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The RobustPlaNet Project: Towards Shock-Robust Design Of Plants And Their Supply Chain Networks

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Abstract: This paper provides an overview of the research goals and current research status of the EU-FP7 project RobustPlaNet. A description of the general concept and vision of the project is presented and the adopted definition of robustness at plant and supply chain levels are discussed. Moreover, the RobustPlaNet approach and its innovative technologies and methods are described, followed by a summary of the different industrial use cases. The architecture of the decision support cockpit that will emerge from the integration of these tools is presented. At last, the overall impact of the RobustPlaNet solution is discussed, supporting the European manufacturing industry in the transition towards shock-robust plants and supply chains

Keywords: Manufacturing Systems, Robustness, Flexibility, RobustPlaNet.

1. INTRODUCTION

World economies have become increasingly complex and more susceptible to experience dynamics behaviours, as social, political and economic forces are constantly changing over time (Lanza & Peters 2012). For example, the German automotive market development has experienced a very dynamic behaviour over the past years (VDA Association 2012), with changes of up to 50% of production volume, both upwards and downwards. Furthermore, as reported by McKinsey in 2012 (McKinsey 2012), the number of natural disasters has been increasing at a pace of around 3% annually since the start of the 80s. Besides these externally driven disturbances, the intrinsic development of products is continuously acting as a driving force of change. In fact, current market dynamics have motivated rapid product and technological changes, like new materials and production technologies, further miniaturization and increasing integration of "smart" function and features into the products. Even the nature of the business-product relations, like in the case of Product Service Systems (PS2) (Meier et al 2010), has changed for many companies over the last decades (e.g. leasing in the automotive industry).

The RobustPlaNet project described in this paper has the goal of supporting industry - and more specifically the European manufacturing industry - in coping with the aforementioned challenges. RobustPlaNet is an EU-7th Framework Program founded project aiming at developing an innovative technology-based business approach to drastically change rigid supply chain mechanisms and product-based business models into collaborative and robust production networks that are able to timely deliver innovative product-services in very dynamic and unpredictable, global environments. The goal is to provide a general approach to tackle disturbances at the three production levels, namely production network, plant and shop-floor levels, thus covering, in the same framework, the strategic, tactical and operational decision making levels (Wiendahl et al 2007).

2. ROBUSTNESS

The term robustness is used in different engineering disciplines as a property of systems that are able to perform appropriately even under the presence of disturbances. In this sense, the more robust a system is, the better it will cope with uncertainty and unexpected system inputs. In this sense, robustness measures the ratio at which changing system conditions affect the system's outputs, generally measured at the hand of Key Performance Indicators (KPIs) (Stricker et al 2015). Furthermore, the concept of robustness is also coupled to the concept of system stability. Stability itself being defined as the capacity a system has of not experiencing unbounded increase of its responses. For the case of a production system, stability is mostly related to the chosen KPIs. Therefore, a robust production system can be said to be one in which the chosen KPIs deviate within permitted limits under the presence of varying input conditions.

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For the RobustPlaNet project, the possible types of disturbances to be addressed by increasing a systems robustness are the following:

- (sudden) machine and equipment failures / equipment defects /non-functioning equipment
- defective / precipitation of tools / tool breakage
- lack of planning in tool change and provision of tools
- absence / lack of staff
- work failure / incorrect operation / inappropriate treatment
- temporal distortions of goods receipts / delays / deployment delay
- (sudden) loss of suppliers
- change in customer demands

As this list shows, the first disturbances play a role on the short term, while the later do so on the medium term. As a consequence, measures to increase the robustness of the system need to be performed in a multilevel approach. Furthermore, as disturbances propagate from one level to another, proper coordination mechanisms are required to manage the supply chains robustness.

This complex scenarios motivate companies to search new mechanisms, that are global and implemented at all levels (strategic, tactical and operation), to enable them to become more robust (Stricker et al 2015). These new mechanisms at supply chain level include:

- Setting up new supply chain configurations quickly.
- Determining and implementing new production schedules as soon as changes in supply chain configurations are occurring.
- Reducing the impact of small-lot orders for obsolete products required by the aftermarket through efficient and high quality remanufacturing of cores offered to the aftermarket instead of new parts.
- Increasing the level of coordination among suppliers and producers by information sharing protocols and contracts.

Moreover, new mechanisms at single plant level include:

- Changing planning directly as system disturbances appear.
- Implementing reconfigurable and co-evolving production cells, driven by the concept of equipment re-use.
- Improving the ability to perform preventive maintenance in opportunistic way, thus reducing the impact of maintenance on production logistics and quality performance of the system (Colledani et al 2014).

The implementation of these mechanisms needs to be supported by efficient and effective decision making tools as well as enabling technologies. The RobustPlaNet project provides solution to these challenges supporting managers in improving robustness in poorly predictable environments.

3. THE ROBUST PLANET APPROACH

In the RobustPlaNet concept, multi-level production robustness can be achieved by following the framework described in Figure 1. On the one hand, external disturbances, related to changing production conditions, can affect the different levels and can propagate from one level to another in a top-down manner. On the other hand, internal disturbances, such as machine and component degradation and disruptions, may take place at shop floor level and propagate in a bottom-up manner. To smooth the propagation of these disruptions along the different levels and to ultimately increase the robustness of the whole system the architecture of a *Navigation Cockpit* is being designed to assist decision makers in identifying the most promising combinations of actions to consider and implement against disturbances. This cockpit supports decision makers in anticipating possible disturbance scenarios and determine the right strategies to handle them, a priori. This functionality enables the cockpit to be used both in a *proactive way* (determining in advance possible disturbances and their countermeasures) as well as in a *reactive way* (determine strategies as the disturbance is occurring). To this aim, the RobustPlaNet solution incorporates both data gathering technologies as well as models and tools to support "what if?" analysis for improved robustness. The first set of technologies is dedicated to the monitoring of the production process and system in order to (i) detect the occurrence of classified internal disturbances and to (ii) identify unobserved disturbances for classification. The second set of tools and models are fed with the collected shop floor data and act as virtual models of the production system and network. Their role is to test in advance the effectiveness of countermeasures to smooth the impact and the propagation of disturbances among levels, thus making it possible to achieve the target performance, also in presence of unexpected events. These tools, all integrated in the cockpit, include discrete-event simulation, analytical modelling, statistical learning and optimization algorithms, for fast generation of user-driven recovery plans, which are visualized through a personalized user interface.

Therefore, since the effectiveness of production plans is undermined as a consequence of the unpredictability of disturbances, the RobustPlaNet approach integrates the design and planning tools with detailed information gathered at shop floor. By doing so, coherence between the strategic and planning decisions and the status of the production system is envisaged, thus improving the overall robustness by managing, in a multilevel way, the propagation of disturbances (Tolio et al 2011, Radke et al 2013). The following section describes the use cases the RobustPlanet project aims at solving.

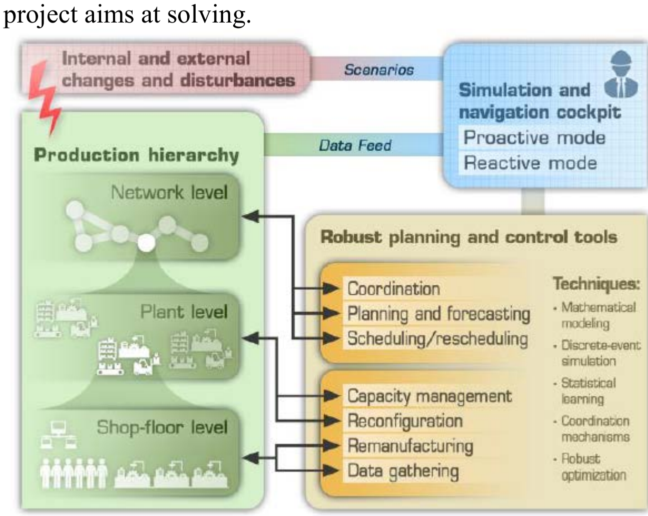

Figure 1: Framework for multi-level robustness

3.1. Reconfigurable Production Cells: Voestalpine

Just as the automotive industry in general, Voestalpine (http://www.voestalpine.com/group/nl/) is facing major trends: shorter product lifecycles, mass customization and decreasing production volumes per part type. Concerning this use case, special challenges can be found in varying production volumes, which depend on the current phase of the product lifecycle and represent a major issue for equipment planning. This challenge affects assembly by creating a conflict between placing universal (many variants) or dedicated (high volume) production cells on the limited shop-floor space. Therefore, the goal is to develop an equipment strategy (i.e. strategy for a more efficient use of hardware and technologies) that serves the needs of varying volumes, simultaneously respecting the complexity and variability of processes taking place in production. This requires work in two areas: the development of a concept for assembly cells and of resource allocation methods, both of which taking into account the flexibility of manufacturing systems.

3.2. Robust Planning and Scheduling: Knorr-Bremse

Within the project as well as in the case study, the main goal of Knorr-Bremse (http://www.knorr-bremse.com/en/global/) is to carry out state of the art techniques that harmonize production with customer orders by implementing cooperative and robust production planning methods. These methods and results should be supported by software tools embedded in the Simulation and Navigation Cockpit. As the planning and control methods of the assembly lines in the factory are very similar, a high volume production line is in the scope of the case study, that provides the as-is status of the processes. Then, novel on-line statistical monitoring and data analysis and production planning methods will be developed in RobustPlaNet in order to improve the utilization of the capacities considering the human operators as well as the machines and to achieve a more balanced load of the factory even in stochastic demand periods. Regarding the specific objectives in the Knorr case, five different domains have been identified:

- Production planning methods: Increase robustness against fluctuating customer orders and disturbances; improve the efficient co-operation with supply chain processes by a more reliable and stable output stream of the pilot line; combine the long- and medium-term horizon planning decisions in the decision support system developed in the project.
- Cost efficient production execution: Generate optimal production sequences and amount of resources; increase the utilization of the resources, define optimal shift patterns for the human operators.
- Online control, monitoring and reduction of reject rates for the pilot line
- Optimize intra-line stock levels

Increase the utilization of the test bench, by decreasing idle testing processes

3.3. Flexible Supply Chain: FESTO

Modern globalization leads the Festo AG & Co. KG (http://www.festo.com/) in a global competitive environment. Products are sent within days and information - within minutes around the world. Customers can choose among competing companies from all over the world. Persistent dynamics and uncertainty of the global trade can be furthermore assumed. Internal (e.g. availability of new production technologies), as well as external factors of influence (e.g. fluctuation of exchange rates, local-content requirements, wage growth), require flexible adaptations of the production and logistics networks of Festo AG Co. KG. Due to the short-cycle character of the uncertainties, the future competitiveness will be determined, in particular, by the ability to efficiently adapt the production and logistics networks to the current market situation. A crucial factor that differentiates Festo AG & Co. KG from the global competition is an efficient and stable market supply despite rising uncertainties. As a result of massive wage increases and fast aging of society the upcoming automation and digitalization in emerging markets (e.g. China) can be seen as a central challenge for Festo AG & Co. KG as a provider of innovative automation solutions.

Mastering the massive growth in demand while, at the same time, increasing products' diversity due to the growing customers' individualization that is needed, requires adaptable production and logistics structures. In addition, the increasing customers' individualization and the number of product variations require an adaptation of traditional business models as well. In particular, system solutions where customers are able to configure individual systems from a variety of different products and product variants, are increasingly becoming the focus of Festo AG & Co. KG. This in turn has an impact on the global production strategy. A realignment of the order processing organization (e.g. make-to order or assemble to-order instead of make to-stock) is just as necessary as an adaptation of the global production and logistics network of Festo AG & Co. KG, which was traditionally oriented on economies of scale. The production and logistics networks of Festo AG & Co. KG are characterized by a combination of sites which are taken into account due to historical and opportunistic reasons. The production sites are characterized by heterogeneous production technologies.

3.4. Condition based strategies: OMA

Amongst others, OMA (http://www.omafoligno.it/) produces titanium aircraft structural components, characterized by complex free-form geometries, large variety and relatively small batches. The raw titanium parts machined in OMA are very expensive and are machined in very long work cycles. Roughing and finishing operations may last hours. During this operational time, several tools may need to be replaced due to deterioration and wear, also considering the titanium toughness and thermal behaviour. Zero defect manufacturing is the target, while meeting, at the same time, the respect of the due dates, which, as a supplier, represents a relevant competitive priority. Moreover, the processed parts show high "buy-to-fly" ratio that, together with the frequent tool changes for ensuring the high precision of machining operations, makes the total operational costs considerably high. Currently the tools are replaced based on machining time thresholds imposed by the company. As the quality of the machined features is the top priority target objective, a very conservative policy is used while fixing these thresholds. This results in a high tool cost and low observability of the process conditions.

By observing the degradation level of the tools based on the analysis of the machines' operating condition, gathered by a suitable network of sensors, improved tool change and opportunistic maintenance plans would be enabled. Such a condition-based policy would allow to keep the resources in the best operational condition without detrimental effects on the service level, thus considerably reducing operational costs, also meeting the same quality performance.

3.5. Mechatronics Remanufacturing: Knorr Bremse

The aftermarket is an important business area in the automotive market, generating about 40% of the total revenues of automotive companies. In the aftermarket, the possibility of offering to the customers both new spare parts and remanufactured spare parts contributes to the increase of competitiveness of the overall automotive supply chain. Among the different type of products, mechatronic parts present relevant challenges and opportunities with respect to remanufacturing (Colledani, Copani & Tulio 2014, Peters et al 2014). Improving the ability of remanufacturing mechatronic products in automotive represents an opportunity for high-wage countries.

This use case deals with remanufacturing of mechatronic componets found in EBS (Electronic Breaking Systems) at Knorr-Bremse, Germany. The company implements remanufacturing on mechatronic products, with a human intensive process. Automated technologies are currently not adopted for the disassembly stage. Instead, semi-automated technologies are adopted for the cleaning and reconditioning stages. Finally, the reconditioned product is sent to the main assembly line used to produce the „new products" for the re-assembly operations and final quality testing.

The objective of RobustPlaNet for this Use Case are threefold. Firstly, the developement of a new technology-based Decision Support System (DSS) to enable to standardize the criteria to be adopted to decide the best remanufacturing options, based on the specific status and quality of the cores received in input. This tool will make it possible to predict the feasibility of the remanufacturing process beforehand, thus increasing the regeneration rate of cores. Secondly, a software tool for the disassembly planning, considering the specific conditions of the cores will be developed to determine the optimal granularity of disassembly, for parts to be remanufactured. Thirdly, technological solutions for the automatic disassembly and re-assembly of electronic components on the PCB surface for remanufacturing will be investigated. This technology would substitute the manual disassembly of the components from the PCB, that is the currently adopted practice. All in all, these solutions will allow to achieve higher ability to remanufacture mechatronics in a sustainable and effective way.

4. COCKPIT METHODS AND TOOLS

Presently, the RobustPlaNet project has created clear visions on tools to support the network level and the plant level. The following is a description of the main decision support tools developed during this phase to be integrated into the cockpit.

4.1. Supply chain configuration

This tool supports the design and evaluation of reconfigurable production cells. The goal is to determine possible production cell's architectures together with the enabling equipment, devices and control system, for a seamless and fast re(arrangement) of manufacturing resources to cope with high uncertainty.

The inputs to this tool are a database with the available equipment (technologies, robots, tools, fixtures, etc), the information related to the products to be manufactured (type, dimension, production process, cycle times, etc.) and a set of constraints and target performance (capabilities, product volumes and the related variability, space constraints, binding agreements, etc.). The output of this tool is a set of feasible configuration of a production cell, together with an optimized reconfiguration strategy in relation to the considered evolution scenarios. The tool enables the exploration of the trade-off between investments and performance, thus helping to identify a target of flexibility and formulate an equipment investment strategy. The flexibility available through different hardware and control solutions is also considered to leverage robustness at the plant level.

4.2. Optimal configuration strategies in production networks

This tool supports decision makers in the identification of optimal (re-)configuration strategies of a production network under uncertainty. It is a management controlling tool for the continuous monitoring of critical factors and control of the migration planning. The tool implements a stochastic, dynamic optimization model for flexible migration planning in production networks.

The inputs to this tool are analytically modelled network objects (production sites, technologies, material- and component supplier, transport strategies), stochastic models of external and internal uncertainty (influencing factors) and quantified migration processes of network configuration. The outputs this tool generates are:

- Identification of robust migration paths for continuous adaptation of the network configuration
- Identification of point in time and demand of adaptation
- Monetary assessment of the efficiency and the effectiveness of migration processes

Identifying robust migration strategies enables a continuous adaption of the production network to the external and internal uncertainty of the business environment. Furthermore, by assessing the efficiency and effectiveness of migration processes an optimal (re-)configuration strategy can be derived and the total landed cost of migrating and operating the production network can be minimized

4.3. Reconfigurable manufacturing systems

This tool supports the design and evaluation of reconfigurable production cells. The goal is to determine possible equipment strategies based on investments and re (arrangement) of manufacturing resources in an environment with high uncertainty.

The inputs to this tool are a database with the feasible equipment (technology, capacity, investment, need of space) and information of the products to be manufactured (product structure, demand & variability, sequence & flexibility, cycle times). The output is a solution set of feasible combinations of flexible and reconfigurable production cells and its calculated performances. The tool enables to explore the trade-off between investments and performance, thus helping to identify a target of flexibility and formulate an equipment strategy. Once flexibility is available on hardware level, it should help to leverage robustness at the plant level.

4.4. Robust planning and scheduling for assembly lines

This tool support the robust production planning based on a proactive, simulation-based method that applies regression functions in the optimization models to capture the effects of the dynamic underlying processes. That method relies on up-to-date production MES and SCADA data, in order to provide executable results. Moreover, it also determines the best operator control policies (operator-task assignment) for each product variants that provides the desired throughput besides the least losses possible. The tool is based on a simulation-based optimization method to predict the effect of disturbances during the production, and consider them already in the production planning phase (in a proactive way). The tool consists of three modules.

The Simulation module includes stochastic and unpredictable effects (e.g. machine breakdowns, varying processing times, missing material etc.), to predict the best operator control policies (operator-task assignment), to maintain the target level of the KPI-s. Input to this module are processing and testing times (SCADA), possible operator-task assignments, historical reject rates. Outputs are best operator-task assignments for each products, capacity requirements.

The Data analysis detects the patterns in the production data, and understand the relationship between the stochastic parameters (mainly the rework) and the true capacity requirements. Inputs to this module are from simulation (the capacity requirements and production volumes), while the outputs are regression models to predict the real capacity requirements considering the production batches and stochastic parameters (rework).

The Optimization module applies the pre-calculated regression models, and plans the production (production batch sizes) accordingly. Inputs to this module are order volumes and capacity requirement functions (from the data analysis module), while its outputs are production lot sizes, time horizon, and resolution.

The simulation module enables flexibility by offering the best operator task assignment for each product, enabling the assembly of different product with the same number of operators besides minimal losses (switch from one product to another in the same shift, with the same staff but different assignment). The data analysis module provides regression functions that predict the actual capacity requirements including the effects of possible reworks. Lastly, by integrating the regression models in the optimization constraints, the robustness of the production plans can be increased, as the effect of stochastic events are handled already in the planning phase.

4.5. Production System Opportunistic Maintenance Planning

This tool has the objective to provide (i) Condition-Based Maintenance capabilities to manufacturing system users, (ii) combined with the ability to select the best time windows (opportunities) to carry on preventive maintenance without interfering with the achievement of the production plans. The tool is composed of three major modules:

***Data gathering from sensorial data*:** this module receives in input data from the multiple sensors implemented at shop floor level to observe the degradation behaviour of the critical components in the system. In RobustPlaNet, a subset of signals and the related sensors has been selected for the interested use case. Then, these signals are elaborated and associated to states of the monitored machines.

***Machine degradation modelling**:* This module takes in input the association of signal patterns to degradation states and initial sample data obtained from the shop floor. It provides in output a Markovian state-transition model that represents the dynamics of the machine while visiting its different degradation states (Colledani et al 2012)

Manufacturing system model: this module integrates the developed resource degradation models into a production system model (including finite capacity buffers, part routings, cycle times). It provides in output estimates of the main system KPIs (throughput, lead time, WIP) under specific maintenance policies.

***Opportunistic Maintenance Policy Optimization**:* based on the previous model, this tool applies optimization algorithms to select the best possible opportunistic maintenance policy that look both at the degradation state of the specific machine and the state of the remaining resources in the system.

The output of this tool will be the derivation of a specific opportunistic maintenance policy to be implemented at each monitored machine for improved robustness of the system.

4.6. *Tools vs. user cases*

The goal of the cockpit is to provide an integrated approach for decision makers to applying the afore described tools for dealing with supply chain disturbances. A quick overview on how each tool is applied at each user case is provided in Table 1. The Voestalpine case will be approached by iterating the *reconfigurable manufacturing systems* tool with the *robust planning and scheduling* tool to design production cells configurations concurrently with planning and scheduling. Sensitivity analysis on cell configuration against planning and scheduling performances will allow choosing robust solutions. The Knorr-Bremse user case will mainly focus on the application of the Robust planning and scheduling for assembly lines. The FESTO case will use on the one hand the supply chain configuration tool to set-up strategies on the configuration of supply chain networks outside their existing relations, and on the other hand will apply the *optimal configuration strategies* tool to determine migration strategies to aid the continuous adaption of the production network to the external and internal uncertainty of the business environment. Finally, the OMA use case will apply the *production system opportunistic maintenance planning* tool.

5. EXPECTED IMPACT ON EUROPEAN AUTOMOTIVE INDUSTRY

The main result of the project is expected to be a technology-based, user-oriented method to integrate decision-making on plant level with global supply chain network management by using new business models to share risks, innovative optimization approaches and latest technology for data collection and system reconfiguration. The overall goal is to increase the ability to react on market changes (e.g. demand-shocks) and legal conditions (such as Non-Tariff Barriers (NTBs) or emission standards for trucks and production plants) in order to stabilize delivery times and increase flexibility. The user cases addressed in the project belong to different companies in the supply chain of European automotive industry. Cars are with about 12 million manufactured units (EU27) one of the most important products in Europe and create an annual turnover of about 700 billion (Vision 2020 2012). In Germany, Italy, Hungary and the Netherlands more than one million employees work directly in automotive industry (which means about 50% of total in EU) (ACEA 2012). Automotive is the sector with the largest percentage of private R&D investments with more than 5800 patents in 2011 (ACEA 2012). By the year 2020 the amount of sold cars in the world will climb up by 25% to 100 million cars per year – meanwhile experts expect a smaller percentage of cars built in Europe (decrease from 29% in 2004 down to 20% (VDA 2012). Therefore plants in Europe will have to work hard on new innovative technologies to increase productivity and especially flexibility. Flexible and robust plants in well-defined supply networks with a close partnership between OEM, supplier and equipment supplier, supported by the RobustPlaNet approach, have the potential to remain a market share of about 30% in 2020.

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