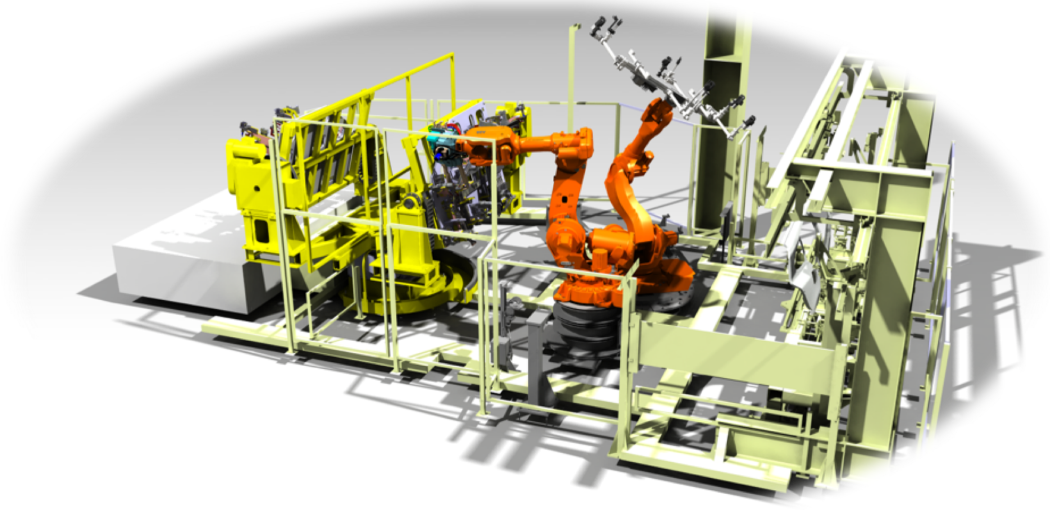
VIRTCOM2

Virtual preparation and commissioning of productions systems including PLC-logic

Publik rapport



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Projekt inom Hållbara produktionssystem

FFI Fordonsstrategisk Forskning och Innovation
VINNOVA Energimyndigheten TRAFIKVERKET FKG VOLVO SCANIA VOLVO

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1 Sammanfattning

För att stärka svenska företags konkurrenskraft på en modern marknad driven av tekniska innovationer och storskalig kundanpassning, syftade VIRTCOM2 till att öka användningen av virtuella verktyg och matematiskt formella metoder för utveckling av produktionssystem, och därmed minska behovet av fysiska prototyper och tester. Avsikten var att kunna korta "time-to-market", öka kvalitet av både produkt och produktionssystem, och erbjuda mer tekniskt avancerade och hållbara produkter.

Projektet bestod av sex arbetspaket (WP) som tillsammans hade målet att skapa effektiva verktyg och metoder för att skapa en komplett arbetskedja från virtuell beredning, via automatiskt genererad PLC-kod, till virtuell och fysisk idrifttagning. WP1 innefattade projektledning, medan WP2 handlade om att skapa virtuella beredningsmetoder och verktyg för att garantera korrekt PLC-logik. WP3 utnyttjade sen resultat från WP2 för att utveckla metoder för automatisk generering av PLC-kod. Genom att använda resultaten från WP2 och WP3 utfördes i WP4 virtuell idrifttagning både av en demonstratoranläggning vid Chalmers, och en industriell pilotanläggning. Verktyg, metoder och erfarenheter från WP2, WP3 och WP4 demonstrerades sen i en demonstratoranläggning skapad i WP5. Projektarbetet och resultaten har kontinuerligt disseminerats under WP6, och detta fortsätter även efter projektet avslutats.

Som projektet visade finns det många fördelar med att introducera virtuella verktyg och matematiska metoder i tidiga utvecklingsfaser av produktionssystem. De virtuella verktyg och metoder framtagna inom VIRTCOM2 utvärderades i pilotprojekt, där nya produktionsstationer utvecklades i karosserifabriken på Volvo Torslanda, i samarbete mellan Volvo Cars och dess underleverantör. Volvo AB utvärderade virtuell idrifttagning tillsammans med Siemens. Dessa pilotprojekt visade hur virtuell idrifttagning kan signifikant korta tiden för fysisk idrifttagning med upp till 50% då möjligheten av att kunna utveckla, testa och validera styrfunktioner i virtuell miljö möjliggör att felaktigheter och detaljerad utveckling av styr-logik kan genomföras innan fysisk idrifttagning. Denna tidsbesparing kommer både av att programmen är mer kompletta men framförallt på grund av att upp till 50% färre fel behöver åtgärdas på fabriksgolvet.

Den kompletta arbetskedjan från virtuell beredning, via automatiskt genererad PLC-kod, till virtuell och fysisk idrifttagning är ännu inte helt fullständig, men VIRTCOM2 har adresserat och kopplat ihop flera saknade länkar i kedjan. Användningen av virtuella verktyg och formella metoder möjliggör också stöd och förenkling av andra komplexa procedurer såsom återstart efter fel, energioptimering, varianthantering, hantering av säkerhetslogik m.m.

Projektet har utvecklat metoder för automatisk extrahering av "återstartstillstånd" från en modell av produktionssystemets styrfunktion, så att återstart efter fel kan hanteras på ett semi-automatiskt sätt. Under beredningsfasen kan då utvecklaren fokusera på systemets nominella beteende och enbart specificera (o-)önskat beteende under återstartsfasen. Vid återstart efter fel under systemets exekvering får operatören automatiskt genererat stöd av systemet för korrekt hantering av återstarten, och återstart kan också göras på ett mer detaljerat sätt än att bara återställa allt till initialtillståndet. Dessa metoder har applicerats på en station för montering av vindrutor på Volvo Cars.

Energioptimering av robotrörelser har också utvecklats och demonstrerats på en Kuka IIWA robot. Resultat från EU-projektet AREUS vidareutvecklades och applicerades. Detta visade på möjligheten att spara 20–30% energi genom matematiskt optimerad acceleration. Metoden har också anpassats till multi-robot-stationer, där robotarnas rörelsemönster kan optimeras relativt varandra. I båda fallen med bibehållen trajektoria och cykeltid.

Kundanpassning av konfigurerbara produkter medför avsevärd komplexitet när det gäller hantering av möjliga varianter, både för produktionssystemet såväl som produktdesignen. Inom VIRTCOM2 har verktyg för hanteringen av denna komplexitet utvecklats, där det automatiskt kan avgöras om alla möjliga produktvarianter kan produceras samtidigt som alla sekvenskrav på operationerna är uppfyllda. Dessa verktyg ger också stöd för införandet av nya varianter på existerande produktplattformar och produktionssystem.

VIRTCOM2 har klart visat att kombinationen av virtuella verktyg och formella metoder är fullt möjligt och medför stora fördelar vid utvecklingen av komplexa produktionssystem. Projektets resultat hjälper ingenjörer att hantera den ökade komplexitet som kommer med ökad kundanpassning och tekniska framsteg; ökad produktflora och större produktvariabilitet. Att förenkla denna hantering gör företagen mer konkurrenskraftiga på en marknad driven av tekniska innovationer och storskalig kundanpassning.

2 Executive summary in English

The VIRTCOM2 project aimed at increasing competitiveness by developing complete work chain from virtual preparation, through automatically generated PLC code, to virtual and physical commissioning. The project was divided into six work packages aiming at developing efficient methods and tools to aid engineers in the preparation and commissioning of production systems. WP1 involved the project management and WP2 involved the creation of PLC program preparation methods in order to establish a virtual preparation of PLC logic. WP3 involved the development of methods for automatic generation of complete programs and uses results from WP2. In WP4 virtual commissioning on both a demonstrator at Chalmers and an industrial pilot case were performed using results from both WP3 and WP2. Results from WP2, WP3, and WP4 were demonstrated using a demonstrator created in WP5. The project scope and results have continuously been disseminated and exploited in WP6 during the project and will continue after the project has ended.

The project objectives were to achieve sustainable production facilities that can adapt to future requirements on flexibility, availability etc. Another aim was to realize flexible and efficient systems able to handle a large number of existing and coming environmentally friendly powertrains. The goal was to increase the use of virtual tools for preparation to make accurate decisions without prototyping and tests. The aim was to achieve completely virtually designed, simulated, verified, and implemented systems; both software and hardware with shortened lead time for preparation, installation, and ramp up of automation systems as a result. Additional goals have been to realize reduced energy consumption per vehicle produced and improved product quality by development and use of robust automation systems. High personnel and machine safety by verification and simulation, including safety systems in a virtual environment has been an important part of the project.

The project aimed at contributing to the programs overall goal within production and production preparation with a 30% increase in productivity within the area of production preparation and a 25% increase in productivity in the production process. In addition, a goal was to establish a 25% decrease of the environmental influence of the production processes.

The project has developed procedures for how virtual commissioning should be implemented at the OEMs and how the requirements should be defined in collaboration with the suppliers and especially the line builders. Requirements on what the line builders should deliver and what the expectations from the OEMs are has been defined. A pilot project was performed at Volvo Cars where virtual commissioning where evaluated and work procedures where defined. The result was then applied in a real development project at Volvo Cars when they were developing two new production stations for the body-in-white factory in Torslanda. Doing this there was a requirement that virtual commission should be performed by the line builder and that it should be done according to the specification and procedures developed in the VIRTCOM2 project. At Volvo trucks virtual commissioning was introduced and evaluated in collaboration with Siemens at the UMEÅ plant.

The work on virtual preparation and commissioning also identified new areas that need to be addressed and researched when it comes to reducing the time required to create the models necessary for performing a virtual commissioning. As a result of the VIRTCOM2 project this problem addressed in a new three-year ITEA3 project (ENTOC) together with a German consortium including e.g. Daimler, Festo, FFT. Another project coming out of the VIRTCOM2 as well as the ENTOC project is the ITEA3 SPEAR project that aims at including energy use as an important parameter, together with cycle time, in the production design and preparation phase. The aim in the SPEAR project is to extend the component models from ENTOC with energy use and thereby extend the virtual model with accurate dynamic models together with the ability to analyze the energy use. As a consequence of this energy use research another important topic have arisen connected to the maintenance need and component life span. It has been shown that minimizing the energy use of equipment and components normally means that smoother motions are created. This could also result in less stress and fatigue and could result in less demand on maintenance and that equipment could be used for a longer period of time. As a result, a new three-year project, SmoothIT, have been applied for and granted and will focus on energy use and maintenance.

The VIRTCOM2 project has successfully introduced the use of formal methods within the production preparation by connecting virtual preparation tools i.e. Process simulate from Siemens with Sequence Planner. Sequence Planner is a tool based on formal methods developed by Chalmers and have in the project been extended with important methods for handling the virtual preparation and verification of logic in early preparation stages. The results have shown that it is possible to handle a greater degree of complexity in a more efficient way. The results also clearly show that it is possible to guarantee a correct behavior without any blocking or collision situations while delivering an optimized sequence of operation. The project has

shown the results and developed methods aid the engineer in developing production stations and results in an increase in productivity within the area of production preparation.

The project has performed research and developed methods within the area of energy optimization and focused on multi robot energy optimization and this was performed and demonstrated using an acquired KUKA robot (iiwa) during. The task was to apply the results from the EU project Aureus and further develop these. Methods for energy minimization were developed and implemented. The major result was that it is possible to save up to 20-30 % energy without changing the robots path or the cycle time. Modeling techniques for the problem of optimal velocity control of multiple robots on given intersecting paths were also developed. Advantages and disadvantages of the modeling approaches were evaluated and the performance of the two approaches were evaluated in a case study with an industrial robot.

Configurable products, like vehicles, face the challenge of handling all possible variants which are needed to answer the various customer needs. For these configurable products the support of all variants need to be addressed both by the design phase and the production phase. The project has developed an automated method that can determine if all possible product variants can be successfully assembled while still satisfying precedence constraints between operations. The results have been conducted on an industrial example which further exemplifies the needed input for the method and the possible method outputs as a result of introducing a new variant to the product platform.

The project has developed methods for modeling the control system to enable automatic derivation of restart states applied to an existing station for automatic mounting of windscreens onto car bodies at Volvo Cars. This aids the preparation phase by letting the developer focus on modeling the nominal production and on specifying (un-)desired behavior during the restarted production, and then automatically retrieve the restart states for all control states. The online restart process is then reduced to a semi-automatic process where an operator can be supported with instructions for how to correctly resynchronize the control and the physical systems in a selected restart state. An implementation has been developed and demonstrated where error situations could be simulated in a virtual. The Implementation and demonstration also included the use of virtual reality glasses that enables an engineer or operator to walk inside a running virtual production system. Error situations can in this way be introduced and recovery situations can be tested. A benchmark related to how restart is dealt with, within industry today, has been performed in order to identify the state of the art. This study also included new trends within manufacturing such as Industry 4.0, internet of things, human-machine collaboration etc. and how this will affect how restart should be treated in the future. A new framework for how smart data collection from real time production could aid in designing an efficient restart method and procedure has been developed. The framework enables collecting information from the real time production and then analyses this information applying machine learning techniques. As a result, from this a new complex production station at Volvo Cars has been modified in order to include the method of gathering real time data.

Project results have been presented at a number of conferences and resulted in conference papers and two PhD theses that have successfully been presented during the project. Project results have also been presented at companies and lead to new collaborations with both industry and academia. Demonstration days have been organized and the results have also been presented at conferences where both industry and academia meet. Project participants have also been invited as speakers at relevant conferences.

VIRTCOM2 has clearly shown that the combination of virtual tools and formal methods is fully feasible and brings great advantages in the development of complex production systems. The results of the project help engineers deal with the increased complexity that comes with increased customer customization and technical progress; increased product flora and greater product variability. Simplifying this management makes companies more competitive in a market driven by technological innovations and large-scale customization.

3 Bakgrund

Vehicle manufacturing companies are today forced to handle a rapidly growing variety of vehicles due to increasing restrictions on energy consumption and CO_2 emissions. For the manufacturer to stay competitive, these new innovative and environmentally friendly vehicles must be produced in existing factories. A trend today is also that production volume has to be adjustable with short notice to meet changing market demands. Manufacturing systems have thus to be both efficient and flexible. Additionally, energy and material requirements for both preparing and running the production systems have to be minimal.

This places great demands on manufacturing systems design, development, and testing before implementation. It also places great demands on optimized use of equipment, material, and energy when production systems are up and running. This further means that the number of production errors must be kept at a minimum, and that when (not if!) an error does occur the automated production can be efficiently and safely restarted.

An effect of this is that accurate preparation, including simulation, verification, and optimization, must be performed before systems are taken into use. It is also important to be able to quickly and efficiently react at low cost to market changes. Information reuse and automatic generation of control functions are crucial to fulfil all these requirements.

Simulation is increasingly used within industry to evaluate different manufacturing solutions. Robot simulation seems currently to be the most advanced area, with robot control routinely generated in a 3D simulation environment and downloaded into the actual robot controllers. This typically works with very little manual adjustments on the factory floor, but there are still activities that do not involve the use of advanced software tools that generate information directly usable by other activities. One example is the programming of PLCs, which handle the logic control on the factory floor, including safety and restart procedures. Currently it is not possible (or at least very hard) to extract the logic from the simulation model and transfer it to any PLC generation tool. Thus, reusing information from earlier preparation activities is not straightforward and the whole process, from virtual preparation to executable PLC code, cannot yet be realized.

A common approach for automatic generation of PLC programs is to generate the overall sequence, often using formal languages. One challenge has been to generate the complete PLC program, including low level control, safety system, communication, signal mapping etc. Virtual commission software tools are continuously developed and there are many examples of virtual commissioning being tested for validation and verification of production solutions. Minimizing energy consumption in industrial applications is important both from an environmental and an economical point of view. One of several approaches to this problem is to improve existing hardware solutions. Energy optimization of mechatronic devices is well investigated. Finding ways of minimizing the energy cost for trajectories in robot applications is in itself a big area of research. The production system complexity is constantly increasing due to the flexibility requirement. Today the same production system has to handle many different product types as well as many different configurations. Being able to guarantee correct and safe behavior is of great importance and formal evaluation techniques can be a powerful way to solve the complexity problem. A lot of research has been done in the area of verification and controller synthesis. Industrially, restart procedures are typically implemented manually on an error-by-error basis. The code is run (or simulated) and specific code is added for the specific errors that arise. This is a time-consuming procedure; typically, 50% of development time is spent implementing code for non-nominal behavior, mainly alarms and restart. Furthermore, there are no guarantees that all errors are handled, or that it is done correctly, safely or efficiently. Within academia, different methods to manage restart have been reported; see [20] for an overview. However, very few practical implementations have been described, and mainly predictable errors are treated.

The existing and proposed production preparation workflow is illustrated in Figure 1. The existing workflow is described by the upper part of Figure 1 and was used as base line for the VirtCom project. The VirtCom project performed a great number of case studies and developed several methods in order to answer specific questions regarding the possibilities of moving the PLC programming and commissioning into earlier preparation phases. Case studies were used to investigate which benefits could be achieved if PLC programming and commissioning was performed during earlier phases. The major results of VirtCom were; shorter preparation and commissioning time, greater possibilities to perform good cycle time and energy optimization, efficient restart and operator support, allowing a higher level of complexity by using formal evaluation and automatic generation of programs, testing by virtual commissioning that leads to shorter physical commissioning.

The very promising results of the VirtCom project led to a great interest from all partners to develop methods and tools in order to accomplish a *complete* virtual preparation of PLC programs and virtual commission. The VirtCom2 project therefore involves a large number of motivated partners that make great investments, both resources and person month's, in order to develop a new workflow for production preparation.

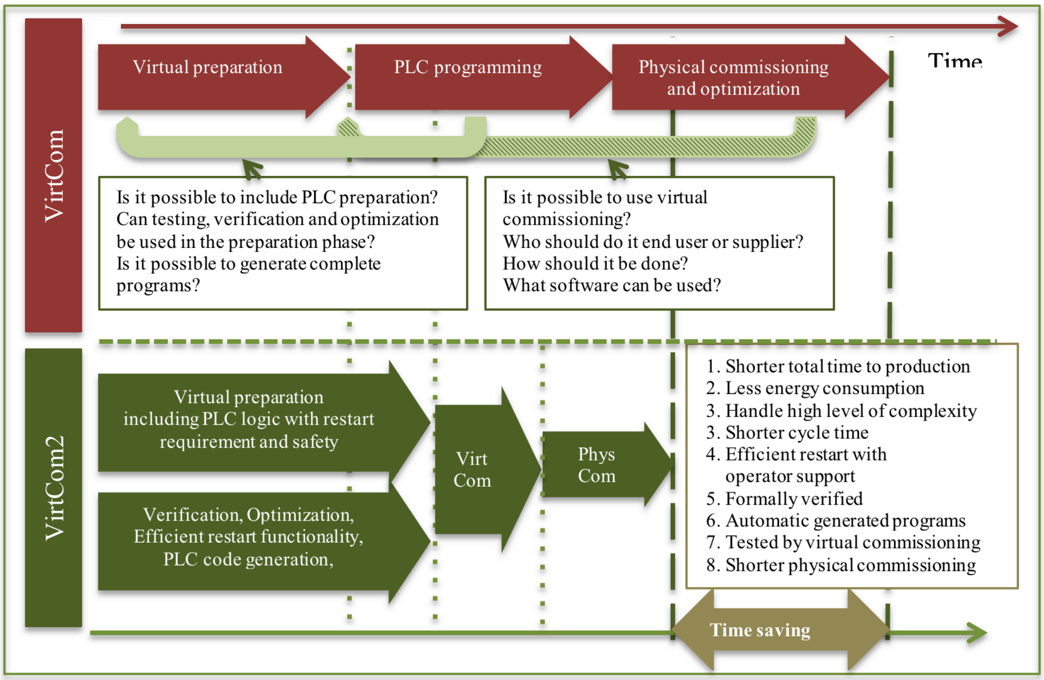

Figure 1 Existing and proposed production preparation workflow

The proposed production preparation workflow for VirtCom2 is described by the lower part of Figure 1. The workflow involves two parallel activities. The first is to include the specification of reusable logic, including specification of safety and restart requirements. The second is to utilise the specified logic in order to perform testing, verification, optimization and restart functionality in early preparation stages. An important advantage is also to include automatic generation of complete PLC programs and in that way remove the additional task of manually implementing these. The proposed workflow involves a virtual commissioning that reuses the simulation model used in the preparation phase and the automatically generated PLC programs in order to visually validate the final production solution. The automatically generated and tested PLC solution and robot programs are then used in the physical commissioning and results in a shorter commissioning time. This means that the time real production is stopped for introducing new equipment is shortened.

The VirtCom2 project is a natural continuation of the VirtCom project, but with more focus on preparation and reuse of information in early stages, including taking into account safe and efficient procedures for restart after unforeseen errors.

4 Syfte, forskningsfrågor och metod

The purpose of the VIRTCOM2 project was to increase the use of virtual methods within the preparation of the automation solution including the creation of the control system i.e. PLC logic. This included the introduction of the use of formal methods within industry in order to aid the engineer to handle the increasing complexity that comes as a result of the introduction of more product models and a higher degree of variety when it comes to costumer specific specifications and the increasing number of different power trains.

The research questions can be summarized as follows:

1. How should Swedish industry make the best use of virtual commissioning in order to minimize ramp up time and decrease the preparation time of new production systems.
2. How can formal methods and tools be applied in industry and more specifically how can these be incorporated into existing industry workflow.
3. How can restart situations be more efficiently handled by applying formal methods in combination with process mining.
4. How could energy optimization of systems and equipment be applied without changing the overall requirement on cycle time.
5. How can safety logic be handled in a virtual environment in order to decrease the time for testing the safety system during physical commissioning.
6. How can mathematical methods aid in handling the variability problem that occurs as a result of the introduction of more product variants.

The method for achieving the goals and answering the research questions have been to, in close collaboration with the industry partners, define the requirements and use cases used throughout the project. Necessary information has been collected both within the area of preparation and commissioning i.e. a tight collaboration between the research partner and the engineers at the industry partners have identified and collected the necessary information. This information has been product- and production related information as well as working procedures, models, programs etc. Methods, algorithms and implementations has been developed by the research partner and the developed tools has been implemented, tested and evaluated at the industry partner facilities.

5 Mål

The project's overall objective is to increase competitiveness by developing complete work chain from virtual preparation, through automatically generated PLC code, to virtual and physical commissioning. The project objectives are in more detail:

- Sustainable production facilities that can adapt to future requirements on flexibility, availability etc.
- Flexible and efficient systems able to handle a large number of existing and coming environmentally friendly powertrains.
- Use of virtual tools for preparation to make accurate decisions without prototyping and tests.
- Completely virtually designed, simulated, verified, and implemented systems; both software and hardware.
- Shortened lead time for preparation, installation, and ramp up of automation systems.
- Reduced energy consumption per vehicle produced.
- Improved product quality by development and use of robust automation systems.
- Optimized energy efficiency and minimized use of material.
- High personnel and machine safety by verification and simulation, including safety systems in a virtual environment.

The project aims at contributing to the programs overall goal within production and production preparation in the following way:

- 30% increase in productivity within the area of production preparation
- 25% increase in productivity in the production process.

- 25% decrease of the environmental influence of the production processes

A goal is to reduce the complete project time with almost 50%. A more specific aim is a reduction of the production preparation time by 25% and decrease the time for PLC code generation by 50%. Additionally, a 25% decrease of the time to resume automatic production after errors can be expected by inclusion of efficient and safe restart procedures.

6 Resultat och måluppfyllelse

Expected results of this project are:

- Method for specification, modelling and calculation for efficient restart.
  The results in the project are:
    - A case-study has been performed at Volvo Cars for implementing and demonstrating a restart procedure that will simplify the restart of production systems with a high level of automation.
    - A PHD thesis in the area of efficient restart using formal methods were published in 2015.
    - A method for enabling testing of restart situation in a virtual environment has been carried out where a connection between the Chalmers developed software Sequence planner and the Siemens simulation and commissioning software Process simulate were created.
    - The method enabled inferring error situations in in *Process Simulate* and generate restart solutions in *Sequence Planner* based on the error situation and the current state of the controller.
    - An implementation was during spring 2016 developed and demonstrated where error situations could be simulated in a virtual environment using Sequence Planner (Chalmers software) and Process Simulate (Siemens software). The Implementation and demonstration also included the use of virtual reality glasses (Oculus Rift) that enables an engineer or operator to walk inside a running virtual production system. Error situations can in this way be introduced and recovery situations can be tested.
    - A benchmark related to how restart is dealt with, within industry today, has been performed in order to identify the state of the art. This study also included new trends within manufacturing such as Industry 4.0, internet of things, human-machine collaboration etc. and how this will affect how restart should be treated in the future. Based on the resulting state of the art several research and development questions have been identified. A paper was presented at ETFA 2016.
    - A new framework for how smart data collection from real time production could aid in designing an efficient restart method and procedure has been developed. The framework takes early results from the LISA2 project when it comes to collecting information from the real time production and then analyses this information applying machine learning techniques. As a result, from this a new complex production station at Volvo Cars has been modified in order to include the method of gathering real time data. A paper describing this new restart framework was presented at ETFA 2016.
- Methods for automatic generation of PLC programs.
  The results in the project are:
    - A case-study has been performed at GKN and NEVS that focused on automatic generation of complete PLC-programs including safety.
    - A benchmark was also conducted related to how safety logic is dealt with within industry today has been performed in order to identify the state of the art. This study also included new trends within manufacturing such as Industry 4.0, Internet of things, human-machine collaboration etc. and how this will affect how safety logic should be created in the future. Based on the resulting state of the art several research and development questions have been identified.
    - A framework for handling, creating and testing safety logic has been developed based on the benchmark. The main idea of the framework is to be able to make the risk analysis in a more efficient way. Another aim was to formalize the procedure and formalism to be able to use mathematical calculations and software tools to guarantee a safe production system. An additional aim was also to minimize the task and time for testing in the commissioning phase by developing techniques for decreasing the amount of test cases required and also to be able to perform tests in the virtual model. The results were presented at CASE 2017.
- Methods for formal verification of logic behavior.
  The results in the project are:
    - Preparation and simulation tools have been implemented that integrate formal methods and virtual preparation. The method aid engineers in decision making when performing early

simulation and sequencing. The result has been validated and the proposed workflow were presented at MIM 2016.

  - A method has been developed and implemented that enables an efficient method for defining operation sequences based on the structure and equipment of a virtual production station. A connection has been created between Sequence planner (Chalmers software) and Process simulate (Siemens simulation software) that enables exporting operation and component data from process simulate. The implemented method enables production specifications and operation requirements to be gathered in order to formally generate a model that fulfils all defined specifications. The result can be used for testing operation sequences within the production station with regard to for example cycle time or energy consumption while knowing that all requirements always are fulfilled. This is a first step in aiding the engineer in designing the automation solution in a more efficient way while knowing that it will behave in an appropriate way. Results were presented at IFAC 2017.
  - A method for automatic generation of operation sequences based on existing production stations has been developed and implemented in Sequence planner and connected to Process Simulate. This method makes it possible to determine how event based controlled systems are behaving. It is possible to visualize the possible sequences and to determine how well or bad the different sequences behave. The method provides a possibility to efficiently analyze a production system in a virtual environment and based on different criteria choose the best solution i.e. the single best operation sequence. An additional aspect that will be analyzed and developed is to be able to perform a robust optimization, which means that if an event-based solution is used it will be possible to guarantee a worst case. The method was tested and evaluated at Volvo Cars during fall 2016. The result was presented at the 8th IFAC Conference on Manufacturing Modelling, Management and Control [3].
  - A method for automatic generation of operation sequences has been validated on a real industrial case at Volvo cars during autumn 2016 and the results clearly shows that this method and software could be used both for analysis of existing production lines in order to analyze its current behavior but also aid in developing new stations or making changes to existing stations when a new car model is to be introduced. The method involves robot behavior and the next step is to include all moving parts in a production system in order to encompass all logic behavior. The goal is to be able to foresee the behavior of a production solution in a virtual environment. Two master theses were carried out during 2017 at Volvo Cars. The same station from Volvo Cars were used both for information/data collection and behavior analysis in the virtual world and the results from these two cases were compared. The results were presented at the IFAC World Congress 2016 and FAIM 2017.
- Methods for cycle time and energy optimization.
  The results in the project are:
  - An activity around multi robot energy optimization conducted and demonstrated using an acquired KUKA robot (iiwa) during Nov 2016. The task was to apply the results from the EU project Aureus where methods for energy minimization were developed and implemented. The major result from that project was that it is possible to save up to 30 % energy without changing the robots path or the cycle time.
  - Modeling techniques for the problem of optimal velocity control of multiple robots on given intersecting paths were developed. Advantages and disadvantages the modeling approaches were evaluated, involving a variable change with square of velocity, or alternatively inverse of velocity. The performance of the two approaches is evaluated in a case study with an industrial robot. The result was presented at CASE 2017. A PhD thesis were defended in the area of robust and energy efficient scheduling autumn 2017.
- Methods for virtual preparation of PLC logic including visualization.
  The results in the project are:
  - One aim in the project was to develop Sequence planner in a way that enables a virtual development of logic during the whole chain from product development to implementation of control functions. In connection to this a method for visualize and specify logic connected to robot simulation activity has been developed and implemented. The method was tested at Volvo Cars for evaluation.
  - The software Sequence Planner has been developed and the connection to Process Simulate has been extended and a work procedure is being developed to enable SMEs that do not have all the competence within both virtual preparation, robot programming and PLC-logic development to be able to create logically controlled simulations in order to have better control

    - over their own production systems. The resulting method and implementation was developed in collaboration with GKN.
    - Sequence planner and Process simulate has been successfully connected and a solution for handing this solution over to the industry partners is developed in order for the companies to test and evaluate how sequence planner could be used in their organizations. Three master theses have been conducted in order to further develop the solution and increase knowhow within the respective companies.
- Procedures for virtual commissioning.
  The results in the project are:
    - A pilot study was conducted in the beginning of the project at Volvo Cars
    - Student projects has been performed during the hole projects and more than 5 master and bachelor projects has been conducted within the area of virtual commissioning.
    - A virtual commissioning laboratory has been created at Chalmers.
    - A collaboration was established with a German consortium within ITEA3 project framework (ENTOC and SPEAR). Important collaborators such as Daimler, FESTO, FFT, EKS, IFAC and EDAG has been established.
    - An implementation of the demonstration cell at Chalmers were carried out during the project with the focus on connecting the real PLC using the Siemens hardware SimbaBox towards the virtual model of the production plant. In addition, a method for using HTC vive goggles has been developed and tested. The aim is to be able to walk around in the station while the production is running. The goal was to be able to test safety systems as well as train operators and maintenance persona in a virtual commissioning environment.
    - The VR method using HTC-vive, simba box and Process simulate were extended making it possible to interact with a live virtual production station controlled by a real PLC with the actual programs. The interaction is for instance to open safety doors and thereby test that the safety logic is correct. This include the resume of production by closing the door and acknowledge using the virtual HMI. The results were presented at ETFA 2017.
- Knowledge, skills, experience, industrial workflow, and organizational issues for virtual commissioning and virtual preparation of logic in early preparation.
  The results in the project are:
    - A Virtual Commissioning pilot performed at Volvo Cars 2014 and lessons learned have been presented at the Industrial automation conference 2015 in San Francisco.
    - The developed procedures were utilized and refined at the Chalmers demonstrator cell.
    - Virtual commissioning was performed in a real development project at Volvo Cars. The supplier/line builder performed the virtual commissioning according to developed proposed procedures and methodologies.
    - A virtual commissioning of two stations at Volvo Trucks was performed by Volvo Truck engineers. A virtual commissioning education of Volvo Truck engineers has been performed during spring summer 2016.
    - A master thesis with the focus on virtual commissioning were performed at Scania during fall 2016.
    - More than 50 students were involved in both bachelor projects as well as master thesis work during 2016 and 2017.
    - An education in how to create a virtual commissioning model in Process simulate was given to involved students during Feb. 2017.

- Licentiate thesis in the field of PLC preparation and visualization in early phases.
  The results in the project are:
    - PhD-student started Jan 2015 and licentiate presentation planned to Mars 2018.
    - PhD-student started Dec 2015 and licentiate presentation is planned for autumn 2018.
- Doctorial thesis in the field of cycle time and energy optimization.
  The results in the project are:
    - Nina Sundström, Robust and Energy Efficient Scheduling, PhD thesis, 2017.
- Doctorial thesis in the field of efficient restart and operator support.
  The results in the project are:
    - PhD-defence Feb 2015
    - PhD-student started Oct 2015
- MSc theses in the field of preparation, simulation and virtual commissioning.
  The results in the project are:
    - Virtual Commissioning using Oculus rift project performed during spring 2015.

- StrathClyde students perform a master thesis at Chalmers with the focus on virtual commissioning procedures and state of the art.
- BSc thesis: Virtual Commissioning using Oculus rift project performed during spring 2016
- BSc thesis: Optimering och dynamisk styrning av en produktionsprocess modellerat med ett operationskoncept 2016
- BSc thesis: Den flexibla klossfabriken - En utvärdering av operationskonceptet för produktion av modulära produkter 2016
- BSc thesis: On-linestyrning av tvåarmad robot 2016.
- Project course with 8 master students implemented an efficiently control a reals production station partly controlled by sequence planner.
- Four master thesis projects performed during spring 2017 at both SCANIA and Volvo Cars in the area of virtual preparation and commissioning.

- Virtual commissioning pilot case at Volvo cars.
  The results in the project are:
  - First Pilot performed 2014
  - Second Pilot case 2015
- Virtual and physical demonstration facility at Chalmers implementing the proposed methods and workflow for virtual preparation and commissioning of production systems including PLC logic, efficient restart, and safety.
  The results in the project are:
  - First design implementation was planned for spring 2016
  - Demonstrator developed during spring 2016
  - Demonstration day at Chalmers May 2016
  - Demonstration performed at Chalmers May 2017.
- Dissemination of project scope and results outside the consortium, international and domestic, to large enterprises as well as SMEs. Presentations at fairs and scientific conferences and publication in journals and popular science magazines.
  The results in the project are:
  2017
  - Presentation at ETFA 2017 in Limassol, Cyprus
  - Presentations at CASE 2017 in Xi'an, China
  - Presentation at FAIM 2017 in Modena, Italy
  - Presentation at IFAC 2017 in Toulouse, France
  - Presentation at The Swedish Manufacturing R&D Clusters in Katrineholm, Sweden
  - Demonstration day for Chalmers students and employees as well as industry at Chalmers May 2017.

  2016
  - Keynote speaker at industrial automation conference, Athens
  - Invited speaker *9º Fórum Internacional de TI Banrisul 2016*
  - Presentation at ETFA 2016 in Berlin, Germany
  - Presentation at MIM 2016 in Troyes, France
  - Presentation at The Swedish Manufacturing R&D Clusters in Katrineholm, Sweden
  - Presentation at CIRP 2016 in Guimarães, Portugal
  - Demonstration day for Chalmers students and employees as well as industry at Chalmers May 2016
  - Keynote speaker at world congress Industrial automation, Philadelphia

  2015
  - Interview with Petter Falkman about the project (in Swedish)
  - Presentation INCOM 2015 in Ottawa, Canada.
  - Presentation at The Swedish Manufacturing R&D Clusters in Katrineholm, Sweden
  - Presentation at the Industrial automation conference 2015 San Francisco

7 Spridning och publicering

7.1 Kunskaps- och resultatspridning

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	X	The results are spread in the production community at OEMs, line builders as well as SMEs. New projects have already been initiated and new partners has been involved within Swedish production community.
Föras vidare till andra avancerade tekniska utvecklingsprojekt	X	New projects have been created as a result of the VIRTCOM2-project where lessons lerarned have been input in defining new research and development projects. Examples are ENTOC, SPEAR, SmoothIT.
Föras vidare till produktutvecklingsprojekt	X	A clear connection between efficient production system preparation and product development projects has been identified. Early product design concepts can be evaluated in an more efficient and accurate way already in the early preparation phase with regard to the control and automation solution. The need for more detailed models of products and equipment is required in order to reduce the amount of engineering time necessary. This issue have resulted in two new projects (ENTOC and SPEAR) that will be conducted with wide range of industry partners.
Introduceras på marknaden	X	The implemented methods, implementations and tools have been evaluated by the industry partners and the tools and methods can today be used in industry.
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut		

7.2 Publikationer

2017

- Adnan Khan, Petter Falkman, Martin Fabian
  Virtual Engineering Framework for Automatic Generation of Control Logic including Safety
  13th IEEE Conference on Automation Science and Engineering – CASE 2017
- Martin Dahl, Kristofer Bengtsson, Martin Fabian, Petter Falkman
  Automatic modeling and simulation of robot program behavior in integrated virtual preparation and commissioning,
  27th International Conference on Flexible Automation and Intelligent Manufacturing – FAIM 2017
- Oskar Wigström, Nikolce Murgovski, Sarmad Riazi et al, Computationally efficient energy optimization of multiple robots, Proc. 13th IEEE Conference on Automation Science and Engineering CASE, 2017.
- Nina Sundström, Robust and Energy Efficient Scheduling, PhD thesis, 2017.
- Martin Dahl, Kristofer Bengtsson, Patrik Bergagård, Martin Fabian, Petter Falkman
  Sequence Planner: Supporting Integrated Virtual Preparation and Commissioning
  20th World Congress of the International Federation of Automatic Control – IFAC 2017
- Martin Dahl, Anton Albo, Johan Eriksson, Julius Pettersson, Petter Falkman
  Virtual Reality Commissioning in Production Systems Preparation
  22nd IEEE International Conference on Emerging Technologies And Factory Automation – ETFA2017

2016

- Ashfaq Farooqui, Patrik Bergagård, Petter Falkman, Martin Fabian
  Error handing in highly automated automotive industry: current practice and research needs,
  21st IEEE International Conference on Emerging Technologies and Factory Automation – ETFA 2016.
- Amir Hossein Ebrahimi, Knut Åkesson, Pierre Johansson et al, Automated analysis of interdependencies between product platforms and assembly operations, Procedia CIRP. Vol. 44, p. 67-72, 2016.
- Martin Dahl, Kristofer Bengtsson, Patrik Bergagård, Martin Fabian, Petter Falkman
  Integrated Virtual Preparation and Commissioning: supporting formal methods during automation systems development,
  8th IFAC Conference on Manufacturing Modelling, Management and Control – MIM 2016
  IFAC-PapersOnLine Volume 49, Issue 12, 2016, Pages 1939–1944

2015

- Patrik Bergagård, Martin Fabian, Petter Falkman
  Modeling and automatic calculation of restart states for an industrial windscreen mounting station, 15th IFAC Symposium on Information Control Problems in Manufacturing – INCOM 2015,
  IFAC-PapersOnLine Volume 48, Issue 3, 2015, Pages 1030–1036
- Patrik Bergagård, On restart of automated manufacturing systems, PhD thesis, Chalmers university of technology, 2015.
- Zhennan Fei, Knut Åkesson, Spyros A. Reveliotis
  Symbolic computation and representation of deadlock avoidance policies for complex resource allocation systems with application to multithreaded software.
  CDC 2014: 5935-5942

8 Slutsatser och fortsatt forskning

The VIRTCOM2 has given the possibility to take a big step towards virtual preparation and commissioning of production systems including PLC-logic. The project's overall objective was to increase competitiveness by developing complete work chain from virtual preparation, through automatically generated PLC code, to virtual and physical commissioning and many achievements have, as described above, been developed in this direction. The developed methods and tools have been successfully tested in a real industry environment at the industry partner facilities. An important result is that new projects have been initiated based on the research done in the VIRTCOM2 project and new collaborators has been identified. ENTOC is an ITEA3 project where a German consortium is collaborating with a Swedish consortium. In VIRTCOM2 the possibilities with preparation and commissioning has been shown. However, the time required for creating accurate dynamic models necessary is very high and therefore ways of creating these models in an efficient and standardized manner is crucial in order to make the best use of virtual preparation and commissioning. The main aim in the ENTOC-project is therefore to develop efficient methods for creating the necessary dynamic models of production equipment and components in order to achieve a digital twin. Another project that has been applied for and granted is the SPEAR-project that also is an ITEA3-project. The SPEAR-project is a collaboration between a Swedish, German, Portuguese, Spanish and Turkeys consortium. The focus in SPEAR is to extend the dynamic models of equipment with energy models in order to include energy optimization as an important part of production preparation and commissioning. The VIRTCOM2-project has also identified the connection between energy optimization and maintenance optimization. As a result a new Swedish Vinnova project SmoothIT has started during 2017 with the focus to optimize the energy use of production systems and equipment and to analyze the effects on maintenance requirement and life span of equipment and systems. The hypothesis in SmoothIT is that optimized energy use means smother motions and will therefore

9 Deltagande parter och kontaktpersoner

CHALMERS

Industrial Partners	Volvo Car Corporation	AB Volvo	Scania CV	GKN Aerospace	National Electric Vehicle Sweden AB
Contact persons	Stefan Axelsson	Meit Larsson	Andreas Rosén	Andreas Rudqvist	Dan Svensson

Industrial Partners	KUKA Norden AB	Schneider-electric sweden AB	Siemens	Dassault Systemes Sweden AB/Delmia
Contact persons	Conny Pettersson	Peter Grönwall	Johan Nordling	Hans Eriksson

Academic Partners	Chalmers University of Technology
Contact persons	Petter Falkman, project leader