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A standardization approach to Virtual Commissioning strategies in complex production environments

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Abstract

The ongoing industrial revolution puts high demands on the component manufacturers and suppliers to meet the tough requirements set by the development industries to follow the technological advancement of highly digitalized factories with more future-oriented applications as Virtual Commissioning for cyber-physical systems. This paper provides a production system lifecycle assessment regarding the technical specification strategies using Virtual Commissioning for implementation and integration of new systems or plants and its predicted future challenges. With the use of standards and a common language practice between a purchaser/contractor procurement situation and across the different technical disciplines internally and externally, the implementation strategies is reiterated to achieve a new sustainable business model. The paper investigates different types of production systems and how a defined classification framework of different levels of Virtual Commissioning can connect the implementation requirements to a desired solution. This strategy includes aspects of standardization, communication, process lifecycle, and predicted cost parameters.

Keywords: standardization; implementation strategies; virtual commissioning; industry 4.0; cyber-physical systems

1. Introduction

When it comes to integration of new technologies, upgrade of an existing production system or an implementation of a whole new system accordance with modern concepts as Industry 4.0, changes can occur in multiple layers within the company [13, 16]. It is not only the technological aspects that needs to be considered since the new industrial revolution can affect both the business model, infrastructure, organization hierarchy, financial cost, system control, IT and production performance in general [20].

For a manufacturing industry upgrade, this transition can be an internal investigation or an in-house project, some parts of the scope can be beneficial to outsourced to some kind of contractor due to time management, financial reasons or lack of knowledge. Some projects can also be integrated in a close collaboration between the company and a contractor.

It is natural that some areas need more time to develop due to relatively major changes or high risks of failure when facing complexity, short time horizon or just an internal struggle to understand what technical solution would best fit the current situation [14].

It is difficult to coordinate a complete transition from a well-established Industry 3.0 situation into the new Industry 4.0 overnight. Some areas adapt faster with simplicity, other areas have a higher priority or could be more cost efficient or just have a greater driving force and support from the management [14, 26].

Areas that, under some circumstances, develop faster at a higher rate risk leaving less developed areas behind, creating a gap both technologically, organizationally and mentally [26].

This gap can cause problems in several aspects and deteriorates the conditions for bridging the internal collaboration between different work disciplines and teams when not operating on the same technical level [14].

This problem occurs to a greater extent in larger companies and not limited to the manufacturing industry where several

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technical fields within the company can be segmented and divided into separated, geographically distinct areas as well on different organizational levels [14].

Taking actions in attempts to even out the differences become more expensive the greater the gap becomes. In some cases, tearing everything down and starting over in a greenfield scenario could become more economically justifiable than to slowly integrate and reform into an existing brownfield scenario that over time might have burst out of proportion to the company's understanding and ability to comprehend the situation [2, 13].

One of many benefits by using virtual preparation and commissioning before implementation and integration of new production system and technologies is the possibility to test and verify solutions virtually in advance to real commissioning [7, 15], resulting in reduced lead time as well as actual commissioning time [19].

The intention of virtual preparation is to detect and prevent technical issues from occurring in a later stage of the installation and can result in improved software quality, making the technological transition easier [18, 21].

Virtual Commissioning (VC) as a concept demands a solid collaboration between each different work discipline for it to be successful [19]. Simulation of movement and sequences together with construction drawings or CAD models in correlation with the control and logic aspect from both high and low order control systems will all be of great importance to the technical solution.

The organizational structure of a VC project may help to prevent the technological gap to keep expanding by improving the internal communication within a company or end user, as in this paper referred to as OEM (original equipment manufacturer) [19].

1.1. Challenges within the industry

There is an increasing customer demand of product variety and quantity in the automotive industry and in the manufacturing industry in general, which correlates to a demand of more flexible production systems to satisfy this need [24].

The ongoing transition of Internet of Things and Industry 4.0 applications creates multiple opportunities as well as challenges for both OEMs, contractors, software providers, research centers and universities around the world to test and overcome the technical obstacles [6].

The increasing complexity within the production process is palpable when several control systems is highly integrated and connected to a virtual cloud using process data to support the innovative functionalities that represent Industry 4.0 [1, 11].

Virtual Commissioning, as one of these beneficial industrial concepts, is used to wider extent to guarantee the behavior digitally of complex systems and has proven to be economically advantageous for the OEM if it is done properly [25].

A common challenge for the industry is dealing with the integration of modern technologies as VC into planned and existing production structures regarding greenfield and brownfield scenarios and needs to be considered during early planning phase in both cases [13, 16].

Due to the high practical and theoretical relevance of digital and interconnected systems, the essential need to understand the multi-dimensional structure and underlying dynamics of the implementation practice and strategy work addresses the importance of standardization in all disciplines and methods relied upon to realize VC [14, 26].

The need for a wider framework to connect all relevant technical standards within each disciplines is necessary, all the way from low control [12] into the OEMs multi-dimensional infrastructure and how it correlates with the business model, finance and technology [28], in order to translate the digital world to the physical plant in addition to how VC can be performed to make that happen [20].

1.2. Motivation

Extensive use of standards for Industry 4.0 has been proven beneficial to improve the technical transition and performance in general [26] and this paper will investigate if a standardization approach can be beneficial for reducing errors in different VC scenarios for complex systems.

Important key aspects for implementation strategies is to understand what is given and to be familiar with the starting position and its limitations. A mutual understanding of the objectives and the desired solution between the OEM and the contractor is vital for the internal collaboration between the technical cross-functional disciplines to be successful since all parties will benefit from sharing a technical language when a technical specification is constructed to be understood and delivered by a contractor.

VC has different advantages depending on the prerequisite regarding both greenfield and brownfield scenarios. The indented lifespan and the level of complexity of the production system will also be of important as for a process industry where changes may not be as frequent as a production line implementation [1]. Optimizing traditional implementation methods will also lead to reduced waste of both time and integrated errors [8].

1.3. Objectives and goals

The objectives for this paper is to define and classify the different level of details when describing Virtual Commissioning with respect to complexity, size, function, dynamic and details.

By being familiar with the determine key factors in a transition scenario, when implementing or integrating modern technologies as VC into an industry and how the different outcome can take form, will be advantageous knowledge to make sure that the technical solution satisfies the requirements set by the OEM.

How a certain starting position and a desired technical solution affect the cost aspect of a planned implementation project between an OEM and contractor is of high interest both in a financial perspective and just for the matter of clearness and reduced risk of misunderstanding when a mutual technical language is established.

1.4. Scope and limitations

This paper will focus on a general approach inspired, tested and evaluated towards a real automotive industry plant. The work is strictly connected to the design and development of production systems using virtual preparation in the form of a technical specification constructed by an OEM as preparation documentation and material for contract signing with a supplier or line builder, referred to as contractor from now on.

Virtual preparation methods shall never contradict standard practice for the actual construction work or physical commissioning and should remain feasible towards the machinery directive, given safety regulation and cybersecurity according to international standards and directives.

Technical realization and modeling of VC is not a part of the concept presented in this paper and will only provide preparational guidelines if a certain application require it.

1.5. Structure of paper

Several definitions of used concepts and supporting notion is presented in Chapter 2 to give understanding to each topic in this paper. Chapter 3 will present the dimensions from a certain starting point to the final end goal followed by a developed framework to classify Virtual Commissioning levels of details in Chapter 4 and how proper discipline and standards correlates with the starting point parameters and estimated cost in Chapter 5.

The resulting formula will cluster and illustrate complex parameters to provide preparatory material for a contract specification to secure the intended technical behavior in a request for quotation between the OEM and a contractor and end with some concluding remarks.

2. Definitions

This section will provide useful knowledge and definitions of certain topics within the field.

2.1. Multidimensional structure of Industry 4.0

Since the fourth industrial revolution, different frameworks has been developed in attempts to illustrate and gather useful data and information of an increasingly complex production environment with a fully connected cyber-physical system [6].

Two of the frameworks is the Reference architectural model Industry 4.0 (RAMI 4.0) [20] and the Industrial Internet Consortium (IIRA) [27] who both make use of existing standards and how the correlations between business model, function of the company, data handling, communication, digitization, hardware and the human relates to one another.

The Internet of Things (IoT) concepts has managed to bridge the world of Operation Technology (OT), concerning the network, communication and control for low and high level logic, with the benefits from the Information Technologies (IT) regarding agility, security, speed, and commercial vision[23].

RAMI 4.0, with its economical perspective, adds several new dimensions to the whole business model by a life cycle value stream through each defined company layers (business, functional, information, communication, integration and asset) from the perspective of different hierarchy levels, stretching from the product itself to the surrounding connected world [20, 28].

By targeting specific areas within these different dimensions, potential improvements can be exploit, especially regarding IoT standards and implementation of VC and to guarantee the behavior digitally to be economically advantageous [25, 26].

2.2. Technical specification

A technical specification in this paper refers to the recipe of information regarding a desired production system or plant with practical instructions developed by an OEM as a part of the procurement process before an order of a new implementation project.

When writing a specification, the OEM decides on which standards the project needs to follow, usually according to guidelines from an international standards organization as the International Organization for Standardization (ISO) or International Electrotechnical Commission (IEC) who is continuously working with development in fields as; cybersecurity, communication in big data environments, product development, systems planning in the Digital Factory, simulation in advance of physical implementation and Virtual Commissioning to name a few [9, 26].

The used standards for procurement documents are collected in what is usually called a ”Request for quotation” (RFQ) and generally means the same thing as Call for bids in a OEM/contractor situation [3].

The structure of a RFQ starts with the technical specification where the objectives and the end goal is defined with supporting information and given standards as appendix, followed by a roll out towards different potential suppliers, followed by a formal acceptance. The OEM and the contractor review the project together, followed by a technical approval before purchasing the order [3].

2.3. Virtual Commissioning and the Digital Twin

Virtual commissioning (VC) is a concept that has been proven to be efficient concerning the modeling, programming, visualization and validation of a production system or process in a virtual environment [1, 4].

VC implementation either starts from a greenfield scenario, when there exist no previous plant or system, or a brownfield scenario when you adopt a solution by integrating it to an existing process to some extent [10]. A greenfield scenario with IIoT (Industrial Internet of Things) project may lead to new results since the latest technology can be validated on a broader scale [17].

Using VC as a preparational step, the implementation progress can create a virtual copy, or a so called Digital Twin

(DT), which can be of further use in parallel to the later running production system regarding testing and improvements which also has been elaborated around a lot since the start of the latest industrial revolution [9, 22].

VC can be adopted and performed in different setup depending on which purpose it should have. It can either be a visual representation of a production system [1], in other cases used together with Virtual Reality hardware to operate and try out safety features [4], or by simulating Human-in-the-Loop behavior for an assembly cell with use of high order control [5].

In this paper, Virtual Commissioning is the implementation strategy to achieve a higher and improved software quality and reduced lead time. By doing VC to its fullest extent regarding control and with the highest level of details both modeled, simulated and tested, it can result as a Digital Twin of the implemented system.

3. Methodology - Know your ground

This section will present the different parameters and factors that have an impact on the technical specification for implementation with Virtual Commissioning as a preparational work to achieve both a general higher software quality towards the Digital Twin and the technical development.

3.1. What do we need? - First dimension

The specification is a vital part of a procurement process and may help a buying OEM to reduce purchasing costs by finding an equilibrium point between the desired outcome, the technical solution and the price tag when negotiating with several suppliers.

The first question to be asked is therefore what the main objectives are. Is it to produce a new product or ramp up the production rate for an existing production line? Does it require just a small pick and place robot, an assembly cell with several parallel operations, a paint process line or maybe a whole new plant? The magnitude and size of the implementation project will most likely affect the technical direction further on.

3.2. What do we want? - Second dimension

The question of what kind of technical solution necessary to carry out the requested task can have different driving forces, nonetheless it is vital for an automotive industry to be able to adapt to the current and future situation and its demands.

To meet and overcome the transition into a smarter, fully connected factory with the already stated benefits, the second question to be asked is how to get a decent solution that will cover both the need and the possibility to adapt with smart functionality to an affordable cost.

3.3. What do we have? - Third dimension

For any planned upgrade or new installment, the OEM will end up in either a greenfield or brownfield scenario, depending on previous production history. In industry terms, a greenfield scenario is when a plant or production system is built from the ground up, and differs from brownfield where the new installation is to some extent integrated with an older system in an existing facility.

Greenfield gives the opportunity to create new rules and set the standards with more freedom compared to brownfield who is more bound to restrictions and will most likely put requirements on backward compatibility.

The two scenarios has different strengths from both an implementation and economical perspective. The main advantages with greenfield can be the time dimension for planning and freedom to create a coherent and modern production environment with a high technical level from start that can be tested without directly interfering with an existing production flow, but it can be a very costly investment and may also be hard to validate due to lack of history and knowledge of a certain system.

The advantages with a brownfield scenario is the knowledge and data from the previous system which can be aligned and verified with more ease. This case can also make use of existing facility and functional surrounding systems, which consequently reduce the cost of investment. The lifespan of the ”new” system is on the other hand a weakness and both quality and function can be hard to guarantee over time. In this case it is also harder to estimate both cost and quality due to extensive dependencies from surrounding systems with a risk of inherit problems and errors from the old version in to the new integrated system.

3.4. Correlations and cost

To put these cases in correlation with the dividing factors from an economical perspective, Table 1 present a developed weight matrix to address which factor has a positive (+) or negative (-) cost impact on either the greenfield (G) or brownfield (B) scenario.

Table 1. Comparison Greenfield/Brownfield.

Category	-/+	Weight	G/B	PRIO
Starting cost	-	θ_1	G	(0-5)
Integration time	-	θ_2	B	(0-5)
Prev. knowledge	+	θ_3	B	(0-5)
Data comparison	+	θ_4	B	(0-5)
Error risk impact	-	θ_5	G	(0-5)
# error risk	-	θ_6	B	(0-5)
Comm. timeframe	+	θ_7	G	(0-5)
Planning timeframe	-	θ_8	G/B	(0-5)
Final tech. quality	+	θ_9	G	(0-5)
Future compatibility	+	θ_{10}	G	(0-5)
Interconnected systems (status)	+	θ_{11}	B	(0-5)
Lifespan/guarantee	+	θ_{12}	G	(0-5)
Energy efficiency	+	θ_{13}	G	(0-5)
CO^2-footprint	-	θ_{14}	G	(0-5)
Material cost	-	θ_{15}	G	(0-5)
Maintenance support	-	θ_{16}	B	(0-5)
Resource allocation	-	θ_{17}	B	(0-5)

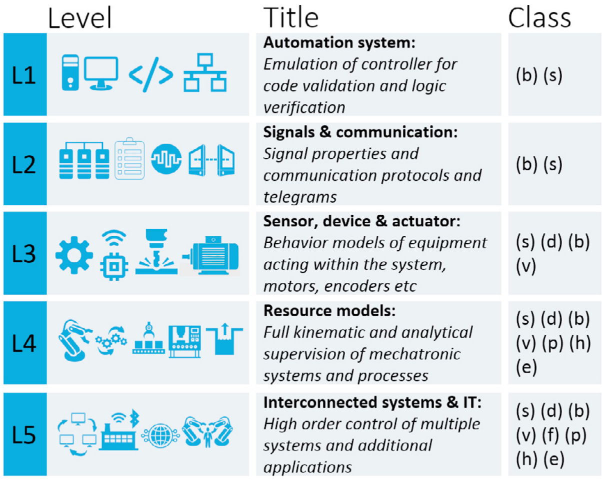

Fig. 1. A framework hierarchy for categorizing different levels of details for Virtual Commissioning implementation with additional classes of functionality for each level.

Table 2. Definition of classes.

Class/domain	ϕ	Description
Black box	b	A unknown input signal or system that affects the system in one or several cases.
Static response	s	Returns a static, time depended or sequenced deterministic behavior from the models to test out system logic.
Dynamic response	d	Returns a dynamic, uncontrollable/sequenced non-/deterministic behavior from an analytical represented models to test out system logic.
Visualization	v	Visual representation of the state/event based simulation of the system logic.
Partial (ϕ)	p	Partial acknowledge if a function or domain only requires to be partially performed.
Human-in-the-Loop	h	Human interaction as an input to the system for control and supervision.
Educational tool	e	Educational tool label the system as a package for educational purposes of technicians etc.
Flow simulation	f	Flow simulation of the a two or several interconnected system from a plant simulation perspective with high order control.

Time is an important factor when it comes to cost, more knowledge is key and preparation work is crucial for a smooth and successful installation. The matrix in Table 1 will therefore be used for estimating the weight (θ_k) of each category according to given circumstances and give a specific category a priority to get an indication of which scenario has the better financial outcome.

Regarding a sustainable lifecycle of a production process, even if a greenfield scenario seems to be more costly; better software and hardware quality, higher lifespan, energy efficiency and a reduced environmental impact in the long run can save money which can be indicated by the matrix in Table 1 by adding proper weight and priority to right parameters.

4. Levels of details for Virtual Commissioning

By understanding the preconditions for technological advancement in Chapter 3, this section will describe how a framework can by utilized for categorizing the different levels of details in virtual preparation work, starting from the low order control and logic up to high order control with a fully dynamic representation of the desired production system or plant.

4.1. The Virtual Commissioning framework

A constructed classification hierarchy for VC is illustrated in Figure 1 and presents five levels of details and each levels' corresponding class that can provide certain functionality or direction for given level.

Table 2 lists all the classes in the Virtual Commissioning framework in Figure 1 with its given definition explaining how it can add functionality to applied level, following subsections will describe each different level with examples and how they can differ from each other.

4.1.1. Level 1 - Automation system

The first level of VC focus on the emulation of the actual controller or PLC for a mechatronic system. A production system require logic to operate and underlying code to translate binary digits into sequences and intelligence.

This preparational work is normally performed by an offline programmer or software engineer and make use of the control system's type-specific software (TIA Portal for a Siemens PLC etc.). The software enables code to be constructed and validated internally in advance before the physical commissioning.

If the controller need to handle external input from another system, the framework assigns the level with a (**b**) for black box. If the developed logic requires signal response which normally is excluded from the code, the framework assigns the level a (**s**) for static response.

Today, this level is standard practice for line builders.

4.1.2. Level 2 - Signal and communication protocols

The second level of VC focus on the signal properties and communication standard and telegram. The extension from Level 1 is the hardware which will be used by the controller and how the properties of each signal is defined and addressed through the fieldbus or network connection (Profibus, Profinet, OPC UA etc.).

This work is normally performed as a SIL or HIL (Software/ or Hardware-in-the-Loop) configuration setup to try out the performance of the logic. If the hardware need to handle external input from another system, the framework assigns the level with a (**b**) for black box similar to Level 1.

If any signal properties or communication protocols requires a interface for testing and verification, the framework assigns the level a (**s**) for static response.

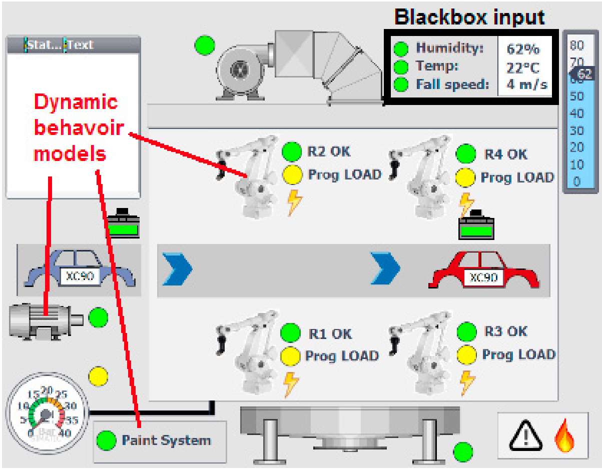

Fig. 2. Example of a paint booth system [1] with a VCL3bdv classification. The example simulates dynamic properties of the models running in the back_end and visualize relevant data of the process in real time with the addition of black box input from an interconnected air supply unit.

4.1.3. Level 3 - Sensor, device and actuator

The third level of VC focus on the different sensors and devices that is connected through the hardware in Level 2 and operates with the output generated from the controller and returns the input to the same system.

This level is the first step to use an additional simulation software to simulate the behavior from the different actuators, connected to the controller software or signal interface.

Similar to previous levels, both black box and static response can be added for testing and validation. This level introduce the addition of dynamic response (**d**), where the behavior of each device has a fully analytical representation which aims to return an authentic reply to the system for more accurate verification of the code.

This level also has the class called Visualization (**v**), which extends the simulation with an additional understanding of visual representation of the static or dynamic models within the system.

Figure 2 shows an example from [1], given the class VCL3bdv. VCL3 stands for Virtual Commissioning Level 3, with both black box input from an air supply unit, dynamic response from simulation of each behavior model and visualization for better understanding.

4.1.4. Level 4 - Resource modeling of systems

The fourth level of VC introduce the kinematic dimension to the simulated system, demanding extensive analytical understanding of each component and the construction aspect connecting all services in one system.

This level requires computational power and recommends a computer with suitable software to satisfy the level of details to make a smooth running virtual process.

Similar to previous levels regarding black box and static response, dynamic response will now include kinematic relation-

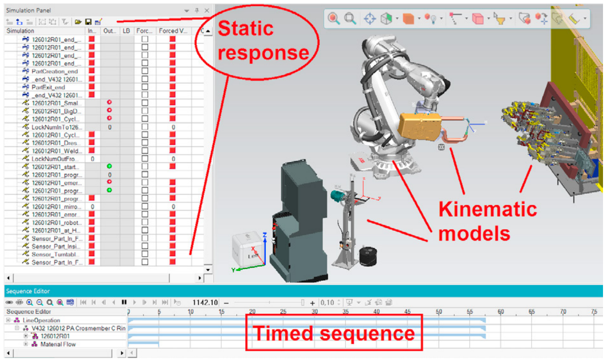

Fig. 3. Example of a VCL4s(pv) system partially visualized and modelled with a timed sequence in Process Simulate with a static control interface.

ship and geographical placement to provide correct response to the control system.

This level also has Visualization, now with more emphasis on the kinematic movement and the interfering regions between each model. But a complete and fully accurate model can be very demanding and complex to modeling or in some case not even feasible or realistic. That is why the assignment of Partial (**p**) is introduced to address that only some part will be visualized. Partial can also be used in combination with (**s**) and (**d**) to limit the scope of simulation.

Figure 3 shows an example of a spot welding robot, classified as VCL4s(pv), meaning Virtual Commissioning Level 4, with static response through built-in user interface and partial visualized to just focus around the robot and its application.

4.1.5. Level 5 - Several connected systems

The fifth and final level of VC expand the concept of Level 4 by adding another system to the setup for further testing between connected system with the use of higher order control, if used by the OEM. This level could be described as a fully Digital Twin or a segment of the virtual smart factory.

This level connects the system on an IT level to try out external system application with a realistic behavior. The level requires computational power but can be distributed by the use of the industrial network connecting each model. Flow simulation (**f**) is beneficial at this level due to the data access of each system.

This level introduce Human-in-the-Loop behavior (**h**) for simulation with the input from a human operator to control or test functionality and safety features. An educational tool (**e**) can be provided to make use of the constructed virtual platform to educate and provide knowledge to any person of interest.

Similar to previous levels regarding black box, static or dynamic response and visualization with partial option applies.

4.2. Virtual verification

When a certain level and classification is assigned to a desired system, it can more easily be addressed or packages with the relevant and necessary standard for each area. By connecting a standard, it is possible to create another helpful tool called

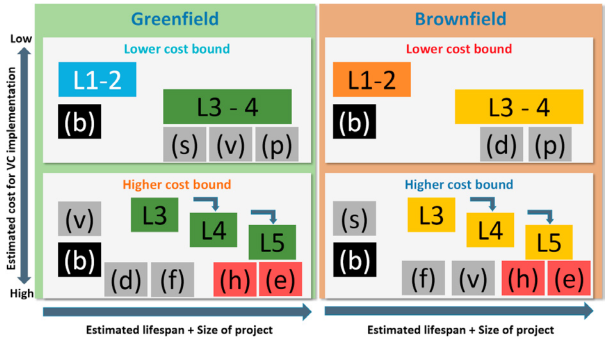

Fig. 4. A chart presenting a greenfield and brownfield scenario showing a indication where each VC level and classification are addressed in correlation to cost investment for the solution regarding magnitude and intended lifespan of the system.

”Virtual Functional Acceptance Testing” (VFAT), used for verification to hand over to the contractor in the procurement phase.

A VFAT-checklist can be constructed to verify that each standard is met in the developed virtual system at every level accordingly. Similar checklist is normally used before real commissioning.

5. Result

A relationship between the wanted end result, start position and its predicted cost can be illustrated by merging the outcome if using Table 1 to both understand the industrial situation together with the defined Virtual Commissioning levels describing the desired technical solution in Figure 1.

A chart of where the technical Virtual Commissioning levels likely correspond to the estimated cost factor for a implementation project depending on magnitude and lifespan is shown in Figure 4, both for a greenfield scenario and a brownfield scenario accordingly.

The chart is divided into four regions, two for each scenario and are distinguished by a lower and a higher cost investment estimation. One region illustrates if a level and class has a significant impact on the cost factor for a final solution, with the dimension of size of the project.

By using Table 1 for a greenfield scenario, it could be concluded that a higher level of VC would be more beneficial due to the high cost for construction work which can be adapted into Level 4 and 5 for visualization.

Since technology can be decided freely, it would be wasteful not to add these features since a greenfield project most likely will have a longer lifespan and the acquired technology can be used for later upgrades as well, resulting in an even better future brownfield start position.

For smaller implementations or upgrades in a brownfield scenario, the same level of technology would be exponentially more expensive since models will need to be re-engineered as well as the surrounding systems just to make a smaller installment to operate properly.

The lifespan of the brownfield system is not guaranteed to be as high and therefore speaks in favor for a lower level of VC and save the energy and money until the demand for a bigger brownfield scenario is required.

An extensive and successful integration of modern technology using Virtual Commissioning in either a greenfield or brownfield scenarios will make a big impact on the future second iteration of the same system, resulting in a brownfield case with a long established system knowledge history, providing suitable and relevant information to its next upgrade.

6. Conclusion

As stated in [26], standardization is a key factor for Industry 4.0 applications regarding the complexity of having several interconnected systems working efficiently together and embedded in the business model to enable cross functional teamwork and understanding within an OEM in accordance with the reference architectures RAMI 4.0 and IIRA.

The same principles applies to the realization and development of Virtual Commissioning preparation strategies to improve the communication between the OT and IT world and at the same time count for how all correlated parameters can affect the complete VC concept and how it would fit into the general business model including the relationship between developer/user, supplier/customer, management/production and industry/society.

Regarding VC, it is therefore of importance for this development to aim for the same speed as the technical evolution. By approaching the technical implementation with the use of standardized frameworks and methods and to include it in the earliest phase, it may be possible to become more efficient and save money along the way.

A technical specification methodology for a highly integrated and technical complex virtual tool such as VC, the concept based on Industry 4.0 standards could prevent each supplier from using their own standards which normally add to even slower adaptation and integration with new technology within a bigger OEM.

A method like the one described in this paper must be financially justifiable for the stakeholders, management, software supplier and line builder and not only by estimated weights and priorities. Therefore, further research could keep investigating the impact of correlating factors in similar circumstances by using the same approach to analyze its efficiency in a longer study for an ongoing integration project with full supervision.

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