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Developing a key performance indicators tree for lean and smart production systems

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Abstract: In this paper, a tree-like structure of Key Performance Indicators (KPIs) is proposed to describe the Performance Measurement System (PMS) of a lean production system. The KPIs and their supporting measurement elements are identified and categorized in a multi-level hierarchy designed to give answers at strategic, tactical, and operational level. Examples of the dependencies between high-level decision variables, KPIs, and their measurement elements are presented with reference to the Bosch Production System (BPS) of a multinational manufacturer leader in the automotive industry. Moreover, the role and the impact of the KPIs selection in supporting, addressing, and evaluating the implementation of smart manufacturing projects in the fourth industrial revolution (I4.0) is shown.

Keywords: KPI, PMS, lean production, BPS, industry 4.0

1. INTRODUCTION

The economic crisis that started in 2008 were more detrimental to manufacturing than to services: in the five years from the beginning of 2008 to 2013, services output declined by 9% in the EU, while manufacturing output fell by 12% (Calleja Crespo, 2014). Even if the crisis adversely affected the most part of the EU companies, on the other hand significantly contributed to increase the ability of the companies to innovate, grow and create jobs.

Therefore, the survival of the companies is strongly related to the long-term competitiveness; in other words, the companies should ensure that production systems are characterized by excellent performance in terms of reliability, sustainability, flexibility, and productivity. These represent the main keywords of the modern manufacturing companies.

In order to guarantee high performance and continuous monitoring of the process control, it is necessary to identify proper indicators in supporting the decision-making process. Therefore, in a global context where the market paradigms radically change and in order to ensure long-term success, the companies need to adapt to shorter delivery times, to increased product variability, and to higher market volatility. As stated by (Goyal et al., 2006), flexible capacity is used as a competitive strategy in market segments in which there are large numbers of competitors. Consequently, the manufacturing companies characterized by complex processes, are subjected to more rigorous constraints than ever before; in most cases they are focused on compliance with low inventories, handling of demand uncertainties, standardisation of the manufacturing process, development of complex products (Mejjaouli et al., 2014) and the evaluation of the human performance affecting the production system (Boenzi et al., 2015a), (Digiesi et al., 2017).

In this context, the so-called Industry 4.0 paradigm (I4.0) represents a major opportunity for EU manufacturing companies. The innovation of I4.0 make easier to analyse machine data, helping to enhance quality and avoid faults in the production process. Although the I4.0 represents an interesting opportunity for most EU companies, the changes arising from the digital revolution, introduced different barriers and challenges for many industries. In terms of risks, companies believe that the I4.0 paradigm, if on one hand enables a greater flexibility and competitiveness of the manufacturing system, while requiring at same time a high level of system control that depends on the capacity of measuring, monitoring, and evaluating the parameters of industrial and services productivity and sustainability (Lu, 2017), (Digiesi et al., 2015). One of the major cornerstones to meet these challenges is the effective implementation of a robust monitoring and control system of the whole factory facility and of the operational performance. A production manager (at both plant or line level) may evaluate performance by analysing the KPIs, that allow to quantify the efficiency and effectiveness of actions in a part of, or in the overall production process. In this way, it is possible to evaluate the state of the systems on the basis of one or more characteristic targets (Braz, 2011). In fact, a structured framework of performance indicators is crucial in measuring the distance between the current and the desired operations, and in many case it can be used for identifying the track progress towards closing the productivity gaps (Muchiri et al., 2009), (Boenzi et al, 2015b).

Cross and Lynch (1992) propose the performance pyramid (see fig. 1) with the purpose to link the hierarchical view of business performance measurement with the business process review. On the top of the pyramid there is a corporate vision that depends on market and financial goals (e.g. market share, return on investment, etc.). At an intermediate level, objectives deal with achieving and maintaining high productivity and quality, with fast response, sufficient flexibility, and short lead times. At the bottom level there are the “operations” mainly characterized by non-financial indicators (e.g. Cycle Time, material losses, Mean Time To Failure, etc.). The pyramid points to a range of target related to both external effectiveness and internal efficiency.

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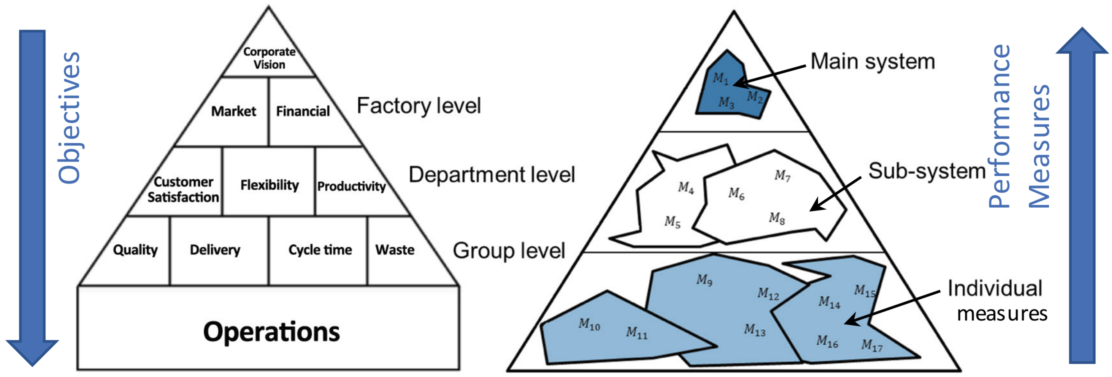

Fig. 1. The performance pyramids. Adapted from (Cross and Lynch, 1992) and (Tangen, 2004)

These objectives can be achieved through measures at various levels in the hierarchy as shown in the pyramid at the right side of figure 1. The measures interact with each other both horizontally at each level, and vertically across the levels in the pyramid. (Tangen, 2004).

Obviously, the pyramid is a tool that requires to be adapted to different industrial contexts, and it represents a very interesting approach for implementing a Performance Measurement Systems (PMS) in a competitive company. The design of the whole framework, the identification of the proper Key Performance Indicators (KPIs) and the implementation of the monitoring system, represents currently the real challenge for most manufacturing plants.

For this purpose, in this paper is proposed a description of the PMS represented as a KPIs tree structured with reference to the lean production system of a multinational manufacturer leader in the automotive industry is proposed. The production plant belongs to the Bosch Group and is located in the South of Italy. In particular is evaluated the impact of the KPIs selection in supporting, addressing, and evaluating steps for the implementation of smart manufacturing projects in I4.0 is evaluated.

The paper is structured as follows: a state of the art of the literature on the PMS and a description of the KPI tree for a lean production system are in section 2 and section 3 respectively; in section 4 the performance evaluation of I4.0 projects is shown. Finally, conclusions are in the last section.

2. PERFORMANCE MEASUREMENT SYSTEMS

The PMSs are considered essential in manufacturing processes, since they allow monitoring and controlling the factory facilities in order to enhancing the productivity and improving the manufacturing system performance.

2.1 State of the art

A PMS consists of a set of metrics that are able to quantify the efficiency and effectiveness of manufacturing operations (Neely, 1995) according to a top down perspective, that depends from both internal and external factors. It is very interesting to note that there are not KPIs identified by this approach. Within a PMS, the strategic goals are first determined according to the companies' needs to success. Then each objective is supported by a set of detailed indicators contributing to fulfil the strategic goals. In most cases this kind of target are managed by business units.

The strategic goals above mentioned can be further differentiated into the measures that drive the business operating system, they are identified as indicator for evaluate the customer satisfaction, flexibility, and productivity. It is possible to identify in the foundation of the performance pyramid four different KPI that are evaluate by departments and work centres (Kang et al, 2016).

In manufacturing systems, once a KPI set is defined in a PMS, every parameter reflects one facet of the system performance. Therefore, KPIs are defined as a set of quantifiable and strategic measurements in a PMS that reflect the critical success factors of an enterprise. The appropriate selection and better understanding of the KPIs can help a firm achieving the desired business success.

In scientific literature many researches describe the relationships of KPIs, most of them based on data methods and apply statistical approaches. Rodriguez (2009) quantitatively investigate the cause-effect relationships of KPIs defined in a performance measurement system. A principal components analysis method is adopted in order to identify the correlations of indicators. Suwignjo (2000) developed a quantitative model for PMS in order to identify different factors affecting performance and their quantitative relationships, in this case the methodology of cognitive maps is adopted by the authors.

Further studies proposed the adoption of a process meta-model for capture the resource allocation and identify the relationship between Internet of Thing devices and the associated software using a Business Process Modelling (Meyer et al., 2013).

Recently (Kang et al., 2016) introduced a multi-level structure for the identification and analysis of KPIs and their fundamental relationships in production systems. In particular, the authors through a hierarchical structure identified multiple levels of basic KPIs; these are adopted in order to investigate the relationships and dependencies between KPIs. The study provided a useful tool for manufacturing engineers and managers to measure and utilize KPIs in the field of the continuous improvement.

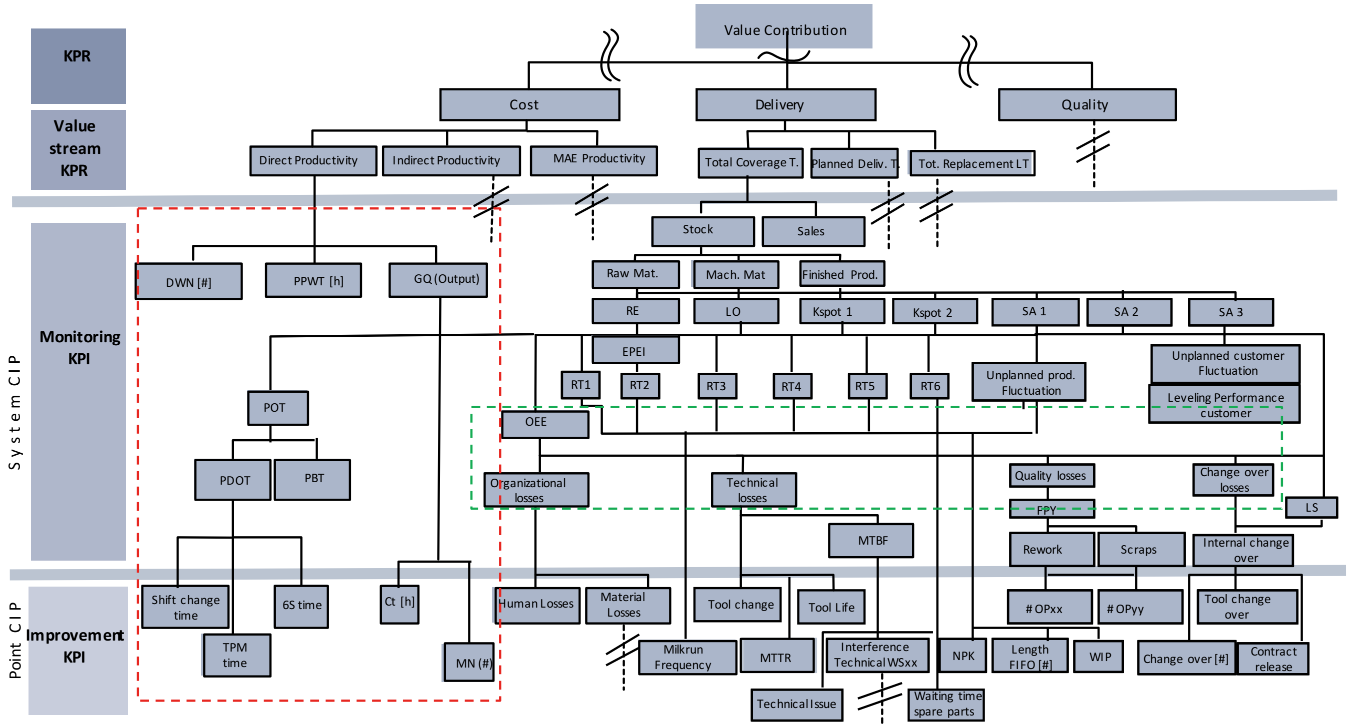

Fig. 2. BPS Performance Measurement System: the KPR/KPI tree

2.2 International Standards

According to the recommendations of the international standards ISO 22400-1:2014 and ISO 22400-2:2014, KPIs play a crucial role in understanding and improving manufacturing system performance. In particular the ISO 22400-2 describes 34 KPIs along with their contexts and contents. In order to identify the relationships among KPIs, it is convenient to group the KPIs into multiple categories characterized by different levels which have explicit cross links. In this way is possible to design a hierarchical framework that allow to indicate the casual relationship between different levels of KPI and supporting elements (Kang et al., 2016).

The Supporting Elements (SE) are the data directly monitored and collected during the production phases. The first element of SE is represented by time elements that identify the time of the production systems, including the activities related to production and maintenance. This parameter can be measured from the points of view of a machine, a production order, or an operator. In this context the time periods can be categorized as planned time and actual time (due to breakdowns, unbalancing, etc.).

The Quantity Elements (QE) provide information on issues related to product quality and quantity. Most important parameters included in QE are: good quantity, scrap quantity, planned scrap quantity, rework quantity, etc.

Finally, the last category is represented by Maintenance Elements (ME) that includes the information related to maintenance and repair issues of machines (e.g. time to failure, operating time between failures, time to repair, etc.)

3. DESIGN OF A KPI TREE FOR LEAN PRODUCTION SYSTEMS

The Bosch execution of Lean Manufacturing is called Bosch Production System (BPS) and it is implemented through a holistic approach called “System CIP - Continuous Improvement Process”.

The vision of BPS tends to the customer satisfaction and continuous improvement of overall value contribution by eliminating waste in the production system and pursuing the ideal state of: 100% delivery, 100% value added, zero defects, one-piece flow. Key tools of BPS are the Value Stream Mapping (VSM) and the Value Stream Design (VSD) where VSM is used to map the current state of the process and VSD is used to identify the target state.

The core element of the approach is the strong link between the key performance indicators and the improvement measures and actions thus enabling the coherence of the designed and implemented activities with the plant/value stream strategy.

All improvement projects are identified during system Continuous Improvement Process (CIP) meetings, where KPI trees are used to identify and prioritize the actions on reliable quantitative indicators. Point CIP (local visual boards) are then used as the systematic approach that ensures visual monitoring and control of results at shop floor level.

The approach ensures that all improvements have a clear impact on performance and that all activities are carried out based on business needs and strategic objectives.

3.1 KPI tree structure

A PMS is required to measure performance at a specific level and cover the effect that different KPIs have on each other. The five-level hierarchical structures of indicators are named in the BPS as KPR/KPI trees (see fig. 2).

At the top level we have the Value Contribution, then, descending the structure, the Key Performance Results (KPR), the Value stream KPRs, the Monitoring KPIs, and finally the Improvement KPIs. At the KPR level synthetic performance measures as Total Cost, Delivery Service, and Quality contribute to determine the overall value of a given value stream (product or area).

The value stream level describes aggregated performances in each of the field cost, delivery, and quality. The specific KPI for a given area of the shop floor system is calculated at the monitoring level.

The detailed measuring of elementary performance is performed at the so-called improvement level where the losses in performance can be identified and measured allowing the design of proper actions for the performance raising.

All the KPIs are derived from the measurement elements. Since one element can be used in the calculations of several KPIs, it is possible that KPIs can be affected by interdependency. All the levels are cross-linked through the KPIs.

3.2 KPIs identification and description

As an example, we can explore one of the value stream KPR in the Cost domain. The focus is on the Direct Productivity (PDIR) (u/h) of the shop floor workforce in the time horizon of the evaluation (usually a shift) with reference to a given product (value stream).

It is calculated as:

$$PDIR = GQ / (DWN\ PPWT) \quad (1)$$

where, GQ is the produced good quantity (u) (output of the system in the time horizon), DWN is the planned number of direct workers (num), the workforce who carry out specific production activities in the shop floor, and PPWT is the planned working time per person (h).

GQ is calculated as:

$$GQ = (POT)\ (MN)\ (OEE) / CT \quad (2)$$

where, POT is the Planned Operation Time (h), MN is the number of the parallel operating machine (num), CT is the Cycle Time (h/u), and OEE is the Overall Equipment Effectiveness.

OEE depends on quality losses, technical efficiency, and process efficiency (organizational and change over losses). These dependencies are not here investigated.

POT is calculated as:

$$POT = PBT + PDOT \quad (3)$$

where, PBT is the Planned Busy Time (h) and PDOT is the Planned Downtime (h) (or machine stop). PDOT depends on the non-productive time of the worker spent in indirect activities as shift change (SCT), total productive maintenance (TPMT), and lean manufacturing (6sT). Therefore, PDOT can be calculated as:

$$PDOT = SCT + TPMT + 6sT \quad (4)$$

In figure 2 the path from the measured elements (in both the time and the quantity domains), up to the monitoring KPIs, and finally to the direct productivity KPR is highlighted as well as the relationships between OEE and the causing losses.

4. PERFORMANCE EVALUATION OF I4.0 PROJECTS

The innovation of the so-called I4.0 paradigm enables easier collecting and analysing of machine and field data, helping to enhance quality and to avoid faults in the shop floor production process. In order to ensuring high performance and continuous monitoring of the I4.0 projects, it is necessary to identify available indicators to support the entire decision-making process in both the design and the execution and control phases.

The area of intervention of the I4.0 projects in the different process cycles known as “Source”, “Make”, and “Deliver” are represented in fig 3. The main objectives and features of the I4.0 projects are briefly described as follows.

#1. Information Technology between BTO Customer and Heijunka Board. The Build to Order (BTO) customer send daily the order to the system within a defined time window. The customer is connected to the BPS via the dedicated web-based application. The system generates automatically the production Kanban cards and put them in the related BTO slot of the digital Heijunka board. The application allows real time process control (confirmation of components availability and status of the order compared with planned time budget).

#2. Digital Heijunka Board. Logistics dpt. develops the levelling pattern for assembly following the standard levelling rules. Logistics dpt. sends the assembly program automatically to the digital Heijunka board in the assembly and machining area. Levelling performance is calculated automatically (no manual intervention).

#3. Intelligent Supermarket (SM). RFID gate declares automatically the goods while they pass. Portable devices assure real time visualization of SNR, MAX, MIN, current stock, for each FIFO lane in SM, alert message in case of Under/Over stock. Active Cockpit shows the current stock for all runner products and the analysis of the past days as well as the former levelling period (base for the next SM stock level calculation). Possibility to carry out an immediate comparison between physical inventory and SAP data.

#4. Interactive Milkrunner. Just in time monitoring of transported materials (including empty packaging). Precise time-tracking and on-line visualization of Milk runner position along the route through automatic data recording.

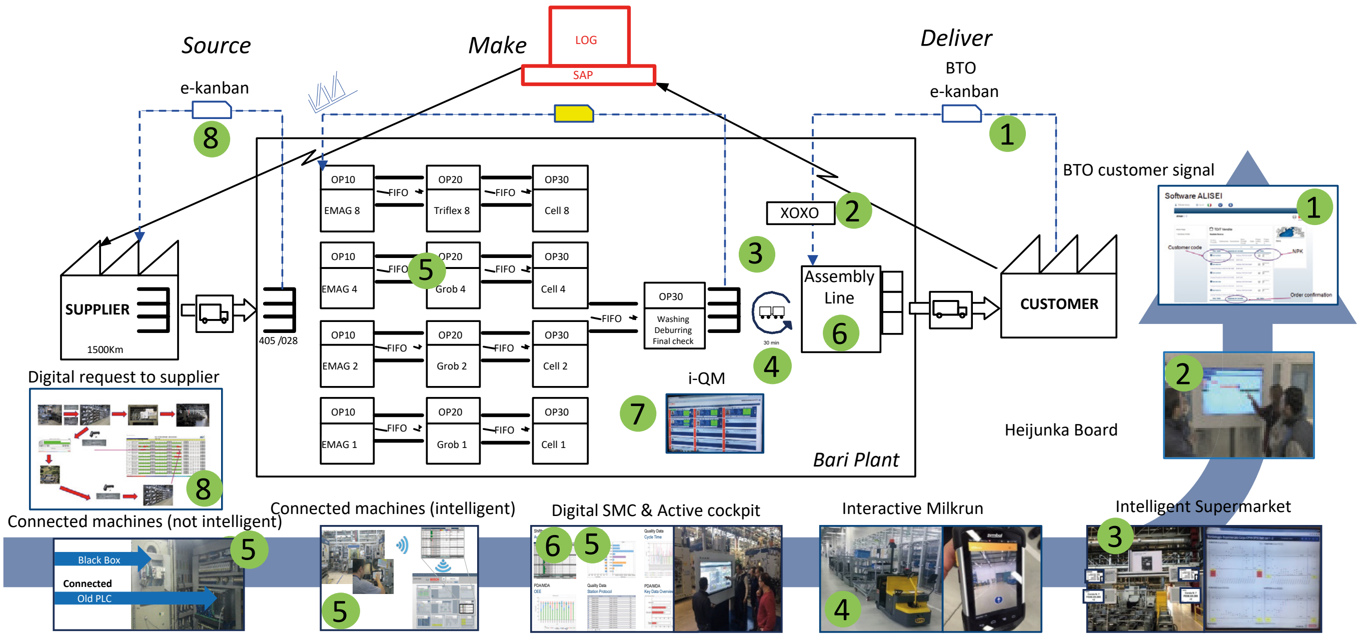

Fig. 3. The BPS value chain and the area of intervention of the I4.0 projects

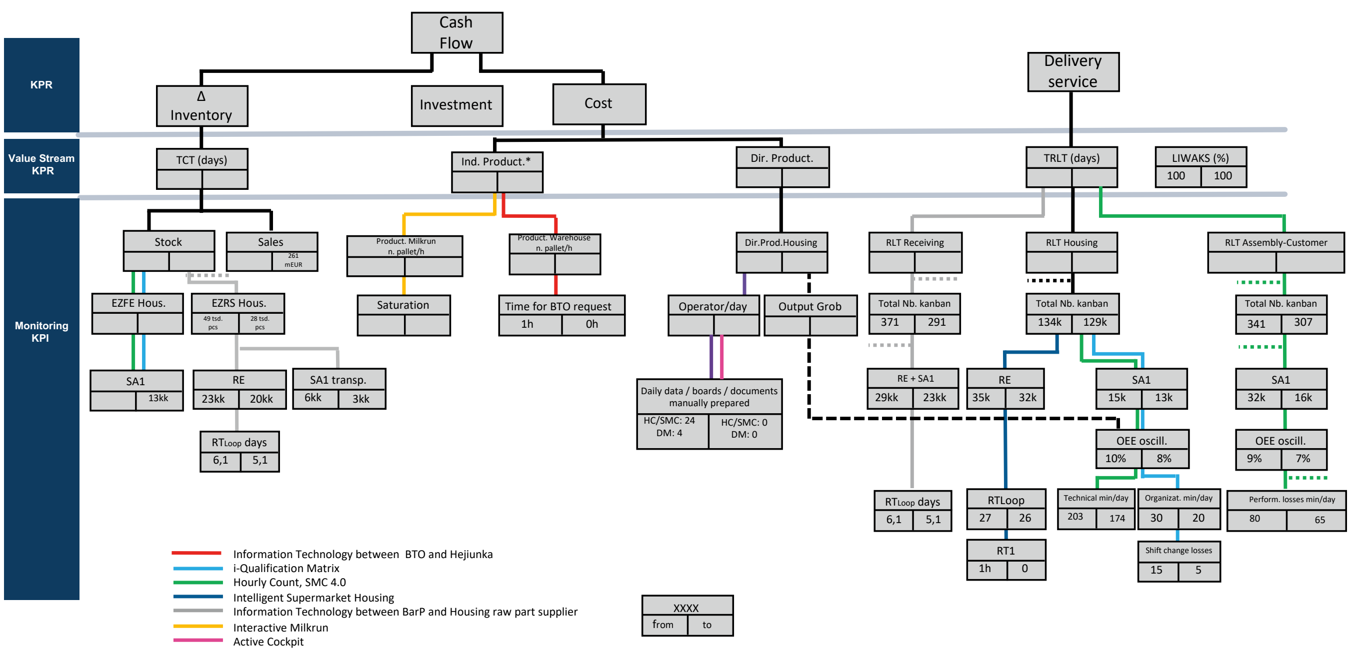

Fig. 4. Correlation of monitoring KPIs and relevant KPR in the I4.0 projects

#5a. Connected "not intelligent" machines. PLC of "old machines" is connected with a so called "Black Box" (dedicated hardware) allowing automatic data transfer from machine by an internally developed software (low cost solution). Functions of Black Box are comparable to MES ones.

#5b. Connected "intelligent" machines. PLCs of CNC Work Centres are connected to MES data-base. OpCon portal is used to check the real time status of machine and related process data.

#6. SMC 4.0. Connection of intelligent/not intelligent machines enables automatic collecting of data and calculation of KPIs: hourly count, cycle time, Pareto analysis, OEE, etc. Active Cockpit is the interactive user interface to visualize and managing data directly in the shop-floor thus enabling the continuous improvement activities in daily Shop Floor Management.

#7. i-Qualification Matrix. Connected Qualification Matrix (QM) for shop floor operators. Assignment of machine to the operator is supported by i-QM which automatically cross-checks the requested and available qualification of operators. Future project extension: possibility to link machine and operator by personal badge.

#8. Information technology between the plant and raw part supplier. Development of a new software on the existing platform (F@CTORY) connecting the plant to the supplier. After picking-up of raw material from the supermarket, the kanban card is read by barcode and the data are used to optimize supplier transport by truck, defining the composition of a virtual lot. All information and data are automatically transferred to the supplier when the virtual lot is ready.

Definitions of the specific targets, monitoring of the activities, and evaluations of the impacts of the projects can be performed by the design of dedicated KPI trees as shown in fig. 4. In the tree the information flows are tracked by different colours enabling the decision-making process from the measured elements to the derived KPIs and KPRs.

The values of the main KPRs and KPIs identified to evaluate the performance at the final stage of each of the I4.0 projects are shown in table 1.

Table 1. Final values of KPRs and KPIs for I4.0 projects

Project id	*1*	*2*	*3*	*4*	*6*	*7*	*8*
Direct Productivity					+2,0 %		
Indirect Productivity	+2,0 %	+1,5 %	+1,0 %	+1,5 %		+0,5 %	+1,8 %
OEE					+1,0 %		
Resource Saturation				+7,0 %			
RTLT [day]							-1,0
Errors [#]			0		-25%		
Indirect Costs (*)			-75k€				

(*) paper sheets

5. CONCLUSIONS

The hierarchical structure of KPIs proposed allows supporting and measuring the performance under strategical, tactical and operational perspective. The KPI structure provides a useful tool for manufacturing engineers and managers in measuring the performance of the studied BPS and allows identifying the relationships among the different KPIs, consistently with operational improvement and floor shop control.

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