Virtual Commissioning for Scalable Production Systems in the Automotive Industry

Model for evaluating benefit and effort of virtual commissioning

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***Abstract*—An uncertain market demand for electrified vehicles leads to the establishment of scalable production systems. Their capacity can be extended step by step depending on the market development. A challenging aspect within this environment is the re-ramp-up of the production system after the implementation or adaption of production facilities. This paper demonstrates how virtual commissioning can be used to shorten and improve the commissioning phase of new production facilities and thereby ensure the re-ramp-up of production systems in time. Despite high cost and time saving potential, the development of a virtual model and the commissioning in the simulation environment causes a lot of effort. The paper identifies basic requirements as well as other factors of influence on virtual commissioning and provides an evaluation model which can be used by production engineers. The focus is to identify projects with a high potential and support the decision for or against using virtual commissioning within the expansion of a scalable production system.**

Keywords-scalable production systems; virtual commissioning; electrified engines; digital factory

I. INTRODUCTION

Scalable production systems play an important role in the environment of electric drive systems. They enable adaptions of the production capacity according to the volatile market progress. Thereby high investments can be avoided and the line capacity can be expanded step by step due to the demand development of electric machines [1]. For the implementation of each step the existing production has to be interrupted. Changes at existing production units are required and new facilities have to be added and integrated. Thereby challenges due to limited commissioning periods, missing holistic function tests and trainings arise.

Despite the forecast of high volumes of electric vehicles, there is a simultaneous uncertainty regarding the actual demand [2]. Scalable production systems allow a minimum initial investment with the option for higher yields with corresponding market demand. The risk of installing too high line capacities is consequently reduced without jeopardizing being unable to meet increasing customer demand.

Despite the mentioned advantages scalable production systems involve challenges especially during the expansion phases between each step. The necessary production interruption for the integration of new facilities means a high importance of a smooth re-ramp-up. [3] A method to reduce problems during the ramp-up is virtual commissioning. A virtual model of production facilities is prepared with the objective of validating control code in a simulation environment. [4] This paper focuses on factors influencing project-specific benefit and effort of virtual commissioning and provides a model to support the decision for or against the use of virtual commissioning in re-ramp-up phases.

II. STATE OF RESEARCH

The paper considers two different areas of research. Firstly, the term scalable production system is introduced and explained. Secondly, virtual commissioning as an instrument to validate control technology and thereby improve software quality without the need of the real production equipment is outlined.

A. Scalable Production Systems

The paper focuses on scalable production systems which are characterized by technical, spatial and personal extensibility and reducibility of factory modules [5]. Investments are kept low in the beginning and the production system is expanded step by step depending on demand development. The development of the production capacity is showed exemplary in Figure 1. To fulfill future demands required production units are determined. Depending on the forecast, the next expansion level of the production system is planned. After the exact expansion volume has been identified, suppliers are selected and orders are placed. The facilities are developed, designed, produced and commissioned. Subsequently the ramp-up the production is turned into serial operation [6].

To prepare the production system for the next expansion level the interruption of the existing production is needed. Then new production facilities can be integrated and necessary changes can be made [7].

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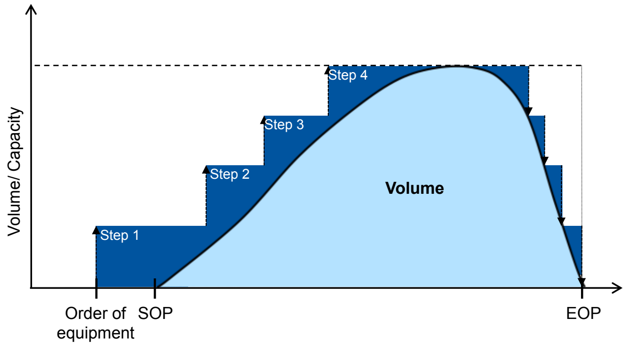

Figure 1. Scalable Production System [2]

B. *Virtual Commissioning*

Virtual commissioning is an instrument that can be used during the construction or conversion of production plants to validate the interaction of electrical and mechanical systems and software at an early stage. Process sequences are simulated by generating a virtual model of the production system and connecting it to the corresponding control technology [8]. Thereby errors can be identified. Ideally, the quality of the control software can be improved by appropriate optimization measures even before the real plant components are ready for operation. It is also expected that the time required for commissioning of the real production system will be shortened [9]. A study showed that a reduction of 75% of the commissioning time and an increased software quality is possible. In this examination 84% of control functions were already correctly implemented at the start of real commissioning [10].

In a conventional plant development process, the production and assembly of facilities is carried out after completion of the design. Afterwards the commissioning of the plant begins. The development of the necessary control software starts as soon as the construction is finished and will be finalized during commissioning. A large part of the development steps takes place parallel to the production of the system. However, certain stages can only be tested once the mechanical, electrical and fluid engineering components of the system have been installed. All errors and difficulties that occur afterwards must be rectified at great expense and cause considerable delays [11].

There are two different approaches to validate control technology with the help of a virtual model. For Software-in-the-Loop simulations the virtual model is connected to an emulation of the control software. Hardware-in-the-Loop in turn describes the coupling of real control technology with a digital model of the plant to perform various tests [12]. The paper will focus on the use of real controllers because different scenarios can be tested close to reality. Another advantage is that the same control soft- and hardware can be used for testing as well as for the integration into the real production facilities and no additional effort is generated.

III. Virtual Commissioning in Scalable Production Systems

To develop an evaluation model, expected benefits of virtual commissioning will be identified first. In the following, the challenging environment of scalable production systems is introduced, focusing on re-ramp-up phase and handling of new technologies. Subsequently, the potential of virtual commissioning in this environment is derived.

A. *Challenges in the Re-ramp-up of Scalable Production Systems*

Expanding the capacity of the production system means integrating new production facilities or modifying existing ones. The resulting re-ramp-up is characterized by some special conditions which cause various challenges outlined by production experts. These can be divided into two categories, scalable production systems and new technologies, as shown in Figure 2.

Challenges caused by	
Scalable production systems	**New technologies**
Short conversion periods	Lack of experience
Problems of compatibility	Complex processes
Missing pre-inspections	Unknown mistakes
Necessary production interruption	Difficulties with suppliers
Missing trainings	Short-term adaptions
High impact of interruptions on overall system	

Figure 2. Challenges of Scalable Production System

On the one hand, the fact that the production system is established in several stages results in difficulties. On the other hand, the lack of experience with the production of electric machines causes problems.

Since no production capacities are available during the interruption and only a limited quantity can be pre-produced, the conversion and setup should be carried out as quickly as possible. The conversion and commissioning period is therefore short and delays should be avoided. The overall functionality can only be checked after integration into the actual system. However, since interfaces and bondings are very complex, some problems can occur during commissioning, which can lead to delays. There is no pre-inspection by the suppliers involved in the production system. Although they are responsible for the functionality of their systems, verifying the processes before they are set up and integrated into the existing system is not possible. There is a risk that even major problems will not be identified until the system is set up [13].

In addition compatibility problems can occur during the integration of the control technology. In particular, the design of interfaces between system components from different suppliers is usually very complex and requires a lot of coordination. In most cases, after the mechanical structure has been completed, a few adjustments must be made to the software until the communication is error-free. Another aspect that complicates a smooth ramp-up of the converted production system is the lack of training time for operators and maintenance staff of the machines. They cannot familiarize themselves with new activities in advance, as the system is available after integration into the existing part.

The main problem is that those various risks mentioned may lead to delays in the integration of individual expansion stages into the production system. Since the entire system is stopped during conversion and commissioning, any delay has a direct effect on the number of units produced [14]. In order to produce an electric motor with the required performance, complex production processes are necessary and the automotive industry is still working extensively on the optimization. The suppliers of the systems also have little experience with the processes required to manufacture an electric motor. Some of them are developing and producing systems with corresponding functions for the first time. Some inconsistencies may occur, which cannot all be identified in advance.

Commissioning is therefore a decisive phase in ensuring the functionality of the production system. Since only in the first development stage pre-inspections can be carried out, there is a high risk of problems arising in the commissioning phase during further expansions. Due to the necessity of production interruption, any delay has a direct effect on the number of produced units and thus on the success of the company. Small residues may still be absorbed by buffers, but a comprehensive pre-production is not possible due to the constantly high utilization of the system. This shows a high importance of the commissioning phase, during which the functionality is ensured and the basis for a smooth ramp-up to reach the target quantity is laid [15].

B. *Potential of Virtual Commissioning in Scalable Production Systems*

Virtual commissioning as a method that promises a reduction in development and commissioning times and an increase in production efficiency has a high potential in the expansion of scalable production systems. Since topics such as missing tests, short commissioning times, compatibility problems with control components and a lack of experience play a role, virtual commissioning is a suitable instrument for optimizing ramp-ups. As seen on Figure 3 virtual commissioning including modeling, implementation and evaluation can lead to a reduction in commissioning time.

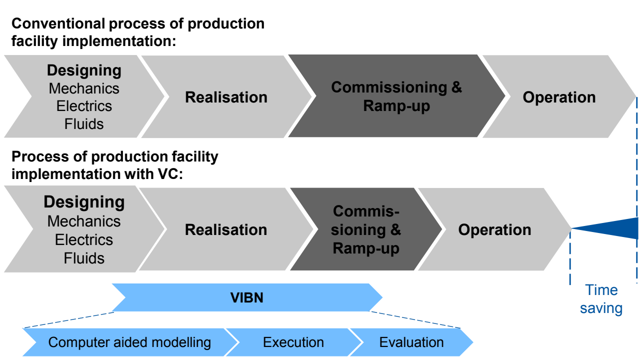

Figure 3. Process with virtual commissioning

The implementation of production facilities into a production system normally includes design, realization, commissioning and ramp-up and at least operation. Virtual commissioning is an additional process which is conducted parallel to the realization. It starts when design and control data is available and runs into the real commissioning period. When the potential which will be justified afterwards can be realized, commissioning time and maybe also overall integration time can be reduced.

To identify advantages of virtual commissioning in scalable production systems specialists engaged in virtual commissioning have been questioned. The results are displayed in Figure 4.

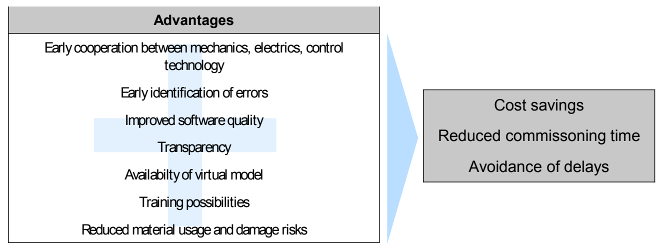

Figure 4. Advantages of virtual commissioning

Main potential of virtual commissioning in scalable production systems is related to the validation of control technology at an early stage. Errors which can be identified and solved early lead to a higher software quality and save time during real commissioning. As the commissioning period is time- and cost-extensive the avoidance of delays is important. Lower error rates can also be achieved because virtual commissioning leads to a better cooperation between development teams. Development results are shared and clear agreements are reached and considered. Thereby misunderstandings causing problems during the integration of facilities can be avoided. The availability of a virtual model offers also other potentials as different test scenarios can be realized at the same time and even when hardware components are missing. Additionally, no material has to be spend and the risk of damages is eliminated. A virtual model also gives the opportunity to train workers and get early feedback from production staff about the operation of the machines. If those advantages can be realized a project benefits highly from the use of virtual commissioning.

IV. Evaluation Model for the Use of Virtual Commissioning in Scalable Production Systems

This chapter describes the structure and application of the evaluation model. Firstly, factors influencing the potential of virtual commissioning which have been identified are presented. Afterwards essentials for virtual commissioning are separated and integrated in the first step of the evaluation model. Step 2 deals with the determination of benefit value of projects. Finally those values are transferred into a matrix to deduce a recommendation regarding the project-specific potential of virtual commissioning.

A. *Evaluation Criteria*

During expert discussions within the company, universities as well as suppliers and service providers, factors which have an impact on benefit and effort of virtual commissioning projects were identified. They can be categorized into groups such as complexity of production facilities, availability of data, urgency, software, supplier and internal factors as experience and equipment. Some of them have an impact on the expected effort of virtual commissioning while others influence the benefit. Some of them, especially the characteristics of the examined production facility, have to be considered in effort and benefit evaluation.

B. *Step 1: Basic Requirements*

In order to enable a reasonable implementation of virtual commissioning some basic requirements have been identified. An important aspect is the availability of data as well as equipment. Missing information about the production facilities, their composition and their functionality would make the creation of a virtual model very difficult or even impossible. In this context the supplier also plays an important role. By being responsible for design and production of the facilities as well as control software, they provide main information and have a high contribution to the benefit of virtual commissioning. Virtual commissioning would not be possible if they reject the cooperation or if the necessary software is not developed until real commissioning.

The criteria is requested in an excel application which advises against the use of virtual commissioning when one of the basic requirements is not fulfilled. If all requirements are met the result shown in Figure 5 is displayed.

Evaluation model Check of basic requirements				
Availability of data	3D CAD data/ Layout	yes	Result: Are all basic requirements fulfilled?	yes
	Functional description	yes		
	Hardware configuration	yes		
Availability of equipment	Capable computer	yes		
	Software	yes		
	Test set-up	yes		
Supplier	Cooperativeness	yes		
	Software development process	yes		
Planning time	Time range to real commissioning	yes		

Figure 5. Basic requirements

C. *Step 2: Value Benefit Analysis*

To find out if a project has a high potential for virtual commissioning both expected benefit and effort should be considered. A tool has been developed including all criteria which have an impact on the potential of a project. To get a meaningful result each criteria has been checked on its impact on effort or benefit and thereby assigned to the appropriate model. During the evaluation each criteria has to be rated with a low, medium or high value. An algorithm converts this rating into an evaluation value. “1” means low benefit or low effort, “2” stands for medium benefit or medium effort and “3” finally means high benefit and high effort. The results are multiplied with a weighting factor considering the importance of each criterion. For the determination of weighting factors each criterion was compared to each of the others considering their importance. This paired comparison enables weighting factors for each criteria and the categories they belong to [16]. By this approach an overall benefit value and an overall effort value between “1” and “3” can be determined.

Figure 6 shows an exemplary evaluation of a project in which virtual commissioning was used to validate control technology.

	Evaluation model Check on benefit of virtual commissioning				
	Criteria	**Weight**	**Rating**	**Evaluation**	**Result**
Complexity of production facility	Size	15%	medium	2	0,3
	Technological complexity	30%	high	3	0,9
	Amount of control technology	25%	high	3	0,75
	Control related complexity	30%	low	1	0,3
	Sum	**33%**			**2,25**
Urgency	Time for implementation	40%	low	3	1,2
	Importance	40%	high	3	1,2
	Project value	20%	medium	2	0,4
	Sum	**50%**			**2,8**
Supplier	Experiences with the technology	100%	low	3	3
	Sum	**8%**			**3**
Internal factors	Re-utilisation potential of virtual model	100%	high	3	3
	Sum	**8%**			**3**
Evaluation of benefit					**2,62**

Figure 6. Evaluation of benefit

Following figure 7 shows the effort evaluation of the same project.

	Evaluation model Check on effort of virtual commissioning				
	Criteria	**Weight**	**Rating**	**Evaluation**	**Result**
Complexity of production facility	Size	15%	medium	2	0,3
	Technological complexity	5%	high	3	0,2
	Amount of control technology	25%	high	3	0,8
	Control related complexity	35%	low	1	0,4
	Maturity of processes	20%	medium	2	0,4
	Sum	**35%**			**2,0**
Availability of data	Compatible data formats	20%	high	1	0,42
	Consistent data	50%	low	3	0,24
	Expected maturity of design data	15%	high	1	0,25
	Expected maturity of control software	15%	medium	2	0,5
	Sum	**35%**			**1,41**
Software	Complexity of virtual model	33%	low	1	0,3
	Automatic generation	25%	medium	2	0,6
	Existing library	25%	low	3	0,3
	Requiered detail level of simulation	17%	medium	2	0,6
	Sum	**20%**			**1,8**
Supplier	Reliability	100%	high	1	1
	Sum	**5%**			**1**
Internal factors	Available competencies	60%	medium	2	1,2
	Available Equipment	40%	high	1	0,4
	Sum	**5%**			**1,6**
Evaluation of effort					**1,62**

Figure 7. Evaluation of effort

D. *Step 2: Benefit and Effort Matrix*

To interpret the results of the evaluation model the right way, a matrix has been set up which gives a recommendation based on previous results (Figure 8). The y-axis represents the benefit while the x-axis represents the effort value. As mentioned before the highest value in both categories is 3. Values under 1.5 are related to a “low” benefit or effort while values between 1.5 and 3 are defined as “high”. Thereby four segments can be established. By classifying the results of the value benefit analysis into the matrix a recommendation is given. In projects where high benefit combined with low effort is identified, virtual commissioning should be used. On the contrary no virtual commissioning is recommended when the effort is evaluated high and the benefit low. In all other cases a more detailed examination by experts should be considered, because the determined values do not allow a clear recommendation since the real potential is hard to estimate.

The following figure shows the matrix with the classification of the selected project based on results previously outlined. The "star" is an example for a planning project, in which virtual commissioning is recommended as benefit is "high" and effort is "low".

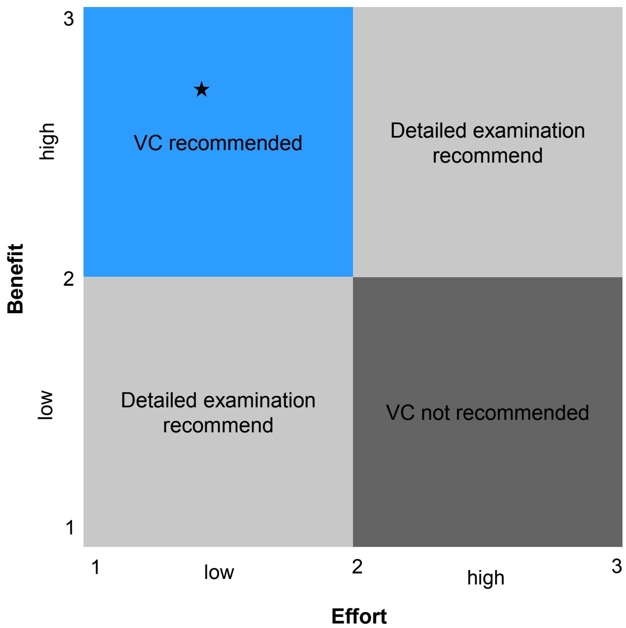

Figure 8. Recommendation matrix

V. Conclusion and Outlook

The present work presents a model for the evaluation of the potential of virtual commissioning in the implementation of scalable production systems. By using the evaluation model before ordering new production facilities or implementing changes to the existing system, benefit and effort of the development of a virtual model and the validation of control technology can be estimated.

The model can be used independently of the product to be manufactured, the production possibilities and the structure of the scalable production line. It allows both evaluation of basic requirements and thereby general feasibility of virtual commissioning as well as reflection of required effort and expected benefits. Thus, not only the influencing factors on successful virtual commissioning projects are summarized, but also a tool to support the production engineer´s decision for or against using virtual commissioning is provided.

In the near future the evaluation model should be adapted depending on changes of virtual commissioning software, equipment and organization. Advancements can have an influence on potential and effort of virtual commissioning in general. Therefore especially the weight of each weighing factor should be verified based on new findings.

As the creation of the virtual model is one of the most extensive parts in virtual commissioning re-utilization potential plays an important role. Further research should investigate on how to ensure the conformity of the virtual model after start of production. In addition recorded data from programmable logic controllers can be used for the enhancement of the generated models.

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