Final Report Summary - ROBUSTPLANET (Shock-robust Design of Plants and their Supply Chain Networks)

Executive Summary:
The project “Shock-robust of Plants and their Supply Chain Networks (RobustPlaNet)” developed innovative, technology-based solutions in the field of opportunistic maintenance, factory level robust production planning and scheduling, reconfiguration of assembly lines and supply-chain networks and remanufacturing of mechatronic components.

The overall platform, the supporting tools and methods defined and implemented within the RobustPlaNet project aim at supporting the decision makers at different hierarchical levels of production enterprises to react or even to proactively plan and manage their activities in a more robust way than it used to be in the traditional practice.

Robustness in RobustPlaNet involves refined approaches that aim at handling both predictable and
unpredictable changes and disturbances, responding to the occurrence of uncertain events (reactive approaches) or protecting the performance of the production plans by anticipating the occurrence of uncertain events (proactive approaches).

RobustPlaNet covered all three the operational, the mid-term tactical, and the long-term strategic decision layers (Figure 1) and resulted in a set of new mathematical and simulation based algorithms and tools, which strengthen the planning loops within the operation of industrial partners’ companies of the project. Built on a workflow based approach, the functional algorithms, different solvers, data filtering and aggregation modules were chained together in the RobustPlaNet Simulation and Navigation Cockpit, tailored for different industrial cases. This cockpit constitutes the central, web-based framework with a friendly graphical user interface and assists the final users to define scenarios, construct what-if experiments and evaluate their impacts before a final decision is taken.

Project Context and Objectives:
RobustPaNet aimed at developing innovative technology-based business approaches that considerably change the current rigid supply chain mechanisms and the current product-based business models into collaborative and robust production networks able to timely deliver innovative product-services in very dynamic and unpredictable, global environments. This technology-based business approach allow distributed supply chains to efficiently deliver innovative product-services to a distributed network of customers with extremely high service levels in markets characterized by volatile demand, complex variants and a high level of globalization, thus particularly exposed to worldwide disruptive events e.g. economic crisis.

The development of this new business approach is based on four major pillars: (i) innovative services, delivered by suppliers to OEMs (B2B) and by OEMs to customers (B2C), on (ii) innovative enabling technologies, supporting the product-service delivery, (iii) innovative methodologies for decision-making, supporting the co-evolution of the product-services and the related production systems and supply networks and on (iv) innovative business and assessment models, for value creation from the product-services.

The innovative services include mechanisms for supply network coordination by production-related risk- and information sharing between supplier and OEM, opportunistic and aggressive maintenance, equipment reconfiguration and rescheduling services provided by the equipment suppliers to the aerospace supplier and component suppliers, as well as finally remanufacturing services provided by the component supplier to the distributed customers in the aftermarket.

The enabling technologies that allow the implementation of these services and include both hardware and ICT solutions. They consist in an integrated software platform supporting the service delivery and the integrative decision making at both shop floor and supply network level, with user-friendly interfaces, reconfigurable and modular automation and system flexibility for increased system life-cycle management and multi-sensor systems for remote process chain and reliability state monitoring.

The methodologies for supporting the co-evolution of the product-services and the related production systems act at single plant level and at supply network level. Herein, production systems can also be regarded as products in a product-service system (e.g. production machines which are sold together with maintenance contracts). At single plant level, advanced methods for dynamically defining the thresholds for implementation of the predictive and load-dependent maintenance policies were developed. Moreover,
dynamic optimization techniques for risk compliant reconfiguration planning were designed and implemented. At supply network level, methods for dynamic network configuration and organization were implemented as well as advanced techniques for robust production planning and scheduling with availability of production data from suppliers.

With the aim of developing a universal approach that can be integrated into different production and process chains, its feasibility has been demonstrated at machining and assembly processes at both macro scale (titanium aircraft structural components) and medium scale (production of mechatronic components for breaking systems).

RobustPlaNet consortium believes that the integration of the innovative approaches into the production chain will increase the competitiveness of the European automotive market by offering new added value services that make the product more attractive (e.g. more individualized and shorter delivery times) at different levels of the supply chain (final product, but also components and equipment). Moreover, it can provide effective mechanisms to smooth the propagation of external and internal disturbances and disruptive events, thus increasing the robustness of the supply chain, ultimately allowing to meet higher customer service levels and due-time performance (95-98% is the target region of the project; today for truck manufacturing this value is 90% in best practices; this means 1 order out of 10 is not delivered on time).

Finally, it should be noted that the results achieved in the remanufacturing domain can improve the “green services” which car and truck manufacturers are able to provide to customers by drastically rethinking the remanufacturing business through an effective coordination and cooperation between OEM and suppliers, for particularly attractive mechatronic components of wider use in automotive. This can enhance consistent energy and material savings in the aftermarket spare part provision (remanufactured mechatronic components require 80% less materials and energy with respect to virgin spare parts) and will boost the achievement of the ELVs European regulation targets (95% of cars recycled or re-used by 2015) also providing guidelines for new standards and EU regulations on component re-use and upgrade in automotive.

Project Results:
RobustPlaNet was organized in 7 workpackages. In this section the main results of the project are presented according to the first 6 workpackages, as the 7th WP included the management activities. In RobustPlaNet the following main results were achieved:

WP 1: Design of innovative business approaches and service models
In this workpackage the demonstrators of the project were defined, surveys were made and assessed within the consortium regarding the robustness of service models and requirements for generalization. Moreover, a comprehensive framework of the innovative product-services and related business models were designed and used by identifying all relevant B2B and B2C services. Especially concerning the second half of the project, an economic and risk assessments for the implemented product-services and their related business and financial models was made. For this reason a Supply Chain Risk Framework was applied, relevant product-services for each use case were selected and assessed, both qualitative and quantitative. The qualitative assessment included a questionnaire among the partners of the consortium to evaluate the risks from the potential user’s/provider’s of the services.
The objective of WP2 was to develop the technical enabling technologies allowing the implementation at shop floor level innovative technical services and business models developed within the project. In order to achieve this objective, analysis of the plant existing co-evolution degrees of freedom was completed in the application domains related to the shop floor level. In order to link the physical system with the tools developed in the project, multi-sensor network was realized that monitors the critical states of the system. The framework of the multi sensor system was configured in tight connection with the opportunistic maintenance case. Besides, a service-level-oriented integrated model of production systems was developed and implemented, considering production logistics, part quality and equipment maintenance.

Reconfigurability was one of the project’s main application domains, therefore automation modules and control logic were proposed for modular reconfigurable equipment followed by new algorithms and software modules supporting the reconfiguration decisions on longer-, mid- and short-term. The modules developed in WP2 can propose optimal reconfigurable system settings taking the change of the production volumes, the increase of variety of the produced parts, the evolving assembly technologies, equipment life-time and also limited space into consideration.

Regarding the remanufacturing domain, robust disassembly and remanufacturing solutions for mechatronic components were defined, in order to decrease the costs and time of the remanufacturing procedure. Moreover, a decision support system enabling the operator to select the best disassembly and remanufacturing strategy depending on the specific conditions of the core under treatment has been developed, starting from product data directly obtained in-line by sensor systems. This tools and methods were provided to WP4 where they were all integrated in the RobustPlaNet Cockpit.

WP 3: Decision-making support for reconfigurable Supply Chains

The aim of this work package was to develop decision support tools applicable for planning and managing supply chains and production networks. Methods and models were developed to cover both finding supply chain configurations on strategic level and identification of (re-)configuration strategies on tactical/operational level. In the second part of the project a three-level toolbox for decision support of reconfigurable Supply Chains was designed and implemented.

(I) The first tool allows the user to build decision support systems based on Computational Design Synthesis. Knowledge models for specific problems can be built and demand scenarios can be defined with which supply chain configurations can be generated and analysed. Afterwards the design solution explorer can be used by the decision maker to navigate and make comparative assessments.

(II) The second tool helps the user to find migration strategies between Supply Chain configurations. It supports the multi-stage decision process. The robustness of such decisions is assured by taking into account multi-dimensional dynamic and uncertain influencing factors which affect the business environment.

(III) The third and last tool provides a simulation environment, which enables performance evaluation of the Supply Chain configurations. Different Supply Chain configurations from parametrized data bases can be built and analyzed, extending the level of detail of the tools aforementioned and serving as operational evaluator and comparator.

Furthermore a robust production scheduling methodology was developed and intensively tested. The algorithms and methods developed and presented in the prototype concentrate on KPI’s influencing the overall performance of the system in question. Furthermore the uncertainty parameters consider the quality issues, mostly coming from the problematic parts provided by different suppliers. Also the system
supports the creation of plans where the allocation of the operators is considered with high importance. The input data is provided locally from a MES.

WP 4: Fusion to „simulation and navigation cockpit“
The objective of WP4 was to specify, implement and test the Simulation and Navigation Cockpit that serves as a software framework of the RobustPlaNet project. The cockpit was panned to be capable of integrating each modules, models and methodologies related to the application domains and developed separately in WP2 and WP3. Firstly, the initial data-model and the architecture of the cockpit were specified. An early prototype was implemented and demonstrated in 2nd project meeting only focusing on the production planning case. The Cockpit was later further extended and all the modules from WP2 and WP3 were integrated. The implemented version is now a web-based application with a graphical user interface and a databased behind it, supporting the integration of the different modules and tools of the project. The deployed Simulation and Navigation Cockpit was built around a comprehensive workflow system, includes role management and data connectors all of which were developed in WP4.

WP 5: Demonstration
The objective of this workpackage was to demonstrate and validate the technological solutions gathered in WP1 to WP4 by integrating the technological developments into several industrial demonstrators. While the initial plan was to have 3 industrial demonstrators, finally the consortium decided to build four industrial and one experimental demonstrator more thoroughly covering the needs of the RobustPlaNet industrial partners.

The first use-case demonstration aimed at showing how the RobustPlaNet architecture and solution is applied in a context of the production of aerospace components, focusing on how opportunistic maintenance can be exploited by the company to enhance the overall system robustness. This solution is grounded on three different objectives, each one looking at a different scale level of the overall problem. All the results presented in the context of the demonstration came along with a clear measurement of the improvements obtainable, in terms of quantitative KPIs. Moreover, for each result, a list of generalization possibilities was proposed as well.

The second demonstration case shows the plant-level reconfiguration concepts. As basis for the developed reconfiguration concept and the implementation of the pilot system, an in-depth process analysis has been made in Voestalpine’s assembly segment. After that the details of the technical concept were specified and its performance estimated based on the data collected in the analysis phase. In this step also the connections between the plant-level reconfiguration and supply chain related information were evaluated. The software tools developed as part of the demonstrators enable the industrial partner to analyze risk and define the boundaries of the reconfiguration problem, allowing to assess the dynamics induced by significant demand changes, the high number of part types and part-mix.

The third use-case scenario focused on implementing novel production planning and scheduling methods that results in solutions that were robust against the considered internal (intra-plant) disturbances.

Primarily, the assembly lines were in the focus of the demonstrator, however, the target method needed to consider the complementary processes to cover the entire process chain of the plant. The goal of the use-case was to define a robust planning methodology that is able to cope with changes and disturbances that
occur in the everyday production. Further purposes of the method was to provide an optimal plan that is based on the minimization of the production costs on a certain horizon, increase the utilization of the capacities (machines and human operators) and provide pattern-based shift schedule.

The outcome of the fourth demonstrator (Reconfigurable supply chain networks) was the development of multi-level decision support for reconfigurable supply chain networks. As a result of the use case the development of an integrated toolbox for multi-level decision support for reconfigurable Supply Chain networks was accomplished. The developed toolbox includes the workflow-based support of the following activities (I.) Design support for supply chain configurations, (II.) Reconfiguration tool for the identification of an optimal reconfiguration strategy and (III.) Evaluation of configuration in an agent-based stochastic environment.

Last but not least the fifth, experimental demonstrator focused on the remanufacturing. In this use-case the partners developed a set of technological enablers for improving the effectiveness, in terms of regeneration rate, in the remanufacturing process chain of mechatronic components. Preliminary testing at pilot plant scale has been carried out in order to validate the applicability and effectiveness of the developed technologies. These individual innovation sources have been demonstrated to the company at the demanufacturing plan in Milan and specific feedback on improvements for future industrialization of the proposed solutions have been collected. Also in this demonstrator the development of the Decision Support System as an ICT solution to drive the operator in the selection of the best remanufacturing route for each specific product under treatment has been implemented.

WP 6: Dissemination and Exploitation
WP6 dealt with the coordination of the project-related dissemination and exploitation activities. Regarding the dissemination, a detailed plan and protocol was defined first and later used, mostly in the second half of the project, to achieve an effective dissemination. The website of the project was set-up (www.robustplanet.eu) and is functional from the beginning of the project. The scientific results of the project were published in conference and journal papers and a project cluster was established on Resilient Production Networks with the cooperation of the FLEXINET and ManSys projects. Several PhD students were directly involved in the project from each academic partners, three of them defended their thesis’s in the subjects of RobustPlaNet. Special session on RobustPlaNet scientific results were organized by the academic partners in the IFAC MIM conference in 2016. Concerning the promotion of the results, RobustPlaNet partners intensively participated in national and international fairs (Hannover Fair, I4.0 Hungary, Smart Technologies Amsterdam, INDUSTRIE France, etc.). In parallel with the 2nd project meeting, an exploitation seminar was held, where the 1st exploitation strategy related to the outcomes of the project was defined. Through the end of the project, the exploitation planning was facilitated by a valorisation workshop at M32 where the exploitable results of the project were refined and more precisely detailed with the support of exploitation expert.

In the second part of this section details about the results of the project and the generalization of the result for third parties are provided.

Generalization opportunities of the RobustPlaNet project results
The RobustPlaNet project concluded in the end of September 2016. The final meeting of the project consisted of two days; in the first day the project and its result were presented in internal way at the consortium partner OMA in Foligno while in the second day an industrial workshop organized by Marposs was held in Bentivoglio (Bologna) on 5th September. In the industrial workshop the presentations were focused on specific demonstration use-cases specially tailored to the requirements of the industrial project partners in RobustPlaNet. A valid request from optional third party users is to see how, in which extent and on what cost the results would be applied in their case. In the following part the possibilities in the usage of the results of RobustPlaNet are presented

1.1 Summary, further steps and generalization possibilities of solutions in the OMA demonstrator

The use-case demonstration presented in the OMA case aimed at showing how the RobustPlaNet architecture and solution was applied in a context of the production of aerospace components, focusing on how opportunistic maintenance can be exploited by the company to enhance the overall system robustness. This industrial context exhibit peculiar challenges, both from the product as well as from the production system viewpoint. For example, a zero defect production must be achieved, and a zero defect product is the only acceptable solution for the customer.

This solution is grounded on three different objectives, each one looking at a different scale level of the overall problem:

• Cutting tool level. The first objective aims at creating a proper policy of the tool management decisions, which can be used to provide a reliable estimation of the tool life, thus reducing the tool life planning time. This objective is about the tool condition monitoring by data fusion of process and in-process tool wear data.

• Machine level. The second objective aims at identifying and monitor multiple components’ degradation modes. This objective is about the machine degradation monitoring by fingerprint cycles.

• System level. The third objective aims at increasing the overall production system level, considering the components’ degradation state coming from machine level and the cutting tool wear state coming from cutting tool level. This objective is about a state-based production and opportunistic maintenance planning.

For each one of these objective, the partners provided a proper set of tools:

• At machine level, the partners developed a technique for the machine condition monitoring by fingerprint cycles. With this technique, it is possible to use the signals coming from the sensor network to determine if a component of the machine tool is experiencing a degradation in its functionality. The main idea behind the fingerprint analysis developed in this project, consists in defining a sequence of operations to be cyclically repeated over the entire lifetime of the system, and the acquired signals can be considered as a signature (the fingerprint) of the machine behaviour. When a fault or a degradation of some component performances occurs, a statistically significant departure from the healthy signature can be detected and signalled.

• At cutting tool level, the partners developed a methodology for the tool condition monitoring by data fusion of process and in-process tool wear data. The proposed approach is a periodic in-situ laser-based measurement of each single cutter wear, combined with continuous torque/power signal acquisition to enhance the tool life prediction.

• At system level, the partners developed an analytical model for the state-based production and opportunistic maintenance planning. The objective of the tool is to perform the quantitative analysis of
production system performances, considering critical production resource degradation dynamics and the current state of the system configuration, under a given maintenance policy and considering specific requests in terms of production plans. The tool evaluates the service level of the system under alternative production plans, maintenance policies and provides the optimal solution under the given set of constraints.

All the results presented in the context of the demonstration come along with a clear measurement of the improvements obtainable, in terms of quantitative KPIs. Moreover, for each result, the following list of generalization possibilities is.

1.1.1 Generalization of state-based production and opportunistic maintenance planning

The OMA production and opportunistic maintenance planning tool is based on general Markovian structures that can be used to model machines and production systems with complex behaviours. The individual behaviours of the machines are further combined by using a process chain model to capture the system level behaviour of the entire production system. This method allows modelling a wide range of machines characteristics and their interactions in a flexible production environment considering stochastic events. The following are the summary of the main advantages that this tool offers if it is extended to other general applications.

- Multi-resolution modelling of components and machines

The modelling approach chosen in the demonstration embeds the capability to define and embed critical components that compose a machine. This component level modelling capability allows the user to define complex and detailed machine behaviours with higher resolution/detail. However, if the user is only interested to see the machine level behaviour the detailed models, this model can be aggregated and a simplified model at a machine level can be generated. Therefore, the user can decide on the level of modelling detail required to be adopted based on the modelling requirements and the availability of the information to feed the model. Furthermore the aggregation of component level model to machine level model is performed by the software by using automatic operations. Therefore the user does not need to have the knowledge how to aggregate this information into a system level model with fewer details. This flexibility is an added advantage to analyse the behaviour of the system by considering multi-resolution models which comes at no cost for the user.

- Scalability of the solution to bigger systems

Currently the tool has the capability to be extended for the analysis of the OMA system by considering the addition of other machines, degradation components, without any further need of modification. The extensibility of the method is an added advantage of this tool over traditional simulation techniques which has to be developed again when significant system changes occur. Such techniques require continuous involvement of an expert for the model development and this takes significant time. However the process chain modelling approach makes it a suitable approach to include additional machines into the flexible manufacturing and carry out performance analysis. Moreover, the evaluation method is an analytic approach which is very fast, thus, the addition of more machines into the analysis can be handled within a reasonable computation time. This is another advantage compared to simulation based evaluation tools which comparatively take significant amount of computational time.

- Variety of machines and complex system architecture

Another significant benefit of this tool is the possibility to be used for supporting integrated production and maintenance planning decisions even for systems with different manufacturing technologies and diversified system architectures/layouts. The process chain model which is adopted as the basis of the
production system representation can also be used for modelling production systems with other layout configurations such as: serial production lines, parallel lines, closed-loops and assembly and disassembly systems. Thus, this capability to model diversified production technologies, system layouts and complex part flow is a huge leverage in exploiting the applicability the tool in flexible production scenarios.

1.1.2 Generalization of machine degradation monitoring by fingerprint cycles
The fingerprint methodology allows monitoring the health state of a machine tool by performing repeatable sequences of operations during the entire machine life cycle. This approach can be extended to any machining center by tailoring the definition of the fingerprint cycle depending on specific needs and interests.

The frequency for the cycle execution depends on the dynamics of the faults and degradation states on interest. During the cycle, multi-sensor data can be acquired by using sensors already installed into the system (e.g. axis speeds, positions and torques) and/or additional sensors (e.g. accelerometers, temperature sensors, etc.). In both cases the sensor data must be made available to a PC unit where the data processing, analysis and monitoring algorithms are implemented.

The scientific results of the project can be exploited (1) by machine tool builders who want to provide their customers with a new machine monitoring service, (2) by end-users who need to keep under continuous control their systems, and (3) by third-party components (sensor systems) developers, who may provide the on-board data acquisition and analysis platform.

1.1.3 Generalization of tool condition monitoring by data fusion of process and in-process tool wear data
The multi-sensor data fusion methodology for tool wear monitoring developed in the frame of the OMA use case is suitable to keep under control the evolution of the tool wear during each process run by using both a direct in-situ measurement system (i.e. the MIDA laser) and the indirect information provided by the continuously acquired torque signal.

The methodology was tested in roughing scenarios but it is extendable with no modification to the more critical finishing phase of the process. In addition, thanks to the fusion of data-driven and model-based information, it can be used in any milling process, regardless of the complexity of the tool path. Indeed, the normalization of the torque signal via the chip thickness estimation makes it applicable to any part-program.

The laser-based measurement can be extended to any machine tool mounting a similar laser pre-setting system, although additional experimental activities are needed to validate the measurement procedure in the presence of different tool geometries. Moreover, the model for the in-situ estimation of the VB level of each insert depends on the tool type, and hence it needs to be adapted to different kinds of tools (a setup phase is needed to tune the model parameters to the current application).

1.2 Summary and generalization of the reconfiguration solution
Deliverable D5.2 presents the individual tools for decision-support and their integrated workflow developed for the reconfiguration case. The combination of multiple computer-aided decision support tools for individual, subsequent decision problems forms the backbone of the workflow and promises a significant improvement potential, as it can be transferred and adapted to other application domains. Also the principle of concept selection and initial constraint formulation by the users, together with automated optimization and simulation in later phases appears a reasonable support strategy for other application areas. Nevertheless, to evaluate the effort required to apply the approach in other manufacturing...
industries, it is necessary to assess each of the tools individually.

1.2.1 Design synthesis tool
To enable implementation of the design synthesis tool in additional application domains, only minor additions are required. Due to the generic separation of design synthesis algorithm and design modelling environment, the implementation of other cases requires smaller efforts than for the RobustPlaNet use-cases, as the synthesis algorithm stays the same and only the design model of the new application domains has to be created. Depending on the exact application domains and their solution characteristics, additional user interfaces may be required to visualize the solution spaces. Nevertheless, an interface for easily integrating such GUI into the framework was created and should allow for efficient adaption to new applications.

Hence, the effort for transfer to new engineering applications is expected to be mainly caused by modelling activities. With respect to this activity, the implemented model is fairly flexible and thus capable of being efficiently adapted to various problems in the domain of production system design. The University of Twente will continue exploring the opportunities of exploiting this system in other industrial contexts.

1.2.2 Layout and cell evolution tool
The Layout and cell evolution tool is flexible and adaptable to other problem types as well. It is flexible because it addresses very general KPIs like time consumption and costs that could be used as configuration driven performances for every type of production system under analysis. Additionally, it can be considered adaptable because its architecture is modular and thus, by changing one sub-tool for another, the focus of analysis of the tool can be changed completely.

In particular, the layout generation and analytical performance analysis sub-tools are suitable for the cellular system already described. The layout generation and consequently performance evaluation are tightly coupled to the technological approach used in the real system. This coupling is caused by the system model implemented in the tool. Thus, for another type of production system, additional models for layout generation and evaluation may be implemented. A Flexible Manufacturing System, which is composed of several machining centers arranged in a line rather than in a cell, could serve as example for this; in this case, due to the different nature of the used production technology and its layout, the layout design tool has to follow different rules, and the performance evaluation as well. By substituting these two technological connected sub-tools with other sub-tools adapted to the new system type, it is possible to adapt the analysis to any production system.

Grounding on these considerations, the approach and connected software architecture designed and validated during the project will be further developed in order to explore further industrial contexts.

1.2.3 Production planning & simulation tool
As for the generalization of this tool, one can identify two approaches that can be utilized in other application cases: (a) the mathematical optimization model of production planning, and (b) the reconfigurable simulation model. Considering the planning, the model is derived from a generic, multi-item lot sizing model, and specified with some constraints on reconfigurable systems. Consequently, the model can be applied in other modular reconfigurable systems as well, where the production modules can be exchanged among different cells or lines. This generalization is also supported by the applied declarative programming approach, which means that only the desired result is characterized without any further required modifications in the program flow. Moreover, the data and the model is fully separated, therefore,
exactly the same model can be applied for different input data-sets either coming from third party production planning requirements.

In the simulation model, self-building approach was applied, enabling very dynamic model building. This means that static parts of the model are only the cell controller the rest of the model including the FAGs and other processing units are built online, based on the input data. Therefore, the model itself is generic to be applied in other systems, only the data describing the system structure and material flow need to be updated, without modifying the core model. This enables to use the approach —similarly to the planning model— in other cases, where simulation of reconfigurable systems is necessary.

1.3 Summary and generalization of the robust production planning solution

Regarding the generalization of the plant level robust production planning, four main methods can be identified to be used in other application cases. First method is aimed at processing the raw testing data to obtain the real processing and testing times, as well as the reject rates. The functions used for filtering and indexing the data are generic, only feature names need to be changed, to which the distribution functions need to be fitted. In this way, mean values and deviations can be obtained for any parameters, even for large scale data. The calculation of the reject rates works similarly, however, their definition and also the operation of the testing equipment might be corporate-specific, but only slight modifications are needed to extract the same kind of data that is currently used.

The simulation model in this use case is static (in contrast to the one used in the reconfiguration use case), however, the basic methodology of utilizing near-real time data to project future scenarios and build data-sets with simulation can be applied for any kind of production systems (assembly, manufacturing etc.). Regression modelling with the simulation data is very general also possible for all system types but the results are only useful if correlations among the required capacities and the simulation features are strong enough to predict future cases. This is valid especially for systems, where the processes are done manually, or at least supported manually. As a consequence, the proposed mathematical optimization model of production planning works reliable, only if accurate model fitting can achieved in the preceding data analysis.

All in all, each of the applied sub-modules are individually generic, and the overall methodology is generic for complex, manually operated assembly lines, where unbalanced output rates are mostly caused by the stochastic nature of manual processes.

1.4 Summary and generalization of the supply chain solution

Within the Reconfigurable supply chain networks demonstrator an integrated planning workflow for decision support in supply chain networks was developed. The different phases of the workflow are supported by decision support and data analysis tools as well as innovative modelling techniques. The decision support tools can be either applied consecutively (according to the workflow) or individually. The developed and applied tools for data gathering and processing support the different phases of the workflow.

According to Deliverable 1.1 the results of the use case were analyzed whether the developments fulfill the identified general requirements or not.

1. Generality of the framework/tools: The integrated planning workflow describes a framework for planning and operating reconfigurable supply chain networks. In a structured way, multiple decision (strategic, tactical and operational) and system levels (production system, plant and network) are integrated into one workflow. Generally, the workflow can be established in companies as a business workflow. Then again, it
is possible to use the workflow as a consulting approach for external service provider. The tools themselves support the phases of workflow and can be applied separately or consecutive along the workflow. Each tool is developed for a specific problem situation within the use case. Nevertheless, the tools can be applied for other use cases as well, as the underlying decision models are formally described (c.f. Deliverable 3.3). Moreover, a common data base was developed, which describes exactly the required data format for applying the tools. Within the use cases the tools were tested and verified. Hence, one can say that a tested and verified prototype exists. The developed toolbox could be used as a strategic planning toolbox in companies. Moreover, it could be sold as a software suite on a pay per use basis or a product itself. Since the data gathering and processing tools are specific for the use case IV, the general methodology could also be applied for other cases but not the tool itself.

2. Technological progress of identification technologies and improved data transparency: The developed tools, models and methods allow the consideration of already available but also future possible technologies. Moreover, the tools can be adapted easily to the conditions and technological requirements.

3. Use Case specific parameters: The variables can be parametrized specific for the use case. A data base is developed and all attributes are defined. The concrete parameters can be set specific for a third party use case. Naturally, in the case of an implementation in a new case a project should be set-up, in which the collection and grouping the data according to the data model of the implemented use-case is utmost important.

Potential Impact:

1. The main results of the RobustPlaNet project are grouped according to the five demonstrators. The short introduction of the impacts presented in the section below also follows this grouping.

Impact of the RobustPlaNet solution on opportunistic maintenance use case

In the current context of the manufacturing of complex aeronautics parts, the introduction of corrective maintenance operations can strongly influence the service level of the components’ manufacturer, as well as its capability of answering the demand of parts in a competitive and economically sustainable way. This effect is amplified by a generalized lack of condition monitoring of machine components and tools. This results in a conservative and expensive tool management policy and in a static corrective maintenance policy application, which limits the effective production system flexibility.

The new RobustPlaNet technological and methodological solutions for the opportunistic maintenance in the manufacturing of complex aeronautics parts will affect the overall competitiveness of the EU aeronautics industry as well as of the machinery manufacturing one by means of:

- Increase the overall service level by meeting the needs of satisfying small batches of large variety of complex products, which are characteristics of the aeronautics industry;
- Reduction of the tool-life planning time, thus reducing the overall time to market for complex mechanical products;
- Increase the robustness of the overall production efficiency, by the optimal integration of machine tools and in-line sensors, all supported by advanced engineering software.

The RobustPlaNet solution benefits in the aeronautic sector can be summarized in three figures. The first improvement, as a result of the opportunistic maintenance planning, can lead to an improvement of up to +20% of service level of the component manufacturer. This improvement can have a realistic high impact on the whole EU aeronautics industry, since one of the partners is among the biggest aeronautic
manufacturing players in EU market, contributing effectively in spreading the RobustPlaNet solution along the supply-chain (i.e. market impact of 1-3% of RobustPlaNet solution). The second figure involves a consistent overall reduction of the tool-life planning time (-70%) that can lead to a reduction of the time-to-market of the entire production. The last figure entails a complete and effective sensorisation of a machine components, enabling the users of machine tools to identify an arbitrary number of component degradation modes. This last figure is the result of the integration of machine tool, in-line sensors and advanced engineering software, in line with the “Industrie 4.0” approach. It is worth mentioning that BCG predicts a productivity increase of 13-16 B€ within ten years just for Germany, as a result of the application of the “Industrie 4.0” approach throughout the value chain of machinery and equipment manufacturing industry. Realistically, considering the market share and technological expertise of the industrial partners involved in the consortium, it is reasonable to expect a potential market penetration of 1-2.5% after RobustPlaNet.

Impact of the RobustPlaNet solution for the reconfiguration use case.

The results of the reconfiguration case of the Robust PlaNet project can be split into the two domains of production technology and decision-support.

With regard to production technology, a reconfigurable system architecture was developed, which consists of modular system components to provide flexibility at plant level and enable system modifications to reconfigure the system in response to customer demand. Before implementing the novel architecture in a real-life pilot system, various analyses were made to quantify the benefits of the approach. Most importantly, applying the novel concept in the production of spare part should allow to increase cell capacity utilization in the long-term by 25 to 40%. The industrial partner expects that the number of logistics movements can be reduced by 70%. Also, decreasing stock levels are among the expected effects (-50%). As the system and its performance could be observed only for a short time since implementation, no real figures are available so far. Nevertheless, three additional cells are going to be implemented with the new architecture. Thus, the approach appears promising and will be incrementally scaled up.

As the novel architecture offers numerous opportunities for configuring and managing the production system and each of its sub-systems, the use case also needed to address these decision processes. This was achieved by developing an integrated support framework, which aims at supporting the main steps in the design process of the new system architecture. It makes use of three software tools to support the industrial partner in various inter-related decisions: (tool 1) high-level configuration of the production system; (tool 2) layout planning of production cells; (tool 3) production planning and scheduling. As the framework was not available when designing the first prototypes, the expected effects were quantified by estimating the time for application of the tools and comparing it to the previous duration of the design and planning processes. The design space exploration tool (tool 1) was estimated to reduce the concept design time by roughly 60% and the layout configuration tool (tool 1) is supposed to reduce cell layout planning time by approximately 50%. Lastly the duration of production planning is expected to decrease by roughly 40%. Besides these gains in absolute terms, the main improvement is expected to take a place in the quality of the concepts, as much more alternatives can be assessed with the new framework. This should lead to a very strong increase in process efficiency, when considering the time spent per assessed design candidate.

Lastly, an evaluation of the usability was carried out. This study showed that the functionality of the design space exploration tool is mature enough to apply it frequently and for varying design problem settings of the industrial partner. Moreover, the approach was confirmed to reduce the complexity of a large number
of alternative actions to a manageable level. These positive effects have motivated the start of a longer lasting study that should reveal the effects of using the tool as part of a new decision routine. Similar confirmative studies are envisaged by the industrial partner for the other two software tools.

Impact of the RobustPlaNet solution for the robust production planning use-case.
The current global trend in manufacturing is the increasing number of product variants, as well as the increasing customer-expected service level concerning to both delivery time and quality. These factors lead to complex production planning tasks on the plant level, while the internal efficiency is also need to be kept on the desired level. Therefore, matching supply with demand by proper production planning is of crucial importance to stay competitive on the market.

In the RobustPlaNet project, the general objective was to increase the robustness of internal (plant level) production planning processes, while minimizing the overall costs related to execution of the plans. This was achieved by selecting the main internal causes of disturbances, and developing the planning methodology to be robust against these effects. As a result, the calculated plans are characterized with increased robustness against the machine breakdowns, rejects rates and the related reworks, as well as against the stochastic manual processing time. The robustness of the plans is increased by 11% in average, for only 3% additional cost of robustness. The robustness is measured by the lateness of the plans, therefore the average service level could be also increased. Besides, internal KPIs were also improved by 14% reduced resource idle times, as well as 6% increase in direct labour productivity. As the planning method is not corporate but system specific, it can be applied by other companies to increase the robustness of the internal production planning processes and reduce the wastes caused by improper production planning and control policies.

Impact of the RobustPlaNet solution for the supply-chain use case.
Within the supply Chain Use case an OEE increase in between 3 and 5 %, a reduction in time to serve of about 12 % and an increased delivery reliability of 10 % could be achieved at Festo, which represents well the automotive supply sector in Europe. The European automotive supplier industry with more than 3.000 companies and an annual turnover of 600 billion Euro [62] will significantly benefit from the projects results. It is not only expected to increase the turnover by the higher OEE, but also to attract more business by improvements in the crucial time to serve and delivery reliability. This will strengthen the sector in Europe. Besides the direct use for companies in the automotive supply sector, the results enable Consultancy Business for global production companies. So also new companies can emerge from the results and existing companies can widen their portfolio.

Impact of the RobustPlaNet solution for the remanufacturing use case.
The current remanufacturing process (baseline situation) for braking systems' mechatronic components (EBS2) and automotive parts is carried out in emerging countries and it is mainly based on manual operations and remanufacturing decisions are taken by the operator. This results in a current regeneration rate of about 70%, which means that 1 over 3 potentially remanufacturable cores (returned products) are currently discarded. The new RobustPlaNet technological and methodological solutions for remanufacturing under a circular economy perspective will affect the competitiveness of the EU automotive industry through:
- Increase the regeneration rate of collected cores, through the introduction of the Remanufacturing Decision Support Tool for cores classification and sorting;
• Reduction of the disassembly time and increase in throughput by new in-line inspection technologies and data gathering solutions for collecting information about the cores conditions and to avoid production losses in processing parts that are already identified as un-reusable;
• Increase the robustness of the remanufacturing process-chain with respect to highly variable and uncertain quality conditions of incoming cores.

A business case has been evaluated considering a new remanufacturing installation for processing the EBS5 modules both in high wage and low wage countries. The results in terms of Net Present Value (NPV) at the tenth year after installation and PayBack Time (PBT), considering an actualization rate of 7%, have been calculated. With the RobustPlaNet solution, the investment is highly profitable for high-wage countries (NPV = +11.62 M€ and a PBT = 2 years) and can also be profitable for low wage countries (NPV = +4.77 M€ and a PBT = 3 years) under specific performance achieved by the RobustPlaNet solution, i.e. with a regeneration rate of 85% and a disassembly time reduction of 50%. It is important to highlight that the RobustPlaNet solution enables the feasibility of automotive remanufacturing and re-use processes in high-wage EU countries, which is currently rarely the case.

Economic Impact on whole EU28 automotive part remanufacturing sector: Starting from the previous concrete figures, and considering market projections of APRA, the consortium has elaborated a business case for the entire automotive part remanufacturing sector in Europe. A marginal increase in the turnover of the European automotive parts remanufacturing sector of about 300 million Euro per year is expected by 2025, only for the automotive aftermarket. Due to the lower costs for these sustainable products, the end users in the EU28 will save cumulative up to 1 Billion Euro until end of 2025. From an economic point of view, it can be assumed that the aforementioned improvements can increase the competitiveness of the EU in the worldwide automotive industry, and especially the aftermarket sector. According to the most recent data of APRA, the aftermarket generates roughly 50% of the profits for the whole automotive sector. This would predictively lead to an annual increase of value added in the European Automotive Industry from 20% to 20.3%, corresponding to a potential gain in the annual value added of the entire industry of approximately 1.8B€ that could be achieved, according to the current turnover figures, if the share of the RobustPlaNet solution was 100% in the targeted sector.

CO2 Emissions: it was shown that, additionally to current practices, the solution can bring the opportunity to remanufacture and sell in the market 3.68 Million parts, that without the solution would be manufactured as new products for the aftermarket. Since remanufacturing allows saving about 50% of the CO2 emissions, this would result in a save of 50,030 Tons of CO2e by 2025.

Energy Consumption in manufacturing operations: remanufacturing allows saving about 53% of the energy with respect to manufacturing of new parts for the aftermarket. According to the previous impact figures, this would result in an annual save of 3 TWh of manufacturing energy by 2025.

Raw material use in manufacturing operations and reduction of waste going to landfill: remanufacturing allows saving about 67% of the raw materials with respect to manufacturing of new parts for the aftermarket. According to the previous impact figures this would result in a save of 13 KTONs of raw materials, mainly steel, aluminum, plastics and composites, by 2025.

Dissemination Results

The standard report contains all dissemination activities in the tables with the most important data about the dissemination activity. In the following section only the most important events will be further described.
1.1 Webpage
A dedicated website for the project was established right after the kick-off meeting. The public website can be reached on the https://www.robustplanet.eu/ URL and was built by SZTAKI. The website of the project promotes both the research activities carried out in the project and the results of the project in consumable brochures, videos and other promotion material for third parties interested in the outcomes. It also includes a restricted area that support the management of the project and serves as a document repository. The webpage has overviews of news, events, publications and articles related to the project. The webpage also enables visitor to inscribe for receiving the project news brief.

1.2 Industrial events
As it is indicated in the list of dissemination events, the project participated in a large number of industrial events in several countries across Europe. Two of the most important events where the project was present were the Hanover Fair and the Industrial Technologies congress. Both events served as a platform to showcase the project demonstrators. This allowed to show the concrete industrial results to a large audience, both industrials and academics. The presentation at the Hannover Fair was organized as an activity of the RPN Cluster, which resulted in having the CREMA, FLEXINET and RobustPlaNet project presenting their final results together.

1.3 Appearance in EU events
The project participated in three FoF Impact workshops organized in Brussels in 2014, 2015 and 2016. In the last event RobustPlaNet was selected and presented as a success story. Based on this presentation, the project was invited to present its results in the 1st Factory of The Future Conference, titled Factory 4.0 organized by EFFRA in September 2016 in Brussels.

1.4 Special Session at MIM Conference
The RobustPlaNet project organized a special session on entitled: Multi-level, Collaborative and Robust Production Networks at the 8th IFAC Conference on Manufacturing Modelling, Management and Control. The session was used to show case some of the main results of the project. A total of 5 peer reviewed papers where presented during this event. The papers where organized such that both the general overview of the project as well as some key results from each use case was presented.

The following papers were presented:
1.5 Main Journals and Conferences

The project participated in a large number of conferences and published important articles in well-known journals. Special focus was set on conferences organized by CIRP (CIRP General Assemble and CIRP Manufacturing Systems), as they are well positioned in both the academic and industrial environment and have important impact factors.

1.5.1 Published journal papers

The following journal papers were published during the project:


1.5.2 Published conference papers

The following papers were presented at conferences:


[14] Johannes Unglert, Juan Jauregui-Becker, Sipke Hoekstra. Computational Design Synthesis of...


1.6 PhD and Master Thesis

All together 5 PhD Theses were related to RobustPlaNet, 2 of them defended in the reporting period and three is expected to be defended in the next year

1.6.1 PhD thesis’s related to RobustPlaNet

Nicole Stricker: Robustheit verketteter Produktionssysteme - Robustheitsevaluation und Selektion des Kennzahlensystems der Robustheit (KIT)

Emanuel Moser: Flexible Migration Planning for Globale Production Network (KIT)

Dávid Gyulai: Production and capacity planning methods for flexible and reconfigurable assembly systems (SZTAKI, expected in 2017)

Johannes Unglert: Combining set-based and automated design: an approach for supporting configuration space exploration of production systems (UTWENTE, expected in 2018)

Massimo Manzini: POLIMI, (expected in 2017)

Apart from PhD’s, more than 20 Master students were involved in the project who defended their theses.

1.7 Courses

The results of the research project have been incorporated at a pilot level at two courses being provided at the University of Twente in the Production Management master program. One subject is Manufacturing Facility Design. In this subject, a new theme on the Design of Reconfigurable Production cells has been included. The second subject is Design of Production and Inventory Systems. In this subject, a new theme has been included on Integrated Planning and Scheduling. The course material (power point presentation, reading material and example cases) will be disseminated among our project partners such that the theme
can be easily integrated into their educational programs.

1.8 Final dissemination event
The final review meeting of the project was held at the OMA plant in Foligno with all the consortium partners on 5th September 2016. Thereafter, the consortium presented all project results at an industrial workshop in Bologna, with several participants delegated by industrial companies. Besides the presentation of each use-cases, live demonstrations took place at stands, dedicated to the developed solutions. During this demonstration session, standalone applications, as well as their cockpit integrated versions could by live tested by the participants, as well as the implementation results were discussed. Moreover, rollup posters were installed and flyers were distributed —dedicated to each use cases— to summarize the applied methods, their implementation and the results.

List of Websites:
www.robustplanet.eu

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