technology, which embodies the communication standard among I4-components (CPS); the technology is a novel data provision tool. The actual data transmission utilizes the consumer-producer scenario. Defining all customers will generate a specialized communication network.

In the present project, the administration shell is well applicable to the individual products (drinks), where the product retains and provides its manufacturing information; further, the shell can be employed in the manipulator, supplying the CNC programs necessary for the motions, and it also contains the manipulator's digital twins. Naturally, the AS then finds use in the cells too, where, apart from the digital twin, it provides also the logistic information on the inventory level.

3.5.2 MES + ERP

At the initial stage of the project, a simple MES system is designed, complying with elements of Industry 4.0 as set forth in chapter 3.4 above. The system is implemented utilizing multiple technologies, including, for example, NET Framework, Windows Communication Foundation, and DotVVM Framework (Riganti 2018). In addition to production planning and control, in this system we envisage the implementation and deployment of a historical data recording module. Moreover, as the data presentation task is one of the most important requirements in industrial automation (Mikolajek, 2015), we also plan to focus on the visualisation module.

To receive, confirm, and administer orders, but also to perform inventory management and other activities, we will again develop a single-purpose ERP system, exploiting the technologies described in the previous paragraph.

In order to ensure the maximum interoperability in the MES and ERP systems or, alternatively, their commercially available equivalents, the information exchange will materialize in accordance with the XML implementation of the ANSI/ISA-95 standards (IEC/ISO 62264), namely, in B2MML.

3.6 Production life cycle administration

As the entire testbed designing process is a complex decentralized task requiring us to carry out the actual design-related operations and also make multiple decisions at various levels, we chose to collect information via the Siemens Teamcenter platform. The Teamcenter facilitates effective data administration from the mechanical framework, electrical structure, and software development, all within one environment; it is thus possible to effectively administer the versions and revisions, workflow, and connection to the product data. The system also facilitates data publishing. Other major advantages of the Teamcenter are uniform working with bills of materials and the availability of a complete and up-to-date source of information (database), which markedly eliminates the necessity to create stand-alone tables and systems.

The actual structuring process utilizes Siemens NX, a program fully integrated in the Teamcenter platform. All design-related data of the testbed are thus also fully integrated in the Teamcenter; here, they are archived and made available for further processing. The system, moreover, comprises all existing documents. These aspects then ensure coordinated and planned changes. Generally, such integration enables us to reuse the data outside the development of the testbed and to apply them for tuition and student theses.

3.7 CPS simulation

The CPS simulation and virtual commissioning are carried out with Tecnomatix Process Simulate, a tool for the designing and optimization of manufacturing processes that exploits the information interconnection principle of what – where – how;

naturally, these basic questions relate to details on what is to be produced, what with, where, and how in terms the procedures (for example, robotic welding requires a robot, a tool, and clamps, and Process Simulate connects all these components and sources with the welding operation). Following the general definition of the operations, its is possible to launch detailed simulations and to refine the manufacturing processes. Process Simulate offers a time-based simulation, namely, a time-controlled procedure unconnected to a physical control system; such an option enables us to verify the timing of the manufacturing tasks and to check their interlinking characteristics. Another mode then is event-based simulation, which can be connected with a virtual (software) or real PLC to fine-tune the manufacturing processes and their control (Guerrero, López, and Mejía 2014). This type of refining is termed *virtual commissioning*.

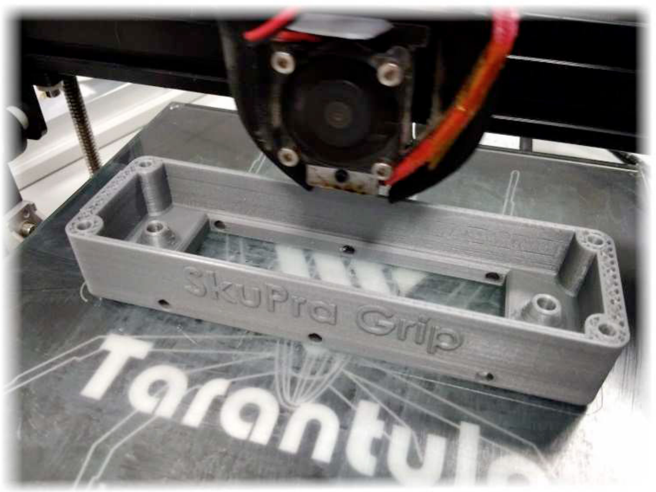

Fig. 5: A gripper being manufactured.

The testbed is further supposed to use TIA Openness, an API to facilitate the automated control of the TIA Portal platform. Using this API, a configuration system for the manufacturing cells will be designed. The SW developer will utilize an interactive form to specify the functionality of a concrete cell and to enable the physical mapping of the individual Simatic PLC I/O channels; then, using TIA Openness, the control application will be generated and uploaded to the given PLC.

3.8 Additive manufacturing

Materializing the testbed requires a significant amount of material, in addition to all the automation tools. Apart from the aluminium profiles employed for the actual structure, the material includes multiple other components, especially plastic ones. As most of these parts are unique, and only a single testbed is envisaged, classic manufacturing and machining procedures appear to be very ineffective for the purpose, and rapid prototyping (namely, additive manufacturing) is used instead.

The most widely applied and financially available additive manufacturing option is 3D printing with thermoplastics; during manufacturing, the material melts in a nozzle on the printhead and is gradually deposited in thin layers from the bottom up.

CONCLUSION

The present gradual transformation of industrial manufacturing has been reflected in our research through the decision to fabricate a testbed to bring new options for industrial automation tutorials. This paper discusses multiple problems we had to resolve already at the early stages of the project, including, above all, defining the control principle for distributed manufacturing and selecting the form and implementation of the asset administration shell. The finalized testbed will enable us to design, demonstrate, and optimize solutions that comply with the principles of Industry 4.0.

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Communication Systems for Industry 4.0 and the IIoT

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Abstract: The paper discusses the basics of communication systems for open, safe, secure, near real–time, standardized communication interfaces and examines the problem of a unified architecture to comply with the principles of Industry 4.0 as applied to enterprises of the future. The first part of the analysis presents Open Platform Communication – Unified Architecture (OPC UA), a common SW basis to interconnect communication interfaces and control plus information protocols for the purposes of Industry 4.0. The platform enables readers from different branches of engineering to understand the fundamentals of state-of-the-art open communication, a necessity for further development of the Industrial Internet of Things (IIoT) and Industry 4.0 concepts.

The following portion of the text then presents the most topical activities within enhancing the real – time properties of Internet of Things and Industry 4.0. The basics of Time Sensitive Networks (TSN) are explained and compared with the features and possibilities of standard public networks (the Internet) in relation to the onset of the 4th industrial revolution as outlined in the article.

Keywords**:** Internet of Thinks, Industry 4.0, communication systems, OPC UA, Time Sensitive Networks.

1. INTRODUCTION

This paper deals with basics of communication systems for purposes of open, safety, security, near real-time (R-T) standardized communication for purposes of Industry 4.0 (I4.0) system in enterprises of the future. The first part deals with the common SW communication interfaces of control, information and communication basis of the I4.0. There are explained basic features, principles and aims of the design and implementation of the Open Platform Communications (OPC) - Unified Architecture (UA), abbreviated as the OPC UA. The difference between previous OPC as the Object Linking and Embedding (OLE) for Process Control and the OPC classics and the OPC UA is explained it this contribution. Next there are specified basic properties, stay of the art and an expected future development of this important phenomenon of recent industrial automation in this contribution. There are discussed distinguishing characteristics of the OPC UA and evaluation how OPC UA corresponds requirements from industry on a communication for I4.0 purposes in this contribution.

In the second part of the contribution there is introduced the most actual topic of the communication in the whole production chain in the I4.0 systems, hence the Time Sensitive Networks (TSN), e.g. Ethernet based open Industrial Internet of Things (IIoT). There are specified important standards IEEE 802.1 for R-T enhancement of the existing public Internet.

2. OPC UNIFIED ARCHITECTURE (OPC UA)

The OPC UA is a machine-to-machine communication protocol for industrial automation developed by the OPC Foundation. Shortly OPC UA is an open standardized SW interface on highest communication levels in production control systems (VDMA, 2017; Burke, 2017).

The Foundation's goal for OPC UA was to provide a path forward from the original OPC communications model (namely the Microsoft Windows-only process exchange COM/DCOM) that would better meet the emerging needs of industrial automation. The original OPC is named OLE for Process Control. The original OPC is applied in different technologies such as in building automation, discrete manufacturing, process control and many others and is no more intended for the Microsoft Windows OS only, but it enables to include other data transportation technologies including Microsoft's .NET Framework, XML, and even the OPC Foundation's binary-encoded TCP format (Matrikon, 2017).

On the other hand, the OPC UA differs significantly from its predecessor, OPC. OPC UA better meets the emerging needs of industrial automation (Burke, 2017).

OPC UA shows distinguishing characteristics (Burke, 2017):

- Focus on communicating with industrial equipment and systems for data collection and control.

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- Open - freely available and implementable without restrictions or fees.
- Cross-platform - not tied to one operating system or programming language.
- Service-oriented architecture (SOA).
- Robust security.

Integral information model, which is the foundation model of the infrastructure necessary for information integration where vendors and organizations can model their complex data into an OPC UA namespace take advantage of the rich service-oriented architecture of OPC UA. There are over 35 collaborations with the OPC Foundation currently. Key industries include pharmaceutical, oil and gas, building automation, industrial robotics, security, manufacturing and process control (Marcon *et al*., 2017; Afanasev *et al.*, 2017 Jadlovská *et al.* 2016, Konecny *et al.* 2016 and Bangemann *et al.* 2016).

Even for above-mentioned features, OPC UA is very convenient for the I4.0 information and communication infrastructure. It enables free, open, rapid, safety and security and at least soft R-T communication.

The first version of the Unified Architecture (UA) was released in 2006. The current version of the specification is on 1.03 (10 Oct 2015). The new version of OPC UA now has added publish/subscribe communication in addition to the client/server communications infrastructure (Matrikon, 2017, VDMA, 2017).

2.1 OPC UA in more details

OPC UA specification defines a platform independent service-oriented Architecture (SOA). The platform enables the same operability in sense of classical OPC functions such as the Data Access, Alarms and Events, as well as Historical Data Access. The OPC UA Communication stacks are implemented in ANSI C/C++, Java and .NET and they create basic protocols for the TCP/IP networks communication. The standard contents already also marking of signals, autentification and authorizing over the X.509 Certification. An important feature of the OPC UA is an intensive support of Information Modelling. Nodes and relation among them are object oriented. Therefore, a data form and related meta information are semantically specified and generically created.

2.2 Where is a difference between OPC and OPC UA

The classical OPC data interface, alarms, historical data access is strongly linked with the Microsoft Technology COM/DCOM and they are solely unified with the operating system Windows. The new OPC UA specification defines a SOA. In the addressed area of an UA server there are situated and generically created and over the network translated not only data but also meta-data.

2.3 Migration from OPC classic to OPC UA

Members of the OPC Foundation recommend following procedure and the proper time for migration from the OPC classic and the OPC UA (Matrikon, 2017).

Complete migration refers to replacing OPC classic via a comprehensive switch to OPC UA. To that end it is needed to keep 3rd party data accessible using an open standard that enables reliable communication between HMIs, applications and devices. The procedure how to enable it is shown in the Fig. 1. There are several SDKs of OPC UA in the market to solve those problems. The new control infrastructure with already implemented OPC UA devices communicates already by the OPC UA protocols (the right part of the Fig. 1). Data sources with OPC classic Server go into the IIoT Gateway via the link way in the Fig. 1.

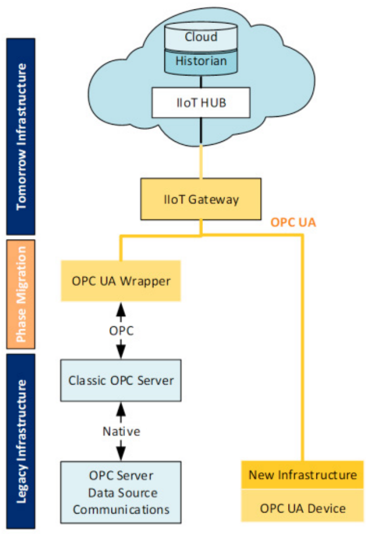

Fig. 1. Migration from OPC to OPC UA *(Matrikon, 2017).*

2.4 I4.0: OPC UA communication technology

I4.0 is driven by advanced information and communication technologies (Zezulka *et al.*, 2016, Pereira *et al.*, 2017, Blazek *et al.* 2016). The OPC UA seems to be the main common communication standard for the I4.0 and IIoT activities and will be accepted by standardization institution in EU as well as in America and all developed countries and economies. In the Fig. 2 there is shown a mapping of OPC UA protocols into the main general RAMI 4.0 model (Burke, 2017).

OPC UA functions and protocols are mapped into the RAMI 4.0 model as follows:

- Approach for implementation of a Communication Layer is done by Basic IEC 62541 standard (OPC Unified architecture, 2017).
- Approach for implementation of an Information Layer (of the RAMI 4.0) by IEC Common Data Dictionary

(IEC 61360 Series/ISO 13584-42; Characteristics, classification and tools to eCl@ss; Electronic Device Description (EDD); Field Device Tools (FDT).

- Approach for implementation of a Functional and Information Layers by Field Device Integration (FDI) as integration technology.
- Approach for end-to-end engineering by Automation ML; ProSTEP iViP; eCl@ss (characteristics).

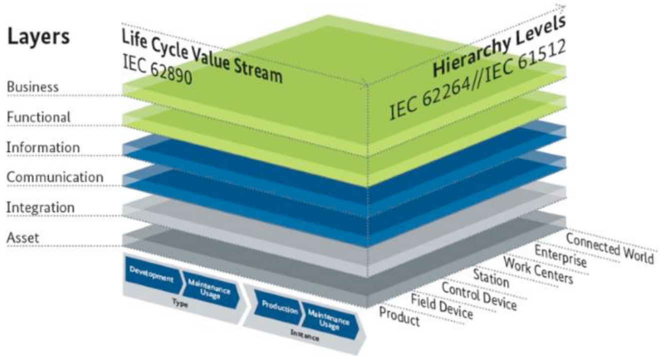

Fig. 2. RAMI 4.0 (Plattform Industrie 4.0 and ZVEI).

The communication stack of the OPC UA reflects the beginning of various innovations. The OPC UA architecture is a service-oriented architecture (SOA) and is based on different logical levels.

OPC Base Services are abstract method descriptions, which are protocol independent and provide the basis for OPC UA functionality. The transport layer puts these methods into a protocol, which means it serializes/reserializes the data and transmits it over the network. Two protocols are specified for this purpose. One is a binary TCP protocol, optimized for high performance and the second is Web service-oriented one.

The OPC information model is a so-called Full Mesh Network based on nodes. These nodes can include any kind of meta information, and are similar to the objects of object-oriented programming (OOP). A node can have attributes for read access (DA, HDA), methods that can be called (Commands), and triggered events that can be transmitted (AE, DataAccess, DataChange). Nodes hold process data as well all other types of metadata. The OPC namespace contains the type model (Zipper *et al*, 2017).

Client software can verify what profiles a server supports. This is necessary to obtain information, if a server only supports DA functionality or additionally AE, HDA, etc. Additionally, information can be obtained about whether a server supports a given profile. New and important features of OPC UA are:

- Redundancy support.
- Heartbeat for connections in both directions (to indicate whether the other end is "alive"). This means that both server and client recognize interrupts.
- Buffering of data and acknowledgements of transmitted data. Lost connections don't lead to lost data anymore. Lost datagrams can be re-fetched.

2.5 *Specification of OPC-UA*

The OPC-UA protocol specification consists of 14 documents for a total of 1250 pages. Due to this complexity, existing implementations are usually incomplete. In addition, the existence of several serialization formats, as well as the possibility of selectively implementing certain services such as PubSub, eventually lead to a great heterogeneity of the OPC-UA connection points. Under these conditions, it is finally difficult to develop client applications that are independent of the specific implementation of each server. In this sense, OPC-UA does not achieve its promise of ensuring good interoperability of systems. This can be seen typically in factory and infrastructure projects integrating various PLC technologies, each delivered with a different and limited implementation of the OPC UA protocol.

As a result, despite considerable marketing efforts to support its adoption, OPC UA may be considered at this stage as a standardization attempt rather than an established standard.

The OPC UA specification is a multi-part specification and consists of the following parts:

1. Concepts, 2. Security Model, 3. Address Space Model, 4. Services, 5. Information Model, 6. Mappings, 7. Profiles, 8. Data Access, 9. Alarms and Conditions, 10. Programs, 11. Historical Access, 12. Discovery, 13. Aggregates, 14. PubSub.

In contrast to the COM-based specifications, the UA specifications are not pure application specifications. They describe typically UA internal mechanisms, which are handled through the communication stack and are normally only of interest for those that port a stack to a specific target or those that want to implement their own UA stack.

The OPC UA application developers code against the OPC UA API and therefore mainly use API documentation. Nevertheless, part 3, 4, and 5 may be of interest for application developers (Matrikon, 2017).

It has been told, that OPC UA will be accepted as a common communication protocol for the 4th industrial revolution in the most developed industrial countries in a near future. Reader can evaluate this statement from following Fig. 3.

Until now OPC UA has used a client/server mechanism, where a client requests information and receives a response from a server. On networks with large numbers of nodes, traffic increases disproportionately and impairs the performance of the system. The publisher / subscriber model in contrast, enables one-to-many and many-to-many communication. A server sends its data to the network (publish) and every client can receive this data (subscribe).

This eliminates the need for a permanent connection between client and server, which is particularly resource intensive.

Industry 4.0 requirements	OPC-UA solution
Independence of the communication technology from manufacturer, sector, operating system, programming language	The OPC Foundation is a vendor-independent non-profit organization. Membership is not required for using the OPC-UA technology or for developing OPC-UA products. OPC is widely used in automation but is technologically sector-neutral. OPC-UA runs on all operating systems – there are even chip layer implementations without an operating system. OPC-UA can be implemented in all languages – currently stacks in Ansi C/C++, .NET and Java are available.
Scalability for integrated networking including the smallest sensors, embedded devices and PLC controllers, PCs, smartphones, mainframes and cloud applications. Horizontal and vertical communication across all layers.	OPC-UA scales from 15 kB footprint (Fraunhofer Lemgo) through to single- and multi-core hardware with a wide range of CPU architectures (Intel, ARM, PPC, etc.) OPC-UA is used in embedded field devices such as RFID readers, protocol converters etc. and in virtually all controllers and SCADA/ HMI products as well as MES/ERP systems. Projects have already been successfully realized in Amazon and Microsoft Azure Cloud.
Secure transfer and authentication at user and application level	OPC-UA uses X.509 certificates, Kerberos or user/password for authentication of the application. Signed and encrypted transfer, as well as a rights concept at data point level with audit functionality is available in the stack.
SOA, transport via established standards such as TCP/IP for exchanging live and historic data, commands and events (event/ call-back)	OPC-UA is independent of the transport method. Currently two protocol bindings are available: optimized TCP-based binary protocol for high-performance applications and HTTP/HTTPS web service with binary or XML coded messages. Additionally Publish/Subscribe communication model can be integrated. The stacks guarantee consistent transport of all data. Besides live and real time data also historical data and their mathematical aggregation are standardized in OPC-UA. Furthermore method calls with complex arguments are possible, but also alarm and eventing via token based mechanism (late polling).
Mapping of information content with any degree of complexity for modeling of virtual objects to represent the actual products and their production steps.	OPC-UA provides a fully networked concept for an object oriented address space (not only hierarchical but full-meshed network), including metadata and object description. Object structures can be generated via referencing of the instances among each other and their types and a type model that can be extended through inheritance. Since servers carry their instance and type system, clients can navigate through this network and obtain all the information they need, even for types that were unknown to them before. This is a base requirement for Plug-and-Produce functionality without prior configuration of the devices.
Unplanned, ad hoc communication for plug-and-produce function with description of the access data and the offered function (services) for self-organized (also autonomous) participation in "smart" networked orchestration/combination of components	OPC-UA defines different "discovery" mechanisms for identification and notification of OPC-UAcapable devices and their functions within a network. OPC-UA participants can be located local (on the same host), in a subnet or global (within enterprise). Aggregation across subnets and intelligent, configuration-less procedure (e.g. Zeroconf) are used to identify and address network participants.
Integration into engineering and semantic extension	The OPC Foundation already collaborates successfully with other organizations (PLCopen, BACnet, FDI, AIM, etc.) and is currently expanding its cooperation activities, e.g. MES-DACH, ISA95, MDIS (oil and gas industry), etc. A new cooperation initiative is with AutomationML, with the aim of optimizing interoperability between engineering tools.
Verification of conformity with the defined standard	OPC-UA is already an IEC standard (IEC 62541), and tools and test laboratories for testing and certifying conformity are available. Additional test events (e.g. Plugfest) enhance the quality and ensure compatibility. Expanded tests are required for extensions/amendments (companion standards, semantics). Additionally various validations regarding data security and functional safety are performed by external test and certification bodies.

Fig. 3. I4.0 requirements – OPC-UA solution (Burke, 2017).

3. TIME SENSITIVE NETWORKS – COMMUNICATION OF FACTORY FOR THE FUTURE

3.1 OPC UA and TSN

Despite of that OPC UA will be a common communication standard for the I4.0 factory of the future and that is already accepted by designer and producers of industrial automation systems as well as by cooperating industrial branches, one important feature is still missing. It is the real time property, which would be sufficient for rapid industrial processes. Therefore was established in the TSN a standardization group with the aim to enhance OPC UA properties towards R-T features in the all technical – business chain of industrial production. This goal can be titled OPC UA over TSN.

There has been done more attempts with a goal to enable open, safety, secure, R-T communication for purposes of industrial use in the past. One of them had been specified and provided during the period of 2005 – 2008 in the Integrated project Virtual Automation Network: VAN FP6/2004/IST/NMP/2-016969 (Beran *et al*., 2010).

The goal of the project was development, design, testing and case study implementation of a virtual network for purposes of automation. Virtual automation networks represented recent trend of communication in heterogeneous networks in industrial automation. Heterogeneous networks consisted of industrial automation systems such as fieldbuses, office LANs, and public networks (Internet and telecommunication technologies). Architectural principles were shown on VAN device profiles and intended network topologies. Salient innovative approaches to industrial automation, such as name-based addressing, integration of Web Services and OpenVPN tunnelling were developed. Security aspects paid proper attention for being utmost sensitive in industry. The project VAN reflected the state of the development of the VAN (Integrated project of the 6th FP) in first years of the new millennium and had been worked on by a consortium of dominant European automation vendors (Siemens, Phoenix Contact, and Schneider Electric), research institutions and technical universities. Because of less interest from the EU industry ten years before the very begin of the I4.0, successfully proved case studies in mechanical engineering industry in Milano and in a biofuel mini power plant in Saxony (East Germany) were not sufficient project outputs for a standardization attempt in German and EU standardisation organizations (Zezulka *et al.*, 2008).

3.2 Time-Sensitive Networking

The Time-Sensitive Networking (TSN) is a set of standards under development by the Time-Sensitive Networking task group of the IEEE 802.1 working group (Bradac, 2018). The TSN task group was formed at November 2012 by renaming the existing Audio/Video Bridging Task Group (see ref. TSN, 2018) and continuing its work. The name changed because of extension of the working area of the standardization group. The standards define mechanisms for the time-sensitive transmission of data over Ethernet networks.

The majority of projects define extensions to the IEEE 802.1Q – Virtual LANs (ref. OPC, 2017). These extensions in particular address the transmission of very low transmission latency and high availability. Possible applications include converged networks with real time Audio/Video Streaming and real-time control streams, which are used in automotive or industrial control facilities.

Work is also currently being carried out in AVnu Alliance's specially created Industrial group to define Compliance & Interoperability requirements for TSN networked elements (see ref. TSN, 2018).

Time sensitive networks are to be general communication tools for communication in the I4.0 environment. They have to fulfil real time requirements on the larger process area then do that industrial Ethernet standards (IE) such as Profinet, PowerLink, Ethernet/IP, EtherCAT and other IEC 61588 standards for real time communication among control systems, operator level, sensors and actuators in the industrial automation systems. The TSN are under development, but the success of the I4.0 implementation is dependent on their standardization. A close cooperation of IEC 61588 standards and development of the standardization process of TSNs is expected. The reason of the TSN topic stems from importance of real – time topic in the I4.0 production, which differs from the existing industrial communication networks in the huge amount of links, entities, data, conditions, distances, heterogeneity of components and business models in smart factories of the future (Diedrich et al., 2015; Grube et al., 2017).

From a technical standpoint, it would certainly be feasible to add real-time capability to OPC UA itself, but doing so would involve considerable effort and would still have disadvantages. That is why a large group of automation and robotics manufacturers have joined forces to move in a different direction. OPC UA will take advantage of TSN. TSN is a set of extensions currently in development that will later be included in the IEEE 802.1 standard. The goal is to provide real-time data transmission over Ethernet. A significant advantage of the TSN standard is that the automotive industry is behind it. That means that the required semiconductor components will be available very quickly and relatively inexpensively. The amount of data being transmitted in automobiles has skyrocketed in the past several years. Conventional bus systems don't have nearly the bandwidth to handle it. The first step for the automotive industry was adoption of the 802.1 AVB (Audio/Video Bridging) standard, which enables synchronized, prioritized streaming of audio and video files. This allows images from rear view cameras mounted on the back bumper to be transferred via Ethernet. To pursue the goal of reaching new industries and broadening the spectrum of applications, the AVB working group became the TSN initiative. The automotive industry would also like to handle all control tasks and applications that require functional safety over Ethernet. For this to be possible, they will need cycle times in the real- time range and deterministic network behaviour. These are the exact same requirements faced in the automation of production lines. OPC UA TSN bridges the gap between the IP based world of IT and the field of factory automation. OPC UA TSN is the perfect solution for all applications in factory automation. With sub-millisecond synchronization, it offers sufficient precision for tasks such as line synchronization, SCADA system integration, basic control tasks or even conveyor belt operation and I/O integration (Sachse, 2017).

OPC UA TSN combines IT mechanisms with OT requirements to allow network nodes to communicate and exchange information automatically.

3.3 Technical basis of the TSN

TSN goes out from the technical development of industrial as well IT networks. They have a goal to utilize all what has been done in the OPC UA development and standardization as well as in real-time properties of the development in industrial Ethernet area. The R-T features are in the I4.0 and the IIoT needed not only in the lowest control and communication level of the classical control pyramid, but in the all technical – production – business chain. It is the reason, that the TSN goes out from technical features of Industrial Ethernets such as the PTP (precision Time Protocol) from the IEC 61588 which is implemented in the most rapid industrial Ethernet standards (EtherCAT, Profinet, EPL, CC-Link IE. The TSN organization cooperates during the time of TSN developing with other standardization organization to fulfil all requirements in consideration of requirements from the OT as well from the IT branch. To enhance R-T properties of IIoT, it is necessary to use newest standards in the suite of the IEEE 802.1. This tendency goes out from the first attempt to translate video and audio data in the real time in cars. The appropriate standard is the 802.1 AVB. For next industrial processes are the IEEE 801.1Qbv – the prioritized Time – Aware – Scheduler. It enables packets and frame transmission of time critical data in a prioritized way. In the Fig. 4, are titled several time synchronization mechanisms, which can be implemented for enhancement of R-T features of TSNs and are already standardized by the IEEE 802.1 (Vojacek, 2018).

IEEE 802.1 TSN TASK GROUP: Projects/Standards Overview	
IEEE 802.1Qbv	Time-aware shaping (per-queue based)
IEEE 802.1ASrev	Timing and synchronisation (mechanisms for faster fail-over of clock grandmasters)
IEEE 802.1Qbu	Frame pre-emption
IEEE 802.1CB	Redundancy (frame replication and elimination)
IEEE 802.1Qcc	Enhancements and improvements for stream reservation
IEEE 802.1Qca	Path control and reservation (based on IEEE802.1aq; IS-IS)
IEEE 802.1Qch	Cyclic queuing and forwarding
IEEE 802.1Qci	Per-stream filtering and policing
IEEE 802.1CM	Time-sensitive networking for fronthaul

Fig. 4. TSN Sub-Standards Overview, (Vojacek, 2018).

The frame of the very basic protocol IEEE 802.1Q (Wikipedia, 2018) is specified in the Fig. 5. The standard 802.1Q adds a 32-bit field between the source MAC address and the EtherType fields of the original frame. The minimum frame size is left unchanged at 64 bytes (Marcon *et al.*, 2018). The maximum frame size is extended from 1.518 bytes to 1.522 bytes. Two bytes are used for the tag protocol identifier (TPID), the other two bytes for tag control information (TCI).

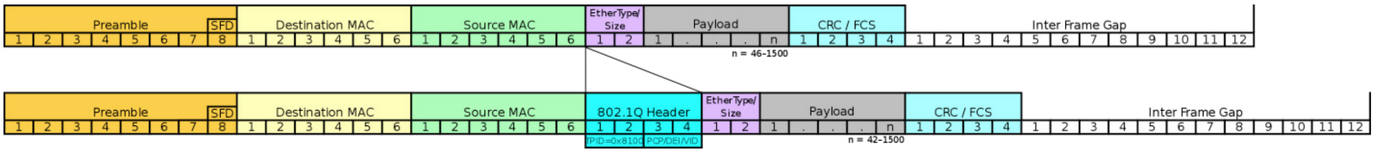

Fig. 5. 802.1Q tag in an Ethernet frame *(Wikipedia, 2018)*.

4. CONCLUSIONS

Contribution deals with principles and technologies for data and command communication for purposes of IIoT as well as for communication in the I4.0 factories of the future. Authors specify requirements from I4.0 and search for technologies and methods, which can fulfil them. Therefore, there are specified OPC UA which is proposed to be open SW interface and communication protocol for automation and information subsystems of the I4.0 applications. As a real-time option of OPC UA are discussed the TSN which in connection of the OPC UA will probably fulfil real-time, openness, virtual, safety, security features of an appropriate common communication channel in shop as well in the top floors of the factory control architecture. Authors makes small excursion in one predecessor of recent communication standards which has been solved in the integrated project of the 6th FP the with the acronym VAN.

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sensors

MDPI

Article

New Approaches to Implementing the SmartJacket into Industry 4.0 ‡

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Abstract: The paper discusses the possibilities of incorporating sensors and indicators into the environment of an Industry 4.0 digital factory. The concept of Industry 4.0 (I4.0) is characterized via a brief description of the RAMI 4.0 and I4.0 component model. In this context, the article outlines the structure of an I4.0 production component, interpreting such an item as a body integrating the asset and its electronic form, namely, the Asset Administration Shell (AAS). The formation of the AAS sub-models from the perspectives of identification, communication, configuration, safety, and condition monitoring is also described to complete the main analysis. Importantly, the authors utilize concrete use cases to demonstrate the roles of the given I4.0 component model and relevant SW technologies in creating the AAS. In this context, the use cases embody applications where an operator wearing a SmartJacket equipped with sensors and indicators ensures systematic data collection by passing through the manufacturing process. The set of collected information then enables the operator and the system server to monitor and intervene in the production cycle. The advantages and disadvantages of the individual scenarios are summarized to support relevant analysis of the entire problem.

Keywords: Asset Administration Shell (AAS); Industry 4.0; LPWAN; MQTT; OPC UA; RAMI 4.0; SmartJacket; Internet of Things (IoT); WiFi

1. Introduction

The concept of Industry 4.0 (I4.0) embodies large-scale digitization of production procedures, formation of digital twins during the life cycle of a plant [1], and sensor data processing, cloud storage, and application [2–6]. The current set of state-of the-art manufacturing element includes predominantly those that simplify a production or maintenance procedure; such items comprise, for example, augmented reality smart glasses or the SmartJacket. The jacket was previously described, on a comprehensive basis, within paper [7,8]; at present, the product finds use in multiple branches of industry, and its properties often differ from the original design. Thus, the SmartJacket is marketed by companies such as Google, Levi's (with an emphasis on cell phone connection and entertainment), Kinesix (the World's First Customizable Smart Heating Jacket), and, generally, manufacturers of biking, firefighting, and medical equipment [9]. Major drawbacks consist in sensitivity of the jacket to adverse weather conditions and limited washability, although new materials and integrated fabric antennas are being designed to improve the durability and capabilities of the product [10–12].

This paper presents case studies that focus on interconnecting the sensors installed in the SmartJacket, and these studies are employed to demonstrate how and by what means digital factory (DF) components should communicate and operate within the entire value chain. Importantly, on these grounds, the article discusses the formation and functioning of the Asset Administration Shell (see Section 2) component in the context of manufacturing based on I4.0 [13]. Thus, the first chapters below briefly summarize the fundamental theory of I4.0 and outline the elements of the basic RAMI 4.0 (the Reference Architecture Model Industry 4.0) metamodel to provide a perspective of the value chain, including supplementary views of relevant economic and commercial aspects. The life cycle of a component within the I4.0 manufacturing process is also examined, especially in Section 2, which characterizes the model of an I4.0 component in greater detail to ensure effective interpretability of the underlying case studies. Importantly, the opening sections of the paper (Section 3 in particular) then discuss the concept, structure, and methods of creating the AAS, namely, the digital envelope of a manufacturing component. Such an arrangement, together with the introductory information, conveniently enables the authors to propose within the core chapters a SmartJacket design and related case studies that describe the link connecting a SmartJacket and other digital factory components.

The fundamental model of I4.0 exploits RAMI 4.0 (Figure 1), an architecture designed by the VDI/VDE, VDMA, BITCOM, and ZVEI corporations and associations [13]. RAMI 4.0 is registered as German standard DIN SPEC 91345:2016-04.

The metamodel defines, in a three-dimensional space, all basic aspects of Industry 4.0; thus, relevant comprehensive relationships are classified into smaller and simpler substructures, which can be developed independently. Relevant standards of I4.0 are discussed in detail within paper [14].

The right-hand horizontal axis subsumes the hierarchical layers according to standard IEC 62264 *Enterprise-control system integration*; these layers represent the actual structure of control systems, from primary functions of large-scale manufacturing units to their interconnection with the Internet of things and services, also termed *Connected World*.

The left-hand horizontal axis then outlines the life cycle of equipment and products pursuant to IEC 62890 *Life-Cycle Management*; the items included find application in manufacturing and technological units and components. The axis differentiates between two main classes, namely, *type* and *instance*. A type becomes an instance after a product has been completed, inclusive of the prototype testing, and the serial production has commenced.

The layers in the vertical axis represent the various viewpoints associated with the individual aspects (those of the relevant market, function, information, communication, and integration-based abilities of the components) [13–18].

At each of its hierarchical levels, the RAMI 4.0 metamodel characterizes the access to information across the entire manufacturing cycle. Conversely, the ISO/OSI reference model (RM) embodies a tool to be employed by open communication technologies; as such, the ISO/OSI RM reaches only up to the RAMI 4.0 communication layer, which is connected with the integration and information layer. The use cases within this paper (see the following sections) stick to the RAMI 4.0 model, utilizing the RM ISO/OSI standard to describe/design the individual methods of communication.

In modern engineering, major criteria consist in product life cycle and the related value stream. The features are displayed on the left-hand horizontal axis in the above image. The set of items shown comprises, for example, constant data acquisition throughout the entire life cycle. By extension, even with a completely digitized development cycle, the market chain still offers a large potential for improving the products, machines, and other layers of the I4.0 architecture. This perspective matches well the IEC 62890 draft standard.

The other axis (the right-hand one at the horizontal level) indicates the positions of component functions in I4.0, defining and assigning the functionalities involved. The axis respects the IEC 62264 and 61512 standards and represents the standardized hierarchical architecture of the enterprise control pyramid; however, the standards are intended to specify components at positions applicable to one enterprise or manufacturing unit only. Thus, the highest level on the right-hand horizontal axis embodies the connected environment (Connected World), taking into account the expected openness of the Industry 4.0 production chain towards the IoT.

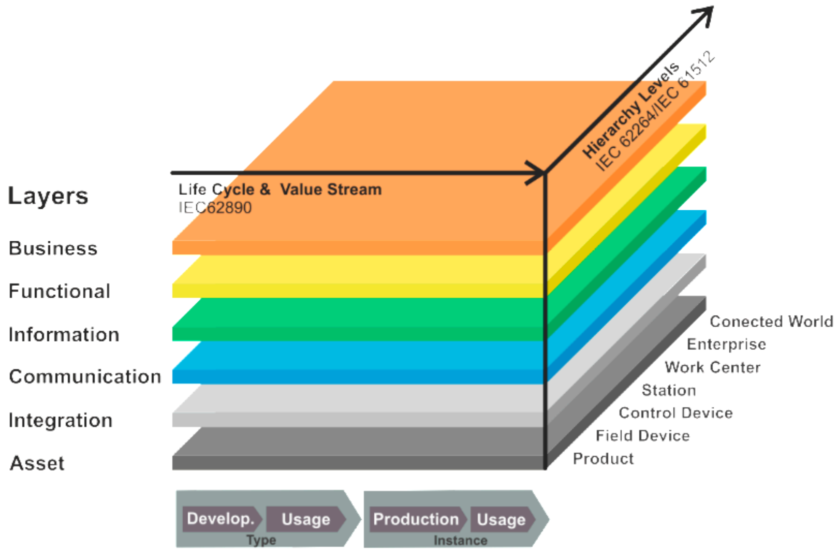

Figure 1. The RAMI 4.0 metamodel (inspired by ZVEI and VDI/VDE [17]).

As mentioned above, the other essential model for the purposes of I4.0, developed by VDI/VDE, VDMA, BITCOM, and ZVEI, is the I4.0 component model. The tool is intended to help automation system designers in digital factories (DFs) of the future to create individual components of I4.0 production according to IEC 52832 CD2 Part 1. The fundamental precondition consists in that each manufacturing component is accompanied with a systematic digital model that contains all data of not only the physical form (the asset) of the component but also the functions to be executed by or on the component during the entire value chain of the operation, such as initiating an operational cycle or performing configuration and maintenance. The component must also contain data related to the history of the component's digital form (the twin) and other information that will enable the I4.0 component to be active and to communicate with the DF. For this purpose, the organizations and associations repeatedly mentioned above created the I4.0 component model. Within I4.0, each component (thing) is denoted as an *asset* and has its specific *administration shell*, see Figure 2.

The difference between a regular manufacturing component and an I4.0 one is presented in Figure 2, which displays four asset types (out of the significantly larger number of options): the SmartJacket or another means of production; the terminal; the 3D printer; and the control software or other programs. The model exploits the idea that an I4.0 component embodies jointly an asset and its digital form. The digital incarnation, made via the already discussed standard procedure, is then termed the Asset Administration Shell (AAS).

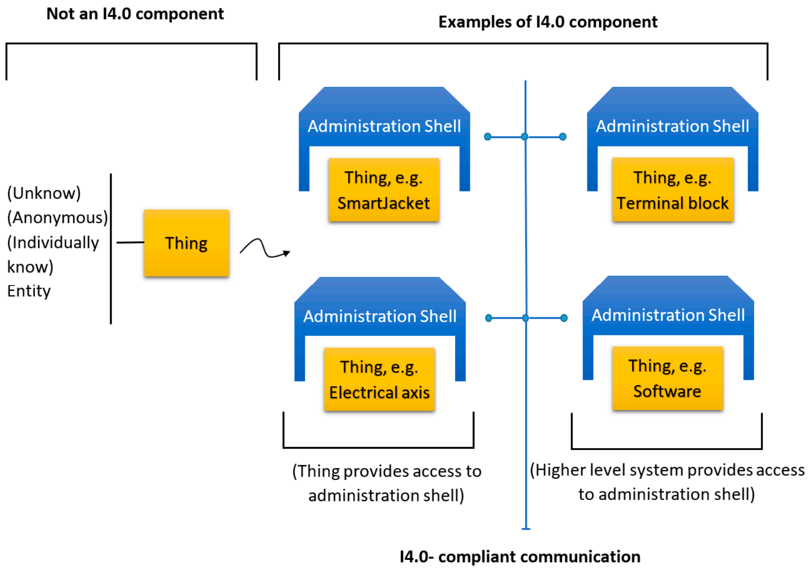

Figure 2. From an asset to the I4.0 component (inspired by ZVEI and VDI/VDE [17]).

2. Asset Administration Shell

The Asset Administration Shell (AAS) is the standardized digital representation of the asset, the cornerstone of interoperability between the applications that manage manufacturing systems. The digital envelope identifies the administration shell and the assets represented by it, contains digital models of various aspects of the asset (sub-models), and describes the technical functionality exposed by the administration shell or respective assets.

After the German research and development companies indicated herein were joined by relevant French (Alliance Industrie du Futur in France) and Italian (Piano Industria 4.0 in Italy) organizations, the I4.0 component model changed as indicated in Figure 3. The AAS consists of a body and a header; the header contains details identifying the AAS and the represented asset, while the body comprises a certain number of sub-models for an asset-specific characterization of the AAS.

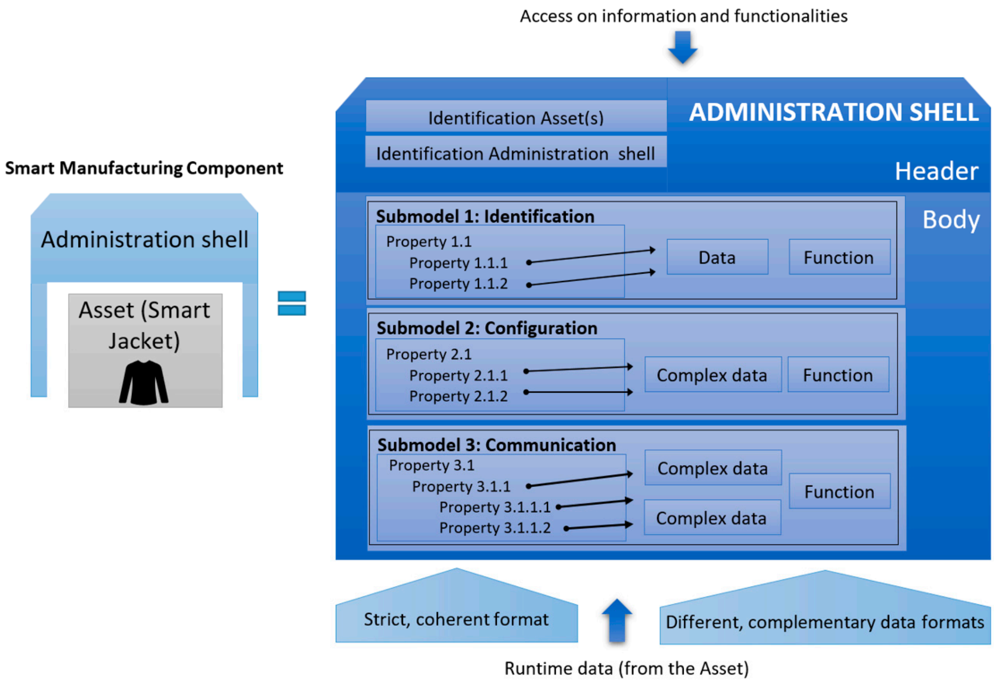

Figure 3. The Asset Administration Shell (inspired by [13,19]).

These sub-models represent different aspects of the asset concerned; thus, for example, they may contain a description relating to the safety or security but also could outline various process capabilities, such as drilling or installation. Possible sub-models of the AAS are indicated in Figure 4.

Administration Shell
IEC TR 62794 & IEC 62832 Digital factory

Submodels	**Standards**
Identification	ISO 29005 or URI unique ID
Communication	IEC 61784 Fieldbus profiles
Engineering	IEC 61360/ISO13584 Standard data elem.; IEC 61987 Data structures and elements; Ecl@ss database with product classes
Configuration	IEC 61804 EDDL; IEC 62453 FDT
Safety (SIL)	EN ISO 13849; EN/IEC 61508 Functional safety discrete; EN/IEC 61511 Functional safety process; EN/IEC 62061 Safety of machinery
Security	IEC 62443 Network and system security
Lifecycle status	IEC 62890 Lifecycle
Energy Efficiency	ISO/IEC 20140-5
Condition monitoring	VDMA 24582 Condition monitoring
Examples of AAS usage	Drilling, Milling, Deep drawing, Clamping, Welding, Painting, Mounting, Inspecting, Printing, Validating

Figure 4. Possible AAS sub-models (inspired by [19]).

Generally, the aim is to standardize only one sub-model for each aspect. Such a scenario will enable us to search for, e.g., a welding machine via seeking the AAS containing "welding" with relevant properties. A second sub-model in the example, e.g., "energy efficiency", could ensure that the welding station will save electricity when idling.

Each sub-model contains a structured quantity of properties which can refer to data and functions. A standardized format based on the IEC 61360 is required for the properties; the data and functions may be available in various complementary formats. The standards that govern the formation of the individual sub-models (Identification, Communication, Engineering . . .) are summarized in Figure 4.

The properties of all the sub-models therefore result in a constantly readable directory of the key information of the Head of the AAS and thus also of the I4.0 components. To enable binding semantics, we must clearly identify the AAS, assets, sub-models, and properties. The permitted global identifiers are the ISO 29002-5 (e.g., eCl@ss and the IEC Common Data Dictionary) and URIs (Unique Resource Identifiers, e.g., for ontologies).

At present, the literature [13,19–21] available from the Industry 4.0 Platform website enables the researcher to seek the requirements concerning the creation of the AAS; such requirements are also outlined within this chapter, Figure 5. These items, including relevant examples, are characterized more closely in papers [13,19].

ID	Requirement
1	An administration shell accepts properties from different technical domains in mutually distinct submodels that can be version-controlled and maintained independently of each other.
2	The administration shell should be capable of including properties from a wide range of technical domains and identifying which domain they derive from.
3	To find definitions within each relevant technical domain, different procedural models should be allowed that respectively meet the requirements of standards, consortium specifications, and manufacturer specification sets.
4	Different administration shells associated with an asset must be capable of referencing each other. In particular, elements of an administration shell should be able to play the role of a "copy" of the corresponding components from another administration shell.
5	Individual administration shells should, while retaining their structure, be combined into an overall administration shell.
6	Identification of assets, administration shells, properties and relationships shall be achieved using a limited set of identifiers (IRDI, URI and GUID), providing as far as possible offer global uniqueness
7	An administration shell should allow retrieval of alternative identifiers such as a GS1 and GTIN identifier in return to asset ID (differencing).
8	The administration shell consists of a header and a body.
9	The header contains information about the identification.
10	The body contains information about the respective asset(s).
11	The information and functionality in the administration shell is accessible by means of a standardized application-programming interface (API).
12	An administration shell has a unique ID.
13	An asset has a unique ID.
14	An industrial facility is also an asset: it has an administration shell and is accessible by means of ID.
15	Types and instances must be identified as such.
16	An administration shell can include references to other administration shells or Smart Manufacturing information.
17	Additional properties, e.g. manufacturer specific ones must be possible.
18	A reliable minimum number of properties must be defined for each administration shell.
19	The properties and other elements of information in the administration shell must be suitable for types and instances.
20	There must be the capability of hierarchical and countable structuring of the properties.
21	The properties shall be able to reference other properties, even in other administration shells.
22	The properties must be able to reference information and functions of the administration shell.

Figure 5. The requirements on the Asset Administration Shell (inspired by [19]).

Although the majority of the requirements relate to the software, some of the points have to be considered already in the procedure of designing the hardware, or the entire system. The set of requirements that can be regarded as pivotal comprises items 1, 4, 5, 14, and 17 from the table in Figure 5.

3. Asset Administration Shell of Operator

As mentioned earlier, every production element (e.g., a product, a machine, and control systems) has its own AAS in the context of I4.0. The question, however, is how to implement an operator AAS. We suggest that the manufacturing operator wear a SmartJacket with sensors; the jacket is designed to collect and evaluate data of the operator and the manufacturing cycle, facilitating easier decision-making or intervention in emergency situations.

The sections below characterize the properties of the design and propose three use cases to illustrate the connection of sensors in a SmartJacket worn by an operator.

3.1. Use case I: Wireless Connection of the Sensors at the Shop Floor Level

This use case describes the *smart* sensor implementation scenario where each SmartJacket sensor communicates in a decentralized manner with the coordinator present at the shop floor level (Figure 6). Such sensors, being independent of the centralized element embedded in the operator's jacket, are labeled as *smart*. The data can be dispatched directly to a cloud or to a local server via data concentrators. The Asset, namely, the operator, will carry an HMI device (a tablet or a cell phone) that can function as the Administration Shell. Another option rests in running the Administration Shell on a cloud/server to which the HMI will be connected as a client.

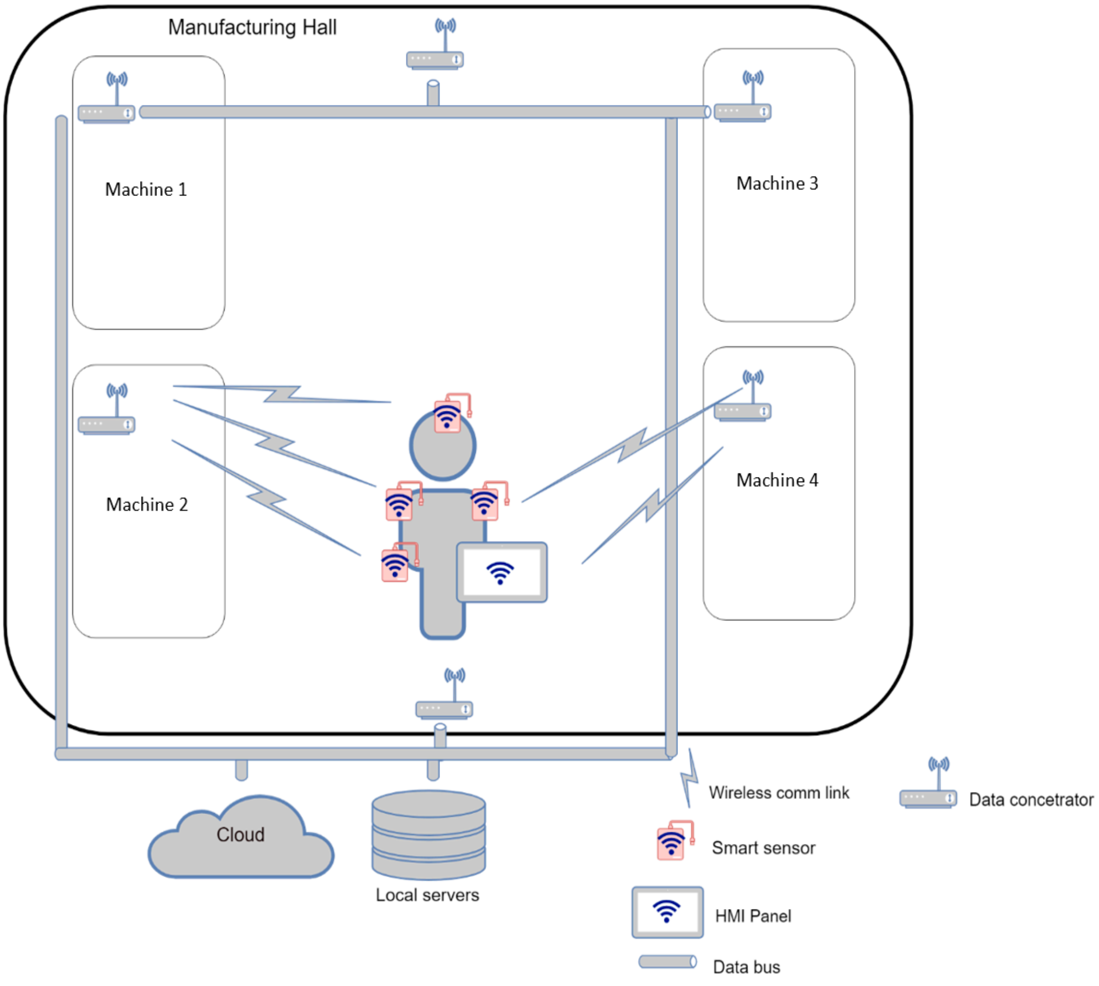

Figure 6. *Use case I*: wireless connection of the sensors at the shop floor level.

The described solution is based on the idea that none of the sensors depends on the centralized module in the operator's jacket.

This concept offers the following advantages:

- The sensor can be embedded into any jacket having a suitable pocket.
- Connection to the centralized element is not required.
- The sensors are easily removed from the jacket before washing or similar tasks.

The disadvantages:

- Large shop floors require more powerful transmitters, thus potentially causing and increase in the energy consumption as well as shortened battery life.
- The devices may overload or interfere in the communication line. Practically, wherever multiple devices are assumed, we need to use networks designed for servicing the required load. A network collapse or malfunction may be prevented also by reducing the communication interval or utilizing various bands and channels.
- A higher transmitting power may cause problems related to applicable health or safety limits (SAR).
- Wireless networks are more vulnerable to cyber-attacks. Research is being performed in this field to substantially reduce or eliminate such risks.
- Although the communication is mostly non-deterministic, the WIA-PA network supporting TDMA is usable. Such a solution, however, could result in a major data delay if multiple devices are connected.

The advantages and drawbacks indicate the necessity to discriminate between the data in terms of their importance to ensure preference and deterministic transmission/reception for important items; the remaining data will then be sent during low preference periods.

As regards the wireless networks convenient for *Use case III*, it is possible to consider several standards, namely, the IEEE 802.11 (WiFi); 802.15 (Bluetooth, ZigBee, WirelessHART, WIA-PA, and others); 802.16 (WiMAX); and ISO 18000-7 (ISM radio frequencies and LPWAN). After comparing the capabilities of the networks as well as the availability and cost of the modules, appropriate modules can be selected.

In this use case, the communication is performed over WiFi and LPWAN (Sigfox, LoraWAN, NB-IoT). The assumed operations include data monitoring and logging from the sensors, operator warning or instruction, and HMI-based evaluation and visual representation.

3.1.1. Communication between the Sensors over a WiFi Network

Multiple factories guarantee WiFi connection at every spot inside the shop floor. Such a solution does not place any additional demands in view of the communication infrastructure, with a transmission power and theoretical coverage of up to 500 mW and 1 km in free space, respectively. The transmission power rates depend on the distance, ranging between 250 Mb/s at short distances and minimum speeds in the order of kbps in more complicated situations.

The SmartJacket sensors can be suitably completed with the IoT ESP8266 or the more modern ESP32 modules [22]. The modules are certified for the IoT, and their benefits rest in the comparatively low cost, good availability on the market, and a large developer community.

The Table 1 shows that the ESP8266 module is more convenient for a battery-supplied *smart* sensor: In case of a signal loss, the sufficient memory capacity enables the data to be logged inside the device and then sent with a timestamp. The module can pass into the deep sleep mode and awake periodically to reduce the average consumption by up to two orders of magnitude.

Table 1. Specification of the ESP8266 and ESP32 modules.

Specifications	ESP8266	ESP32
Memory	160 kB	512 kB
GPIO	17	36
Working Temp (°C)	−40 to +125	−40 to +125
Clock Speed	80 MHz	160 MHz (DualCore)
Price including VAT	5 €	20 €
Range	<100 m	<130 m
Power consumption, Tx	150 mA	210 mA

The drawback of any solution utilizing the module lies in the very 2.4 GHz band, which may be significantly busy and noisy; moreover, when multiple sensors are employed, the WiFi method becomes completely inapplicable for the given purpose. Using the IEEE 802.11b/g/n standard is also less dependable with respect to cyber safety. Further, the energy consumption reaches such levels that a 1 Ah battery would not last more than a day.

The discussed issues seem to be less serious with the 802.11ah WiFi HaLoW [23], which provides for less energy intensive communication at 2.4 GHz, 5 GHz, and 900 MHz. The last of these frequencies is beneficial at larger ranges, and it offers reduced interference by other devices. Interestingly, despite the fact that devices operating with WiFi HaLoW are still scarcely available and the infrastructure to support the standard is yet to be established, the presented option exhibits a major application potential in IoT networks.

3.1.2. Sigfox

The Sigfox network finds use in sending short messages at longer intervals (the maximum of 144 messages can be sent out in 24 h, once per 10 min). Message reception is possible only four times a day, and charges apply to each device. These aspects then make Sigfox unsuitable for SmartJacket sensors. As regards the properties of the network, its European version operates at 868 MHz, and the transmission performance reaches up to 25 mW. Theoretically, the transmission is effective as far as 40 km (or 10 km in urban areas) from the source [24,25].

3.1.3. LoraWAN

Using the LoraWAN radio communication protocol facilitates long-distance data transfer at low energy consumption; moreover, the inherent interference resistance and sufficient communication safety rate are indispensable in the industrial environment [26,27]. LoraWAN exploits the *mesh* architecture, meaning that the protocol not only sends each end element but also receives and forwards messages; such a capability expands the range of the network, yet only at the expense of its higher complexity and lower throughput. The European mutation of LoraWAN operates at 868 MHz, and the transmission performance reaches up to 25 mW. Theoretically, the transmission is effective as far as 20 km in an open space (or 5 km in urban areas). The communication is standardized.

The network consists of end instruments and gateways (data concentrators). The initial gateway cost amounts to approximately 300 € per item. To increase the coverage rate, several LoraWAN gateways have to be applied. The indoor reach is about 1 km.

Different LoraWAN modules are marketed, featuring diverse frequencies, trasmission power rates, and consumption. The prices oscillate between 5 € and 30 €, but this range does not comprise the cost of a microcontroller to drive the communication module. Common module parameters are as follows: working temperature −40 °C to +80 °C; sleep mode current approx. 0.2 μA; data reception current <10 mA; and transmission current <120 mA.

The description reveals that LoraWAN embodies a prominent solution for SmartJacket and other industrial sensors. The protocol's inexpensive infrastructure guaranteeing a long-distance range, good interference resistance, and long battery duration are ideal properties for the given purpose.

3.1.4. NB-IoT

NarrowBand utilizes a licensed LTE band [28,29]. The network is characterized by low energy demand and a high indoor coverage rate, properties that make it convenient for mobile signal areas. Simultaneously, however, the solution is among the most expensive ones within LPWAN, with the end device prices starting at 40 € depending on the features. For SmartJacket sensors, the optimum choice rests in the cheapest and least energy intensive variant. The price of the actual communication chip, although lower than that of the end module, does not compromise the cost of an applicable microcontroller and related electronics.

From the perspective of the purchase cost, the use case does appear suitable for the SmartJacket. This network nevertheless embodies a viable approach to configurations with multiple devices, especially where large factory implementations are assumed. The infrastructure can be built at a cost smaller than that of numerous sensors, jackets, and other equipment.

3.1.5. Use case I: A Brief Summary

In this use case, the SmartJacket functions only as a signal carrier. No interconnection of the sensors is required, because the SmartJacket AAS is stored and run in the HMI, and all data associated with the operator (the AAS of operator) are downloaded from a cloud or local server. The operator AAS too can be run on a server or cloud; in such a case, the HMI is only a client of the AAS. The data to be sent to the jacket (such as an alert or a navigating instruction) can pass directly to the end device or cloud/local server, from which the information is then periodically drawn.

Another option is to store the AAS in the local server or cloud; in this case, the operator's HMI would connect as a client.

In terms of effectivity classification, WiFi constitutes the optimum response to the requirements of small-sized factories that do not wish to create a new network infrastructure; the coverage, however, must be sufficient at all spots where operator presence is likely. The ideal configuration would then rely on separate operator, administration, and manufacturing networks to avoid possible security risks. A major drawback of the WiFi scenario is the low battery life, an issue which may cause the overall cost to reach a level where the LoraWAN-based solution already seems to be more beneficial (see Table 2).

Table 2. *Use case I*: A comparison of the communication technologies.

Technology	PHY Standard	Pros	Cons
WiFi	IEEE802.11 a/b/g/n	+ Widespread + Medium range, typically 100 m + High data rate + High radiation performance	- Very complex - High protocol overhead - High latency, typically 300 ms - High radiation pollution - Signal interference - High power consumption
Sigfox	LPWAN	+ High range + Wide range coverage + Low power consumption	- Low message rate
LoraWAN	LPWAN	+ High range + Wide range coverage + Low power consumption + High message rate	- Medium initial costs
NB-IoT	LPWAN	+ High range + Wide range coverage + Low power consumption + High message rate	- High initial costs

If the funds to be invested into the network infrastructure are not a critical factor, LoraWAN embodies an interesting option: Even though the modules and end devices will be more sizeable, they will last markedly longer during one battery active cycle. The range is also much larger, reducing the number of gateways needed.

The scenario that exploits individual modules offers the significant advantage of quick faulty device removal. Further, it is possible to create a new module with another sensor and to assign this sensor to the given operator in the AAS; such a step will diminish the possible need to reset the central concentrator.

The interconnection of the end devices and the AAS or a different factory infrastructure at the physical and the link layers will be executed via the above technologies. For the application layer it appears most convenient to apply UPC UA or MQTT, which support publish/subscribe. Compared to MQTT, OPC UA carries the advantage of being independent from the central element. When modifying the AAS of operator, OPC UA is more effective as it enables us to easily configure the structure by using an XML definition; thus, we can add or remove a device comprised in the operator AAS.

3.2. Use case II: Wireless Interconnection of SmartJacket Sensors

Use case II demonstrates the possibilities of implementing a SmartJacket with wireless *smart* sensors; from the external perspective, the implementation then behaves like an autonomous (or cyber-physical) system within the shop floor. For illustration, we will employ the previously described wire system to define available options as regards its conversion into a wireless one in terms of the architecture, design, and implementation technologies. In this use case, the AAS is integrated directly into the central component (data concentrator).

The fundamental idea of the present scenario is that each sensor in the SmartJacket system will communicate with the central control component (the central communication element behaves like an *edge interface*) and will also be physically contained in the system (Figure 7).

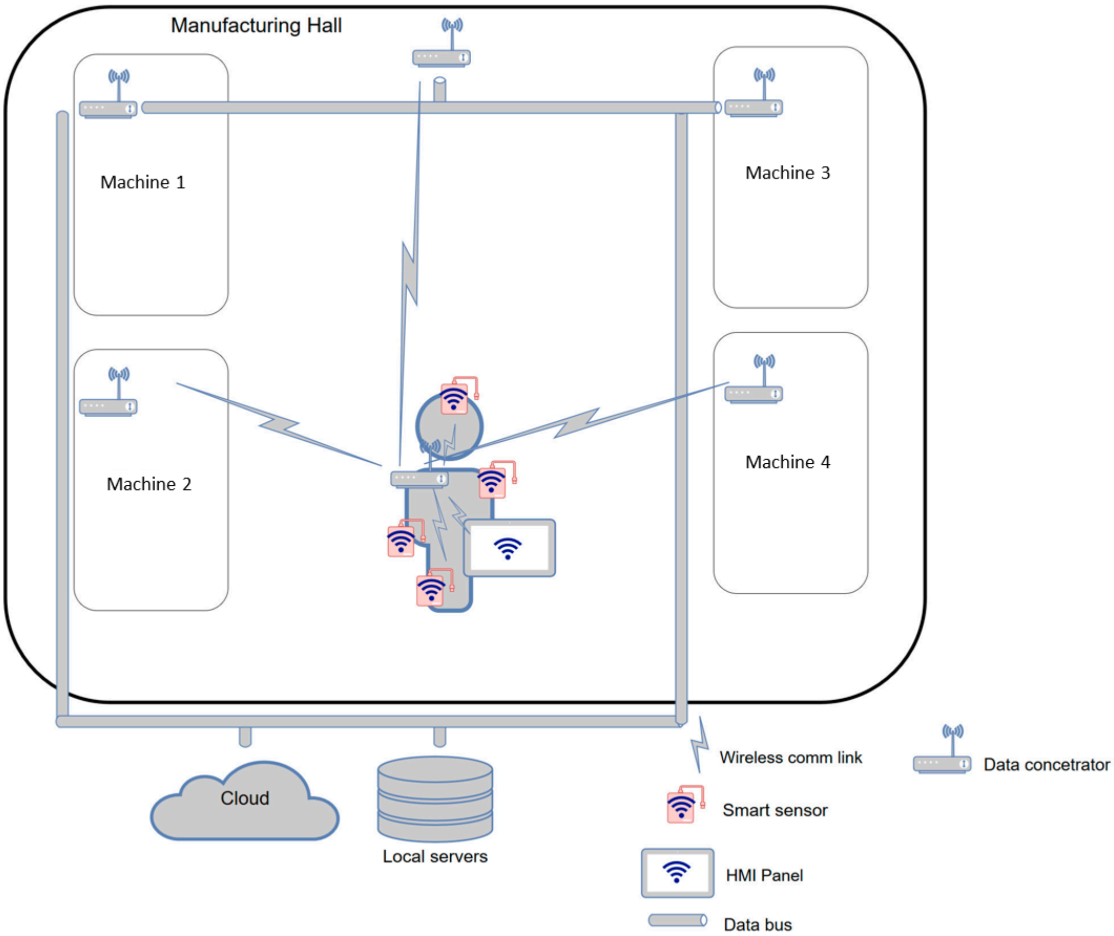

Figure 7. *Use case II*, with the data concentrator directly in the SmartJacket.

The approach is characterized by the following advantages:

- Each sensor will be encased at its location to reach a higher level of water and particle ingress protection.
- No wire has to run between the sensor and the central component, and such a configuration eliminates possible damage due to regular use or washing.
- The user may opt for wireless transmission components with lower radiation to meet safety and health-related limits (such as those regulating EMC interference or SAR).

- Components having lower wireless radiation performance consume less energy that those with a regular performance rate.

The concept, however, also exhibits certain specific drawbacks, and these are currently examined in both the industrial and the academic environments to reduce their overall impact. Such disadvantages include:

- Less reliable communication due to interference and effect of the environment.
- Non-deterministic communication process, an issue eliminable via various academic and industrial solutions that emphasize more robust transmitters and receivers as well as higher radiation performance.
- Increased sensitivity to attacks seeking data invalidity or misappropriation. Research is being conducted in this field to substantially reduce such risks.

In this scenario, we will characterize individual technologies usable on individual layers of the ISO/OSI communication model for interconnection between the sensors and the data concentrator. Further, the suitability of the technologies will be discussed, and a real system will be designed with inexpensive and well available components.

3.2.1. Connecting the Sensors: the Physical and the Link Layers

On the physical layer of the ISO/OSI reference model, wireless communication (such as that realized over the radio) is determined by relevant standards, which not only specify the communication bandwidth and speed together with the maximum radiation performance but also define the link layer as it directly interacts with the physical layer. Major standards for physical layer communication include the IEEE 802.11 (WiFi), IEEE 802.15 (Bluetooth, Zigbee and others), 802.16 (WiMAX), and ISO 18000-7 (ISM radio frequency).

On the physical layer, the IEEE 802.11 standard recognizes various transmission procedures, and this variation gradually produced partial standards such as the IEEE 802.11a/b/g/n. Such standards utilize diverse methods that define the frequency and modulation specifications. Each standard comprises two layers, and these are as follows: (a) A PMD (Physical Medium Dependent) layer, which is associated with the radio transmission of the signal, ensures the modulation, and specifies the signal frequency and magnitude; (b) a PLCP (Physical Layer Convergence Procedure) layer, which adds data on the method applied at the PMD level to the link layer frameworks, ensures synchronization, identifies the beginning of a framework and implements the safety measures.

Leaving out the possibility of utilizing the infrared band, the techniques applicable at the level of the PMD layer are the following ones:

- Direct Sequence Spread Spectrum (DSSS): exploits transmisson over a spread spectrum with a pseudorandom spread code and redundancy to improve the reliability;
- Frequency Hopping Spread Spectrum (FHSS): utilizes carrier frequency switching across the spectrum by means of a pseudorandom code (applicable in Bluetooth);
- Orthogonal Frequency Multiplex Division (OFMD): relies on securing orthogonality in signals coded via amplitude (QAM) or phase-shift keying (PSK) modulation.

The IEEE 802.15 standards specify local wireless networks; the IEEE 802.15.1 embodies the basic standard for the Bluetooth physical layer and the IEEE 802.15.4 applies to the ZigBee and WirelessHART layers. The IEEE 802.15.5 standard characterizes the *mesh* technology directly at the data link layer, enabling us to set a communication topology other than *star*. At the physical layer, the technologies operate on frequencies similar to those used by WiFi; the standard thus also specifies how these networks can coexist.

The IEEE 802.16 and IEEE 802.15.3 standards relate to wide (metropolitan) range networks, where higher radiation performance limits are available; these technologies therefore remain inapplicable for the SmartJacket, considering its transmitters are located very close to the human body.

Another state-of-the-art wireless technology consists in Near Field Communication (NFC), described within the ISO/IEC 14443 standard. This approach facilitates bidirectional communication at speeds and lengths up to 424 kb/s and 10 cm, respectively. In view of such parameters, the technology cannot be employed in the present use case.

Another option to conduct communication between the sensors and the data concentrator rests in utilizing a free sub-1GHz ISM radio frequency (for example, 433 or 868 MHz). As these bands are reserved for free use, many of their sections are noisy due to the effect of other devices, and the overall reliability of the technique is thus reduced. The discussed frequencies exhibit major absorptivity by the human body; thus, the transmitter would have to provide a high radiation performance, resulting in an increased energy consumption rate. For these reasons, the approach also appears to be inconvenient in the given context.

At the link level, the IEEE 802.11 standard defines a MAC (Medium Access Control) layer, for which a non-deterministic method to facilitate access to the CSMA/CA bus is specified, and an LLC (Logical Link Control) layer to ensure the addressing and to direct the data flow.

The IEEE 802.15.4 defines at the link layer merely a MAC sublayer, whose purpose is to interconnect the participants into a network by using the CSMA/CA protocol. The networked devices then may communicate over the peer-to-peer mode or, alternatively, respect *star* topology. The higher levels are defined by the individual technologies, such as ZigBee.

In version 4.0, Bluetooth contains the Bluetooth Low Energy (BLE) mode to cooperate with devices exhibiting a performance, range, and communication speed of up to 0.5 W, 50 m, and 1 Mb/s, respectively. The mode is also capable of defining profiles for certain tasks, including blood pressure or heart rate measurement, localization, and other operations. At the application level, the *mesh* function is supported to facilitate communication between the network participants.

The ZigBee technology ensures contact up to the distance of 75 m; multi-hop ad-hoc routing, if used, nevertheless enables data transmission over longer distances even without direct radio visibility. The maximum transmission speed equals 250 kb/s. The link layer defined by the IEEE 802.15.4 offers the possibility of using either the *star* of the *mesh* topologies, ensured by the network layer. At the application layer, the technology comprises application objects; the layer is also responsible for pairing devices as required [30].

3.2.2. Interconnecting the System and a Factory Server

The system can be connected with a factory server by employing one of the above technologies at the physical or the link layer. At the application layer, it is generally convenient to apply a standard protocol, for example, Message Queuing Telemetry Transport (MQTT) or Open Platform Communication Unified Architecture (OPC UA) [31]. Both of these options facilitate the use of variables and also publish/subscribe communication.

The MQTT tool is only a protocol for sending short, periodic messages; functionally, it requires a central element, the Message broker, to control the data flow and the contact between the participants. The OPC UA connects the data model, or the defined structure, and the communication protocol to handle the data and to execute the operations.

3.2.3. Use case II: A Brief Summary

Considering the basic facts (as summarized in Table 3), WiFi, Bluetooth (its low power version in particular) and ZigBee appear to be convenient for interconnecting the sensors and the central data concentrator. As specified within the IEEE 802.11 standard, WiFi provides higher radiation performance rates, and humans are recommended to maintain a distance of no less than 1 m from relevant transmitters to avoid spurious health effects; thus, the technology is not suitable for the discussed use case. The second candidate, Bluetooth (or the BLE mode), exhibits a lower protocol overhead and a short response time; this property facilitates faster device connection, increases the theoretical data transmission speed up to 1 Mb/s, and reduces the energy consumption rate down to as low as 5%. When in the BLE mode, the devices sleep and may send data at pre-defined time intervals. The interrupted data flow embodies a major disadvantage; simultaneously, however, the standard specifies applicable health care profiles. ZigBee exploits the *mesh* technology at the network layer, and therefore its range may be expanded; compared to BLE, ZigBee is characterized by a higher radiation performance and energy consumption.

Table 3. *Use case II*: A comparison of the communication technologies to interconnect the sensors.

Technology	PHY Standard	Pros	Cons
WiFi	IEEE802.11 a/b/g/n	+ Widespread + Long range, typically 100 m + High data rate + High radiation performance	- Very complex - High protocol overhead - High latency, typically 300 ms - High radiation pollution
ZigBee	IEEE802.15.4	+ Topology star/mesh + Short latency, typically 30 ms + Long range, typically 75 m	- Low data rate (typically) 250 kb/s
Bluetooth LE	IEEE802.15.1	+ Low radiation + Short latency, typically 3 ms + Data rate up to 1 Mb/s + Low power consumption	+ Low range typically 10 m
sub-1GHz	ISO18000-7	+ Lone range up to 100 km + Low power consumption	- Signal interference - Low data rate, typically 200 kb/s.

As regards the communication between the data concentrator and a factory server, WiFi seems to be the optimum choice due to the high availability of relevant components on the market and wide use. At the application layer, the MQTT tool seems to offer a viable solution because it features energy saving operation and supports periodic sending of short messages. This capability is advantageous especially in cases where the data concentrator does not contain advanced artificial intelligence functions and is expected to transmit the sensor data directly to the server or, alternatively, to the manufacturing system operator. The OPC UA technology is currently considered the upcoming data representation standard; according to VDE/VDI, it even constitutes the basis of the AAS. The AAS as such may communicate by using MQTT operating above OPC UA. In the data concentrator, it appears more beneficial to employ solely OPC UA as this tool contains elements that satisfy the standard communication security requirements.

3.2.4. Designing a Demonstration System

Based on the data in Table 3, we identified the BLE mode as the most suitable option for connecting the sensors with the data concentrator embedded in the jacket. The best option for the data concentrator probably consists in a *smart* phone because such a device is normally available to the operator. The phone will then communicate with the factory system over WiFi, which offers a suitable pass rate and superior accessibility. Thus, WiFi is the best choice for communicating at the factory level. At the application level, the data exchange will materialize through the OPC UA protocol, mainly due to its role as a standard industrial data exchange instrument and the basis of the AAS. The Asset Administration Shell will then constitute the communication interface to monitor and exchange data between the SmartJacket and the factory system. The diagram of the system is identical with the common scheme of *Use case II* (Figure 7).

3.3. Use case III: the Interconnection of SmartJacket Sensors

The last use case consists in utilizing the wired technology to connect the SmartJacket sensors to the central element (see Figure 8), which is to ensure wireless communication with the environment; this scenario enables us to save a significant amount of electricity.

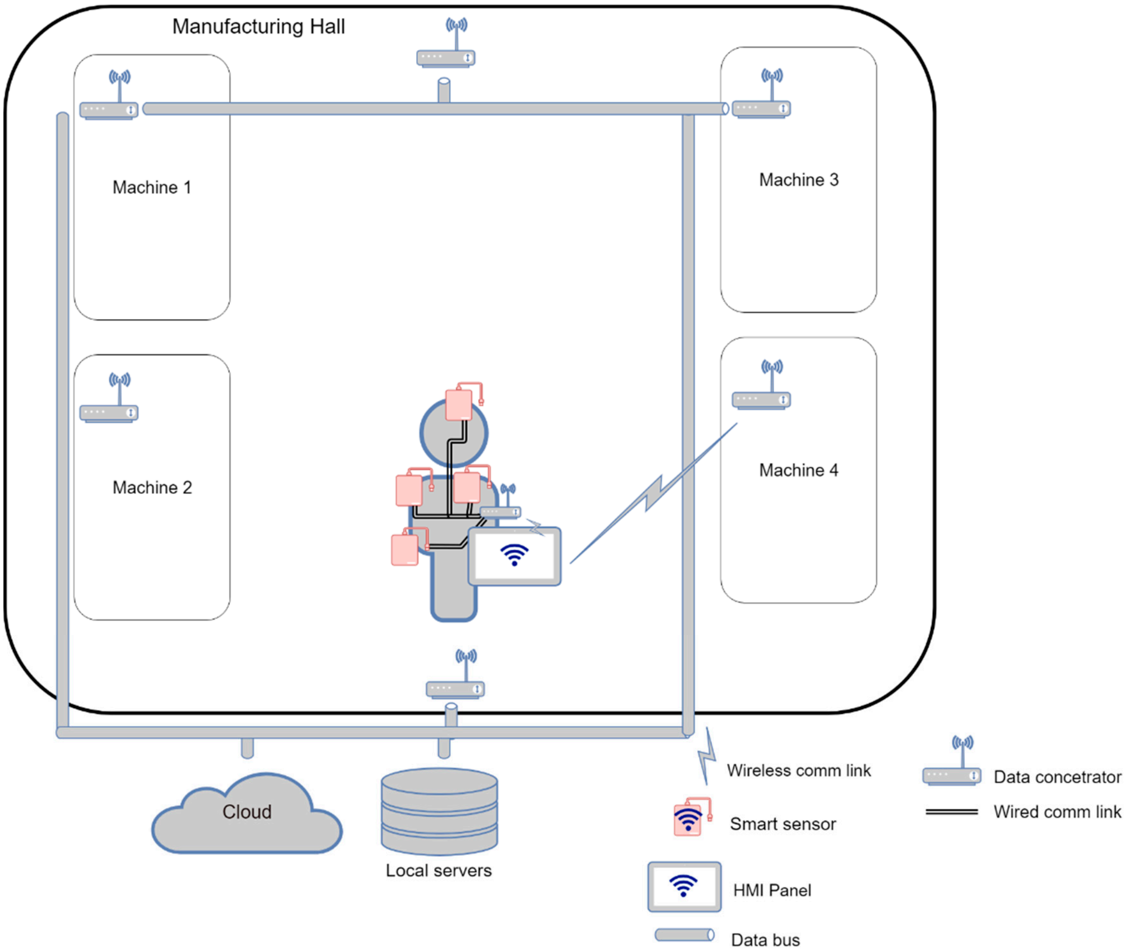

Figure 8. *Use case III*: Wired interconnection in the SmartJacket.

Within *Use case III*, the operator AAS can be stored either in a data concentrator or directly in the HMI. The central unit, namely, the data concentrator, gathers all data from the sensors and sends the information to the HMI via a low-energy wireless path (Bluetooth LE, 802.15.4 LR-WPANs etc.)

3.4. Summarizing the Use Cases

The wireless mode contributes multiple advantages to the entire concept; in our case, however, the primary drawback, namely, the electricity consumption and vulnerability of the network to spurious signals, markedly exceeded the benefits. For this reason, we chose the wired option to design the operator AAS, utilizing Bluetooth Low Energy to transmit the data between the asset and the administration shell (the operator and the HMI). The actual procedure is outlined in the following chapter. Table 4 contains the main characteristics of all the above-described scenarios.

Table 4. A comparison of the use cases.

Use case	Topology	Pros	Cons
I	Star	+ No single point of failure: if one or more endpoints fail, others can still work. + A wireless SmartJacket is easier to wash. + New sensors can be added independently from the central data concentrator; configured; and assigned to operator remotely.	- Highest power consumption. - Battery at every endpoint. - Signal interference.
II.	Extended star	+ Due to less distance, the power consumption is significantly lower than in *Use case I*. + No wires on the SmartJacket: better washing and sensor replacement/addition.	- Single-point-of-failure central data concentrator.
III.	Extended star	+ Lowest power consumption. + No spurious signals from multiple wireless transmitters. + More robust than the other two use cases.	- SmartJacket difficult to clean. - Single point of failure. - Wires may break when used in an industrial cycle.

4. Implementing Use case I: the Wired Interconnection of the SmartJacket Sensors

In this use case, as well as in the two following ones, we assume the example of an operator AAS represented by a Human-Machine Interface (HMI) connected wirelessly with a SmartJacket. *Use case III* relies on wire connection between the sensors and the central microcontroller, which ensures not only the data collection from the individual SmartJacket sensors but also the HMI communication. The network, therefore, is of the *star* type.

4.1. Block Diagram of the Designed AAS of Operator

Figure 9 shows the block diagram of an operator AAS and the communication interface with other AASs in a manufacturing process.

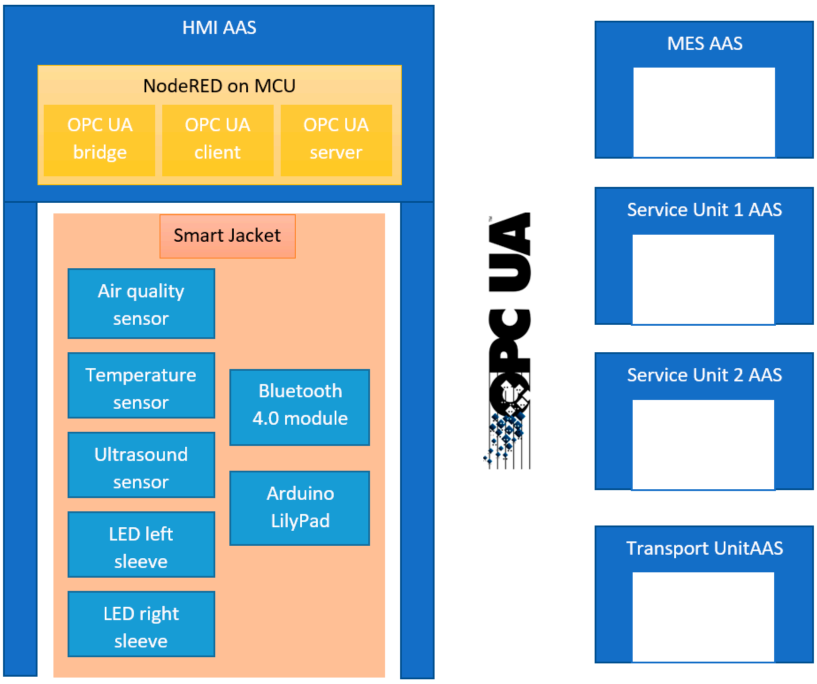

Figure 9. A SmartJacket operator represented via the HMI.

The HMI includes information about the operator and also values from the SmartJacket sensors. Our design assumes generation of an operator AAS via NodeRed running in the HMI. NodeRed is a programming tool to wire together hardware devices, APIs, and online services in new, interesting ways. The communication within a smart factory will involve using the OPC Unified Architecture (OPC UA). Figure 9 indicates that three significant elements are created in NodeRed: a) an OPC UA bridge to facilitate data conversion from string or MQTT messages into an OPC UA message; b) an OPC UA client to communicate information to other AASs, such as an AAS or MES service and transport units, in the production cycle; and c) an OPC UA server to receive information for visualizing the Graphical User Interface (GUI).

4.2. SmartJacket Component

Based on the scenario and intention to control and monitor important industrial parameters at a shop floor, the *smart* maintenance jacket is integrated with a use case. To preserve worker or operator safety on the industrial shop floor, the item is configured with an Arduino LilyPad and sensors (Figure 10), [7,32]. The primary functionality and components of the jacket are outlined below.

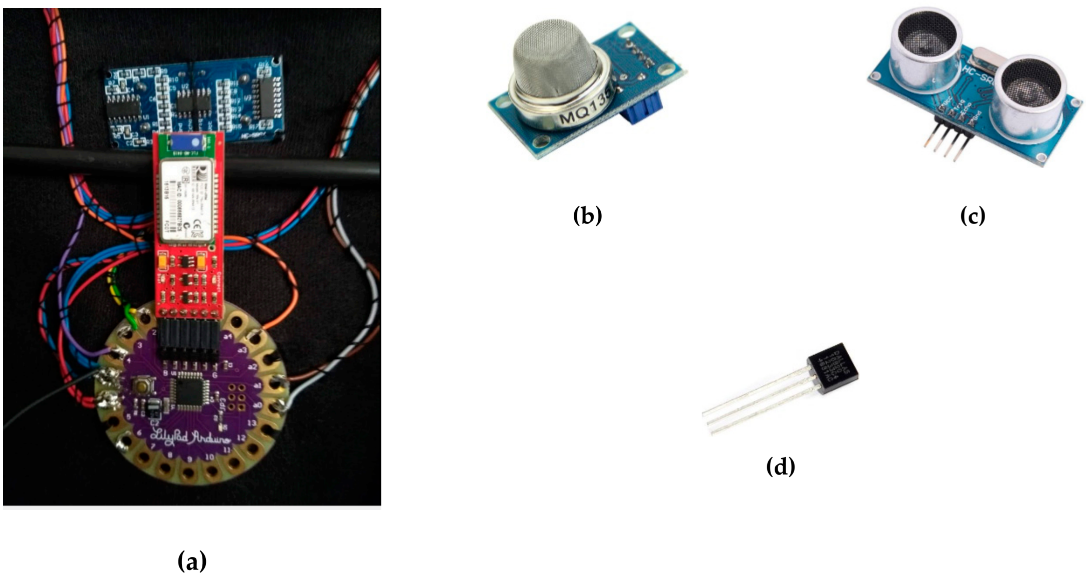

Figure 10. (**a**) An Arduino LilyPad and the wire connection of the sensors; (**b**) An MQ-135 air quality sensor; (**c**) An HC-SR-04 ultrasonic sensor; (**d**) a DS18B20 1-wire temperature sensor.

The central part of the *smart* maintenance jacket consists in an Arduino Lilypad with a SparkFun bluetooth module (BlueSMiRF). The Lilypad is suitable for *smart* wearable things (e-textile projects) due to its size and weight. The Lilypad model configured in the jacket utilizes an ATmega168 microcontroller, which has 14 analog and digital I/Os. The LilyPad Arduino was designed and developed by Leah Buechley and SparkFun Electronics (Niwot, CO, USA).

The BlueSMiRF is the latest Bluetooth 4 wireless serial cable replacement by SparkFun Electronics (Niwot, CO, USA). The modems work as a serial (RX/TX) pipe: any serial stream from 2400 to 115,200 bps can be passed seamlessly from Arduino.

The components wired to the central Arduino LilyPad MCU are as follows:

- An MQ-135 air quality sensor to detect NH_3, NOx, alcohol, benzene, smoke, or CO_2 and to analyze air quality. This sensor is embedded in the *smart* maintenance jacket, with the aim to prevent breathing at a polluted area or processing plant.
- An HC-SR-04 ultrasonic sensor. This small module embodies a cheap solution to measure distance up to 4–5 m via ultrasound. In order to prevent hazardous situations at the shop floor (heavy manufacturing plants), the sensor warns the bearer quickly with a buzzer located at the back of the jacket neck.
- For the temperature measurement, we used a DS18B20 1-Wire digital temperature sensor by Maxim IC. The device reports degrees of Celsius between -55 and 125 at 9 to 12-bit precision,

with a resolution of ±0.5 °C. Each sensor has a unique 64-bit serial number etched into its body; this allows a large number of sensors to be used on one data bus.

- The SmartJacket contains an RGB LED strip (five diodes) on the left and right sleeves. If the MQ-135 sensor recognizes impaired air quality, the operator's right sleeve flashes yellow. If a problem is detected nearby, both sleeves blink red and the buzzer produces an intermittent tone. Similarly, upon a manufacturing fault event the left sleeve will flash red and the right one green. The operator will then identify the GUI where the malfunction occurred.
- A power bank (10,000 mAh).

4.3. NodeRED Dashboard

The Arduino LilyPad utilizes a Bluetooth module to send data addressed to the HMI. In the proposed solution, the serial data are received also via a Bluetooth module. We obtain one string consisting of the temperature value, distance value, and air quality. The next step then lies in splitting the data into separate variables to be publishable via the GUI (dashboard). Figure 11 presents the current and daily data of the measured values in charts. In addition to the actual visualization, the measured data can be sent to the OPC UA server [31]. To execute this operation, we use the node OPC UA IoT Write.

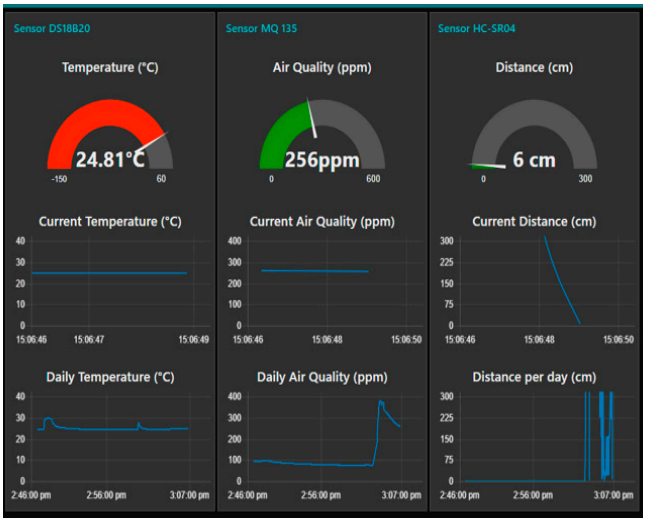

Figure 11. The Graphical User Interface: the value measured by the SmartJacket.

The Write node facilitates sending the data to the OPC UA server: It handles single and multiple data requests. All write requests will produce an array of StatusCodes for writing in the server.

The main drawback of this use case is the fixed attachment of the sensors by means of wires or *smart* fabric because such a solution prevents easy removal of the sensors before washing the jacket. In our research, the SmartJacket and the HMI also become centralized elements, although decentralized systems are the preferred recommendation for I4.0 implementations.

5. Discussion and Conclusions

The paper discusses the options available for introducing sensors and other manufacturing process instrumentation into the environment of a digital factory within Industry 4.0. The concept of I4.0 is characterized by a brief description of the RAMI 4.0 and the I4.0 component models. In this context, the article outlines the structure of an I4.0 production component, interpreting such an item as a body integrating the asset and its electronic form, namely, the Asset Administration Shell (AAS). The formation of the AAS sub-models from the perspectives of identification, communication, configuration, safety, and condition monitoring is also described to complete the main analysis.

The authors propose the idea that the SmartJacket embodies a solution fully applicable in a digital factory. The jacket carries data collecting sensors and safety elements such as RGB LED sleeve strips; upon a pre-defined production event, a LED strip will flash with an appropriate, assigned color.

The research published in papers [12,18] involved creating the AAS of operator and setting up three use cases to describe the interconnection of SmartJacket sensors in both the actual equipment (its fabric) and the shop floor.

The use cases demonstrate the advantages and drawbacks of the individual applicable scenarios, specifying the diverse options and solutions as follows: a) The entire jacket embodies an I4.0 component, and the information from the sensors is communicated to the database either over the wires in the fabric or wirelessly; b) each of the sensors and instruments is equipped with its own means of communication to independently convey data to the database (a cloud or a local server); c) a *smart* phone is employed to function as the edge device to implement the AAS and to wirelessly send information to the sensors. In all of the cases, the operator is invariably an active subject influencing the process via *smart* tools, such as Google glasses.

Prospectively, the capabilities of the SmartJacket AAS will be expanded to cover artificial intelligence tasks, including *smart* operation, evaluation of the operator's biological functions, emergency warning, and rescue intervention.

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Time-Sensitive Networking as the Communication Future of Industry 4.0

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Abstract: The paper discusses new trends within communication protocols of the Internet of Things (IoT), focusing especially on the enhancement of the IoT's real-time abilities and summarizing the long-term knowledge and experience of the authors. Considering the previous standardization attempts of the ISO and IEEE, we may expect that the novel research projects will facilitate major progress in real–time communication systems to satisfy common requirements of industrial automation, information and audiovisual technologies, mechanical engineering, management, banking, medical care, and multiple other sectors covered by the Internet of Things (IoT). In this context, time-sensitive networks (TSNs) appear to embody a most effective approach to securing reliable communication for the future.

Keywords: Internet of Things (IoT), Industrial Internet of Things (IIoT), Open Platform Communication – Unified Architecture (OPC UA), Time-Sensitive Networks (TSN)

1. INTRODUCTION

Industry 4.0 reflects recent demands and directions of the advanced, customer-specific market within various manufacturing sectors. The prospective aim of large-scale factory production then consists in reducing the prices of final products. This ambitious goal is to be reached by utilizing the method of automated production exploiting data from individual production processes; the research and development stages of the manufacturing procedure; edge and cloud computing; and, first of all, powerful open global communication systems facilitating the transfer of multiple data types. In this respect, a tool of major importance rests in, the Internet of things (IoT). Due to the great variety of data in the IoT, the system - its European version in particular - might be classified into three categories: the IoT (Internet of Things), CIoT Commercial IoT), and industrial IoT (IIoT) (Marcon *et al.*, 2017 – 2019, Slanina *et al.*, 2017, Dedek *et al.* 2017).

The individual branches differ in performance and applicability: While the CIoTs puts less emphasis on hard real-time (R-T) communication, the IIoT enables communication in near real-time parameters. By extension, the CIoT has been set up to be a standard commercial homogenous Ethernet-based network, whereas the IIoT exploits heterogeneous industrial networks based on Industrial Ethernet standards. Thus, IIoT networks require solving gateways among different communication protocols; the entire activity then comprises strongly oriented issues, such as the application of Internet technologies and networks in diverse industries and within information exchange between various components of industrial production.

The commercial CIoT is intended for more commercial purposes and activities, including Smart Building, Smart home, entertainment systems, connected cars, Smart TV, cloud connections, big data, and homogenous TCP/IP networks. The IIoT, conversely, finds use in Smart Grids, Smart Cities, Smart Factories, and all sections of the I4.0 in general; in this domain, heterogeneous Industrial Ethernet is used, in association with industrial fieldbuses and lower industrial networks and protocols.

A major precondition for realizing the above-specified production style consists in the actual IoT. For the purposes of the process, the data transmission in the existing IoT technology is not sufficient, because the current Internet of Things and Industrial Internet of Things exploit the stipulations of the IEEE 802.1 group. To facilitate real-time communication with a hard deadline and precise synchronization, the present IoT technology cannot be recommended; at this time, relevant properties are embedded in industrial Ethernets only. These, however, are intended for the transmission of small data frames; smaller and simple network topologies; and lower amounts of nodes than necessary for IoT use. The disadvantage was indicated already during the launching of the IoT, and the ISO and IEEE, major producers of industrial automation designers and manufacturers, and the IEEE 802.1Q standardization group thus undertake intensive corrective efforts. These activities are oriented towards enhancing the real-time properties of the IEEE 802.1 standard. Given the interest of highly developed

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countries in the development and implementation of Industry 4.0, time-sensitive networks appear embody the only communication technology that can be standardized to enable interfactory communication of the future.

2. THE INDUSTRIAL ETHERNET AND REQUIREMENTS OF R-T COMMUNICATION VIA IOT

Previously, since the very beginning of the 21st century, there arose and persisted the necessity to enhance the communication speed of industrial networks (field-, device-, and sensor-actuator buses). As no solution was proposed by the IEEE's standardizing branches, manufacturers and related corporations developed their own real-time Ethernet-based communication tool, namely, the Industrial Ethernet. The IEEE organizations eventually only established about 10 Industrial Ethernet variants as industrial automation standards; at present, approximately 10 fieldbus standards are available in addition to the 10 Industrial Ethernet ones. In all, more than 20 industrial communication standards are regularly used, prominently including Profinet, EtherCAT, PowerLink, CCnet IE, Ethernet/IP, and Modbus/RTPS. Below we will show why the existing industrial Ethernets (IE) are not appropriate for the IoT and IIoT.

2.1 Profinet

Profinet, a full real-time communication system, comprises two complementary solutions. By definition, Profinet RT embodies a factory solution with a cycle time of up to 1ms. The quality of services (QoS), however, does not completely resolve the resource and latency problem. The system ensures good compatibility with other protocols (HTTP, SNMP, TCP/IP) but, because of the QoS, is intended for soft real-time solutions only. Profinet offers the isochronous real-time (IRT) extension. A relevant part of the Ethernet bandwidth is reserved for IRT traffic through an extension to the standard Ethernet HW, Fig. 1.

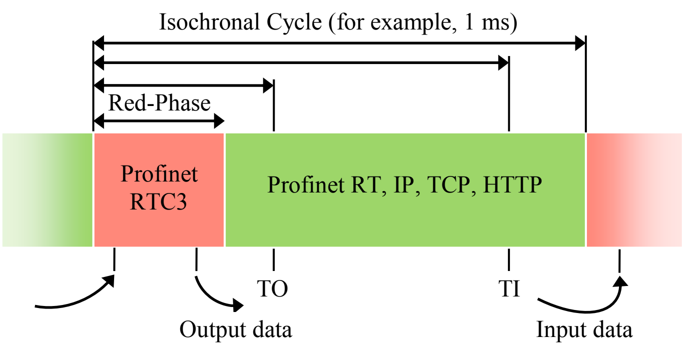

Fig. 1. Profinet IRT (Goller, 2019).

Such an arrangement is made possible by precise synchronization of the clocks in all IRT nodes (by the PTP protocol); thus, a channel (the Profinet RTC3 phase of the frame) can be blocked for normal traffic in every cycle. Only IRT frames in the Red-phase reach the network, and the nodes send the frames exactly at precalculated times, enabling efficiency maximization within the red phase. The red phase can occupy up to 50 % of the Ethernet channel bandwidth, meaning that the arriving traffic has to wait a necessary minimum time only.

2.2 EtherCAT

The physical layer of EtherCAT is the standard Ethernet, and even layer 2 is optimized for fieldbus applications and high throughput. EtherCAT is not equipped with the classic Ethernet bridge: It uses a summation frame telegram, which renders data transmission particularly efficient. Unlike the classic Ethernet, where a separate frame is dispatched by each device, EtherCAT sends one frame per cycle. This frame then contains all data for the addressed devices. While an EtherCAT frame is being forwarded by a device, the data for that particular device is inserted into and taken out of the frame live. Through this procedure, very short cycle times (even ones below 31.25us) can be achieved. EtherCAT has also time synchronization, based on the PTP protocol (EtherCAT Technology Group team, 2019).

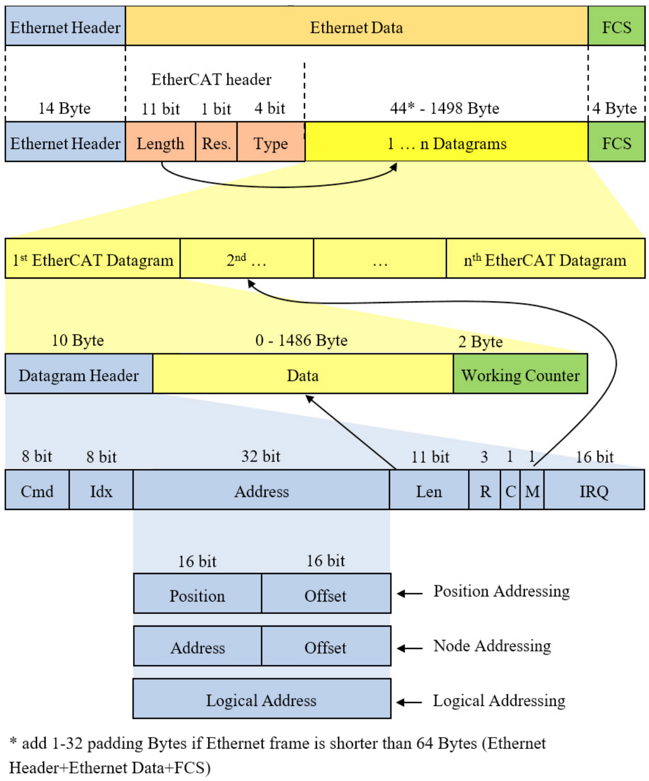

Fig. 2. An EtherCAT Datagram (Beckhoff, 2014).

2.3 PowerLink (EPL)

Ethernet Powerlink has adopted the same basic approach as EtherCAT: It assumes complete control over the Ethernet and transports IP applications to the nodes by piggy-backing. But other properties already differ, for example in that Powerlink does not comprise a summation frame protocol. The real-time performance in practical applications is nevertheless very good. A Powerlink cycle consists of three periods, Fig. 3.

During the Start period, the MN sends a Start of Cycle Frame (SoC) to all CNs to synchronize the devices; the second period, or the asochronous phase, then contains payload data exchange; and the third period marks the beginning of the asynchronous phase, allowing for the transfer of larger, untimed data packets, such as parameterization-related ones.

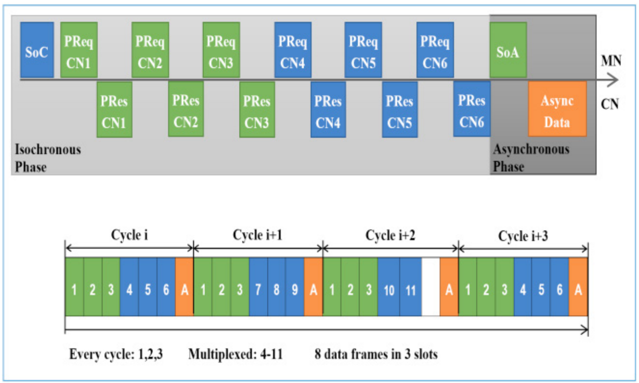

Fig. 3. A Powerlink cycle (Industrial Ethernet Book).

With its mixture of bandwidth, short cycle times, and general flexibility, Powerlink is suitable for both centralized and decentralized automation concepts. Close adherence to the Ethernet standard yields two key features for decentralized use: cross traffic and free choice of the network topology.

Powerlink can operate exclusively as a software stack running on a general processor; such an adaptation delivers soft real-time performance. A more deterministic system would have to use a co-processor to produce cycle times in the region of several hundreds of microseconds.

A gatekeeper organization places major emphasis on Powerlink's ability to use the IEEE802.3 Ethernet standard. While this is true of the letters and numbers of the standard, the reality is somewhat less well defined. The most deterministic Powerlink implementations require master and slave device nodes to run the protocol stack on gate array hardware, and the use of any store-forward Ethernet switch on a Powerlink real-time segment degrades deterministic behavior. In practice, the network infrastructure is restricted to the utilization of hubs.

2.4 Other IEs

Industrial Ethernets such as the CCnet IE, Ethernet/IP, Modbus/RTPS, P-Net on IP, EPA, Vnet/IP, SERCOS III, and TCnet exhibit features similar to those of the most advanced embodiments of EtherCAT, Profinet IRT, and PowerLink.

To summarize the characteristics of the above-specified Industrial Ethernet systems, we can note that their real-time properties are fully sufficient in industrial applications as regards the technical parameters. An advantage rests in the transmission of small data frames, mostly cyclically in the real-time or hard-real-time benchmark. However, in cases of more general use, which correspond to the original operating intentions of the IoT, small amounts of data in a cyclic mode may be unacceptable; no Industrial Ethernet standard is therefore used as a communication protocol in the IoT framework.

3. TIME-SENSITIVE NETWORKING

3.1 General interpretation of TSN

Time-Sensitive Networks (TSN) constitute a set of standards under development by the Time-Sensitive Networking task subgroup of the IEEE 802.1 working group (Zezulka et al., 2016 – 2018, Bradac, 2018). The TSN task group was formed in November 2012 through renaming the existing Audio/ Video Bridging Task Group. The name changed at the time because the standardization group's activities had expanded significantly. The standards define mechanisms for the time-sensitive transmission of data over Ethernet networks.

The majority of the projects define extensions to the IEEE 802.1Q – Virtual LANs (Goller, 2019). These extensions address in particular data transmissions of very low latency and high availability. Possible applications include converged networks with real-time Audio/Video Streaming and real-time control streams, which are used in the automotive or industrial control sectors. Presently, multiple work tasks are being carried out also by the AVnu Alliance's specially created Industrial group, whose efforts are directed towards defining the Compliance & Interoperability requirements for TSN networked elements.

Time-sensitive networks are to become the central communication tools for the I4.0 environment, with the purpose to fulfill real-time requirements in larger process areas and to provide or support Industrial Ethernet standards (IEs) such as Profinet, PowerLink, Ethernet/IP, EtherCAT, and other IEC 61588 instruments to enable real-time communication between control systems, operators, sensors, and actuators in industrial automation systems. Although TSNs are still being developed and refined, the overall success of the I4.0 implementation depends on the relevant standardization. Close cooperation of the IEC 61588 standards and progress in the TSN standardization procedures is expected. The importance of the TSN topic stems from the the impact of the real-time issue on Industry 4.0-based production; compared to present industrial networks, the envisaged novel communication process comprises a large amount of links, entities, data, conditions, distances, heterogeneity of components, and business models. Such a configuration then constitutes a significant aspect of smart factories of the future (Diedrich et al., 2015; Grube et al., 2017).

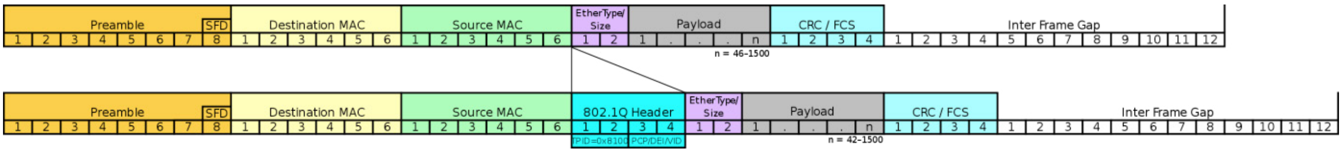

Fig. 5. Insertion of 802.1Q tag in an Ethernet frame (Wikipedia, 2018)

3.2 *Technical basis of the TSN*

The Time-Sensitive Networking goes out from the technical development of industrial as well as IT networks. They have a goal to utilize all that has been done in the OPC UA development and standardization as well as in real-time properties of the development in the industrial Ethernet area. The R-T features are in the I4.0 and the IIoT needed not only in the lowest control and communication levels of the classical control pyramid but in the all technical – production – business chain. It is the reason, that the TSN goes out from technical features of Industrial Ethernet such as the PTP (Precision Time Protocol) from the IEC 61588 which is implemented in the most rapid industrial Ethernet standards (EtherCAT, Profinet, EPL, CC-Link IE). The TSN organization cooperates during the time of TSN developing with other standardization organizations to fulfil all requirements in consideration of requirements from the OT (Operation Technology) as well from the IT (Information Technology) areas. To enhance the R-T properties of IIoT, it is necessary to use the newest standards in the suite of IEEE 802.1. This tendency goes out from the first attempt to translate video and audio data in real time in cars. The appropriate standard is 802.1 AVB. For the next industrial processes are the IEEE 801.1Qbv – the prioritized Time – Aware – Scheduler. It enables packets and frame transmission of time-critical data in a prioritized way. In Fig. 4, there are titled several time synchronization mechanisms, which can be implemented for enhancement of R-T features of TSNs and are already standardized by the IEEE 802.1 (Vojacek, 2018).

IEEE 802.1 TSN TASK GROUP: Projects/Standards Overview	
IEEE 802.1Qbv	Time-aware shaping (per-queue based)
IEEE 802.1ASrev	Timing and synchronization (mechanisms for faster fail-over of clock grandmasters)
IEEE 802.1Qbu	Frame pre-emption
IEEE 802.1CB	Redundancy (frame replication and elimination)
IEEE 802.1Qcc	Enhancements and improvements for stream reservation
IEEE 802.1Qca	Path control and reservation (based on IEEE802.1aq; IS-IS)
IEEE 802.1Qch	Cyclic queuing and forwarding
IEEE 802.1Qci	Per-stream filtering and policing
IEEE 802.1CM	Time-sensitive networking for fronthaul

Fig. 4. TSN Sub-Standards Overview, (Vojacek, 2018).

The frame of the very basic protocol IEEE 802.1Q is specified in Fig. 5.

The standard 802.1Q adds a 32-bit field between the source MAC address and the EtherType fields of the original frame. The minimum frame size is left unchanged at 64 bytes. The maximum frame size is extended from 1.518 bytes to 1.522 bytes. Two bytes are used for the tag protocol identifier (TPID), the other two bytes for tag control information (TCI). The TCI field is further divided into PCP, DEI, and VID.

More precisely we can consider the work of the IEEE 802.1Q working group in Fig. 6. The TSN streams can now be set up in consideration of the existing resources in such a way that no frame has to be discarded anymore. The bridges now use their resources for loss-free forwarding of the TSN streams. The best effort traffic (standard Ethernet, IP, web) takes place completely normally with the remaining resources (memory/bandwidth).

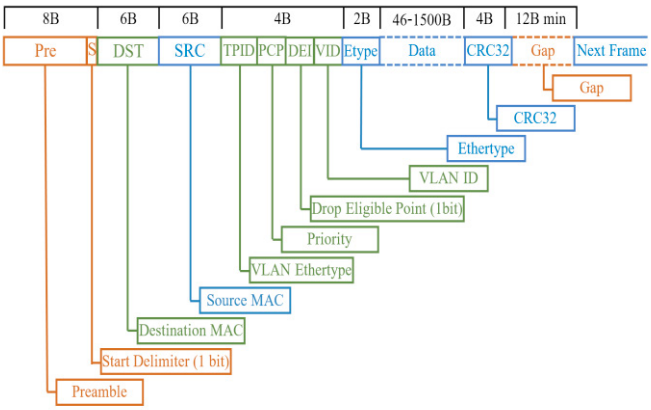

Fig. 6. An Ethernet frame with relevant parts to TSN data stream (Goller, 2019).

Very long time was necessary for the industry to develop proprietary communication standards pro relatively small industrial market (hard – real-time applications in control of protection systems, in control of quick drives and some other non – numerous applications). This development took place in 80th and 90th under protection and recommendation of the ISO and IEEE, but by means of firms, corporations and partly from governments of European developed countries. It has been also paid by customers of industrial automation instrumentation, because of the higher price of control and communication systems. But now days in the digitization and internet age, there is a big interest of standardization of real-time open, safe and secure communication not only in time-critical applications (protection systems, drives, other non – numerous special applications), but in all application everywhere (hospitals, repair shops, banks and other financial institution, insurance companies, travel, entertainment and other agencies, etc.). Therefore, standardization group of the IEEE802.1Q become quicker, more cooperative with the understanding of other interested groups and big sectors of industry, services, commerce. It is accelerated by the communication of big data and technologies for cloud and edge computing as well. The list already developed standards in wireless and other areas is depicted in the Fig.4. This support for standardization makes many things easier. For example, the well known industrial networks are nearly all defined for 100 Mbps. But today gigabit Ethernet is a reality and the 10Gbit Ethernet has become attention in some special applications. The most important is, that the TSN standards cover all speeds. With TSN all of the existing standards would have to be redefined for gigabit! Let us title the main requirements on the principal specifications of the TSN.

4. REQUIREMENTS ON IEEE 802.1 NEW SUB-STANDARDS

TSN extends layer 2 of the Ethernet standard to include a series of mechanisms needed for the real-time modus:

- 802.1AS/802.1AS-Rev provides for extremely precise synchronization of the clock in the network
- The time-aware – shaper (TAS) option enables Ethernet to be operated with precise scheduling. Thanks to it, one or more ques of the QoS model can be blocked/released at specific times
- Pre-emption (interspersing express traffic) enables long frames to be subdivided into smaller parts so that delays are minimized for higher priority frames. The option is applicable in optimizing the guard band for the TAS or replacing the TAS at speeds above 100 Mbps.
- Frame replication and elimination to increase reliability can be employed in defining redundant paths through the network (for example, in rings).
- Use of SW: Defined networking consists in that frames are no longer forwarded to the destination by means of the hardware MAC addresses of the target node but rather via a combination of special MAC addresses (locally administered multicast MAC) and VLAN IDs. How these frames are routed through the network is not determined automatically but rather SW-configured. Such a combination of multicast MAC and VLAN IDs is called the stream ID, and all TSN frames with the same stream ID are referred to as the TSN stream. Although a TSN stream has invariably only one sender, there can be several recipients. Setting up TSN streams is executable with respect to the existing resources, in such a way that no frame has to be discarded. The bridges now use their resources for loss-free forwarding of the TSN streams. The standard Ethernet, IP, and web take place in a completely standard manner, utilizing the remaining resources (memory, bandwidth); see Goller, V. (2019).

4.1 Perspectives in Industry 4.0 Communication Protocols.

Profinet offers a relatively short path to TSN, as it already comprises experience with time-aware shaping (very similar to IRT) and supports the coexistence of industry and IT protocols. EtherCAT will then render TSN accessible above the field level. The EtherCAT automation protocol (EAP) is very suitable for networking the standardized EtherCAT segments via TSN at a low overhead. As far as the authors are aware, EPL (Ethernet PowerLink) will simultaneously employ the standard real-time Powerlink protocol and will correspondingly ensure the development of automated production via the TSN communication protocol after TSN standardization by the IEEE Goller, V (2019).

The main advantage probably rests in recent development within the TSN domain, namely, fusion of TSN at the low level with OPC UA protocols at the highest communication levels. Prospectively, the popular OPC UA software interface and application level protocol will become real-time capable, especially if used with the OPC UA PUB/SUB protocol.

CONCLUSION

The paper outlines the main aspects of recent development and changes in the IEEE 802 3 Ethernet standard as the technical basis underlying the real-time properties of the Internet of Things. The trend in the current Ethernet technology towards absorbing real-time properties in an industrial environment is characterized and completed with the reasons why the traditional, sophisticated industrial communication standards (Industrial Ethernets) are unsuitable for the IoT. In the given context, the authors also explain the aims behind the development and implementation of new substandards within the IEEE 802.1Q. The readers are thus introduced to the principles of time-sensitive networks (TSNs), which are expected to form the technical basis for effective real-time extension of OPC UA communication interfaces and the related application protocol usable in mutliple branches or activities of Industry 4.0 and the IoT.

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Digital Twin and AAS in the Industry 4.0 Framework

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Abstract. The paper goes out from the state of the art in the area of Industry 4.0 initiative of the most developed countries. There are also discussed reasons of Industry 4.0 development and implementation into existing still developed technologies. According to the last development, the term digital twin became a very often-used word. Authors explain differences in the content of the digital twin and recommend to use for the Industry 4.0 area the more appropriate and precise specified term – the Asset Administration Shell (AAS). Next parts of the contribution therefore deal with the Asset Administration Shell (AAS) in details to enable engineers, technicians and informatics from the praxis much more simple introduction in the Industry 4.0 problems and their solution. There is introduced and explained the structure of the AAS, the model and sub-models architecture, parameters and features in the contribution.

1. Introduction

The contribution deals with Industry 4.0 (I4.0) as with a phenomenon, with its properties and procedures of its solution and implementation. Authors introduce readers in the state of the art after some years of the I4.0 initiative has been started in the most developed countries. Authors catch attention on what has been already done and how to utilize these outputs from the research and development for implementation for practical use. They point out also on the importance of standardization in each step of the value chain of industrial production systems, they present a list of them, and show an outlook of the next standards. One part of the contribution deals with a comprehensive list of requirements, which led to the specification of the most important idea and the most important component – the Asset Administration Shell – the electronic rucksack or digital twin of components in the I4.0 smart production systems.

As it has been told in many forums by different opportunities, the I4.0 phenomenon is something like the 4th Industrial revolution. But as has been also said, the I4.0 is more then revolution a rapid and complex evolution of existing automation and automated production with sometimes still a significant level of robotics, complex automation, global communication, digitization, standardization, and openness. The existing industrial production, which can be titled as production in the intention of the Industry 3.0, still shows attributes, which are a challenge and respectable steps towards the creation of a higher type of organization, architecture, and realization of industrial production and even next social aspects of human activities. It can lead to too optimistic evaluation (self-evaluation) of managements of firms, that they already implemented I4.0 principles into their production systems. However, in the most case, there is missing a lot of very important features, characterizing the really I4.0 ideas, principles and technologies. For example, the digitization is used for many years, but not systematically. Authors are the opinion, that only systemically utilized digitalization can grow int the Industry 4.0 world period.

The truth is, that still many features of existing Industry 3.0 (I3.0) production support a statement that we are on the boarder towards a new, higher level of industrial production, tell the 4^{th} industrial revolution This statement is supported by following phenomenones.

Accelerated chain from idea via research, development, and realization of a new product, next a high value of digitization of information from production, next utilization of this digitized information in the control infrastructure of machines, production lines and technological processes. In addition, the high level of intelligence in process instrumentation, control, and monitoring systems, in MES and ERP systems supports the chance of a possibility of transformation existing production systems from the I3.0 to the I4.0 world. Also digitization of all attributes of physical components, marketing methods and procedures and technical and technological development periods, big data flow in the production process, storing and processing of measurement and control values in the cloud supports idea of the coming Industry 4.0 period. This opinion is supported as well as by activities of standardization organizations in highly developed countries to standardize interfaces, communication protocols, production procedures, requirements on the functional safety and security of the all value chain play a significant role.

One of the most promising phenomenon of this historical period, which still influences significantly all the human society is Internet. Internet influences the production processes - the Internet of things (IoT) and the Industrial Internet of things (IIoT) represent the highest development phenomenon horizontal and vertical integration for Industry 4.0 purposes.

Authors are an opinion, that still the slow progress in the implementation of I4.0 principles is caused by non- systematic digitization, non- optimal data acquisition and data processing and low level of application of standards, an unwillingness of specialists in control, measurement and informatics to apply still existing standards and in missing some of needed standards. It appears particularly in communication subsystem, in communication interfaces and protocols. On the other hand the I4.0, its popularity, broaden up, much work which already has been done during last years, and due to competences of many standardization working groups, mutually cooperated across Germany, France, Italy, but also with support and cooperation with the USA, China, Japan bring and open an excellence opportunity and challenge in technical development, that was not possible still 5-7 years ago. I4.0 activities bring the following opportunities:

- An opportunity for unified communication in the all control pyramid.
- Communication by a unified communication protocol from the shop to the highest levels of the office floors of the all value chain.
- Interconnection of all activities in the value chain of industrial production thanks to unified interfaces of HW as well as SW interfaces, protocols, production procedures, production documentation, quality control, safety, and security.
- A significantly higher degree of cooperation among producers and consumers.
- Support of the informatics branch in research, development, standardization, and implementation of unified real-time communication not only in time-critical production processes but also inside the all value chain.
- Acceleration of the activities design – development – production, increasing of digitization and the use of it, decreasing of redundancy in data acquisition processes.

These opportunities will be utilized only, when following preconditions will be to provided systematically and in a standardized way:

- Solid, systematic and standardized digitalization of information from the all value chain.
- Virtualization of production, process modeling in a virtual environment and after tuning all the process to transmit optimized control algorithms into the physical production, output quality checking, marketing and service.
- A higher level of the horizontal integration of the all value chain.

- Intelligence until the component of the production.
- Creation of a standardized architecture of a digital twin of physical components (machines, components of machines), components of a transport system, supermarkets, control SW, technical documentation, product, and market documentation.
- Production components will be designed, developed and implemented as the Industry 4,0 components, specified by the ZVEI, VDE/VDI, and cooperating organizations [1], [2], [5], [8].

The contribution goal is to help technical experts from praxis to understand the importance of the I4.0 component model and to win skills in working with it. This I4.0 component model is described in the next chapter. The official term of the production component is the "I4.0 component” and its electronic form is oft titled “the digital twin”.

2. Digital twin alias Asset Administration Shell (AAS)

The term digital twin was for the first time used by NASA (National Agency of Space and Aeronautics of the U.S.A.) for approximately 60 years to name an electronic version of the physical model of physical comics systems (space shifts, and other systems to fly in the space. Such a very precious mathematical description and consequently very precise digital realization (digital twin) enables monitoring, control and maintenance of the American space system on very long cosmic distances. Because of similar functionality and an appropriate and with the most important element of the I4.0 activity, the Asset Administration Shell – the electronic rucksack is the AAS oft in the last time named digital twin. It was seen also during the last Hannover Fair that the term digital twin very oft used the title. However, in the sense of the NASA, the digital twin is a virtual representation, an embodiment of an asset of any type, material or non-material – including everything from power turbines to services and maintenance. The digital twin is described by the structure and behavior of connected "things" generating real-time data [3].

In comparison, the asset administration Shell (AAS) is the crucial item in the all I4.0 idea. It creates an interface between the physical and virtual production steps. AAS is a virtual digital and active representation of an I4.0 component in the I4.0 system [2]. Any component of production in the I4.0 environment has to have an administrative shell [2].

Fig. 1 shows the structure and connection of the physical thing and the administration shell (AS). The component of the I4.0 is a unity of an asset and the electronic model – the corresponding AS.

The AAS in Fig. 1 is composed of a body and a header. The header contains identifying details regarding the AAS and the represented asset. The body contains a certain number of submodels for an asset-specific characterization of the AAS [4-7].

The co-author of this contribution lived such a misunderstanding of term digital twin during one oral presentation of one tutor by a tutorial in the ZVEI Forum I4.0 in this April in Hannover. The tutor needed several digital twins for one I4.0 component, but from the AAS definition would be fully acceptable and recommended only one AAS with several sub-models.

Much wrong is, that from commercial reasons, the term digital twin is used also for the 3D model, e.g. of a production unit, machine, or car, including simulation. This interpretation is currently state of the art and used by a broad industrial community. However, the 3D model is an I3.0 technology only [3].

Maybe, that existing digital twins in the commercial interpretation will step by step grow to cover all useful information which is relevant across the lifetime of the related asset, from the initial idea to the engineering, logistics, operation, maintenance, reuse, and destruction. They could become a future digital twin that will contain a simulation model, the 3D model, a lot of other properties, historical data, handbooks, installation guidelines, property function blocks, interlockings, state models, alarms, event definition, etc. On the other hand – a static asset will not include in its digital twin any simulation model [3].

In this context, the term AAS is for purposes of the I4.0 more appropriate title then the term digital twin. Therefore authors emphatically recommend to preferably use the term AAS in the I4.0

environment. How great is the difference between the AAS and a pure digital twin in the commercial interpretation can be seen from the following chapters, dealing with the structure of the AAS.

3. Asset Administration Shell Advanced Topic

Much work has been done by working groups of the ZVEI, VDI/VDE, BITCOM exactly in the structure and its components in the Asset Administrative Shell specification. A very comprehensive material of the detail of the AAS was prepared for publication at the end of 2018.

This material is a result of the new situation in Europe. The initial I4.0 idea of the German state institutions ZVEI, VDI/VDE, BITCOM, and some private companies and organizations became newly a larger European background when it has been started initiatives to keep up and improve three the most developed industrial European countries in the manufacturing industry. Alliance Industrie du Future in France, Platform Industrie 4.0 in Germany and Piano Industria 4.0 in Italy have agreed to join forces working on a shared action plan towards internationalization as an end to end digital continuity and global standardization are of crucial importance for a digitized economy [4].

Let us explain more comprehensively, because of high importance, the term AAS:

– The I4.0 component is the combination of the asset and its logical representation, the AAS.
– The AAS is the standardized digital representation of the asset, cornerstone of the interoperability between the applications managing the manufacturing systems.
– The AAS may be the logical representation of a simple component, a machine or a plant at any level of the equipment hierarchy.
– From the manufacturer point of view, the asset is a product. The manufacturer manages different types that have a history with different versions. In parallel, he produces instances of these different types and versions.
– The manufacturer provides the standardized digital representation to his customers, creating both an AAS for the asset type and for asset instance. The system designers, the asset users, the applications, the processes and the asset itself update the information of AAS during the life of the asset until its disposal [4].

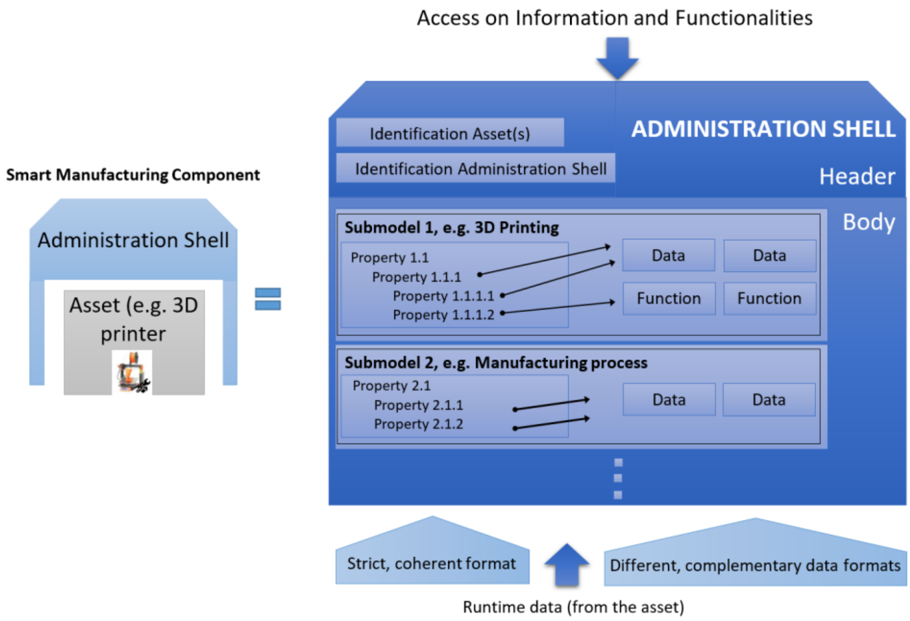

Figure 1. AAS Structure in details (inspired by [4,8]).

Figure 1 shows the AAS structure associated with some specific use cases and much more specifies the contents of the AAS towards the body's part, hence towards submodels.

What is a submodel? Submodels represent different aspects of an asset. Possible aspects and therefore a possible submodel could be: Identification, Communication, Engineering, Configuration, Safety, Security, Lifecycle status, Energy Efficiency, Condition Monitoring, etc.

Each submodel contains a structured quantity of properties that can refer to data and functions. Properties can be specified in accordance with the standard IEC 61360, but data and functions can be specified in various formats [4]. The following example stemming from the project RACAS shows how a specific communication process (bidding process or "interaction pattern") is directed towards the domain-specific submodels in the AAS, Fig. 1 [8]. The bidding between two assets in an industrial production line with 3D printers is described in the top of Fig. 2: an asset (e.g. semi-finished product) asks another asset (3D printer) situated in the production line, if its capacity, functionality, availability are able to provide the specified operation (printing on the semi-finished product of its dimensions <150x200x50 mm from material PLA by filament density 50 % printing operation in color RAL1003, a quality 0.2 mm taking time shorter than 4 hours.

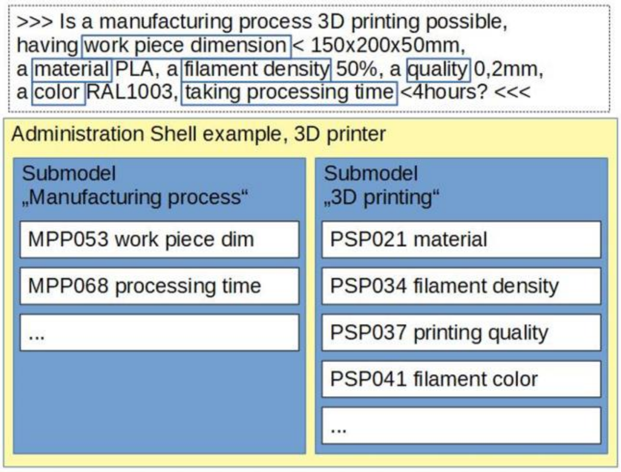

Figure 2. Bidding process directed towards the specific submodels of the AAS.

For such purposes, there have to be implemented in the AAS of the 3D printer at least two submodels ("Manufacturing process" submodel with parameters of the printer such as MPP053 work-piece dimension, MPP068 processing time and, and. There should be also implemented the second submodel the "3D printing" with parameters of the printing – PSP021 material, PSP034 filament density, PSP041 filament color.

This example recovers a principle of decentralized control in the I4.0 environment. The I4.0 components of the I4.0 production would control self their live cycle by negotiation with other I4.0 components. By this way, many problems with fronts in narrow places in production processes will be solved dynamically without a central control system. This architecture also enables more rapid and more flexible reaction of production processes in malfunction of machines, production lines, control systems, transport system and other parts of enterprises technologies.

An important pre-condition for such a production process is, that each I.0 component will be equipped by its standardized AAS.

4. Requirements regarding the AAS

The structure, properties, content of submodels, parameters and other features the AAS have been specified, developed and implemented into the AAS on requirements which have been collected, sorted and specified in detail by working groups of ZVEI, VDI/VDE, GMA, and others and will be openly published in the 2019 year. Contribution contents a proposal of them.

Requirements regarding the AAS sorted into three groups:

1. General requirements (R#1 – R#5)
2. Requirements regarding identifiers (R#6 - R#7)

3. Requirements regarding the AAS self (R#8 – R#22)

Particularly the Requirements regarding the AAS self have significantly influenced the existing model of the AAS [8,9]. All requirements are listed in the following summary [4].

Requirement # 1
The AS shall accept properties from different technical domains in mutually distinct submodels that can be version-controlled and maintained independently of each other.

Requirement # 2
The AS should be capable of including properties from a wide range of technical domains and of identify which domain they derive from.

Requirement # 3
For finding definitions within each relevant technical domain, different procedural models should be allowed that respectively meet the requirements of standards, consortium specifications, and manufacturer specifications sets.

Requirement # 4
Different ASs in respect of an asset must be capable of referencing each other. In particular, elements of an AS should be able to play the role of a “copy” of the corresponding components from another AS. E.g., one or more assets can be portrayed in an AS - mechanical axis, motor, servo amplifier, and additional assets constitute an “encapsulate-capable” Smart Manufacturing Component. The ASs of several individual assets that a manufacturer brings into the market individually is consolidated into one AS, if this manufacturer also sells a whole axis system.

Requirement # 5
Individual ASs should, while retaining their structure, be combined into an overall AS

Requirement # 6
Identification of assets, ASs, properties, and relationships shall be achieved using a limited set of identifiers (IRDI, URI, and GUID), providing as far as possible offer global uniqueness.

Requirement # 7
The AS should allow retrieval of alternative identifiers such as a GS1 and GTIN identifier in return to asset ID (referencing).

Requirement # 8
The AS consists of header and body, see Fig. 1.

Requirement # 9
The header contains information about the identification, Fig. 1. The header contains minimal information about identification. It uniquely identifies the AS. This identification can therefore also serve as a root entry point for an application programming interface (API) to browse for information and functionalities. The header contains also the identification of one or multiple assets that are described by the AS. The header also indicates if these assets are asset types or asset instances.

Requirement # 10
The body contains information about the respective asset(s).
The body contains information about the asset(s) and describes functionalities that are associated with the asset(s) or the AS. The information can concern asset type(s) and/ or asset instance(s). Thus, the body serves as the actual carrier of information and functionality.

Requirement # 11
The information and functionality in the AS are accessible by means of a standardized application programming interface (API).

Requirement # 12

The Administration Shell has a unique ID.

Requirement # 13

The asset has a unique ID. It should be ensured that the link between assets and ASs does not break, even if they are saved in digital repositories or saved in a manner that spans all value-added partners.

Requirement # 14

An industrial facility is also an asset; it has an AS and is accessible by means of ID. The concepts of the AS shall be applicable on all hierarchy levels of an industrial facility, such as factories/plants, production lines, stations, controls and field devices.

Requirement # 15

Types and instances must be identified as such. ASs can be formulated for both types and instances of assets. It must be possible to differentiate between these. Ideally, an information relationship will also be established between component producers and the system integrator that, where required, allows updated developments regarding asset types to be communicated to the system integrator and conversely feedback to be transmitted to the component producer about the component use.

Requirement # 16

The AS can include references to other ASs or Smart Manufacturing information. For the cross-linking of information to knowledge, it is important that this can also take place on an over-arching basis. Thus, for example, a component can model the dependencies on other components or can contain a circuit diagram, which refers to other components.

Requirement # 17

Additional properties, e.g. manufacturer specific must be possible. The Smart Manufacturing component can only meet future requirements if, in addition to the information content stipulated by standards, consortia and manufacturer properties can also be quickly agreed and processed. The AS should, therefore, support this consortia and proprietary information content and, associated accordingly, necessary collaboration processes.

Requirement # 18

A reliable minimum number of properties must be defined for each AS. ASs shall be a reliable source of information to other ASs or other systems. To do so, it shall be possible to define for each asset class a minimum set of properties and value statements that can be relied upon. The following requirements are applicable to the properties of an AS; the properties are structured by submodels. Standardized submodels types can require the presence of properties in submodel instances.

Requirement # 19

The properties and other elements of information in the AS must be suitable for types and instances. ASs can be formulated for both types and instances of assets; thus, properties need to be able to describe particularities of on asset type and, maybe, in addition, the asset instance. An AS of an asset instance shall also feature the properties of the AS of the respective asset type, as long as these properties were not overridden. NOTE: This can for example also mean, that the descriptions of an asset type are extended over the lifetime or, for an asset instance, properties are added, amended or deleted depending on (maintenance) activities of the respective asset.

Requirement # 20

There must be a capability of hierarchical and countable structuring of the properties. The volume of properties to be organized is rather large and it is anticipated that it will steadily increase in the progress of Smart Manufacturing. This means that these quantities should remain manageable for humans and machines. It is thus necessary to be able to organize properties using combinations of structures and arrays.

Requirement # 21

Properties shall be able to reference other properties, even in other ASs. Properties referring to other properties allow expressing dependencies on values contained in other ASs. In addition, knowledge can be modeled by interrelating two properties by a predicated relationship.

Requirement # 22

Properties must be able to reference the information and functions of the AS. The structure of submodels and properties serves as a clearly defined "table of contents" for all information and functions within the AS. Properties are of uniform structure, they are standardized and they are thus providing a very stable source of information. Complex data (digital models) and functions, on the other hand, can have a large variance and can be very complex in structure. Therefore, properties shall be able to refer to these complex data and functions in order to provide an anchor point for these entities in the above "table of contents". NOTE: This concept relies on an extended understanding of an IEC 61360 property concept.

5. Conclusion

Contribution deals with the most important term of the Industry 4.0 theory and application – the AAS. This fundamental term has been already specified in details and can create a reliable basis for the realization of not only I4.0 case studies and test beds, but for the real design, development and implementation of I4.0 principles in reality of factories of the future. Authors repeat terminology and associate technical as well as theoretical basis of the I4.0 idea based on the AAS.

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Article

Automated Design and Integration of Asset Administration Shells in Components of Industry 4.0

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Abstract: One of the central concepts in the principles of Industry 4.0 relates to the methodology for designing and implementing the digital shell of the manufacturing process components. This concept, the Asset Administration Shell (AAS), embodies a systematically formed, standardized data envelope of a concrete component within Industry 4.0. The paper discusses the AAS in terms of its structure, its components, the sub-models that form a substantial part of the shell's content, and its communication protocols (Open Platform Communication—Unified Architecture (OPC UA) and MQTT) or SW interfaces enabling vertical and horizontal communication to involve other components and levels of management systems. Using a case study of a virtual assembly line that integrates AASs into the technological process, the authors present a comprehensive analysis centered on forming AASs for individual components. In the given context, the manual AAS creation mode exploiting framework-based automated generation, which forms the AAS via a configuration wizard, is assessed. Another outcome consists of the activation of a virtual assembly line connected to real AASs, a step that allows us verify the properties of the distributed manufacturing management. Moreover, a discrete event system was modeled for the case study, enabling the effective application of the Industry 4.0 solution.

Keywords: Asset Administration Shell; digital twin; Internet of Things; industrial Internet of Things; Industry 4.0; Manufacturing Execution System; Manufacturing Operation Management; Open Platform Communication—Unified Architecture (OPC-UA); MQTT

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1. Introduction

The concept of Industry 4.0 (I4.0) has been investigated and developed in economically advanced countries for at least 5 years [1–6]. In this context, the most important research groups include ZVEI, VDI/VDE, and BITCOM, especially in terms of refining models such as Reference Architectural Model Industrie 4.0 (RAMI 4.0) and, consequently, the I4.0 component model [7,8]. The entire strategy gradually evolved in Germany and spread across Europe. In 2018, three European countries began to collaborate closely within the manufacturing domain to improve and disseminate the concept, and their efforts yielded the following initiatives: the Alliance Industrie du Futur in France, the German-based Platform Industrie 4.0, and the Piano Industria 4.0 in Italy [9]. These actions and policies enabled innovative ideas to expand into other domains, such as standardization, industrial communication [10,11], informatics [12–14], functional safety, cybersecurity, economics, marketing, energy production, and social economy. Most notably, the diversity of influences has been reflected in the concept of smart factories [15–20]. Outside Europe, the scheme has found wide reception in the USA, China, and Japan.

Implementing the principles of I4.0 into industrial applications is a slow process, mainly due to the generally nonsystematic approach. At present, relevant technologies involve and rely on digitization, robotics, non-optimal data acquisition, virtual reality, IoT, and advanced data processing [21–27]; simultaneously, however, application standards remain undeveloped or are lacking completely, and a similar deficiency also affects corporate economy and common initiative in any given field [28–32]. Conversely, these separate technologies help to accelerate the implementation of I4.0 principles and open new opportunities and challenges for technical development; in the given context, such benefits were considered unfeasible 5–7 years ago. The overall impact of I4.0 and its recent transformations or outcomes—digitization and virtualization in particular—can then be interpreted as epitomizing the difference between the present situation and the conditions preceding the introduction of the initial I4.0 in 2013.

In the current process control, the Manufacturing Execution System (MES) and Manufacturing Operation Management (MOM) play integral roles as the central points of job planning and management [33]. Thus, all relevant data must be transferred to these software, of which only the MES can execute a job command task. Conversely, the concept of I4.0 relies on decentralized (distributed) control—i.e., procedures without a central entity; the decision-making process is then distributed between the entities in the communication network. Within this concept, the MES/MOM ensure new product initiation and are not involved in the job scheduling stage.

A major component of I4.0 is embodied in the AAS, which, in the industrial domain, characterizes assets such as the product, machine, equipment, and factory; an AAS also communicates with other AASs as standard entities interconnected throughout a network. The actual concept originates from a novel interpretation of the management, where relevant components are integrated both horizontally and vertically. While the current management methods are structured mostly vertically, in a hierarchical manner, the novel approaches exploit the markedly higher intelligence (managing capabilities) of the individual manufacturing components, from the top level items down to the sensors and actuators. This concept changes the architecture of the industrial process control system into a distributed (decentralized) form, embedding flexibility in job scheduling, failure responses, and product customization.

The authors characterize a novel procedure for the automated creation of AASs via a configuration wizard, the aim being to accelerate the formation process and to achieve the easier implementation of AASs. In functional terms, the administration shells are generated in compliance with the requirements and standards of I4.0. The operability of the design is verified on a case study involving an assembly line to produce printed 3D toy cars; this step also comprises considering and comparing two communication protocols, Message Queuing Telemetry Transport (MQTT) and Open Platform Communication—Unified Architecture (OPC UA).

This paper discusses AASs (Chapter 2) together with a methodology for creating the wizard; this methodology is based on requirements relating to the functionality, formation, and structure of the AAS. The virtual production testbed and implementation are partially analyzed in Chapter 3, which also defines the communication interface separating the administration shell from the asset; in our case, the assets embody the virtual manufacturing components and items that participate in the manufacturing procedures. The results, outlined in Chapter 4, are characterized more broadly in the last section of the article, with relevant research perspectives complementing the overall discussion of the project (Chapter 5).

2. Asset Administration Shell

The Asset Administration Shell (AAS) is a major constituent of I4.0, creating an interface between the physical and the virtual production variants. An AAS represents—virtually, digitally, and actively—an I4.0 component in the I4.0 system. Any production component in the I4.0 environment has to have an administrative shell [34–38].

In addition to multiple other modes of use, the AAS facilitates the virtualization of the manufacturing process to model, fine-tune, and monitor the algorithms and economy of production already before the cycle actually starts [39]. The AAS is an indispensable precondition for decentralized industrial manufacturing management, yielding flexibility and emergency robustness to reduce queues, bottlenecks, and other issues that limit the efficiency of production units during their service lives.

Alternatively, the AAS can be also designated as the digital twin of a production component [40]; in this context, however, it has to be emphasized that our approach strictly observes and exploits the rules or procedural laws presented in the literature [7–10].

Figure 1 shows the structure of and connection between a physical item and the corresponding administration shell (AS). A component within I4.0 integrates an asset and its electronic model—i.e., the appropriate AS. The AAS in Figure 1 consists of a body and a header. The header contains identifying details regarding the AAS and the represented asset, and the body comprises a certain number of submodels to facilitate the asset-specific characterization of the AAS (see [41–48]).

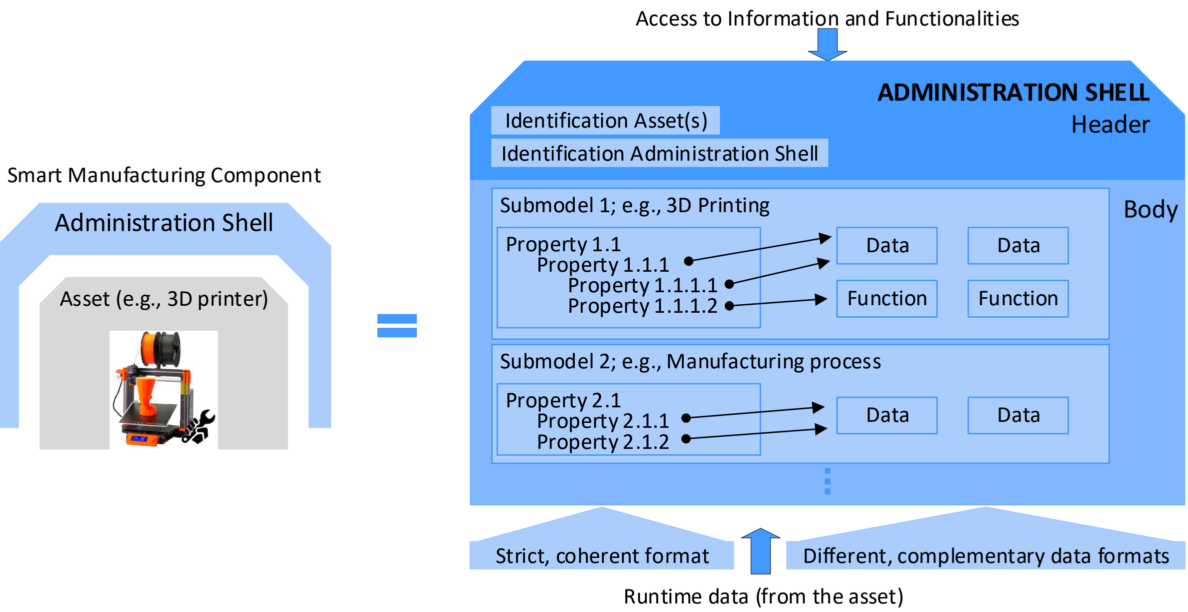


Figure 1. The detailed structure of an AAS.

The submodels represent different aspects of an asset. Possible aspects and associated submodels encompass, among others, the following items: identification, communication, engineering, configuration, safety, security, lifecycle status, energy efficiency, and condition monitoring.

Each submodel contains a structured quantity of properties that can refer to data and functions. The properties are specifiable in accordance with the standard IEC 61360, but the data and functions can be defined in various formats. Figure 1 shows a graphical example of an AAS [7].

The bidding between two assets on an industrial assembly line consisting of 3D printers is described in Figure 2, where an asset (such as a semi-finished product) asks another asset (a 3D printer) on the assembly line if its capacity, functionality, and availability can ensure the completion of the task using the pre-specified parameters (for example, the dimensions of a printable semi-finished product must not exceed 150 $\times$ 200 $\times$ 50 mm; the applied material is PLA with a filament density of 50%; the color corresponds to RAL1003; the layer thickness equals 0.2 mm; and the printing time has to be below 4 h).

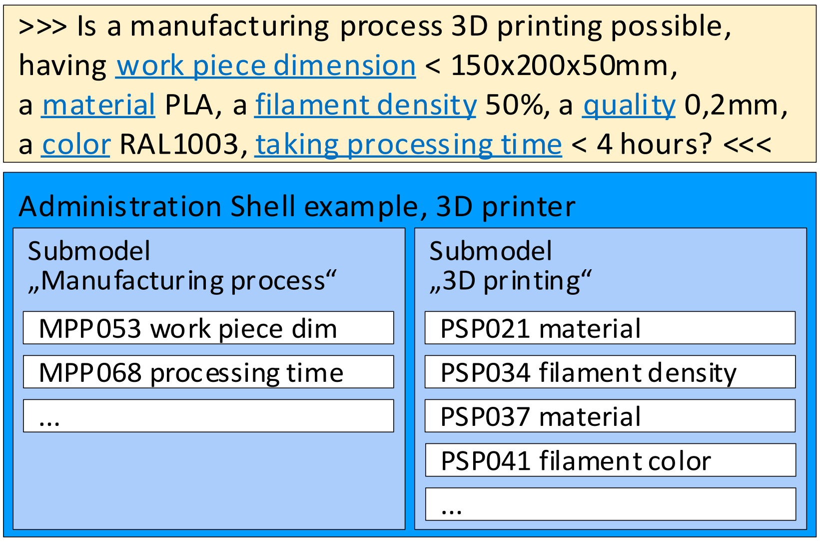


Figure 2. The bidding process related to specific submodels of the AAS.

The requirements concerning the contents of AASs can be classified into three groups [7,9]:

1. General;
2. identifier-related;
3. AAS-specific.

All such requirements are specified in sources [7,9] and included in our proposal. Exploiting knowledge of the procedural principles relating to AASs and their practical usage, we designed ConfigWizard, an innovative tool to allow the comfortable and partially automated generation of AASs. To fulfill this purpose, the software assists in the essential steps that enable AAS formation and functions (access via a webservice; information modeling: submodels, parameters, and events; asset integration: the mapping of the communication properties; OPC UA server configuration), see Figure 3.

Without such a configuration wizard, all the steps must be carried out manually, requiring intensive programming, see Figure 4. The ConfigWizard reduces the AAS development efforts to inserting relevant configuration data via a GUI (frontend, Figure 5). The user can add, edit, or delete each of the AAS submodel entities, such as a property, method, or event. The ConfigWizard's backend then automatically generates an AAS software package based on the configuration entered by the developer; the necessary configuration data are usually derived from a scenario-specific use case and sequence diagrams.

Regarding the underlying OPC UA technology [49–57], the user must also define the parameters of the OPC UA channel and other items according to the OPC UA stack—i.e., in agreement with the OPC UA standard at each level of the ISO/OSI model (Table 1). Using this procedural step, the connection with the AAS environment is established by the OPC UA.

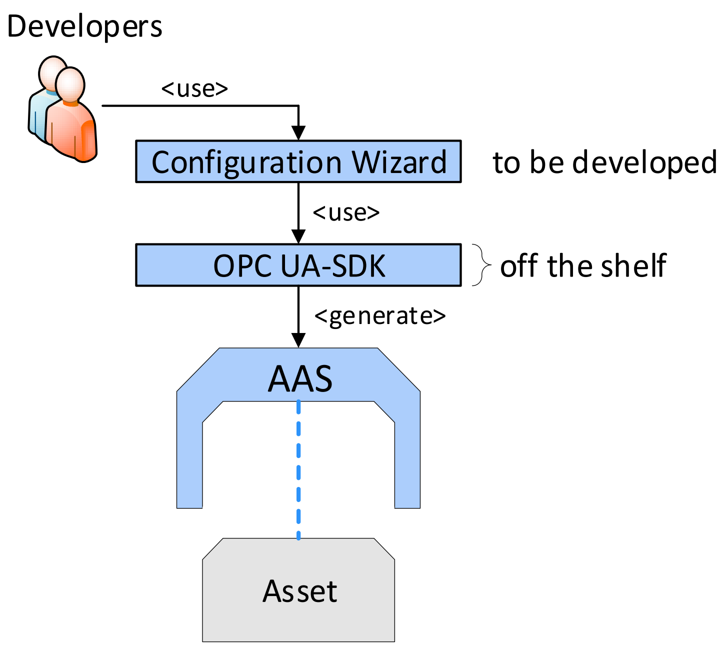


Figure 3. A block diagram to define the functioning of ConfigWizard.

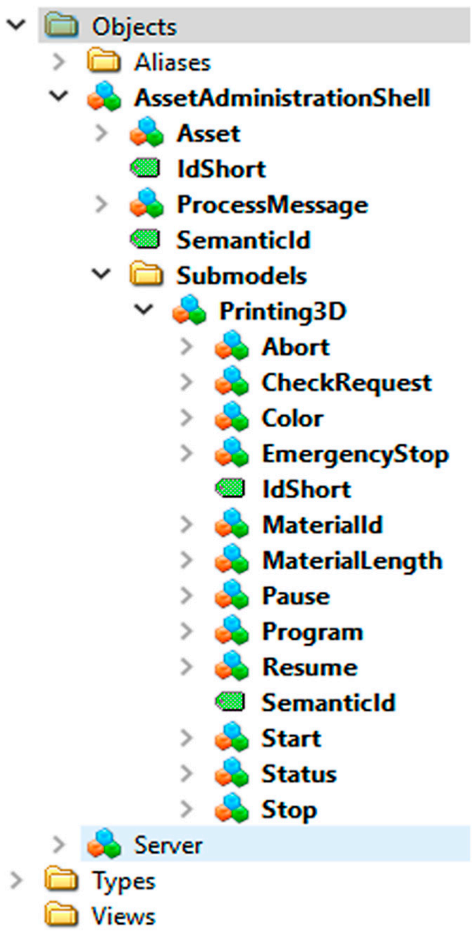


Figure 4. A manually formed AAS.

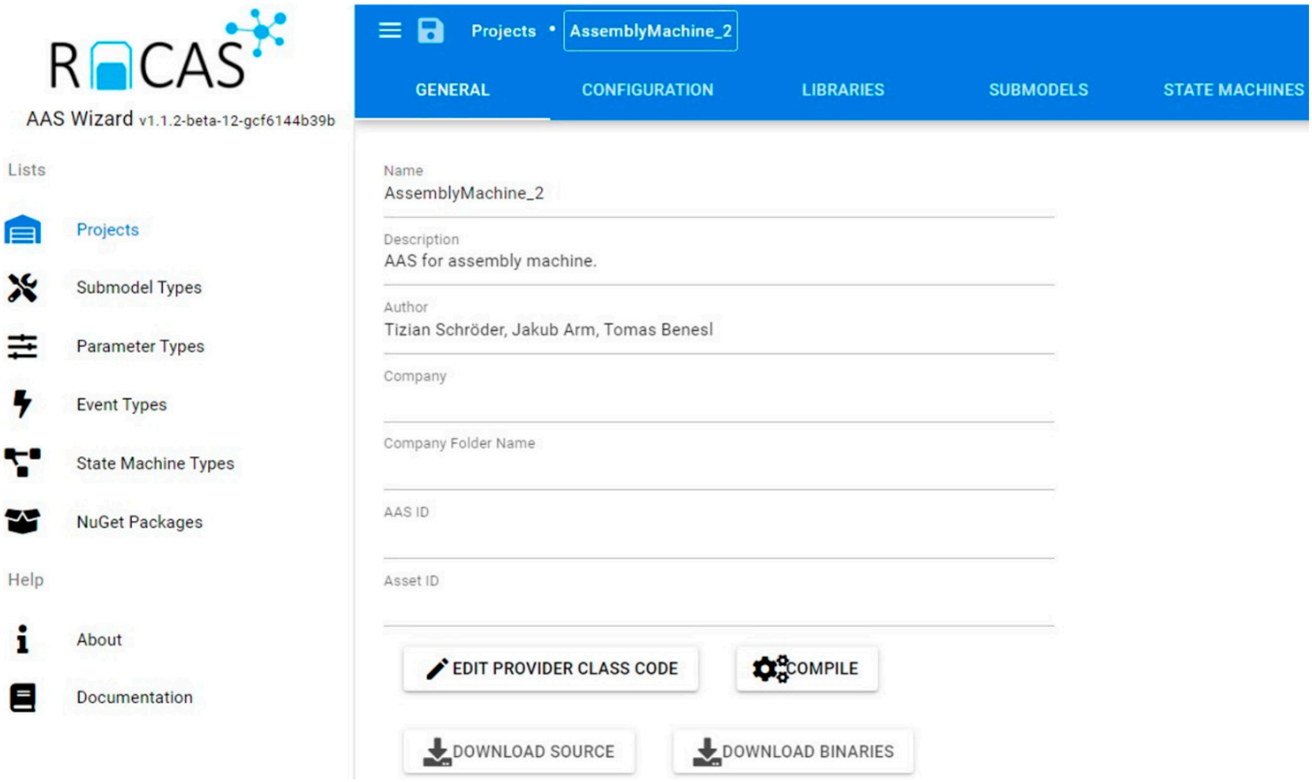


Figure 5. A ConfigWizard screenshot: front end.

Table 1. The OPC UA ISO/OSI model.

Layer	Description	
7 Application	UA Application (C/S, Pub/Sub)	
6 Presentation	UA Binary	UA XML
5 Session	UA TCP	OAP/HTTP
	UA Secure Conversation	WS-Secure Conversation
4 Transport	TCP (RFC 793)	
3 Network	IP (RFC791)	
2 Data Link	MAC (IEEE 802.3)	
1 Physical	e.g., Ethernet (IEEE 802.3)	

ConfigWizard thus allows us to avoid accessing the OPC UA server creator (our research relied on Unified Automation) itself; instead, it facilitates the utilization of a user-friendly, web-based wizard. The most significant advantage of the tool consists in the ability to create the OPC UA nodes automatically, especially if there are more objects of the same type (for example, more temperature sensors in a machine unit). In terms of the fundamental idea, development, and testing, the Wizard for the automatic configuration of AASs in different assets fully exploits the long-term experience of the authors of this paper, offering two ways to implement I4.0 components:

- Manually formed AASs (indicated in the Industry 4.0 component model, Figure 4).
- Automated AASs (see ConfigWizard, Figure 5).

3. Implementing the Industry 4.0 Component Model

This chapter discusses the procedures, standards, programming languages, communication methods, interfaces, bidding processes, and all associated elements that are necessary for the successful realization of the "factory of the future". This case study demonstrates the use of ASSs in an I4.0 virtual assembly line designed to produce plastic models of cars (Figures 6 and 7).

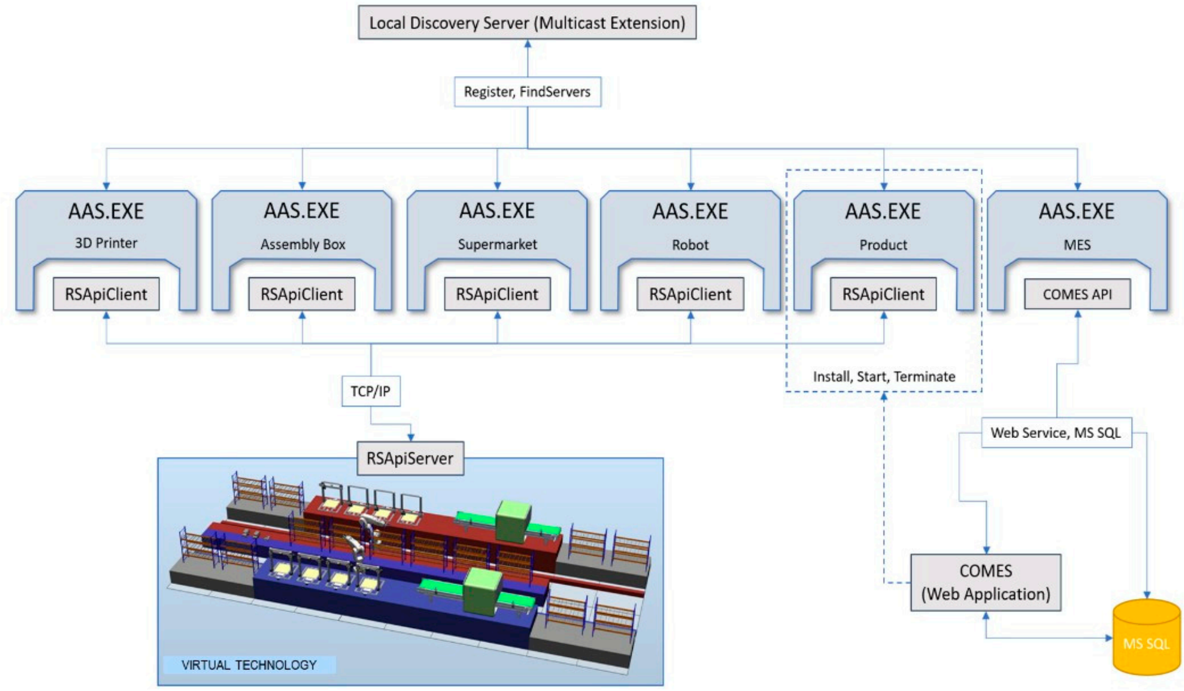


Figure 6. The architecture of the presented case study.

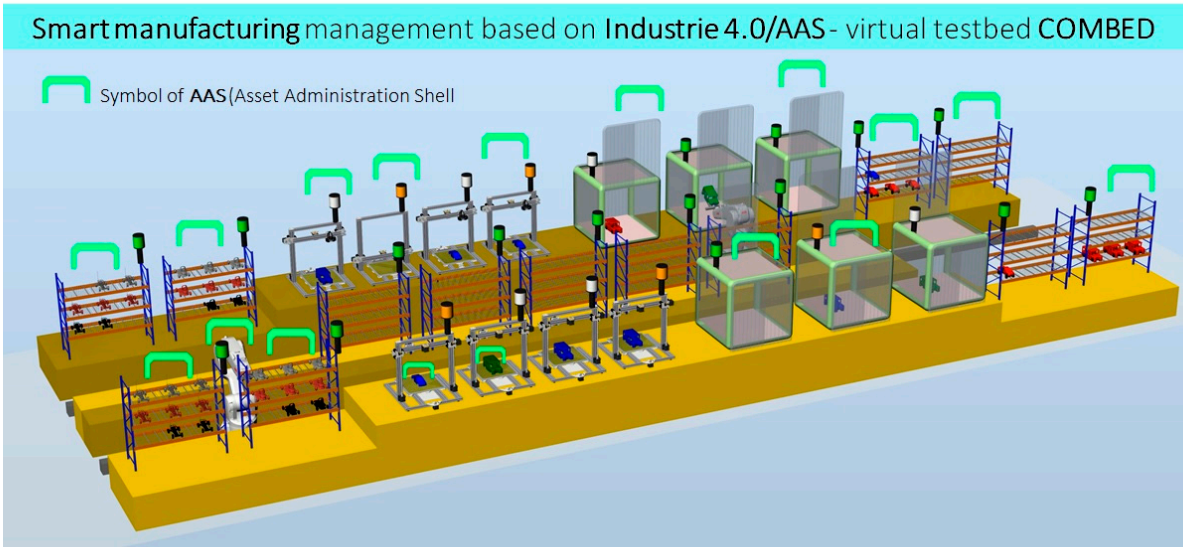


Figure 7. The virtual production segment (COMBED) introduced at the 2019 International Engineering Fair in Brno, the Czech Republic.

3.1. Case Study

The case study is based on a virtual production technology (the COMBED virtual testbed), as shown in Figure 7, consisting of two assembly lines with assets—i.e., machines (3D printers, assembly boxes), transport robots, and storage racks. The study demonstrates a smart production management method which utilizes smart assets according to the I4.0-based component model. Each virtual asset (for example, a product, machine, robot, conveyor, line, or warehouse rack) has its administration shell. The AASs communicate with each other and negotiate the production priorities and requirements according to a pre-specified set of rules. The manufacturing operations are negotiated by a product with respect to the principles of I4.0, enabling us to incorporate smart features into the production processes.

The COMBED system is employed to demonstrate the automated optimization, adaptation, and setup on an example of a production segment that manufactures products to order. Multiple scenarios are possible and can be adapted by the user, in view of the tables of parameters; the options either consider the "ideal" state or assume failures and downtimes to approach practical conditions. Based on these scenarios, we can test the smart production management's responses to diverse situations in real-world industrial cycles. Our solution automatically modifies the product processing steps and stages (material flow) to allow the use of currently available tools. The manufacturing management is also capable of supporting very flexible production cycles (in small orders—i.e., ones down to batch size 1), as it automatically and in real time adapts the equipment to the manufacturing operations required by the product variant or specifications (auto-setup). With flexible machinery, the factory can simultaneously manufacture various products and their versions, and the equipment setup operations eliminate the losses that otherwise accompany the material/semi-product transport. The case study utilizes COMBED to demonstrate the manufacturing of simple products—namely, plastic toy cars, each comprising a body and a chassis.

Our smart production management technique features a completely new, decentralized approach using the ideas and standards of the Industry 4.0 platform. The actual research involved applying and refining some of the objectives of I4.0, including automated optimization, adaptation, and setup of the manufacturing and logistics equipment; all of these steps were performed according to the needs of the manufacturing operations required by the product, as also stipulated within I4.0. Importantly, the entire project was designed with respect to observing the possibilities and benefits provided by the Plug and Produce (P&P) option. This mode enables machine builders to deliver their technologies with standardized AASs, allowing factories that run P&P to smoothly incorporate a new asset into the product negotiation process. The new asset carries its features, abilities, and parameters in the AAS submodels, facilitating the smart production management process.

3.2. Production Control Function of the AAS

With the scenarios (meaning production scenarios that simulate manufacturing behavior at various limit states), the smart production management can be tested and easily evaluated by standard MESs, as are often applied in factories. The MES is routinely employed to compute manufacturing efficiency and other relevant indicators, and an interconnection between this system and the AAS would allow the computing functions to be suitably utilized and expanded. For such evaluation of the management, we used the COMES MES/MOM system, collecting data from the COMBED virtual assets to validate the KPI (downtime analysis, Overall Equipment Effectiveness—OEE, and other relevant indicators). In a real-world factory, this approach is expected to yield innovative effects, including automatic production control according to the objectives pre-specified by the factory managers (for example, in response to the market situation) and high robustness of the manufacturing processes, which thus resist diverse types of failures. From the perspective of production control, the AAS functions can be classified into 3 implementation groups, as follows: a service requester (SR), a service provider (SP), and a common part of the code, involving such operations as communication and logging. Together with structured access to data, negotiation embodies a key AAS functionality. To ensure appropriate control, it is important that each SP be able to offer its services. The SR can browse through the SP to find a service ideal for the processing of the required operation. Figures 8 and 9 indicate that products actually are SRs that negotiate tasks to secure their own production.

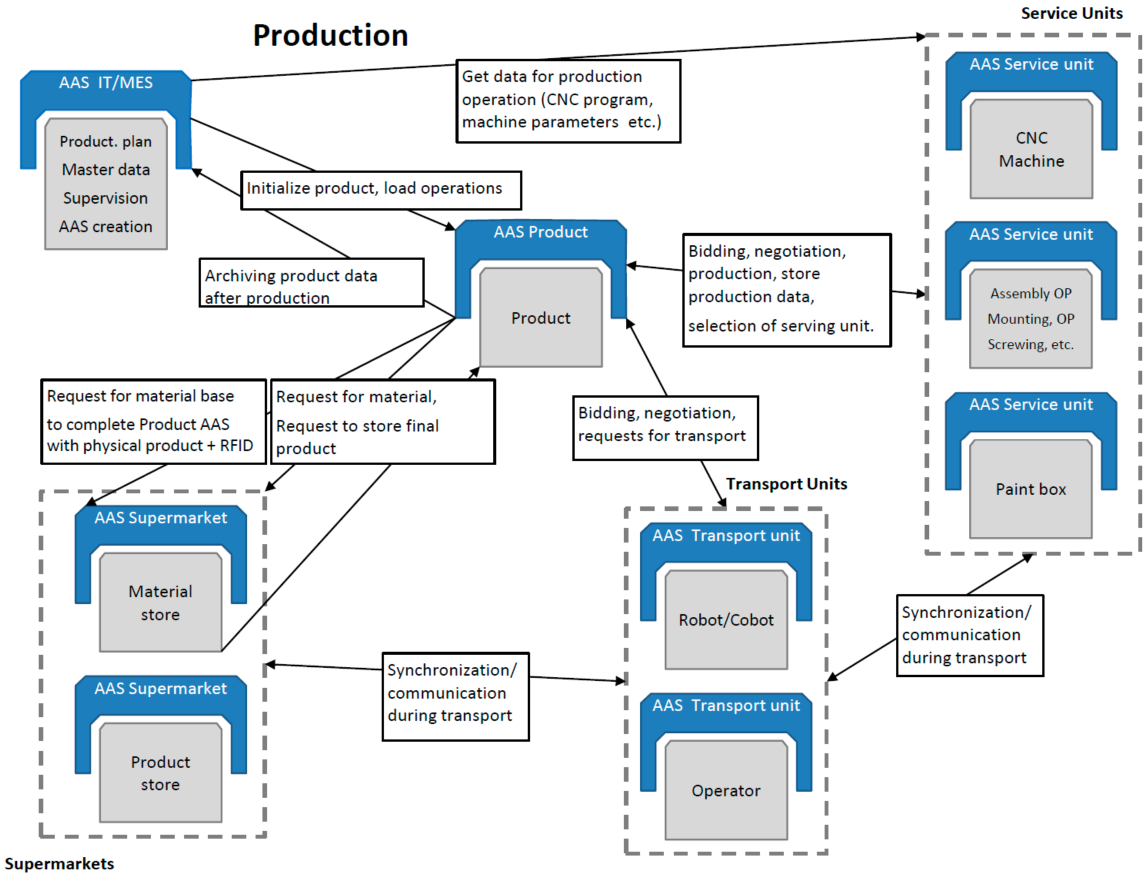


Figure 8. The data flow in a smart factory.

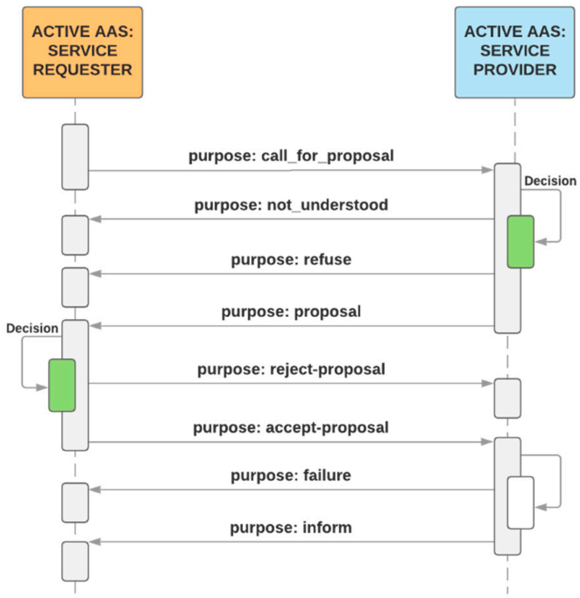


Figure 9. The bidding sequence.

However, manufacturing units, such as a CNC machine or an assembly line, require service intervention, material, tools, maintenance, and other steps or items; in such situations, the units become SRs to negotiate their requirements. Thus, the negotiation submodel has to be fully implemented in each AAS.

Figure 9 illustrates the standard negotiation sequence applicable to any operation. This sequence embodies an automated process comprising a demand, offer (call for proposal), order (proposal), and confirmation. With the algorithm, it is possible to request all available SPs offering services and select the most suitable SP. The discussed actions and processes then create the theoretical area that enables us to investigate, implement, and improve the optimization algorithms, exploiting, for instance, the condition where a demand is not valid only for the next manufacturing step but facilitates negotiating all the production stages, including transport. In implementing the wizard-formed AASs, the basic content element is the Component Manager (part B in the Figure 10), which brings together the sub-models to support the functionality of the AASs. The SR negotiation algorithm begins with the requirement for another component—namely, the mode in that no production step is active or scheduled for the product and the production unit does not need any service operation or resources. The Component Manager initiates negotiation to create a Call for Proposal (CfP), which is passed on to the Interaction Manager (IM), and the IM then sends the CfP to the service-supporting device. The communication between the individual AASs utilizes the OPC UA communication protocol, allowing the messages to be sent in the JSON format. The OPC UA framework alone interacts with the lower layers of the ISO/OSI model, requiring the user to implement the application layer only (Figure 6). The data in the JSON format are well readable and ideal for debugging the algorithms and testing the functionality; in future aggregations, a lower data size message format will be applicable if necessary. When the waiting time for the offers has expired, the IM will pass on the proposals available, and the negotiation algorithm will call the optimization function to select the best bid. Subsequently, an order is created and handed over to the IM, the SP confirms the order, and the negotiation of the next production step terminates.

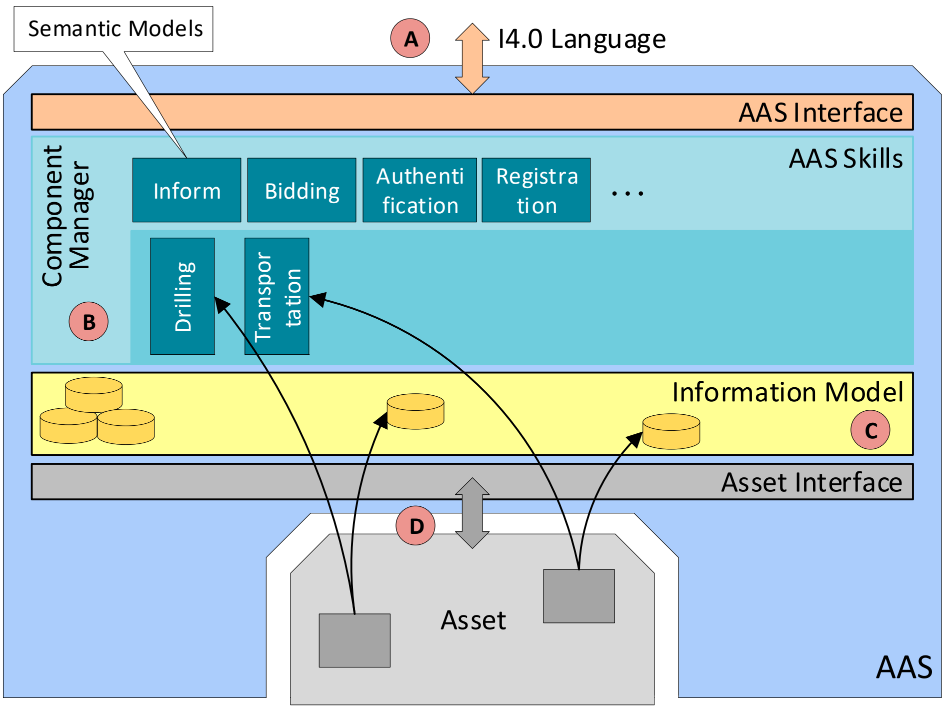


Figure 10. A block diagram of an AAS.

Due to the concurrent communication, the SP may encounter a situation where more than one proposal has to be responded to before being accepted by the SR. We suggest that the problem be resolved via one of the following approaches (for illustration, we selected the first option):

1. The SP will not respond to any other CfP before an acceptance or rejection is received. This scenario involves ineffective communication arising from the undefined busy time of the SP.
2. The SP will add the SR (sending the CfP) to a queue; if accepted, the SR's CfP will be handled by using one of the queue's algorithms (e.g., first come, first served). Moreover, the SP could inform other SRs to cancel the request.
3. The SP will add the SR (sending the CfP) to a list; if accepted, the SR will be selected by the pre-defined priority and other SRs will be informed of the delay.

The manufacturing commands are based on the PackML standard. The product, if on the requested spot, sends the "Start" command to change the production unit's status according to the current stage of the manufacturing cycle. At the end of the cycle, the status signal "Done" appears to complete the current production phase. The negotiation and transport are carried out until the final product has been located in the warehouse or another outgoing point. The production process requirements for the SRs should be defined in the CfPs, including whether the relevant data are to be retained by the production unit's AAS or deleted after negotiation. If the data are not to be retained, the SR will send them again before the start of the manufacturing cycle. In the current implementation of our AAS, the data are sent out immediately before the "Start" command; it would nevertheless be more advantageous if the production unit's AAS stored the CfPs' data, mainly due to the busy communication lines in larger-scale production. The hypothetical scenario, however, places greater demands on the AAS's data storage space in the case of long-term production planning.

3.3. Interating the AASs into the Demonstrator

The COMBED system, characterized in the previous chapter, replaces the real assets (production machines) in the factory. The simulation tool facilitates integrating a "Smart Component" that behaves like a server. A client-server connection is then established for each device. The client simulates a control system, such as a programmable logic controller (PLC), and runs independently of the AAS, requiring the designer to create a communication interface between the asset (client) and the administration shell (Figure 11). This communication interface is formed as a tag definition, which can be sent to the asset. In our implementation, the AAS communication driver integrates a TCP/IP connection and sends a TCP stream; thus, it is possible to employ any communication protocol and simply assign it to the selected AAS.

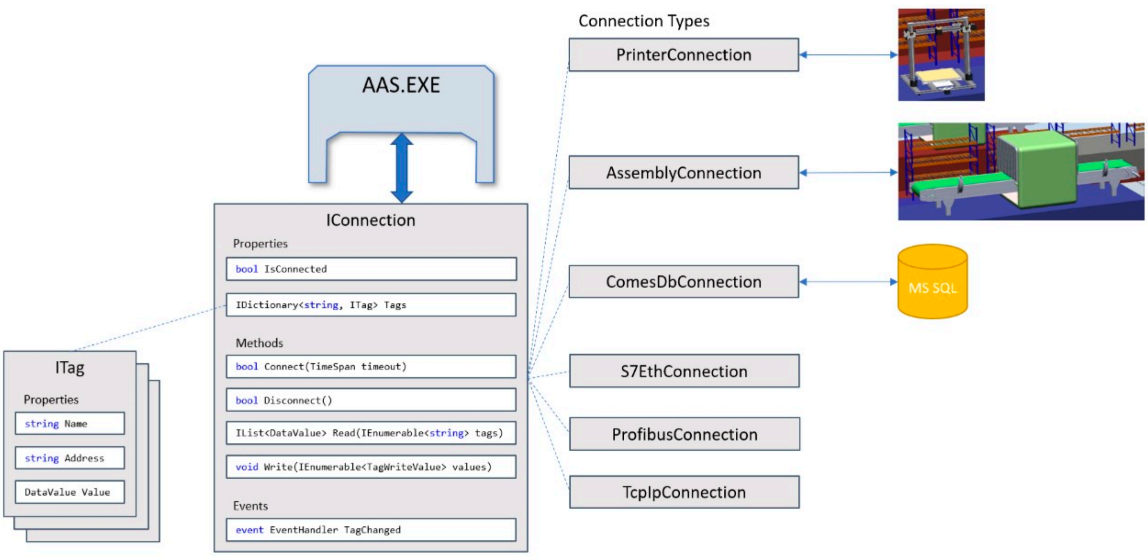


Figure 11. Integration of different communication drivers without rebuilding the AAS.

The AAS design, whose implementation allows using any communication driver for diverse types of assets, is indicated in Figure 10, part D. However, we have to follow the standard for communication with I4.0 components via the I4.0 language (part A in Figure 10). Figure 11 presents in detail the integration of different communication drivers without rebuilding the AAS or submodels. The tags are created by using the ITag definition, which needs to be linked to an asset—i.e., a control PLC, a distributed control system (DCS), a database, or another component.

In the given context, Read and Write methods must be implemented to enable data exchange. If the AAS hardware is able to use not only Ethernet but also other interfaces (RS485/232), we can establish communication with almost any asset. The overall implementation of our AASs is carried out in C#, using NET Core to ensure platform independence. However, there may appear a difficulty with the OPC Foundation's local discovery server (LDS), as this server can be installed on Windows only. In general terms, using AASs on embedded devices or single-board PCs such as the R-Pi requires a Global Discovery server or a different implementation of the LDS server. During the testing, MQTT-based communication was also employed, exhibiting communication latencies lower than those achieved by the OPC UA; in the MQTT option, however, a centralized broker had to be utilized. Such an approach appeared to suit both the fine-tuning of the algorithms and the whole scenario. In real-world applications, the OPC UA technology is more convenient than MQTT because, thanks to the LDS Multicast Extension, it can be used without the central element (broker). An administration shell is formable manually by such steps as providing data structures, tags, and other elements during the actual development and implementation phases; however, to simplify the generation and configuration, the wizard characterized in the previous chapter has been developed.

3.4. Formal Modeling

In addition to the continuous-variable dynamic simulation, as outlined above, we also created a formal model using the discrete event system technique (powered by the SimPy library available in Python). This model reflects our use case and consists of entities such as a machine and a product (the simulation design is depicted in Figure 12). Utilizing these elements, we follow the command level of details; thus, every machine or product can interact with the others via commands (such as the call for proposal, start, and unload) and events (such as started, production phase done, and unloaded). In this context, the modeled production then comprises the bidding sequence and the Pack-ML interaction concept.

Moreover, fault injection is incorporated into the simulation, allowing us to induce a failure in the machine operation phase and, thus, to simulate downtimes. In failure activation, based on the assumed exponential time distribution, the machine changes its state, informs the product, and waits a Gaussian time to facilitate the repair cycle. Meanwhile, the product aborts the current operation to launch the negotiation routine, attempting to find another machine to be served. To transform the simulation code into a discrete event system, some issues must be mitigated. The relevant tasks include decomposing the execution code into atomic chunks according to the discrete event system definition; in the bidding interaction, adopting the separate service (machine) reservation technique instead of reservation during CfP handling; and ensuring that the service proposal evaluation is atomic across all the machines in the factory that are associated with the product. The discrete event simulation can run under various conditions and settings. Thus, the machine counts and operation times were specified as close as possible to the dynamic simulation settings, and we incorporated the Gaussian time in every operation (manipulating, producing). Unlike the dynamic demonstrator, we simulated random product initiation (one product per 2 s) and applied different failure-injection procedure settings.

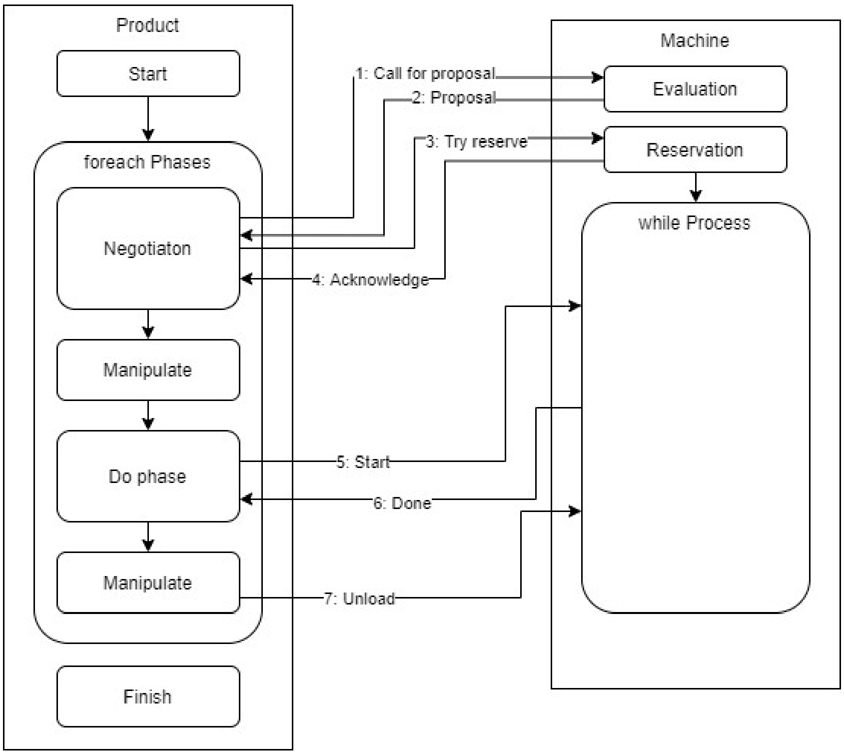


Figure 12. The architecture and flow of the discrete event simulation scenario.

4. Results

To compare the manual (via an OPC client) and automated (utilizing the presented wizard, Figure 5) approaches to the formation of an AAS, we identified the pros and cons qualitatively (Table 2).

Table 2. Comparing the AAS formation options.

Category	Manually	ConfigWizard (Automated)
Developing time	very exhausting	minimized
Knowledge of the developer	demanding	straight-forward
Modifications	not featured	supported
User-friendly	dependable	click and play
Compliance with the standard	dependable	hard-wired

The wizard-based designing was tested on the COMBED testbed, which contains several machines involved in the manufacturing cycle. Each of these units is autonomous and has an AAS capable of negotiating with other AASs. A product entering the cycle asks for the services that allow it to be produced, and the machine is selected according to the price and relevant associated parameters, with respect to the prespecified optimization criterion. Importantly, the position of the machine on the assembly line is a major factor determining how the products will be transported during the operational stages and after completion, namely, when they are to be handed over to a distribution point or warehouse. The advantage of autonomous machinery consists in its quick response to a failure. In the event of a fault, the affected machine switches to the non-service state; if the problem persists, the product can be re-routed and negotiated with another machine. After being repaired, the machine returns to the operating mode to start offering its services again. At this point, the unit may alter the price of the services due to the increased OEE. The testing involved fourteen machines and nine warehouse rooms, with diverse quantities of products entering production at different moments; importantly, the scenarios also comprised failure and repair times. The entire simulation cycle was conceived to determine whether the

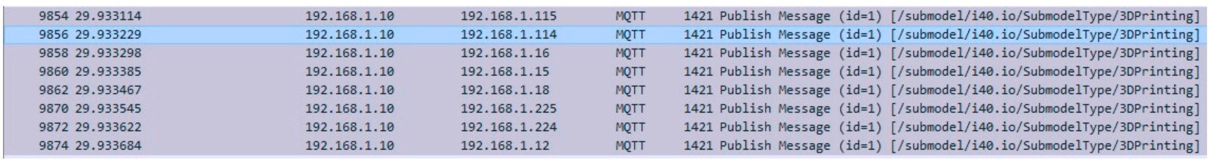
AAS product algorithms can respond to emergencies, normal failures, and similar states or conditions. In all of the scenarios tested, the planned products were manufactured without operator intervention, as is typical of an ideal operating scheme. Regarding the communication latencies, with a larger number of one-minute assets (the OPC UA clients and servers) the delays were so long that the timeouts expired.

Initially, the tests were performed on only one PC, which hosted all of the AAS instances. In this operation, the communication issues were not as prominent as those that accompanied the scenario utilizing 14 computers with routers and switches, because the local host interaction did not involve major packet delays, eliminating retransmission. The high latency rates were primarily caused by the firewall and persisted even after deactivation; due to this fact, MQTT replaced OPC UA, resulting in a significantly lower latency. Considering possible origins of the issue, the OPC UA's inferior performance may have been induced by a bug in the applied framework. The latencies ranged from hundreds of milliseconds in OPC UA to tens of milliseconds in MQTT; see Table 3.

Table 3. The communication statistics.

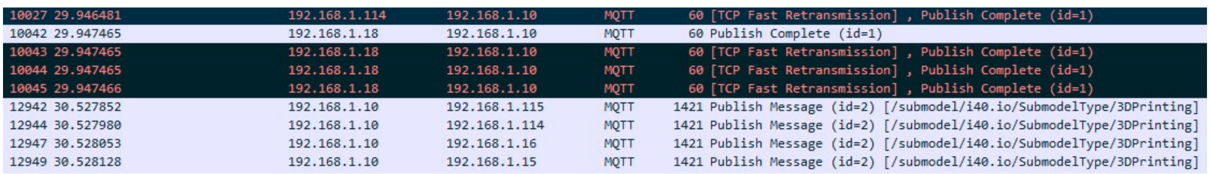
Message Communication Type	Message Count	Average Time to Receive Proposal or Refuse Message [ms]	First Product Manufacturing Time [mm:ss]	Duration of Whole Production [mm:ss]
OPC UA LDS and OPC UA method call	5277	363	03:00	06:58
MQTT	6666	28	02:51	06:45
MQTT providers using queue	1488	130	01:35	12:16

Using MQTT in a network of multiple PCs is associated with certain problems, and these affected the AAS testing cycles on some of the computers. Generally, the issues manifested themselves as follows: When initiated, an AAS product began to actively negotiate the first service (Figure 13). This service, however, was being simultaneously targeted by multiple other products, rendering the machines' AASs unable to respond quickly enough; thus, after the timeout has expired, the product started to renegotiate the required item, and the collision domain became congested almost immediately. The firewalls, switches, routers, and related network components then caused spurious competition between the messages and, consequently, their erroneous processing (Figure 14). As the response time was found to be within units of seconds, a timeout would have had to equal at least 10 s; such an approach, however, might eventually lead to undesired delays in the manufacturing cycle.



9854	29.933114	192.168.1.10	192.168.1.115	MQTT	1421 Publish Message (id=1) [/submodel/i40.io/SubmodelType/3DPrinting]
9856	29.933229	192.168.1.10	192.168.1.114	MQTT	1421 Publish Message (id=1) [/submodel/i40.io/SubmodelType/3DPrinting]
9858	29.933298	192.168.1.10	192.168.1.16	MQTT	1421 Publish Message (id=1) [/submodel/i40.io/SubmodelType/3DPrinting]
9860	29.933385	192.168.1.10	192.168.1.15	MQTT	1421 Publish Message (id=1) [/submodel/i40.io/SubmodelType/3DPrinting]
9862	29.933467	192.168.1.10	192.168.1.18	MQTT	1421 Publish Message (id=1) [/submodel/i40.io/SubmodelType/3DPrinting]
9870	29.933545	192.168.1.10	192.168.1.225	MQTT	1421 Publish Message (id=1) [/submodel/i40.io/SubmodelType/3DPrinting]
9872	29.933622	192.168.1.10	192.168.1.224	MQTT	1421 Publish Message (id=1) [/submodel/i40.io/SubmodelType/3DPrinting]
9874	29.933684	192.168.1.10	192.168.1.12	MQTT	1421 Publish Message (id=1) [/submodel/i40.io/SubmodelType/3DPrinting]

Figure 13. The CfPs from the products to the 3D printers.



10027	29.946481	192.168.1.114	192.168.1.10	MQTT	60 [TCP Fast Retransmission] , Publish Complete (id=1)
10042	29.947465	192.168.1.18	192.168.1.10	MQTT	60 Publish Complete (id=1)
10043	29.947465	192.168.1.18	192.168.1.10	MQTT	60 [TCP Fast Retransmission] , Publish Complete (id=1)
10044	29.947465	192.168.1.18	192.168.1.10	MQTT	60 [TCP Fast Retransmission] , Publish Complete (id=1)
10045	29.947466	192.168.1.18	192.168.1.10	MQTT	60 [TCP Fast Retransmission] , Publish Complete (id=1)
12942	30.527852	192.168.1.10	192.168.1.115	MQTT	1421 Publish Message (id=2) [/submodel/i40.io/SubmodelType/3DPrinting]
12944	30.527980	192.168.1.10	192.168.1.114	MQTT	1421 Publish Message (id=2) [/submodel/i40.io/SubmodelType/3DPrinting]
12947	30.528053	192.168.1.10	192.168.1.16	MQTT	1421 Publish Message (id=2) [/submodel/i40.io/SubmodelType/3DPrinting]
12949	30.528128	192.168.1.10	192.168.1.15	MQTT	1421 Publish Message (id=2) [/submodel/i40.io/SubmodelType/3DPrinting]

Figure 14. The retransmission of unacknowledged messages and new calls for proposal.

With multiple devices in the network, OPC UA appears to be more beneficial, especially if installed together with local discovery servers (LDSs) and supported by a multicast extension (ME). This architecture, however, requires swapping the public keys (the PKI standard); in such a procedure, each device to be registered by the LDS server provides its public key, thus becoming a trusted item. In large networks comprising multiple LDS servers, however, the same problem as that affecting the use of MQTT may appear.

The testing and measurement cycles allow us to conclude that MQTT does not match conveniently with a greater number of AASs; in this context, OPC UA embodies the more suitable option, despite the demanding implementation and the necessity of transferring the public keys.

To test and fine-tune the algorithms, we created an environment to visualize the messages sent between the individual assets. This procedure enabled us to define the communication latency and the number of messages required to complete the test scenarios. The bidding process messages are presented in Figure 15.

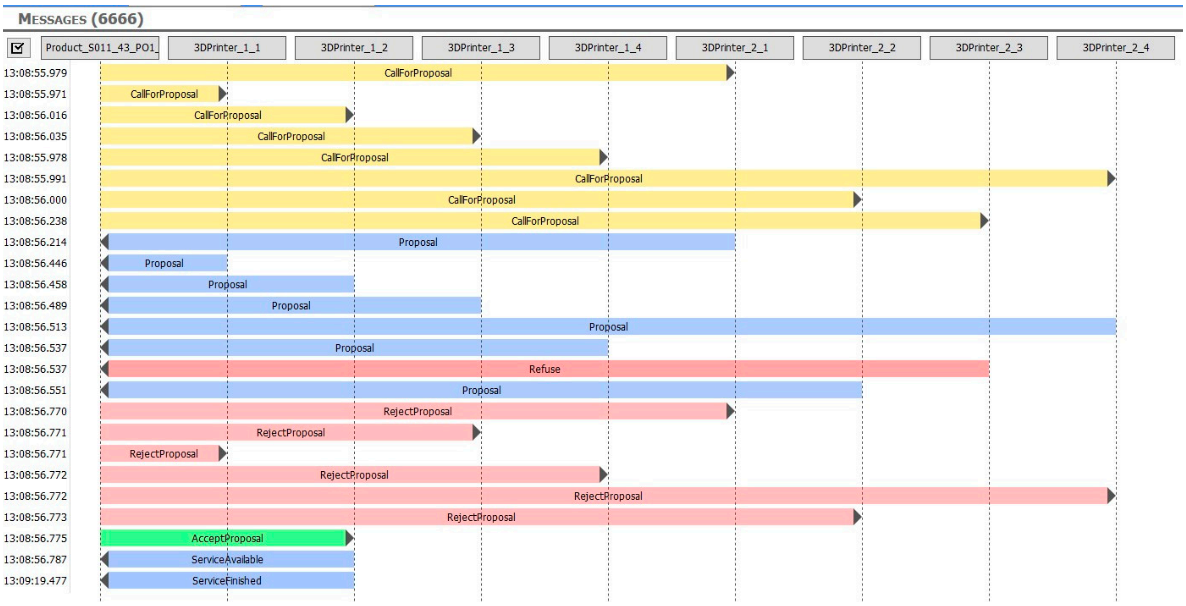


Figure 15. The bidding between a product and multiple printers.

Regarding the discrete event simulation, the results also indicate that the manufacturing cycle is capable of fulfilling the product requirements as fast as possible in normal conditions (Figure 16); with multiple products to be served, however, the availability of free machines becomes markedly reduced. Moreover, in a machine failure, the product operations are actively restarted without any intervention from the central system, ensuring the completion of all products; the overall production time nevertheless increases (Figure 17).

The entire procedure, comprising 30 products, took 1.94 s using a single-threaded engine on a normal PC and covered about 300 s of the manufacturing cycle. The following run was characterized by the simulation time span of 31.365 s, and the computational time equaled 15.749 s. Thus, the results exhibited a strong correlation between the simulation and execution times, an effect that could be caused by the large amount of short-term events.

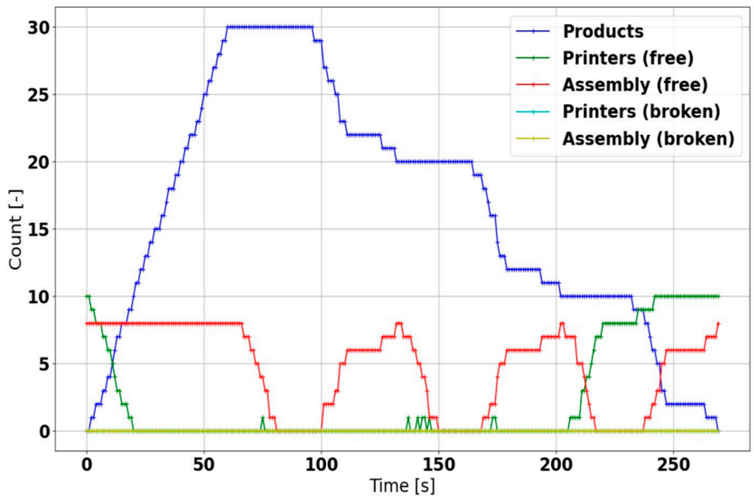


Figure 16. The regular discrete event simulation scenario.

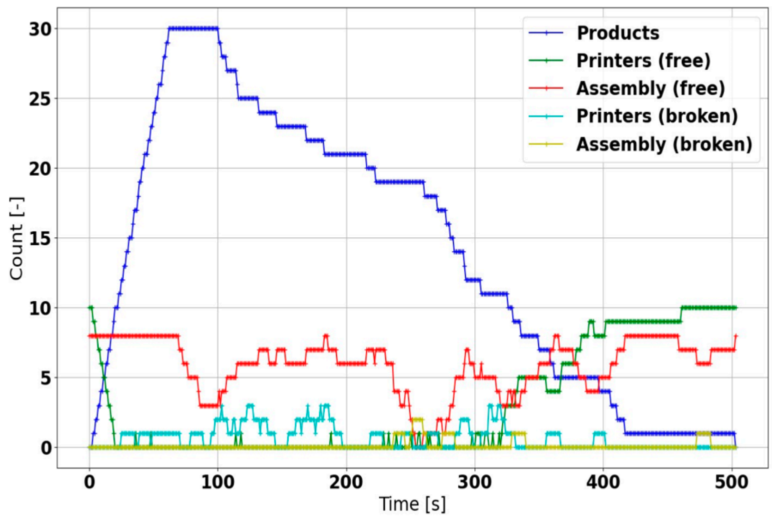


Figure 17. The discrete event simulation scenario with failure injection activated.

5. Discussion and Conclusions

The results show that the ConfigWizard software allows an AAS to be formed in a clearer and more user-friendly manner, especially as regards the specifications of the individual submodels and their parameters, methods, and events. The automated AAS generation process then not only saves a substantial amount of time but also utilizes relevant standards according to the user-defined input data, such as the names and attributes of the parameters. Another outcome of the research consists of exploiting the generated AASs to create a virtual manufacturing demonstrator facilitating production management. The interface between the AAS and the actual assets of the virtual demonstrator can be characterized already at the stage of designing the individual AASs, via both parameterizing the communication technology and mapping the transmitted variables. The interface of the real asset is then specifiable in the same manner. Within the presented use case, the production management utilizes AASs that comprise functions outlined in distributed production planning as set out through I4.0—namely, functions to enable bidding between semi-finished products which require processing services and also between machines or tools providing such services. The initial simulations (both the dynamic and the event systems) indicated that the manufacturing system flexibly responds to incoming requirements for new products (by including them in the queue) and actively resolves problems associated with manufacturing faults. To optimize the applied distributed production planning, it is, however, necessary to perform multiple simulations, all complemented with artificial intelligence algorithms. For this purpose, the created event- system simulation is considered the best candidate. The dynamic simulation, namely, the integration of the AASs in the test demonstrator, yielded the manufacturing times needed to produce the virtual car. A more significant parameter nevertheless lies in the service bidding mean time (the period required to accept or decline a bid), which, in the described scenario (5 AASs in a local network), ranged within lower hundreds of milliseconds. The outcomes of the discrete event simulation point to the suitability of a short time horizon and the need of an engine optimization process. In order to be usable by machine learning algorithms, the model should work as fast as possible to support a high amount of simulation iterations; this paper then proposes a convenient trade-off between the complexity and quick executability of the model to maintain the functions sufficiently credible. A major factor supporting smooth applicability of the system and related procedures can be identified in the fact that the AAS actually performs its functions, using a standard communication interface to operate in the heterogeneous environment of a manufacturing plant. The AAS is present at all levels of automated plant management, facilitating their effective interconnection. Thanks to the standardized parameters, attributes, events, and communication, the data associated with the design, preparation, order, and manufacturing stages are eventually assignable to the final product.

The future research aims and objectives involve linking the testbed to a standard MES control enabled by an experienced production operator and testing the production response rate, robustness, OEE, and other factors related to both of the production control options in the same scenarios. Importantly, the use of the created discrete event system will be further investigated too. This plan, however, involves certain limitations, especially in that the research and real-world production testing will require the technology to be employed in the entire manufacturing plant; such a precondition then means that the lengthy fine-tuning and commissioning may generate substantial costs. In this context, the testbed facilitates monitoring and improving the functionalities and responses to diverse errors and nonstandard situations.

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Revisiting the Role of Manufacturing Execution Systems in Industry 4.0

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Abstract: The aim of the article is to describe the changes in the approach to the design and use of production management systems that occurred during the digital transformation - the advent of Industry 4.0. From the original, purely centralized solutions in the form of monolithic applications with proprietary communication protocols, it is gradually moving to a distributed form, open interfaces and modular platforms. This transformation brings a number of benefits, but also certain problems that this article seeks to characterize.

Keywords: MES, Industry 4.0, Interoperability, IEC 62264, Asset Administration Shell.

1. INTRODUCTION

The previous three industrial revolutions arose from the invention and advancement of steam-powered mechanical manufacturing devices, electrified mass production, and operational electronic systems and computers (Mařík 2016). By comparison, the present - or fourth - revolution, in addition to being focused on industrial production, also introduces fundamental changes to multiple fields beyond the traditional interpretation of the concept. Thus, the process virtually embodies a novel philosophy to transform various branches of industry, technical standardization, safety, education, legislation, science, research, the job market, the social system, and other related provinces.

The onset of novel technologies leads to procedural requirements such as the pressure for higher flexibility in industrial production, increased cyber safety, and effective interdisciplinarity. In this context, Industry 4.0 does not constitute merely an effort to digitize production but rather a comprehensive system of changes associated with different activities. Within industrial manufacturing, the concept transfers production from individual automatized units to fully integrated, automatized, and continuously optimized operating environments. The basic principles of Industry 4.0 applied to production are as follows:

- Interoperability, or the ability of the cyber-physical systems (CPS), persons, and all other components of smart factories to communicate together using dedicated networks.
- Virtualization, or substituting physical prototypes with virtual production designs, means, and processes. The actual commissioning is then realized within a single integrated procedure involving both the manufacturer and the supplier.
- Decentralization, where the decision-making and control are performed autonomously and in a parallel manner within the individual subsystems, which communicate together via a common network (Internet of Things - IoT).
- Real-time operation as a key precondition for communicating, decision-making, and control in real-world systems.
- Concentration on services, in which the naturally preferred actions are the offering and utilization of standard services (Service Oriented Architecture - SOA).
- Modularity and reconfigurability, where the systems exhibit maximum modularity and capability in autonomous reconfiguration based on the automatic recognition of present conditions.
- Horizontal integration, extending from systems that receive and confirm orders through the manufacturing section to dispatching the finished product and supporting its post-production life cycle. This stage includes the possibility of optimizing the manufacturing processes within the entire value chain.
- Vertical integration, from the lowest level of the automatic control of physical processes characterized by critical time demands, through the manufacturing section management to allocating the company resources via Enterprise Resource Planning (ERP) systems with time constants in the order of days or weeks.

Deploying the above paradigms in the areas of production, storage, quality management, and maintenance will create cyber-physical systems. In this way, physical machines, devices, warehouse systems, but also individual products will be represented in the virtual world. Each of these elements will be able to act autonomously through the communication interface and its internal model. Autonomous decision-making, as well as the autonomous collection and evaluation

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of important data, will play an important role not only in the production process but will also provide important information for the entire life cycle of entities (whether products or entire factories).

The cornerstone for making the above-described behavior of individual elements accessible is the possibility of their unambiguous identification, localization (or self-localization), preferably in a continuous-time, knowledge of their history, current state, and the target state. The transformation of an entity from the current to the target state can in principle be achieved in different ways, so the entity must be able to decide which of the ways to achieve is optimal. The vertical and horizontal integration itself is maintained. The systems are arranged vertically within the hierarchical structure of the company. Horizontally, then within the value chain across companies.

2. MANUFACTURING EXECUTION SYSTEMS

Many new entities, categories, levels, platforms, and integration processes are convincing ways in which process automation undergoes dynamic evolution (as mentioned in the introductory chapters). For many years, albeit in different variants and colors, the company's control system presented itself with a two domain pyramid (process control domain/entreprise domain) (Jasperneite, 2020).

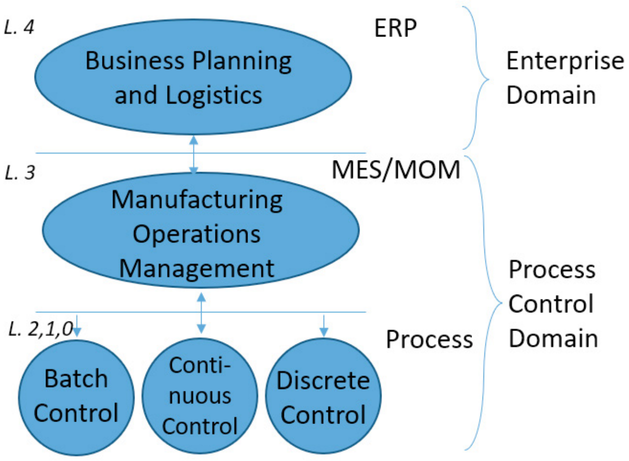

Fig. 1 – four-layer pyramid

Manufacturing Execution System (MES) is an information and control system supporting the efficient implementation of production operations. Using up-to-date and accurate data, the MES system guides and triggers plant activities and provides information about them as production events occur. Ideally, the MES system consists of a set of functions that control production operations from the moment of placing an order in production to the delivery of the product, while plotting all phases of the overall production process.

Sometimes the MES system is omitted and its role is partially taken over by the ERP system. These systems offer a coordinated approach to many functions, including customer management (i.e. digital process support from quotation to product distribution and invoice payment), resource and supply chain management (i.e. inventory management, material purchasing, master orders, recalls, or prospects) as well as production planning according to orders. In certain types of industrial production, the MES system can be replaced by ERP, but more often the role of MES is irreplaceable.

2.1. MES history

The first level was the operational management systems, which represented only the off-line advisor of the operator. The information was provided as a recommendation by the company's management to the operator. Therefore, the action could not be implemented automatically. The time of implementation of the action was calculated in shifts or days.

The next step was the introduction of ERP systems, which allowed rapid evaluation of results for changes in process management, but remained slow and error-prone transmission of information in the form of paper, telephone, fax in both directions of data flow. In such a situation, it often happened that fears of a shortage of raw materials led to the accumulation of raw materials in warehouses. Similarly, fears of a shortage of goods led to the accumulation of products in shipping warehouses.

The introduction of MES has brought opportunities to implement measures such as Just-in-Time and Lean Manufacturing. The systems enable tracking, reporting, quality monitoring, and other functions.

Over time, due to the pressure on the interoperability of various solutions, the ISA-95 standard was established. This standard has created a platform for standardized MES. The platform is called Manufacturing Operations Management (MOM). Basic definitions and terminology have been developed within the standard. Furthermore, general requirements for MES were defined. Another part of the standard is the definition of models and functions for individual data flows at level 3 of the pyramid. The last part of the standard prescribes the forms of interfaces and models for the integration of ERP and MES. It was the American ISA-95 that was the basis for the international standard IEC-62264 for Enterprise Control Integration.

There are currently MES products on the market for which the manufacturers declare some relation with the concepts of Industry 4.0 (Wascher, 2016). An example is MES4 software from FESTO. The manufacturer declares that this software is specially prepared for CP Factory platforms for teaching Industry 4.0 topics. The MES, from the informatics point of view, is based on the MS Access database. In terms of communication, it forms a bridge between the production facilities and the database. From the user's point of view, it provides a graphical environment for creating production plans, defining resources, production operations, and materials on the one hand, and an environment for displaying the production process. All communication is realized through a database, there are no user operations that would allow the initialization of a direct connection to the production modules. In addition to standard functions, the MES4 environment provides a tool for simulating communication on the MES protocol side. The tool simulates incoming queries from application modules and the system responds with the appropriate change on the database side. It is thus possible to simulate the entire production process without connecting to a real or virtual line step by step.

By far the weakest point from the point of view of Industry 4.0 is the creation of production plans. Although the MES4 environment supports the decomposition of the production process into elementary, parameterizable production operations (drilling, heating, etc.), when creating a production plan, it is necessary to define a specific application module that will perform this operation in this case (Christian, 2017). This limitation contradicts the philosophy of the intelligent production line of the basic principle of Industry 4.0, ie the decentralized principle of production management and degrades the whole process of the CP Factory system back into the sphere of Industry 3.

In the case of MES4, if the level of decentralization is to be achieved so that we can talk about the Plug and produce system, changes must be made not only at the level of MES4 itself but also at the level of digital interfaces of production parts of the system (production resources and materials). The first step is mainly the implementation of the system of demand and supply of production operations.

Demanding and offering specific, parameterizable production operations must be implemented at the level of production entities or their digital interfaces (in the case of a system operating based on MES4, we intentionally avoid the AAS designation because the digital interface of modules of this system does not meet the basic requirement for AAS. A standardized, self-describing protocol such as OPC AU, AutomationML, etc.). Each entity can then be at a certain stage of the production cycle ordering or supplier of some production operation. The selection of the optimal supplier for a particular operation will then be performed by a specific algorithm, assessing the specified parameters. Depending on the specific implementation, this selection can be either a simple comparison of the price of a given operation from a specific supplier or a complex process based on many variables and statistical data, using elements of artificial intelligence.

The role of MES4 in such a system can then be either minimalist, where MES4 will only serve as an interface for communication with the data warehouse (this concept is described in more detail in this article), or it can serve as an active intermediary in the process of negotiating and selecting the optimal supplier. This approach may be appropriate if the optimization process is a complex algorithm working with large data. MES4 has direct access to this data and, due to its deployment on a classic PC, practically unlimited computing capacity.

2.2. MES future in the Industry 4.0

As mentioned in the introduction, a lot has already been written about Industry 4 and like the previous example shows, the role of MES is often not fully understood and implemented there. Industry 4 is often reduced to the phenomenon of the so-called digital factory containing self-organizing production machines and equipment based on mutual communication of all participating entities. In this paradigm, the question - What will be the role of MES in such a factory - can be very interesting. Will MES not become completely useless? Or, conversely, will the MES still play a key role in achieving the above? What functions will the MES continue to perform?

One of the main roles of MOM in a traditional manufacturing company falls into the field of planning and management of production processes. The executive module MOM is therefore directly linked to individual production machines and equipment, which are controlled centrally by this module without the possibility of their own decisions. However, technical developments in this area have brought innovations that include not only the above-described smart objects or cyber-physical systems, but also:

- Ability to store or retrieve data or use computing power distributed (cloud computing).
- Ability to store and analyze large amounts of data (big data).
- Ability to access distributed functionality through services (service-oriented architecture)
- Possibility to connect production operators with the rest of the system using digital communication means (smartphones, smart glasses, etc).
- Ability to use artificial intelligence methods and integrate them into existing processes.

There are several ways to answer the question, namely what role MOM should play in such systems. From the answer "it will play no role because it will be taken over by ever-improving Process Control Systems (PCS) and ERP systems", to "absolutely crucial, it will be the most important element of the whole organization and the interconnected value chain".

However, to meet the requirements of Industry 4.0 in all areas of operations management, today's MES systems must transform. Recall that the standard defines 12 functions that can be divided into four areas - production, storage, maintenance, and quality. Within these areas (domains), the standard defines individual functions,

their models and formalizes data flows between these functions. (see Fig. 2) The generic activity model is valid for all four described domains. Some MOMs are created as monolithic solutions in which all four domains and full functionality are implemented. Due to the high degree of decentralization in Industry 4.0, emphasis is also placed on the possibility of decentralized deployment of such a system, where only one or several parts of it are operated in several different host systems (Colombo, 2017). Therefore, the MES must be transformed from a monolithic application to an application (system) with a modular structure. Given that monolithic applications do not have a strong emphasis on creating standardized communication between individual application modules (due to their strong interconnectedness and the need to follow the standard requirements of service-oriented architecture), there is also a need for transformation in the way data is shared between individual modules (services) of the newly emerging system. The exchange of increasingly heterogeneous data between systems is also expected within Industry 4.0. Recall that the original specification within IEC-62264 consists of about 10 different data models (equipment model, personnel model, material model, process segment model, production definition model, and several others).

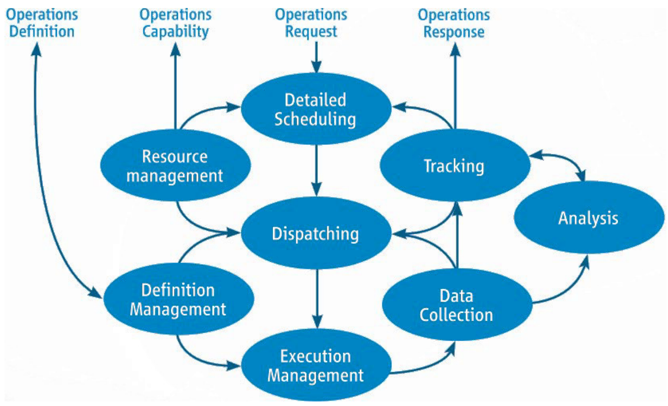

Fig. 2. Generic activities model from IEC 62264

Future MOM platforms will be characterized by the transfer of other types of data beyond these models, so new semantic specifications must be created. It is necessary to note that this will be not only data that will always carry current information from these domains but also data that was generated during the entire life cycle of the product or device (Karnouskos, 2011).

With the increasing modularity, it is also necessary to take into account the disintegration of the existing organizational structures, where the responsibility for the division and control of tasks always fell on the superior element. Smart manufacturing and Industry 4.0, with the support of modular structures with high granularity, tend to record the division of responsibilities among many elements built on a similar level with the possibility of easy substitutability, redundancy, and adaptability (Colombo, 2017).

Over time, the volume of production data that is communicated to higher-level systems continues to grow. It must be said that in terms of the number and volume of data, data analyses in the industry are currently at an incomparably lower level in comparison with, for example, analyses of social networks or customer behavior. There are still many production managers who are skeptical of the big data concept. These people believe that data should only be collected and archived if there are compelling reasons to do so. With the advent of Industry 4.0, due to the process of decentralization, the volume of stored data will multiply and data will also be collected, which today cannot be said to be useful or useful. The use of Data Mining techniques will be necessary to evaluate this data. At the same time, these techniques will enable unprecedented possibilities for context analysis, not only in predictive maintenance.

2.4. Typical process tasks provided by MOM

The individual functions of the original MOM can be divided in terms of the requirement for their logical centralization (better said, uniqueness). It is clear that, for example, order processing and the process of putting products into production, together with the dates of their planned completion, taking into

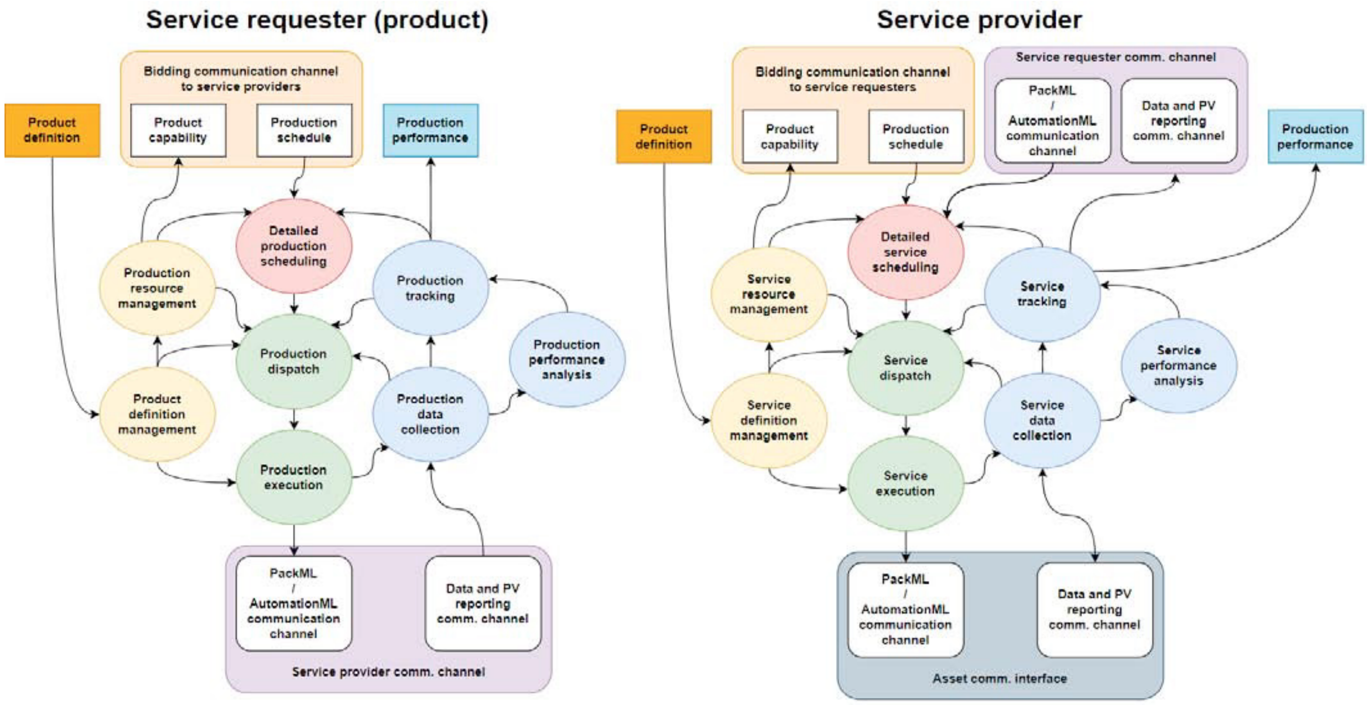

Fig. 3. Extended MOM models for Service Requester (left) and Service Provider (right)

account the availability of resources, will be a task for a single instance of the system. Furthermore, for example, the calculation of the total KPI for a certain group of machines, or the entire production area, will again always be carried out centrally, although it is possible to take into account the partial KPIs calculated at lower levels. The final archiving of production data can in principle be decentralized, but for example, the analytical database used for data analysis is usually centralized.

As already indicated, each of these activities can be widely distributed (KPIs can be calculated in individual machines, production planning can be distributed to the planning of smaller production units, quality and maintenance data can be recorded locally and pre-processed).

3. DISTRIBUTED MOM PLATFORM

All the information provided so far has taken into account the design of MOM as a system whose only running instance within the manufacturing plant is operated in a distributed manner. However, we believe that the right solution for deployment in Industry 4.0 is such a method of distribution, where all the necessary MOM modules are modeled and operated within each asset. For each, let's define all four domains (sometimes called pillars) that MOM describes: production, warehousing, quality, and maintenance, and implement the necessary modules according to the type of asset.

The IEC-62264 standard further specifies 4 information types that are communicated between MOM and ERP systems. These four domains are

- Production definition (**DEF** in following) - transfer of product definitions, the main flow is from ERP systems to MOM.
- Production capabilities (**CAP**) - the transfer of capabilities, such as expected performance, ie future production capacity. The main flow direction is from MOM to ERP systems.
  The information provided can be used in the ERP system for use in production planning.
- Production schedule (**SCH**) - transfer of production requirements, the main flow is from ERP systems to MOM. The predominant type of data in this domain is the task queue.
- Production response (**RES**) - transmission of recorded and (partially) evaluated data from production. The main flow direction is from MOM to ERP systems.

For communication within business and manufacturing domains, 5 types of resources are defined within IEC 62264-2. These are personnel, equipment, physical assets, materials, and process segments. All these sources are communicated through the described types of information between individual systems or parts of one distributed system.

In the case where the mentioned functional model is to be distributed to the AAS, it is necessary to specify, which directions of data flow will prevail for individual types of information (definition - DEF, capability - CAP, schedule - SCH, response - RES), i.e., whether the asset represented by its AAS will be a Service Requester (SR) or Service Provider (SP) for individual domains. The following table summarizes the data flow directions for each type of information and MOM domain. The table is valid for the active part of the lifecycle of a single product instance.

3.1. Extended MOM model for distributed scheduling

Using the basic MOM model with minor modifications (see Figure 3), distributed production control can be achieved according to one of the pillars of Industry 4.0, while maintaining the idea of using AAS according to VDI / ZVEI.

By mapping MES / MOM functions to AAS, it is not necessary to implement standard AAS functions - data provision (passive part) and orchestration (active part). Using the concept of Service Requester and Service Provider, we defined both functions and information flows (as can be seen in Figure 3).

Table 1. Main roles of distributed entities

	Domain	**DEF**	**CAP**	**SCH**	**RES**
Equip./ human oper-ator	Production	SR	SR	SP	SP
	Maintenance	SR	SR	SP	SP
	Quality	SR	SR	SP	SP
Ware-house entity	Storage	SR	SP	SR	SP
Smart prod. *born	Production	SR			
	Quality	SR			
Smart prod. **prod.	Production	SP	SP	SR	SR
	Quality	SP	SP	SR	SR
Coordi-nation entity	Production	SP	SR	SP	SR
	Maintenance	SP	SR	SP	SR
	Quality	SP	SR	SP	SR
	Storage	SP	SR	SP	SR
Data collect./ KPI	Production				SR
	Maintenance				SR
	Quality				SR
	Storage				SR
Product def. mgmt.	Production	SR			SP

*Smart prod. *born – stands for the start of the product instance lifecycle when the product definition is loaded into the product Asset Administration Shell.*

*Smart prod. **prod – stands for the production part of the product instance lifecycle when the product Asset Administration Shell negotiates the production process throughout the production line.*

The passive part consists of submodels providing Production Definition, Production Performance, Production Scheduling, and Production Response. The active part must implement at least a bidding function for both types and a queue for the

Service Provider. The active part consists of submodels implementing Production Scheduling and Dispatch.

The standard (ZVEI, 2019) defines the method and convention of communication between I4.0 components in the form of messages. The content of these messages can therefore be compiled from submodels designed for data segmentation. Segmentation of offered and provided services is provided by the Resource Management function, a command is brought by the Execution function and data concentration is equipped by the Data Collection function. Each of these functions can be implemented by a submodel, appropriate methods, and events.

For the order of SP in the case of successful negotiation of the service by the SR, we chose the PackML standard (AutomationML), which is also widely used in practice. This communication channel connects the scheduling functionality output on the SR side with the scheduling functionality input on the SP side. Furthermore, the instruction to start the service is already planned at the level of SP, resp. at the level of the target device.

According to the standard, the bidding process is also implemented using I4.0 communication, while the SR negotiates the possibilities of completing tasks at individual SRs, while the Resource Management and Detailed Scheduling functions are active.

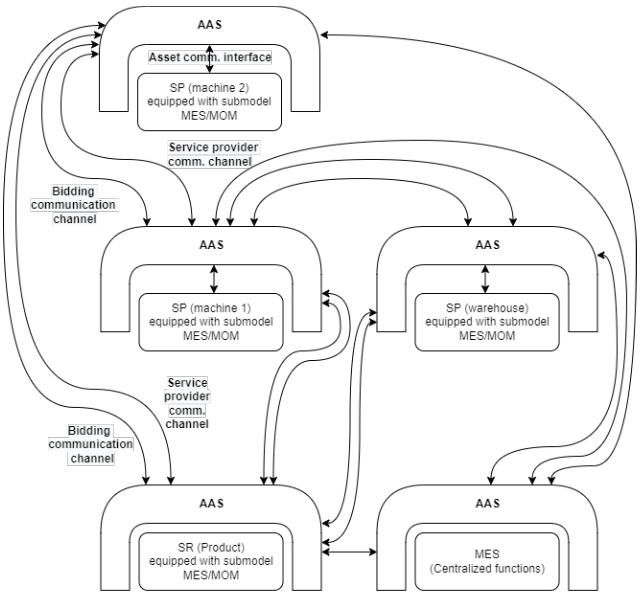

Fig. 4. Communication channels between distributed entities

The flow of the whole process can be as follows: Dispatch (orchestrator) in SR detects that an operation defined by Product Definition needs to be performed. Calls the Detailed Production Scheduling (DPS) function to negotiate and schedule the operation. DPS using I4.0 communication will start negotiating with other SR, resp. with their Detailed Service Scheduling on time options. It will only respond to those SPs that contain the required operations (Product Capability). The dispatch, therefore, receives information about the successful negotiation and issues an execution of order using the Execution function. Using the PackML / AutomationML standard, this command is transferred to the Detailed Service Scheduling functionality in the SR. If the machine is free, resp. when the operation takes place, the Dispatch function issues a command to configure the machine and then uses the Execute functionality to start the operation, which is ensured by the communication between the Dispatch functionality and the asset (machine) itself. Similarly, the flow of the operation and their parameters travels through the functionalities Service Data Collection, Service Tracking, Data and PV reporting channel, Production Data Collection, to the functionality Production Tracking.

Figure 4 shows the implementation of distributed intelligence (distributed production control) within the individual assets in the manufacturing plant. For simplicity, three SPs (two production units and one warehouse), one product, and a MES system are implemented, which serves as a passive database on product tracing and uploads process definition to products and machines.

From this point of view and the definition of individual SP / SR, it is possible to create the same AAS for the operator, which thus becomes an SP and can offer its services, as well as production machines.

From the point of view of individual functions and submodels, the production machine (primarily SP) can also be SR, in case of the need for service intervention, import of raw materials or semi-finished products (parts), etc.

It is therefore a universal model operating in the entire production segment.

4. CONCLUSIONS

The article describes the roles of MES systems, their internal organization, models that are defined within the ISA-95 standard, as well as the specific MES, which is presented by its manufacturer as MES for Industry 4.0. It is shown that this system cannot define the method of production of products on the production line in such a way that it can be carried out in a decentralized manner to achieve attribute 4.0.

The traditional role of these systems, in particular centralized production management, is likely to be replaced by dynamic decentralized decision-making, which appears to be better in the event of emergencies and has other advantages.

The main part of the article deals with the proposal to modify the generic models of the MES system to suit decentralized ideas. First of all, a new communication service channel is proposed, where a pair of entities – provider and requester should communicate together. Typically, in Industry 4.0 there is a smart product, respectively its smart interface – Asset Administration Shell. This shell is responsible for the manufacturing of the product instance itself. Shell thus uses the communication service to negotiate production capacity throughout the manufacturing line.

ACKNOWLEDGEMENT

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Demonstrative Manufacturing System Controlled by MES Utilizing AAS

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Abstract—This work examines today's modern possibilities for production management. More specifically, we focus on MES (Manufacturing Execution Systems) and its integration within the concept of industry 4.0 using AAS (Asset Administration Shell). It also describes a specific integration for a simple virtual line designed in ABB RobotStudio, which is first controlled using MES and then the production is encapsulated using AAS. The AAS is then supposed to interact with ERP (vertical integration) and also with suppliers and other manufacturing units (horizontal integration).

Keywords—MES, AAS, IMES, RobotStudio, virtual factory, OPC UA

1. INTRODUCTION

This article deals with the possibilities of using advanced production management using MES. For demonstration purposes, we will manage a virtual line created with the help of ABB RobotStudio. As MES, we used one of the open source applications available on the Github server.

All communication takes place using the OPC UA protocol, both with the database and the virtual line and in the next phase with the AAS and the virtual line. This communication is mediated through the NodeRed tool, thanks to which we have relatively easy access to the Firebase realtime database.

A similar topic was dealt with by colleagues in the article [1] in their case, however, it was the use of AAS for MES and its superior system - ie ERP (Enterprise resource planning). Our work is more focused on communication of MES with a lower level - ie with line or PLCs. In the article, however, they used MES from a different creator than us.

2. AAS – ASSET ADMINISTRATION SHELL

The Industry 4.0 concept uses their AAS - Asset Administration Shell digital envelope to standardize equipment descriptions. The purpose of these envelopes is to ensure the exchange of information between the facilities, between them and the production coordination system and the engineering tools. [2]

The figure 1 shows the description and connection between the physical device and the AAS. The device envelope (AAS) consists of two parts. Header, which lists unique device identifiers. A body, in which other information about the device, its properties and other important information such as the production process is given. [3]

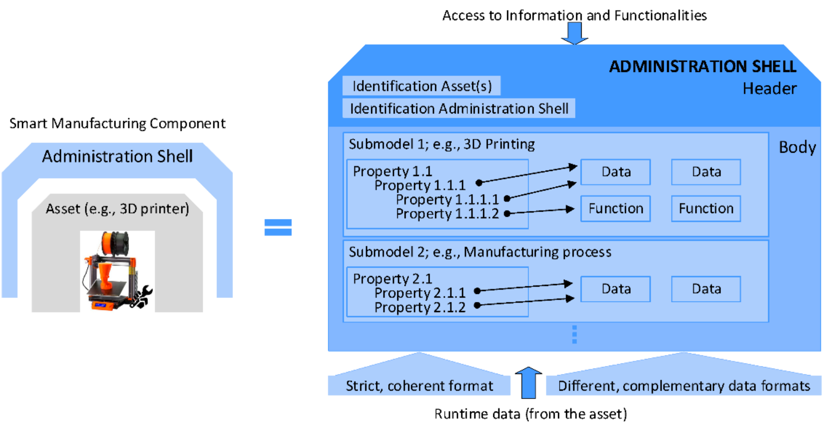

Figure 1: Structure of AAS [3]

3. IMES

We used the available open source IMES application to manage our virtual line. This application is relatively simple and should be fully suitable for our demonstration purposes. The advantage of this application is that it already has a module ready for possible sensors that can record the progress of order processing in the company.

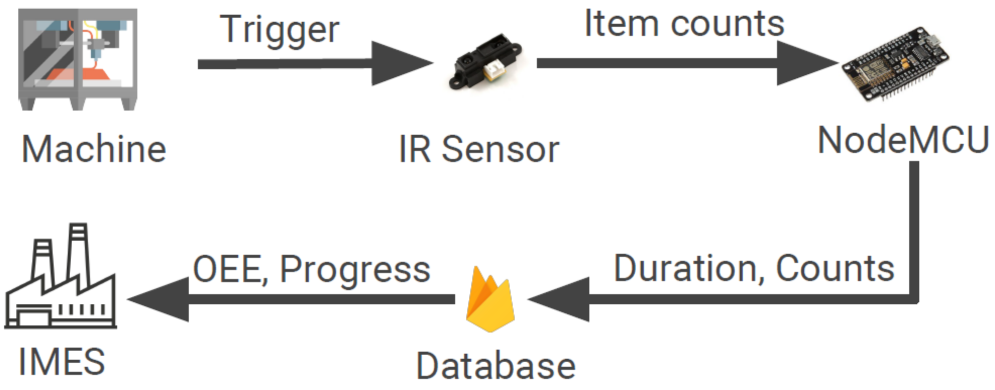

Figure 2: Structure of AAS [4]

4. COMMUNICATION BETWEEN MES AND FACTORY

We will use the protocol for industrial communication for communication between individual components. OPC communication is generally used for the exchange of data between different industrial systems. In automation, it is a universal communication platform that can connect to the data of hundreds of different types of devices from different manufacturers and convert this data into a single OPC communication, understandable to many superior applications such as ERP, SCADA, or in our case MES.

Communication between the client and the server takes place exclusively through calls and processing of services (Services), which deal with the control of individual parts of the OPC UA server functions. Both queries and answers have their common headers, where the client has, for example, the ability to set the required information to be returned by the server for all queries. [5]

5. MANAGEMENT STRUCTURE WITHOUT AAS

In this case, it is practically a classic pyramid control, where data is exchanged between the virtual line and the database of our application. RobotStudio creates the OPC Server and sends the simulation data to it. We read the production progress data from the server using the NodeRed tool. We then send the data to our Firebase real-time database. In the same way, communication takes place in the opposite direction, where we read information from the database and send it to the server.

This is illustrated in the block diagram in Figure 3

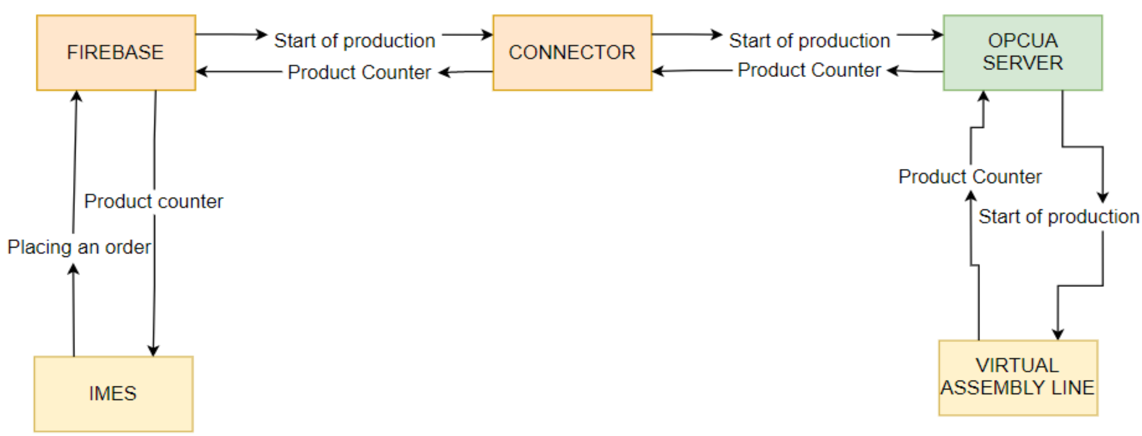

Figure 3: Block diagram classic management

6. MANAGEMENT STRUCTURE WITH AAS

When managing with the help of AAS, we will create an envelope, which we will cover our entire application and we will communicate only with the header of our asset. Eventually, the entire AAS will have modules in place for both communication with the enterprise management system (ERP) and communication with the lower tier. The ISA-95 standard tells us what information should be passed on. In our case, however, this would mean that we would have to modify the database of our MES application. Therefore, we will prepare only the given submodels in our AAS and I will use only those that will be beneficial for our application.

Communication between the asset and AAS blockes takes place on the basis of SQL statements. Based on them, the data will be written directly to the Firebase database of our MES application. The configuration then takes place on the basis of our selected submodels "communication settings" and "definition of variables and methods". However, these submodels can be extended by others.

The block diagram here shows the possible structure of the project

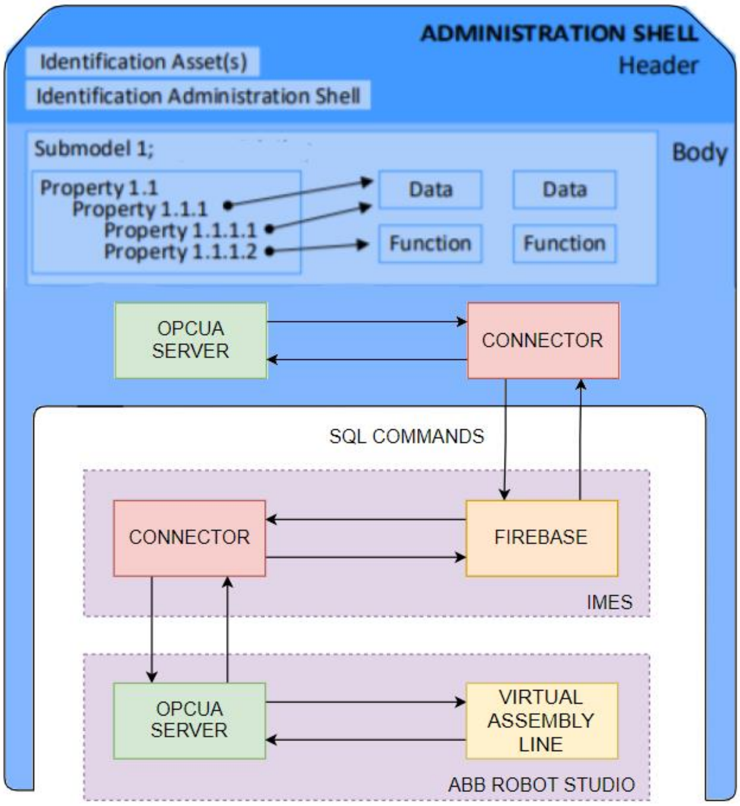

Figure 4: Block diagram management with AAS

7. DEMONSTRATION OF MES AND VIRTUAL LINE DEPLOYMENT

Figure 5 shows one of the possible deployment methods. This is line control without the use of AAS.

Here we see a virtual line created in RobotStudio and part of the IMES application. More specifically, the production monitoring section, to which we receive data from the simulation.

Figure 5: example of IMES deployment

8. CONCLUSION

This work deals with the possibilities of production management on a demonstration virtual line. Both the classical methods of control using the MES itself and the possibilities of control using the AAS are discussed here. This means for us that we will pack our entire application in asset and create submodels according to the ISA-95 standard. This standard tells us which data and information are to be sent one level up (to the ERP) and also one level down, e.g. to the control PLCs.

In our work, we first had to run the IMES application and pair it with the Firebase Real time database. After that, we used the NodeRed tool to connect our database with the OPC UA server, which generates simulations in ABB RobotStudio. In this simulation, pulses are generated for the simulated sensor, we then calculate these pulses and thanks to that we can monitor the production process after that. We try to ensure all data transmission through communication via the OPC UA protocol, which is one of today's standard industry protocols.

9. ACKNOWLEDGMENT

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Asset Administration Shell - manufacturing processes energy optimization

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Abstract: The paper deals with the issue of Asset Administration Shell (AAS), especially from the point of view of production process optimization. From the authors' point of view, Industry 4.0 brings the main advantages especially in decentralization and thus the independence of individual production machines, which will enable greater variability of production and better response to failures. The content is a description of the parts of the AAS that are closely related to production optimization, these are active submodels for autonomous negotiation, optimization (evaluation criteria), predictive maintenance and resilience. In the case of the implementation of the mentioned submodules, a robust production solution will be implemented, which is suitable for discrete piece production with direct links to the customer, who can freely configure his product. This paper provides an overview of optimization in the use of AAS and their main functions - submodules and their possible implementation and benefits for production systems.

Keywords: Asset Administration Shell, Industry 4.0, Optimization, Horizontal integration, Predictive maintenance, Resiliency, Autonomous production

1. INTRODUCTION

Standardization is one of the primary goals of Industry 4.0, mainly due to interoperability, and thus horizontal integration at all levels of the manufacturing company as well as at all stages of the value chain. With the growing trend of agile production (agile production systems), a quick possibility of conversions to a new type of product is required. In the preparation and modernization phase, it is essential that tools in different domains can work together. To achieve such interoperability, it is necessary to have standards so that the same information can be used in more than one sector.

In the Industry 4.0 reference model (RAMI4.0), the Asset Administration Shell (AAS) is presented as the cornerstone of interoperability. Asset Administration Shell can be imagined as an extension of any device that wants to cooperate in the Industry 4.0 world. Such a device can then be called an Industry 4.0 component – ie a device enabling active data exchange within an Industry 4.0 network. AAS consists of several submodels that extend and describe its functionality, but also the functionality of the device (asset). The primary task of AAS is to interpret the functionality, information, parameters, documents, etc. of the asset in a standardized consistent form. AAS of any product, standing, etc. - generally asset, should ideally arise at the beginning of the value chain. AAS can also be used to standardize human actions, thus creating an AAS operator.

AAS functionality can be divided into two parts:

- Passive – part of AAS containing submodels for storing data related to the asset (datasheets, project documentation, 3D models, diagrams, identifiers, etc.). This is a function that does not require a communication interface. It is thus a standardized data storage structure mentioned above. This part is crucial especially at the time of product design (ie before its production) and subsequently after completion, where it is possible to store all the information from the production process of this asset.
- Active – part is the cornerstone for autonomous production management. Machine autonomy is a key pillar of the Industry 4.0 idea. However, the most efficient autonomy can only be achieved with a

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standard machine-to-machine communication interface, which is provided by AAS.

The optimization of the production process can be viewed from different angles. One of the possibilities is energy optimization or optimization of the production process. These are the most frequently addressed issues in production. For example, by optimizing the production process, production costs can be effectively reduced, but also the time required for production. The following can be considered as optimization of the production process:

- Production planning optimization – self-organized production = distributed production management. The consequence of the use is energy optimization and the need for production in stock.
- Resilience of production systems – lower failure rate and in case of failure it is a safe failure. Communication network resilience is an important part of Industry 4.0 horizontal integration.
- Predictive maintenance (PdM) - with the amount of data obtained during the production and creation of digitized service operations, it is possible to predict service operations more and plan them in an ideal time when the production unit is idle or during technology outages. This eliminates unwanted downtime and service operations that can be efficiently scheduled and do not interfere with the smooth running of large production units.

2. RELATED RESEARCH

Currently, standards for AAS are being developed and the idea of these standards is to implement them in real production. The ZVEI / VDI (Verein Deutscher Ingenieure) standard is relatively complex and is therefore difficult to fully implement in existing control systems, so the resulting implementations often differ. Concessions, depending on the platform implemented, can cause incompatibilities between I4.0 components. The basic and most used control system in industrial automation is PLC (Programmable Logic Controller). The authors of the article (Cavalieri, 2020) dealt with the creation of parts of AAS for PLC, and our next work on the I4.0 testbed called Self-acting bartender (Kaczmarczyk, 2018) will also deal with this direction. Another principle of AAS implementation is a server / cloud solution which, in our opinion, is only suitable for machines with an Ethernet-based interface. It would be very complicated to connect the server / cloud version of AAS using buses such as RS485, RS232, CAN etc.

Another significant disadvantage is the theoretical centralization of technology – all AASs run on the same hardware and rely on a single communication interface. This can be solved by redundancy or a similar approach. This can minimize the risk of failure, but in essence it runs counter to the decentralized approach of Industry 4.0 principles.

The ideal solution thus seems to be a full implementation in a PLC or the creation of embedded hardware, which will be part of the production machine. It would also include a suitable interface for the asset.

However, none of these ideas address, for example, where the AAS product or the AAS operator will be physically located. As part of the work on the research project Self-acting bartender, our research group will focus on solving these unknowns in the issue of AAS implementation.

3. ASSET ADMINISTRATION SHELL FOR MANUFACTURING OPTIMIZATION

This chapter details the key features of AAS. These are mainly features that help optimize the production process, which lead to higher efficiency of the entire production chain.

3.1. Distributed manufacturing process

The current principle of production using the MES (Manufacturing Execution Systems) system is very robust until the moment when the production machine fails, and it is necessary to reschedule production. The weakness of the solution using the MES system is also the centralization of the entire solution and the impossibility of modifying the production process, for example in the form of plug and play, the addition of production machines, etc.

In contrast, it is possible to use production control using autonomous production units. The basic idea of Industry 4.0 is the possibility of two-way communication between individual devices. Ideally, production planning can be distributed among separate units because each machine, software, product, operator, etc. is able to communicate with any device.

Using AAS and its submodels, it is possible to implement models for production planning, negotiation (implementation of supply, demand, orders, etc.) and other necessary submodels for the full functionality of distributed production management.

MES, as it is known today, will thus be reduced to a mere passive database containing production steps according to the customer's order. Upon receipt of the order, the MES system creates an AAS for the product and provides it with all the necessary information so that the product can "be manufactured by itself". With the use of unified communication and functional units (submodules), he is able to negotiate individual production steps on machines in production, plan transport to the workplace and possibly optimize its production in case the machine breaks down or a third-party supplier needs to be used.

In order for everything to work properly according to the current vision, it is necessary that everything follows the same standard. In our implementation for production testbed Self-acting bartender, the implementation of AAS will be as closer as possible to be compatible with the ZVEI / VDI standard.

A great benefit of distributed production management is the ability to reschedule the entire production on the fly and it is possible to optimize the production time of the product, and thus the price and potential energy costs for the production of each product. Optimization submodels can be easy for initial validation, but there is a huge opportunity for research on how to implement intelligence and planning optimization in AAS. This approach then leads to the optimization of the entire production from many perspectives.

3.2. Digital Twin

A new approach to production optimization solutions is to use virtual commissioning, often referred to as Digital Twin. As the name implies, this is a digital copy of a real device, which is used not only in development but also, for example, in putting the machine into operation.

Virtual simulation of the production cycle brings us important information not only in real time, but also in a shorter time horizon. This can be used when planning production-related logistics operations or when planning individual production machine operations. The AAS twin thus provides real AAS services in terms of simulation. AAS Digital Twin implements connectors in simulation and emulation software such as PLCSIM Advanced, SIMIT or Matlab. AAS_DT provides complete software in the loop (SiL) and can also be used as hardware in the loop (HiL) in manual mode for debugging purposes.

There are more options for connecting a virtual twin. Mechatronic Concept Design (MCD) supports up to eight external control modes. Of these options are specialized protocols for PLCSIM Advanced, SIMIT (SHM) or Matlab Simulink. The environment is additionally equipped with a universal industrial interface OPC UA / DA, TCP, UDP, or Profinet. Universal industrial interfaces are an ideal option for the HiL method. It uses this solution to control the simulation using a physical PLC.

Another possibility of using the digital twin is for the purpose of training operators, maintenance, and dispatching work. For some operations, this is the only training option, due to the hazardous environment or technology instability. For example, the use of virtual twins for the prediction of immeasurable quantities for PdM is challenging. It is also possible to test collisions that would lead to its destruction on a real device.

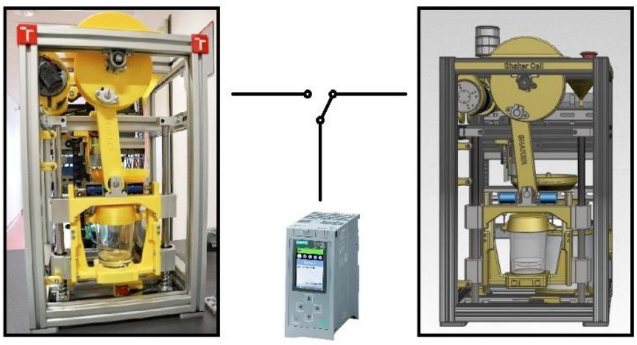

Figure 1 Implementation CPS

Figure 1 shows an example of a real machine on the left and its digital appearance on the right. This is a Shaker production cell, whose virtual image was created in the Siemens NX environment and its MCD module. This is an example of a device whose control is implemented using a virtual PLC in the program PLCSIM Advanced v4.0 for SiL concept. It is able to perform a complete simulation of the entire device without the need for its physical implementation. Communication between the PLC simulator and the virtual model in the MCD takes place via a direct connection. Other connection options are in the testing phase when it is possible to switch between real and virtual machine. Upon completion, the virtual twin could be a valid part of the machine connected via an OPC UA server with a physical PLC (Hardware in Loop Method).

3.3. *Predictive maintenance requirements*

Maintenance is an important function in terms of production optimization, which is the ability to prevent unplanned downtime in production. In terms of practical possibilities, two approaches to maintenance are used today:

- Preventive maintenance (PM) - the disadvantage of preventive service and life cycle planning is the premature termination of parts of the production facility that still have residual production capacity. It is also necessary to maintain stocks of spare parts.
- Predictive maintenance (PdM) - uses all production capacity of the equipment or part of the equipment. By measuring the current state of health of the facility, can be predict when the cut-off score limit for the fault condition will be exceeded. Thanks to this, It is able to plan the maintenance of a fault that has not yet occurred or reduce the capacity requirements for the equipment and delay the shutdown. Flexibility can be used in this direction to optimally cover the production capacity of unexpected demands.

The combination of PM & PdM is a more difficult option in terms of implementing maintenance planning, but it is in demand. State-of-the-art in the field of predictive maintenance does not yet include a diverse range of equipment in the industry, and therefore in some cases it has to rely on preventive maintenance. This is a multicriteria optimization problem with many variables, but also parameter constants.

Vendor-oriented architecture

Vertical integration provides us with a direct link between elements that do not exist in normal production. It is, for example, the link between the maintained equipment and the maintenance worker, which is protected by already superior intelligence such as enterprise resource planning (ERP). The staff in the AAS network is packaged in its own AAS and acts as a unit that provides a maintenance service. They provide maintenance in the form of production capacity, which the equipment orders.
Data for PdM (acquisition, storage, reduction)
For low-cost technologies with higher failure rates, it is advantageous to obtain run to failure data. The service life of such components is extended to the maximum usable life cycle.
Implementing a predictive model in AAS raises questions that needs to be answered.

- Where the implementation of the PdM model is located in the AAS device or separately as a service
- Acquisition of data from sensors and where to place historical data? They don't fit on lightAAS.
- Service intervention changes the predictive model, which must toggle or ignore the original remein useful live (RuL) estimate.

The solution is not to store any data, just to rethink the model. However, this radical step is quite risky due to the retroactive reconstruction of operating conditions, for example when dealing with a batch defect. Historical data is stored in AAS batches, but there may not be all the machine operating data that PdM works with. In the limited function of AAS, which is implemented on a PLC with limited memory, there is another possibility to use a cloud solution as a service for "lightAAS". Light AAS provides only the most necessary functions associated with the execution of production implemented on the edge, the remaining functions of the asset are located for the cloud solution. In the article (Cavalieri, 2021) the authors use PdM fragmented into so-called "logical blocks". Examples of such a block are data acquisition functions, RUL predictor or scheduling functions. However, in our case, these functions will have to be divided into groups executable on the OT and IT side.

Maintenance Decision-making

As already mentioned, the response to the performed maintenance is production capacity and quality of production. The optimal balance between quality and quantity in production has been addressed for a long time. Optimization algorithms exist; however, the implementation of such systems is demanding on the overall understanding of the technology, i.e., it is not transferable between different types of production. Therefore, we chose the knowledge of human experts for our concept and tried to implement it into a multicriteria expert system. We consider this step to be state-of-the-art in the field of maintenance optimization.

3.4. System resiliency

Resilience as such should guarantee fault avoidance and fault tolerance of a given technical system and can be divided into different domains such as information, structural and time domain, as well as into individual attributes such as robustness, integrity (safety and security), recoverability, reconfigurability, testability, adaptability, evolvability and reliability. (Castano, 2015)

In general, the implementation of the principles of the resilient system should predominantly lead to better performance, reliability and security of the system itself, therefore even within the AAS.

Based on the general RAMI4.0 model (Schweichhart, 2016), subject to the horizontal line "life-cycle and value stream", within design/development it is necessary to always include requirements not only for the functionality of a system but also requirements for individual attributes of resilience.

Based on previous, it is not appropriate to implement methods to increase the resilience into the system retrospectively and artificially as ADD-ONs. This approach can bring extra cost, extra complexity and inefficient mitigation actions. Therefore the requirements for increasing the resilience of the system must be included at the beginning of the design. (Hosseini, 2021)

Consider that AAS can be internally divided into active and passive parts (Active and passive AAS), while the active part can be further divided into individual sub-models that manage and functionality of certain areas/parts of AAS (safety and security sub-module), then these principles described in (Hosseini, 2021) can therefore be applied to most of the resilience attributes. Thus, it is possible to incorporate attributes of resilience within the AAS as individual sub-modules (in the active part of the AAS), which provide the required management of each attribute within AAS. However, it is always necessary to think about whether such an implementation will bring the desired results in terms of increasing the resilience of the AAS or will only complicate the AAS unnecessarily.

The concrete implementation of individual resilience attributes in AAS also depends on whether it is a simple AAS, where the asset is a technical device or a human AAS, where the asset is a human being. (Hosseini, 2021)

4. IMPLEMENTATION

The following chapter discusses the possibilities of AAS implementation, both in terms of the standard and structure (models/submodels) of AAS, and in terms of the communication protocol / interface used.

4.1. Standards

Because of the principles stipulated by the Industry 4.0, standards have to be used in the whole life-cycle of any component. This fact is eligible for a production and even for an AAS creation. Nowadays, many standards have been released, thus, only crucial parts will be discussed.

The structure of the AAS is defined by the meta-model presented in (Bader, 2020). The structure consists of head and body. The body comprises types, dictionary, submodels. The submodels contains instances of parameters, methods, and events describing a functionality.

Because of many nationalities have different customs, unit definitions, naming conventions, and taxonomies, a standard need to be followed. So far, there is standard IEC 61360 that defines the dictionary schema and may be used to define vocabularies. The standard (IEC 61360-4) also presents a dictionary (IEC CDD, 2021) for use in the field of electro-engineering and related domains. Based on the standard, other dictionaries can be defined, such as eCl@ss accessible in (ECLASS, 2021).

The dictionaries provide only the description of the properties and metadata in the standardized way comprising the naming convention and taxonomy, which can be used by submodel creation; even though, it is not enough to fully describe the component features, especially the relationships among properties.

When an I4.0 component is created using AAS, it is usually connected with others to share data and implement a function. The standard is also applicable in the interaction between these components. (Details of the Asset Administration Shell, 2020) already defines the interaction protocol, but still a complete standard comprising the message definition is missing.

From our scrutiny, any standard defining the location and runtime framework of AAS is missing. There are some options such as execute on a server to use the computational power to its full extent. Another option rests in the implementation of the AAS into the PLC to comply with the distributive pillar of the I4.0 concept; on the other hand, it will always lack some features and be limited by the hardware platform. So far, the AAS is based on the OPC UA technology, the OPC UA standard could be considered as the general framework for the AAS creation if the explicit mapping between AAS and OPC UA is finally defined by some standard.

4.2. Communication

As already mentioned, it is very suitable to use OPC UA or MQTT protocols for the actual communication of individual devices or their asset administration shell components. Each is suitable for a different use.

OPC UA is, unlike the original OPC specification based on Microsoft's COM / DCOM technologies, a technology based on the commonly used communication standards TCP / IP, HTTP, SOAP and others. OPC UA is therefore cross-platform, with the fact that it can also be used by third-party manufacturers in their facilities. Unlike the original OPC protocols, which had separate access to data (OPC DA), alarms (OPC AE) and historical data (OPC HDA), OPC UA does not define these specific approaches, but only the format of the transmitted messages. Communication here is based on data transfer via a client-server connection. The protocol specifies the structure of the data provided, the methods of authentication, and secure access to the data. Because OPC UA is defined as SOA (Service Oriented Architecture), services are defined within the server that the client can query, and the server always responds with the appropriate response. Communication within the OPC UA is always implemented via a secure channel.
The MQTT protocol is a standardized protocol that allows very simple transmission of a limited amount of data over a common TCP / IP Internet network. The protocol is based on the transmission of messages through a central server - a broker, which acts as a "journalist" receiving messages from the message provider and sending messages to their recipients. It follows from the above that the communication model used is, unlike OPC UA, of the "Publisher - Subscriber" type. One broker can have many different news providers and many readers connected, and only pass on to those readers the news that each reader has subscribed to. Due to the modular architecture of the entire solution, it is possible for one device to be both a message provider and a recipient of (other) messages. Within the MQTT protocol, the transmitted messages are sorted into topics. Each message belongs to exactly one topic, while the topics are defined directly by the message generator - Publisher. The subscriber must then know in advance the name of the topic he wants to subscribe to. The subscriber does not have to know the communication address of the publisher, he only needs the communication address of the broker. MQTT offers the possibility of encrypted transmission via SSL / TLS protocol as well as the possibility of authentication with client certificates, which is the highest possible level of communication security.
The MQTT protocol is very suitable for use in devices with limited computing power. It is also suitable for limited communication bandwidth due to data economy. The big disadvantage of the MQTT protocol compared to OPC UA is its centralization in the form of a single network broker. In the event of its failure or unavailability, the entire MQTT solution immediately becomes unusable.

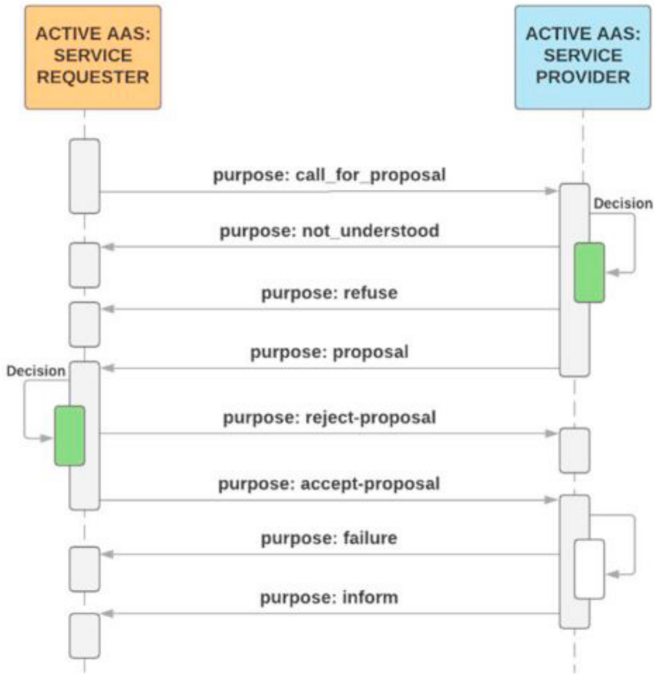

Figure 2 Negotiation flow diagram (Belyaev, 2019)

4.3. Communication principles

Due to the distribution of the decision-making process, it is the basic principle of negotiation. The negotiation algorithm is described by one of the basic AAS submodels. Figure 2 shows a UML sequence diagram of the negotiation process. The principle of the function is similar to the standard process between the customer and the supplier, where the demand is first created and the most suitable one is selected from the received orders. On the service provider side, a time slot is reserved for production.
At the moment, however, it is necessary to treat a large number of limit states that may occur - the service requester (product) does not respond, it is possible to reallocate the time slot for production; service provider does not respond - production on other machines is requested again. However, the validity of the reservation must be checked periodically on both sides, which is very demanding on the amount of communication with a higher number of products in the production cycle.

5. EVALUATION CRITERIA

Not only during the negotiation process - i.e., the attempt to allocate production equipment, but also within the entire production process, it must be possible to quantify the efficiency with which the process takes place at different levels of the hierarchy. In other words, there is a need to calculate some of the known Key Performance Indicators, which are standardized within the ISO 22400 standard and are currently implemented within the production management systems (MES). There is also standardization for these systems, which is a well-known international standard ANSI-ISA 95 defining the so-called manufacturing operation management (MOM) - a set of models (functional, data, communication) and recommendations for creating MES. If the manufacturer follows this standard, a system (MES, level 3) is created that guarantees interoperability with subsequent systems, whether

enterprise resource planning systems (ERP, level 4) or with the domain of technological process management.
Introduce of the term KPI for calculating efficiency, everyone is reminded of one of the most well-known indicators - Overall Equipment Efficiency (OEE), which is used to evaluate the efficiency of one device in terms of availability, performance, and quality. The calculation of this indicator can be interesting within each component of the Asset Administration Shell. The value of OEE can be used in the process of negotiating production resources. By obtaining this value from multiple parallel sources, the AAS of the product can decide which of the sources to allocate. Note that OEE will not be the only indicator that will be key to the product's AAS in such a case. This will also consider, for example, the current length of the registration queue of a particular resource (in other words, the time he will have to spend in the queue) as well as other indicators.
Another problem is the determination of the so-called Overall Factory Effectiveness. This indicator evaluates the complete production process and can be deployed both on a specific production line and on a company-wide level. OFE calculation includes relationships and interactions between devices and processes and divides them into four groups - series, parallel, assembly, expansion. These groups of subsystems can be used to model the entire production operation.

CONCLUSIONS

As part of the research on I4.0, our research group has created a testbed self-employed bartender, on which we try to gradually test most of the principles and approach of I4.0. the testbed is made largely by additive production and a CPS is created for each autonomous cell (production machine).
The next step is to implement a decentralized production principle, which necessitates the implementation of AAS for Siemens S7-1200 PLCs. As this is a low-end PLC from Siemens, it will be necessary to optimize the implementation so that it is interoperable with standard AAS and at the same time it can be implemented in a PLC. The testing will also include finding out the parameters of individual communication protocols and their comparison and applicability to the given use case.
In the case of AAS functionality, the last step will be to optimize the production process, primarily using the evaluation criteria described in Chapter 5.
The result of the effort will be not only a functional prototype of the I4.0 production platform, but also a comparison of the advantages and potential disadvantages of this approach compared to the current I4.0 approach.

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An Experimental Training Production Line to Demonstrate the Basics of Industry 4.0

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Abstract: The paper deals with appropriate possibilities, instrumentation, and technologies for purposes of education, presentation, teaching and research, and development of technologies and procedures of Industry 4.0 ideas, and their implementation in case studies of Factories of the Future. Through the physical module-based production lines of a FESTO Didactic company authors present technologies, standards, and principles of Industry 4.0. They are persuaded, that after some years of simple presentation of ideas and visions, it is necessary to provide a step from theory to the praxis of the Industry 4.0 technologies in the fully standardized matter. Paper presents a state of the art of an enhanced Experimental Education production line, the Cyber-Physical (CP) Factory of the company Festo Didactic. They show existing properties of the technology, stemming from 2016, its disadvantages and provide a proposal on how to enhance CP Factory towards a physical system, implementing and providing properties of fully decentralized control of automatic production systems in a standardized way.

Keywords: Asset administration shell, digital twin, decentralized control, Industry 4.0.

1. INTRODUCTION

The German associations BITKOM, VDMA and ZVEI concluded a cooperation agreement to run the Plattform Industrie 4.0 in April 2013. The launch of the platform was officially announced at the Hanover Fair 2013. In April 2015, the Plattform Industrie 4.0 was expanded. More actors from companies, associations, unions, science and politics were added. The entire strategy gradually evolved in Germany and spread across Europe. In 2018, three European countries began to collaborate closely within the manufacturing domain to improve and disseminate the concept, and their efforts yielded the following initiatives: the Alliance Industrie du Futur in France, the German-based Platform Industrie 4.0, and the Piano Industria 4.0 in Italy (Platform Industrie 4.0, 2018).

The high industrialized world is already able to understand, and mostly accepts ideas of Industry 4.0 (I4.0). There are recently two parallel ways of development first Factory of Future (FoF). The first one is a wild development of fully automated and robotized production systems, which are able to produce by computer control, use of new communication and control technologies, but accepting no standards, which are already developed, checked, evaluated, or are under very quick development (Slany, 2022). The second way accepts as well as the new technologies but prefers at first international standardization process in communication, business models, application of robots, Artificial Inteligence (AI) principles, other news.

Authors are persuaded that the second way is the only right way stemming from the huge research and development activities of a working group of Industrie 4.0 Platform (Platform Industrie 4.0, 2018). The way stays on systematic digitization of process and control data, standardization of interfaces, communication protocols (TSN, OPC UA) through the ISO/OSI model, enhanced visualization, powerful virtualization technologies (ABB Robot Studio, CIROS, Siemens TIA based technologies, and others), security technologies new business models, new control architectures of enterprise control systems (the IEC 62264 series of standards is based on the data standard of the

International Society of Automation (ISA), i.e., ISA-95 (Enterprise-Control System Integration, (2010), (Ye, 2021)), standards of the value chain and product lifecycle (Arm, 2021), (Platform Industrie 4.0, 2018).

Let us present a very enhanced education production line as one representative of an interface or border between Industry 3.0 and the Industry 4.0 staying application of Industry 4.0 principles.

On the basis of the physical module-based production lines of the company FESTO Didactic authors present technologies, standards, and principles of Industry 4.0.

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2. CYBER-PHYSICAL FACTORY

Cyber-Physical Factory is a training assembly line from FESTO, where you can demonstrate the principles of industry 4.0 and conduct research in this area. The factory consists of basic modules (belt conveyor and belt conveyor with switch), robotic cells, autonomous mobile robots, and application parts, which are located on the belt conveyor module. The application part can perform, for example, drilling, pressing, heating, material replenishment, measurement, etc. The two systems are not interdependent and it is, therefore, possible to change, move or remove the application part at any time.

Thanks to the above location of components, the line is very modular. Allows any placement of individual modules, their connection and disconnection are quick and easy. Chassis fitted with wheels allow them to be moved. The main advantage of easy switching and adjustment of modules are connectors, which allow to connect and disconnect adjacent modules of belt conveyors with a single connector. These connectors contain both power wires, pneumatic lines, signal wires, and Ethernet in this case Profinet. Thanks to RFID and the roundabout in the form of an endless strip of line, the location of the individual modules and their application parts does not matter due to the adherence to the work procedure and their continuity. However, it is important to choose the arrangement of the individual modules so that the production time is as fast as possible with respect to the given production task so that the trajectory of the truck is as short as possible.

2.1 CP Factory at College of Polytechnics Jihlava

The line located at VŠPJ in Jihlava consists of four islands, which can be named as an assembly line, manual workplace, warehouse, and machining line, see Fig. 1. Between these individual islands, the semi-finished products are transported by autonomous mobile robots Robotino. Another option would be to use a swarm robotic platform (Docekal, 2017). The issue of charging these platforms often has to be addressed here (Misak, 2017), (Vantuch, 2018).

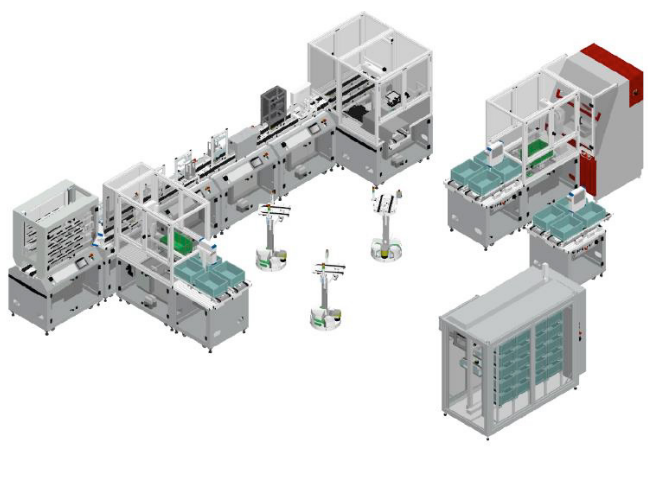

Figure 1. *Current state physical line at College of Polytechnics Jihlava (Festo Didactic, 2018).*

The line is adapted for the production of a very simplified model of a mobile phone consisting of three parts, a front and a back cover, as well as a printed circuit board (PCB) and two electrical fuses. Depending on the selected line configuration and production operations, it is possible to choose the complexity of the product, which can range from mere machining of the cover to complete assembly, drilling, soldering and PCB mounting, including two components in the form of electrical fuses.

The manufactured pieces and materials are transported between the individual modules by means of carriers on belt conveyors or by means of boxes on adapted belt conveyors, which serve as inputs and outputs of the modules, or by means of autonomous mobile robots Robotino between the individual islands. Each carrier or box contains an RFID chip that carries data to identify the element and its load, i.e. the material it carries. The carrier is able to transport one pallet on which one product can be placed in the form of a front cover along an endless belt of the line. The box is adapted for the transport of up to 10 products at a time, whether they are printed circuit boards, upper or lower covers machined or unmachined, assembled or unassembled.

2.2 Basic Belt Conveyor Module

The basic module of the belt conveyor consists of two parallel counter-belts, which allow two-way operation and transfer of material on pallets that are placed on carriers, see Fig. 2. They can be assembled to allow the carriers to move along the endless belt. The carrier can be detected at the beginning of the belt, at the end of the belt and in the working position.

On each side of the belt conveyor there is a 7 "Human Machine Interface (HMI) panel TP 700 from Siemens, which is used to control and manage the application and allows setting some parameters, manual control, process monitoring or automatic production settings without using the MES system. In the working position, both parties have an RFID chip reader and a so-called stopper, which allows the truck to be stopped with an RFID chip exactly in the working position on the RFID reader. Each of these modules or its side is controlled by a Siemens ET200SP PLC with a CPU from the 1512SP F-1PN series. Among other things, this CPU also has a web server and mainly an interface for PLC and MES4 communication. This communication is based on the protocol from FESTO which uses the standard TCP / IP protocol. In the core of this PLC, everything is ready for communication via OPC UA.

The basic module of the belt conveyor with the switch transports the carriers similarly to the basic module of the belt conveyor, with the difference that it also has a third belt. The third conveyor belt is placed parallel from the outside and moves parallel to the original side belt. On the main circuit there is a switch equipped with an RFID reader, which redistributes the material that arrives here on the carrier based on the data it reads from the RFID carrier. This switch allows the carrier to deviate from the main circuit of the endless belt for a more time-consuming application, so that the carrier does not block the smooth movement of the remaining carriers. The additional third belt also has the function of magazines, allowing the placement of up to three carriers with material for the application, which is also located here. If the hopper is full, the carriers will continue on the endless belt until space for the application is freed, or they will find another place on the line that allows the same application, if any, to be performed. After the application is completed, the transport on the associated belt stops and the carrier returns to the main circuit of the endless belt.

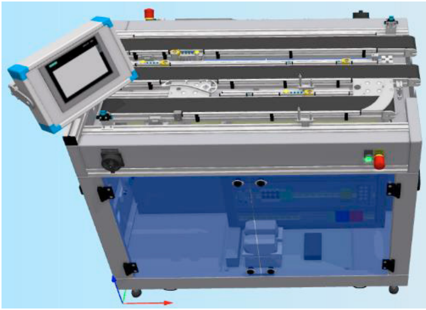

Figure 2. *Basic module of a belt conveyor with a switch (Festo Didactic, 2020).*

2.3 The Cell Module

The cell module consists of integrated modules performing a specific activity, they are adapted for material handling without carriers in three axes, either by means of a Cartesian manipulator or by means of a 6-axis industrial robot, see Fig. 3 a) and b). Modules with a Cartesian manipulator include, for example, a multi-level pallet warehouse module, in which up to 32 pallets can be stored with material or product. It also includes a large warehouse with up to 20 boxes. This warehouse dismantles the input and output parallel conveyor belt, which folds on one side as a access for Robotino, which receives or dispenses boxes here and delivers them to the appropriate places on the line. On the other hand, the input-output unit in the form of conveyor belts is operated by a three-axis Cartesian manipulator, which unloads or stores the respective boxes. The positions of the boxes in the warehouse are numbered. Each box is equipped with an RFID chip, which carries information about what type of material is placed in the box and in what number.

a) b)

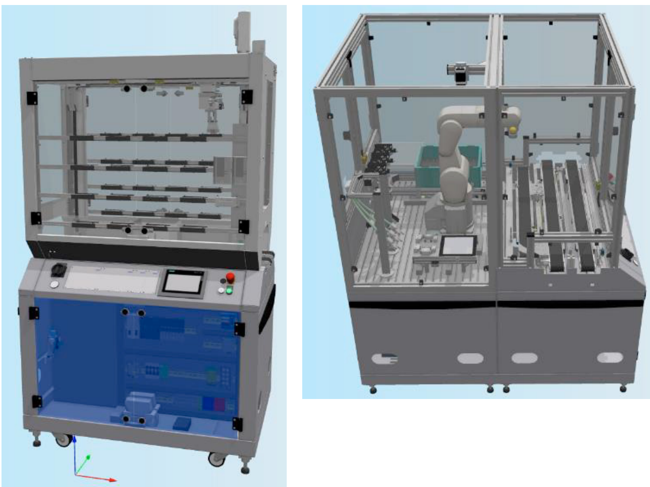

Figure 3. a) *Cell module, b) robotic cell module (Festo Didactic, 2020).*

Robotic cell modules are usually used for material handling from and into boxes and their integration into an application, which can be a 6-axis robot mounting module or a robot-operated CNC milling module and also a module for material handling from boxes to carriers or vice versa.

2.4 The Robotic Cell Module

The assembly robotic cell module has a 6-axis robot, which has three gripping mechanisms for three different materials. First, the robot uses a pneumatically controlled collet to remove the upper part of the cover from the carrier, which it places on a backlit surface, where it uses a camera to evaluate the rotation of the cover and then places it on the work surface. After replacing the gripping tool with a tool with a double vacuum suction cup, the robot places a printed circuit board from the box, which Robotino transported to this workplace, on the cover. He replaces the tool again with pneumatic pliers, which removes the electrical fuse from the magazine, which he places on the printed circuit board. Then the robot selects its first pneumatically operated collet tool and returns the fitted top cover back to the carrier.

2.5 The CNC Milling Module

The CNC milling module operated by the robot consists of two units of a CNC milling machine and a robotic cell. The material is transported to the robot in boxes using a conveyor. The box is transported to this conveyor by a mobile robot Robotino. The robot then inserts the unmachined materials into a CNC milling machine and then places them back in the box after they have been machined.

2.6 Aplication Modules

There are several application modules to perform a specific application and they are placed on the basic modules of conveyor belts for carriers, see Fig. 4. Application modules use at collage polytechnic in Jihlava: application module magazine, heat tunnel, drilling, camera inspection, press a turn over.

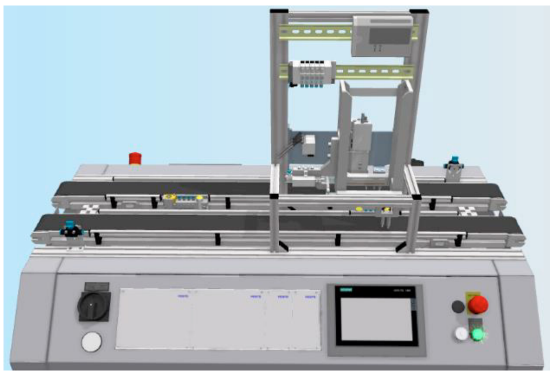

Figure 4. *Application module (Festo Didactic, 2020).*

2.7 Autonomous Mobile Robot Robotino

Robotino is an autonomous mobile robot that is able to transport a box or carrier between modules with cooperating equipped so-called docks. Robotino has three omnidirectional wheels of the network DC motors are independent of each other. Thanks to this, it offers Robotina to move in two axes and rotate on the spot. Using the sensors, you can move autonomously and safely. The Robotino is equipped with several bumper sensors that stop the robot in the event of a collision, distance sensors that should prevent this collision, a gyroscope for more accurate position sensing, a Logitech HD Pro Webcam C920 camera, which generates a live image that can be analyzed for navigation and detection of obstacles and objects. Furthermore, with two optoelectronic sensors, thanks to them, Robotin can detect up to two surface colors at the same time based on different degrees of reflectivity. Inductive sensor for path control in the form of a line, which is located under the floor Robotina. Last but not least, with the S30B-2011BA laser scanner, its main goal is to ensure the travel path of the robot. Its main task is to ensure the travel path of the robot. The scanner does this by scanning the area in which Robotino will move. Based on this scan, a map is created, for example in the Robotino Factory environment, in which the routes along which the robot will move and the directions in which it can move along the routes are marked. The scanner also checks the surroundings in the direction of travel while driving.

3. CP FACTORY COMUNICATION PROTOCOL AND PRODUCTION PROCESS

The communication protocol of the CP Factory production line (protocol for communication between MES and application modules) and the process of creating and executing orders will be described in this chapter. Both things are really closely related.

3.1 HW Equipment

he production line is mainly composed from conveyor belt, able to transport carriers with material and application modules placed on the top, which offers various production operations (see Fig. 1 and Fig. 2). The most important component for communication is RFID chip, placed on each carrier where all necessary information for identification is stored. This information is read and process upon arrival of the material to application module.

Exceptions of this concept are material warehouse module and Robotinos. These modules operate with material boxes, not single pieces placed on carriers. There is a different way of identification here.

In carrier's RFID chip are stored these attributes:

- CarrierID – unique identification number of each carrier.
- OrderNumber – number of order, connected with material placed on this carrier. Each order could contain several positions – several products requested in one order.
- OrderPosition – identify target product in one order. This product is produced according to target working plan.
- PartNumber – identification number of final product.
- ResourceID – identification of application module where next operation will be processed.
- OperationNumber – unique ident of next operation

Parameters OrderNumber and OrderPosition unambiguously identify the target workpiece and a working plan for its production. This working plan is completely stored in a database and only next step identification is stored in the carrier's chip.

3.2 Manufacturing Execution System

All data about production, materials, working planes and line states are stored in an SQL database. In the described case, it is an MS Access database, because it is easily portable (it is a normal file, there is no necessity to deploy a database to an SQL server) what is very helpful for education. Intensive communication between the database and application modules is needed during the production process and it is provided by software MES4 – Festo implementation of Manufacturing Execution System (MES).

From a communication point of view, MES is a bridge. On one side is a server for communication with application modules (it will be called MES protocol in the following text), on the opposite side, there is an API to a database (in this case ODBC is used). Each MES protocol command is related to a specific SQL query by a hash table. Parameters of this SQL query are filled by data, parsed from related MES commands.

For a user, MES4 offers a graphical interface for work plans creation, the definition of resources (a term for application module used in MES4), operations, material, and data collection and evaluation (for example some of OEE parameters could be evaluated here). All these user actions are realized as read or write operations into a database. There is any user action, which initializes a communication via MES protocol from MES4 to some resource (appl. module).

Beyond these functions, MES4 provides a tool for simulation communication via MES protocol. User can simulate incoming commands from resources and the system react by appropriate action on the database side. So there is a possibility to simulate all production process manually step by step without a connection to a physical or virtual production line.

3.3 Creating a Work Plan

Unfortunately, the creation of work plans is the weakest point of the entire production process. Trough MES4 supports a division of the production process into elementary, parametrizable operations (drilling, heating etc.), there is a necessity to define which resource makes this operation in the target work plan.

3.4 Communication Protocol

The communication protocol between MES and the application module is an open, unencrypted protocol, based on simple TCP/IP. This solution is not so usual in the real industry (minimally because is not safe), but it is very advantageous in education because direct access to transported data is possible. On the other side, in Industry 4 the requirement for using a standard solution (like OPC UA) is given clearly. MES protocol is a proprietary solution offered by Festo mainly for education.

There are two possibilities how devices that used MES protocol can communicate. The first way is the text form of this protocol, which is really ideal for education or manual setting command from an external terminal. The second form is binary and is used for communication in automatic mode. Chosen communication form has no effect on system behavior. Binary communication was listened to and parsed by a developed tool for the purpose of this article. But the meted of parsing this data isn't relevant from the point of view of the following text.

On the TCP level, the communication is processed on two independent ports. The first port (by default 2001) is reserved for the "Heartbeat" signal. As the name suggests, this pipe application module sends a periodical packet with basic information like online, error level, busy or automatic, or manual mode. This communication isn't relevant in terms of material flow and order processing and will not be addressed in the next text.

3.5 Data Communication

Communication on data port (by default 2000) runs in mode request-response whereas the request is sent from application module (or substitute software in case of Robotinos) in every case. MES protocol data packet is composed from a 128-byte length header and optional data with maximal length 1272 bytes. So maximal length of MES data packet is 1400 bytes. Struct of the header is fixed for all protocol commands, struct of optional data depends on type of the command. Each request command can be simply identify by two numbers. MessageClass which identify a group of command (commands for operation management, buffer management aso.) ad MessageNumber specified target command in one class. The response of target request uses the same MessageClass and MessageNumber identifications and rest of the packet is filled by valid data (if it is necessary) or by zeros. In actual implementation MES protocol contains around 100 types of commands.

Communication is based on TCP/IP so the response is sent to correct module. Packets routing is processed on this layer and there in no control in MES protocol. Basic principle of the communication can be described on two model cases.

a) *An empty carrier arrives at the application module*. In this case, empty data is read from an RFID chip and the request command *GetFirstOperationForResource* is sent to MES with the *ResourceID* parameter of this application module. This is a query for a case that the first operation of the target work plan would be started here. If it would, MES will send valid data of target order in its response, especially *OrderNumber*, *OrderPosition*, *PartNumber*, and *OperationNumber*. In the case of some specific application modules like Small Storage of material modified version if described request is sent. But the difference is only formal. Another *MessageNumber* is used, and the application module expects another data in MES response (it is necessary to specify a material position in storage). But the meaning of the query is the same.

b) Carrier with some material arrives at the application module. In this case, valid data is read from the RFID chip and the module sends a request command *GetNextOperationForThisOrderNumberAndOrderPosition*. In the sent query is only these parameters:

- *ResourceID* of the module
- *OrderNumber* read form RFID chip
- *OrderPosition* read from RFID chip

As a response, MES sends valid data describing a currently scheduled operation of the target order. Especially parameters ResourceID, OperationNumber, and PartNumber. Data from MES are compared with parameters from a carrier and if it is the same the operation will be processed here. If not, the application module release-blocking of the conveyor, the carrier is free, and it goes to another station.

A lot of other communication is necessary for the processing of the operation step itself. It is a sequence of several commands, especially StartOperation, SetParameters, and EndOperation (and others). From a point of view of material flow, the most important is the EndOperation command. MES sends information on the next operation in the target work plan as a response to this command. Especially ResourceID and OperationNumber. This information is written into an RFID chip at the end of this operation. When the carrier arrives in another application module, the sequence described in point two is processed.

This solution can be accepted as Industry 4 suitable only partly. The way the module decides to process the operation is fine. But in the end when the next OperationNumber income from MES the query like "Who can offer me this of operation?" should be sent. This query could be:

- Broadcast – so the negotiation of the intermediary of the operation and its "price" will take place between application modules and the result will be only sent to MES. This should be an ideal solution. All parameters included in the "price" of the operation can be set dynamically and the final decision shout be really optimal.

- Targeted to MES – MES has a connection to the database where information about resources and operations are stored a periodically updated. This solution could be easy to implement but there is a problem with the "price" of the operation. The "price" can be composed only of static parameters like power consumption, time duration of the operation of another. There is no way how to involve a time to transport into this "price". The decision taken in this way wouldn't be the most optimal.

3.6 Robotino Communication and Material Transport

Mobile robots Robotino are used for transport boxes with material (in another HW configuration is able to transport single pieces too) and in MES graphical interface it looks like an ordinary application module. But the communication via MES protocol is completely different. There are two basic differences. The First, the communication does not take place between MES and Robotino but between MES and special service software (in the following text it will be referred to as FLM - FleetManager) which acts as a bridge between MES protocol and Robotino protocol (communication between FLM and Robotinos). Robotino protocol has a completely different struct and set of commands than MES protocol. But its implementation is not important and it will not be addressed in the next text.

The second difference is that transport via Robotino is not a standard operation that could be offered by some resource. The transport from one part of a production line to another is not defined in a work plan, is not described in the database as some production step and it is started and run automatically on the background using a system of buffers. From one point of view, it is fine for a user, because he hasn't have to care about it, but on the other side, there is any information about it. In the work, the plan is not possible to see that some transport is necessary.

Buffers are parts of application modules (some of them) and can be either a place for storing material or an input/output gate. All buffers are indexed and clearly identified. Communication between FLM and MES takes place so that FLM sends a periodical request *GetBufferWithMaterialToTransport*. If there is a material in some buffer serving as an output gate MES sends a response with identification of this buffer and *ResourceID* of the target application module. Then FLM chooses target Robotino to transport this material and sends command *SetRobotinoToPosition* to MES. Additional communication follows between FLM and MES for processing physical and virtual moving material from application modules buffer to Robotino's buffer and then to buffer of target new resource.

This solution is not ideal for several reasons.

a) Transport operation isn't required by the material when it is necessary, but FLM periodically asks MES to buffer states. This style makes a needless communication surplus.

b) The price of the transport isn't negotiated by Robotinos and the application module. The algorithm that decides which Robotino makes a transport is completely implemented in FLM and the communication between FLM, MES, and Robotinos has no effect on this decision. FLM is a powerful manager of all the processes and the responsibility is not distributed into final components.

c) From a user point of view, Robotino looks like an ordinary application module but thy communication style is completely different. After deeper research, it's perceptible that Robotinos hadn't been a part of the system already and they have been added into that later.

4. CONCLUSIONS

CP Factory system offer HW and SW platform for automated production in intentions Industry 4. But in actual configuration (especially the software part of the system) isn't able to meet these requirements. Some individual parts of the systems run well, and they could be declared as Industry 4 fulfilled, but there are several tight throats where the system cannot be marked as data-driven Factory of the future. First of all, it is a missing dynamic assignment of operations to resources and missing negotiation of the price of these operations. The second problematic issue is transport via Robotinos.

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The Ideas of Industry 4.0: Seven Years After

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Abstract: The paper deals with a comparison of initial ideas of the Industry 4.0 activities and the state of the art of recent development of industrial production. Authors demonstrate their professional opinion that standardization of production procedures, communication technologies based on IoT and IIoT, TSN networks, OPC UA protocols, interfaces, new control architectures, cyber security principles, and methods, are the most important background for success in a serious step into the 4th industrial revolution. Authors shortly specify the basic activities in the very up-to-date production in the I4.0 fashion. Next, they explain, in more detail, the basic principle of totally decentralized control fashion, due to high intelligent components of the I4.0 production, hence the I4.0 components. For this purpose, the authors concentrate their attention on the Asset Administration Shell (AAS) as the digital twin from the I4.0 point of view. They provide recommendations in the creation of AAS for any production component. All remarks and recommendations are in conformance with the intention and solution of standardization gremium of Europe, the German-based Platform Industrie 4.0 (ZVEI, VDI/VDE, Bitcom), the Alliance Industrie du Futur in France, and the Piano Industria 4.0 in Italy.

Keywords: Asset administration shell, Digital twin, Industry 4.0, Standardization, Virtualization.

1. INTRODUCTION

A launch of the Platform Industrie 4.0 was officially announced at the Hanover Fair 2013. In April 2015, the Plattform Industrie 4.0 was expanded and in 2018, three European countries began to collaborate closely within the manufacturing domain to improve and disseminate the concept, and their efforts yielded the following initiatives: the Alliance Industrie du Futur in France, the German-based Plattform Industrie 4.0, and the Piano Industria 4.0 in Italy (Plattform Industrie 4.0, 2018). The authors of this paper guess, it is an appropriate time to provide an evaluation of the process by means of comparing initial ideas, technology, standards with the state of the art at the beginning of 2022 year. Let us, therefore, remember a definition of what Industry 4.0 I4.0) should be.

The 4th industrial revolution (Industry 4.0) is characterized by the introduction of information and communication technologies (ICT), which are becoming a growing phenomenon in industrial automation. In these distributed, intelligent systems, the physical components of production and their virtual, data-based components of production remain cyber-physical systems (CPS). These CPS, which are interconnected in terms of information, provide the smart components of future smart factories, in which the production departments can organize themselves and become independent and fully competent, as they will have all the necessary information that they can obtain independently. Such systems can be reconfigured and optimized themselves and will be expandable (plug and produce) without engineering or manual intervention from the outside (Ye, X., 2021). Digitized data on the production of the entire production process and throughout the life cycles of products and other production components are also processed behind the actual industrial production process. Because they will be interconnected, these smart components and products can include a very broad IoT conversation, corresponding to internal and external events with the ability to learn from them, with the resulting benefits for both manufacturers and consumers (OPC UA, 2019).

Production lines will include smart production components that will increase production efficiency, for example, smart jackets (Marcon, 2019), drones (Janousek, 2019), as well as predictive maintenance (Krupa, 2019), and other (Slanina, 2022).

The definition goes up from positives the all existing production process, characterized by relatively high developed control, systems, actuators, sensors, industrial communication, highly widespread use of the internet (Bradac, 2019). But it remembers and takes into account also existing lags, disadvantages, problems of the state of the art of production

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and its technologies and principles, organization of work, existing business models, procedures, and results (Arm, 2018 and Nucera, 2021). The idea of the necessity to provide one great step from a centralized kind of production control towards a highly decentralized one was evoked by the already high degree of digitization, coming evolutionary. Digitization of processes, control systems, field instrumentation, communication electronic embedded devices, microtools embedded everywhere (Esposito, 2021, Slanina, 2021 and Marcon, 2017). This state of the art brings an opportunity and a promising challenge to make production more flexible, intelligent, individualized on-demand of customers, as an appropriate response to lack in production, failures of control, problems in logistics, and other production and marketing troubles. It was identified as an opportunity to make products and all the process infrastructure more intelligent along the all value chain during the all-live cycle of its products (Plattform Industrie 4.0, 2018).

Nevertheless, this challenge brings problems that have to be overcome. Already from the beginning, it was clear, that the only way how to provide the new king of production is in consideration, specification, and realization appropriate technologies, procedures, and methods in its complexity needs:

- a high degree of digitization of production,
- highly used common communication via the Internet of Things,
- Specification and implementation of new control architecture of factories of the future,
- implementation and utilization of AI principles and procedures,
- implementation of security principles and procedures,
- cooperation of standardization grémias of high developed industries all over the World.

As the red thread in the development and implementation of I4.0 technologies and procedures has to be the categorical imperative on standardization of all steps, levels, methods, interfaces, protocols, architectures.

It was also clear from the beginning, that even the stress on standardization, their rapid development, submission by ISA, IEC EU, and other international and national standardization institutions and their evaluation will collide with national, and branch-specific interests.

On the other hand, authors are persuaded, that their role in I4.0 future success is not only in development, implementation of testbeds, systems, and methods from the technical point of view, but even in presentation, popularization, education, training, and implementation of Industry 4.0 and associated standards inside the automatic control community.

Therefore, our conference contribution concentrates the attention on the most key item of the I4.0 system – the electronic rucksack - the digital shall, the Asset Administration Shell (Plattform Industrie 4.0, 2018).

2. STATE OF THE ART OF I4.0 ACTIVITIES

2.1 The role of Artificial Intelligence

Based on the available computing power in the form of server platforms and the large amount of data that can be obtained about the product, the approaches used in data science have penetrated into the field of industrial production management. The task is to automate decision-making processes (production planning, warehouse planning) and to optimize production efficiency based on experience (production data). Currently, the deployed algorithms play the role of a support system that will make it easier for a person to make decisions, but with increasing reliability, the number of deployments will increase, when AI technology will manage the process in real time and one will rather play the role of supervisor.

2.2 Digital twin/AAS

Digital twin, or Asset Administration Shell (AAS) is standardized digital representation of the asset, corner stone of the interoperability between the applications managing the manufacturing systems. It identifies the Administration Shell and the assets represented by it, holds digital models of various aspects (submodels) and describes technical functionality exposed by the Administration Shell or respective assets. AAS can be a file, a server with an interface or a partner in a distributed application (Industrie 4.0 Plattform, 2018 and Ye, 2021).

2.3 Digitalization

Digitization of signals from processes, machines, production lines, any kind of production documentation, and other information sources all of the human society is no phenomenon stemming from I4.0. It is being provided for more years, but non-systematically. However, since the I4.0 age, digitization is being done systematically and in a much larger area. A systematically provided data acquisition procedure is the clue key for the next phases of the I4.0 production. Digitization has been accelerated during the I4.0 age dramatically.

2.4 Decentralization

The goals, technologies, methods such as completely distributed control systems of factories of the future which have been specified in the initial ideas of the 4th industrial revolution evoke a new control architecture. The development of the architecture is shown and specified at the end of this chapter.

2.5 Standardization

It has been already said in the first paragraph of this paper that all aspects and steps of I4.0 implementations fully depend on acceptance, support, and utilization of standards. Any other solutions, such as proprietary and/or non – standardized unique solutions lead outside the I4.0 ideas. Only a fully compatible protocol, interfaces, data formats in interconnection components of the I4.0 implementation, towards factories of the future will be successful in the world market competition.

2.6 I4.0 Component

It is a key item of all I4.0 ideas. It is a very self-dependent component of the all production value chain. The I4.0 component is an asset and an associated electronic shell, e.g. an AAS. There is a comprehensive specification of an I4.0 component in chapter 3.

2.7 Open communication

One of the pillars of the I4.0 concept is standardization. Therefore, the establishment of a single communication protocol is inevitable. OPC Unified Architecture (OPC UA) is currently used as one of the unwritten standards for communication. This technology was originally intended only for communication over classic Ethernet, but currently the OPC UA Foundation is working on extensions for Fieldbus, Device bus, and even TSN interfaces. According to platform I4.0 the AAS server can also be connected via representational state transfer REST, message queuing telemetry transport MQTT, and OPC UA protocols and secure data access is guaranteed (Ye, 2021). Naturally, the basic background of I4.0 communication creates the Internet of Things (IoT) and the Industrial Internet of thing (IIoT).

2.8 OPC UA

In terms of communication between devices, OPC UA provides a server architecture with a hierarchical (tree) structure of the address space. According to the IEC 62541 standard, OPC UA also allows publisher-subscriber communication, notifying changes in variable values and performing predefined methods on the server.

OPC UA technology stores and presents data in a key-value pair. It also allows you to organize the data hierarchically into a tree structure called nodes. A node can be a variable, a method, an object, or an object type, a reference, a data type, and a variable type. The address space defined in this way makes it possible to model an asset (physical or software component), i.e. to create its digital representation. This technology is used in the definition of AAS as a tool for virtualization of the asset.

2.9 AutomationML

AutomationML (IEC 62714 standard) defines an object-oriented modeling language using Extensible Markup Language (XML) technology. It is basically a grouping of existing standards for product description from design to sale: CAEX according to IEC 62424, COLLADA and PLCopen. The aim of this standard is to connect modern tools in different domains (mechanical engineering, electrical design, PLC control).

2.10 TSN

Time-sensitive networks are becoming a general communication tool for communication in the I4.0 environment. They have to fulfill real-time requirements on the larger process area than do those industrial Ethernet standards (IE) such as Profinet, PowerLink, Ethernet/IP, EtherCAT, and other IEC 61588 standards for real-time communication among control systems, operator level, sensors, and actuators in the industrial automation systems. Close cooperation of IEC 61588 standards and development of the standardization process of TSNs has been realized during the 7 years history of I4.0. The reason for the TSN topic stems from the importance of real-time topics in the I4.0 production which differs from the existing industrial communication networks in the huge amount of links, entities, data, conditions, distances, heterogeneity of components, and business models in smart factories of the future.

2.11 I4.0 language

According to Plattform Industrie 4.0, 2018, communication between I4.0 components is to be ensured by exchanging I4.0 messages. Industry 4.0 language is described in detail in Belyaev, 2019 and Plattform Industrie 4.0, April 2018. The structure of the message is defined consistent with the meta model of the asset administration shell in VDI/VDE 2193-1.

The bidding process is defined as an example of a semantic protocol in VDI/VDE 2193-2.

2.12 Interoperability

Interoperability is a feature of different subsystems with different features to interact together. In the I4.0 production, the interoperability is insured by standardization, digitization of information, horizontal integration (new control architecture), I4.0 communication.

2.13 Virtualization

The use of modern software for graphics and computing operations is another of the basic aspects of I4.0. The main impact of virtualization is to reduce product development time and significantly reduce the propagation of design errors. Another important function is the documentation and presentation of data. An example of a virtual model of an I4.0 education production line is given in Chapter 4.

2.14 Virtual reality

Based on the availability of computing power, software simulating virtual reality is created. The basis of these programs is a 3D scene in which the monitored component or production line is located, and a computing core that detects collisions and ensures the most accurate behavior of components according to the laws of physics. Such software includes, for example, Tecnomatix Process Simulate (Siemens), Mechatronic Concept Designer (Siemens), RobotStudio (ABB), or Dynamic Digital Twin (Rockwell).

2.15 Security

State which in the technical context covers among other items functional safety, reliability and IT security. The connection of operational technologies (OT) to the Internet increases the risk of cyber attacks. Nowadays, companies face attacks from the inside rather than attacks from the outside, because they are already equipped with a firewall and even systems that monitor network activity. In addition, some OT components, such as PLC and robot controllers, already contain basic security features such as authentication, encrypted transmission, and program modification security. Unfortunately, the infrastructure is often outdated and Fieldbuses are still used, which do not yet contain this security. With the advent of I4.0, the requirements for new equipment increase, as evidenced by the OPC UA standard, resp. its part describing the secure channel based on X509.3 certificates.

2.16 New control architecture

I4.0 requires demands intelligence and adaptability of individual components. In the classic automation pyramid, data, services and functionalities are relatively rigidly hierarchical. The vision of I4.0 requires a high degree of flexibility with regard to the cooperation possibilities across all participating asset classes. Therefore, a gradual dissolution of the classical automation pyramid towards a distributed, decentrally organized network of service system participants can be expected, see Fig. 1.

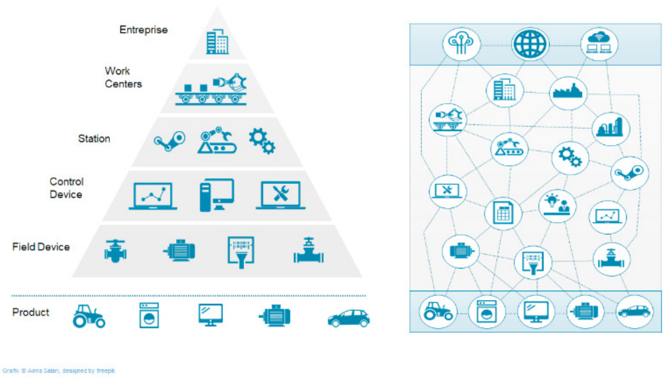

Figure 1. From the automation pyramid to a distributed, decentrally organised network (© Plattform I4.0; Anna Salari).

2.17 New business model

I4.0 contributes to the possibilities for creating of new business models (Nguyen, 2022) or IOTA Foundation (worldwide one of the leading institute for Distributed Ledger ("Block chain") research).

3. AN ASSET ADMINISTRATION SHELL

An AAS is the crusial item of the I4.0 framework.

3.1 AAS, alias Digital Twin by the Industry 4.0 Ideas.

It is well known, that there are two principal models, describing I4.0 idea. The first one is a very general RAMI 4.0 model, which mapped I4.0 components, products, services, others into the 3D space. This model enables to specify standards, already existing, but also in preparation of working groups of ZVEI, VDMA from Germany, Alliance Industrie du Future in France, Plattform Industrie 4.0 in Germany, and Piano Industria 4.0 in Italy. The second very important model for purposes of Industry 4.0 that has been developed by Bitcom, VDMA, and ZVEI and accepted and supported by the above-mentioned standardization organizations during the last years is the I4.0 components model. It is the first specific model which goes out from the RAMI 4.0 model. It enables a better description of cyber-physical features and enables a description of communication among virtual and cyber-physical objects and processes. But not only that, the HW and SW components of future production will be able to fulfill requested tasks using implemented features specified in the I4.0 components model. The most important feature is the communication ability among the virtual objects and processes with real objects and processes of production while this model specifies the conform communication. Physical realization of it is that any component of the I4.0 system takes an electronic container (shell) of secured data during the all life cycle. The data are available to all entities of the technical–production chain.

The I4.0 component is the combination of the asset and its logical representation, the Administration Shell.

The Administration Shell is the standardized digital representation of the asset, cornerstone of the interoperability between the applications managing the manufacturing systems. The Administration Shell may be the logical representation of a simple component, a machine, or a plant at any level of the equipment hierarchy.

From the manufacturer's point of view, the asset is a product. The manufacturer manages different types that have a history with different versions. In parallel, he produces instances of these different types and versions. The manufacturer provides the standardized digital representation to its customers, creating both an AAS for the asset type and asset instance. The system designers, the asset users, the applications, the processes and the asset itself update the information of the AAS during the life of the asset until its disposal (Plattform Industrie 4.0, 2020).

The Administration Shell needs a unique identifier, as well as the asset being described, see Fig. 2.

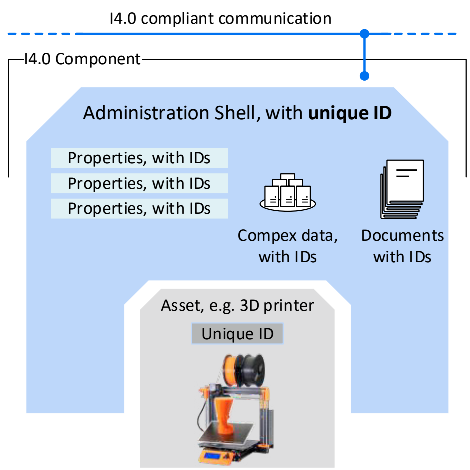

Figure 2. Administration shell of an asset.

Submodels represent different aspects of an asset. Possible aspects and therefore a possible submodel could be Identification, Communication, Engineering, Configuration, Safety, Security, Lifecycle status, Energy Efficiency, Condition Monitoring, etc.

Each submodel contains a structured quantity of properties that can refer to data and functions. Properties can be specified by the standard IEC 61360, but data and functions can be specified in various formats (Plattform Industrie 4.0, 2020).

3.1 How to create an AAS

To be I4.0 compatible, authors are fully persuaded, any design and creation of an AAS must fulfill requirements, specified in publications Plattform Industrie 4.0, 2016, 2018 and 2020. Here is a manual on how to create an AAS of any I4.0 component. It is possible, of cause, don't accept the following requests on the AAS structure and contents and create an individual own digital twin. This way follows many manufactures, big companies, and others. It stems from a lack of understanding of the I4.0 ideas. The standardization of procedures, interface, models others is not only highly recommended, but it is a necessity. The system from Platform I 4.0 ZVEI, VDMA from Germany, Alliance Industrie du Future in France, and Piano Industria 4.0 in Italy is worked out by several high qualified international boards with specialists from research, development, industry, academia and it is accepted also on the World stage. Any testbed and attempt to create its I4.0 application without knowledge and experience in the mainstream, represented above-mentioned organization will be o way far from the 4th industrial revolution. Now and here is the most promising opportunity to move the development of technology and associated economic, business, social movements ahead. Who doesn't accept this, will not be able to concurrency in very near future.

The necessity for all producers, system integrators, designers is to follow specification of AAS, accepting all 22 requirements, which stem from I4.0 European platforms (Plattform Industrie 4.0, 2020).

Plattform Industrie 4.0 has specified a package file format, AASX, based on the open packaging conventions for representing an AAS (Plattform Industrie 4.0, 2020 and GitHub, 2020).

For related implementations of AAS can be used:

- BaSyx - provides various modules to cover a broad scope of Industrie 4.0 (including AAS). Hence its substantially more complex architecture.
- PyI40AAS - is a Python module for manipulating and validating AAS.
- SAP AAS Service - provides a system based on Docker images implementing the RAMI 4.0 reference architecture (including AAS).
- NOVAAS - provides an implementation of the AAS concept by using JavaScript and Low-code development platform (LCDP) Node-Red.
- RACAS Wizard (Arm, 2021).

4. CASE STUDY OF AN INDUSTRY 4.0 TESTBED

This chapter gives an example of a production line from FESTO Didactic GmbH. This line partially meets the requirements of I4.0 production (Festo Didactic, 2018 and 2020).

4.1 CIROS

CIROS is an industry-tested, powerful development studio that can not only draw 3D models from simple applications to complex automated systems and factories composed of many components but also program and simulate these models. After modeling the model, it can be moved using a PLC, either in virtual form or physical. Compatible software such as Siemens STEP7, PLCSIM, PLCSIM Advanced, or via OPC UA or EzOPC with other OPC interfaces such as CoDeSys can be used. In addition to PLC, the model can use more than 1000 robot models from the world's leading manufacturers of industrial robots such as ABB, Denso, Fanuc, KUKA, Mitsubishi, etc. Through CIROS, the robot program can be used in simulation or loaded directly into a physical robot. The CIROS environment enables the programming of these robots in the languages Industrial Robot Language (IRL), Melfa Basic V, Robot Language (KRL), and Rapid. Environment Models in CIROS can be used as digital twins and connected to the Manufacturing Execution System MES4 for teaching factories such as CP-LAB or CP-Factory. Festo Didactic, 2018 and 2020).

4.2 Virtual Digital Twin in CIROS environment

It can be said that at the level of the MES system, the model created in the CIROS environment is the digital twin of the real model. If we focus on the form of the digital twin according to the I4.0 standard, it is not a full-fledged digital twin. For example, from the point of view of the impossibility to simulate in CIROS the physical properties of the system of its components or environment. By means of these physical properties is meant, for example, the simulation of gravity or inertia. CIROS is certainly more than suitable for the design and visualization of a system, model or line for the end customer from the point of view of demonstration, including simulation. The great potential of this software lies in the teaching of PLC or robot programming, where this software serves as a gateway to an unlimited number of demonstration systems. This software is also suitable for creating a digital twin robotic cell of any size and developing a river program

Figure 3. A Modele line (Festo Didactic, 2020).

for either a robot or a PLC. CIROS can be connected to a VR headset and see our model in virtual reality.

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5. CONCLUSIONS

The paper presents the results obtained through the authors' evaluation of the development of the standards, procedures, and technologies of I4.0. The first part of the text briefly characterizes the relevant technologies and their respective roles in the seven-year history of Industry 4.0. In the second part, the authors focus on the most principal I4.0 technology, namely, the Asset Administration Shell, the real digital twin of I4.0 components to facilitate production in factories of the future and to ensure the best sources for its development. Another important technology, which has achieved remarkable progress in the recent years, is virtualization. Using a case study, a CP factory education production line, the authors demonstrate an appropriate virtualization engine, this being the CIROS virtualization SW by the FESTO Didactic company. The precondition for a further enhancement of I4.0 rests in implementing practically a research-based, standardized solution of technologies and procedures that will exploit the diverse embodiments of the European Industry 4.0, following the principles of the platforms and standardization organizations Platform Industrie 4.0 (ZVEI, VDI/VDE, Bitcom) in Germany, the Alliance Industrie du Futur in France, and the Piano Industria 4.0 in Italy.

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