RobustPlaNet—Shock-robust Design of Plants and their Supply Chain Networks

Project acronym: RobustPlaNet
Call and Contract: FP7-2013-NMP-ICT-FOF(RTD)
Grant agreement no.: 609087

RobustPlaNet:
Shock-robust Design of Plants and their Supply-Chain-Networks

FoF Impact @CRIT
10.11.2016, Vignola (MO)

Presenter: Prof. Marcello Colledani, Department of Mechanical Engineering, Politecnico di Milano, Italy
Key Figures
38,000 students:
- Engineering: 24,000 (15% of Italian engineers)
- Architecture: 10,000
- Design: 4,000

12 Departments, 25 PhD programs, 35 MS programs. Ranked in the EU top 10 for Mechanical, Aeronautical & Manufacturing Engineering (QS 2013).

Department of Mechanical Engineering
- Dynamics of Mechanical Systems
- Vehicles
- Machine Design
- Manufacturing Technologies and Systems
- Advanced Materials
- Measurements and Experimental Techniques
- Methods and Tools for Product Design.
A Pilot Plant for the remanufacturing and recycling of PCBs (Printed Circuit Boards) from mechatronic automotive components, is being designed and currently under installation at ITIA-CNR (January 2013). Project Funded by Regione Lombardia: 1.5 Million Euro.

Cell 1: Disassembly

Cell 2: Reworking

Cell 3: Recycling
FP7 and H2020 projects

- Integrated Quality and Production Logistics Analysis of Production Systems.
- Defect propagation avoidance solutions for ZDM at system level.

- Platform for early stage design of RLW automotive assembly lines.
- Knowledge based engineering of automotive assembly lines.
- Multi-objective optimization of manufacturing systems.

FP7. 2013-2016. Shock-robust Design of Plants and their Supply Chain Networks
- Integrated product and production systems evolution.
- System level opportunistic maintenance policy optimization in manufacturing lines.
- Reconfiguration of automotive body assembly systems.
- Remanufacturing decision support system.

- Ontologies for product-process-system information formalization.
- System engineering, visualization and animation.
- Plant capability assessment tools.

- System engineering and reconfiguration planning.
- Mechatronic object description and formalization.

- Project clustering for exploitation, standardization and dissemination.
- Roadmapping on Zero Defect Manufacturing.
Main objective

- Develop
  “technology-based business approaches”
- To support
  “collaborative and robust production networks”
- With the goal of
  “Timely delivering innovative product-services,
  In very dynamic and unpredictable global environments”
RobustPlaNet
Shock-robust Design of Plants and their Supply-Chain-Networks

Challenges

- Volatile business environment and increasing globalization
- Propagation of disturbances and risks
- Hierarchical supply chain and product-based business models

Approach

WP1: Production hierarchy
- Network level
- Plant level
- Shop-floor level

WP2: Capacity management
- Reconfiguration
- Remanufacturing
- Data gathering, maintenance

WP3: Robust planning and control tools
- Coordination
- Planning and forecasting
- Scheduling/rescheduling

WP4: Simulation and navigation cockpit
- Preactive mode
- Reactive mode

WP5: Scenarios

Impacts

- Achieve Collaborative and robust Production Networks
- Increase production system resilience to unexpected disturbances
- Increase service level

Consortium

Industrial Partners
- MCM
- ITConsult
- FESTO
- voestalpine

Academic Partners
- MTA
- KIT
- University of Twente

Enschede - The Netherlands
Link Application Domains to Use Cases

**Use Case 1**
Opportunistic Maintenance

OMA, ITC, FESTO, MAR, MCM, KIT, POLIMI

**Use Case 2**
Robust Planning and Scheduling
Remanufacturing

KNORR, ITC, MAR, MCM, SZTAKI, POLIMI

**Use Case 3**
Reconfiguration

VPN, MCM, FESTO, ITC, SZTAKI, POLIMI, TWENTE

**Use Case 4**
Supply Chain

FESTO

SZTAKI, KIT, POLIMI, FESTO, MAR, MCM, TWENTE, VPN, SZTAKI, KNORR, ITC
Maintenance use case: OMA

Officine Meccaniche Aeronautiche – Foligno, ITALY

- Privately held Italian aerospace Company
- Established in 1950
- Located in Foligno (150 Km North of Rome)
- Currently 600 employees (40 in the Design & Development Department and 20 in the Production Engineering)
- Revenues in the range of 70 Million Euro
- website: www.omafoligno.it
OMA Use Case: Manufacturing of complex aeronautics parts.

Product features:
Critical structural titanium parts.
Small lots, large variability parts.
Complex shape.

System and process features:
3 cutting tools storage units (400 tools each).
8-20 cutting hours.
80% of material is removed.

Specific Challenges:
• Service level strongly affected by corrective maintenance operations.
• Extended tool-life planning times by pre-process experiments (130 hours).
• Conservative and expensive tool management policy (no condition monitoring).
RobustPlaNet opportunistic maintenance solution and architecture

State-based production and opportunistic maintenance planning (+ 20% service level).

Machine degradation monitoring by fingerprint cycles (identification of 5 degradation modes).

Tool condition monitoring by data fusion of process and in-process tool wear data (-70% tool-life planning time, 40 hours).
Multi-sensor data fusion for tool wear monitoring

What does it do?

- In-situ measurement of single cutter radius (proxy of tool wear)
- In-process monitoring of torque/power signals via GEM system (proxy of tool wear)
- Chip thickness simulation via Vericut for torque/power signal normalization
- FUSION

In line procedure for tool wear monitoring and optimization of replacement strategy.
Fingerprint analysis for machine degradation monitoring

What does it do?

• Automatic execution of **fingerprint cycle** via the jFMX Supervisor (current frequency: twice per week)

• Duration: 33 minutes

• Cycles divided into eight sections, i.e., sequences of operations

---

**RPN-FP-CYCLE_V2.PRG file**

```plaintext
;==============================================================================
; RobustPlaNet OMA Use Case
; Machine Fingerprint cycle
; Author: Vittorio Lorenzi, Roberto Galilei, Luigi Calegari - MCM
; Version: V2 10/02/2016
;==============================================================================
;
; Gem Parameters
; ===============
; H20 - Program Version
; H21 - Program Section
; H22 - Axis or Spindle Speed
;
; Sections
; =========
; H21 = 99 Initial Axes positioning
;   Feed = 5000
; H21 = 1 X Axis incremental positioning with inversion
;   From X = -800 to X = +800
;   5 Steps = +400/-100, Feed = 500
;   From X = +800 to X = -800
;   5 Steps = -400/+100, Feed = 1000
;   From X = -800 to X = +800
;   5 Steps = +400/-100, Feed = 2000
; H21 = 2 Y Axis incremental positioning with inversion
;   From Y = +90 to Y = +1390
;   6 Steps = +300/-100, Feed = 500
;   From Y = +1390 to Y = +90
;   6 Steps = -300/+100, Feed = 1000
;   From Y = +90 to Y = +1390
;   6 Steps = +300/-100, Feed = 2000
; H21 = 3 Z Axis incremental positioning with inversion
;   From Z = +80 to Z = +1490
;   6 Steps = +305/-100, Feed = 500
;   From Z = +1490 to Z = +80
;   6 Steps = -305/+100, Feed = 1000
;   From Z = +80 to Z = +1490
;   6 Steps = +305/-100, Feed = 2000
; H21 = 4 B Axis incremental positioning with inversion
;   From B = +0 to B = +360
```

---
How it works?

Multi-sensor signature of first 34 fingerprint cycles (4 months)
Fingerprint analysis for machine degradation monitoring

**Results**

Example: **Faulty cycle 1:** intermittent modification of the feed - Z axis (representative of an anomalous glide along the linear guide)
Integrated Maintenance and production planning

- Production orders
- Deliveries dates
- Machines assignments

- Reliability
- Machine speed
- Buffer configuration

Production Plan

<table>
<thead>
<tr>
<th>M1</th>
<th>1,2,3,4,5,6</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>1,2,3,4,5,6</td>
</tr>
</tbody>
</table>

Initial component states

Production and Maintenance Mgr.

Optimization algorithms

State model of the system

Process chain model

Evaluator

Integrated production and maintenance plan

- When to produce
- When to maintain
- Completion times

Lot completion time

Service levels under alternative policies

Tardiness

Production and Maintenance Plan

<table>
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Lot completion time

Service levels under alternative policies

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Lot completion time

Service levels under alternative policies

Tardiness
RobustPlaNet Relevant Exploitation Stories

A list of 8 new exploitable products have been elaborated. The most promising business opportunities are as follows:

- **MARPOSS** will include the multi-sensor solution, including the laser pre-setter and data fusion algorithms, as a technology for the direct tool condition monitoring in complex machining operations.

- **MCM** will include the sensors and the software for machine signature monitoring as an additional service to the machine tool users for monitoring the state of degradation of critical components.

- **Technology Transfer Ltd.** has been established in Hungary by SZTAKI, partially based on RPN results, to bring to the market the RPN cockpit.

- **Teckno**, a spin-off of Politecnico di Milano, established in cooperation with MCM, will exploit the technology and the software for the efficient planning of the tool life in complex machining operations.
Robust production planning case

- More than 150 products variants with fluctuating customer orders
- Unbalanced utilization of the resources
- Stochastic effect (varying cycle times and reject rates, machine break downs)
- High number of diverse quality parameters causing rework (e.g. test failures, process times)
Robust production planning case

Data gathering
- Combination of ERP (planning) and MES (shop-floor sensor) data
- Merge and process data to use in simulation models

Simulation analysis
- Import shop-floor data in the simulation model (stochastic effects)
- Run simulation experiment to project the behaviour of the system

Data analysis
- Process the simulation-provided data
- Build regression models to predict the real capacity requirements of production scenarios

Production planning
- Integrate regression models in mathematical optimization programs
- Optimize the production plan applying the regression functions

Real-time data aggregation
Simulation data based statistical learning
Optimization

Robust planning method covering the full intra-plant process chain
Knorr Bremse use case
“Premium quality remanufactured products are set to play an even more important part in Knorr-Bremse’s business... And so we are bundling our remanufacturing expertise and increasing our production capacities”.

Wolfgang Krinner, Member of the Executive Board. [Source: Knorr-Bremse invests heavily in remanufacturing business].

The current remanufacturing process is carried out in a plant of 9,000 m² in Czech Republic, for 300 individual product types.

After remanufacturing, the components are re-assembled in Germany.
Knorr Bremse remanufacturing use case

Remanufacturing of mechatronic parts for the automotive aftermarket as a sustainable circular economy business.

Process-chain:
- Input Post consumer part
- Visual Check by the operator
- Operator Reman decision
- Disassembly
- Cleaning
- Final Inspection
- Good for reassembly
- Scrap

Challenges:
- Large variability in the condition of the post consumer products.
- Remanufacturing decisions are taken by the operator based on Standard Operations Sheets – SOS. The resulting regeneration rate is 0.7.
To propose a **Decision Support System** to adapt the disassembly strategy in feed-forward mode, depending on the quality conditions of the input post-consumer products.
RobustPlaNet remanufacturing solution

- Classification of 60 post-consumer parts according to the following criteria.
- Complete disassembly of the test parts. Analysis of the task feasibility and times and derivation of the disassembly precedence graph.
- Statistical analysis of the results by ANOVA and identification of significant quality features:
  - Age of the product.
  - Level of Corrosion.
  - Level of contamination.

Quality Classification Criteria

<table>
<thead>
<tr>
<th>Quality Feature</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damages on the main body</td>
<td>D4: Very Dirty</td>
</tr>
<tr>
<td>Corrosion on the screws</td>
<td>On the Top</td>
</tr>
<tr>
<td>Corrosion on the main body</td>
<td>On the Frame</td>
</tr>
<tr>
<td>Painted / not Pained</td>
<td>On the Holes</td>
</tr>
<tr>
<td>Dirtiness</td>
<td>On the Fixing Holes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Age of the product</th>
<th>Quality Class</th>
<th>Quantity Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2008</td>
<td>Q1</td>
<td>Damages on the main body, Corrosion on the screws, Corrosion on the main body, Painted / not Pained</td>
</tr>
<tr>
<td>&gt;2007</td>
<td>Q2</td>
<td>Damages on the main body, Corrosion on the screws, Corrosion on the main body, Painted / not Pained</td>
</tr>
<tr>
<td>&lt;2008</td>
<td>Q3</td>
<td>Damages on the main body, Corrosion on the screws, Corrosion on the main body, Painted / not Pained</td>
</tr>
<tr>
<td>&gt;2007</td>
<td>Q4</td>
<td>Damages on the main body, Corrosion on the screws, Corrosion on the main body, Painted / not Pained</td>
</tr>
<tr>
<td>&gt;2007</td>
<td>Q5</td>
<td>Damages on the main body, Corrosion on the screws, Corrosion on the main body, Painted / not Pained</td>
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<tr>
<td>&gt;2007</td>
<td>Q6</td>
<td>Damages on the main body, Corrosion on the screws, Corrosion on the main body, Painted / not Pained</td>
</tr>
</tbody>
</table>
Decision Support System - architecture

- Regeneration rate > 0.8
- Disassembly time reduction = -15%.

Part inspection and classification

Optical Character Recognition

Hyperspectral Imaging System

Quality Class of the part under processing
RobustPlaNet remanufacturing solution for Circular Economy: Economic Impact Evaluation

<table>
<thead>
<tr>
<th>Year</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly additional turnover with Reman Products due to the increase of efficiency and robustness brought by the RPN solution</td>
<td>0,50%</td>
<td>1,00%</td>
<td>1,50%</td>
<td>2,00%</td>
<td>2,50%</td>
<td>3,00%</td>
</tr>
<tr>
<td>Additional Cores Collected per Year [Million Units]</td>
<td>0,18</td>
<td>0,53</td>
<td>1,05</td>
<td>1,75</td>
<td>2,63</td>
<td>3,68</td>
</tr>
<tr>
<td>Yearly Saving for End Consumer [Meuro]</td>
<td>49,00</td>
<td>98,00</td>
<td>147,00</td>
<td>196,00</td>
<td>245,00</td>
<td>294,00</td>
</tr>
<tr>
<td>Cumulative Savings for End Consumer [Meuro]</td>
<td>49,00</td>
<td>147,00</td>
<td>294,00</td>
<td>490,00</td>
<td>735,00</td>
<td>1029,00</td>
</tr>
</tbody>
</table>

Added value of RPN extended to the EU automotive remanufacturing industry.
Pilot Idea: Application Domain

The main objective of the De-and Remanufacturing pilot network is to integrate a multidisciplinary set of advanced and innovative enabling technologies and digital innovations (TRL 7-8) and to exploit the regional Smart Specializations in synergic way to offer services to European end-users, mainly manufacturing companies, to solve specific sustainability-oriented problems related to their products.

The pilot network nodes will act as Innovation Hubs for Circular Economy, being a network of competence and technology centers and supporting future producer-driven replication at industrial scale (TRL 9).
Strategy: demonstrating integrated innovative solutions and de-risking private investments in Circular Economy

G7 Summit Declaration June 2015: The G7 Alliance on Resource Efficiency promotes Circular Economy, Remanufacturing and Recycling as strategic actions.

At European level, the Commission has launched in December 2015 the strategic initiative “Closing the loop - An EU action plan for the Circular Economy”.

H2020 R&I projects under the Focus Area “Industry 2020 in the Circular Economy”, calls CIRC, Spire and FOF, at TRL 6-7.

Lack of infrastructures that can demonstrate to industry integrated circular economy solutions and business models, de-risking the private investment.

These Innovation Hubs should act as “technology gateways” that any business sector can use.
A detailed analysis of specific sectorial Use Cases has been performed, involving the related industrial partners, in order to estimate the effectiveness of the Pilot Network business model.
A document has been delivered to the Vanguard ESM Steering Committee reporting the current configuration of the Pilot Network, the operational Business Plan, and the Governance of the Pilots.

For more information contact:
Prof. Marcello Colledani (Polimi): European Coordinator of the Vanguard ESM “De-and Remanufacturing” for Circular Economy Pilot Network.

### Region | Technical contact | Organization | Email
--- | --- | --- | ---
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Regional requirements

North America
Latin America
Europe
Asia

Challenge: Product Range Complexity

4 main product groups

30,000 catalog products

Million variants (customer specific)

Customer requirements

Approx. 300,000 customers

Industrial requirements

Focus industries:
- Automotive
- F&B
- ELA
- Bio & Pharma
- Industrial Water
- End Line Packaging
- Chemicals
Reconfigurable Supply Chain Networks
Challenges and Objectives

Business environment
Fluctuations over time

| Demand | Labour costs | Tariff barriers |

Global

Costs

Delivery reliability

Alternatives
Sourcing / Production / Distribution

Global
Local for Local

Status quo

Reconfiguration strategy

Identification of an optimal reconfiguration strategy of the supply chain network of FESTO AG
### AS-IS situation | objectives

<table>
<thead>
<tr>
<th>Scope</th>
<th>Objective</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategic</td>
<td>▪ Design support for supply chain configurations</td>
<td>Modular Toolbox</td>
</tr>
<tr>
<td>Tactical</td>
<td>▪ Identification of an optimal (re-) configuration strategy</td>
<td></td>
</tr>
<tr>
<td>Operational</td>
<td>▪ Evaluation of configurations in an agent-based stochastic environment</td>
<td>anylogic®</td>
</tr>
</tbody>
</table>

**Integrated decision-support for reconfigurable supply chain networks**
Simulation

- Building supply network model dynamically
- Visualizing supply chain operations
- Evaluating optimized reconfiguration policies in a dynamic and uncertain environment
- Performing what-if analyses for decision support
Details of the Demo | Results

**Methodological**
- Integrated planning workflow
- Generation and analysis of different network scenarios
- Integration of changeability in network planning
- Multi-level analysis tool for identification of disruptive parameters

**Facts and Figures**

<table>
<thead>
<tr>
<th></th>
<th>Time - to- serve</th>
<th>Delivery class reliability</th>
<th>OEE</th>
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<tbody>
<tr>
<td></td>
<td>- 12%</td>
<td>+ 10%</td>
<td>+ 3-5%</td>
</tr>
</tbody>
</table>

**Potentials**

- Network level
- Plant level
- System level

**Enabler**
- ~40 analysed and evaluated design scenarios
- Action lists with potential change enabler
- Implementation plan for reconfiguration process
RobustPlaNet Dissemination Events

Industrial dissemination events
- Constructeurdag 2014, NL
- Cluster Tecnologico Nazionale Fabbrica Intelligente, Milan, Italy
- Important EU industrial fairs: Fastener Fair, INDISTRIE, MSV NIITRA, INTEC

Planned demonstration events:
- Hanover Fair 2016.
- Industrial Technologies in Amsterdam 2016.
- Project workshop in Italy, September 2016.

Other activities
- Regular Newsletter.
- Linked page.
- Exploitation and valorization workshop.

Important academic events
- Special track at MIM 2016.

Overview of scientific outputs:

<table>
<thead>
<tr>
<th>Academic dissemination</th>
<th>Planned in DOW</th>
<th>Total by M24</th>
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</thead>
<tbody>
<tr>
<td>Conference Papers</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>Journal papers</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Successful PhD works</td>
<td>3</td>
<td>6 active</td>
</tr>
<tr>
<td>RobustPlaNet Workshops, Special Tracks or events</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Courses Including RobustPlaNet R&amp;D results.</td>
<td>4</td>
<td>3</td>
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</table>


### Global trends

- Reconfigurability, flexibility and co-evolution, i.e. frequent changes.
- Increasing complexity:
  - Product variants and features;
  - Globally distributed suppliers.
- New ICT for Manufacturing.
- Customization and Personalization of products.
- Sustainable Manufacturing.
- New inspection technologies.

### Challenges for the EU Industry

- Quality performance after the system ramp-up.
- More demanding specifications.
- Additional burden on diagnostics and root-cause analysis.
- Need to manage big data.
- Small lot and one-of-a-kind productions.
- Material re-use and zero-waste.
- 100%, in-line inspections.

"Zero Defect Manufacturing" is an emerging paradigm aiming at going beyond traditional six-sigma approaches in highly technology intensive and strategic manufacturing sectors through knowledge-based approaches.
Addressed Markets and Industries

**SUSTAINABLE TRANSPORT**
- Mass production of electrical drives

**CLEAN ENERGY: WIND POWER**
- Precise large-part machining of components for the gearbox

**AGEING SOCIETY**
- Micro-intravascular catheters production
  - European Medical Techn. Sector:
  1. Innovative industry.
  2. 90 Billion Euros Market in EU (33% of world market share).
  3. Growing at a rate of 5-6% per year.

European Windmill Sector:
1. Markets growth of 130.000 M€ by 2015
2. New higher power producing windmills require bigger components.

Bosch
Gamesa
ENKI
Production of electric drives for the E-mobility sector.

**Challenges:**
- End-of-line product functionality assessment (magnetic torque verification).
- Inefficient feedback on the processes.
- Need for in-line quality control.
**Solutions:**
- New sensor for measuring the magnetic field contribution of each magnet in each stack -> **in-line inspection stage**.
- Prognosis model to relate the rotor magnetic intensity distribution to the single stack magnetization profiles.
- New intelligent **rotor assembly strategies** (rotation adjustment, selective assembly).
Bosch – Electric Drives Assembly

Inspection

New tolerance-oriented assembly strategies

1- Optimized Assembly

<table>
<thead>
<tr>
<th>Strategy</th>
<th>$E^{Eff}$ [parts/t.u]</th>
<th>$E$ [parts/t.u]</th>
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</thead>
<tbody>
<tr>
<td>Base line</td>
<td>0.5752</td>
<td>0.6</td>
</tr>
<tr>
<td>Optimized rotor assembly</td>
<td>0.6704</td>
<td>0.6</td>
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<tr>
<td>Selective Assembly</td>
<td>0.6261</td>
<td>0.6</td>
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</table>

2- Selective Assembly

- Optimized Assembly: 0.6261 (55%)
- Selective Assembly: 0.6261 (35%)

⇒ rotor within tolerances although single stacks show deviations

<table>
<thead>
<tr>
<th>Eff vs. baseline</th>
<th>Variance of Assemble Magnetization</th>
</tr>
</thead>
<tbody>
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</table>
Demonstrator at Bosch GmbH- Stuttgart, Feuerbach

Optimal rotor assembly station.

Inspection device.

Rotor optimization software tool.
Integrated Zero Defect Manufacturing Solution for High Value Adding Multi-stage Manufacturing Systems
Consortium

<table>
<thead>
<tr>
<th>No</th>
<th>Participant organisation name</th>
<th>Short Name</th>
<th>Country</th>
<th>Role</th>
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<td>SME</td>
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</table>
Clustering Initiatives: 4ZDM and Focus

FOCUS – “Factory of the Future Clusters” is a CSA funded under the call FoF 7 – 2014 “Support for the enhancement of the impact of FoF PPP projects”

www.4zdm.eu

… more than 4 individual on-going projects!!

[Image of various logos and text]

Common targeted sectors & market applications
Common addressed manufacturing processes
Share technological approaches within ZDM
Share demonstrator cases & research results

Contribution to international standards
Common vision of a European ZDM paradigm
Contribution to a common ZDM reference architecture
RobustPlaNet — Shock-robust Design of Plants and their Supply Chain Networks

Project acronym: RobustPlaNet
Call and Contract: FP7-2013-NMP-ICT-FOF(RTD)
Grant agreement no.: 609087

RobustPlaNet:
Shock-robust Design of Plants and their Supply-Chain-Networks

FoF Impact @CRIT
10.11.2016, Vignola (MO)

Presenter: Prof. Marcello Colledani, Department of Mechanical Engineering, Politecnico di Milano, Italy