A new vision for the automation systems engineering for Automotive Powertrain Assembly
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### A new vision for the automation systems engineering for Automotive Powertrain Assembly

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A new vision for the automation systems engineering for Automotive Powertrain Assembly

Abstract
Pressure on the powertrain sector of automotive industry is mounting as market demand for higher variety and lower cost automation systems increases. To maintain the market competitiveness, design-to-market time for new products should be significantly shorter and considerable cost saving needs to be made during the design and manufacture of production facilities. Virtual construction, test and validation of systems prior to build is now identified as crucial because engineering changes due to untested designs cannot be afforded any longer, and approved designs need to be reused more efficiently.

In this article, the authors report research collaboration between Loughborough University and Ford Motor Company, to improve the current business and engineering model used in the powertrain industry. The current problems are highlighted and corresponding industrial engineering requirements are specified. The existing end user and supply chain interaction models are captured and a new business and engineering interaction models are proposed to address the requirements. A set of engineering services required for the new interaction models is described and an evaluation approach to identify the impact of the new model on the current enterprises are explained. In addition, an overview given on the research findings on the predicted impacts on the current businesses based on a set of evaluation criteria.

Keywords: Automation system, Powertrain, process and simulation model, Engineering services

Background
According to a survey carried out in 2008 (SMART 2008), global automation market is worth around £180 billion with an average estimated growth of 7.8% annually (prior to the current economical downturn). Factory automation takes 38% of this market and of which £62 billion is the size of the European market in automation systems for control and monitoring sectors. These typically include application design, simulation and modelling, manufacturing, installation and maintenance.
However, global automation industry is changing rapidly. The product lifecycles shrink but demands for product variety and complexity increase and therefore profit margins decline (Molina et al. 2005). This industry is also facing the advent of globalisation businesses, manufacturing practices, organisational and information structures are changing rapidly. Companies are moving from traditional methods, where in-house development teams typically work at a single site, to completely outsourcing or using specialised designed teams working from multiple sites.

For rapid response to such ever changing market demands, the automotive industry is under pressure to shorten production lifecycle time, for example when introducing new engine models in a powertrain sector. The time taken by western automotive firms to design a new engine model, build production lines and commence mass production is typically about 42 months while Japanese firms take around 36 months (Harrison et al. 2001; Monfared et al. 2002; Haq et al. 2007). Also it has been recognised in the automotive industry that 6 months delay for the launch of a new product such as motor vehicle or large subassemblies e.g. transmission units, will cause a significant reduction of its profit margin (Lee et al. 2007). However, the existing state-of-the-art approaches to manufacturing automation systems are facing fundamental limitations and complexity to reconfiguration, integration with supplier chain systems and optimisation. Because of a traditional hard-coded deterministic approach to the logical control of most production automation systems, it is too rigid and inflexible to enable efficient configuration and robust operations (Harrison and Colombo 2005), which is in particular importance when existing plant is being upgraded or a new production system is being installed.

Therefore, the migration from today’s control and management strategies to more flexible, intelligent manufacturing systems is one of the most difficult tasks facing this industry today. It is envisaged that a more proactive engineering approach and life cycle support to automation systems is required to facilitate highly flexible and agile manufacturing systems capable of providing easier and configurable design, installation, commission, and maintenance (Harrison et al. 2006).

This article summarises ongoing research efforts on development of a new approach to the Powertrain sector of western automotive industry in particular Ford Motor Company. The research team in Loughborough University, in close collaboration with Ford Motor Company as a major European automotive manufacturer and its leading automation machine/component builders (e.g. Krause, Schneider Electric,
Bosch Rexroth), is investigating a solution for improving the current engineering approach to design and development of powertrain programs.

**Product Lifecycle Management**

Business changes in all manufacturing sectors, particularly in the automotive sector can be more effectively achieved if appropriate manufacturing systems are able to support reconfiguration, faster ramp-up and better lifecycle support (Haq 2009). Such change is not only limited to the technical systems but it is also essential to extend it to the organisation and employees to achieve an adequate level of changeability. This transformation process becomes an important business process that must be pre-planned and managed effectively (ElMaraghy 2005). To streamline product development and boost innovation in manufacturing by managing all the information about an enterprise throughout the product lifecycle (Sudarsan et al. 2005), the concept of Product Lifecycle Management (PLM) was introduced in 1990s as a business strategy to rapidly plan, organise, manage, measure and deliver new product and services much faster and cheaper in an integrated way (Farhad and Deba 2005; Ming et al. 2005). The importance of PLM solutions has been realised by investment of over $2 billion by different manufacturing companies, mainly automotive and aerospace companies (Sudarsan et al. 2005). However, there is still big gap exists between the increasing demands from industrial companies and available solutions from vendors e.g. using traditional product data management systems. The exchanging engineering data with suppliers has proved difficult, slow and has geographic limitations. Flawed coordination among teams, systems and data interoperability and complex approval processes are common (Ming et al. 2005; Ming et al. 2008). Furthermore, serious data interoperability issues exist because the PLM systems that company employs to support its activities can be made of many components and each of those components can be provided by different vendors (Shyam 2006). Current available engineering systems are considered too complex and general purpose and are typically not focused on the user’s specific needs. For instance providing a visualisation environment to assist the end-user for concurrent design and validation of machine control and mechanical layout is identified as an important engineering requirements needed by end-users (SOCRADES 2008). To facilitate such requirements, different commercially available engineering solutions offers end-to-end Process Lifecycle Management (PLM) solutions and provide an
environment to implement 3D models of production systems with editing, testing and debugging of system control logic against 3D model (SOCRADES 2007). This includes Delmia Automation developed by Dassault Systems (DELMIA 2009) and em-PLC developed by Tecnomatix and Siemens as leading vendors (Tecnomatix 2009). In these applications, the implementation of 3D model of production system (which leads to virtual engineering) is only possible from their proprietary CAD packages rather than through standard 3D formats. Also their editing environment and user interface are quite complex and unintuitive. Several training courses and a large amount of support is required to complete the evaluation process, which reduces the effectiveness of these tools in a mixed/non-specialised skill environment and in the early design phases. Furthermore, end users cannot modularise and reuse the design independently from the vendors (SOCRADES 2008).

Within the automotive industry the design, development and implementation of a new production systems with subsequent lifecycle support involves many globally distributed supply chain partners. This requires specific engineering tools to enable virtual engineering and manufacturing activities to occur concurrently between globally distributed supply chain partners. In recent years a potential breakthrough approach for a sustainable manufacturing industry was initiated by a project named Component based Paradigm for Agile automation (COMPAG 2004). The major goal of this project was to achieve a more efficient and robust design, build, implementation and reconfigurability of automation system via a functionally modular/component-based approach. In response different key areas were identified and investigated with their required new engineering services in depth to improve efficiency and modularity of automation systems. This includes reconfigurability, virtual engineering, concurrent support to product, process and control engineering, lifecycle support and vendor’s independent and open engineering environment. Existing research at Loughborough had created basic technology for a component based approach to automation with the provision of new engineering services. But no research has been undertaken on the application of this approach in a user engineering and business context. This research paper is to summarise this prototype method and associated engineering tools and to devise novel business and engineering processes to enable the component based approach to be applied in industry.

The research in this paper is based on going research projects at MSI Research Institute, Loughborough University. The focus of these research projects is to develop
methodologies and tools to support globally distributed engineering of powertrain assembly machines. A major goal of this research is to achieve more efficient machine design and reconfigurability using functionally modular, component-based approach to the powertrain assembly systems. Similar to this research there are many research projects. For instance, NSF Engineering Research Centre for Reconfigurable Manufacturing Systems (NSF 2009), Radically Innovative Mechatronics and Advanced Control Systems (RIMACS 2007), Model Driven Embedded Systems Design Environment for the Industrial Automation Sector (MEDEIA 2009), Distributed Intelligent Sensing and Control (DISC) for Automotive Factory Automation (DISC 2009) and Distributed IEC 61499 Intelligent Control of Reconfigurable Manufacturing Systems (IEC61499 2008). The mentioned research projects typically investigated general life cycle management or very low level automation systems design, and do not sufficiently address reconfigurability of manufacturing assembly systems in terms of their hard/physical and soft/logical aspects. The focus of this research is to address existing and future challenges faced by powertrain assembly systems within the automotive industry. This research aims to facilitate 1) new engineering environment to build and configure machines from reusable smart modules, 2) concurrent engineering between product, process and control engineering to achieve up to 100% virtual design and validation of manufacturing systems prior to build 3) offer lifecycle support from new set of engineering tools, 4) vendor’s independent environment and 5) provide support for globally distributed engineering teams within the supply chain of powertrain assembly systems (i.e., remote monitoring and maintenance).

Problems facing powertrain sector

According to the European Automobile Manufacturers Association (ACEA), Europe is the largest vehicle producer in the world with over 13 major automobile manufacturers, contributing significantly in the EU economy (ACEA 2008). Ford Motor Company is one of the world’s largest manufacturers of its kind with taking around 15% of the European car market (Bekker 2009). Ford involves with globally distributed suppliers for their automation systems design and development i.e. Powertrain Systems. With ever growing emphasis being placed on global production systems, service and lifecycle support has become an integral part of the manufacturing system.
However, similar to the other leading players in automotive industry to maintain competitiveness, Ford is also facing extreme pressure to provide more agile engineering system to enable rapid response to market changes (Haq et al. 2007). Despite the extreme expertise available in this industry, the engineering systems are fragmented and typically result in delays in production launch and therefore extending the ramp-up time (the ramp up is the time required to get from the first day of series production to the point where it is able to consistently run at the design speed, commonly known as maximum “jobs per hour – JPH”) (Haq 2009). The notion of modular and reusability of design and manufacturing is not new in this industry, nonetheless, the infrastructure required to enable reuse of the past production knowledge is still not in place. Furthermore, it is a common understanding that ability to rapidly reconfigure previous designs (e.g. customisation) must be embedded into the engineering lifecycle, however application of various engineering tools used by hundreds of suppliers, make it almost impossible for the end user (i.e. Ford in this research) to provide a consistent control over the engineering development lifecycle. Throughout the lifecycle of automation system, there is no common representation/visualisation of engineering activities, between supply chain partners (Ong et al. 2006).

To demonstrate the magnitude of the above mentioned problems, which typically leads to delays in launch of a new product or shutting down the production line, it suffices to mention that according to statistics captured by this research work, 50% saving in the ramp-up time would typically save 20 million Euros in a typical European production line, and every minute delay/malfunctioning in production line cost up to 6000 Euros for the end users (Harrison and Colombo 2005).

**Current approach to the engineering of powertrain automation**

In a typical powertrain program, a new engine project starts with strategic planning and market study, which leads to the identification of the product specification and the requirements, volumes, and fund approval. Following several simultaneous engineering meetings with suppliers and machine builders, the machine production lines are conceptually designed and manufacturing of lines is started at the machine builders’ sites. The machine builders carry out the detailed design, test and installation of machines, with frequent inspections by engineers from the engine manufacturers. Machine
builders also sub-contract machine components to specialist component builders and concentrate on overall line design, line assembly and commissioning of the mechanical, electrical, hydraulic, and control systems. Typically about 4 months prior to the completion of the project, the machinery should be dismantled and delivered to the manufacturer sites for final tests and try-out machining. Onsite engineers then perform a detailed examination of all production and assembly lines at the site. At the end of this stage (known as job 1) engine manufacturer is ready to produce the first engine and commence the mass production. At the same time, the assembly lines are ready to assemble various engine components to the engine block. The lines will be under constant inspection for several months to avoid problems related to the training, machine adjustments and maintenance.

Conventionally the design activities by machine builders take place sequentially beginning with mechanical engineering followed by electrical, hydraulic and control engineering activities, as illustrated in figure 1. In the existing approach, the product specifications are typically interpreted by process engineers to produce a suitable machine configuration with process cycle charts written to specify the necessary timing of machine movements, which are later interpreted by programrs to produce structured control software. Associated operator interface screens and machine diagnostics and monitoring applications are finally added (Harrison et al. 2001; Harrison et al. 2006). As a result, the design activities of hardware and control system remain isolated from one another and their verification can only be carried out during commissioning after build, which ultimately causes a longer and more costly ramp-up period.

"[insert figure 1 about here]"

Despite the significant developments in the domain of assembly system design there is still a lack of well developed assembly system engineering techniques and methodologies, also highlighted by different research works (Harrison et al. 2001; Harrison et al. 2004; Harrison et al. 2006), for example: the existing state-of-the-art automation systems are relatively effective but approach to design and build process is almost entirely sequential and heavily segmented organisationally into different engineering disciplines.

This approach also has cost/quality impact later in the production phase of the machines lifecycle. For example if a change is required after several months of
operation the engineers involved will be required to revise a large/ if not all of the process in order to identify and limit the impact of the change on the machine. Furthermore, end-user involves with a number of suppliers, and therefore dealing with inconsistent document formatting and structures. It has been observed that translations to the end user required format has been a root of many problems since there are (i) no common system representation, (ii) ad-hoc integration of engineering partners using fragmented design tools, (iii) the machine control logic is only understood by specialists and (iv) there is no modelling of machine operations. More comprehensive description of the existing system is documented in (Monfared et al. 2002; Haq 2009).

Next-generation of automation design and build

The present global and competitive environment poses formidable challenges to global manufacturers including the automotive industry. To facilitate and accommodate unforeseen business changes within the automotive industry, a new proactive approach is required to design, build, assemble and reconfigure automation systems. Such innovative approach would require promoting new technologies and engineering methods to: a) enable engineering concurrency, b) investigate design alternatives prior to building and testing physical systems, c) provide predefined and pretested design components (as well as physical components), and d) enable application of virtual engineering at early stage of program design phases. Furthermore, such technologies and methods needs to be sufficiently end user oriented to allow them as major investor on the systems to own the engineering knowledge and be able to reuse the business and engineering knowledge for the future programs.

A component based approach to the development of automation system is illustrated by figure 2. Lifecycle phases of automation system design and development and primary role of each supply chain partner are depicted on the left hand side of the figure. During machine design, implementation, build and validation phases, existing approach followed by supply chain partners is also shown in the upper right side of the figure 2. Based on ten years of experience with world leading automotive manufacturers (i.e. Ford and its supply chain collaborators), the Loughborough research group has recognised that this present methodology for design/built is causing fundamental limitations and difficulties in the service, reconfiguration, integration and optimisation of machines, particularly in the face of rapid and often
unpredictable business changes. The current engineering approach may offer adequate operational performance due to well proven and established methods. However, it is not able to cope well with new customer requirements and globally distributed manufacturing demands. The current approach is typically dominated by the use of general purpose engineering tools and the continual reinterpretation of paper-based specifications. Throughout the design process, few tools are available to integrate and verify new design before actual building. Such sequential nature of the detailed engineering design of automation systems provides little chance of concurrent engineering processes in order to shorten the life cycle. Performing test and verification processes at the end of the design phase presents risk of very costly rework on design and build. Moreover, lack of a repository system to store and reuse design mechanisms and manufacturing process modules (known as bill of processes) causes inefficient reuse of engineering knowledge collected from previous engineering programs.

"[insert figure 2 about here]"

A new modular approach proposed for the design and build of automation system is also illustrated in figure 2. The vision is to decompose automation systems into standalone sub-systems and components in a generic manner, which are configurable with a set of parameters and may vary based on specific applications. The components include complete design for mechanic, electric, hydraulic, and control aspects, and are commissioned fully in respect with the functionality defined for the component. Such predesigned and pretested components (or a combination of some components and sub-systems) are to be stored in a library of reusable mechanisms. In this approach the concurrency of design can be significantly improved, leading to compression of program life cycle, with much reduced risk of design related malfunctioning due to the use of pretested systems modules. This new approach facilitates early virtual integration and commissioning of pre-defined and pre-commissioned mechanical, electrical fluid/software components. As a result less business/engineering process management efforts are required and better lifecycle support can be provided. Nevertheless, the proposed approach to the design demands a set of advance engineering services such as comprehensive virtual engineering tools (to develop and then deploy the library of mechanisms), a consistent approach to the system design format across all supply chains, and a new business and engineering interaction model. In order to support a new engineering environment between globally
distributed supply chain partners, a new vision of a Collaborative Work Centre (CWC) is proposed. The aim of CWC is to establish and maintain vendor independent environment in the form of generic and configurable building blocks of machine families (i.e. library of modules as highlighted in the figure 2) prior to “product engineering”. Therefore CWC has significant potential to bring agility within the manufacturing systems with potentially reducing the time, cost and resources. The new approach can also enhance the robustness of the system design, improving the responsiveness and competitiveness of automotive industry.

**Next generation collaborative and configurable automation systems (NGCCAS)**

To deliver agility through modularity and reconfigurability within the future of automation systems, this research work has proposed and developed a new realisation approach called next generation collaborative and configurable automation systems (NGCCAS). Conceptually the application of NGCCAS brings agility and reconfigurability via new business and engineering process interactions for the powertrain automation systems. Figure 3 illustrate realisation model based on NGCCAS approach. The principle focus behind this new realisation approach is to primarily provide a) reconfiguration, b) collaboration, c) visualisation and d) lifecycle support for future automation systems. The application domain of NGCCAS includes integration of generic library of modules with the use of new engineering services. Initially with the application domain of NGCCAS up to 100% virtual design, build and its validation and verification could be achievable during study and planning phases called “simultaneous engineering” as shown in the figure 3. This figure describes a systematic way to design and construct new automation system based on a more integrated, concurrent and vendor independent engineering environment. However, complete business and engineering process models required for NGCCAS approach are described later in this paper.

"[insert figure 3 about here]"

Based on the future needs of the automotive industry, CWC is being developed for multiple facilities (proposed idea is to hold and support number of different generic solutions) with minimum complexity, risk, lead time and minimum skill level using advanced communication technologies. To meet such requirements the CWC is comprised of 1) product engineering (i.e. engine), 2) required generic solutions 3) new engineering method (NGCCAS), 4) new engineering services and 5) business
and engineering process work flows required to design and develop new automation systems. The existing ad-hoc integration mechanisms are replaced by CWC to offer more service oriented support and collaboration within the supply chain for future businesses. Therefore such an environment can bring engineering concurrency and can investigate new design alternatives prior to physical build and test of production/assembly machines.

As illustrated in the figure 3 the proposed CWC can facilitate study and planning phase to manage virtual design, build and validation of new automation systems for a new set of business requirements (e.g. a new engine) in a virtual environment (prior to the physical build). The initial product of the study and planning phase will be a validated virtual design for the complete assembly or manufacturing lines related to the new engine program. The virtual design will then be sent to the machine builders for final detailed design, manufacture and installations within the factory site. To support migration from existing to NGCCAS practice different steps prior to the actual building and implementation of automation system are introduced during planning phases. These steps are called in-process steps (i.e. step 1 to 8) as highlighted in the figure 3 originating from the end-user requirements and will be performed by domain experts. Initially, it contains a standard library of reusable, predefined and pre-validated mechanisms, i.e. predefined system components and bill of processes (BOP) that is required to produce the components. Such library is expected to be developed and completed gradually as knowledge of more engine program is captured. Based on preliminary reconfiguration of generic mechanisms, end user planning teams can identify commonality of the new project in comparison to the past programs and develop new process plan for the reuse of the existing system components and also develop new components and sub-systems level requirements. This allows the program manager to make adequate planning at early phases of the program. After planning, new mechanisms will be virtually designed and built by the supply chain experts and integrated into the existing reused components. Following the virtual engineering, the mechanisms will be assembled with existing mechanisms available in the library to achieve component, sub-system or systems. Furthermore, as part of the detailed design phase, analysis and optimisation services will enable domain experts to optimise components, subsystems and systems level requirements in terms of their cycle time, kinematics, and their control behaviours of the kinematics. This is proposed to be provided through a
simulation services within the machine design build phase (e.g. checking the components/system design integrity, conditions and interlocks, and cycle time). The validation process (i.e. pre-commissioning) starts at the fifth “in-process step” as illustrated in the figure 3. It is proposed that virtual engineering services are required to enable verification of assembled components (and their associated sub-systems) to verify fully the new developed system prior to the real implementation of physical system. At this stage, a set of engineering application capabilities are prescribed to provide the virtual engineering services. Having completed the sub-systems verification, the complete manufacturing and assembly lines should be virtually tested and commissioned. By completing this process a new “Virtual Design J1 (VD1)” milestone would be met. This new milestone is proposed to provide an approval by the end user to authorise development of the physical systems.

The proposed CWC also highlights need for engineering capabilities to develop remote maintenance infrastructure to allow machine and component builders to provide diagnostics, repair, and monitoring services for the end user during the installation and after production launch. In addition, the CWC proposes a model in parallel with the business model to constantly analyse (and predict) the program resources costs and time as it progresses.

Furthermore, the proposed business and engineering model described as NGCCAS approach potentially offers significant improvement to the management of the powertrain programs when a new variation of engine is introduced to an existing line (known as 2nd cycle). This is mainly due to the reusability of the system components and re-configurability of systems based on the proposed engineering services.

The new engineering model described above is being developed in conjunction with real industrial case at Ford Motor Company, in the UK. In the remainder of this article a prediction on the implementation impact of the new engineering model is discussed.

**Evaluation of impacts on engineering processes**

In a close collaboration between Loughborough University and Ford UK, following many industrial visits and several brainstorming sessions, some of the more urgent user needs were realised as follows. The current ramp-up period and reconfiguration of powertrain assembly lines are too costly and too long. The scope of virtual engineering during different phases of automation system lifecycle is limited due to the application of general purpose engineering tools. There is a great difficulty in
reuse of the knowledge from the past powertrain programs. There is no efficient way to predict the cost and effort required for engineering changes (both product and processes). Currently a manual estimating process is used, which is slow, labour intensive and at times does not generate accurate study results. Verification of design can only be completed after build and installation, and therefore they are very costly to change. There is no uniform engineering application available to the end user to monitor, control and in later projects reuse the knowledge generated by globally distributed supply chain partners involved with a powertrain program.

To develop the application of NGCCAS within a real industrial environment, Ford Engineering centre at Duntom Technical Centre, and Dagenham Engine Plant, in Essex, UK were targeted. It was envisaged that prior to any recommendations for change, it is necessary to understand the existing business and engineering processes and be able to propose new NGCCAS approach in a form compatible with the end user business processes.

Figure 4 illustrates the three step approach taken to capture the existing processes for a typical powertrain program for the end user and evaluation criteria/metrics defined to evaluate the required processes changes when proposed migration is deployed as illustrated previously by figure 3.

As shown in the figure 4, definition of the end users’ requirements constitutes the modelling objectives in this research. The aim is to understand and subsequently compare the two engineering models based on a set of criteria to enable prediction of the change impact on the existing engineering model. In general, Enterprise Modelling (EM) approach has been adopted in this research to capture and formalise system interactions. The aim of EM is not only to represent complex process structure of the corresponding organisation, but also to identify and propose possible improvements within systems. EM provides a solid foundation for the capturing, modelling and analyses of the business and engineering system. In this research, EM has been used in compliance with specifications defined by two international standards, namely ISO-19439 and ISO-15704\(^1\). The existing processes were captured

\(^1\) ISO 19439 - Enterprise Integration, Framework for Enterprise Modelling.

from the end user sites and formalised in form of a set of static diagrams developed in Loughborough University (Monfared et al. 2002) in compliance with the CIMOSA modelling architecture (ESPRIT 1993; Berio and Vernadat 1999; Mertins and Jochem 2005). The static models were used to develop process simulation models, as both models share similar modelling constructs (e.g. process decompositions, information and resource objects). The process simulation models facilitate customisation of models based on different variables captured from the physical environment. Both process models and process simulations have been undergone a vigorous validation process leading to the approvals from end users and supply chain engineers. In addition, other standard validation approaches were also deployed, such as those suggested by (Robinson and Bhatia 1995; Robinson 1997; Robinson 2006; Monfared et al. 2007). The NGCCAS approach continues by designing a new business and engineering processes and supply chain interactions. The proposed model is designed based on the end user requirements and engineering services required to meet those requirements. The new engineering model is also subjected to the process modelling, process simulation and validation steps. Completing the development of both business process and interaction models, the two models are compared on the basis of end user most important business performance metrics, e.g. cost, time and reliability of the design as engine program progresses. Finally, the process simulation models are customised and the modelling results are analysed based on the evaluation criteria, to provide predictions on the impact of introducing the new business model to the existing engineering systems.

CASE STUDY
Ford’s DVM4 (Dagenham Plant, UK) engine assembly line, known as “Tiger assembly line” was considered as the case study in this research, as shown in figure 5.

"[insert figure 5 about here]"

Ford’s engine production lines at this site are state-of-the-art industrial application to complex engine assembly operations. The lines typically include various combinations of production resources such as machines, conveyors, human operators. The introduction of a new engine project requires significant engineering competencies, time and budget. Multiple end user program teams are involved to
coordinate thousand of parallel engineering activities with supply chain partners. This assembly line was installed and commissioned in 2007, with a substantial investment for a capacity to produce over 500,000 mixed products per year (combination of various size diesel engines). Krause™ (a global automation machine builder) was mainly involved as a supply chain partner in the design and development of the Tiger assembly line including conveyors and work stations. The fully automated stations with robotic arms were supplied by the ABB™ suppliers (another global automation robot vendor). Assembly line illustrated by this figure consists of work stations and transport system i.e. conveyors that link together with various assembly stations. A conveyor carries pallets with loaded engine blocks which are then moved onto different workstations distributed along the transport system. At different workstations various engine parts are assembled e.g. pistons, connecting rods, cylinder head etc. Sensors and mechanical stops are used throughout the transport system to track the pallets and direct them down to different conveyors according to information stored in each respective pallet. The expected working life of this assembly line is about 7 to 10 years. However, in today’s very competitive and turbulent automotive industry, any assembly line with such long life is required to produce many different engine variations. Therefore robust and less costly re-configurable automation systems are prerequisite.

Process Modelling

As discussed earlier, the process model is represented in form of a set of diagrams as enhanced CIMOSA representation view (Monfared et al. 2002). According to this approach, system processes are decomposed into Domain Processes (DP), Business Processes (BP), and Enterprise Activities. Depending on the granularity of a model, a system can be broken down into various combinations of these modelling constructs. The models are represented in form of 5 different interlinking diagrams formalising context, structure, interaction, activity, and process definitions. The current business and engineering processes are captured and formalised in the manner described above. Figure 6 illustrates a sample of the extensive engine program model developed in this research.
The process model is developed from the end-user perspective in which “planning and business office (DP1)” and “manufacturing engineering (DP5)” domains are responsible to design and build new automation systems from program start to its completion. The “DP5” is further decomposed systematically into seven sub domains as highlighted in figure 6. In order to capture and model rigorous business and engineering processes within all eight different domains, a complete understanding of the “V” system engineering was developed as adopted by the Ford Motor Company as shown in the figure 6. Different milestones from end user perspective are introduced on this “V” model to assure successful completion of new automation from concept to launch. Theses milestones are further mapped into business and engineering process domains. Therefore all the eight domains are firmly linked with “V” model as shown in the figure 6. Further these eight domains are systematically decomposed into activities and mapped with different milestones on the time scale as highlighted in the figure. As an example figure 6 describes activities performed by DP1 and Dp5.1 domains with their required inputs and outputs. Initially a new business case is developed by DP1 to meet future business trends, which ultimately become input to sub domains of “DP5”. This includes “program management (DP5.1)” and “program planning and feasibility (DP5.2)” as shown. Based on a new business case “DP5.2” develops a comprehensive document on “new program planning and feasibility” and delivers to the “DP5.1”. In parallel “DP5.2” start communication with different suppliers. In response machine builders proposed their new ideas and cost models. Finally a letter of intent is issued to the selected supplier.

Program Management (DP5.1) starts when new business case is initiated by DP1 and finishes after completion of Job1 and launch period. Initially an important document called “new program work plan” and “long lead funding” is developed and delivered by “DP5.1” to business process “Simultaneous Engineering (SE) BP525” as highlighted in figure 6. Based on these documents end-user negotiates on time and cost for new program with machine builders. During SE process detail level of understanding is developed to identify system and sub-system level requirements. After detailed negotiations between end-user, machine builder and control vendors program is approved by board of directors and “First Order” is placed by the end-user to machine builder.

Once first order is placed, machine builders start design and build of new assembly machines. At the same time domain process “program engineering (DP5.3)” start
preliminary activities for mass production. Typically new machines are delivered to
the end-user in 12 to 18 months time period. During this time these new machines are
partially commissioned and verified by end-user witness teams in process called “1st
run-off and tryout phase (BP542)” at the vendor’s site. Finally all newly built
machines are shipped to the end-user to start domain process “installation and
commissioning DP5.5”. In this domain the machine builders contribute with highly
skilled commissioning teams to prepare new machines for a vital domain called
“Running Rate and Quality Test (DP5.6)”. The last domain of new program is known
as “job1 and launch (DP5.7)”. The main focus of this domain is to achieve rate of
climb (ROC) i.e. to run the line at its designed capability rate. Once ROC is
confirmed program management (DP5.1) publishes a completion report in the
business process “lesson learned (BP572)” and confirm launch readiness for the
vehicle plant.

Process Simulation

Process simulation modelling is used to measure and analyse performance of static
process models. The process simulation also allows customisation of the process
model based on the operational parameters. The simulation models analyse the
process model over a period of typical powertrain program and measures key
performance factors and allow execution of “what if scenarios”. It was envisaged that
application of simulation model provides sufficient capability to extend the static
model to a dynamic environment and enable the end users to customise the model for
individual cases that ultimately assisted the validation of the models. However, other
approaches such as optimisation methods were also studied to provide support for
analysing the key performances, in particular, calculating the robustness factor. For
this particular factor mathematical approaches were embedded into the simulation
model to provide both flexibility that simulation provides and accuracy in the results.
Figure 7 illustrates part of developed process simulation within this research. In
developing the process simulation the prime focus was to maintain complete
consistency between static process modelling and simulation model in order to
seamlessly integrate the key modelling constructs between the two models (i.e.
process and simulation models). As one of the essential features within the process
models used in this research is a hierarchical support structure and reusability of
modelling constructs used to develop process models. Similarly, the process
simulation models (developed using Arena™ commercial software (Seppanen and Kumar 2002; Bapat and Sturrock 2003)) were designed in several levels (i.e. sub-models) as highlighted in figure 7, which correspond to the hierarchical structure and allow re-usability of modelling modules. Theses sub-models represent eight different business and engineering process domains as illustrated by figure 6. Enterprise knowledge captured for process modelling has different views (i.e. functional, information, resource and organisation view). Such views are either defined as an input or output required for each business and engineering process. To design, build and execute the simulation model all these views are categorised into: a) functional objects, and b) behavioural objects. Functional objects are either inputs or outputs for each process, which may or may not dependent on other process functional objects (e.g. flow of information, physical resources etc.). On the other hand behavioural objects describe the logic or sequence of processes i.e. to define process logically either to make sequential or concurrent flows. To utilise these objects within the process simulation environment, simulation parameters (i.e. execution variables modules) were used to facilitate populating and configuring the process simulation models for specific powertrain program. In order to facilitate tracing and validation of simulation variable in such large and complex models, variables (e.g. information, event, time or human resource) are defined in a symbolic way to represent their concerned domain processes. For instance “INFO_BP435” or “PR_EA21” represent information or physical resource object for certain business process or enterprise activity. This approach also enables triggering simulation process based on preconditions, which correspond to the business and engineering processes of the powertrain program. Furthermore, such structured approach to the simulation design allows integration of the simulation models to (and from) other engineering applications, such as existing project management tools, and central data repository system.

As illustrated by figure 7, the simulation process runs based on a set of default parameters suggested by the end user for typical (semi-generic) programs. The users vary parameters and execute the model. In addition the Arena tool supports the quantitative analysis (e.g. probability function and random generation of entities) as required in this research to measure and compare future approaches robustness. In this research an innovative method is developed to enable domain experts to quantify and predict robustness of a given system for selected issues before implementation. For
instance figure 7 illustrates comparison between existing and new NGCCAS approach against those specific issues which were identified and quantified. Following execution of a number of simulation replications, the modelling results are exported to external analysing tools to be compiled in a suitable format (e.g. reports, comparison graphs, etc.).

"[insert figure 7 about here]"

**New engineering process and interaction models**

Innovative engineering and interaction models are proposed to address a number of user requirements identified at the earlier stage of this research. These include: development of design mechanisms libraries to facilitate reusability, introducing new engineering services to enable consistent virtual design across the end user (and supply chain) program life cycle, description for new supply chain interaction models to integrate the machine/component builders engineering efforts in line with the end user activities, and provide more concurrent design processes to shorten the overall program time.

Figure 8 illustrates part of the new engineering process model developed in this research. As partially appears in the figure, libraries of pretested components, bill of processes, and design mechanisms are available to the end user engineers at various phases of powertrain program. The required engineering services are interpreted into engineering application tools required at each stage of the engineering model. The proposed models identify in great details what application functionality (e.g. component builder or system viewer – see figure 8) is required for each business process (BP’s) and what engineering expertise (with what skill level) should use the new engineering applications. The new model also specifies changes on the current process flow, information and resource requirements for each process. Furthermore, it introduces a set of interaction mechanisms with the supply chain (e.g. exchange of information, documents and the timing within the program life cycle) to outsource certain part of the design process without losing control over the program management or the knowledge ownership. Comparing the models illustrated by figures 6 and 8, it is clear that due to the application of virtual engineering, more engineering activities can be completed concurrently, which will result in compression of the program overall time. In addition, the new “Virtual Design 1” (VD1) program management milestone introduced in this research will represent the
phase that theoretically the design of all processes and facilities are completed virtually and tested fully (up to 100% as libraries are gradually populated). For further detail on the proposed engineering model refer to (Haq 2009).

"[insert figure 8 about here]"

**Evaluation criteria**

After deploying the new business and engineering approach, to predict potential improvement on powertrain automation system, a number of evaluation criteria were identified based on the end user requirements. These criteria naturally include cost and time. In this research domain, the cost and time of the design and manufacturing processes and resources, and the cost of changes (due to errors, or design changes) are from outmost important factors. However, there are unquantifiable factors that also have significant impact on the program performance and are key indicators for the end users to evaluate an engine program design and build. For instance, the correctness of the design at each stage of the design of manufacturing and assembly lines has direct impact on the cost and time of engine program. A slight design misalignment at the early stages of the program life cycle, may lead to a major costly and timely re-design or re-build during the test and installation. In this research, an innovative method was developed to enable measuring and prediction of improvement on design correctness at each phase of the life cycle. The “robustness” factor was introduced as new evaluation criteria to compute (via simulation model) the potential improvement on the design correctness due to the application of pre-defined/pre-validated system component approach. The robustness is defined as a risk factor in achieving planned automation system design due to certain problems associated with design processes. A robustness ratio is calculated based on multiplication of a) severity of impact on the production, b) frequency of occurrence, and c) ability to detect and eradicate a problem at a certain phase of the life cycle. The design problems during the production launch are categorised into 6 different groups. These problems initiate due to inaccuracy in: 1) product concept design, 2) time to achieve production volume, 3) machine design, 4) tooling process, 5) predicted breakdowns, and 6) productivity assumptions. Different robustness ratios are calculated for eight different domain processes modelled (see figure 6) for this case study. Based on the
data captured and analysed from the end users, quantified values were associated to each elements of the robustness (i.e. severity, occurrence, and detection).

A robustness simulation model was developed to compute the robustness of each domain process based on calculating the probability of each 3 elements of robustness ratio against the six groups of design problems.

The occurrence of the design problem in this domain was envisaged to have a uniform distribution due to the nature of the domain processes. In addition consecutive design problems would accumulative impact on the overall robustness. Therefore a cumulative discrete probability function was selected for calculating the robustness.

The robustness ratio (Rr) for each design problem group of one domain process is calculated by

\[
R_r = S_v \times O_c \times D_t
\]

(i.e. Severity, Occurrence, and Detection). The probability of occurrences (POc) are calculated by the simulation model based on distribution function of

\[DISC(CumOc_1, X_{Rep1}, \ldots, CumOc_n, X_{RepN})\]

when X is the possible discrete value and Rep is the range of the function. The range in this simulation model defined by the number of replications of the simulation model and was set to 25 (larger number of replications has insignificant impact on the simulation results). Therefore overall robustness (R) for one domain process is calculated by

\[
R = \sum_{0}^{5} POc
\]

which is cumulative probability of 6 different problem groups for one domain process. Similar approach was taken to calculate the overall robustness related to one problem group against the eight domain processes.

For instance, it is unlikely to reach the nominal volume of engine production as originally scheduled. This is due to many reasons at different phases of the design and build. In this example, according to the data captured from domain experts, problems occurred in the “Program Planning and Feasibility” domain (DP5.2) have severity (Sv) impact of 8 (out of 10) on achieving nominal volume. However at this phase of the engine program it typically occurs on 60% of the cases (Oc) and can be detected (Dt) at this phase in 6 out of 10 cases. The simulation model shows that robustness (R) of the system design at this domain is 52% that means there is a 48% chance that nominal volume will not be met as scheduled due to problems in DP5.2.

**Predicted Results**

The developed process models of the powertrain program highlighted problems areas in the current business and engineering processes. The findings include lack of
infrastructure and application tools to enable reusability of knowledge (e.g. design and processes) and lack of ability for rapid reconfiguration of design after process/product changes or following a 2\textsuperscript{nd} cycle production plan (i.e. introducing new product to the production line). These are represented in the process models as lengthy and expensive business processes, and also as major delays on production launch. It was also realised that many of the process bottlenecks identified by the developed models correspond with the initial business requirements set stated by the end users. This fact not only validates the reliability of the modelling approach, but also highlights that end users understand their current engineering problems as a whole, however they have difficulties in pinpointing the problems within the context of their engineering life cycle and therefore unable to rectify them.

The new business and engineering process model prescribes an enhanced approach for managing powertrain programs, which is predicted to improve some of the current problems. This should be possible though integration of proposed new engineering services (and their application tools – see figure 8), and revised supply chain interaction models suggested by this research. In addition, development of pre-validated design modules and the library of reusable modules have key importance on the business process improvement.

The process simulation models led to an extremely detailed calculation and comparison of system specifications before and after implementing the new business model. The modelling outcomes indicate very promising results in terms of saving in engineering costs, shortening the processes, and improving the reliability of the design of production lines (via calculation of the design robustness). The modelling outcomes are summarised in the Table 1.

"[insert Table 1 about here]"

For instance\textsuperscript{2}, some of the areas that is predicted to be influenced heavily by the proposed approach are “Program Planning and Feasibility- DP5.2”, “Program Engineering – DP5.3”, and “Job1 and Launch – DP5.7”. The modelling results predict 38\% reductions on the length of DP5.2, and 63\% on DP5.3. Similarly, the process DP5.7 is expected to initiate 5 months earlier than current approach (in a 42 month

\textsuperscript{2} Further information on the modelling approach and complete modelling and predicted results are documented by Haq (Haq 2009).
As a result overall 24% less time and 27% less resources can save 30% cost for future new powertrain programs. In particular, resource group called “process and automation engineering” requires 37.5% less resources. However, an increase in “Virtual Engineering” efforts by 3 times is predicted. Furthermore, the mathematical calculations suggest significant improvement in overall design robustness. For instance, the robustness ratio in DP5.2 and DP5.7 is expected to increase from 52% and 60% to 92% and 96%. This has been achieved with the proposed new business and engineering processes, new milestones and usage of new engineering tools as highlighted in the figure 8. This is a significant improvement on the design process, which has direct impact on time and cost of the programs by avoiding reworks and changes.

However, to understand fully the impact of the proposed next generation collaborative and configurable automation systems (NGCCAS), the new approach should be implemented within an industrial environment. Preparation is being made to implement the NGCCAS approach within the Ford engineering centre during its next major engine program in the UK. Initially, the new engineering model will be used in parallel with the program management system to shadow the processes. This will enable a direct comparison of predicted results with actual benefits of utilisation of engineering tools in real engineering processes.

CONCLUSIONS

Lack of agility and responsiveness to the market changes were identified as some of the existing problems with automation industry. An approach to the next generation collaborative and configurable automation systems (NGCCAS) was proposed to improve the current problems in the design and build of powertrain automation systems. The developed approach proposes establishes link between business requirements and engineering applications. It provides changes on the business and engineering processes within this sector of industry, and describes new supply chain interaction mechanism. The existing enterprise processes were captured and compared with a new model of the engineering paradigm. The comparison indicates considerable improvement in the way current automation programs work. A set of engineering services combined as a collaborative work centre (CWC) was defined to be integrated in the current business and engineering model. Description for the corresponding engineering applications and their potential implementation phase
within the engineering life cycle were briefly discussed. The use of enterprise modelling and process simulations was discussed to visualise the current and the future enterprise processes, and enable detail analyses of various production scenarios.

On the basis of the modelling approach taken, it was predicted that the application of NGCCAS approach should enhance significantly the agility and responsiveness of automation system development. The new engineering model is planned to be tested in a real industrial environment as part of collaboration between research group in Loughborough University and Ford Motor Company, UK. This research to date has been principally centred at the end user. However there is strong desire to expand this core concept within the business context of other supply chain partners. This will identify their detailed business needs and to understand their current approach to the design and build of powertrain automation systems. A large body of further research is needed to extend the proposed idea of a CWC and to study new role of supply chain partners and their more service oriented relationships. Particular attention is required to consider the costs and deployment efforts needed in developing a generic bill of process i.e. libraries of mechanisms within the powertrain sector of the automotive industry.

Acknowledgment

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Table of Figures

Figure 1: A convectional sequential approach to the development of automation systems
Figure 2: proposed component based approach to the development of automation systems
Figure 3: Proposed next generation collaborative and configurable automation
Figure 4: Enterprise modelling approach deployed in this research
Figure 5: Tiger assembly line, Dagenham Plant, Ford, UK and a typical schematic for similar engine assembly line
Figure 6: Part of the process and interaction models developed for the current powertrain engineering system

Figure 7: Snap shots of the developed simulation and analysis models

Figure 8: Part of the new business and engineering models proposed in this research

References


For Peer Review Only

Strategic Planning
Market Study

Concept Design

Machine Design and Build

Detailed Design

Installation and Commissioning

Powertrain Life cycle

Fragmented Serial Approach, little modularity, difficult to reconfigure

Interpret Customer Requirements

Mechanical & Electrical Design

Mechanical & Electrical Build

Commissioning

Powertrain Lifecycle

Machine Builder & Control Vendors Design new machines according to end user specifications

Partial Implementation of new machine at Machine Builder Site

Validation by End User Witness Teams

Shipment by Machine Builders to End User Site

Installation & Commissioning by Machine Builders at End User Site

End User develop new business case for new program according to new product requirements

New Approach

Conventional Approach

Time

Verify Application

Machine Design

Software / Commissioning

Figure 1: A conventional sequential approach to the development of automation systems

Figure 2: Proposed component based approach to the development of automation systems

URL: http://mc.manuscriptcentral.com/tandf/tcim Email:ijcim@bath.ac.uk
Realisation of Next Generation Collaborative & Configurable Automation Systems

Study & Planning Phase

2. New Process Planning
3. Virtual Engineering & Assembly (PDE)
4. Analysis & Optimisation
5. Virtual Validation & Verification
6. Virtual ME J1
7. Reliability & Maintenance (REA)
8. Cost Analysis & Physical Resources

Collaborative Work Centre

Domain Experts
- Process Engineering
- Program Management
- Productivity Engineering
- Plant Engineering

Figure 3: Proposed next generation collaborative and configurable automation

Validation by Data Analysis, Experiments and Industrial experts

Modelling Objectives
- Capturing Data
- Process Modelling
- Process Simulation
- Experiments/Customisation

Design New System

1st Step
- Requirement Definition
- System Capture or System Design

2nd Step
- Enterprise Modelling (static or conceptual model)
- Process Simulation

3rd Step
- Evaluation Criteria/Metrics

Figure 4: Enterprise modelling approach deployed in this research
Figure 5: Tiger assembly line, Dagenham Plant, Ford, UK

Figure 6: Part of the process and interaction models developed for the current powertrain engineering system
User interface to customise the model

Figure 7: Snap shots of the developed simulation and analysis models

![Diagram of simulation and analysis models]

Figure 8: Part of the new business and engineering models proposed in this research

![Diagram of new business and engineering models]
<table>
<thead>
<tr>
<th>Domain Process</th>
<th>DP1</th>
<th>DP5.1</th>
<th>DP5.2</th>
<th>DP5.3</th>
<th>DP5.4</th>
<th>DP5.5</th>
<th>DP6.6</th>
<th>DP6.7</th>
<th>Significant Improvements</th>
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<tr>
<td>Robustness</td>
<td>Existing Approach</td>
<td>74.7%</td>
<td>90.1%</td>
<td>92.5%</td>
<td>94.9%</td>
<td>94.6%</td>
<td>99.8%</td>
<td>98.4%</td>
<td>98% (reduction in planning &amp; 35% launch phase)</td>
</tr>
<tr>
<td></td>
<td>NGCCAS Approach</td>
<td>97.3%</td>
<td>77.1%</td>
<td>91.2%</td>
<td>87.0%</td>
<td>97.7%</td>
<td>99.3%</td>
<td>94.8%</td>
<td>96.4%</td>
</tr>
<tr>
<td>Time</td>
<td>Existing Approach</td>
<td>219 (Days)</td>
<td>100 (Days)</td>
<td>006 (Days)</td>
<td>882 (Days)</td>
<td>566 (Days)</td>
<td>746 (Days)</td>
<td>340 (Days)</td>
<td>110 (Days)</td>
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<tr>
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<td>NGCCAS Approach</td>
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<td>100 (Days)</td>
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<td>566 (Days)</td>
<td>746 (Days)</td>
<td>340 (Days)</td>
<td>110 (Days)</td>
</tr>
</tbody>
</table>

Cost & Resources: 30% cost saving per program is predicted due to 27% less required resources (Detail of results are not published due to confidentiality)

Table 1: Summary of the modelling results